The Climate of the Bay of Plenty: Past and Future?

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Contents

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Executive Summary

This report describes the past climate variability and trends for the Bay of Plenty region and presents scenarios for future climate change over the next 50 to 100 years. The following summary has been divided into four parts: climate data, observed climate variability, causes of climate variability, and scenarios of future climate.

Climate Data:

DATA QUALITY: Homogeneity tests (to assess the quality of the data record) were performed on all the climate data used for this report and composite records of data from two or more nearby climate stations were constructed, where necessary, to extend the length of the data records.

REFERENCE STATIONS: Reference climate stations representing high-quality currently operating climate stations with long records have been identified. These stations will be used to monitor climate variability and change in the Bay of Plenty into the future. Recommended rainfall reference stations are Tauranga Airport B76621/B76624, Opotiki B87023, Environment B·O·P Whakarewarewa 86124, and Motu B87251/87255. The recommended temperature reference station is Tauranga Airport B76621/B76624.

Observed Climate Variability:

RAINFALL: Total annual rainfall has generally decreased in the Bay of Plenty since the 1960s or 1970s, but this reduction is only statistically significant at Tauranga where the annual rainfall total has decreased at the rate of 25 mm per decade over this station's period of record: 1910-2002. Seasonal rainfall has decreased over most of the region in most seasons. Decreases have been larger in the west (Tauranga westwards) than in the east (Whakatane eastwards) and south.

RAIN DAYS: There has been a significant, long-term trend towards fewer rain days at Tauranga, Opotiki, and Kaingaroa over the last 100 years, with much of this reduction occurring since the 1960s or 1970s. The reduction is in the order of 1.5 fewer days of rain per decade.

EXTREME DAILY RAINFALL: In the last 30 years (since about 1970) extreme daily rainfall totals have been generally lower, by about 20 mm, than prior to 1970 (at least at coastal or lower elevation stations). The frequency of extreme large daily rainfall has decreased across the Bay of Plenty over the last 100 or so years, but this decrease is significant only at Tauranga at a rate of 0.2 days per decade. The climate of the last 30 years (since the 1970s) has been atypical, in that extreme daily rainfalls have been less frequent than recorded elsewhere in the historical climate record.

DRY SPELLS: The duration of extended dry spells has reduced over the 20th century at Whakarewarewa, with a decline in the extended dry spell duration of around 0.3 days per decade. A weakly significant decline of the same size is observed at Motu, and Tauranga.

AIR TEMPERATURE: All stations show a warming trend in the mean annual air temperature of approximately 0.1 °C per decade over the last 100 years. It is noticeable that Tauranga, the best temperature record in the Bay of Plenty (highest quality, least missing data), recorded very high temperatures in the 1990s. This has been observed elsewhere in New Zealand, with the 1990s being the warmest decade in the last 100 years. Over the 50-year period 1951-2000, mean seasonal temperatures in the Bay of Plenty have increased substantially along the coast by up to 0.2 °C per decade, while inland southern parts of the region have shown little warming, and have even cooled slightly in some seasons.

FROSTS: Air frosts have significantly decreased in the Bay of Plenty since good-quality, daily temperature records began in 1940. They have become rare events in Tauranga, averaging less than one air frost per year in recent times.

COLDEST NIGHTS: The coldest nights have significantly warmed in the Bay of Plenty since 1940 (+0.3 °C per decade), with the greatest warming seen at some stations since 1960, and again following 1976. The number of extremely cold nights has significantly decreased.

MAXIMUM TEMPERATURE: The number of days with maximum temperatures exceeding 25 °C has significantly increased at Tauranga (+0.2 days per decade) and Waihi (+0.4 days per decade) since 1940, while the extreme temperature range (hottest minus coldest temperatures of the year) has significantly decreased in Whakarewarewa (-1.1 °C per decade) and Te Aroha (-0.3 °C per decade).

HOTTEST DAYS: The hottest days have significantly warmed in Tauranga and Waihi (+0.2 to 0.4 °C per decade) since 1940. Most of the warming occurred since 1968 at several of the sites analysed. The frequency of hot days at Tauranga and Waihi has also increased since 1940 by about 1 day per decade.

Causes of Climate Variability:

THE SOUTHERN OSCILLATION: During La Niña periods, both the temperature and rainfall are generally above normal for the Bay of Plenty region, while they are both generally below normal during El Niño periods. The relationships are weakest in summer (Dec-Jan-Feb) and strongest in spring (Sep-Oct-Nov), however the correlations are not large, and much of the year-to-year variability of Bay of Plenty climate can not be explained by what the Southern Oscillation is doing.

RAINFALL RELATIONSHIPS: Seasonal rainfall totals and rainfall intensity for the Bay of Plenty region are shown to be directly related, thus an increase in seasonal rainfall will tend to indicate a corresponding increase in the extreme rainfall regime and vice versa.

IPO: The decrease in rainfall over much of the Bay of Plenty region since 1951, and the relatively larger decreases in the west near Tauranga, is partly attributable to increased westerly airflow over this period, corresponding to the Interdecadal Pacific Oscillation (IPO) phase change from negative to positive. The IPO appears to have switched back to a negative phase, which should result in more frequent La Niña events, higher temperatures, weaker westerlies and increased rainfall for the Bay of Plenty over the next two decades. These changes could be modified by anthropogenic long-term trends.

EXTREME RAINFALL: For very short durations (10-30 minutes), extreme rainfalls tend to be slightly higher in the positive phase of the IPO rather than in the negative phase. For durations from 60 minutes to 12 hours, the rainfalls are generally smaller in the positive phase of the IPO. However, the differences in these short durations extreme rainfall for either phase of the IPO are mostly not statistically significant. This suggests that short duration convective processes are probably not influenced very much by the phase of the IPO. For the longer durations (24-72 hours), the mean level of extreme rainfalls show mixed signals; at some sites (e.g. Whakarewarewa) rainfall is significantly lower in the positive phase of the IPO, and at other sites (e.g. Waihi) it is higher (but not significantly so).

Scenarios of Future Climate:

USE OF SCENARIOS: Climate change predictions given in this report are derived through the use of scenarios, in which a number of greenhouse gas emission pathways are constructed for the future, based on a range of plausible social, economic, and technological developments. For each of these scenarios, predictions are then made for greenhouse gas concentrations and the resulting climate changes, based on scientific understanding and incorporating science-based uncertainty ranges. The result is a set of several different climate "projections", spanning likely future emissions pathways.

SCENARIO UNCERTAINTY: The use of scenarios recognises the uncertainties in predicting future climate. These arise both from the range of possible future global greenhouse gas emissions, and from uncertainties in the computer models for predicting regional climate changes for a given change in greenhouse gas concentrations. Scenario-based future climate projections provide guidance on the range of effects which may occur, rather than definite statements about what "will" happen.

TEMPERATURE CHANGE: Projected mean annual temperature changes for the 2030s (i.e., 2020-2049) and the 2080s (i.e., 2070-2099) relative to the "current" climate (1970-1999) indicate the Bay of Plenty region warms by about +0.80°C by the 2030s (seasonally varying on average between about

+0.75°C in spring and summer to +0.90°C in winter), and by about +1.80°C by the 2080s (seasonally varying on average between about 1.65°C to 1.75°C in spring and summer to 2.00°C in winter).

RAINFALL CHANGE: Mean annual rainfall is projected to decrease in the Bay of Plenty by between about 1% and 4% by the 2030s (seasonally varying on average from a slightly wetter winter (by 0 to 4%) to a rather drier spring and summer (up to 8% drier in Tauranga in spring)), with no further drying trend by the 2080s. This "nonlinearity" in the drying (i.e., virtually all the drying occurring in the first 50 years) is typical of all the models.

SEASONAL RAINFALL CHANGES: Summer rainfall for the Bay of Plenty is projected to return to near the current climatology by the 2080s. Autumn is also projected to be wetter than currently by the 2080s, and winter also slightly wetter than the 2030s. However, the spring season is projected to get drier, and by the 2080s spring rainfall is projected to be about 10% lower throughout the region than it is at present.

EXTREME RAINFALL CHANGES: Reduced return periods of heavy rainfall are likely by the 2080s. However, it is possible that projected long-term trends in extreme rainfall will not be noticeable in the Bay of Plenty district until the latter half of the 21st century since mean rainfall changes suggest a drying trend over the next 50 years. Ex-tropical cyclones might be slightly less likely to reach New Zealand over the next 50 years, but if they do their impact might be greater.

WIND CHANGES: The mean westerly wind component across New Zealand is projected to increase by approximately 10% of its current value in the next 50 years. Westerly airflow is also projected to increase by the 2080s, but the uncertainty is much greater: it is projected that there could be almost no change up to more than double the current mean speed of westerly airflow in the annual mean. Changes in the north-south wind component are less clear, although the spread of model results suggests a bias towards more southerlies in all seasons except winter.

HIGH WIND CHANGES: On the timescale of daily weather, there are also good arguments in favour of increasing risk of high wind. Strong winds are associated both with intense convection, which is expected to increase in a warmer climate, and also with intense low-pressure systems, which might also become more common. Thus an increase in severe wind risk could occur, but we do not yet have enough information to make a quantitative prediction.

1. Introduction

Environment Bay of Plenty (also known as Environment B·O·P) promotes the sustainable management of the Bay of Plenty's natural and physical resources, and is responsible for on-going planning and policy to ensure this. The Council's main functions are:

- management of the effects of use of fresh water, coastal waters, air and land;
- biosecurity control of regional plant and animal pests;
- river management, flood control and mitigation of erosion;
- regional land transport planning and contracting of passenger service;
- harbour navigation and safety, marine pollution and oil spills;
- regional civil defence preparedness.

In order to achieve a number of the functions listed above, Environment B·O·P have commissioned NIWA to assess climate variability and climate change at the regional scale – within the Bay of Plenty. In particular, Council planners are interested in the broad changes we may see in the climate of the region looking forward 50 to 100 years.

This report will serve as a 'building block" of information for a tier of other investigations. Bringing the regional climate change scenarios together with pertinent regional problems (low flows, high flows, droughts, coastal erosion) will enable specific impact scenarios to be developed. For example, the information contained in this report will be used as a basis for an assessment of hydrological variability and change within the Bay of Plenty (report to be issued by Environment B·O·P), and similarly in a study on coastal variability and change (report to be written by NIWA). In the years ahead, other reports investigating the impacts of climate variability and change on the natural environment and the flora and fauna of the Bay of Plenty may well stem from this knowledge base. Helpful guidance on methods for assessing effects of climate variability and change on local government functions and activities will be available from two "Guidance Notes" currently under preparation for the Ministry for the Environment.[1]

In the past, significant climate variability and climate shifts have been observed in the Bay of Plenty region. There are many illustrations of the impacts that these have brought to both the local environment and community; for example, floods, droughts and coastal erosion. Past climate variability and change are described in Section 3, using climate indices, and answer the question 'how has the climate of the Bay of Plenty changed in the past?' The identification of the major climate processes contributing to this variability and change are outlined in Section 4.

Section 5 answers questions about past trends and changes in high intensity rainfalls in the Bay of Plenty. Looking forward to the future, updated climate changes scenarios are provided in Section 6, in order to better manage the associated risks and opportunities of a changing world. The latest climate change scenarios have been taken to the New Zealand scale, and then localised (down-scaled) to the Bay of Plenty region. A range of scenarios project possible changes in mean temperature and mean rainfall over the coming century.

[1] The two guidance notes which will be published during 2003 by the Ministry for the Environment are: "Overview of Climate Change Effects and Impacts – A Guidance Note for Local Government in New Zealand" and "Coastal Hazards and Climate Change - A Guidance Note for Local Government in New Zealand".

2. Existing Data Sources

Climate data used in this report were either sourced from the NIWA National Climate Database (Clidb) or Environment B·O·P. Because of the data requirements for long-term climate analysis (in Sections 3 and 5) – namely extended record length, high quality record with a minimum of site changes or alterations, and a preference for climate stations which are still operative today – the majority of data extracted for analysis were sourced from the NIWA National Climate Database. The primary reason for the non-selection of most Environment B·O·P station records was the issue of data length (i.e. the records were too short for the purposes of this report).

For each analysis in this report, the issue of data frequency arises. In Section 3, quantifying how the climate of the Bay of Plenty has changed in the past, *daily* rainfall and temperature data were used because international methods for analysis of extreme events focus on daily data. Daily data records analysed here extend back about 100 years for rainfall, and about 50 years for temperature.

In Section 5, analysing changes in high-intensity rainfall in the region, rainfall data over intervals of *between 10 minutes and 3 days* were assessed. This type of high-frequency automatic rainfall record does not usually extend very far back in time – some records started in 1967 or 1968, but most began in the 1980s or 1990s. However, manual (daily) rainfall records, at the 24-hour, 48-hour and 72-hour frequency, are much longer.

For the climate change scenario modelling in Section 6, *monthly* rainfall and temperature data were used. The aim was to assess how current climate has fluctuated in response to regional climate and circulation variations. This analysis used data from 1969 onwards. Stations were selected to minimise missing data and ensure a homogeneous record over this period.

2.1 Homogeneity Testing

Homogeneity tests (to assess the quality of the data record) were performed at each time scale. Depending on the use of the data, the rigorousness of the homogeneity testing differs.

Because *daily* data were used to analyse extreme as well as mean temperature and rainfall events, a rigorous quality control procedure was followed for daily data. All major outliers in the rainfall and temperature records were examined, and confirmation that these data were related to real meteorological events, rather than being erroneous, was made manually, with the outlier data checked against other records within the region.

Metadata (information about station instrumentation used, site location and changes in site location, observing procedures, etc) were also used to assess data record quality. Major events, such as instrumentation change or environment change, which may have altered the record stationarity, were noted down. Data were then examined using the Multiple Analysis of Series for Homogenisation (MASH) software (Szentimrey, 1996). MASH is essentially a 'nearest neighbour' analysis tool, in that it compares climate changes across a group of stations, at the monthly or annual scale. When there are divergent changes within the group, usually one station changing relative to the others, it is probable that a site change has affected this individual station record. Metadata is then used to confirm the inhomogeneity that MASH has identified.

If MASH has identified an inhomogeneity in a rainfall or temperature series, which coincides to a known metadata event (e.g. a site change, or change to automatic instrumentation), a data adjustment calculated by MASH is adopted. Otherwise, no adjustments to the record are made. Effects caused by environmental changes around a site (such as urbanization or the growth of vegetation), which may result in an observed trend in the data, were also considered. However, these effects are very difficult to quantify and in general can be disregarded if the station has been properly sited (e.g. at an open area like an airport) and the enclosure and its surrounds have been carefully maintained.

For durations from *10 minutes to 72 hours*, 9 annual rainfall maxima series were calculated for each of the four automatic gauges in the Bay of Plenty with the longest record length and the highest data quality (percentage complete). For durations from *24 hours to 72 hours*, 3 annual rainfall maxima series were also calculated for each of the four manual gauges in the Bay of Plenty (highest quality, longest record). Homogeneity testing was performed on those series where it was necessary to combine data from two nearby locations, in order to create a composite record that spanned the full 54-year period under analysis. A Wilcoxon Ranksum test was performed to see if any adjustments were needed because of series composition.

Basic outlier checks were performed on the *monthly* data used for climate change scenario modeling. At the monthly scale, gross errors are typically readily apparent, using nearest neighbour checks. The stations used in this report have been identified over a number of years as being of good quality and appropriate for the needs of climate change modeling.

The accuracy of climate data is also affected by instrumental accuracy. For example, rain gauges are known to underestimate rainfall in windy conditions. Non-recording and recording (such as the tipping bucket design) rain gauges typically have an accuracy of ± 0.1 mm, while air temperature recorded in a standard Stevenson screen at a height of 1.3 m above a grass surface can be measured with an accuracy of ± 0.1 °C (Brock and Richardson, 2001).

2.2 Extracted Data

2.2.1 Daily Rainfall Data

Homogeneity tests identified that 11 out of the 16 locations in Table 1 were suitable to be used for further analysis – these are shaded in grey. Information about each series is listed in the Appendix (section 9.1).

Table 1: Records selected for analysis of daily rainfall data (shown in grey shading).

Daily rainfall totals									
Station	Location	Records		Status	Years of record	% data	Authority	Map reference	Alt (m)
		Begin	End						
B75492	Athenree	1-Sep-1890	30-Apr-1912	closed	22	85	N/A	N/A	N/A
B75381	Waihi	1-Oct-1898	31-Dec-1989	closed	91	99	Private	T136181194	91
B75382	Waihi, Barry Rd EWS	1-Jan-1990	12-Dec-2001	closed	11	91	Waihi Gold Mining Co.	T13623198	114
B75495	Athenree	1-Oct-2000	31-Jul-2002	open	2	100	Private	T13698127	4
	Waihi composite	1-Oct-1898	12-Dec-2001		102				
B75571	Te Aroha	1-Nov-1907	31-Oct-1999	closed	92	97	Private	T13502027	18
B75562	Te Aroha, Bowler Rd	1-Aug-1992	31-Jul-2002	open	10	100	Private	T13463053	13
	Te Aroha composite	1-Nov-1907	31-Oct-1999		95				
B76621	Tauranga Airport	1-Jan-1910	31-Jan-1996	closed	86	100	Sun Air Aviation	U14924873	4
B76624	Tauranga Airport AWS	1-Jun-1990	17-Sep-2002	open	12	100	MetService	U14921874	4
	Tauranga composite	1-Jan-1910	17-Sep-2002		92				
B76991	Whakatane	1-Jul-1929	30-Jun-1950	closed	21	100	N/A	N/A	10
B76981	Thornton	1-Dec-1948	30-Apr-1995	closed	47	92	BOP Regional Council	W15507577	3

B76982	Thornton East	1-Jan-1948	30-Apr-2002	open	54	100	Private	W15505563	3
B76993	Whakatane Mill	1-Sep-1947	30-Mar-1983	closed	36	100	Whakatane Board Mill	W15584531	2
B76994	Whakatane Airport	5-Dec-1974	31-Aug-1990	closed	16	99	East Bay Flight Centre	W15544566	6
B76995	Whakatane Airport AWS	1-Aug-1990	17-Sep-2002	open	12	100	MetService	W15546568	7
B78601	Mataraoa	1-May-1913	31-Jul-2002	open	89	95	Private	Y14583801	152
B86126	Rotorua Sanitorium			no data					282
B86124	Whakarewarewa	1-Jan-1899	31-Jan-1982	closed	83	100	NZ Forest Research Inst.	U16960327	307
B86123	Rotorua Airport 1			no data			Civil Aviation	U16953333	297
B86131	Rotorua Airport 2	11-Nov-1963	31-Dec-1991	closed	28	100	Airways Corp.	U16010384	287
B86133	Rotorua Airport AWS	31-Dec-1981	17-Sep-2002	open	21	96	MetService	U16009388	283
B86341	Waiotapu Forest	1-Apr-1901	31-Oct-1997	closed	96	97	Forestry Corp. of NZ	U16093155	435
B86451	Kaingaroa Forest	1-Jul-1929	31-Mar-1999	closed	70	96	Private	V17210044	544
B86471	Murupara	1-Sep-1932	30-Jun-1987	closed	55	100	NZ Forest Service	V17325985	198
B86481	Galatea	1-Nov-1954	31-Jul-2002	open	48	100	Private	V17412025	189
B87023	Opotiki	1-Sep-1913	31-Jul-2002	open	89	100	Opotiki District Council	W15861467	6
B87251	Motu, Te Miro	1-Apr-1920	31-Jul-1960	closed	40	97	Private	N/A	463
B87255	Motu	1-Aug-1960	31-Jul-2002	open	42	100	Private	X16073154	488
B87256	Motu EWS	1-Nov-1990	17-Sep-2002	open	12	81	NIWA	X16063143	488
	Motu composite	1-Jan-1920	31-Jul-2002		82				
B87104	Ruatoki Taneatua	1-Jul-1913	31-Mar-1939	closed	26	96	N/A	N/A	N/A
B87101	Ruatoki North	1-Apr-1939	31-Dec-1975	closed	36	79	School	W16611317	38
B87102	Waimana, Sunnydale	1-May-1950	31-Aug-1960	closed	10	100	Private	N/A	91
B87103	Waimana	1-Jun-1955	31-Mar-2002	closed	47	99	Private	W16676318	37
870005	Darby	1-May-1981	31-Jul-2002		21		c/-Environment Bay of Plenty	W156145 4140	15
860701	Kawerau	1-May-1961	31-Aug-2002		41		c/-Environment Bay of Plenty	V15361409	50
86124	Concatenated Whakarewarewa (EBOP)	1-Jan-1899	13-Jun-2002		103		c/-Environment Bay of Plenty		

2.2.2 Daily Temperature Data

Homogeneity tests identified that 4 of the 8 locations in Table 2 were suitable to be used for further analysis – these are shaded in grey. Information about each series is listed in the Appendix (section 9.2).

Table 2: Records selected for analysis of daily temperature data (shown in grey shading).

Daily maximum & minimum air temperature									
Network or site No.	Location	Records Begin	Records End	Status	Years of record	% data	Recording Authority	Map reference	Alt (m)
B75381	Waihi	1-Jan-1951	31-Dec-1989	closed	39	98	Private	T136181194	91
B75382	Waihi, Barry Rd EWS	1-Jan-1990	13-Dec-2001	closed	11	87	Waihi Gold Mining Co.	T13623198	114
	Waihi composite	1-Jan-1951	13-Dec-2001		50				
B75571	Te Aroha	1-Jan-1951	31-Oct-1999	closed	48	94	Private	T13502027	18
B76621	Tauranga Airport	1-Feb-1941	1-Mar-1989	closed	48	100	Sun Air Aviation	U14924873	4
B76624	Tauranga Airport AWS	1-Jun-1990	19-Sep-2002	open	12	100	MetService	U14921874	4
	Tauranga composite	1-Feb-1941	19-Sep-2002		61				
B76993	Whakatane Mill	1-Jan-1951	30-Apr-1983	closed	32	100	Whakatane Board Mill	W15584531	2
B76994	Whakatane Airport	5-Dec-1974	24-Aug-1990	closed	16	98	East Bay Flight Centre	W15544566	6
B76995	Whakatane Airport AWS	6-Aug-1990	19-Sep-2002	open	12	100	MetService	W15546568	7
	Whakatane composite	1-Jan-1951	19-Sep-2002		51				
B86124	Whakarewarewa	1-Jan-1940	31-Jan-1982	closed	42	100	NZ Forest Research Inst.	U16960327	307
B86131	Rotorua Airport 2	1-Jan-1972	1-Jan-1992	closed	20	100	Airways Corp.	U16010384	287
B86133	Rotorua Airport AWS	19-Dec-1991	19-Sep-2002	open	10	100	MetService	U16009388	283
	Rotorua composite	1-Jan-1940	19-Sep-2002		62				
B86341	Waiotapu Forest	1-Jan-1972	31-Dec-1986	closed	15	100	Forestry Corp. of NZ	U16093155	435
B86451	Kaingaroa Forest	1-Jan-1951	31-Mar-1999	closed	48	92	Private	V17210044	544
B87023	Opotiki	1-Jan-1955	31-Jul-2002	open	47	98	Opotiki District Council	W15861467	6

2.2.3 High Intensity Rainfall Data

Eight records in the Bay of Plenty were selected for analysis of high intensity rainfall, and these were primarily chosen because of record length. Short-duration rainfalls, from 10 minutes to 72 hours, have been measured only rarely prior to the 1970s in most parts of New Zealand, including the Bay of Plenty (see Appendix, section 9.3). Although there are several excellent sites in the Bay of Plenty that now record high-intensity rainfall at shorter durations, they have not been able to be used in this report, as the period of interest for analysis in Section 5 was 1946 to 1999.

Table 3: Records selected for analysis of high intensity rainfall (shown in grey shading).

MANUAL (DAILY) RECORDS USED								
Network or site No.	Location	Records Begin	End	Status	% data	Recording Authority	Map reference	Alt (m)
B75381	Waihi	1946	1989	closed	99	Private	T136181194	91
B75382	Waihi, Barry Rd EWS	1990	1999	closed	91	Waihi Gold Mining Co.	T13623198	114
	Waihi composite (manual)	1946	1999					
B76621	Tauranga Airport	1946	1996	closed	100	Sun Air Aviation	U14924873	4
B76624	Tauranga Airport AWS	1997	1999	open	100	MetService	U14921874	4
	Tauranga composite (manual)	1946	1999					
B76993	Whakatane Mill	1947	1983	closed	100	Whakatane Board Mill	W15584531	2
B76994	Whakatane Airport	1984	1990	closed	99	East Bay Flight Centre	W15544566	6
	Whakatane composite (manual)	1947	1990					
B86124	Whakarewarewa	1946	1982	closed	100	NZ Forest Research Inst.	U16960327	307
B86131	Rotorua Airport 2	1983	1991	closed	100	Airways Corp.	U16010384	287
	Whakarewarewa composite (manual)	1946	1991					
AUTOMATED (10 MINUTE TO 72 HOUR) RECORDS USED								
B76993	Whakatane Mill	1967	1983	closed	90	Whakatane Board Mill	W15584531	2
B76994	Whakatane Airport	1984	1990	closed	95	East Bay Flight Centre	W15544566	6
	Whakatane composite (auto)	1967	1990					
B76621	Tauranga Airport (auto)	1967	1996	closed	94	Sun Air Aviation	U14924873	4
B86131	Rotorua Airport 2 (auto)	1967	1991	closed	96	Airways Corp.	U16010384	287
B87023	Opotiki (auto)	1968	2001	closed	84	Opotiki District Council	W15861467	6

Therefore, based on record length, annual rainfall maxima series for both manual and automatic rain gauges were used at Waihi, Tauranga, Whakatane, and Whakarewarewa (manual records), and at Opotiki, Rotorua, Tauranga and Whakatane (automatic gauges) – see Table 3. Although there may be some concerns about homogeneity based on prior MASH analyses (at the 24-hour duration for Whakatane automatic, Whakatane manual, and Whakarewarewa manual), only 2 series of annual rainfall maxima were identified as significantly inhomogeneous (the 10 minute series at Whakatane automatic, and the 2-day series at Waihi manual).

2.2.4 Monthly Rainfall and Temperature Data

Table 4 lists the monthly data extracted for climate change scenario modelling.

Table 4: Monthly data extracted for climate change scenario modelling, data from 1969

Rainfall stations		Temperature stations	
Network No.	**Station Name**	**Network No.**	**Station Name**
861204	Whakarewarewa	B75382	Waihi
870005	Taneatua	B75571	TeAroha
B75381	Waihi	B76624	Tauranga
B75571	TeAroha	B86124	Whakarewarewa
B76624	Tauranga	B86341	Waiotapu
B78601	Mataraoa	B86451	Kaingaroa
B86341	Waiotapu	B87023	Opotiki
B86451	Kaingaroa	B76995	Whakatane
B86481	Galatea	B86133	Rotorua
B87023	Opotiki	B86704	Taupo
B87255	Motu	C64971	Mangere
B75182	Tairua	C75321	Maramarua
B78501	Rukuhanga	C75731	Ruakura
B86704	Taupo	C85061	Arapuni
C64971	Mangere	C85821	Taumarunui
C74261	Waiuku	C94012	NewPlymouth
C75731	Ruakura	D87695	Gisborne
C75951	Karapiro		
C84761	Mohakatino		
C85821	Taumarunui		
C94012	NewPlymouth		
D87462	Otoko		
D87695	Gisborne		
D87811	Onepoto		

Data from 1969 were used. Note that stations listed below Taupo in Table 4 are located outside the Bay of Plenty, but were necessary for the climate change scenarios in order to provide correct boundary conditions for the Bay of Plenty region.

2.3 Recommended Reference Stations

An important aim of this report was to identify "reference" stations within the Bay of Plenty, for both rainfall and temperature. Reference stations represent high-quality, long-record, *open* climate stations, and these stations will be used to monitor climate variability and change in the Bay of Plenty into the future. Selection of reference stations was primarily based on the homogeneity checks performed at the daily scale, and the criteria as listed above.

Only one temperature reference station is recommended:

Tauranga Airport B76621/B76624

The operating station B76624, Tauranga Airport AWS (automatic weather station), is operated by MetService New Zealand Limited. 'Best practice' WMO[2] observational methods (WMO, 1996) are employed by MetService (pers. comm). MetService is also ISO 9001 certified, for the calibration and installation of its weather stations, and because Tauranga Airport AWS operates within an airport, the company also adhere to Civil Aviation Authority's 'Part 174' (relating to the certification of Aviation Meteorological Service Organisations).

See http://www.caa.govt.nz/fulltext/rule_pdf/part174.pdf for more information.

Tauranga Airport AWS records temperature at an hourly frequency, so daily, monthly and annual data can subsequently be calculated. Historical data and metadata from this station are archived in the NIWA National Database Clidb.

Recommended rainfall stations are:

Tauranga Airport B76621/B76624

[2] World Meteorological Organisation

Opotiki B87023

Environment B·O·P Whakarewarewa 86124

Motu B87251/87255

These stations are operated by MetService, Opotiki District Council, Environment B·O·P, and by a volunteer, respectively. Note that it was taken into consideration that these stations are spread across the Bay of Plenty, from the coast to the mountains, which include a range of climates.

All of these stations, except the private Motu record, are operated in line with WMO procedures regards reporting and metadata collection, since the recording authorities involved have some expertise in rain gauge operation. Environment B·O·P may wish to consider ensuring training and support for the volunteer observer at Motu was available, to ensure high quality data, with minimal missing data (at present, the proportion of missing data is higher than optimal).

The historical data and metadata from all of these stations, except Environment B·O·P Whakarewarewa 86124, are archived in the NIWA National Database (Clidb). Environment B·O·P Whakarewarewa 86124 data are archived within Environment B·O·P.

Note that the Tauranga station records rainfall hourly, and rainfall is now measured every 15 minutes at Whakarewarewa. The Motu and Opotiki records as listed above are daily rainfall readings. Overall, rainfall at all four stations can be concurrently assessed at the daily, monthly and annual data time scale.

Lastly, no recommendations are made regarding high-intensity rainfall reference stations. The lower portion of Table 3 lists the long-duration, high-intensity Bay of Plenty rainfall records, held by NIWA, all of which are closed. However, Table 14 in the Appendix (section 9.3) lists a number of more recent, high frequency rainfall recording stations in the Bay of Plenty, operated by Environment B·O·P (or by NIWA on behalf of the regional council). The decision as to which Bay of Plenty high-intensity stations are suitable for reference status should be left to the regional council, after they have considered this report.

3. How has the Climate of the Bay of Plenty Changed in the Past?

It is valuable to assess how climate has varied or shifted in the past, when planning a climate-sensitive activity for the future. For example, it is known that many floods and extended wet periods in the Bay of Plenty occurred before 1977, but that there has been a relatively dry period since that time – so much so, that a whole younger generation living in the Bay of Plenty would be surprised if the rainfall were to alter back to levels seen in the past!

But decisions for activities such as storm water and flood management schemes are made *now* for systems designed to be in use for the next several decades. So knowledge about the climate variability seen in the past, and information about climate processes that contribute to this variability, become very important.

This section answers the question 'how has climate changed in the past?' in the Bay of Plenty region. The following section addresses the question of 'why the climate has changed', and section 6 deals with the issue of future changes.

3.1 Historical Bay of Plenty Climate

Both mean (average) and extreme (unusual) climate is examined, for both temperature and rainfall. In line with international guidelines, annual *indices* are used to determine whether mean or extreme climate in the Bay of Plenty has altered over the historical record. All annual indices are calculated on daily data, and statistical tests are performed on daily data, except for the mean temperature, which uses monthly data in order to extend the series length.

Most weighting should be given to reference climate station results, because these typically have the longest and highest-quality climate records. Quality is particularly important when assessing climate extremes. However, for interest and comparison, other stations, which are spread across the geographical range of the Bay of Plenty, are included. The drawbacks in these comparison stations is that the station is either now closed, there are significant amounts of missing data, or at some stage in the record, there has been a site move or alteration which means the data quality are not as high as the reference station data quality.

The indices were calculated for each year where sufficient daily data existed at each reference station. If, in any year, the probability that the particular extreme event of interest might be missing exceeded 0.5, then the index for that year was set to missing.

Plotting and statistically testing these indices answer such questions as 'has the climate altered?' and 'are extreme climate events changing?' That is, are heavy rainfalls becoming heavier, or more frequent? Are dry periods or droughts becoming more common? Have frosts in the Bay of Plenty region almost disappeared? And is it really getting hotter?

Before we introduce the indices, it is useful to graphically present the distribution of daily rainfall at a site, and discuss some concepts about percentiles.

3.2 The Rainfall Distribution

Over a long period of time, measuring daily rainfall at a rain gauge, it is possible to calculate the median (i.e. the middle value), highest, and lowest recorded rainfalls. In mathematical terms, the median is known as the '50th percentile', because 50% of the time, recorded rainfall has been at or below this value. Since 1910, when rainfall records began at Tauranga, the median daily rainfall total has been 3.6 mm (calculated on raw data not shown here).

The most common daily rainfall total is 0 mm (again calculated on raw data not shown here) – it was a dry day at Tauranga for about 19,500 days (about 53 years) of the last 90 years or so. This means that over half the time (roughly a 60 % chance), it is a dry day at Tauranga. 0 mm is also, of course, the lowest daily rainfall recorded at Tauranga (there are no negative rainfalls!).

The maximum daily rainfall recorded at Tauranga was 239mm. This type of large and rare event is on the extreme 'right hand' end of the distribution, and is depicted in the 'More' box in Figure 1. Because the counts of rainfall in the larger boxes, including the 'More' box, are so small, they cannot be seen easily with the large scale seen on the y-axis (the count axis). But these boxes are not empty. The maximum rainfall event is called the 100th percentile (meaning that 100 % of the time, recorded daily rainfalls have been at or below this value).

What if we look at the '99th percentile'? This implies that 99 % of the time, recorded rainfall has been at or below this value e.g. it is still a very wet event. This corresponds to 361 days per year being drier than this value, and only 4 days per year being wetter. Several of the indices analyse the "top four" or "fourth highest" events per year – because it is important to assess the nature of extremely wet events in a robust way (that is why the indices do not look at the single wettest event by itself).

