An acceleration in New Zealand’s sea level record?

Theresa Cole

A thesis submitted for the degree of

Master of Science

at the University of Otago, Dunedin,

New Zealand

2010

Optimæ familiæ,

cārissimīs amīcīs,

sapientissimis magistris,

amantissimis spōnsis.

Abstract

Since the later part of the 19th Century, tide gauge records indicate that global sea levels have risen with an average rate of 1.7 ± 0.3 mm/yr. Satellite altimetry records indicate that the rate of sea level rise between 1993 and 2010 was 3.2 ± 0.4 mm/yr. It is currently uncertain if this latter figure is indicative of an increased rate of rise, or the result of a periodic signal. In any event, if the future sea level rise is to be predicted accurately, it is of great importance that changes in the rate of sea level rise be detected as soon as possible.

This study utilises a variety of techniques, including Least Squares and Fast Fourier Transform analyses, to assess the sea level records from New Zealand's four longest tide gauge stations, located in Auckland, Wellington, Lyttelton and Dunedin, to detect any significant changes in the rate of relative sea level rise. It finds that Wellington's records demonstrate a relative acceleration of 0.013 ± 0.01 mm/yr^2 between 1891 and 2007, which is superimposed over the decadal and interdecadal signals that are present in the records. However, continuous Global Positioning System measurements that have been collected at the site over the past decade indicate the presence of significant tectonic motion in the form of subduction. The records from the Auckland, Lyttelton and Dunedin tide gauges do not demonstrate significant accelerations. The longest significant signals that are present within the sea level records from Auckland, Wellington, and Dunedin have periods in the range of 45 to 50 years.

The establishment of continuous Global Positioning System stations at long-term tide gauge stations is imperative to isolate non-constant vertical deformations from the observed relative rates of sea level rise to detect accelerations, and also to isolate the absolute rate of sea level rise.

Acknowledgements

To my supervisor, John Hannah, for supporting me throughout this project.

To my co-supervisor, Robert Tenzer, for the advice provided.

To Ross Vennell, Patrick Caldwell, Gregory Leonard and Wilton Sturges for the assistance offered to help clarify areas of interest.

To the National Oceanic and Atmospheric Administration for providing the atmospheric pressure datasets required for this study.

The National Climate Database through Land Information New Zealand for the hourly sea level records required.

The National Institute of Water and Atmospheric Research for providing New Zealand's meteorological records.

The sea level records provided originally by the Auckland, Wellington, Lyttelton and Dunedin Harbour Boards, and the derived annual mean sea levels provided by Land Information New Zealand.

To CPG New Zealand Ltd, for supporting me throughout my university career and my pursuit of further education.

The University of Otago, and the National Institute of Surveyors for the financial support they provided throughout my study.

To my partner, Sharleen Swami, for encouraging and supporting me throughout this year.

To my family, for inspiring me.

To my friends, especially Jem, Nell, Ella, Whitney, Julia, Libby and Sarah, for the mental health breaks.

Table of Contents

Masters Thesis Declaration Form iii
Author Declaration Form v
Abstract vii
Acknowledgements ix
Table of Contents x
Table of Figures xiv
Table of Tables xviii
List of Abbreviations xx
1 Introduction 1
1.1 Purpose of this study 2
1.2 Significance of this study 2
1.3 Structure of this study 4
2 Literature Review 6
2.1 The nature of mean sea level 7
2.1.1 A review of the factors that influence monthly and annual mean sea levels 8
2.1.2 A review of historical sea level trends 8
2.1.2.1 Evidence of historical sea level trend 10
2.1.2.2 Satellite altimetry in similar investigations 14
2.1.3 Contributors to sea level rise 16
2.1.4 Mean sea level summary 18
2.2 A review of factors that influence monthly and annual mean sea levels 19
2.2.1 Tectonic deformation 20
2.2.1.1 The structure of the Earth 23
2.2.1.2 Glacial isostatic adjustment 25
2.2.1.3 Significant active tectonics in New Zealand 27
2.2.1.4 Tectonic deformation summary 32
2.2.2 Meteorological driver: Thermal expansion 32
2.2.2.1 Temperature trend in New Zealand 33
2.2.2.2 Thermal expansion effect variability due to salinity changes 34
2.2.2.3 Effect of thermal expansion on derivation of acceleration trend in sea level rise 35
2.2.3 Meteorological driver: Atmospheric pressure 35
2.2.3.1 Water salinity content 36
2.2.3.2 Decadal and interdecadal atmospheric signals 37
2.2.3.3 Associated influence of wind set-up 37
2.2.3.4 Atmospheric pressure measurement corrections 40
2.2.3.5 Inverted barometer effect summary 41
2.2.4 Decadal and interdecadal oscillations 41