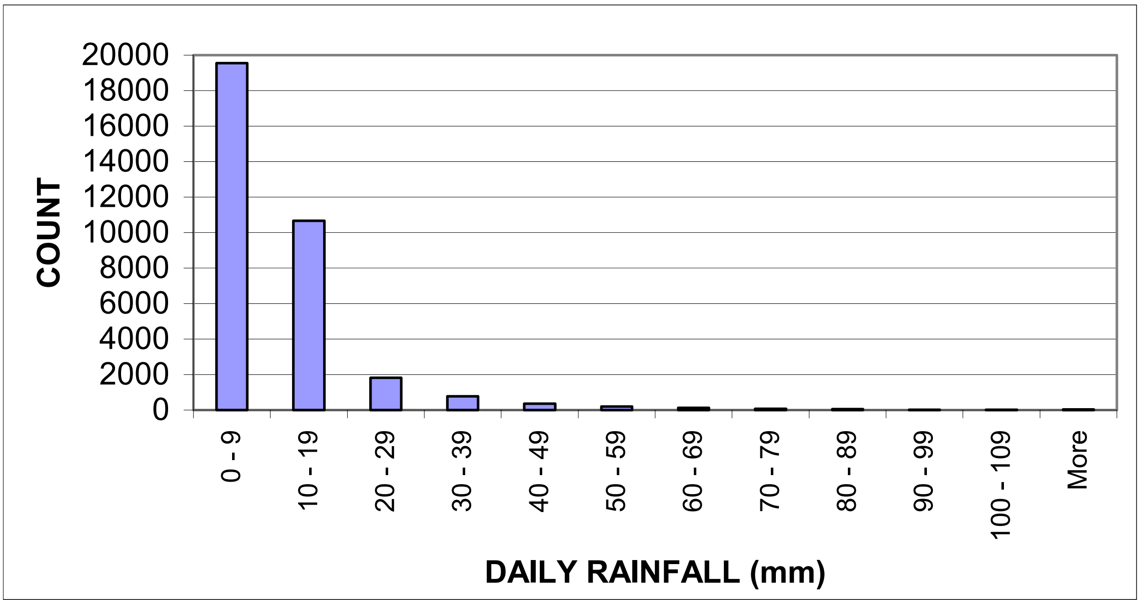


Figure 1: A histogram of Tauranga daily rainfall since 1910. This approximates a distribution of daily rainfall at Tauranga, by partitioning the rainfalls into bins: 0 to 9 mm, 10 to 19 mm, 20 to 29 mm, etc.

3.3 Indices

The annual rainfall indices analysed here are:

- Rainfall total – mm ***(total rain)***
- The number of rain days, where a rain day is defined to have rainfall greater than or equal to 2 mm – days ***(rain days)***
- The size of the fourth highest rainfall (99^{th} percentile) – mm ***(extreme rain)***
- The frequency of exceeding a long-term 'heavy rainfall' threshold (the 1961-1990 average 99th percentile) – days ***(extreme frequency)***

- The average size of the highest four daily rainfall events – mm ***(extreme intensity)***

- The maximum number of consecutive days with rainfall less than 1mm – days ***(dry spell)***

The annual temperature indices, all based on air temperature[3], are:

- Mean temperature – °C ***(average temperature)***

- The number of days with minimum air temperature less than or equal to 0 °C – days ***(frost days)***

- The number of days with maximum air temperature greater than or equal to 25 °C – days ***(25°C days)***

- The intra-annual extreme temperature range – the hottest temperature recorded each year minus the coldest temperature recorded each year – °C ***(extreme temperature range)***

- The average size of the coldest four minimum temperatures – °C ***(cold nights)***

- The percentage of days when the daily minimum temperature is lower than a long-term 'cold' threshold (the 1961-1990 average 1st percentile of minimum temperatures) – % ***(frequency of cold nights)***

- The average size of the warmest four maximum temperatures – °C ***(hot days)***

- The percentage of days when the daily maximum temperature is higher than a long-term 'hot' threshold (the 1961-1990 average 99th percentile of maximum temperatures) – % ***(frequency of hot days)***

[3] The "air temperature" is the temperature measured in a standard Stevenson screen located 1.3 m above a grass surface.

3.4 Statistical Methods

Time series of these annual indices have been plotted, and a Mann-Kendall statistical test performed on each series to assess whether a significant trend (either increase or decrease) has occurred. The Mann Kendall test is 'non-parametric', which simply means that the test makes no assumption about the shape of the distribution it is testing. The test is a two-sided test, and 'significance' here implies a significant statistical result at the 95% level (i.e. there is only a 5% probability that the result could have happened by chance).

Another test was also performed – the Pettitt test was used to determine abrupt shifts or changes in the time series. This test signals a change in a series of observations, with no assumptions made about the distribution of the variable (Pettitt, 1979). Identification of change points in a time series is viewed as complementary to the analysis of trends for a given time period (Tarhule and Woo, 1998), since a linear trend across natural change points in a time series can result in 'artificial' trends, which do not adequately reflect the variability or cyclic nature of the underlying processes. For example, a significant linear trend can result across an abrupt jump in a time series, even with the series being stationary both before and afterwards. Most often, however, these change points occur at changes in slope from increasing to decreasing, or vice versa.

3.5 Results

3.5.1 Total Rain – Total annual rainfall

Figure 2 shows *total rain* for six stations in the Bay of Plenty between 1900 and 2002, four of which are reference stations. Kaingaroa Forest and Waihi data have been included for geographical coverage across the Bay of Plenty, to analyse whether climate across the district moves coherently ('in tandem').

Firstly, it is evident that it rains most at Waihi and at Motu, with typical annual rainfall totals of around 2100 mm. At places like Whakarewarewa and Kaingaroa, total annual rainfall is generally around 1450 mm, while the driest of the six stations would be Tauranga, with a mean annual rainfall of about 1300 mm.

Large year-to-year variability is seen at all stations. For example, rainfall at Waihi varies from a record wet year in 1928 (3234 mm) to a record dry year in 1982 (1249 mm). The difference between these two years is nearly 2 metres of rainfall!

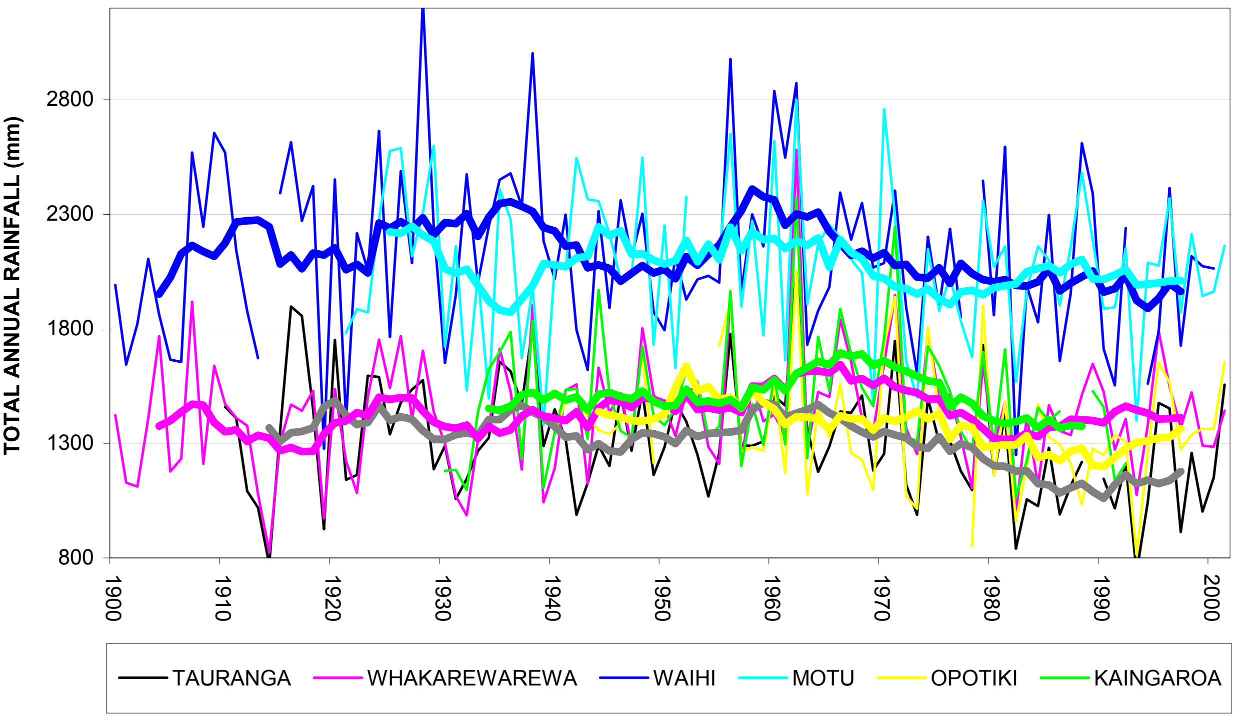


Figure 2: ***Total rain*** **indices for six Bay of Plenty stations. Thin lines show annual data, while thick lines depict 9 year (centred) moving averages.**

Generally, during very wet years, such as 1956, all of these stations record wet years, even though the stations are spread across the Bay of Plenty. And usually, during very dry years, most stations record low rainfall relative to their own rainfall climate. That is, the stations typically respond coherently, at least on the annual time scale, to the climate processes that are occurring.

There are a few exceptions, an obvious one being between Motu and Waihi, located at opposite ends of the Bay of Plenty. Looking at the moving average (thick line) in Figure 2 to gain better insight into longer-term climate variations, it can be seen that in the 1930s, Motu briefly dried out relative to Waihi. This discrepancy may be 'real', caused by some difference in rainfall between the western Bay and the eastern parts of the region at that time, or may be caused by data problems at one of the sites. Because of the extensive data quality checks that have occurred using nearest-neighbour methods, it is probably a real difference in rainfall between Motu (high elevation, located in the ranges, in the far east of the region) and Waihi (lower elevation, sited in the western portion of the district).

Decadal variability is also seen in Figure 2. By looking at the moving averages (thick lines) at all stations, it is evident that the late 1950s (at Waihi, Motu) and into the 1960s (elsewhere), it was wetter than usual. This was followed by a reduction in *total rain* in the 1980s and 1990s. Tauranga *total rain* has decreased significantly over the record available there (1910-2002), at a rate of 25 mm per decade (see Table 5). All other stations, except Whakarewarewa, exhibit a decrease in *total rain,* over their respective record lengths, but these are not statistically significant at the 95% level and it must be kept in mind that these record lengths are all different (Whakarewarewa shows a trend of zero).

Significant change points (abrupt changes) in *total rain* were identified for Tauranga in 1971 (with a large decrease in *total rain* following this), and in 1994 for Opotiki (with an increasing trend after this time) (see Table 6). Waihi exhibited a weak shift in 1922, and a significant one in 1998.

In summary: total rainfall has generally decreased in the Bay of Plenty since the 1960s or 1970s, but that this reduction is only statistically significant at the 95% level at Tauranga. Year to year variability of total annual rainfall is large in the Bay of Plenty.

Table 5: Significant decadal trends (at the 95% level) in rainfall indices, identified by the Mann Kendall test. Note that the trends are calculated over the entire station record length, which differs for each station. A negative entry indicates values decreasing with time. An asterisk (*) marks change points weakly significant at the 90% level.

	Tauranga	Whaka	Waihi	Motu	Opotiki	Kaingaroa
RECORD:	**1910 to 2002**	**1900 to 2002**	**1900 to 2002**	**1921 to 2002**	**1940 to 2002**	**1930 to 1992**
Total rain	-25 mm					
Rain days	-1.3 days				-1.7 days	-1.6 days*
Extreme rainfall frequency	-0.2 days					
Extreme rainfall intensity	-1.1 mm*					
Dry spell	-0.3 days*	-0.3 days		-0.3 days*		

Table 6: Significant change points (at the 95% level) in rainfall indices as identified by the Pettitt test, marking abrupt changes in a time series. An asterisk (*) marks change points weakly significant at the 90% level.

	Tauranga	Whaka	Waihi	Motu	Opotiki	Kaingaroa
RECORD:	**1910 to 2002**	**1900 to 2002**	**1900 to 2002**	**1921 to 2002**	**1940 to 2002#**	**1930 to 1992#**
# indicates earlier data not used due to high proportion missing						
Total rain	1971		1922*, 1998		1994	
Rain days	1971*	1978	1922, 1998		Late 1990s	1976
Extreme rainfall	1974	1979	1953, 1998		1969*, 1995	1975
Extreme rainfall frequency	Late 1990s	1922,1947, 1979, 1993			1995	~1970
Extreme rainfall intensity	1974	1975			1969*, 1995	1976*
Dry spell		1998		1955*, 1997	1979	

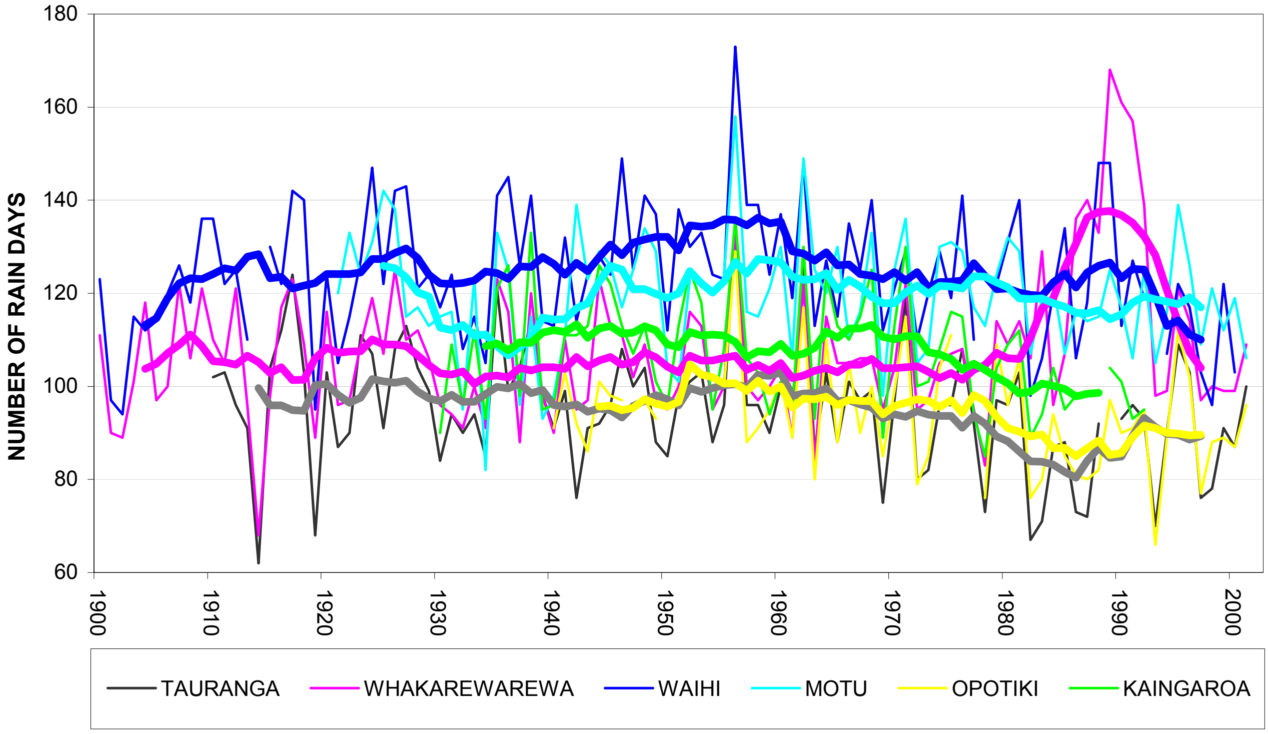


Figure 3: *Rain days* indices for six Bay of Plenty stations. Thin lines show annual data, while thick lines depict 9 year (centred) moving averages.

3.5.2 Rain Days – A measure of how often it rains

Figure 3 shows the *rain days*[4] index for six stations in the Bay of Plenty between 1900 and 2002, four of which are reference stations. Typically, there are about 95 rain days per year at coastal sites such as Tauranga and Opotiki, although in extreme years this can drop as low as 62 days per year, and rise as high as 134 days, at these locations. At Whakarewarewa and Kaingaroa there would typically be about 110 rain days per year, while for wetter sites such as Waihi and Motu, there is, on average, about 120 rain days per annum.

Again, large year-to-year variability is seen at all stations. For example, the number of rain days at Whakarewarewa has varied over the past century between 68 and 168 days per year, this being the largest variation observed at the six stations. Large outliers are observed, such as 1956 at Waihi and Motu, and 1989 at Waihi and Whakarewarewa.

It is generally clear that in very dry years, such as 1919, rain days are low for all recording stations. Also, during exceedingly wet years, such as 1956, all stations show a large number of rain days. However, in the 1980s and 1990s, it looks like this coherency has reduced between the sites in the Bay of Plenty. For example, in 1989, there is a big peak in *rain days* at Whakarewarewa and Waihi, but the magnitude of any peak is much reduced at Motu and Opotiki (the Kaingaroa and Tauranga records have missing data). This discrepancy may be ‘real’, caused by some difference in rainfall between the western Bay and the eastern parts of the region at that time, or may be caused by data problems at one or more of the sites.

Figure 4 shows a comparison of three rainfall indices at one site, to evaluate the coherency between the indices. At Tauranga, the *rain days* index is highly coherent and in phase with *total rain* – meaning that in very wet years, the number of rain days is high (the converse is also true). The *extreme intensity* index also shows coherency with total annual rainfall – meaning that the magnitude of extreme daily rainfall events is often larger during wet years. This relationship between parts of the rainfall distribution has been seen in many regions of New Zealand in earlier work (Salinger and Griffiths, 2001), and it may imply that the rainfall distribution in the Bay of Plenty generally moves ‘linearly’, with the shape of the daily precipitation distribution remaining fairly stable (see Figure 1).

[4] As noted in section 3.3, a “rain day” is a day on which 2 mm or more of rain is recorded.

Trends in the number of rain days were significant at Tauranga, Opotiki, and Kaingaroa, over their respective (differing) record lengths (Table 5), and showed a decrease in the order of 1.5 days per decade, or extrapolating, 15 days per century. Looking at Figure 3, it can be seen that most of this decline occurred since about 1970.

Significant change points in *rain days* were identified at 1922 at Waihi, and in the 1970s at Tauranga, Whakarewarewa and Kaingaroa (Table 6). Later change points in 1998 or the late 1990s were identified at Waihi and Opotiki, respectively. Most of these points appear to identify changes in trend from increasing to decreasing, or vice versa.

In summary: there has been a significant, long-term trend towards fewer rain days at some stations in the Bay of Plenty over the last 100 years, with much of this reduction occurring since the 1960s or 1970s. In very wet years, the number of rain days is typically high, and the converse is also true.

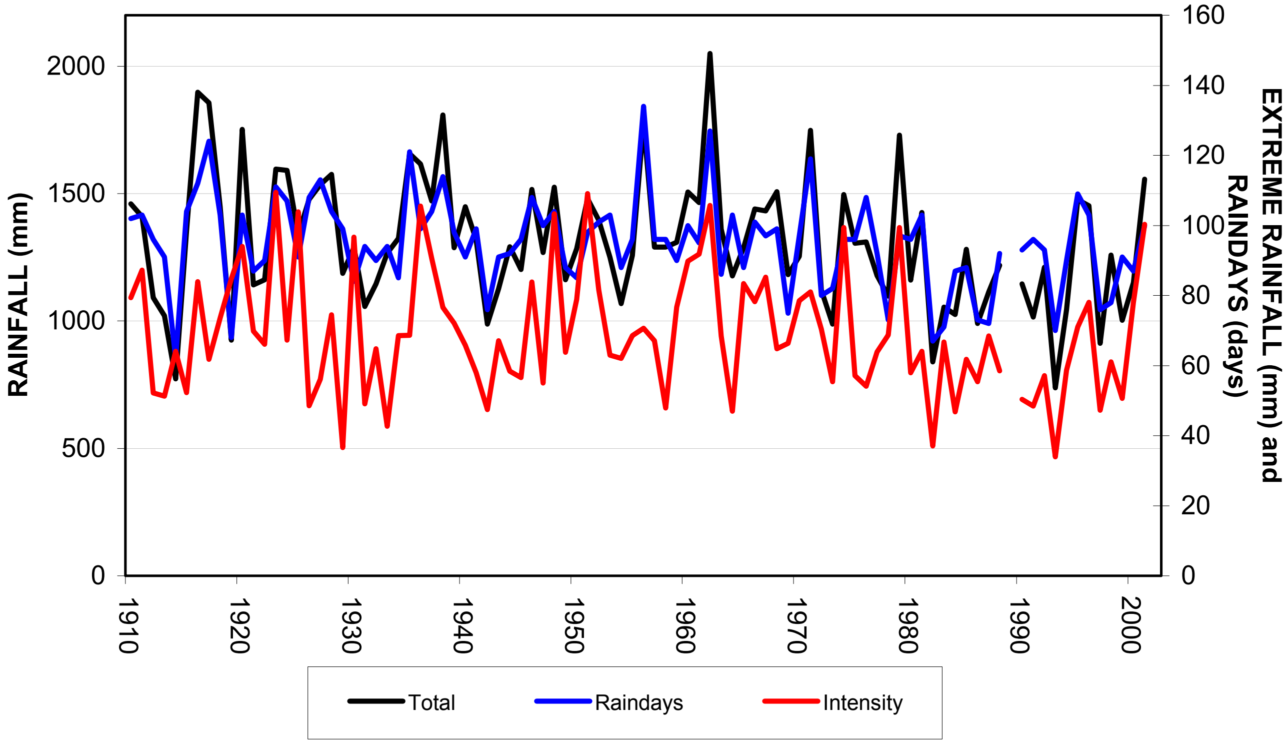


Figure 4: Comparison of three rainfall indices at Tauranga, over its record from 1910 to 2002.

3.5.3 Extreme rain – A measure of the magnitude of the extreme large daily rainfall event

The *extreme rain* index is calculated as the size of the fourth largest rainfall per year.

Figure 5 shows time series of the *extreme rain* index at the six stations across the Bay of Plenty. It can be seen that the size of the fourth largest rainfall event per year is typically around 50 to 55 mm for coastal stations like Tauranga and Opotiki, and is comparable for inland locations like Whakarewarewa and Kaingaroa. An average *extreme rain* value is about 70 mm at Motu, and about 80 mm for Waihi.

Again, all of the stations show large year-to-year variation; for example, Whakarewarewa exhibits a minimum in the *extreme rain* index of only 23 mm in 1991, and a maximum of 115 mm in 1962.

Although the stations do move with a certain degree of coherence from year to year, for example in 1973 the stations all show a dip in the index, the largest peaks in the index appear independently of neighbour stations. For example, in 1928 Waihi recorded an enormous value of *extreme rain*, while the other stations measured fairly typical peaks. Again, around 1960, Motu and Waihi exhibit very large values of *extreme rain*, which are not observed at the other stations.

Analysing the moving averages, a clear decline occurs after about 1970 in the coastal and inland locations like Opotiki, Tauranga, Kaingaroa and Whakarewarewa, while Motu and Waihi do not show such an obvious decline. An obvious minimum in *extreme rain* is evident around 1990 at coastal and inland stations analysed here.

There are no significant trends for any station for the *extreme rain* index, for the length of each station's record (although it must be kept in mind that these record lengths are all different).

Shifts in this index are identified in 1953 at Waihi and in 1969 at Opotiki, respectively (Table 6). A group of change points are indicated in the mid-to-late 1970s across several stations, with 1995 and 1998 also identified at Opotiki and Waihi. Again, most of these points appear to identify changes in index trend from increasing to decreasing, or vice versa.

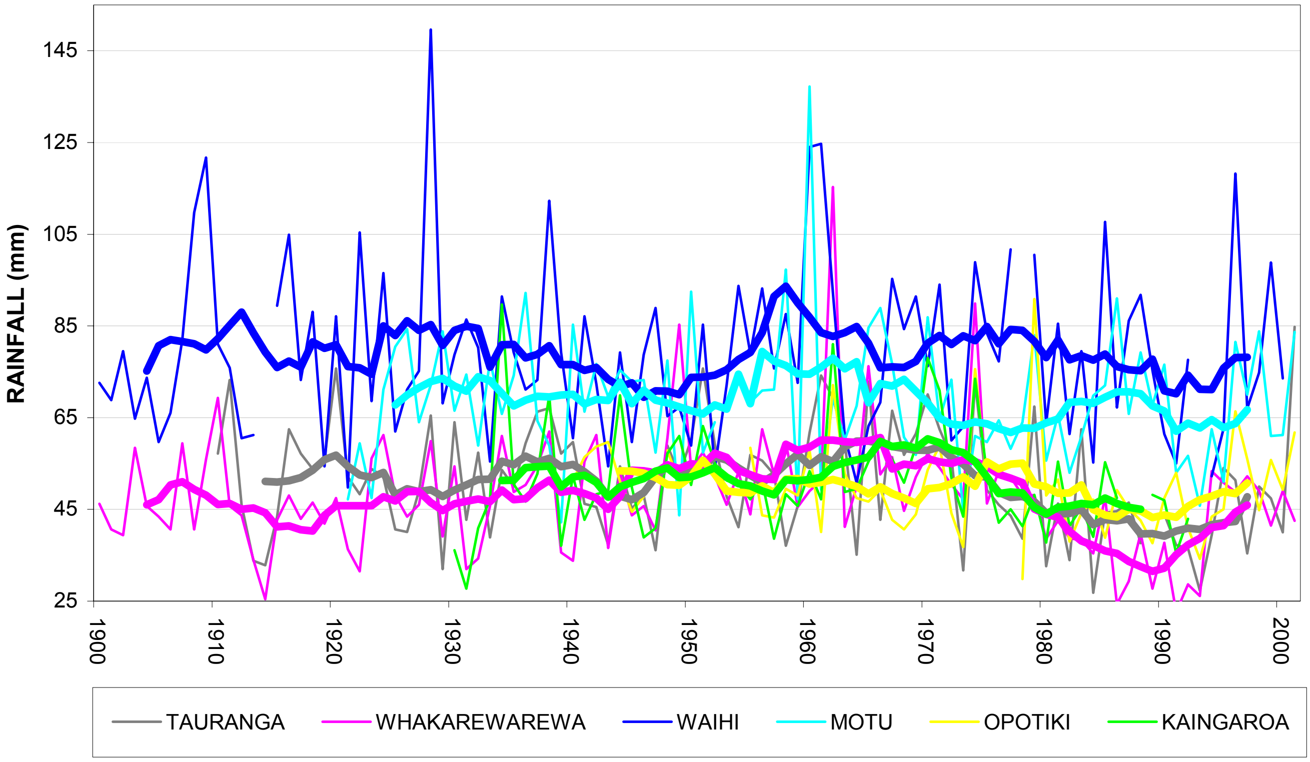


Figure 5: ***Extreme rain*** **indices for six locations in the Bay of Plenty. Thin lines show annual data, while thick lines depict 9 year (centred) moving averages.**

In summary: extreme (large) daily rainfall has not changed significantly over the last 100 or so years in the Bay of Plenty. However, in the short term, the last 30 years (since about 1970) have been atypical, in that extreme daily rainfalls have been generally lower than seen elsewhere in the historical climate record (at least at coastal or lower elevation stations) – and planning or policy decisions should not be made on this part of the record alone in these areas. Variability in extreme rainfall in this region remains very large and also needs to be considered.

3.5.4 Extreme frequency – A measure of the frequency of the extreme large rainfall event

Figure 6 illustrates two key features – that the frequency of extreme daily rainfall events per year has varied between 0 and 11 over the last century in the Bay of Plenty (e.g. there is large year-to-year variability), and that there has been a distinct drop in the number of extreme large daily rainfalls since the 1970s.

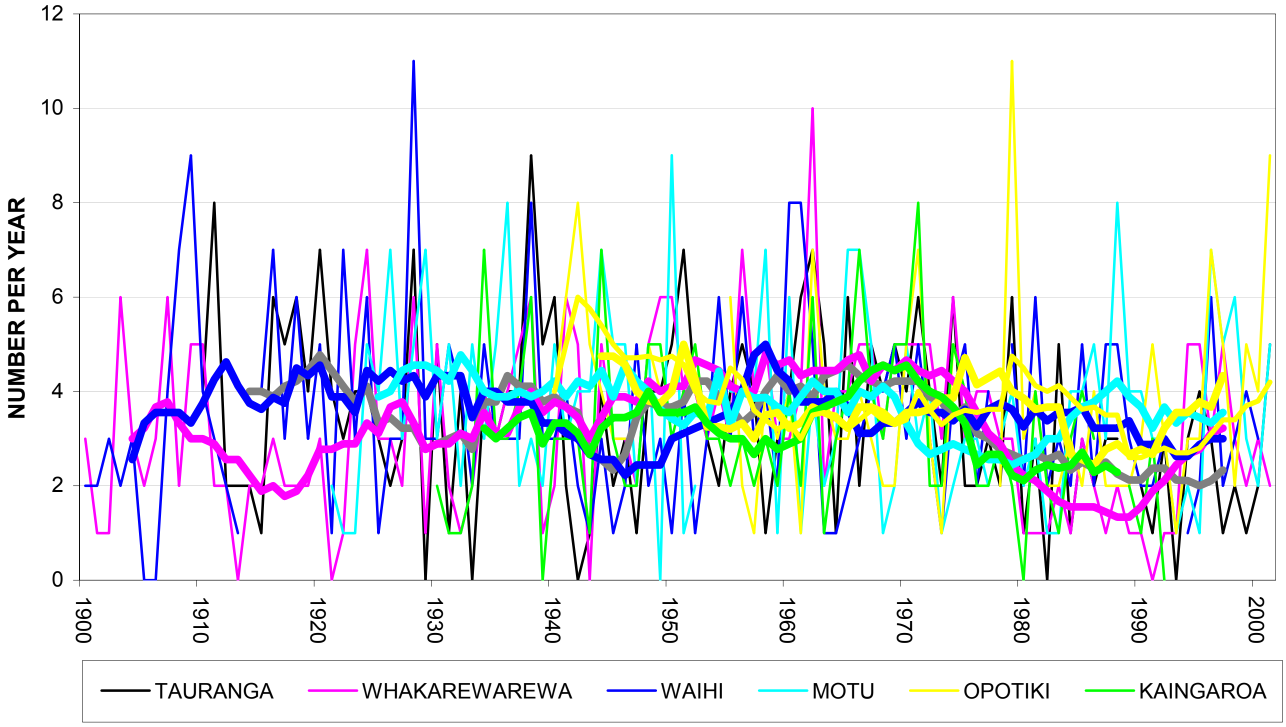


Figure 6: *Extreme frequency* indices for six locations in the Bay of Plenty. Thin lines show annual data, while thick lines depict 9 year (centred) moving averages.

Again, the 1980s and 1990s were atypical. The frequency of extremely large daily rainfalls was lower throughout the Bay of Plenty during these two decades than it was earlier in the 20th century. This is consistent with all of the rainfall indices analysed so far.

All stations show a linear decrease over their respective (differing) record lengths, but the only statistically significant decline is observed at Tauranga (with a decrease of 0.2 days per decade, or extrapolating, 2 days per century) (Table 5).

Table 6 summarises the significant change points in this index – around 1970 at Kaingaroa (followed by a decreasing trend in the index), and during the 1990s at Tauranga, Whakarewarewa, and Opotiki (all followed by an increase in *extreme frequency)*. Whakarewarewa is an interesting example of the information to be gleaned from change points. Four shifts were calculated on the Whakarewarewa index, at 1922 (followed by an increasing trend), 1947 (smaller increasing trend), 1979 (decreasing trend), and 1993 (increasing trend). The first three coincide with shifts in the Interdecadal Pacific Oscillation (or IPO, refer to Section 4 for details).

In summary: the frequency of extreme large daily rainfall has decreased across the Bay of Plenty over the last 100 or so years, but this decrease is significant only at Tauranga. Regardless, the climate of the last 20 –30 years (since the 1970s) has been atypical, in that extreme daily rainfalls have been less frequent than recorded elsewhere in the historical climate record. Large variability exists in extreme rainfall frequency in this district.

3.5.5 Extreme intensity – A measure of the magnitude of four very extreme daily rainfalls

The *extreme intensity* index is calculated as the average of the four largest rainfalls per year. It is a very similar index to *extreme rain*, except that it captures information not only about *the fourth* highest rainfall per year, but *averages all four* of the highest rainfalls per year. Therefore, the *extreme intensity* index should be a measure of even more extreme daily rainfall than the *extreme rain* index.

Figure 7 captures much of the same of the information that Figure 5 shows – a clear decline in the size of the very extreme (high) rainfalls in the latter part of the century at Tauranga, Opotiki, Whakarewarewa, and the available record at Kaingaroa, but no clear signal at Waihi and Motu. This means that the 1980s and 1990s are not a representative period of climate with respect to very extreme (high) daily rainfall across some parts of the Bay of Plenty.

It can be seen that the average size of the fourth largest rainfalls per year is typically around 65 mm for coastal stations like Tauranga and Opotiki, and is comparable for inland locations like Whakarewarewa and Kaingaroa. An average *extreme intensity* value at Motu is around 85 mm, and about 110 mm at Waihi.

Similarly to the *extreme rain* index, large year-to-year variation is evident in the *extreme intensity* index. For example, Waihi records a minimum in this index of only 60 mm in 1921, and a maximum of 204 mm in 1938. There appears to be less coherency between the stations than seen in the *extreme* rain index, for example, a high value of *extreme intensity* at one station does not necessarily correlate strongly with high values elsewhere.

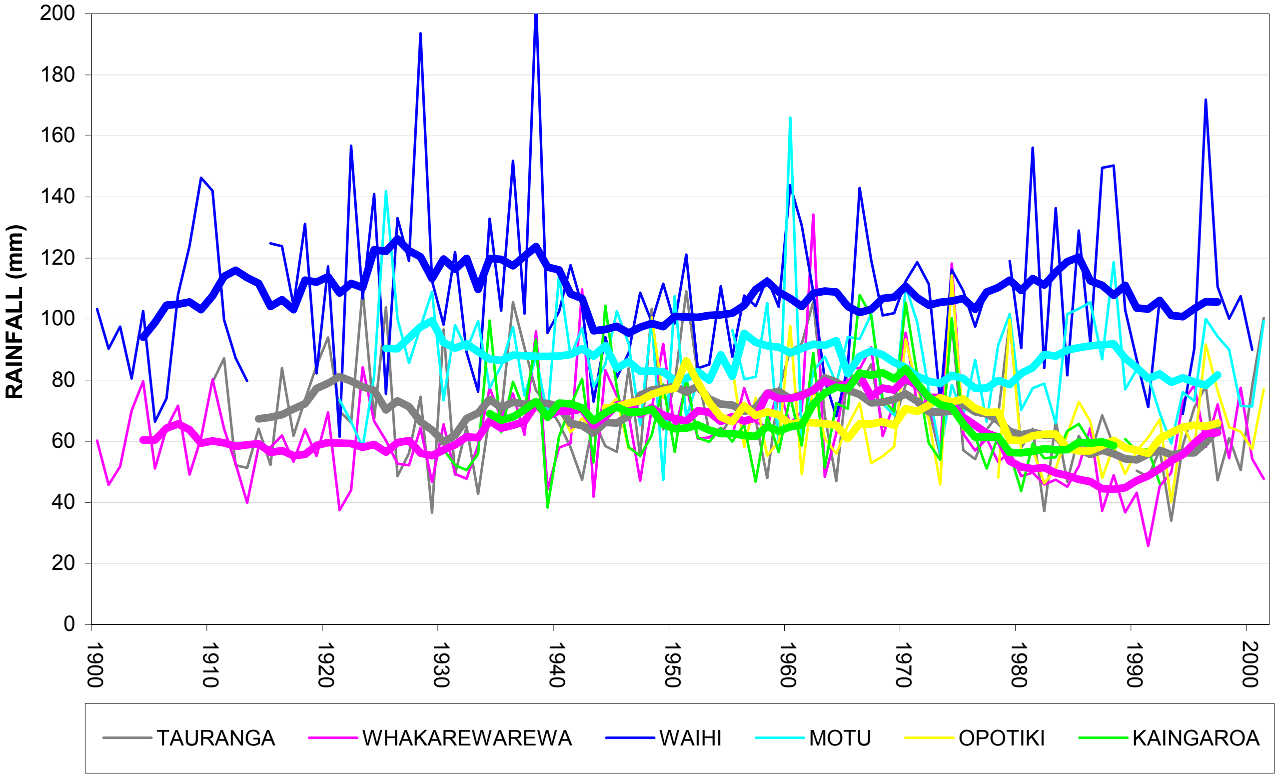


Figure 7: ***Extreme intensity*** **indices for six locations in the Bay of Plenty. Thin lines show annual data, while thick lines depict 9 year (centred) moving averages.**

A weakly significant trend exists at Tauranga for the period of its record (1910 – 2002), with a decrease in *extreme* intensity of 1.1 mm per decade in the average size of the wettest four events (Table 5).

Significant shifts between 1969 and 1976 are observed in the *extreme intensity* index at Tauranga, Whakarewarewa, Kaingaroa, and Opotiki, with a clear decrease in the index following this time (Table 6). Opotiki also exhibits a change point around 1995.

In summary: the average size of the top four (very extreme) daily rainfalls per year has not significantly changed in the last 100 years across the Bay of Plenty, except at Tauranga, which shows a small decrease over the period 1910-2002. However, the 1980s and 1990s have been unusual at some stations in the region, in that extreme daily rainfalls have been generally smaller in magnitude than seen at other times in the past. These stations exhibit a large decrease in the *extreme intensity* index after the early 1970s, and therefore recent climate is not generally representative for longer-term planning. It is also important to again note that large variability exists in extreme rainfalls in the Bay of Plenty.

3.5.6 Dry spell – the duration of the extremely long dry spell

This index defines the longest dry spell, in days, each calendar year. It is important to note that on occasion, extended dry spells might occur across the break between calendar years, and therefore would not be adequately reflected.

The *dry spell* index cannot accurately be called a drought index, since agricultural drought is a function of both rainfall (moisture entering the agricultural system), and evapo-transpiration (moisture exiting the agricultural system). This index is calculated from rainfall alone, looking at extended dry spells, but could be used as a proxy marker of drought duration. However, it says nothing about drought *severity* (how bad is the drought?).

The large variability seen over the last century in the *dry spell* index is notable (see Figure 8). For example, the average *dry spell* value is about 21 days at the coastal stations of Tauranga and Opotiki but in the past, this has varied between 11 and 43 days. 1919 is an obvious outlier at Tauranga, with a *dry spell* of 42 days (almost a month and a half without rain!), and similarly in 1998 at Opotiki (43 days). At Waihi and Motu, the average *dry spell* value is 17 days, while the average is 19 days at Whakarewarewa and Kaingaroa.

A significant decreasing trend in the *dry spell* index is observed at Whakarewarewa, with a decline in the extended dry spell duration of around 0.3 days per decade, or extrapolating, 3 days per century (Table 5). A weakly significant decline of the same size is observed at Motu, and Tauranga, over their respective (differing) record lengths.

Change points in the *dry spell* index are identified as 1955 at Motu (followed by a clear decrease following this time), and 1979 at Opotiki (the variability in the index appears larger after the change point). A recent change point is flagged around 1997/ 1998 at Whakarewarewa and Motu, possibly indicating a recent increase in the *dry spell* index (Table 6).

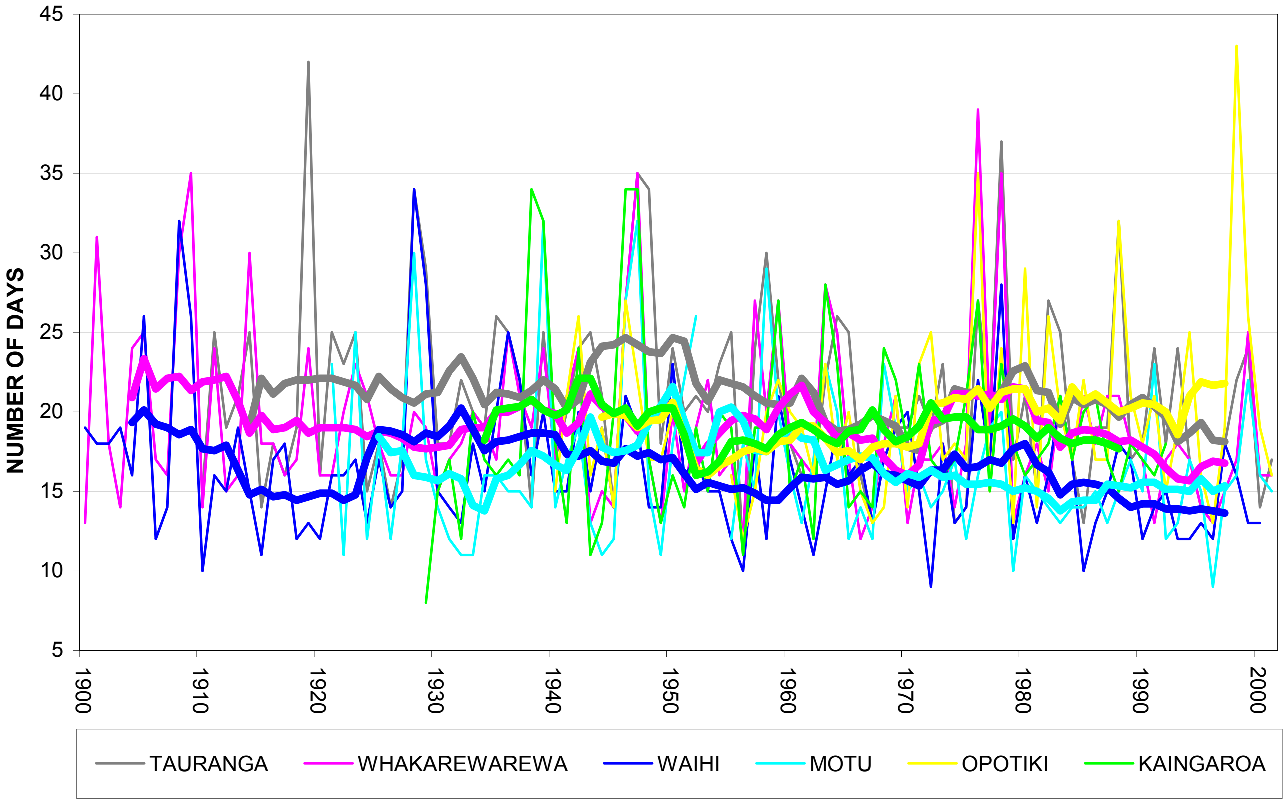


Figure 8: ***Dry spell*** **indices for six locations in the Bay of Plenty. Thin lines show annual data, while thick lines depict 9 year (centred) moving averages.**

In summary: the duration of extended dry spells has reduced over the 20th century at some stations, spread right across the geographical spread of the Bay of Plenty (mountainous, coastal and inland). The variability in *dry spell* duration in this region is very large.

3.5.7 Average temperature – The mean temperature

The *average temperature* index uses monthly mean temperature data to calculate an annual mean, in order to extend the series length. However, significant missing data on the monthly scale also excludes data on the annual scale. Therefore, because of the large amount of missing annual data when extending the time series back to the turn of the century and beyond, no formal statistical tests are made on this index.

This index can be used to compare whether different temperature stations, spread across the full geographical range of the Bay of Plenty, respond coherently at the annual time scale. This is useful when looking at the other temperature indices, based on daily maximum and minimum temperature data - for which there are fewer data stations.

Looking at Figure 9, which shows mean annual temperature data from six locations in the Bay of Plenty, it can be seen that a typical annual temperature is approximately 14 °C at coastal sites such as Tauranga, Waihi and Opotiki, closer to 14.5 °C at Te Aroha, and much lower at higher elevation sites such as Whakarewarewa (around 12.5 °C), and at Waiotapu Forest (closer to 11 °C).

All sites respond 'in tandem' to climate signals at the annual scale, with stations generally recording cool years or warm years together. A good example of this is 1938, which was a very hot year. Every station also shows a warming trend, evident even against the variation in temperatures seen from year-to-year and decade-to-decade, and apparent even with missing data. It is noticeable that Tauranga, the best temperature record in the Bay of Plenty (highest quality, least missing data), recorded very high temperatures in the 1990s. This has been observed elsewhere in New Zealand, with the 1990s being the warmest decade in the last 100 years.

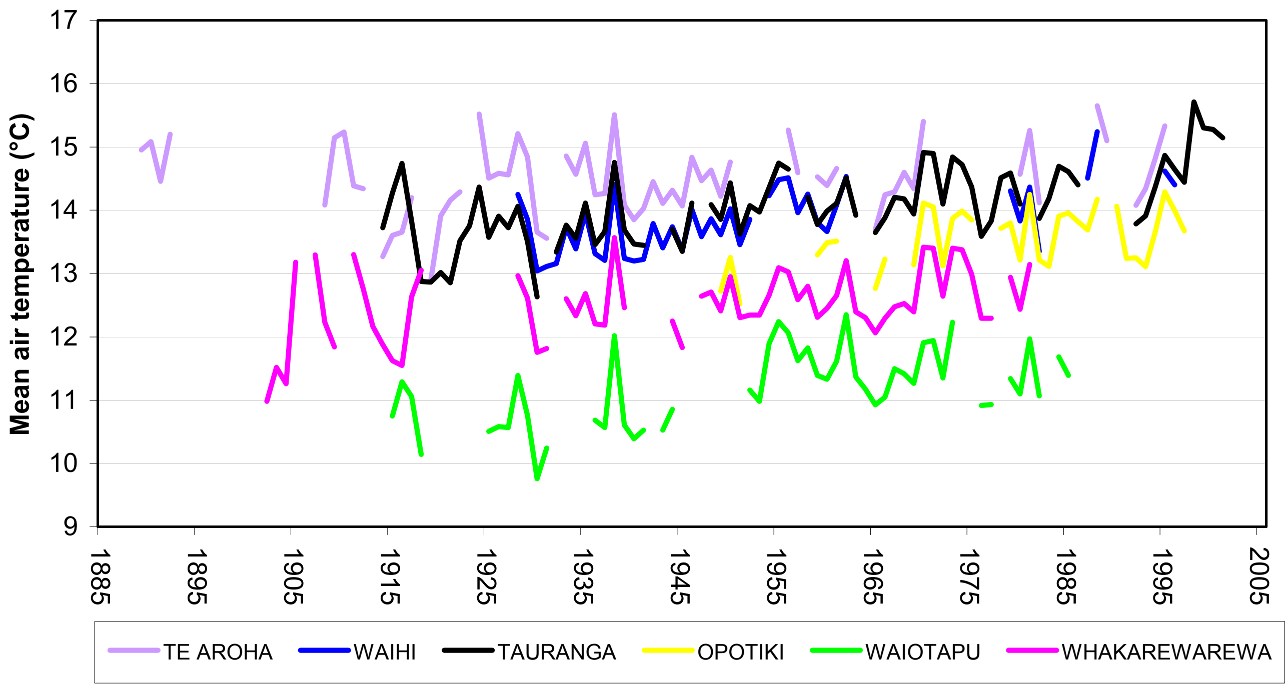


Figure 9: ***Average temperature*** **at six locations in the Bay of Plenty. During years with significant amounts of missing data, annual temperature is set to missing.**

3.5.8 Frost days – The air frost frequency

Figure 10 shows a large decrease in the number of air frosts[5] at all four temperature stations. The decreases are highly significant at every station, over their respective (differing) record lengths, and range from a decrease of around 1 frost day per decade at Tauranga, to a decrease of about 5 frost days per decade at Whakarewarewa (Table 7). Even Te Aroha, a relatively rural station, shows this clear and significant decrease in air frosts, which is consistent with a strong nation-wide trend towards fewer frosts (Salinger and Griffiths, 2001). Temperature increases at rural stations are important because any ‘urban’ warming factors, such as increased asphalt, are minimised.

To see what this means in practical terms, let us look at Tauranga, our reference temperature record. At Tauranga, there were typically 5 air frosts per year prior to1960, but it is evident that frosts have become very rare since about 1980, averaging less than one air frost per year in recent times. Significant change points occur in the *frost days* index around 1960 at both Tauranga and Whakarewarewa (with higher variability and incidence of air frost prior to this), and in 1985 at Waihi (Table 8).

In summary: Air frosts have significantly decreased in the Bay of Plenty since good-quality, daily temperature records began in 1940.

Table 7: Significant decadal trends (at the 95% level) in temperature indices, identified by the Mann Kendall test. Note that the trends are calculated over the entire station record length, which differs for each station.

	Tauranga	Whakarewarewa	Waihi	Te Aroha
RECORD:	**1941 to 2001**	**1940 to 1982**	**1951 to 1990**	**1951 to 1999#**
# Indicates large proportions of missing daily data after 1995				
Frost days (days per decade)	-1.0 days	-5.5 days	-1.2 days	-2.2 days
25 °C days (days per decade)	+0.2 days	-0.3 days	+0.4 days	
Extreme temperature range (°C per decade)		-1.1 °C		-0.3 °C
Cold nights (°C per decade)	+0.3 °C	+0.4 °C	+0.3 °C	+0.3 °C
Frequency of cold nights (days per decade)	-1.8 days	- 3.0 days	-0.9 days	-1.1 days
Hot days (°C per decade)	+0.2 °C	-0.5 °C	+0.4 °C	
Frequency of hot days (days per decade)	+0.9 days	-1.8 days	+1.1 days	

[5] An “air frost” occurs when the minimum air temperature measured in a standard Stevenson screen at 1.3 m above a grass surface is less than or equal to 0 °C.

Table 8: Significant change points (at the 95% level) in temperature indices as identified by the Pettitt test, marking abrupt changes in a time series.

	Tauranga	Whakarewarewa	Waihi	Te Aroha
RECORD:	**1941 -2001**	**1940 - 1982**	**1951 – 1990**	**1951 –1999#**
# Indicates large proportions of missing daily data after 1995				
Frost days	1959	1960	1985	
25C days				
Extreme temperature range		1960		
Cold nights	1961, 1976, 1992	1959		1976
Frequency of cold nights	1966, late 1990s	1959		
Hot days	1967	1950	1979	1969
Frequency of hot days	1967	1950	1985	1969

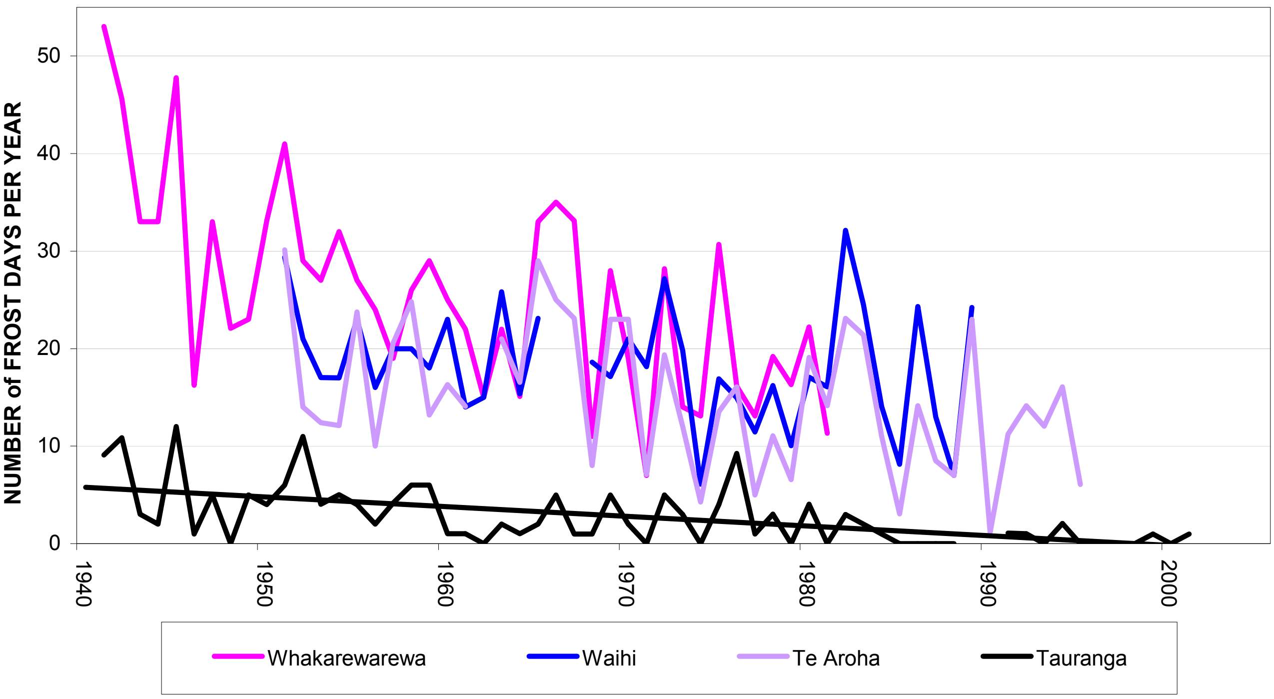


Figure 10: ***Frost days*** **at four Bay of Plenty stations. A linear trend has been added to Tauranga, the reference station.**

3.5.9 25 °C days – The frequency of days exceeding 25 °C

This index, which measures the frequency of days that achieve a maximum temperature of 25 °C or more, appears to move in tandem for all four temperature stations shown in Figure 11. For example, in 1970, all stations record a clear peak in the frequency of *25 C days.*

On average, Te Aroha records the most *25 C days*, averaging around 51 days per year. Waihi and Whakarewarewa typically average about 20 days per year, while Tauranga, often subject to the cooling effects of the coastal sea breeze, usually only records around 15 *25 C days* per annum.

The number of *25 C days* has varied enormously in the past at all the stations – with Tauranga recording just 2 days with temperatures exceeding 25 °C in 1963, but 46 days in 1998!

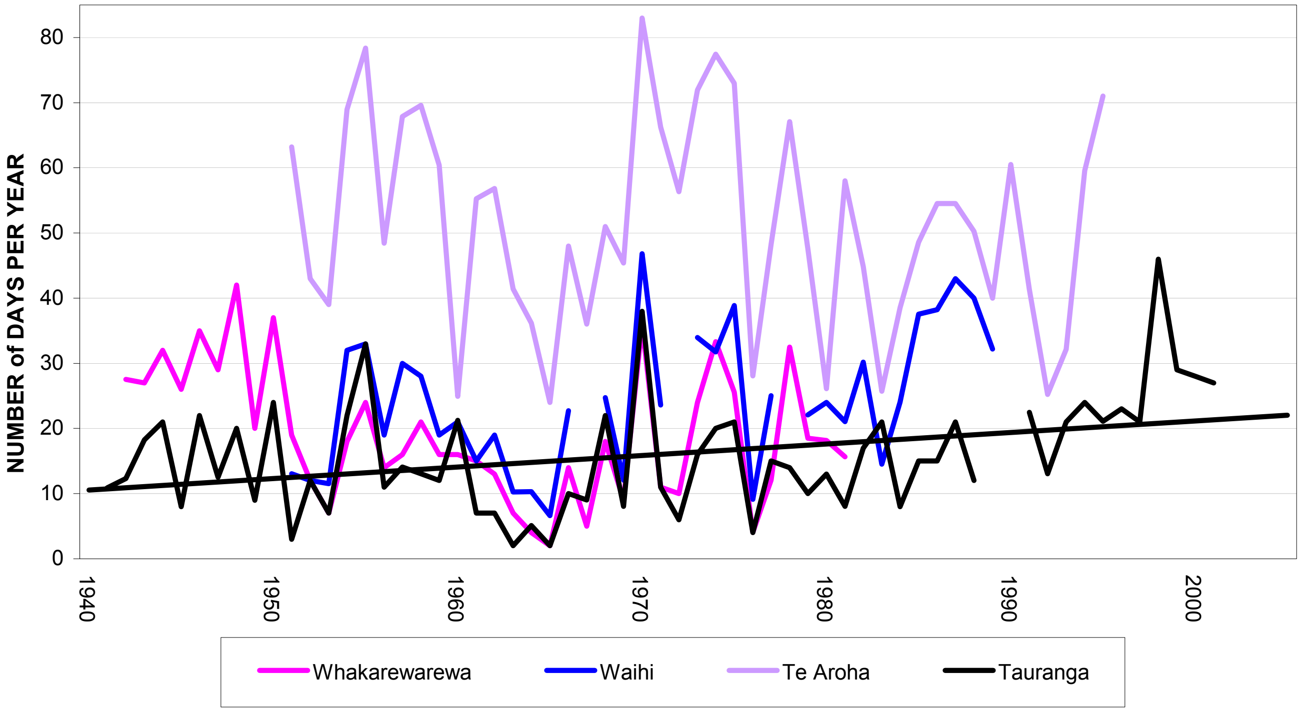


Figure 11: *25C days* at four Bay of Plenty stations. A linear trend has been added to Tauranga, the reference station.

Significant increases in the *25 C days* index occur at Tauranga (+0.2 days per decade), and Waihi (+0.4 days per decade), over their respective (differing) record lengths (Table 7). Te Aroha, probably being the most rural site, shows no significant trend. Interestingly, Whakarewarewa measures a significant decrease in the index over its record length 1941 to 1982, but this is probably an artifice of the period of data, rather than a trend one might expect to continue, given that the Whakarewarewa index moves coherently with the other station indices over the common (longer) record length.

There are no significant change points for any station for this index.

In summary: The number of days with maximum temperatures exceeding 25 °C shows large year-to-year variability in the Bay of Plenty. The frequency of *25 C days* has significantly increased in some, but not all, parts of the Bay of Plenty since good-quality, daily temperature records began in 1940. The rate of this increase is typically less than that observed for a range of minimum temperature indices.

3.5.10 Extreme temperature range – The hottest minus the coldest

A time series of the intra-annual extreme temperature range - the hottest temperature recorded each year minus the coldest temperature recorded each year - is shown in Figure 12. Typical values of this index range between 32 °C or 33 °C at Waihi, Whakarewarewa, and Te Aroha. At coastal sites, such as Tauranga, the *extreme temperature range* is much less (around 29 °C), due to the moderating effect of the sea.

The index appears to move coherently for all the Bay of Plenty records – a large *extreme temperature range* recorded at one site tends to correlate with a large *extreme temperature range* recorded elsewhere in the Bay of Plenty.

A significant decreasing trend in the index is observed for Whakarewarewa (-1.1 °C per decade), and for Te Aroha (-0.3 °C per decade) (Table 7). Note that the strength of the Whakarewarewa decreasing trend may be due to its shorter record length of 1941 to 1982, over which period all of the available data show a decline. A decline in the intra-annual extreme temperature range is consistent with the strongly significant increase observed in minimum temperatures across the Bay of Plenty, and the somewhat slower (but sometimes still significant) increase in maximum temperatures in the region.

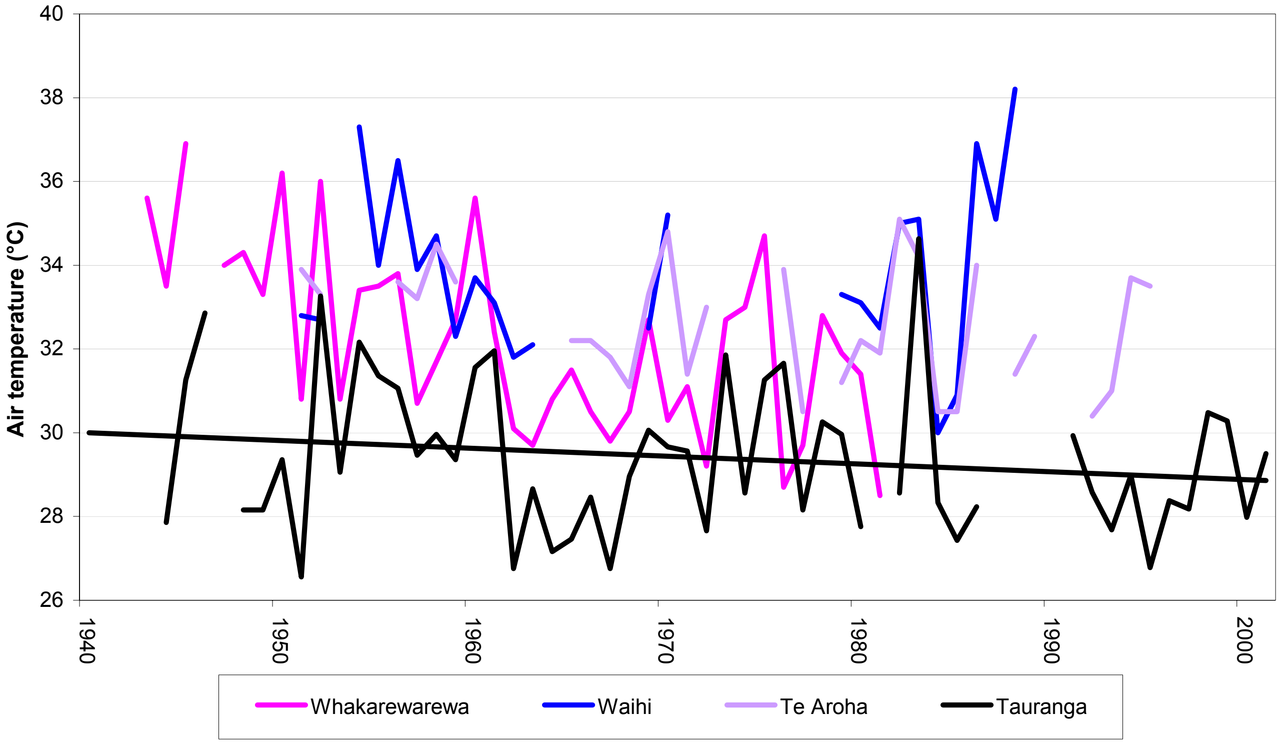


Figure 12: ***Extreme temperature range*** **at four Bay of Plenty stations. A linear trend has been added to Tauranga, the reference station.**

No significant trends are observed otherwise, with our reference temperature record at Tauranga exhibiting a non-significant decrease in the index.

1960 is flagged as a significant change point at Whakarewarewa, with the largest decrease in the *extreme temperature range* prior to this time (Table 8).

In summary: The *extreme temperature range* is largest inland, and smaller near the coast. The *extreme temperature range* has significantly decreased in some, but not all, parts of the Bay of Plenty since good-quality, daily temperature records began in 1940. A decline in the intra-annual extreme temperature range is consistent with the larger warming observed in minimum temperatures across the Bay of Plenty, and the somewhat smaller increase in maximum temperatures in the region.

3.5.11 Cold nights – Depicts the typical temperature of an extremely cold night

This index averages the size of the coldest four minimum temperatures per year. On average, the *cold night* index is around 0.5 °C at Tauranga, –1.5 °C at Te Aroha, -2.0 °C at Whakarewarewa, and about –3.0 °C at Waihi (Figure 13). It is evident that extremely cold night time temperatures are influenced by proximity to the sea, and elevation above sea level.

The *cold nights* index moves in tandem across the Bay of Plenty – large values of the index at any site correspond to large values elsewhere.

It is clear by eye from Figure 13 that there has been a strong increase in this index. Indeed, all stations exhibit a highly statistically significant increase of the order of +0.3 °C per decade over their respective (differing) record lengths, even Te Aroha, a relatively rural site (Table 7). This is important, as it suggests that the trends cannot be attributed to "other" effects such as urbanisation.

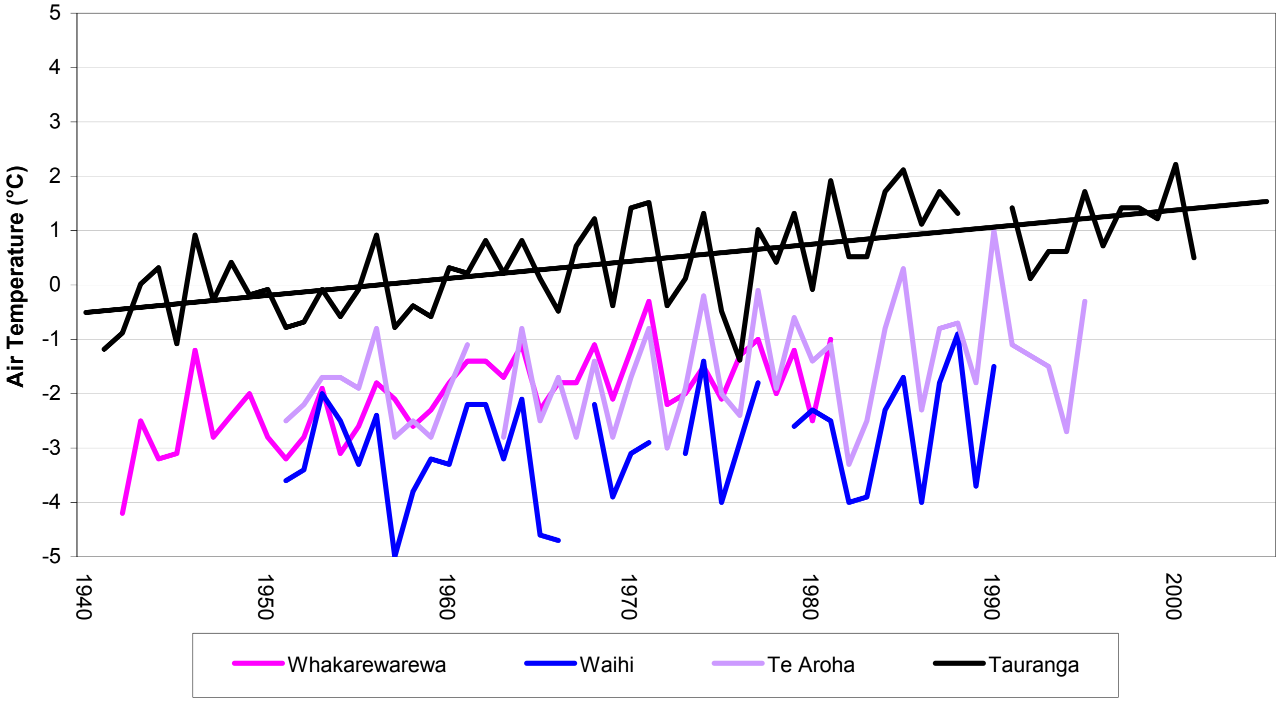


Figure 13: *Cold nights* at four Bay of Plenty stations. A linear trend has been added to Tauranga, the reference station.

Circa 1960, a significant change point is identified at Tauranga and Whakarewarewa, with the largest warming trend observed following this time (Table 8). 1976 is also flagged as a change point in the index series at Te Aroha and Tauranga, along with 1992 at Tauranga, but this may be because of the extremely low values of the index (outliers), which occur at these times.

In summary: The coldest nights have significantly warmed in the Bay of Plenty since good-quality, daily temperature records began in 1940, with the greatest warming seen at some stations since 1960, and again following 1976.

3.5.12 Frequency of cold nights – Measures the frequency of the extremely cold night

Figure 14 and Table 7 show highly significant decreases in the *frequency of cold nights* at all Bay of Plenty stations analysed over their respective (differing) record lengths. The decline ranges from approximately 1 day per decade at Waihi and Te Aroha, to a decrease of 3 days per decade at Whakarewarewa.