2.2.4.1 Decadal-scale signals affecting mean sea level 42
2.2.4.2 Interdecadal-scale signals affecting mean sea level 43
2.2.4.3 Relationship between decadal and interdecadal oscillations and sea level rise 45
2.2.4.4 Decadal and interdecadal oscillations summary 45
2.3 Summary of literature review 46
3 Analysis datasets 47
3.1 Tide gauges used 49
3.1.1 Errors in the measurement of mean sea level 51
3.2 Sea level data 54
3.3 Quality of sea level records 59
3.3.1 Criteria used for sea level data selection 59
3.3.2 Tide gauge maintenance records 61
3.3.2.1 Result of tide gauge maintenance investigation 65
3.4 Summary of the analysis datasets 65
4 Methodology 66
4.1 Inverted barometer effect investigation 66
4.1.1 Obtaining sea level residuals using SLPR2 software 67
4.1.2 Hourly sea level measurements 68
4.1.2.1 Hourly sea level residuals 69
4.1.3 Atmospheric pressure data 70
4.1.3.1 Local hourly sea level atmospheric pressures 71
4.1.3.2 Global average annual sea level atmospheric pressure 72
4.1.3.3 Local average annual sea level atmospheric pressure 78
4.1.4 Inverted barometer trend analysis 87
4.1.4.1 Relative atmospheric pressure change response 88
4.1.4.2 Impact of atmospheric pressure variations on annual mean sea levels 88
4.2 Sea level trend investigations 90
4.2.1 Derivation of linear trend first estimate 91
4.2.2 Correlation coefficients 92
4.2.3 Analysis of Decadal and Interdecadal trends 93
4.2.3.1 Datasets used in Fast Fourier Transform signal analyses 94
4.2.4 Sea level trend analyses 98
4.2.4.1 Wellington tide gauge correction analysis 99
4.2.4.2 Full dataset analysis 102
4.2.4.3 Changing linear trends analysis 103
4.2.4.4 Non-consistent acceleration rates 104
4.2.4.5 Input datasets 105
4.3 Statistical analyses applied in this study 105
4.3.1 Confidence interval of the mean 106

4.3.2 Comparison of two means ... 106
4.3.3 Error propagation ... 107
4.4 Summary ... 108
5 Analyses and Results ... 109
5.1 Annual mean sea level datasets ... 110
5.2 Influence of inverted barometer effect ... 110
5.2.1 Local inverted barometer effect responses ... 111
5.2.1.1 Local hourly sea level residuals ... 111
5.2.1.2 Local hourly atmospheric pressures ... 112
5.2.1.3 Local atmospheric pressure variation responses ... 113
5.2.2 Relative atmospheric pressure differences ... 115
5.3 Analysis methodologies used ... 119
5.3.1 Least Squares analysis ... 120
5.3.1.1 Weaknesses associated with Least Squares analysis ... 120
5.3.1.2 Least Squares approach to minimise analysis weaknesses ... 121
5.3.1.3 Least Squares analysis derivation ... 121
5.3.1.4 Least Squares analysis summary ... 125
5.3.2 Fourier Function Digital Signal Processing ... 125
5.3.2.1 Application for investigating sea level rise trend ... 126
5.3.2.2 Fast Fourier Transform analysis summary ... 127
5.4 Results obtained from the datasets considered ... 127
5.4.1 Linear trends initial estimates ... 127
5.4.2 Corrected annual mean sea level datasets ... 128
5.4.2.1 Fourier Function Digital Signal analysis on corrected annual mean sea levels ... 129
5.4.2.2 Acceleration analyses using data corrected for inverted barometer effect ... 132
5.4.2.3 Changing linear trend analyses ... 139
5.4.2.4 Non-consistent acceleration rates ... 144
5.4.3 Uncorrected annual mean sea level datasets ... 148
5.4.3.1 Fourier Function Digital Signal analysis on uncorrected annual mean sea levels ... 148
5.4.3.2 Acceleration analyses using data corrected for interdecadal signals ... 152
5.4.3.3 Changing linear trend analyses ... 158
5.4.3.4 Non-consistent acceleration rates ... 163
5.5 Summary of results from analyses ... 167
6 Discussion ... 169
6.1 Implications of the trend results ... 169
6.1.1 Combined analyses' results ... 169
6.1.2 Acceleration within Wellington's sea level records ... 170
6.2 Meteorological influences on sea level ... 172
6.2.1 Atmospheric pressure and the inverted barometer effect ... 172