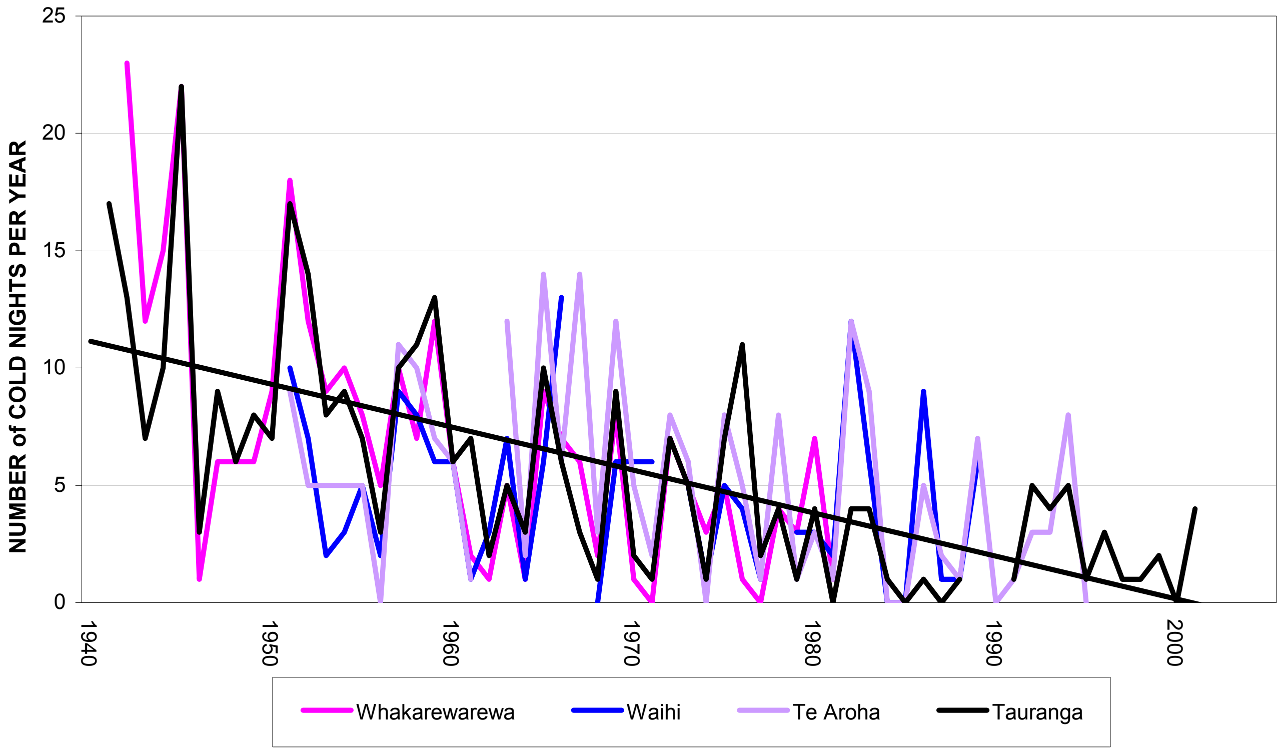


Figure 14: ***Frequency of cold nights*** **at four Bay of Plenty stations. A linear trend has been added to Tauranga, the reference station.**

As a practical illustration of what this means, prior to the 1960s at Tauranga, there were on average 10 nights per year colder than the 1961-1990 average 1 percentile of minimum temperatures. In the 1990s, there were only, on average, 2 to 3 nights per year colder than this value.

The *frequency of cold nights* index also moves coherently throughout the Bay of Plenty – large values of the index at any site correspond to large values universally.

Circa 1960 has been identified as a significant change point at Tauranga and Whakarewarewa, consistent with the change point flagged for the *cold nights* index.

In summary: The number of extremely cold nights has significantly decreased in the Bay of Plenty since good-quality, daily temperature records began in 1940.

3.5.13 Hot days – Depicts the typical temperature of an extremely hot day

This index averages the size of the warmest four maximum temperatures per year (Figure 15). A typical *hot day* is approximately 27 °C in Tauranga, 27.5 °C at Waihi and Whakarewarewa, and 28.5 °C at Te Aroha. Large year-to-year variability is seen in all the station records, and a large outlier is recorded at Waihi in 1988 (with the *hot days* index measuring 33 °C!).

A significant increase is seen in the *hot day* index at Tauranga and Waihi (+0.2 to 0.4 °C per decade), with no significant trend at Te Aroha (Table 7). Whakarewarewa, analysed over a shorter period 1941-1982, shows a significant decrease (-0.5 °C per decade), but again this is probably an artifice of the period of data, rather than a trend one might expect to continue, given that the Whakarewarewa index moves coherently with the other station indices over the common record length.

Significant change points in the index time series are identified in 1950 at Whakarewarewa, and around 1968 at Tauranga and Te Aroha (Table 8). Both change points indicate a change in slope of the series, with a decreasing trend prior to the change points, and an increasing trend following the change points. 1979 is also flagged for Waihi, with a similar change in trend across the change point.

In summary: The hottest days have significantly warmed in some, but not all, parts of the Bay of Plenty since good-quality, daily temperature records began in 1940. Most of the warming occurred since 1968 at several of the sites analysed.

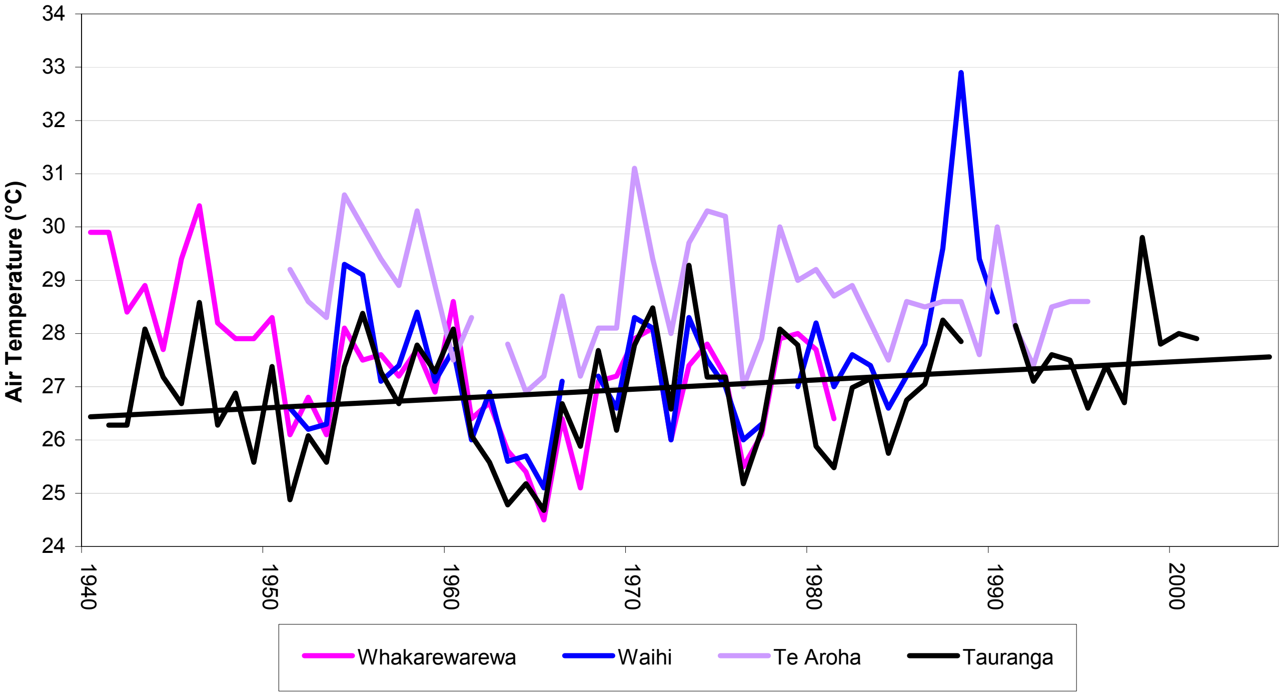


Figure 15: ***Hot days*** **at four Bay of Plenty stations. A linear trend has been added to Tauranga, the reference station.**

3.5.14 Frequency of hot days – Measures the frequency of the extremely hot day

The hottest days have become more frequent at some sites in the Bay of Plenty. Tauranga and Waihi record a significant increase in the number of *hot days* (see Figure 16 and Table 7) over their respective (differing) record lengths, of about 1 day per decade. Significant change points were identified around 1968 at Tauranga and Te Aroha, with an increase in frequency following this time. For example, at Tauranga, the average frequency of hot days before 1968 was approximately 3.3 days a year, but rose to about 6.4 days following this time – nearly double the number of extremely hot days. 1985 was also flagged as a significant change point at Waihi.

Whakarewarewa, analysed over a shorter period 1941-1982, shows a significant decrease (-1.8 days per decade), but once again, this is probably an artifice of the period of data, rather than a trend one might expect to continue, given that the Whakarewarewa index moves coherently with the other station indices over the common record length. 1950 was identified as a significant change point at

Whakarewarewa, consistent with change points flagged for the *hot days* index (Table 8).

In summary: The hottest days have become more frequent in some, but not all, parts of the Bay of Plenty since good-quality, daily temperature records began in 1940. Most of the increase occurred following 1968 at several of the sites analysed.

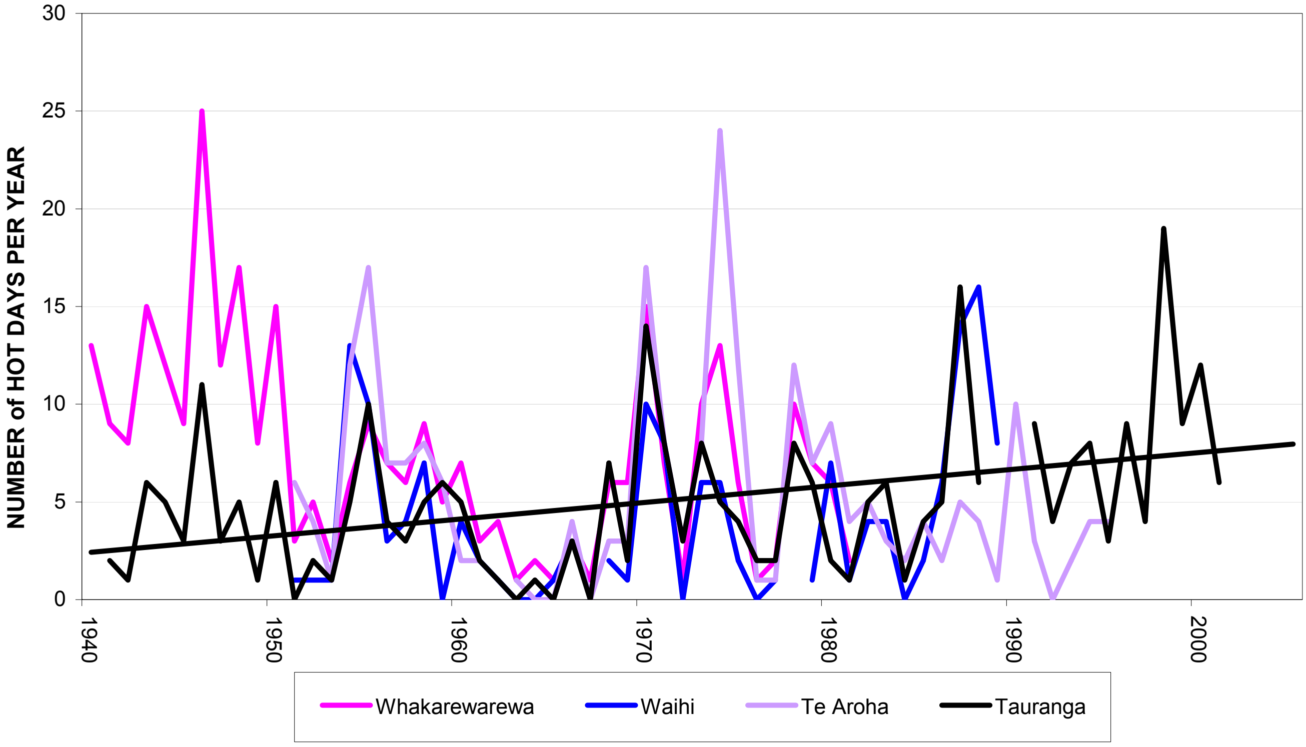


Figure 16: ***Frequency of hot days*** **at four Bay of Plenty stations. A linear trend has been added to Tauranga, the reference station.**

3.6 Patterns of Trends in Mean Temperature and Precipitation

Previous parts of this section have used primarily daily data to describe historical climate variations in the Bay of Plenty. The results have emphasised variations in extremes, and have been illustrated by time series of various indices at selected stations. Before going on to section 4 on reasons behind the observed changes, it is useful to summarise recent trends in mean climate with a series of maps.

Linear trends in mean temperature and rainfall are calculated over the 50-year period 1951-2000, and shown in Figures 17 and 18. Monthly data are used, and aggregated up into seasonal values (Summer = December-January-February). In order to have realistic gradients around the borders of the Bay of Plenty region, it is necessary to include a number of other New Zealand stations. The so-called "Full" set of stations, and method of data synthesis, is described in section 6 dealing with future scenarios.

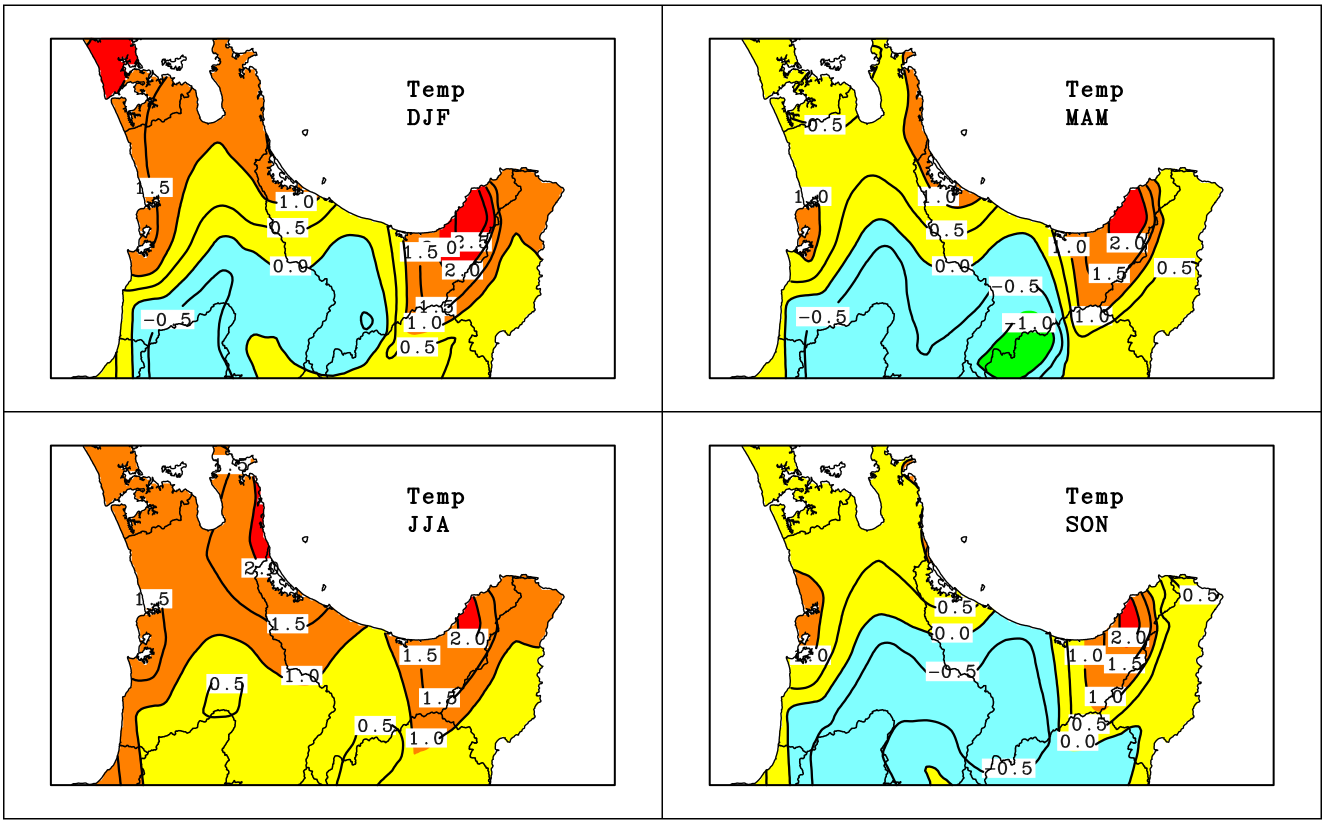


Figure 17: Trend in seasonal mean temperature over the period 1951-2000, in units of 0.1°C per decade, for Summer (DJF), Autumn (MAM), Winter (JJA) and Spring (SON). Contours are drawn every 0.5 (ie, every 0.05°C per decade). Colour shading differentiates cooling trends (blue, green) from warming trends (yellow, orange, red being successively warmer).

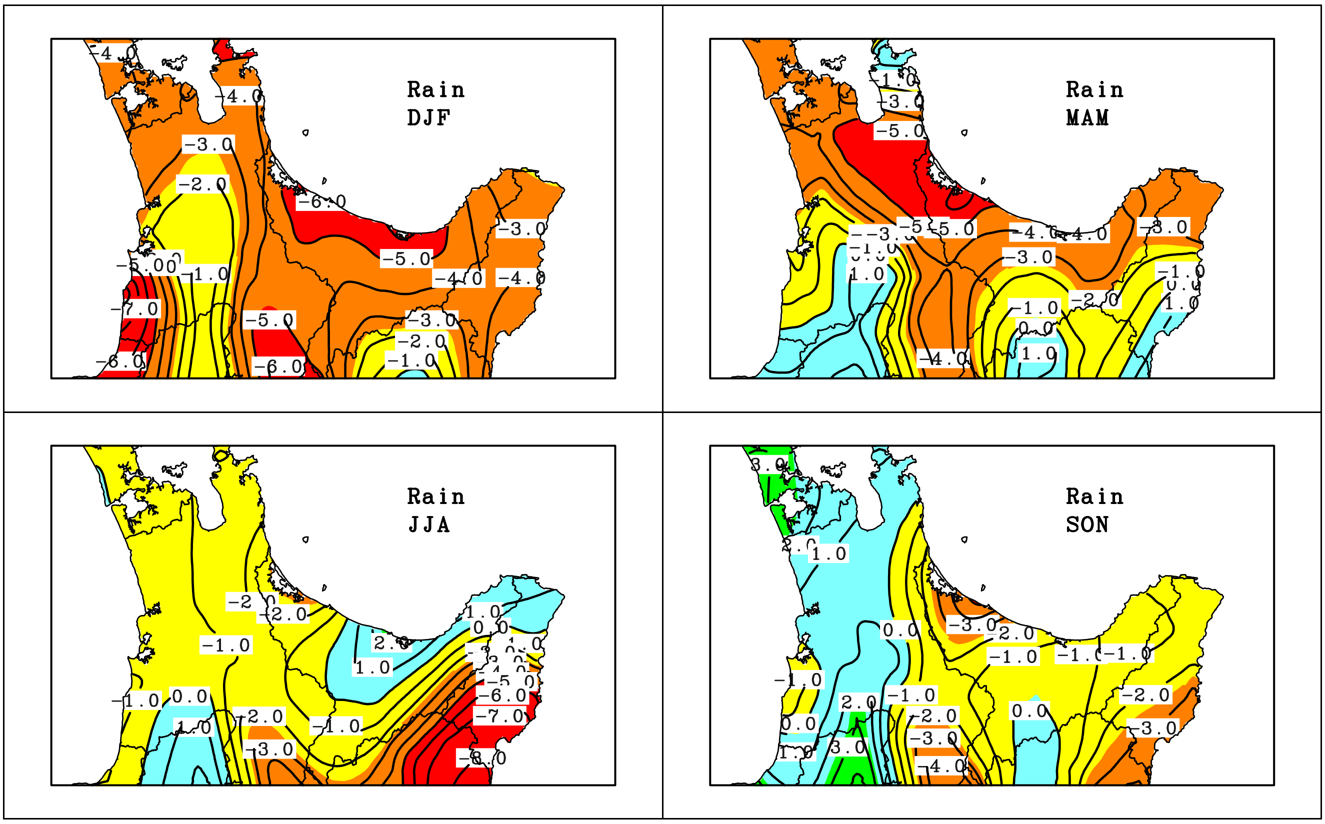


Figure 18: Trend in seasonal mean rainfall over the period 1951-2000, in percent per decade (relative to 1961-1990 baseline), for Summer (DJF), Autumn (MAM), Winter (JJA) and Spring (SON). Contours are drawn every 1%. Colour shading differentiates drying trends (yellow, orange, red being successively drier) from wetting trends (blue, green being successively wetter). Regional Council boundaries are marked on the basemap.

The seasonal temperature trends (Figure 17) show that warming predominates over the period 1951-2000. Warming is most pronounced in coastal Bay of Plenty, in both western stations (Waihi, Tauranga) and eastern stations (Opotiki). A contour value of +2 (red shading) implies a warming of +1.0°C over the 50 years, which is substantial. Inland Bay of Plenty, from Kaingaroa southwards, shows a weak cooling trend in all seasons except winter, when warming is seen everywhere.

Seasonal rainfall trends (Figure 18) show that most stations in the Bay of Plenty region have become drier over the 50-year period, except for eastern coastal regions from Whakatane eastward in winter. A contour value of –2 implies a drying of 10% (of the 1961-1990 seasonal climatology) over the period. In much of the region, the drying trend has been substantially larger than this in the summer and autumn seasons. In particular, Tauranga rainfall has decreased by about 10% in winter to 30% in summer since 1951. This trend towards decreasing rainfall over 1951-2000 is evident in many of the index time series in the earlier part of this section (e.g., Figures 2, 3, and 5). These earlier figures also show that the 1950s and 1960s tended to be a wet period. The 1930s and 1940s were drier, although not as dry, in general, as the 1990s. The cause of these multidecadal climate trends is discussed in the following section.

In summary: Over the 50-year period 1951-2000, seasonal mean temperatures in the Bay of Plenty have increased substantially along the coast. Inland southern parts of the region have shown little warming, and have even cooled slightly in some seasons. Seasonal rainfall has decreased over most of the region in most seasons. Decreases have been larger in the west (Tauranga westwards) than in the east (Whakatane eastwards) and south.

4. Possible Mechanisms for Climate Shifts and Trends in the Bay of Plenty

New Zealand climate varies naturally with fluctuations in the strength and position of the prevailing westerlies and the subtropical high-pressure belt. Local climate variations often have a strong spatial pattern imposed on them because of interactions between the circulation and southwest/northeast alpine ranges of the country. On timescales of a year or more, three main factors need to be considered: long-term trends, the natural cycles of the El Niño-Southern Oscillation (ENSO), and the Interdecadal Pacific Oscillation (IPO). The actual climate experienced will be a superposition of these three factors, plus other irregular influences such as large volcanic eruptions in the tropics.

The interpretation of long-term trends can vary according to the length of record analysed. The simplest view is to assume a change in one direction (to higher temperatures, say) over the 100-year timescale, that would be linear except for the influence of natural cycles and random events that complicate the time series. Air temperature in the New Zealand region has increased by more than 1.1°C since 1861 (Salinger et al., 1996). This local warming is consistent with, although larger than, the global average temperature increase over the same period of about +0.6°C (IPCC, 2001).

There are no consistent trends in New Zealand rainfall over the century timescale, although there is substantial variability from decade to decade. Thus, quasi-cyclic variations in circulation tend to dominate the local rainfall climate. The remainder of this section will focus on the natural variations. Section 6 will consider scenarios of future anthropogenic change in New Zealand climate.

4.1 El Niño-Southern Oscillation (ENSO)

The El Niño-Southern Oscillation is a tropical Pacific-wide oscillation that affects pressure, winds, sea-surface temperature (SST) and rainfall. In the El Niño phase, the easterly trade winds weaken and SSTs in the eastern tropical Pacific can become several degrees warmer than normal. There is a systematic eastward shift of convection out into the Pacific: Australia experiences higher pressures and droughts, whereas New Zealand experiences stronger than normal southwesterly airflow. This generally results in lower seasonal temperatures for New Zealand, and drier conditions in northeastern parts of the country such as the Bay of Plenty. The La Niña phase is essentially the opposite in the tropical Pacific, and New Zealand experiences more northeasterly flow, higher temperatures and wetter conditions in the Bay of Plenty. Alternating El Niño and La Niña events will therefore produce large interannual variations in Bay of Plenty climate.

Figure 19 shows a time series of the Southern Oscillation Index (SOI), a common measure of the intensity and state of ENSO events derived from the pressure difference between Tahiti and Darwin. Persistence of the SOI below about –1 coincides with El Niño events, and periods above +1 with La Niña events. Because the tropical Pacific SST anomalies persist for up to a year, there is substantial predictability in how ENSO events affect New Zealand climate, and there has been considerable research to identify local impacts. However, the ENSO cycle varies between about 3 and 7 years in length, and there is large variability in the intensity of individual events.

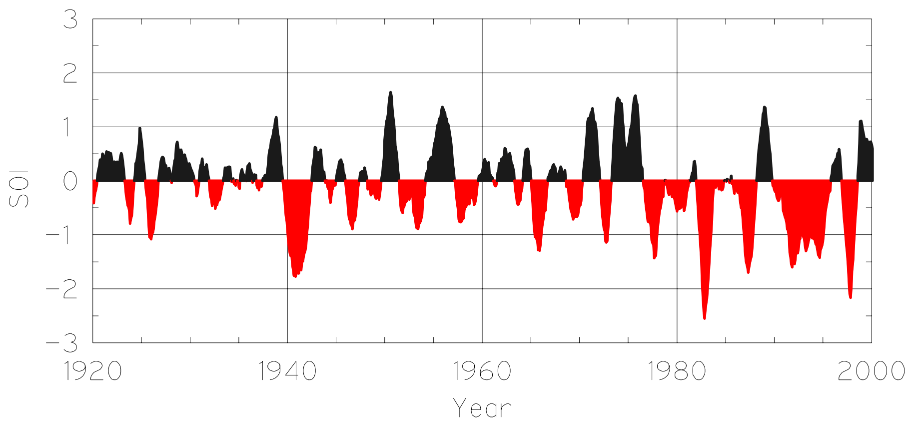


Figure 19: Southern Oscillation Index, derived from Tahiti minus Darwin pressure difference anomalies, and normalised by the standard deviation of the monthly differences. Monthly values have been smoothed by taking a 12-month running mean, in order to highlight El Niño events (SOI below about –1) and La Niña events (SOI above about +1).

Figure 20 shows typical summer rainfall anomalies associated with El Niño periods. Much of the Bay of Plenty region is shaded orange, indicating seasonal rainfall of at least 15% below normal. Other parts of New Zealand that frequently experience drought conditions during El Niño are Gisborne, Hawkes Bay, Marlborough and coastal Canterbury.

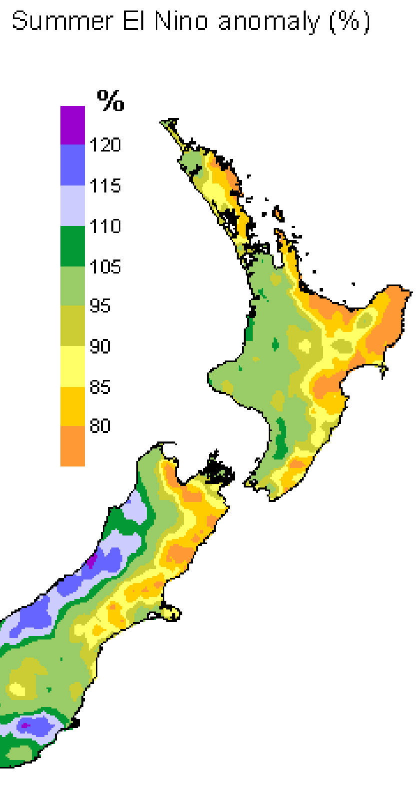


Figure 20: Composite rainfall anomalies (in %) over nine El Niño summer seasons from 1957/58 to 1997/98. Blue shading highlights the wetter regions, and orange shading the drier regions. Note that rainfall patterns for individual El Niño summers can vary significantly from this "average" picture.

Relationships between the SOI and Bay of Plenty climate are clarified by Figures 21 and 22, which show correlations between the SOI and seasonal temperature and rainfall anomalies. For temperature (Figure 21), the correlations are all positive, implying higher than normal temperatures for positive SOI (ie, in La Niña periods), and lower than normal temperatures for negative SOI (El Niño). The correlations range from a weak +0.20 ("20" contour line) in summer (Dec-Jan-Feb) to over +0.40 throughout the region in spring (Sep-Oct-Nov).

For rainfall (Figure 22), the correlations are also positive throughout the Bay of Plenty district, implying higher than normal rainfall for positive SOI (ie, in La Niña periods), and lower than normal rainfall for negative SOI (El Niño). The strongest correlations, exceeding +0.40, occur around Whakatane in spring, but correlations above +0.30 occur over much of the Bay of Plenty region in both winter and spring.

These correlations, although statistically significant (r > +0.28 is significant at the 95% level on 50 years of data), are not large, and much of the year to year variability of Bay of Plenty climate can not be explained by what the Southern Oscillation is doing.

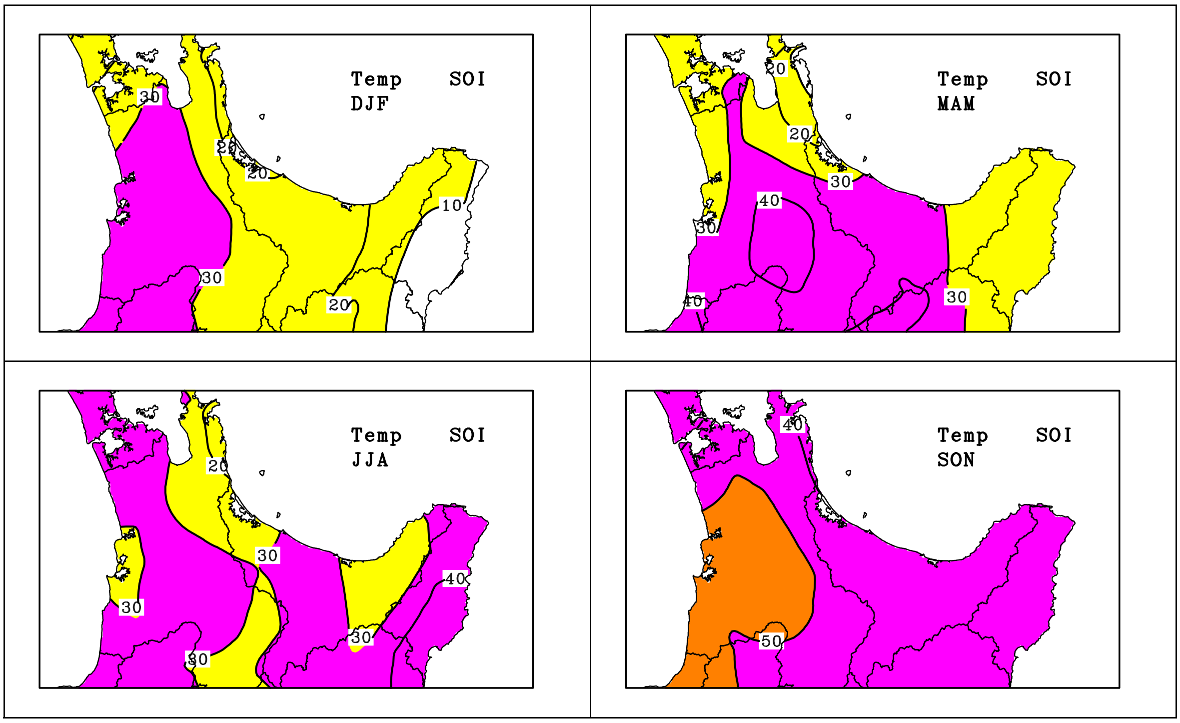


Figure 21: Correlation of SOI versus Temperature for each season, over the period 1951-2000. Contour values are correlation times 100, drawn every 10 units.

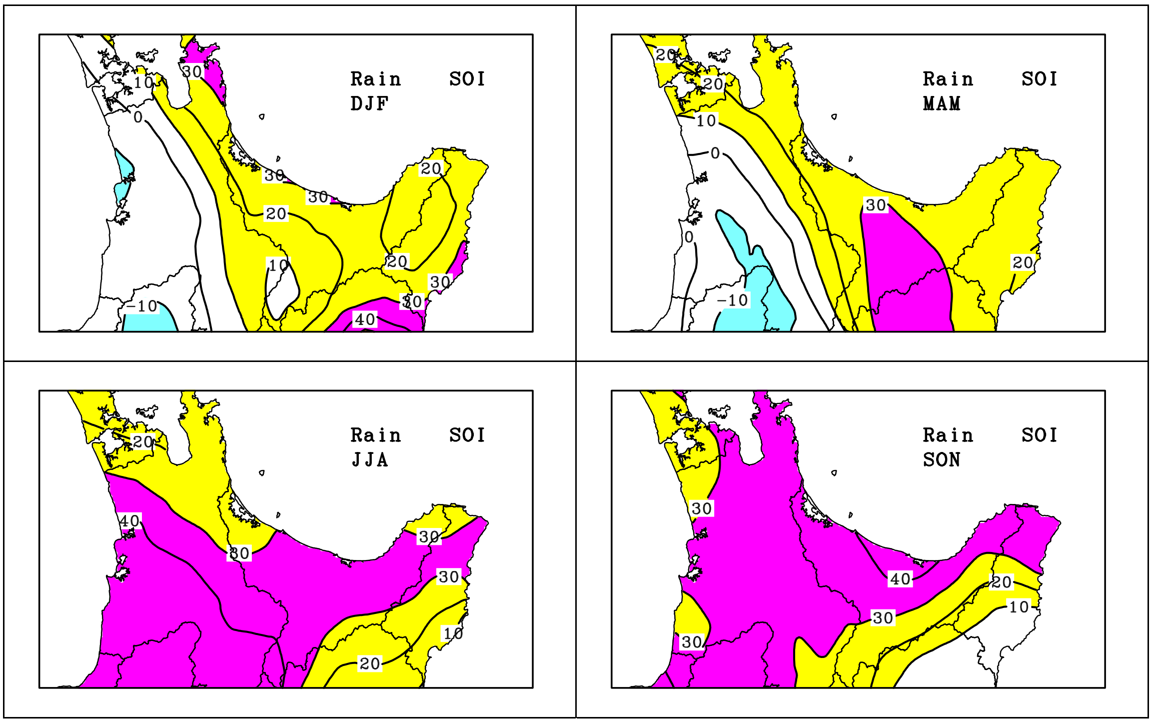


Figure 22: As Figure 21, but for correlation of SOI versus Rainfall.