6.3 Drivers of significant decadal and interdecadal signals in sea level records......176
6.4 Discussion summary......176
7 Conclusions and Recommendations 178
7.1 Conclusions......178
7.2 Recommendations 179
7.2.1 Further investigations into the trend in sea level rise......179
7.2.2 Improvements to the inverted barometer effect model 180
7.2.3 Isolation of the decadal and interdecadal drivers......180
7.2.4 Summary of future research 181
8 References......182
9 Appendix 202
9.1 Sea level residuals versus sea level atmospheric pressure plots......203
9.2 Calculated trends 209
9.3 Derived Harmonic Constituents 213
9.4 Spyder Fast Fourier Transform Processing......235

Table of Figures

Figure 2.1: The general eustatic sea level trend since the last glacial maximum (Fleming *et al*., 1998; Milne *et al*., 2005) 11

Figure 2.2: The Holocene sea level curve [(Gibb, 1986) *cited in Kennedy, 2008*]....12

Figure 2.3: Reconstructed sea level changes at Pounawea, southern New Zealand, since 1500 AD. Also shown are Lyttelton tidal records (open dots) and Bluff (black dots) (Gehrels *et al*., 2008)....13

Figure 2.4: Preliminary relative change in vertical positions over time at the Auckland, Wellington, Lyttelton and Dunedin tide gauges (Denys *et al*., 2010)....22

Figure 2.5: Internal Composition of the Earth (edited from Heidtke, 2003)....24

Figure 2.6: Tectonic plates and boundary interactions around the globe (Original Image: Silverstein et al., 2009) 24

Figure 2.7: Major fault lines in New Zealand the boundary between the Australian and Pacific tectonic plates (National Institute of Water and Atmospheric Research, 2010-b)....28

Figure 2.8: Significant Earthquakes in New Zealand since 1848 in proximity to New Zealand's four long-term tide gauges....30

Figure 2.9: Significant 1942 Wairarapa earthquakes in proximity to Wellington tide gauge 31

Figure 2.11: Inverted barometer effect 36

Figure 2.12: Dunedin Harbour 38

Figure 2.13: Sea level set-up due to wind-stress 39

Figure 2.14: Pressure variations with altitude (National Aeronautics and Space Administration, 2010) 40

Figure 2.15: Annual mean sea level at the Port of Auckland since 1899. The record is subdivided into phases of the 20 to 30 year cycles of the Interdecadal Pacific Oscillation, accompanied by a piece-wise fit to sea-level rise (Goring and Bell, 2001). 44

Figure 3.1: New Zealand's four long-term tide gauges....48

Figure 3.2: Float activated tide gauge (Hannah, 2010-b)....50

Figure 3.3: Staff tide gauge (photo: Hannah, 2010-b) 53

Figure 3.4: Original Annual Mean Sea Levels for Auckland from 1899 until 2007 57

Figure 3.5: Original Annual Mean Sea Levels for Wellington from 1891 until 2007....57

Figure 3.6: Original Annual Mean Sea Levels for Lyttelton from 1901 until 2007 58

Figure 3.7: Original Annual Mean Sea Levels for Dunedin from 1899 until 2007....58

Figure 4.1: Musselburgh weather station in proximity to Dunedin's tide gauge and other weather stations 72

Figure 4.2: Locations of the 58 supplementary coastal and island sea level pressure stations (Smith and Reynolds, 2003)....73

Figure 4.3: Representation of global coverage of extended reconstructed sea level pressures provided by the National Oceanic and Atmospheric Administration (2002), with cells 2° latitude by 2° longitude in dimension on WGS84 projection....74

Figure 4.4: Stations used to compile Hadley Centre sea level pressure dataset (Met Office Hadley Centre for Climate Change, 2007)....75

Figure 4.5: Representation of global coverage of Hadley Centre sea level pressure dataset provided by the National Oceanic and Atmospheric Administration (2002), with cells 5° latitude by 5° longitude in dimension on WGS84 projection 76