4.2 Interdecadal Pacific Oscillation (IPO)

The Interdecadal Pacific Oscillation (IPO) is a recently identified natural cycle that has been shown to be associated with decadal climate variability over parts of the Pacific Basin (Mantua et al., 1997). Three phases of the IPO have been identified during the 20th century: a positive phase (1922–1944), a negative phase (1946–1977) and a second positive phase (1978–1998). The pattern associated with the positive phase is warmer SSTs in the tropical Pacific (more El Niño-like) and colder conditions in the North Pacific. Around New Zealand, the SSTs tend to be lower, and westerly winds stronger, during the positive IPO phase.

Figure 23 shows a time series of the IPO, derived from a UK Meteorological Office analysis of global SST patterns. There were abrupt changes from positive to negative values around 1945, and back to positive around 1978. These are two key “change points” in the New Zealand climate record. A number of the abrupt climate shifts identified by the Pettitt test in Section 3 match up approximately with the timing of IPO phase changes.

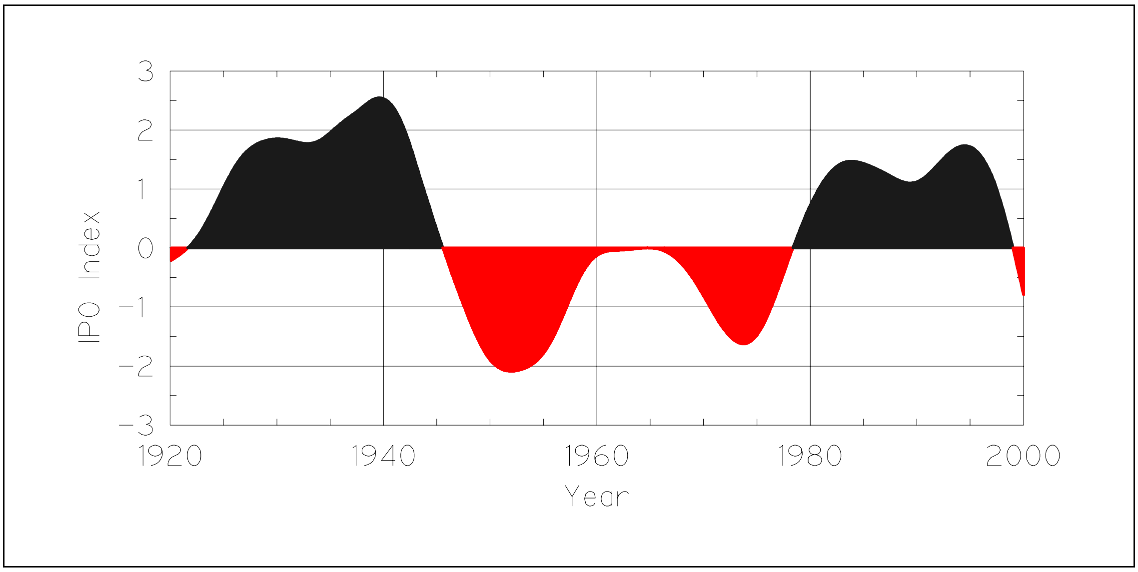


Figure 23: Interdecadal Pacific Oscillation from 1920 to 2000.

Figure 24 maps annual rainfall changes between negative and positive IPO periods centred on 1978, and Figure 25 shows the corresponding time series for the northern region of the country that includes the Bay of Plenty district. In Figure 24, we see that after 1978 the west of the South Island became about 10% wetter, whereas the north of the North Island became drier to a similar degree. The time series of rainfall (Figure 25) shows large interannual changes in rainfall amount, that match up well with the SOI time series of Figure 19 (e.g., the large El Niño of 1982/83 and the long-running 1991-94 El Niño period). These changes in means could potentially affect extreme short-duration rainfalls too (see Section 5).

The higher frequency of El Niños during the 1978-1998 positive IPO phase appears to be the main cause of the decreased Bay of Plenty rainfall in recent times. Note too the long-running dry period in the early 1940s, that coincided with a persistent El Niño period at the end of the earlier 1922-1944 positive IPO period.

Analysis of the latest sea temperature data suggests that we have entered another negative IPO phase, under which more La Niña (and less El Niño) activity compared to the 1978-1998 period might be expected, together with a period of higher temperatures for New Zealand. Weaker westerlies are also likely, along with an implied increase in the mean (multi-annual) Bay of Plenty rainfall.

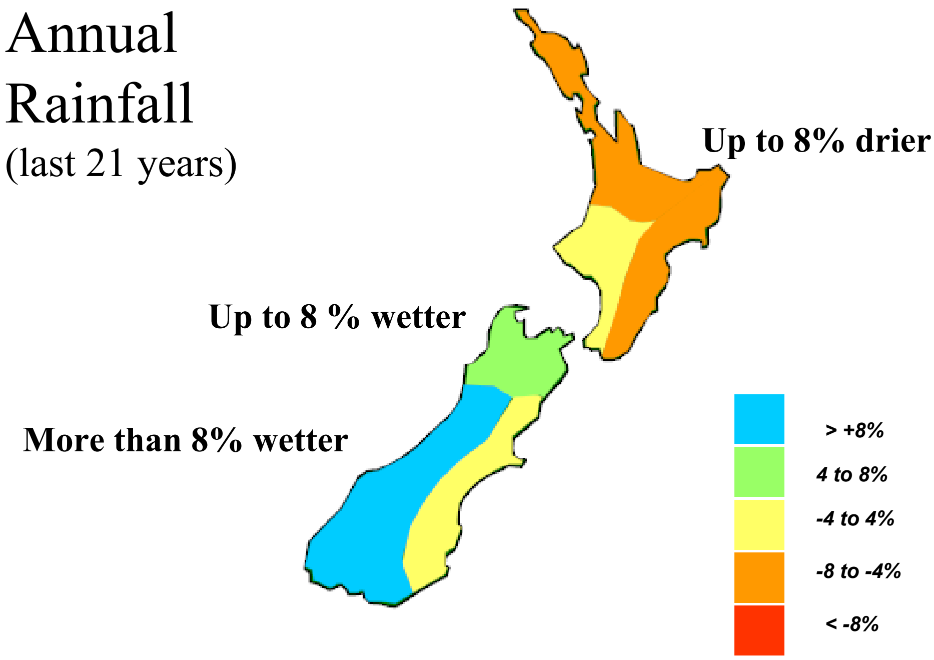


Figure 24: Change in annual rainfall (in %) for 1978-98, when IPO was in positive phase, compared to preceding 21 years of IPO negative. Changes are shown for the six forecast regions of NIWA's National Climate Centre (http://www.niwa.co.nz/ncc/).

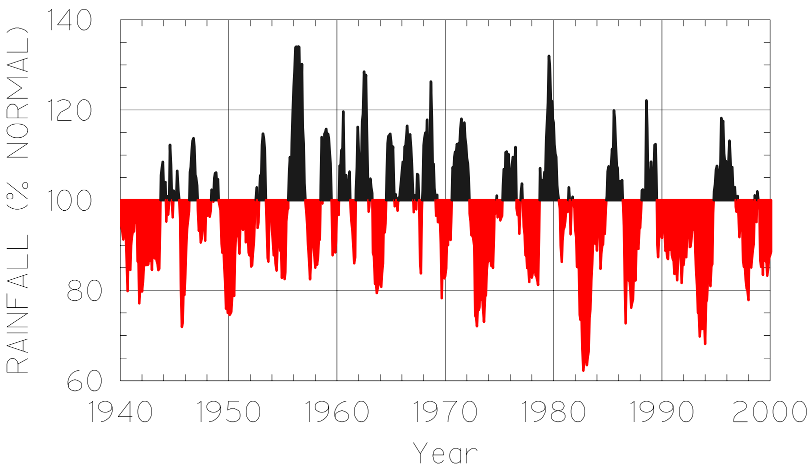


Figure 25: Annual rainfall for the northern region of the North Island (Northland, Auckland, Bay of Plenty, and the northern part of Waikato).

4.3 Influence of Circulation Changes on Bay of Plenty Climate

The climate variations described earlier in this section have persistent circulation changes associated with them (Salinger and Mullan, 1999). The SOI is rather an indirect measure of circulation over the New Zealand region; SOI-circulation relationships vary with the season, and also appear to change multi-decadally with different IPO phases. Clearer inferences can be drawn by correlating climate against direct indices of the atmospheric circulation. For the purposes of illustration, we have chosen here two indices commonly used to describe New Zealand circulation. The time series of these indices are shown in Figure 26, and their correlations with Bay of Plenty temperature and rainfall shown in Figures 27 to 30.

The two circulation indices are known as Z1 and M2. Z1 is the anomalous pressure difference between Auckland and Christchurch, and monitors fluctuations in the zonal (east-west) flow across the country. Positive Z1 values mean stronger than normal westerly, and negative values weaker westerly (or more easterly, although seasonal mean easterly flow in an absolute sense is very uncommon). M2 is the anomalous pressure difference between Hokitika and Chatham Islands, and monitors fluctuations in the meridional (north-south) flow over and east of the country. Positive M2 values mean stronger than normal southerly flow, and negative values more northerly (or less southerly, depending on the season and magnitude of M2).

Figure 26 shows the time series of the Z1 and M2 circulation indices. Both indices exhibit trends over the 1951-2000 period (Table 9); Z1 has been increasing in all seasons, but particularly in winter, and M2 has been decreasing in the summer and winter seasons.

Table 9: Seasonal trend per decade (as fraction of 1961-1990 standard deviation) in circulation indices Z1 and M2, over period 1951-2000.

INDEX	Summer	Autumn	Winter	Spring
Z1 (Auckland-Christchurch)	0.71	0.66	1.79	0.20
M2 (Hokitika-Chatham)	-1.21	0.03	-0.77	0.08

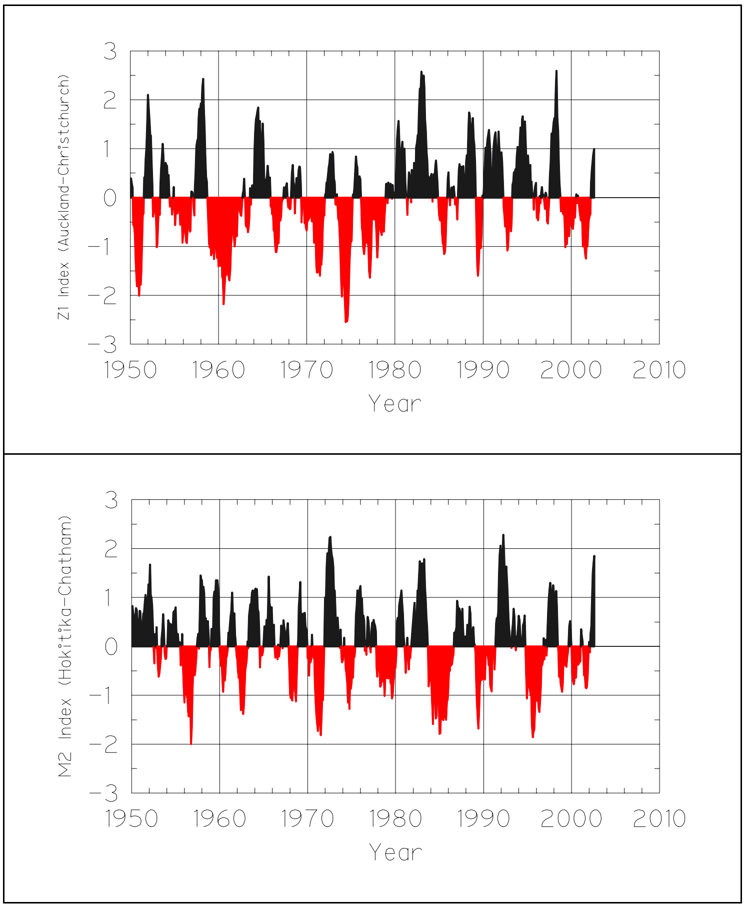


Figure 26: Circulation indices Z1 (upper panel) and M2 (lower panel).

Figures 27 and 28 show the seasonal correlations between the Z1 index and temperature and rainfall, respectively, over the 1951-2000 period. Correlations between Z1 and temperature are very weak in the Bay of Plenty. Correlations between Z1 and rainfall are moderately strong and uniformly negative, indicating lower rainfall under increased westerly airflow. The rainfall correlations are also somewhat more negative in the western Bay of Plenty, implying that as Z1 increases there are bigger rainfall decreases around Tauranga (more sheltered from westerlies) than further east.

Figures 29 and 30 show the correlations with the M2 index. Correlations between M2 and temperature are strongly negative in all seasons, but particularly in autumn and winter. Thus, decreases in M2 (i.e., more northerly airflow) go along with increased temperature. The increased northerly flow over New Zealand is also consistent with stronger warming locally relative to the average around the Southern Hemisphere at our latitudes. Correlations between M2 and rainfall are also negative in all seasons, and particularly strong in autumn. This would imply increasing rainfall as M2 decreases (Table 9). Rainfall increases have not been observed, suggesting that the changes in Z1 have dominated over the period analysed.

In summary:

- The decrease in rainfall over much of the Bay of Plenty region since 1951, and the relatively larger decreases in the west near Tauranga, is partly attributable to increased westerly airflow over this period, corresponding to the IPO phase change from negative to positive.

- The IPO appears to have switched back to a negative phase, which should result in more frequent La Niña events, higher temperatures, weaker westerlies and increased rainfall for the Bay of Plenty over the next two decades. These changes could be modified by anthropogenic long-term trends (see Section 6).

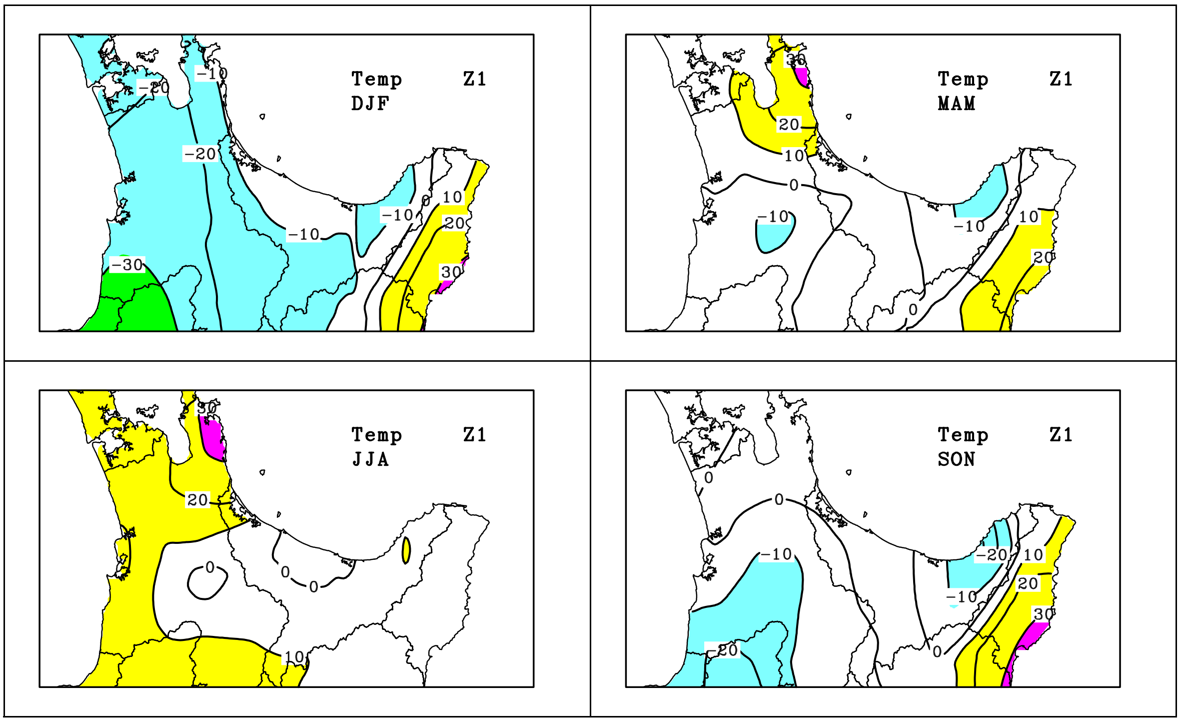


Figure 27: Correlation of Z1 westerly index versus Temperature for each season, over the period 1951-2000. Contour values are correlation times 100, drawn every 10 units.

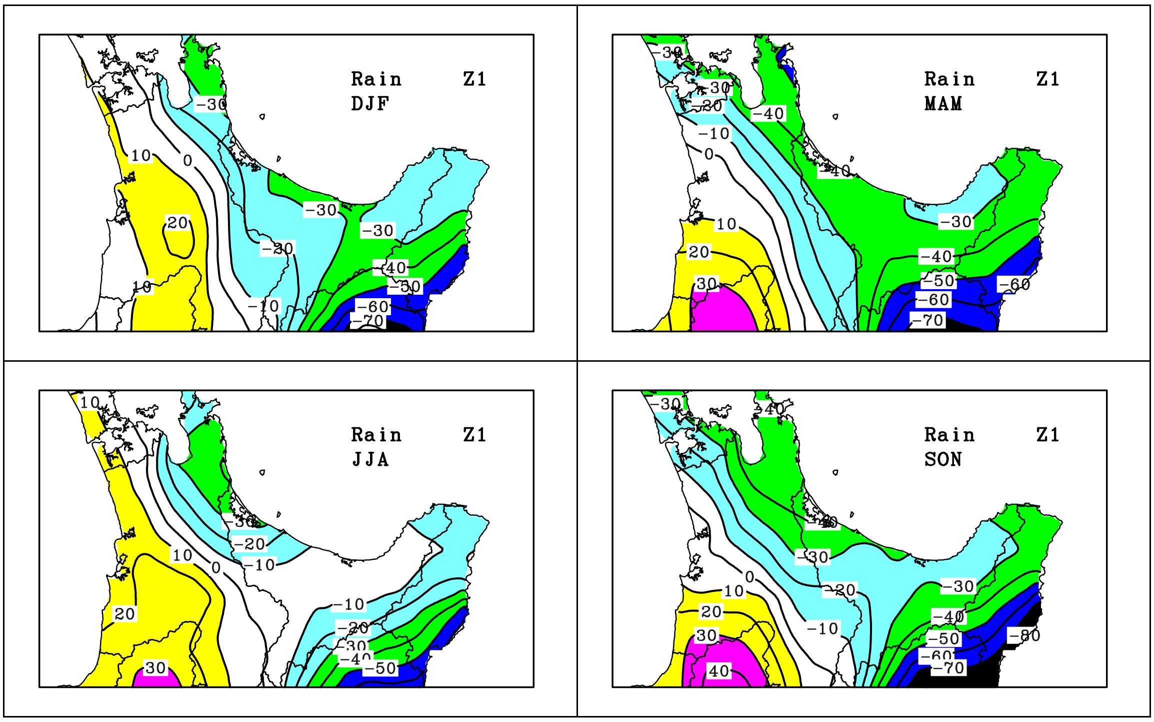


Figure 28: As Figure 27, but for correlation of Z1 versus Rainfall.

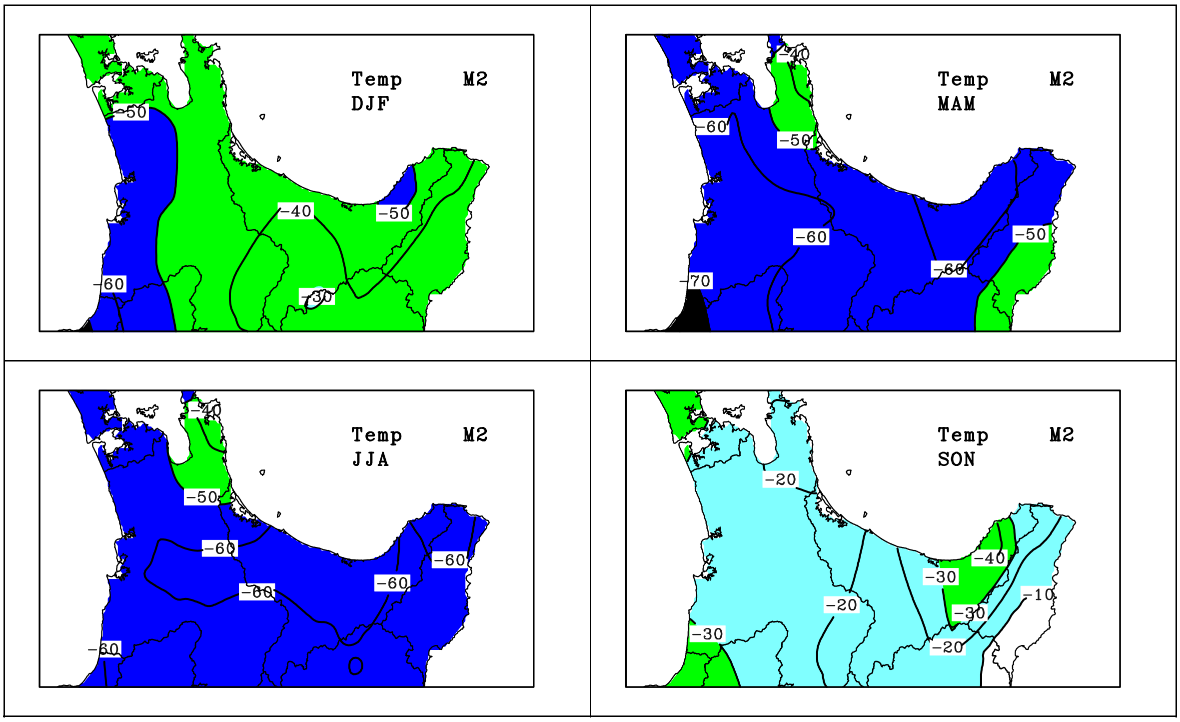


Figure 29: As Figure 27, but for correlation of M2 southerly index versus Temperature.

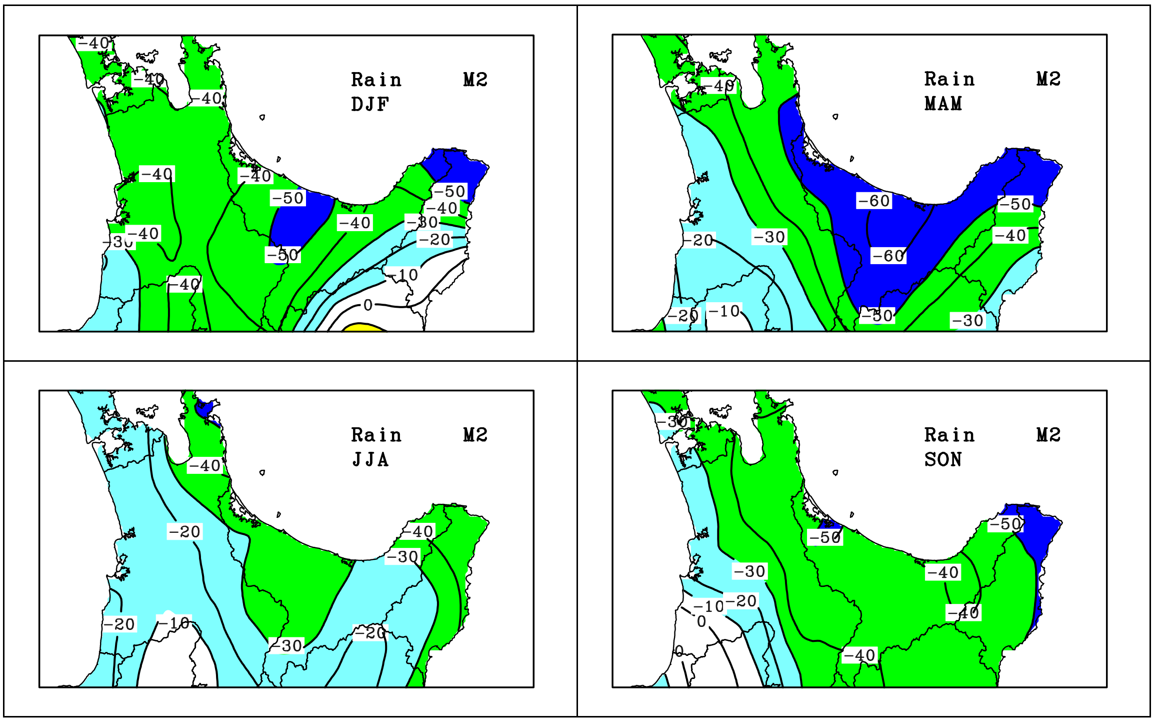


Figure 30: As Figure 28, but for correlation of M2 southerly index versus Rainfall.

5. The Influence of the IPO on High Intensity Rainfall

In this section, an assessment is made of the frequency of extreme rainfall for a range of durations from 10 minutes to 72 hours from annual maximum records to examine whether there have been changes in the frequency of extreme events that could be associated with the phases of the IPO.

Recording rain gauge and daily rainfall observations have been made at a number of sites in the Bay of Plenty region that cover the period of the two most recent IPO episodes: an earlier negative phase covering the period 1946 to 1976, and the just recently completed positive phase covering the monitoring period 1977-1999. Annual maxima for the durations from 10 minutes to 72 hours were extracted from NIWA's national climate database (Clidb). Table 10 provides details of the sites used in this analysis. For a number of sites, it was necessary to combine data from two nearby locations to create a composite record that spanned the 54-year period (i.e. 1946 to 1999).

Table 10. Site data information used in analysis.

Location	Data period	Gauge type	Composite	Ranksum test
Whakatane	1967-1990	Automatic	Yes	10 minute significant
Tauranga	1967-1996	Automatic	No	
Rotorua	1967-1991	Automatic	No	
Opotiki	1968-2001	Automatic	No	
Waihi	1946-1999	Daily	Yes	2-day significant
Tauranga	1946-1999	Daily	Yes	Not significant
Whakatane	1947-1990	Daily	Yes	Not significant
Whakarewarewa	1946-1991	Daily	Yes	Not significant

No adjustments for changes of sites were made, although a Wilcoxon Ranksum test was performed to see if adjustments were needed. The ranksum test indicated that for all but three of the tests performed at the 8 rain gauge sites, no adjustment was required. At Waihi, there was a significant difference at the 0.05 level between the 2-day annual maxima rainfall in each phase of the IPO, while at Whakatane the 10-minute maxima were significantly different. The question arises as to what is the appropriate adjustment: for example an adjustment in the 2-day or 48-hour records will also necessitate an adjustment to the 3-day/72-hour records since it is not feasible to have a 2-day annual maximum rainfall larger than the 3-day value.

The following analyses were undertaken:

(i) Analyses of Bay of Plenty sites of high intensity rainfall during the negative and positive phases of the IPO.

(ii) Assessment of the significance of the changes in rainfall amounts for the same recurrence intervals between the two IPO phases.

(iii) Description of whether the changes in high intensity rainfall are related to seasonal mean rainfall totals.

5.1 Analyses of annual maximum rainfall

Historical annual maximum records were separated into the negative (1946-1976) phase and positive (1977-1999) phase of the IPO. Three statistical tests were performed to see whether there were significant differences that are due to the IPO. The first was a Students t-test on the mean annual maximum rainfall; the second was to perform the Wilcoxon Ranksum test, and the third to conduct an extreme value analysis on the data sets.

The mean and variances of the high intensity rainfall for each phase of the IPO are given in Table 11. A Students t-test on the split samples was carried out and the significance levels were computed for each duration. This test makes an assumption about the shape of the statistical distribution (i.e. it becomes asymptotically normal as the sample size increases), and uses annual maximum data that is generally positively skewed. The t-test is not as powerful as the Wilcoxon Ranksum test, which makes no assumptions about the statistical distribution, and assesses whether the median values in each phase of the IPO are statistically similar. In both these tests, a small probability level (e.g. 0.05) indicates a significant difference between the samples.

Table 11. Means, variance, significance of Students t-test, and significance of Wilcoxon Ranksum test of annual maxima for the specified durations for positive and negative phases of the IPO at (a) Whakatane automatic gauge, (b) Tauranga, (c) Opotiki, (d) Rotorua, (e) Waihi manual gauge, (f) Whakatane manual gauge, (g) Tauranga manual gauge, and (h) Whakarewarewa manual gauge. Probability levels less than or equal to 0.10 have been italicised.

a. Whakatane Automatic

	10m	30m	60m	2h	6h	12h	24h	48h	72h
Negative Phase IPO (1967-1976)									
Mean	9.9	19.9	29.0	39.2	63.1	96.9	107.4	127.0	139.5
Var	2.9	71.3	353.4	942.5	997.0	540.2	823.0	1515.8	2062.0
Positive Phase IPO (1977-1990)									
Mean	12.3	22.8	28.6	33.4	46.2	51.6	68.1	95.3	114.2
Var	19.5	99.0	119.8	95.4	80.4	90.6	468.4	3331.4	3407.2
Students t-test									
t-test	-1.24	-0.49	0.03	0.36	1.03	3.64	2.85	1.28	0.94
Prob	0.25	0.63	0.98	0.73	0.33	*0.01*	*0.01*	0.22	0.36
Wilcoxon Ranksum test									
Prob	0.35	0.48	0.52	1.00	0.32	*0.01*	*0.02*	0.11	0.19

b. Tauranga Automatic

	10m	30m	60m	2h	6h	12h	24h	48h	72h
Negative Phase IPO (1967-1976)									
Mean	9.8	18.0	25.7	41.2	64.0	81.1	95.5	112.8	127.5
Var	7.4	20.2	88.8	162.1	138.2	379.0	528.0	1078.8	1516.1
Positive Phase IPO (1977-1996)									
Mean	10.5	20.4	28.8	37.6	56.8	73.6	97.7	113.9	119.0
Var	16.4	67.7	186.0	316.6	567.1	959.1	1091.2	2515.6	3159.6
Students t-test									
t-test	-0.39	-0.74	-0.55	0.42	0.80	0.63	-0.19	-0.06	0.43
Prob	0.70	0.46	0.59	0.68	0.43	0.54	0.85	0.95	0.67
Wilcoxon Ranksum test									
Prob	1.00	0.66	0.73	0.43	0.15	0.21	1.00	0.77	0.42

c. Rotorua Automatic

	10m	30m	60m	2h	6h	12h	24h	48h	72h
Negative Phase IPO (1967-1976)									
Mean	11.1	21.9	33.4	41.5	70.1	92.2	117.0	143.0	152.6
Var	12.6	55.8	136.2	330.0	953.6	1459.9	1800.8	2100.4	222.9
Positive Phase IPO (1977-1991)									
Mean	12.7	21.3	27.0	36.2	57.3	71.4	88.7	110.8	126.0
Var	20.4	46.4	47.0	85.7	176.6	539.7	589.4	1708.6	2241.0
Students t-test									
t-test	-0.91	0.19	1.40	0.82	1.14	1.63	2.05	1.83	1.38
Prob	0.38	0.85	0.18	0.42	0.27	0.12	*0.05*	*0.08*	0.18
Wilcoxon Ranksum test									
Prob	0.39	1.00	0.19	0.60	0.20	*0.07*	*0.06*	0.11	0.19

d. Opotiki Automatic

	10m	30m	60m	2h	6h	12h	24h	48h	72h
Negative Phase IPO (1968-1976)									
Mean	10.9	17.1	22.7	30.4	48.6	65.0	93.6	118.0	126.8
Var	13.3	42.3	45.5	93.2	207.9	35.5	543.5	1206.3	1750.2
Positive Phase IPO (1977-1999)									
Mean	10.5	19.5	26.5	34.4	53.5	70.4	91.8	105.5	114.1
Var	8.5	31.8	44.9	48.9	224.4	363.6	751.9	1051.5	1164.8
Students t-test									
t-test	0.25	-0.75	-1.03	-1.05	-0.60	-0.56	0.17	0.01	0.85
Prob	0.80	0.46	0.32	0.31	0.56	0.58	0.87	0.37	0.40
Wilcoxon Ranksum test									
Prob	0.93	0.45	0.26	0.24	0.45	0.72	0.75	0.32	0.45

e. Waihi Manual

	10m	30m	60m	2h	6h	12h	24h	48h	72h
Negative Phase IPO (1946-1976)									
Mean							144.6	183.8	202.0
Var							1678.0	1862.2	2220.3
Positive Phase IPO (1977-1996)									
Mean							155.2	212.6	231.0
Var							2028.2	8502.4	11457.9
Students t-test									
t-test							-0.54	-1.47	-1.48
Prob							0.59	0.15	0.15
Wilcoxon Ranksum test									
Prob							0.58	0.79	0.85

f. Tauranga Manual

	10m	30m	60m	2h	6h	12h	24h	48h	72h
Negative Phase IPO (1946-1976)									
Mean							102.4	126.5	141.6
Var							1176.1	1619.4	2040.7
Positive Phase IPO (1977-1999)									
Mean							86.3	107.2	114.9
Var							993.7	2134.7	2772.5
Students t-test									
t-test							1.37	1.65	2.28
Prob							0.18	*0.10*	*0.03*
Wilcoxon Ranksum test									
Prob							*0.08*	*0.05*	*0.01*

g. Whakatane Manual

	10m	30m	60m	2h	6h	12h	24h	48h	72h
Negative Phase IPO (1947-1976)									
Mean							91.4	120.9	135.5
Var							928.9	1667.2	1975.9
Positive Phase IPO (1977-1990)									
Mean							76.9	110.0	118.4
Var							682.2	1982.9	2059.9
Students t-test									
t-test							1.07	0.80	1.26
Prob							0.29	0.19	0.22
Wilcoxon Ranksum test									
Prob							*0.10*	0.30	0.25

h. Whakarewarewa Manual

	10m	30m	60m	2h	6h	12h	24h	48h	72h
Negative Phase IPO (1947-1976)									
Mean							95.2	130.5	144.0
Var							954.4	1671.4	1905.5
Positive Phase IPO (1977-1990)									
Mean							73.8	98.3	115.5
Var							544.4	1192.1	2481.7
Students t-test									
t-test							2.43	2.69	2.02
Prob							*0.02*	*0.01*	*0.05*
Wilcoxon Ranksum test									
Prob							*0.00*	*0.01*	*0.02*

In Table 11, the following points can be noted. For very short durations (10-30 minutes), extreme rainfalls tend to be slightly higher in the positive phase of the IPO rather than in the negative phase. For durations from 60 minutes to 12 hours, the rainfalls are generally smaller in the positive phase of the IPO. Apart from the 12-hour duration at Whakatane Automatic, the table also indicates that the differences in the short durations extreme rainfall for either phase of the IPO are not significant. This suggests that short duration convective processes are less likely to be strongly influenced by the phase of the IPO.

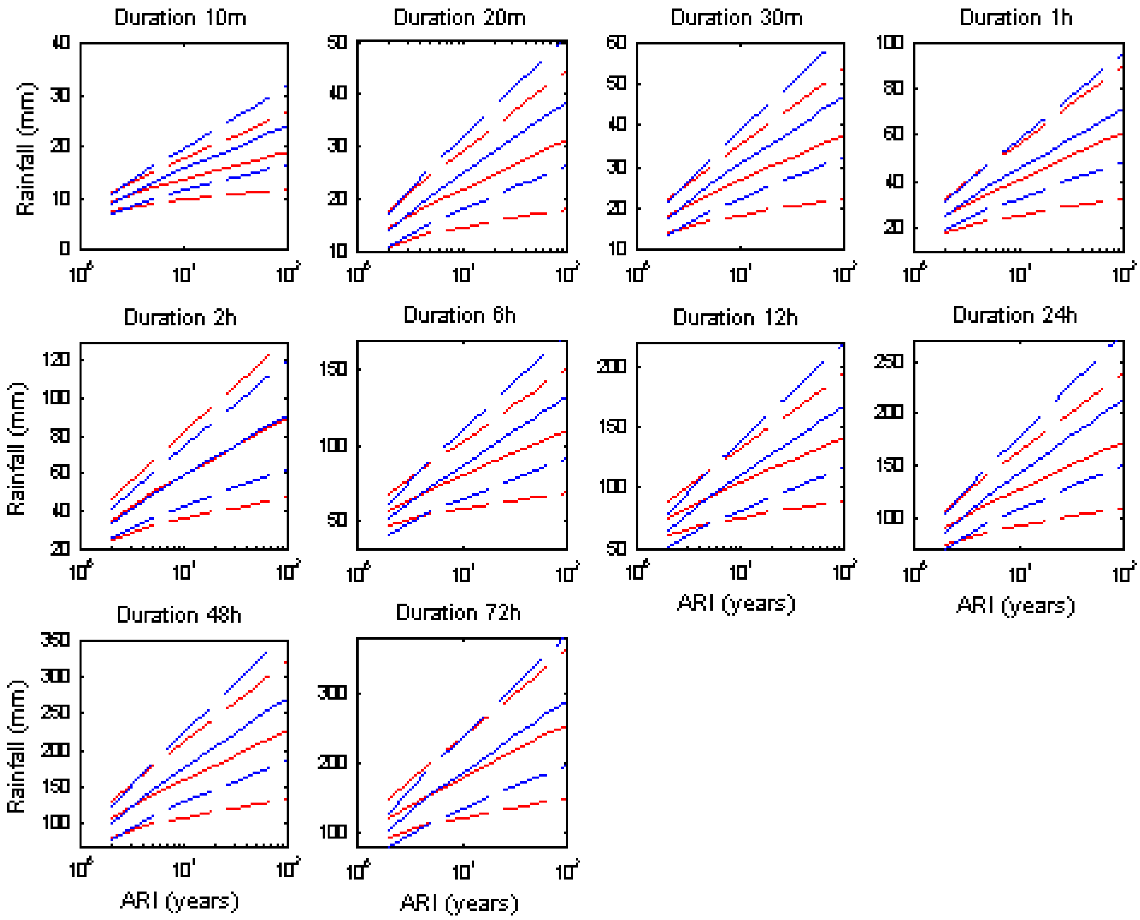
For the longer durations (24-72 hours), the mean level of extreme rainfalls show mixed signals; at some sites rainfall is lower in the positive phase of the IPO, and at other sites it is higher. The table also shows that some locations have significantly different rainfalls; other sites do not. For example, at Whakarewarewa there are significant differences in the high intensity rainfall between the phases of the IPO, but at Waihi and Opotiki the difference is not significant. A high level of agreement exists between the shorter automatic records at Tauranga and Whakatane in 24-72hr durations is generally supported by the longer daily data sets. At Tauranga, there appears to be an IPO influence in the two sets of rainfall data types, that is seen only in the Whakatane data at 24-hours. That there is a difference in the extreme rainfall arising from the opposite phases of the IPO at Tauranga is seen in two of the three t-tests and in all three Wilcoxon Ranksum tests. At Whakatane, the two sets of test statistics are also in broad agreement.

Finally in summary: in qualitative terms of significant differences in extreme rainfalls between the phases of the IPO, the test statistics obtained by the t-test and the Wilcoxon Ranksum test show the same result for nearly every duration from 10 minutes to 72 hours.

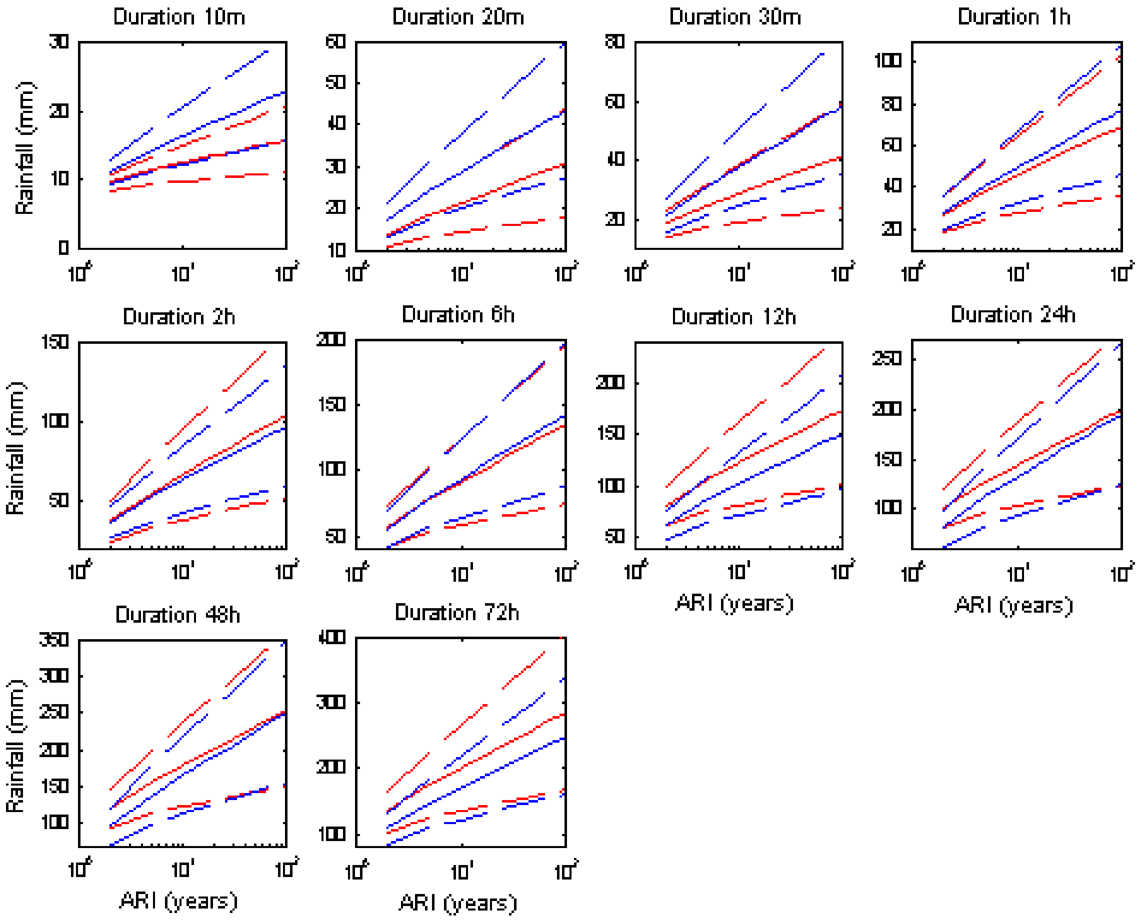
Figure 31 shows in graphical form a depth-duration-frequency analysis of extreme rainfalls from and EV1 distribution, for the four sites with automatic rain gauges. The high intensity rainfall plots are given for the negative (in blue) and positive (in red) phases of the IPO. The solid lines are the rainfall estimates, and the dashed lines the 95 percent confidence limits about the estimates. In order for the extreme rainfalls to be statistically significant from each other, they must lie outside the confidence intervals.

Figure 31. Depth-frequency rainfall plots for given durations at (a) Tauranga, (b) Whakatane, (c) Opotiki, and (d) Rotorua, for a positive (blue) and negative (red) phase of the IPO, and their associated 95 percent confidence intervals. Rainfall in millimetres is along the y-axis and frequency (average recurrence interval) in years is along the x-axis.

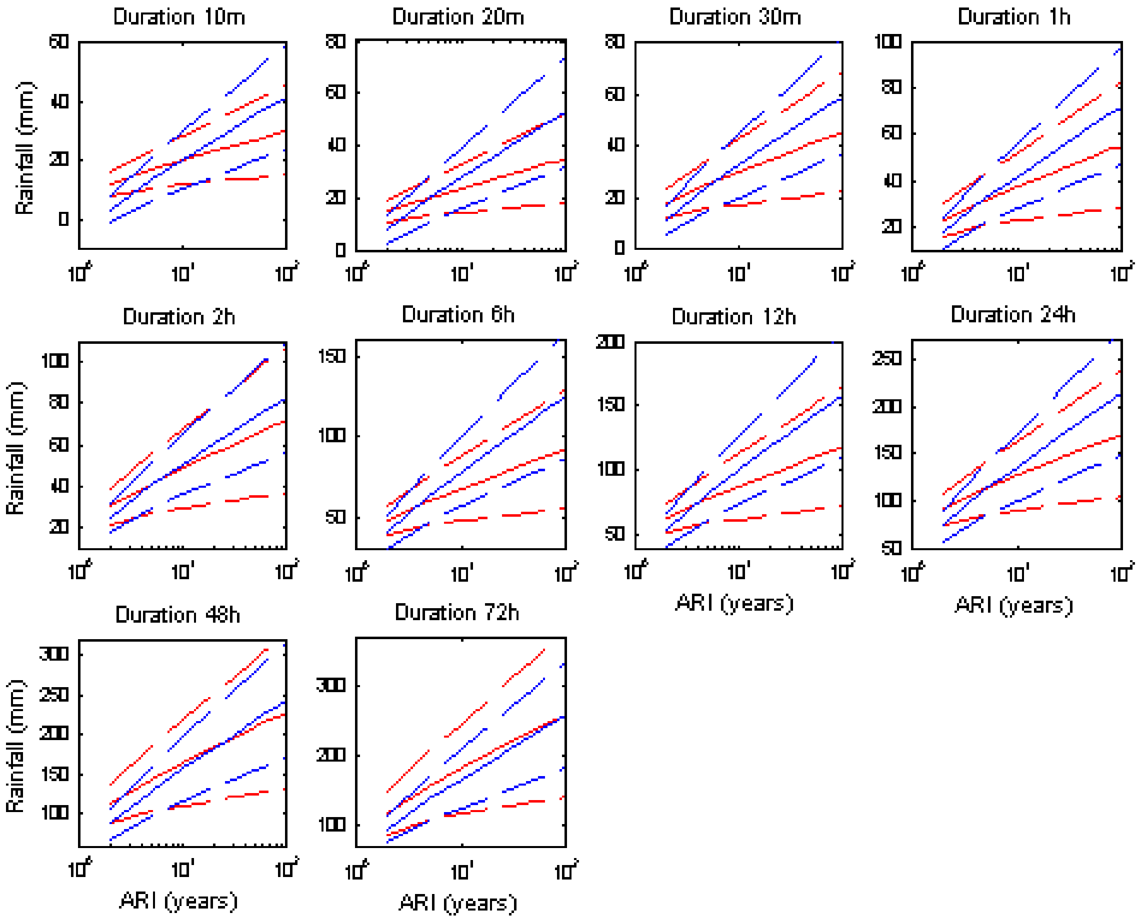
a. Tauranga Automatic



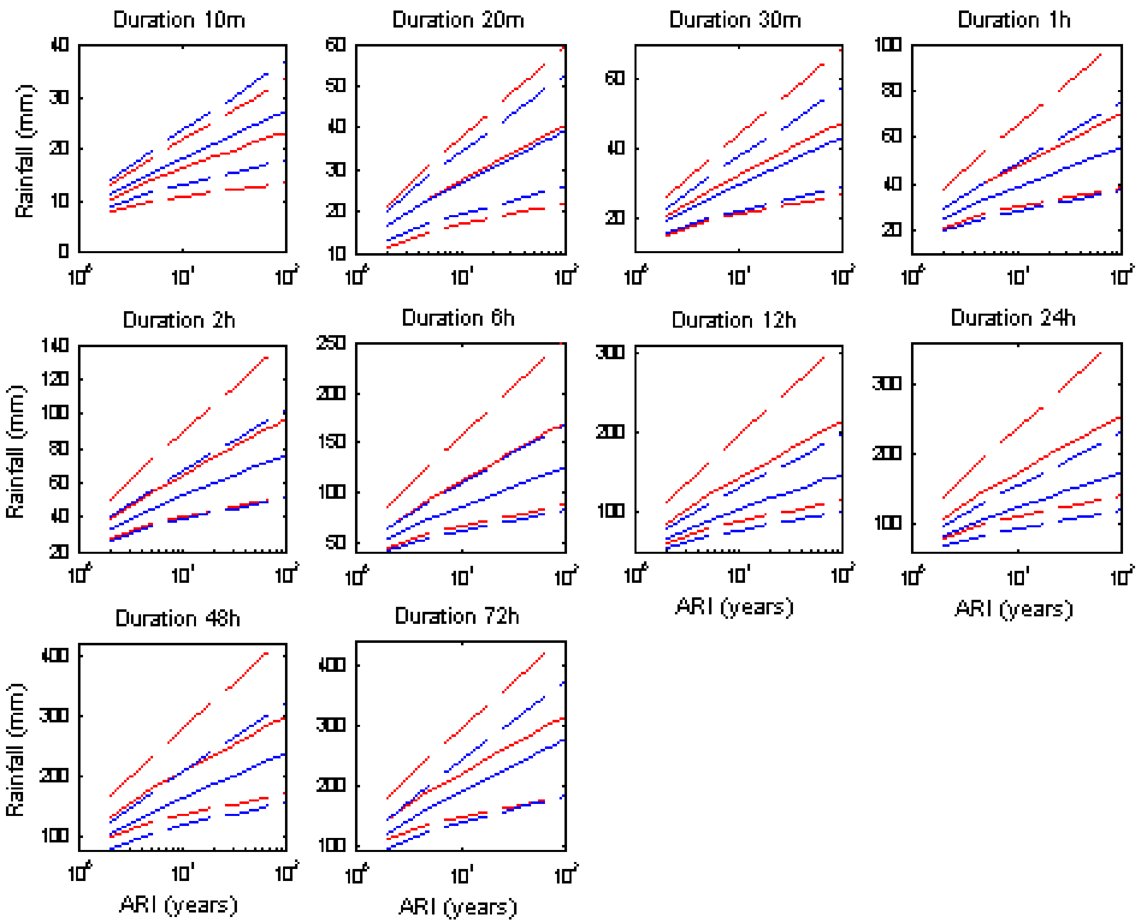
b. Whakatane Automatic



c. Opotiki Automatic



d. Rotorua Automatic



At the 0.05 level of significance, the figure shows that with the exception of Opotiki, there is no significant difference between the high intensity rainfall estimates for either the negative or positive phase of the IPO. At Opotiki, the figure (Figure 31c) shows the for the 10, 20, and 30 minute durations, the 2 year events are sufficiently different and lie on or outside the 95 percent confidence limit. It can also be seen that at Opotiki, the solid line representing the rainfall depths have different slopes, whereas at the other three locations, these slopes are approximately parallel, with the differences in rainfalls, due to the phase of the IPO, a nearly constant offset.

For the sites displayed in Figure 31, there is no strong relationship between event size and IPO. At some locations (e.g. Rotorua), there is more intense rainfall during the positive IPO, while at Whakatane for example, the short durations show the negative phase to provide more rainfall, while the longer durations show more rainfall is likely with the positive IPO.

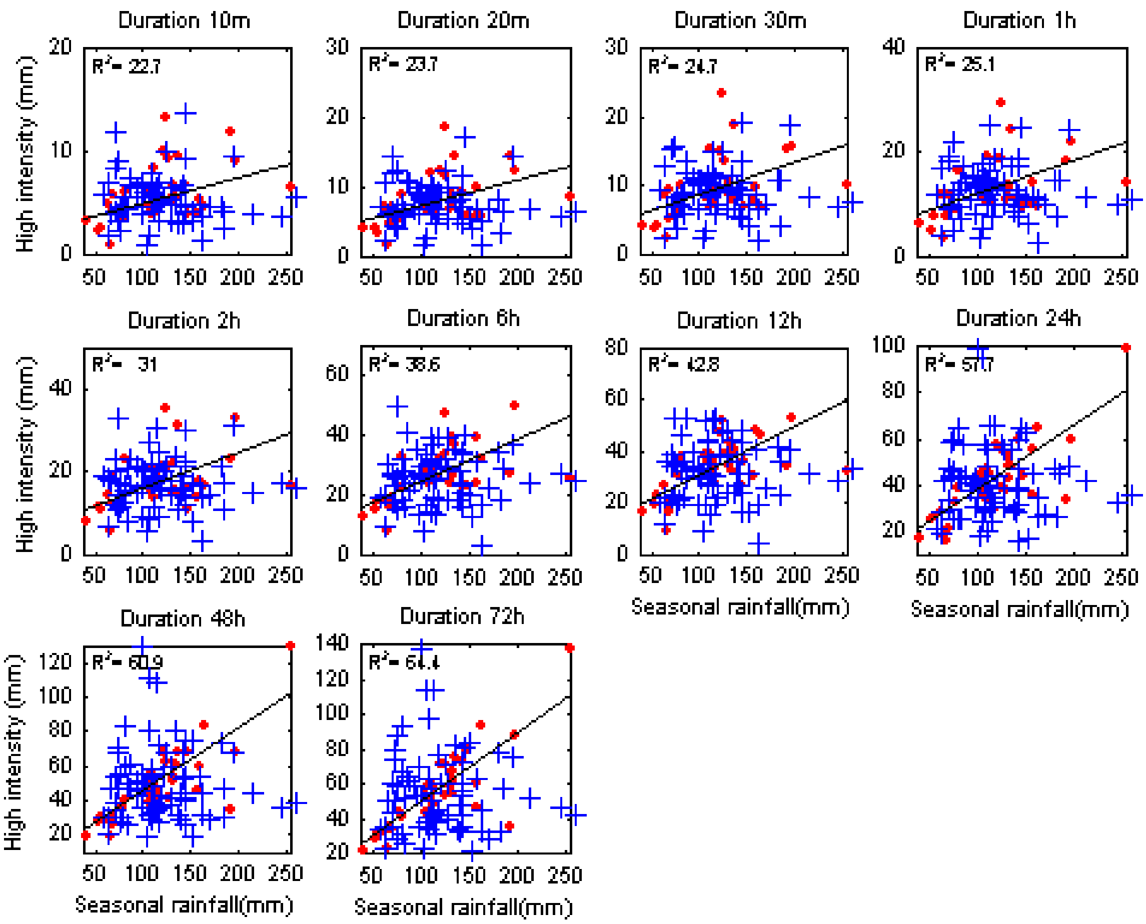
In summary: like the early analysis the graphical plots are indicating that there are mixed signals/influences of the IPO phase on the high intensity rainfalls in the Bay of Plenty.

5.2 Seasonal rainfalls and seasonal extremes

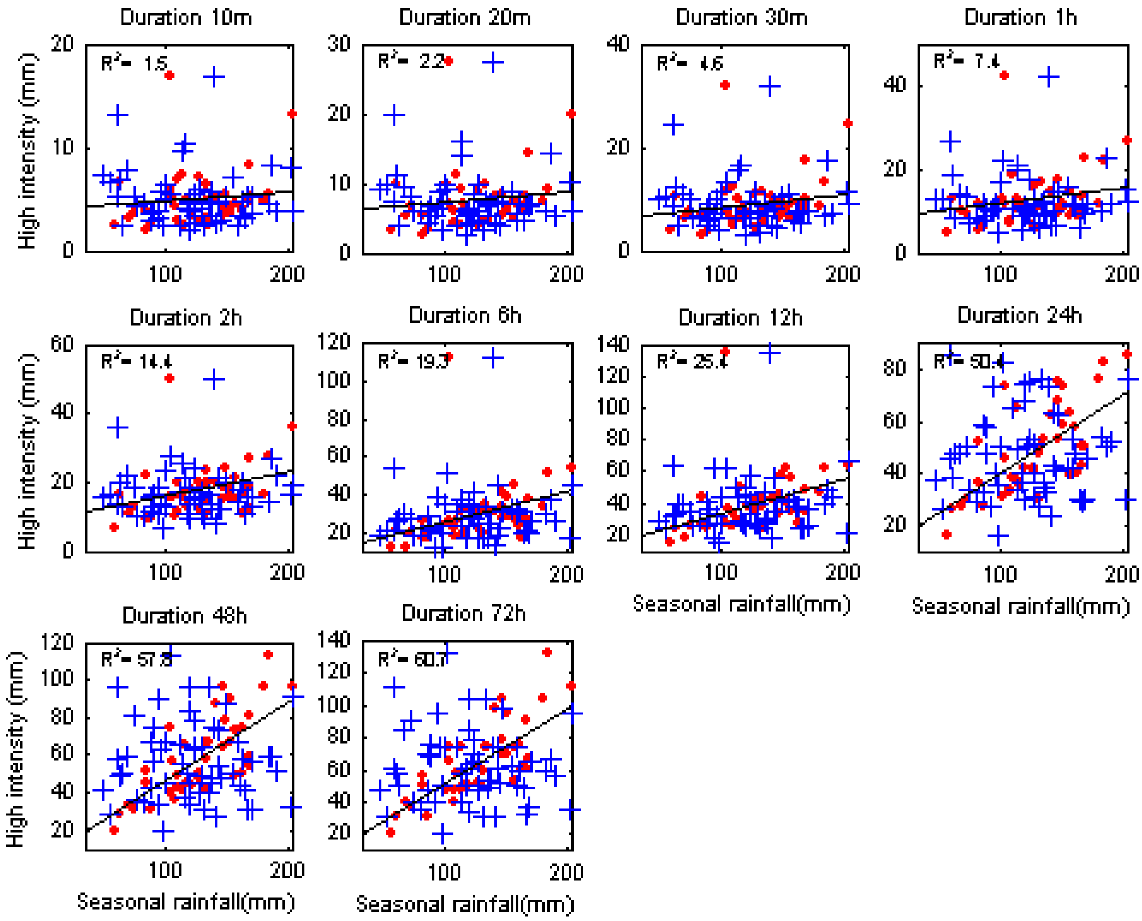
In this section of work, relationships between seasonal rainfalls and seasonal extremes are assessed. Average seasonal rainfalls and extremes for each of the 10 durations for Bay of Plenty sites were computed from monthly values. Taking seasonal averages of rainfall accumulation and extremes, smoothes the data and enhances any relationship between them. Scatter plots between seasonal and extreme rainfall are given in Figure 32. The data have been stratified by IPO phase and are represented as red dots for the negative IPO and blue crosses in the positive phase. There appears to be no significant difference between the phase of the IPO and the stratification of the data, although there is more scatter in the observations during the positive phase than in the negative phase.

Figure 32. Scatter plots of seasonal mean rainfall (mm) and seasonal mean extreme rainfall (mm) for given durations from automatic rain gauges at (a) Opotiki, (b) Rotorua, (c) Tauranga, and (d) Whakatane, during a negative phase of the IPO (red dots) and a positive phase of the IPO (blue crosses). The percentage explained variance between rainfall accumulation and extremes is given by the R^2 value, and the solid line is the least squares regression relationship.

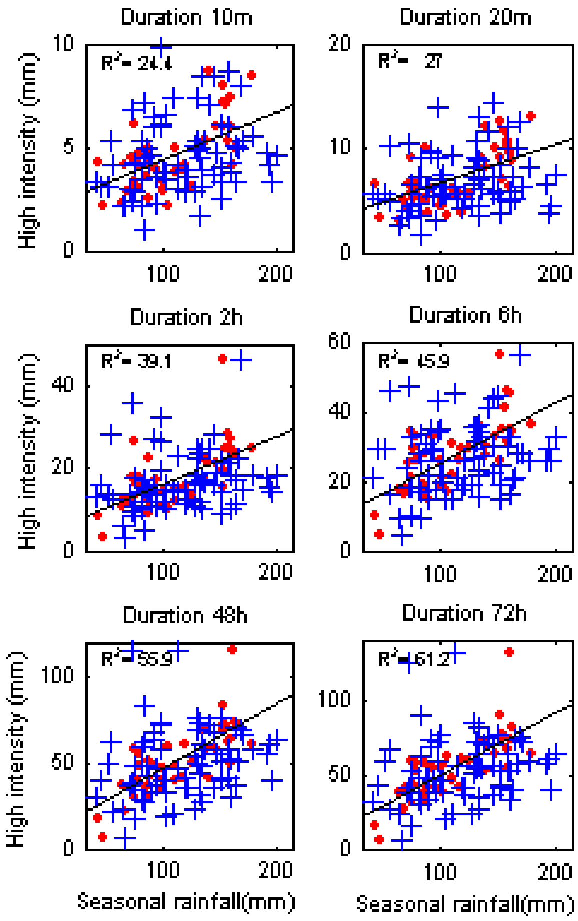
a. Opotiki Automatic



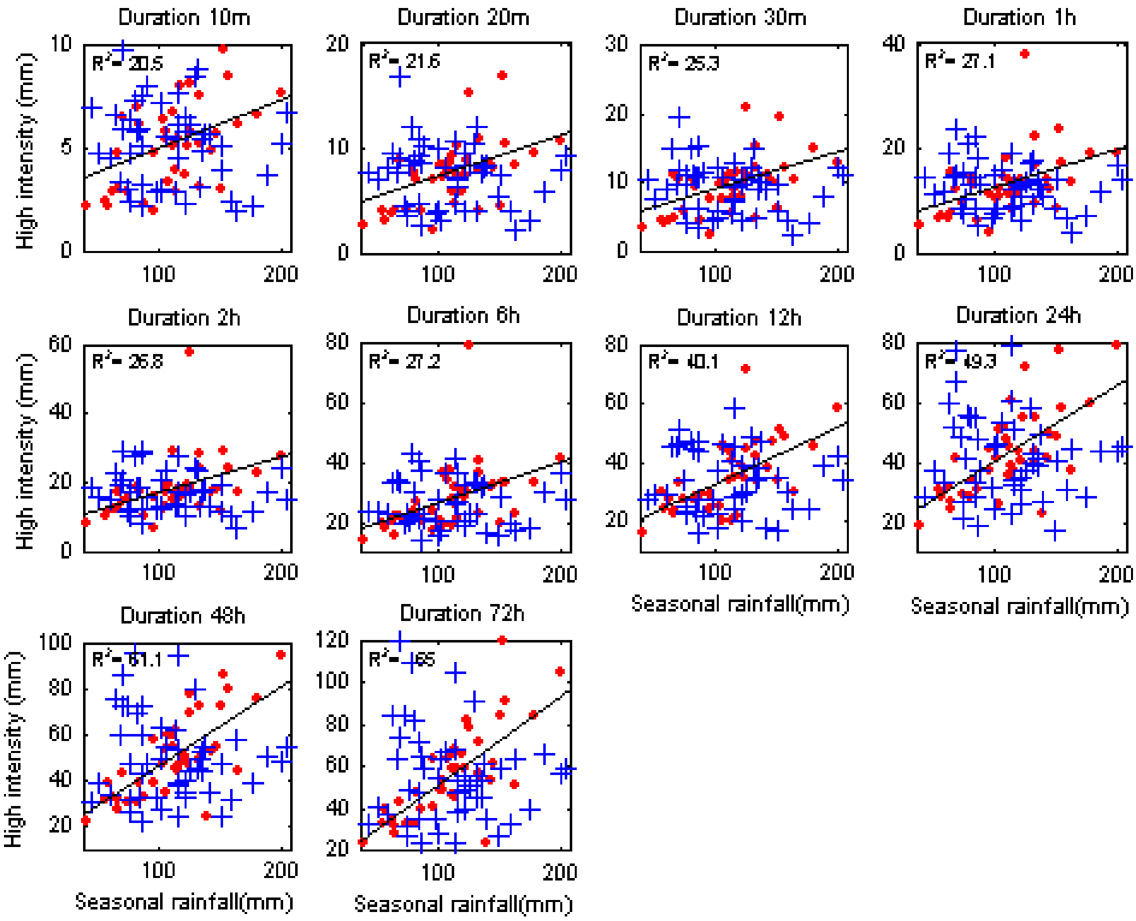
b. Rotorua Automatic



c. Tauranga Automatic



d. Whakatane Automatic



Least squares regression between seasonal rainfall and extremes was carried for the four Bay of Plenty sites. The regression lines and percentages of explained variance are displayed in Figure 32. The explained variances are small for the short durations, but increase as the duration of extreme rainfall increases. The relationship between seasonal rainfall and high intensity rainfall becomes significant at the four locations for durations larger than 20 or 30 minutes. At the four sites, the scatter-graphs show that seasonal rainfall and intensity are directly related: an increase in seasonal rainfall, will tend to indicate a corresponding increase in the extreme rainfall regime and vice versa.

The scatter-graphs show the deviation about the regression line during the negative phase of the IPO (red dots) is less than during the positive phase (blue crosses). In the negative phase, there are fewer observations than in the positive phase of the IPO, which may give the impression that the relationship between seasonal rainfall and high intensity rainfall is stronger than it is in reality. On this note of caution there is also a large fraction of high intensity rainfall variation that cannot be attributed to seasonal rainfall.

6. Climate Change Scenarios

Section 4 analysed causes of past climate variations in the Bay of Plenty and suggested future decadal changes due to a change in phase of the Interdecadal Pacific Oscillation. This section draws together information on anticipated long-term trends due to anthropogenic greenhouse gas increases. Although climate projections are uncertain, the global atmosphere is definitely changing, and it is no longer defensible to assume the recent past climate is the best guess for the future.

The results are drawn from a number of previous studies, but particularly from the IPCC Third Assessment (Chapter 9, Cubasch *et al*., 2001), interpreted within the local context, from the data analysed for the New Zealand downscaling study of Mullan *et al.* (2001a), and from the CLIMPACTS 2000 National Assessment discussed in Mullan *et al*. (2001b). Other information on New Zealand impacts of global warming can be found in the syntheses of Pittock and Wratt (2001) and Ministry for the Environment (2001). Another key report (MfE, 2003) is currently being prepared by NIWA and collaborators for the New Zealand Climate Change Office, and some conclusions of that report will be noted where relevant to the Bay of Plenty region.

6.1 IPCC Third Assessment

The Intergovernmental Panel on Climate Change, in its Third Assessment of 2001 concluded that ”There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities” (IPCC, 2001). This statement, of course, applies to the *global* average temperature. While we cannot yet prove this statement applies to a small region such as New Zealand, it is very likely that a substantial part of the New Zealand warming is also due to human activities (on the global scale).

Predictions of future climate depend on projections of future concentrations of greenhouse gases and aerosols in the atmosphere. These in turn depend on projections of emissions of these substances, which depend on changes in population, economic growth, technology, energy availability and national and international policies. As a basis for projecting future climate changes, the IPCC developed 35 different future emissions pathways or “scenarios” [the so-called “SRES” scenarios, developed in the IPCC Special Report on Emissions Scenarios, Nakicenovic and Swart, 2000]. These SRES scenarios formed the basis of much of the climate projection work done for the IPCC’s Third Assessment. Complex atmosphere-ocean global climate models (AOGCMS) were run on supercomputers to simulate future global and regional climate for a sub-range of these scenarios. A much simpler globally-averaged model (known as "MAGICC") was then tuned to these AOGCM runs, and applied to all 35 SRES scenarios. This led to the global temperature projections shown in Figure 33.

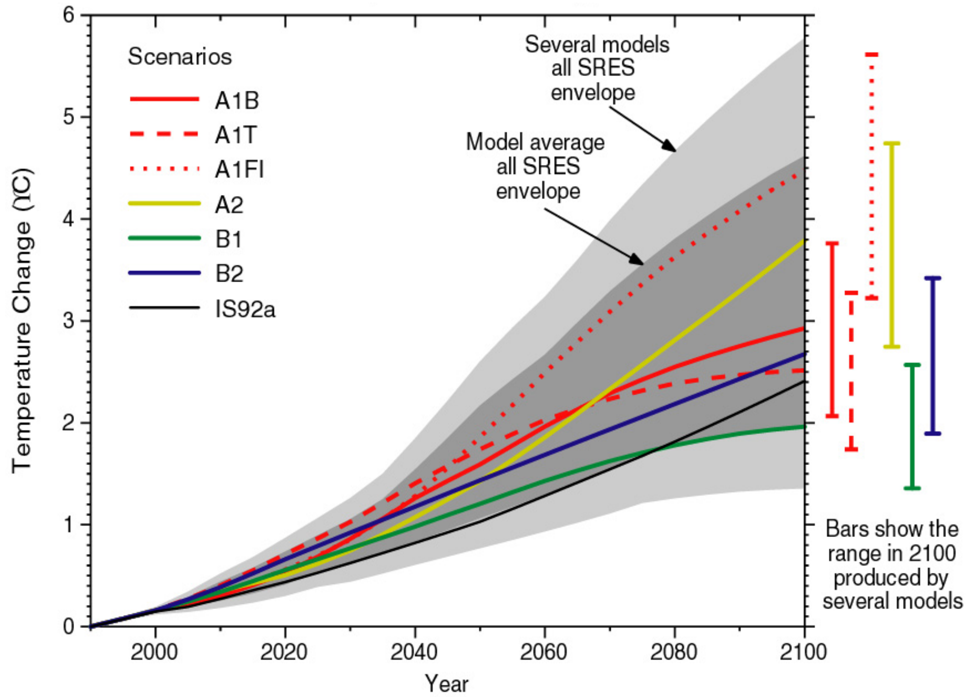


Figure 33: Global mean temperature change for 6 illustrative SRES scenarios (plus one IS92 scenario) using the MAGICC model tuned to 7 AOGCMs (ie, lines are the ensemble average across the 7 GCMs). The coloured bars to the right show the range of MAGICC results at 2100 for the 7 AOGCM tunings for each illustrative SRES scenario. The dark shading represents the envelope of the MAGICC ensemble averages across the full set of 35 SRES scenarios. The light shading represents the envelope of all MAGICC results across all 35 SRES scenarios. Figure is variant of Figure 9.14 (page 555) from IPCC Third Assessment (Cubasch *et al*., 2001).

Figure 33 indicates a range of possible future global temperatures, which incorporates both the range of plausible emissions scenarios and the range of AOGCM predictions for a specified scenario. Note that the global climate models give a wide range of projected global changes, even when forced by the same emissions or atmospheric concentrations (the coloured bars at the right of Figure 33).

This simple MAGICC model only provides values for globally-averaged annual surface temperature and sea-level change, and gives no information on other climate elements or any regional breakdown. For the regional projections, we need to examine the output of the AOGCMs. A further step, known as "downscaling", is required to go from the coarse grid-point scale of the GCMs (values several degrees of latitude apart) to the local Regional Council scale.

Such a downscaling was applied by Mullan *et al*. (2001a) to the output from 6 AOGCMs run for the IPCC Third Assessment, all using the same forcing scenario of a 1% per annum compounding CO_2 concentration, which lies near the middle of the IPCC range. The quantitative changes in mean temperature and rainfall, as presented in Section 6.3 of this report, are derived from these 6 climate models. *The results therefore do not cover the entire IPCC scenario range of Figure 33.* A rescaling of the New Zealand downscaled changes to cover the full IPCC range is currently underway (MfE, 2003).

6.1.1 Cautionary Note on Use of Climate Change Scenarios

Statements on future climate change are subject to substantial uncertainty – this is one of the reasons that IPCC has refused, so far, to assign any probabilities to its 35 emissions scenarios. The word "scenario" itself is carefully defined by IPCC as: "A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models."

The IPCC scenarios have storylines of economic and social development associated with them. The climate change "projections" that arise from the scenarios are often based upon simulations by climate models. Climate *projections* are distinguished from the more definite climate *predictions* in order to emphasise that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on many assumptions (e.g., future socio-economic and technological developments), that may or may not be realised. On the other hand, climate predictions or climate forecasts are the result of an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future, general restricted to only a few seasons ahead. Predictions start from an existing climate state which is well known, and GCMs are capable of simulating a realistic future evolution.

The comments in this Section should be viewed as projections (based on scenarios), rather than climate forecasts. Thus, results ideally should be applied to impact or sensitivity studies. If the Bay of Plenty Regional Council currently experiences a climate-related problem, and the climate change projections are in a direction that would aggravate the existing situation, then detailed follow-up studies are recommended.

6.2 Climate Change Scenario Development and Data Analysis

Projections of New Zealand climate for the 21st century were developed by Mullan *et al*. (2001a) from the simulations of 6 AOGCMs, which were all forced by 1% per annum compounding CO_2 concentration. The method used is known as statistical downscaling, whereby firstly observed year-to-year variations at a local site are related to regional (Tasman Sea scale) climate and circulation, and then these relationships applied to the GCM projected changes. This technique overcomes the scale mismatch of GCMs, and generates changes at high spatial resolution that are consistent with the climate model output.

Changes in mean temperature and rainfall were calculated at 58 temperature sites and 92 rainfall stations nationally. All changes were expressed relative to the "current" climate (model years 1970–1999), and covered the periods 50 years beyond (i.e., 2020–2049) and 100 years beyond (2070–2099). These future periods were referred to as the "2030s" and the "2080s". Of the 6 models used, only 4 of them had simulations that went beyond 2050. For the 2030s scenarios, where 6 models were available, the range of projections was presented in terms of "Low" to "High". These limits were determined by ranking the 6 projections at each site from lowest to highest (or most negative to most positive), and identifying the second to bottom value as "Low", and second to top as "High". The extreme model projection at each site was deliberately excluded to avoid possible outliers (following Whetton *et al*., 1996).

The same downscaling and presentation methodology is applied to this study for the Bay of Plenty. However, extra climate stations within the Bay of Plenty region were added to the national set. The study area is shown in Figure 34, where all the stations used are indicated as closed circles. The station names, numbers and locations are listed in Table 12. The national data set used by Mullan *et al.* (2001a) was augmented by an additional 10 rainfall stations and 3 temperature stations within the Bay of Plenty region (called the "Full" set).

Monthly mean rainfall and temperature data, expressed as anomalies relative to the 1961-1990 climatology, were the basic climate data used in this study. Missing monthly values were filled in by cross-correlations with other stations (using data from a non-missing station with the highest cross correlation in that season). The downscaling regression relationships were re-derived over the period 1969-1998 for

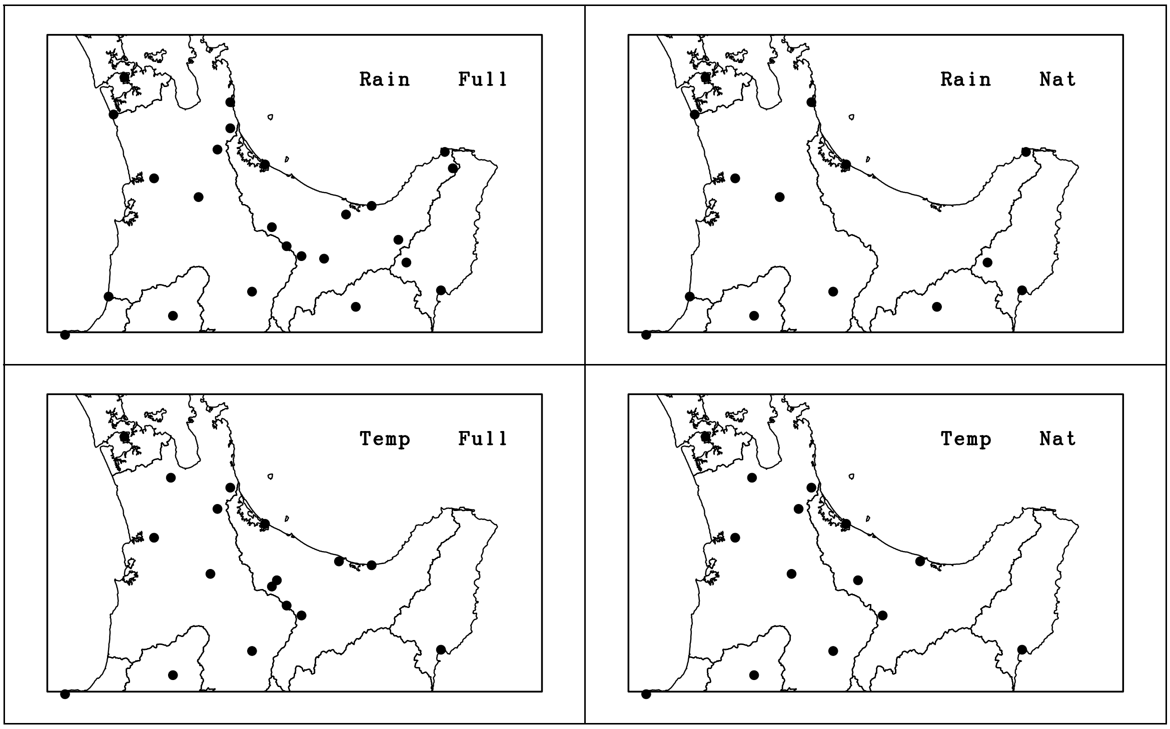


Figure 34: Location of rainfall stations (upper panels) and temperature stations (lower panels) used in Bay of Plenty downscaling. Right-hand panels show the distribution used for the "National" analysis of Mullan *et al.* (2001a), and left-hand panels the "Full" set with additional Bay of Plenty sites.

consistency with Mullan *et al.* (2001a). The same data set of seasonal anomalies was used in the correlation analyses of Section 4 and the trend figures of Section 3. Because of inhomogeneities in the Whakatane temperature records, the Whakatane site listed is for Whakatane Mill where the data end in 1983.

6.3 Bay of Plenty Scenarios for Temperature and Rainfall

This part of Section 6 displays maps of temperature and rainfall scenarios for the Bay of Plenty region. Subsequent parts (sections 6.4 to 6.6) provide more qualitative comments on other climate elements.

Table 12: Temperature and rainfall stations used in downscaling study. The sites used in the national study of Mullan *et al*. (2001a) are given first, followed by the additional Bay of Plenty stations.

RAINFALL Stations			TEMPERATURE Stations		
Station (Code and Name)	Latitude	Longitude	Station (Code and Name)	Latitude	Longitude
National Subset					
B75182 Tairua	37.17S	175.85E	B75382 Waihi	37.38S	175.85E
B76624 Tauranga	37.67S	176.20E	B75571 Te Aroha	37.55S	175.72E
B78501 Rukuhanga	37.57S	178.02E	B76624 Tauranga	37.67S	176.20E
B86704 Taupo	38.68S	176.07E	B76993 Whakatane	37.97S	176.95E
C64971 Mangere	36.97S	174.78E	B86133 Rotorua	38.12S	176.32E
C74261 Waiuku	37.27S	174.67E	B86451 Kaingaroa	38.40S	176.57E
C75731 Ruakura	37.78S	175.08E	B86704 Taupo	38.68S	176.07E
C75951 Karapiro	37.93S	175.53E	C64971 Mangere	36.97S	174.78E
C84761 Mohakatino	38.72S	174.62E	C75321 Maramarua	37.30S	175.25E
C85821 Taumarunui	38.87S	175.27E	C75731 Ruakura	37.78S	175.08E
C94012 New Plymouth	39.02S	174.18E	C85061 Arapuni	38.07S	175.65E
D87462 Otoko	38.45S	177.63E	C85821 Taumarunui	38.87S	175.27E
D87695 Gisborne	38.67S	177.98E	C94012 New Plymouth	39.02S	174.18E
D87811 Onepoto	38.80S	177.12E	D87695 Gisborne	38.67S	177.98E
Extra BoP Stations					
861204 Whakarewarewa	38.17S	176.27E	B86124 Whakarewarewa	38.17S	176.27E
870005 Taneatua	38.07S	177.02E			
B75381 Waihi	37.38S	175.85E			
B75571 Te Aroha	37.55S	175.72E			
B78601 Mataraoa	37.70S	178.10E			
B86341 Waiotapu	38.32S	176.42E	B86341 Waiotapu	38.32S	176.42E
B86451 Kaingaroa	38.40S	176.57E			
B86481 Galatea	38.42S	176.80E			
B87023 Opotiki	38.00S	177.28E	B87023 Opotiki	38.00S	177.28E
B87255 Motu	38.27S	177.55E			

6.3.1 Annual Mean Scenarios and Influence of Additional Bay of Plenty Stations

Figures 35 and 36 show projected annual mean changes for the 2030s (i.e., 2020-2049) and the 2080s (i.e., 2070-2099) relative to the "current" climate (1970-1999). The changes are the average over 6 models for the 2030s and 4 models for the 2080s. These figures highlight the influence of adding extra stations to the downscaling analysis. The Bay of Plenty warms by about +0.80°C by the 2030s, and by about +1.80°C by the 2080s. There is not much difference in the rate of warming across much of the North Island, and therefore the three additional Bay of Plenty stations in the Full set have little effect.

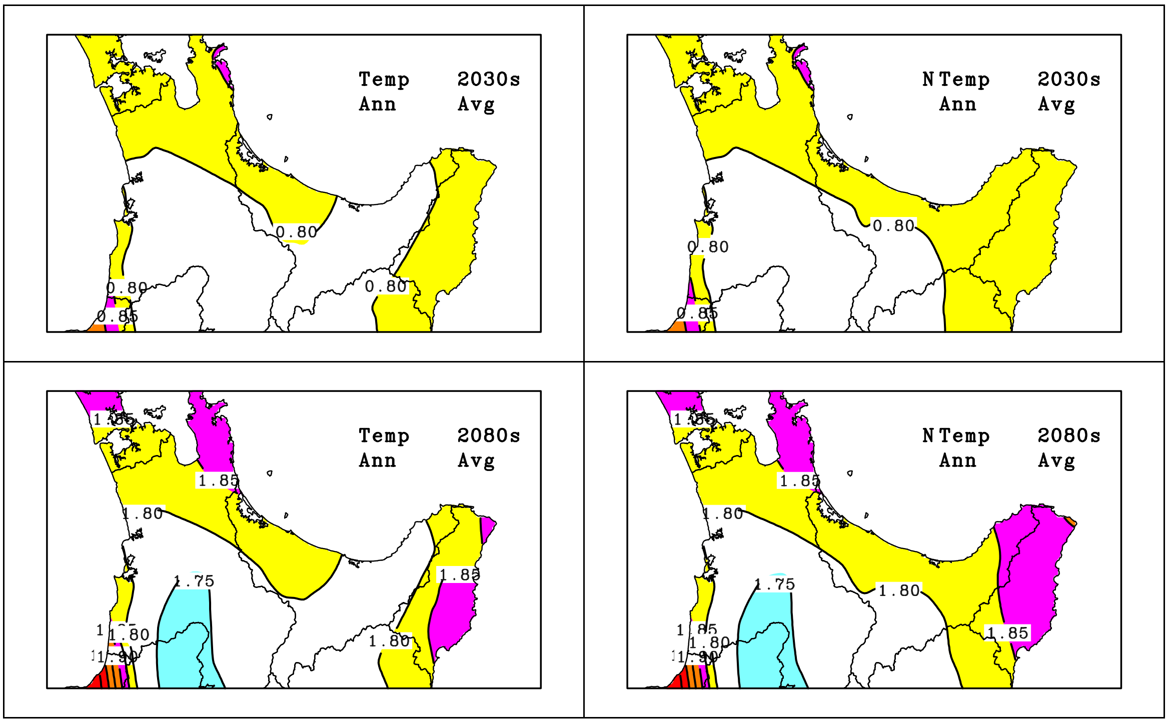


Figure 35: Scenarios of annual average temperature changes by 2030s (upper) and 2080s (lower), using the "Full" set of Bay of Plenty stations (left panels) compared to using the older "National" set (right panels). Contours every 0.05°C.

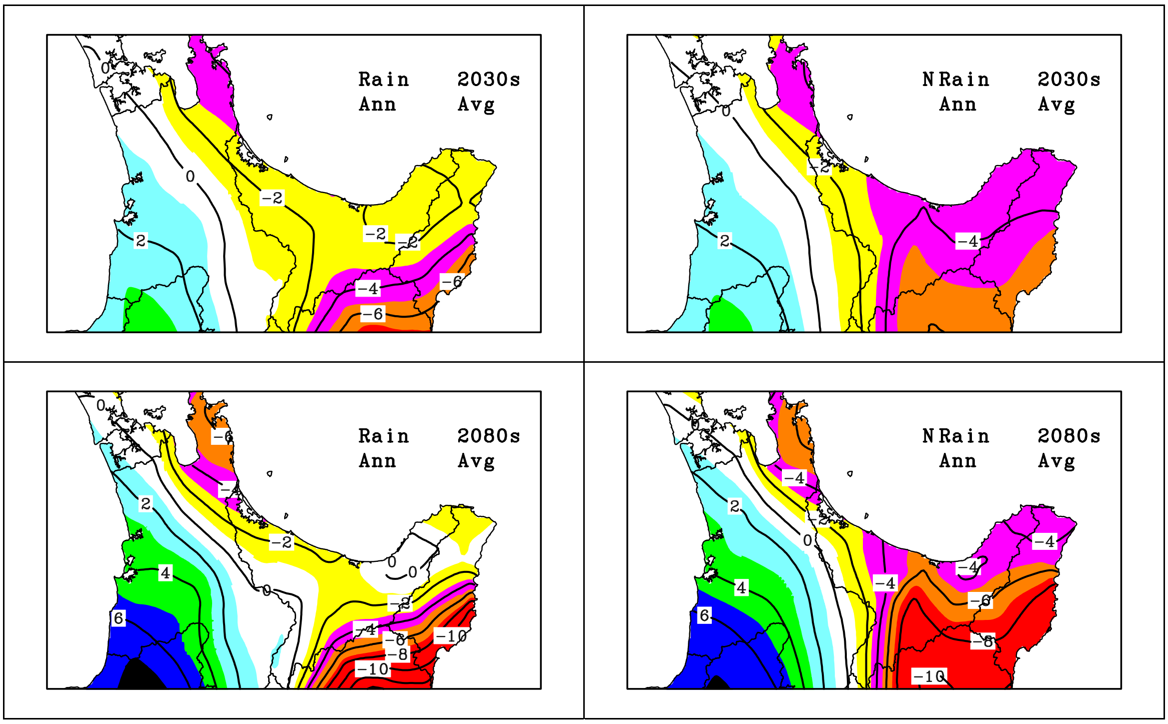


Figure 36: As Figure 35, but for rainfall. Contours every 2%.

On the other hand, there are marked gradients in rainfall changes, and the additional stations in southern and eastern Bay of Plenty (left-hand panels of Fig. 36) show the drying trend in that part of the region is not as strong as suggested by the sparser station set used in the Mullan *et al.* (2001a) national analysis, which is influenced by the large rainfall reductions in Gisborne. Annual mean rainfall is projected to decrease in the Bay of Plenty by between about 1% and 4% by the 2030s, with no further drying trend by the 2080s. This "nonlinearity" in the drying (i.e., virtually all the drying occurring in the first 50 years) is typical of all the models, and is *not* an artefact of the change from 6 models to 4 models at the extended period.

6.3.2 Seasonal Scenarios and Low-High Ranges

Seasonal differences in the climate change scenarios could be important in some cases. It is also sensible to consider a range of likely changes, rather than a single scenario. Figure 37 shows the range of temperature changes by the 2030s for each season, and Figure 39 the range for rainfall. Figures 38 and 40 show the model-averaged seasonal changes by the 2080s, for temperature and rainfall, respectively. Because only four model simulations were available for the 2080s, it is not feasible to show a range in the same way as for the 2030s. Note that for all figures in this sub-section, we have used the Full set of stations.

The annual average temperature change by the 2030s (top left panel of Fig. 35) is broken down into the seasonal changes in Figure 37b. The warming rate is smallest in the spring (SON) and summer (DJF) seasons, and largest in the winter (JJA) season. Thus, the annual warming over 50 years of about +0.80°C varies between about +0.75°C in spring and summer to +0.90°C in winter, as an average over all 6 GCMs. However, the climate models show quite a range of warming, as illustrated by the second smallest warming ("Low", Figure 37a) and second highest warming ("High", Figure 37c). Seasonally, the 2030s warming can vary from a low of about +0.50°C in summer in the south of the district to a high of about 1.05°C in autumn over most of the district. These local changes are rather smaller than the global average annual-mean warming of the same models, which varies from +1.08°C to +1.54°C for the 2030s.

By comparing Figures 37a and 37c, the likely range of warming at any location can be estimated. It is important to realise, however, that this range is the range of model projections for the *same* global emissions scenario. The IPCC considered a large number of emissions scenarios, and consequently a very large range in the potential global warming (Figure 33). Rescaling our results to take the full IPCC range into account (MfE, 2003) expands the possible range of changes, as shown in Table 13.

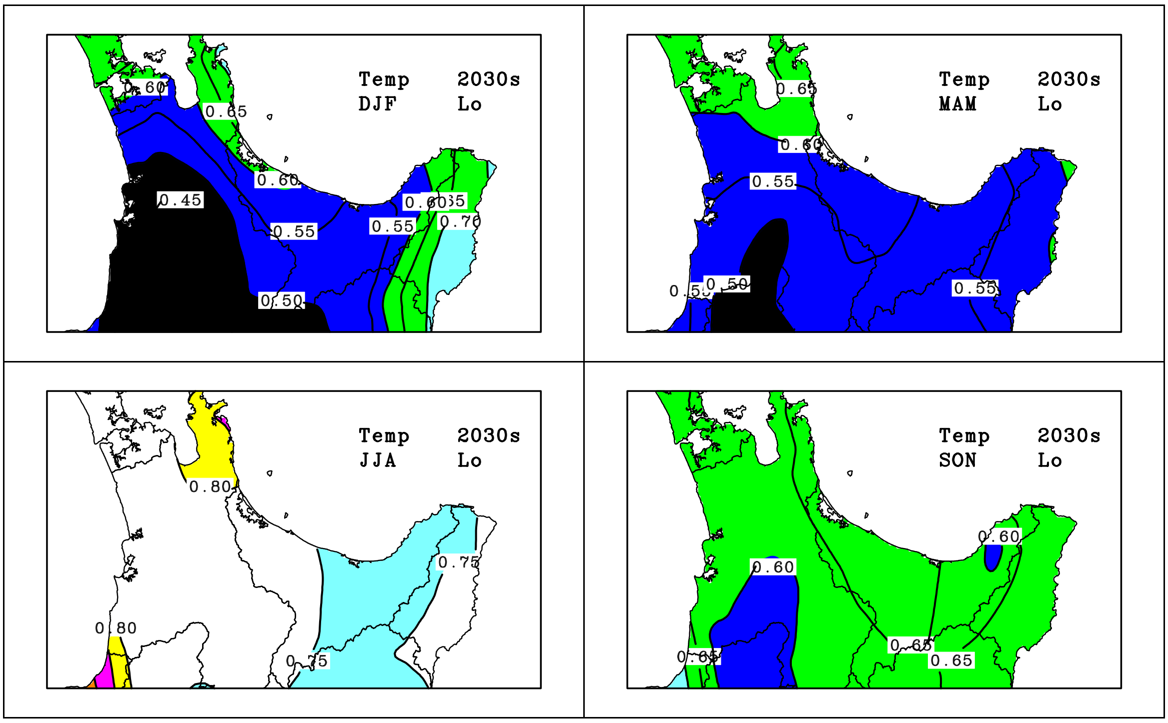


Figure 37a: Scenarios of seasonal average temperature changes by 2030s, at the "Low" end of the climate model range. Contours every 0.05°C.

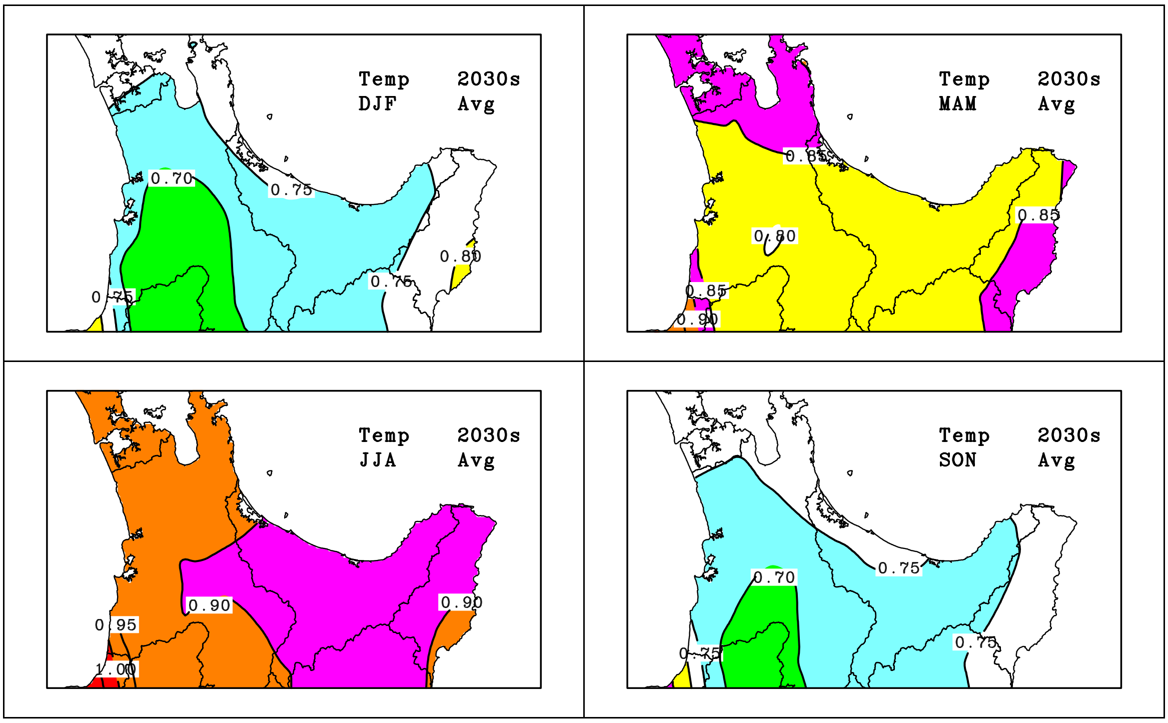


Figure 37b: As Figure 37a, but for "Average" over six climate models.

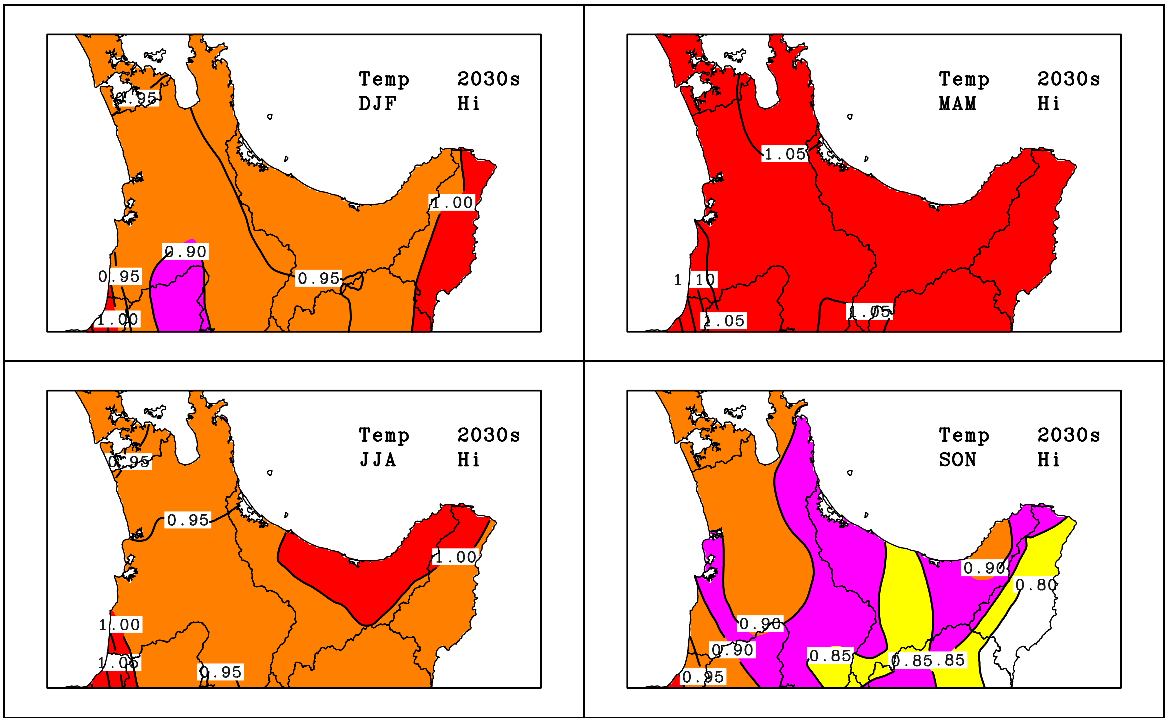


Figure 37c: As for Figure 37a, but for "High" end of the climate model range.

Table 13: Projected temperature changes (in degrees Celsius) and rainfall changes (in %) for the Bay of Plenty, by the 2030s and the 2080s, scaled to the full IPCC range (see forthcoming report MfE, 2003). The temperature changes are the average over all downscaling sites in the Bay of Plenty region, whereas the rainfall changes are for the specified site (because of sub-regional spatial gradients).

Projected Change	Summer	Autumn	Winter	Spring	Annual
Temperature (°C)					
Change by 2030s	0.0 to +1.2	0.0 to +1.3	+0.4 to +1.6	+0.2 to +1.2	+0.2 to +1.3
Change by 2080s	+0.3 to +3.8	+0.4 to +3.9	+0.8 to +4.2	+0.4 to +3.6	+0.5 to +3.8
Rainfall at Tauranga (%)					
Change by 2030s	-10 to +4	-16 to +4	-5 to +7	-20 to +8	-9 to +2
Change by 2080s	-7 to +19	-18 to +15	-2 to +9	-41 to -3	-15 to +2

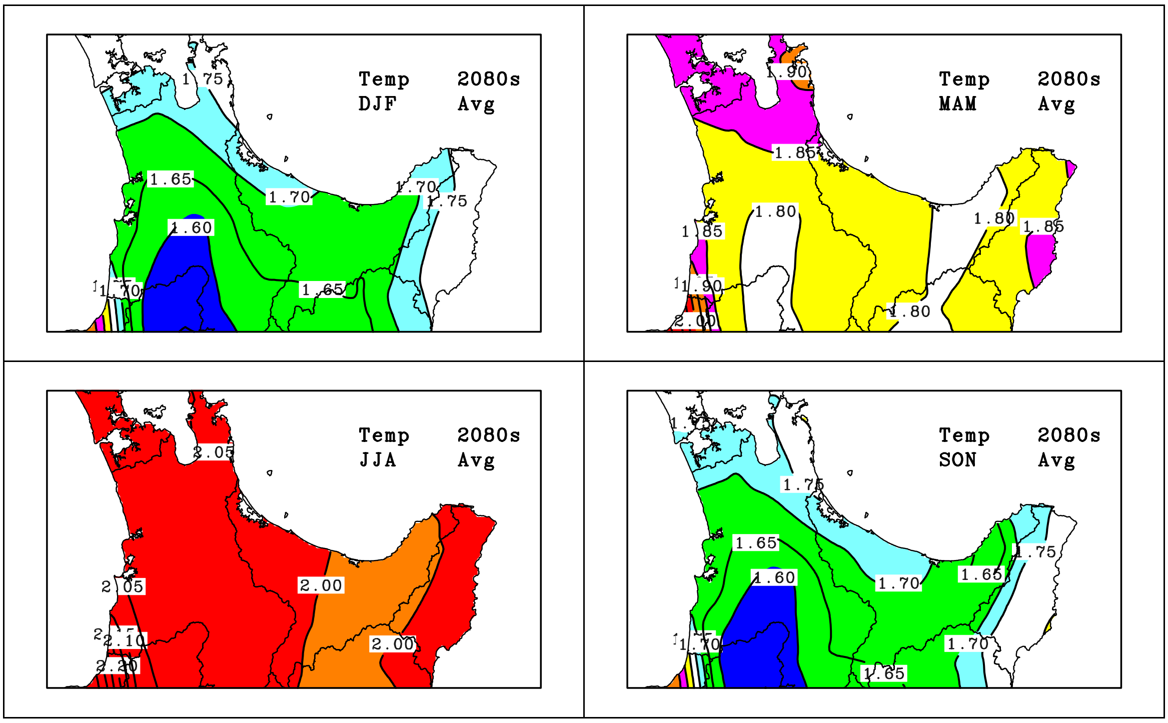


Figure 38: Scenarios of seasonal average temperature changes by 2080s, using the "Average" of four climate models. Contours every 0.05°C.

Figure 38 shows the model-average warming by the 2080s for each season. Again, the least warming occurs in spring and summer (about 1.65°C to 1.75°C), and the greatest in the winter season (2.00°C). These changes lie near the middle of the full range covering 35 IPCC emissions scenarios (Table 13).

Figure 39 shows the 2030s range in rainfall projections, and Figure 40 the 2080s model-average change. Table 13 shows the expanded IPCC range at Tauranga. Although the 2030s annual average (top left panel of Figure 36) indicates a rainfall reduction of about 2%, Figure 39b shows that this could vary seasonally from a slightly wetter winter (by 0 to 4%) to a rather drier spring and summer (up to 8% drier in Tauranga in spring), as an average over 6 GCMs.

The likely range (Low to High) can be estimated at any point within the Bay of Plenty region from Figures 39a and 39c. For example, for Tauranga in the 2030s, summer rainfall is projected to vary from about an 8% reduction (Low projection in Figure 39a) from present totals to about 2% wetter (High projection of Figure 39c). Expanding this range from the 6-GCM simulation set to cover the entire IPCC emissions scenarios gives us the range –10% to +4% in Table 13.

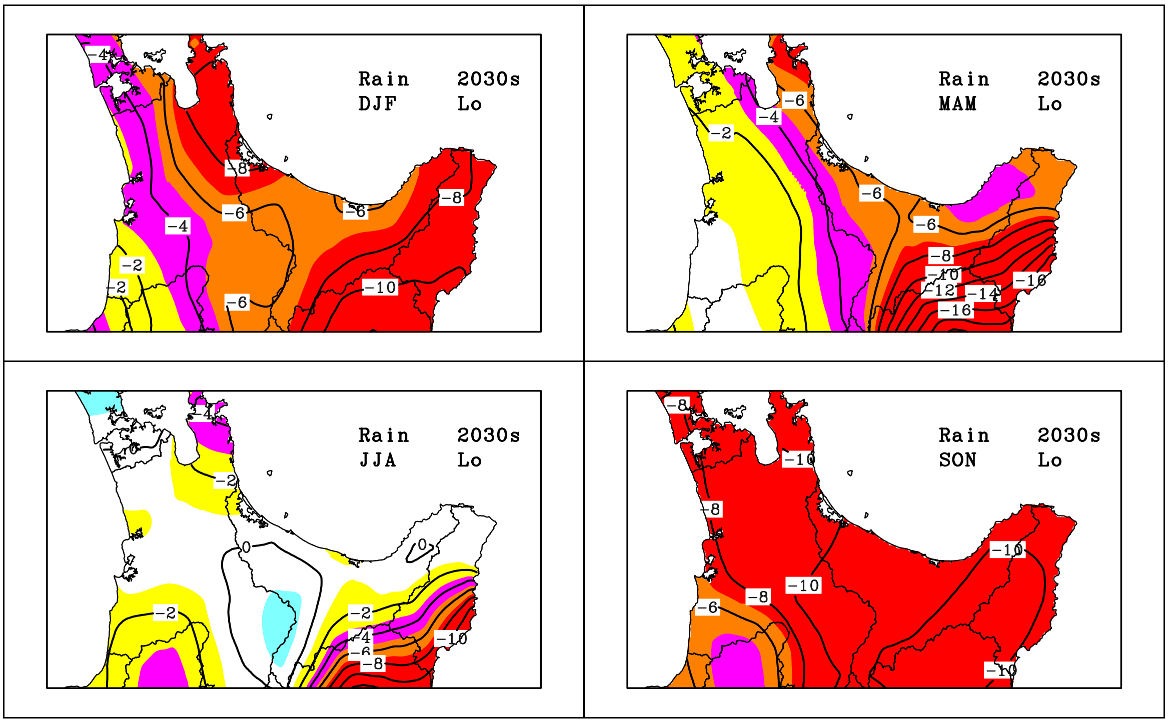


Figure 39a: Scenarios of seasonal average rainfall changes by 2030s, at the "Low" end of the climate model range. Contours every 2%.

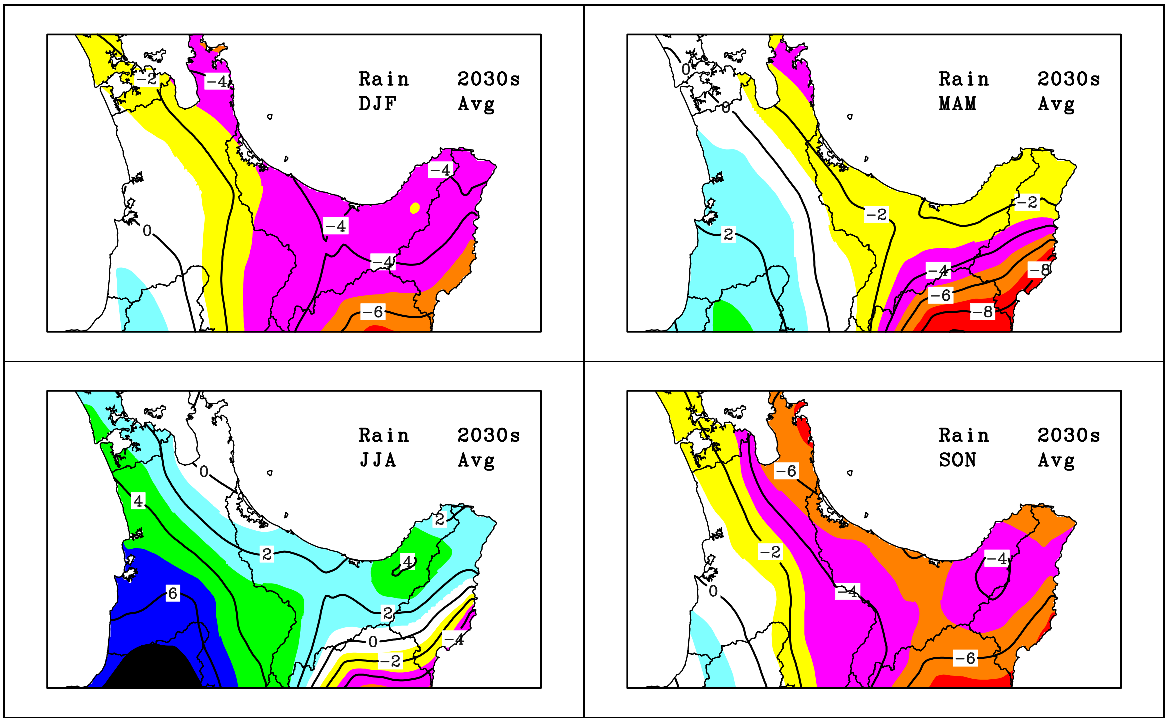


Figure 39b: As Figure 39a, but for "Average" over 6 climate models.

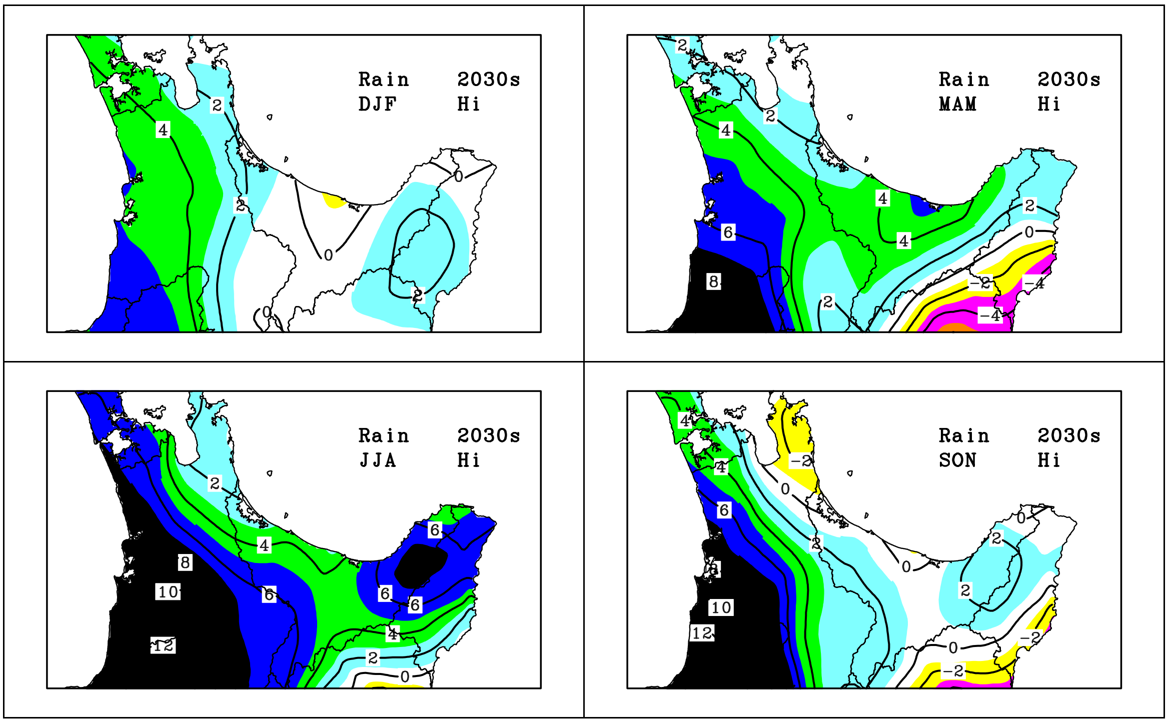


Figure 39c: As for Figure 39a, but for "High" end of the climate model range.

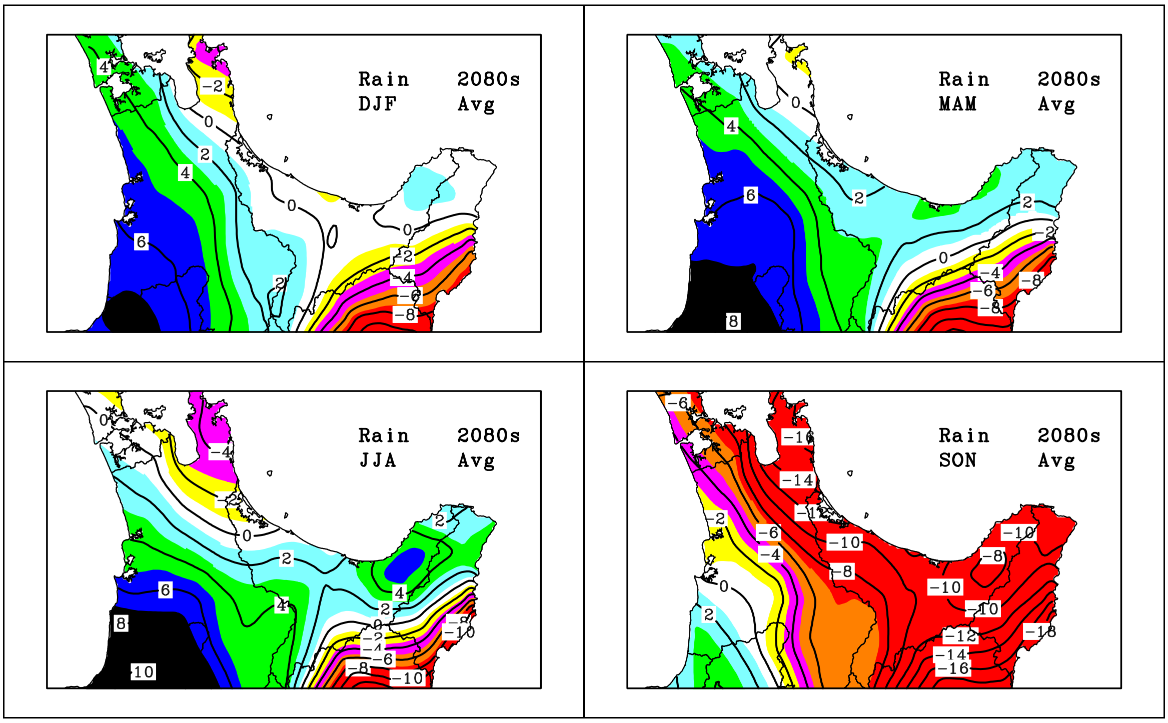


Figure 40: Scenarios of seasonal average rainfall changes by 2080s, using the "Average" of four climate models. Contours every 2%.

In the 2080s (Figure 39), the drying trend evident in Figure 39b in summer and autumn has reversed. Summer rainfall for the Bay of Plenty is projected to return to near the current climatology, although note that increased westerlies have produced substantial rainfall increases in the west of the North Island. Autumn is also wetter than currently by the 2080s, and winter also slightly wetter than the 2030s. However, the spring season has continued to get drier, and by the 2080s spring rainfall is projected to be about 10% lower throughout the district. Of course, these projections are somewhat dependent on which AOGCMs are considered, and could change with further development of the climate models.

6.4 Bay of Plenty Scenarios for Circulation and Wind Flows

Mullan *et al.* (2001c) suggested that, under global warming, the mean westerly wind component across New Zealand is expected to increase by approximately 10% of its current value in the next 50 years. This "mean westerly" is composed of individual days where the actual wind is sometimes westerly and sometimes easterly. Thus, as with other climatic elements, changes in the mean do not translate easily into changes in extremes.

More recent projected wind changes, downscaled to the full range of IPCC SRES scenarios (MfE, 2003), strongly support an increasing westerly flow, particularly in the annual mean. (More variability is possible in the seasonal means). By the 2080s, there could be almost no change up to more than double the current mean speed of westerly airflow in the annual mean. Changes in the north-south wind component are less clear, although the spread of model results suggests a bias towards more southerlies in all seasons except winter. Increasing westerlies are one reason for a drying trend in the Bay of Plenty (see Figure 28). Another factor is the more southerly location of the hemispheric high-pressure belt.

On the timescale of daily weather, there are also good arguments in favour of increasing winds. Strong winds are associated both with intense convection, which is expected to increase in a warmer climate, and also with intense low-pressure systems, which might also become more common (see extra-tropical cyclones below). Thus an increase in severe wind risk could occur.

6.5 Bay of Plenty Scenarios for Extreme Rainfall

A warmer atmosphere can hold more moisture (about 8% more for every 1°C increase in temperature), so there is a potential for heavier extreme rainfall as climate warms. The IPCC in its Third Assessment declared that more intense rainfall events are “very likely over many areas”. However the information available for deciding on which areas of New Zealand this might apply to is limited.

Whetton *et al.* (1996) predicted a reduction in the return period of heavy rainfall events for Australasia. (This is the average number of years between days with rainfall exceeding some specified high value). They suggested that by 2030 for New Zealand there would be “no change through to a halving of the return period of heavy rainfall events” and by 2070 “no change through to a fourfold reduction in the return period”. More recent return period estimates (MfE, 2003), using the results from an AOGCM simulation (Semenov and Bengtsson, 2002), confirm that reduced return periods are likely, at least where mean rainfall increases. Because the mean rainfall changes suggest a drying trend in the Bay of Plenty over the next 50 years, before conditions become wetter, it is possible that long-term trends in extreme rainfall will not be noticeable in the Bay of Plenty district until the latter half of the 21st century. The IPO phase switches are likely to be a more important factor for the coming 50 years.

6.6 Bay of Plenty Scenarios for Ex-Tropical and Extra-Tropical Cyclones

The IPCC Third Assessment indicates that by the end of the 21st century, it is likely that in some regions the peak wind intensities in tropical cyclones will increase by 5-10% and peak rainfall intensities by 20-30%. Tropical cyclones have changed their characteristics by the time they reach New Zealand, but still have strong winds and heavy rainfall associated with them that could affect the Bay of Plenty region. We also know that during El Niño periods, tropical cyclones tend to track further east in the South Pacific, and many climate models show an El Niño-like change in the mean state of the tropical Pacific over the next 50 years. However, whether or not this decreases the likelihood of ex-tropical cyclones reaching central New Zealand is not yet clear.

The intensity of mid-latitude storms (also known as extra-tropical cyclones, that move in the westerly wind belt) might also increase in a future warmer atmosphere. Increased storminess would result both from greater moisture release (a warmer atmosphere can hold more water vapour) and from a stronger equator-pole temperature gradient (the southern ocean will warm more slowly than the tropics). However, we cannot yet say whether increased storminess in the Southern Hemisphere generally would mean more intense storms, or a higher frequency of passing cold fronts, or indeed any changes locally in the small sector of the hemisphere that New Zealand occupies. The regional changes vary considerably between models.

6.7 Conclusions

In summary:

- Additional Bay of Plenty stations were used to augment the downscaled climate change scenarios previously produced by NIWA. The extra stations actually made little difference for temperature, where spatial gradients are weak and only three further sites were available. For rainfall, the added stations reduced the projected drying trend in eastern and southern parts of the Bay of Plenty district, which were otherwise unduly influenced by large changes in the Gisborne region.

- Scenarios of mean temperature change suggest that winter temperatures will increase faster than in other seasons. Averaging over six climate models with a mid-range IPCC emissions scenario, annual mean temperatures increase by about 0.8°C by the 2030s, with an additional 1.0°C increase in the following

50 years to the 2080s. Allowing for the differences between models produces a wider estimate, ranging from a minimum warming of about 0.5°C in summer to a maximum warming of 1.0°C in summer, autumn and spring. Allowing for more extreme IPCC emissions scenarios extends this range further.

- Scenarios of mean rainfall change suggest a decreasing trend in rainfall until the 2030s, in all seasons except winter, as an average over six climate models. Beyond the 2030s, the models indicate conditions getting wetter (back to or wetter than the present climate), except for the spring season where continued drying occurs. There is substantial variability between models.

- Various modelling studies suggest that heavy rainfall events will occur more frequently in New Zealand over the coming century, but the likely size of this change is not yet very certain, particularly for the Bay of Plenty over the next 50 years where the mean rainfall is likely to decrease.

- Ex-tropical cyclones might be slightly less likely to reach New Zealand, but if they do their impact might be greater.

7. Conclusions

This report describes the past climate variability and trends for the Bay of Plenty region and presents scenarios for future climate change over the next 50 to 100 years. Homogeneity tests (to assess the quality of the data record) were performed on all the climate data used for this report and composite records of data from two or more nearby climate stations were constructed, where necessary, to extend the length of the data records.

7.1 Rainfall

Analyses for trends and change points performed on the rainfall data indicate that total annual rainfall has generally decreased in the Bay of Plenty since the 1960s or 1970s, but this reduction is only statistically significant at the 95% level at Tauranga where the annual rainfall total has decreased at the rate of 25 mm per decade over this station's period of record: 1910-2002. Seasonal rainfall has decreased over most of the region in most seasons. Decreases have been larger in the west (Tauranga westwards) than in the east (Whakatane eastwards) and south. Consistent with this trend, there has also been a significant, long-term trend towards fewer rain days at Tauranga, Opotiki, and Kaingaroa over the last 100 years, with much of this reduction occurring since the 1960s or 1970s. The reduction is in the order of 1.5 fewer days of rain per decade.

In the last 30 years (since about 1970) extreme daily rainfall totals have been generally lower, by about 20 mm, and less frequent than prior to 1970 (at least at coastal or lower elevation stations). Likewise, the frequency of extreme large daily rainfall has decreased across the Bay of Plenty over the last 100 or so years, but this decrease is statistically significant only at Tauranga at a rate of 0.2 days per decade. The duration of extended dry spells has reduced over the 20th century at Whakarewarewa, with a decline in the extended dry spell duration of around 0.3 days per decade. A weakly statistically significant decline of the same size is observed at Motu, and Tauranga.

Thus it can be concluded that in the last 30 to 40 years the Bay of Plenty region has been becoming generally drier, with fewer and less intense extreme rainfalls. However, this has not resulted in an increase in the dry spell duration across the region. This observed decrease in rainfall over much of the Bay of Plenty region, and the relatively larger decreases in the west near Tauranga, is partly attributable to increased westerly airflow over this period, corresponding to the Interdecadal Pacific Oscillation (IPO) phase change from negative to positive.

For very short durations (10-30 minutes), extreme rainfalls tend to be slightly higher in the positive phase of the IPO rather than in the negative phase. For durations from 60 minutes to 12 hours, the rainfalls are generally smaller in the positive phase of the IPO. However, the differences in these short durations extreme rainfall for either phase of the IPO are mostly not significant. This suggests that short duration convective processes are less likely to be strongly influenced by the phase of the IPO. For the longer durations (24-72 hours), the mean level of extreme rainfalls show mixed signals; at some sites (e.g. Whakarewarewa) rainfall is significantly lower in the positive phase of the IPO, and at other sites (e.g. Waihi) it is higher (but not significantly so).

Seasonal rainfall totals and rainfall intensity for the Bay of Plenty region are shown to be directly related, thus an increase in seasonal rainfall will tend to indicate a corresponding increase in the extreme rainfall regime and vice versa. Also, during La Niña periods, rainfall has been shown to be generally above normal for the Bay of Plenty region, while it is generally below normal during El Niño periods. The relationships are weakest in summer (Dec-Jan-Feb) and strongest in spring (Sep-Oct-Nov), however the correlations are not large, and much of the year-to-year variability of Bay of Plenty climate can not be explained by what the Southern Oscillation is doing.

The IPO appears to have switched back to a negative phase, which should result in more frequent La Niña events, weaker westerlies and increased rainfall for the Bay of Plenty over the next two decades. These changes could be modified by anthropogenic long-term trends.

In terms of the future, mean annual rainfall is projected to decrease in the Bay of Plenty by between about 1% and 4% by the 2030s (seasonally varying on average from a slightly wetter winter (by 0 to 4%) to a rather drier spring and summer (up to 8% drier in Tauranga in spring)), with no further drying trend by the 2080s. This "nonlinearity" in the drying (i.e., virtually all the drying occurring in the first 50 years) is typical of all the models. Summer rainfall for the Bay of Plenty is projected to return to near the current climatology by the 2080s. Autumn is also projected to be wetter than currently by the 2080s, and winter also slightly wetter than the 2030s. However, the spring season is projected to continue becoming drier, and by the 2080s spring rainfall is projected to be about 10% lower throughout the region.

It is possible that long-term trends in extreme rainfall will not be noticeable in the Bay of Plenty district until the latter half of the 21st century. Ex-tropical cyclones might be slightly less likely to reach New Zealand, but if they do their impact might be greater.

7.2 Temperature

All of the Bay of Plenty climate stations that were analysed show a warming trend in the mean annual air temperature of approximately 0.1 °C per decade over the last 100 years. It is noticeable that Tauranga, the best temperature record in the Bay of Plenty (highest quality, least missing data), recorded very high temperatures in the 1990s. This has been observed elsewhere in New Zealand, with the 1990s being the warmest decade in the last 100 years. Over the 50-year period 1951-2000, mean seasonal temperatures in the Bay of Plenty have increased substantially along the coast by up to 0.2 °C per decade, while inland southern parts of the region have shown little warming, and have even cooled slightly in some seasons.

Air frosts have significantly decreased in the Bay of Plenty since good-quality, daily temperature records began in 1940. They have become rare events in coastal places such as Tauranga, averaging less than one air frost per year in recent times. This is related to the fact that the coldest nights have significantly warmed in the Bay of Plenty since 1940 (+0.3 °C per decade), with the greatest warming seen at some stations since 1960, and again following 1976. The number of extremely cold nights has also significantly decreased.

The number of days with maximum temperatures exceeding 25 °C has significantly increased at Tauranga (+0.2 days per decade) and Waihi (+0.4 days per decade) since 1940, while the extreme temperature range (hottest minus coldest temperatures of the year) has significantly decreased in Whakarewarewa (-1.1 °C per decade) and Te Aroha (-0.3 °C per decade). The hottest days have significantly warmed in Tauranga and Waihi (+0.2 to 0.4 °C per decade) since 1940. Most of the warming occurred since 1968 at several of the sites analysed. The frequency of hot days at Tauranga and Waihi has also increased since 1940 by about 1 day per decade.

During La Niña periods, the temperature has been shown to be generally above normal for the Bay of Plenty region, while it is generally below normal during El Niño periods. As with rainfall, the relationships are weakest in summer (Dec-Jan-Feb) and strongest in spring (Sep-Oct-Nov), however the correlations are not large, and much of the year-to-year variability of Bay of Plenty climate can not be explained by what the Southern Oscillation is doing.

As previously stated, the IPO appears to have switched back to a negative phase, which should result in more frequent La Niña events and hence higher temperatures for the Bay of Plenty over the next two decades. These changes could be modified by anthropogenic long-term trends.

Projected mean annual temperature changes for the 2030s (i.e., 2020-2049) and the 2080s (i.e., 2070-2099) relative to the "current" climate (1970-1999) indicate the Bay of Plenty region could warm by about +0.80°C by the 2030s (seasonally varying on average between about +0.75°C in spring and summer to +0.90°C in winter), and by about +1.80°C by the 2080s (seasonally varying on average between about 1.65°C to 1.75°C in spring and summer to 2.00°C in winter).

7.3 Wind

The mean westerly wind component across New Zealand is expected to increase by approximately 10% of its current value in the next 50 years. By the 2080s, there could be almost no change up to more than double the current mean speed of westerly airflow in the annual mean. Changes in the north-south wind component are less clear, although the spread of model results suggests a bias towards more southerlies in all seasons except winter.

On the timescale of daily weather, there are also good arguments in favour of increasing winds. Strong winds are associated both with intense convection, which is expected to increase in a warmer climate, and also with intense low-pressure systems, which might also become more common. Thus an increase in severe wind risk could occur.

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9. Appendix

9.1 Information about Bay of Plenty Rainfall Stations Analysed for Homogeneity

- A Waihi composite series was used, with B75381 data until 31/12/1989 and B75382 data used from 1/1/1990, with no adjustments. This Waihi series did not include either Athentree series (B75495 and B75492). This was both because of the large amount of missing data in the Athentree records, and also MASH establishing that the Waihi and Athentree rainfall series were inhomogeneous.

- The Te Aroha daily rainfall series was used from B75571 between 1907 and 31/10/1999 without adjustment. We did not add any B75562 daily rainfall data to this series as significant discrepancies were identified by MASH and metadata between the overlapped daily data.

- A Tauranga composite series was used, with B76621 data from 1/1/1910 to 31/1/1996, then B76624 data from 1/2/1996 onwards. No adjustments were made. This is an excellent quality site.

- No Whakatane/Thornton composite record was considered homogeneous at the daily scale by MASH. The individual station records also have quality concerns.

- Mataora B78601 daily rainfall data were used over the entire length of record without adjustment.

- No Rotorua composite record was considered homogeneous at the daily scale by MASH. The individual station records were generally too short a record to be of interest for this analysis.

- Waiotapu Forest B86341 daily rainfall data were used over the entire length of record without adjustment.

- Kaingaroa Forest daily rainfall data were used over the entire length of record without adjustment.

- It is possible to use either Galatea B86481, or Murapara B86471, at any frequency without adjustments – but not to concatenate these series. Murapara is (subjectively) the slightly better record, with less missing data and better data quality – but the station closed in 1987. Galatea had a period of missing data in the middle of the record, but is active today.

- Opotiki B87023 daily rainfall series was used over entire length of record without adjustment.

- Daily rainfall data at Motu B87256 from 1920 until 31/7/1960, then B87255 from 1/8/1960 onwards, were used without adjustment. We did not add any Motu EWS daily rainfall data to this series as significant discrepancies were identified by MASH and metadata between the two sites.

- No Ruatoki or Waimana composite daily rainfall series were used as these were poor quality records as flagged by MASH and metadata, with significant missing data, and many site changes.

- We did not use Darby 87005, as this daily rainfall series was consistently flagged by MASH. It was ultimately rejected because of a lack of solid metadata to make decisions with and because of the short length of record.

- We did not use Kawerau 860701 daily rainfall series, which is a short (40 year) record, with significant amounts of missing data, and at least four site changes, none of which are adequately documented.

- Whakarewarewa EBOP (861204) is a composite record analysed and provided by EBOP staff. It comprises of B86124 from 1899 to 1982, then various adjusted data from Whakarewarewa FRI (0.8km NE of the original site), and Rotorua Hydro B86128 (2.0km NW of the original site) until a new Whakarewarewa gauge was installed by EBOP 100m from the original site, on 08/09/1992 (e.g. 10 years of adjusted/composite data, before the ‘new’ station data). Occasional missing data after 1992 was filled using either Whakarewarewa FRI or Rotorua Hydro. Based on the output from MASH, this composite site was homogeneous.

9.2 Information about Bay of Plenty Temperature Stations Analysed for Homogeneity

- The Waihi temperature record is generally of moderate quality. One large outlier was identified in Waihi minimum temperatures – in 1971, when compared to neighbour records. Two adjustments were recommended and should be used for minimum temperatures: before and during 1989, +0.13 °C correction (i.e. add 0.13 °C to raw data), and for the years 1990, 1991, and 1992, a correction of +0.90 °C. For the years 1993 (inclusive) onwards, the correction is 0.00 °C (nil). One large outlier year was identified in Waihi maximum temperatures – in 1992, when compared to neighbour records. However, although this has flagged as statistically significant, *all* stations showed 1992 as an anomalously cold year for maximum temperatures, and Waihi data, on closer inspection, looked reasonable. Two adjustments were recommended and were used for maximum temperatures: Before and during 1976, +0.13 °C correction (i.e. add 0.13 °C to raw data). For the years 1977 (inclusive) onwards, the correction is 0.00 °C.

- Te Aroha B75571 temperature data (maximum, minimum, mean) requires no adjustments over the period of its record. This is an excellent record, although recently closed.

- The Tauranga temperature (maximum, minimum, mean) record is generally of good quality. A possible outlier was identified in minimum temperatures in 1971 (but this was not statistically significant at the 95% level). For Tauranga minimum temperatures, a breakpoint was identified in either 1989 or 1990. This may correspond to the change to the automatic weather station (AWS) in 1990. Therefore before 1/6/1990, apply a correction of +0.32 °C (i.e. add 0.32 °C to raw data), and from 1/6/1990 onwards, the correction is 0.00 °C (nil). For Tauranga maximum temperatures, three breakpoints were identified, as multiple neighbour series analysis revealed that maximum temperatures at Tauranga are cooler than they 'should' be since the AWS installation. The correction used prior to and including 1982 is –0.51 °C (i.e. subtract 0.51 °C from the raw data). Between 1983 and 1991 inclusive, the correction is –0.25 °C. From 1992 inclusive onwards, the correction is 0.00 °C.

- We did not concatenate any Whakatane temperature record as homogeneity tests fail on any composite series, at least on the daily scale.

- We did not concatenate any Rotorua/Whakarewarewa temperature record as homogeneity tests fail any composite series. However, Whakarewarewa B86124 was used as a single temperature record, although the station is now unfortunately closed (closed in 1982).

- We did not use any Waiotapu Forest temperature record, because it was too short for these purposes.

- We did not use any Kaingaroa Forest temperature record; many outliers were identified, and numerous breakpoints and inhomogeneities identified in the record. Metadata and MASH analysis revealed that this forestry site was a poor temperature record, at least at the daily scale, and the high number of missing data meant it generally was unsuitable for this type of daily data analysis.

- A number of site changes and probable exposure changes meant that there were concerns about data quality at Opotiki. Large outliers were identified for both maximum and minimum temperatures, not all of which could be accounted for. Also, two major breakpoints were identified, for both minimum and maximum temperature, with very large adjustments recommended. If external climate influences could be removed, it would be unlikely that any temperature record at Opotiki would be stationary. The Opotiki temperature records are considered poor for this type of analysis, at least at the daily scale.

9.3 High Frequency Rainfall Recording Stations in the Bay of Plenty

Table 14: High frequency rainfall data recorded at hydrological sites around the Bay of Plenty, with data archived by NIWA up until 31 December 1999. Note that all of the high-frequency recording records as listed here are too recent to be analysed in this report.

Site No	Location	Records		Recording	Recording	Map	Alt	Comments
		Begin	End	Authority	Interval	Reference	(m)	
755811	Tuapiro at Woodlands Road	17-May-93	31-Dec-99	EBOP	15 min	T13:661057	30	
757901	Waipapa at Goodalls Road	8-Oct-91	31-Dec-99	EBOP	15 min	U14:738824	240	
766002	Te Puna Stm at Stannett	25-Sep-90	31-Dec-99	EBOP	Hourly to 27.4.94, then 15min	U14:792890	10	
768301	Kaituna at Te Matai	1-Apr-90	31-Dec-99	EBOP	15 min	U15:044632	10	
769402	Pongakawa at Pongakawa	26-Jun-96	31-Dec-99	EBOP	15 min	V15:164603	55	
769701	Tarawera at Awakaponga	28-Aug-89	31-Dec-97	EBOP	15 min	V15:412555	10	
778801	Haparapara Raingauge	20-Jun-96	31-Dec-99	EBOP	15 min	Y15:368615	1040	
781310	Waioeka at Gorge Mouth	12-Dec-89	31-Dec-99	EBOP	15 min	W16:861365	40	
781410	Otara at Browns Bridge	13-Dec-89	31-Dec-99	EBOP	15 min	X16:929378	38	
860205	Mangorewa at Kaharoa Link	2-Sep-85	31-Dec-97	EBOP	Combination hourly/daily to 6.9.92, then 15min	U15:970493	420	
860206	Mangorewa at Kaharoa	1-Sep-85	31-Dec-99	EBOP	Combination hourly/daily to 19.12.90, then 15min	U15:984479	400	
860710	Rangitaiki at Te Teko	8-Sep-89	31-Dec-97	EBOP	15 min	V15:436445	10	
861204	Whakawerawera at FRI	6-Jan-03	29-Dec-97	EBOP	Daily to 1.1 84, then 15min	U16:959328	300	
868410	Rangitaiki at Kokomoka	29-Aug-95	31-Dec-99	EBOP	15 min	V18:128591	780	
870201	Waimana at Ranger Station	12-Apr-96	31-Dec-97	EBOP	15 min	W16:696153		
871302	Otara at Tutaetoko	19-Dec-89	31-Dec-99	EBOP	15 min	X16:926280	790	
871410	Pakihi at Pakihi Stn	2-Jan-70	31-Dec-99	EBOP	Daily 2.1.70-30.6.86 15min from 20.1.89	X16:980325	80	
872101	Otara at Town Wharf	31-May-95	31-Dec-99	EBOP	6min to 26.6.96, then 15min	W15:861466		
872301	Waioeka at Cableway	20-Jan-89	31-Dec-99	EBOP	15 min	W16:877220	70	
872507	Rakanui at Rakanui Station	8-May-91	31-Dec-97	EBOP	15 min	X16:064216	715	
873002	Whakatane at Huitieke	1-Apr-77	31-Dec-97	EBOP	Daily to 31.5.87, hourly to 25.12.89, 15 min from 14.6.90	W17:607081	274	
873103	Waimana at Ogilvies Bridge	14-Aug-87	31-Dec-95	EBOP	Hourly to 24.7.88 15min from 27.11.88	W16:704128	150	Site closed
874304	Waioeka at Koranga	1-Aug-76	31-Dec-99	EBOP	Daily up to 11.1.90, then 15min	W17:886025	940	
876002	Whakatane at Huiarau Summit	1-Mar-75	31-Dec-99	EBOP	Daily to 14.8.87, hourly from 31.12.87, 15min from 14.8.91	W18:628786	1170	
767010	Mangawhai at Stables	4-Aug-71	13-Jan-94	NIWA	Digitised from charts to 3.3 74, then 6min	U14:756857	91	Site closed
776917	Tauranga at Orete	4-Oct-84	12-Jan-94	NIWA	6min	Y14:426836	70	Site closed
779017	Wairere at W1	13-Oct-67	6-Jan-94	NIWA	Digitised from charts to 23.2 76, then 6min	W15:620526	72	Site closed
860116	Kaituna at Dodds	10-Nov-75	24-Apr-78	NIWA	6min	U15:905448	332	Site closed
861114	Kaituna at Te Reinga	17-Nov-75	3-Apr-78	NIWA	6min	U16:838318	573	Site closed

861218	Kaituna at 8 Mile	6-Nov-75	4-Apr-78	NIWA	6min	U16:976287	366	Site closed
861313	Kaituna at Carrs	4-Nov-75	18-Jan-78	NIWA	6min	U16: 50382	494	Site closed
861315	Te Ngae Drain at PRD	15-Dec-81	6-Aug-86	NIWA	6min	U16:957349	282	Site closed
862212	Pomare at Pukehangi Rd	19-Dec-81	18-Sep-86	NIWA	6min	U16:925343	311	Site closed