Figure 4.6: Radius of the Earth at a given latitude 77

Figure 4.7: Auckland's monthly sea level atmospheric pressures between 1916 and 2007 81
Figure 4.8: Wellington's monthly sea level atmospheric pressures between 1904 and 2007 81
Figure 4.9: Christchurch's monthly sea level atmospheric pressures between 1905 and 2007 82
Figure 4.10: Dunedin's monthly sea level atmospheric pressures between 1913 and 2007 82
Figure 4.11: Auckland's weather stations in proximity to Auckland's tide gauge station 83
Figure 4.12: Wellington's weather stations in proximity to Wellington's tide gauge station 84
Figure 4.13: Christchurch's weather stations in proximity to Lyttelton's tide gauge station 85
Figure 4.14: Dunedin's weather stations in proximity to Dunedin's tide gauge station 86
Figure 4.15: Axes of data plot investigating inverted barometer effect 89
Figure 4.16: Illustration of the effect the presence of a partial wave in a dataset has on a derived linear trend 93
Figure 5.1: Complete annual mean sea level records for Auckland, Wellington, Lyttelton and Dunedin, relative to arbitrary datum 110
Figure 5.2: Hourly sea level measurements throughout January 2003 in Auckland 111
Figure 5.3: Hourly predicted sea level heights throughout January 2003 in Auckland using constituents derived from 2004 data 112
Figure 5.4: Hourly residual values with predicted and measured sea level heights throughout January 2003 in Auckland 112
Figure 5.5: Derived hourly sea level residual values plotted with atmospheric pressure values (with reversed axis) throughout January 2003 in Auckland 113
Figure 5.6: Auckland’s hourly sea level residual values calculated for 2003 using constituents derived from 2004 plotted against corresponding sea level atmospheric pressures to find local trend 114
Figure 5.7: Auckland's historic annual mean atmospheric pressures at sea level between 1916 and 2007 116
Figure 5.8: Historic global annual mean atmospheric pressures at sea level between 1916 and 2007 117
Figure 5.9: Difference between Auckland's annual mean atmospheric pressures at sea level and the global annual mean values 117
Figure 5.10: Difference between Wellington's annual mean atmospheric pressures at sea level and the global annual mean values 118
Figure 5.11: Difference between Lyttelton's annual mean atmospheric pressures at sea level and the global annual mean values 118
Figure 5.12: Difference between Dunedin's annual mean atmospheric pressures at sea level and the global annual mean values 119
Figure 5.13: Complete annual mean sea level records corrected for the inverted barometer effect for Auckland, Wellington, Lyttelton and Dunedin, relative to arbitrary datum......................................129
Figure 5.14: Significance of signals from Fast Fourier Transform Analysis using Auckland's annual mean sea level values from 1903 until 2007 that are corrected for the inverted barometer effect 130
Figure 5.15: Significance of signals from Fast Fourier Transform Analysis using Wellington's annual mean sea level values from 1903 until 2007 that are corrected for the inverted barometer effect 131
Figure 5.16: Significance of signals within Auckland's corrected annual mean sea level and temperature records 132
Figure 5.17: Significant decadal and interdecadal signals present in Auckland's corrected annual mean sea level records 135
Figure 5.18: Auckland's annual mean sea levels with inverted barometer effect and significant decadal and interdecadal signals removed 135

Figure 5.19: Significant decadal and interdecadal signals present in Wellington's corrected annual mean sea level records 136

Figure 5.20: Wellington's annual mean sea levels with inverted barometer effect and interdecadal signals removed 136

Figure 5.21: Significant decadal and interdecadal signals present in Lyttelton’s corrected annual mean sea level records 137

Figure 5.22: Lyttelton’s annual mean sea levels with inverted barometer effect and significant decadal and interdecadal signals removed 137

Figure 5.23: Significant decadal and interdecadal signals present in Dunedin’s corrected annual mean sea level records 138

Figure 5.24: Dunedin’s annual mean sea levels with inverted barometer effect and significant decadal and interdecadal signals removed 138

Figure 5.25: Changing linear trends in Auckland's corrected annual mean sea levels 140

Figure 5.26: Changing linear trends in Wellington’s corrected annual mean sea levels 141

Figure 5.27: Changing linear trends in Lyttelton’s corrected annual mean sea levels 142

Figure 5.28: Changing linear trends in Dunedin’s corrected annual mean sea levels 143

Figure 5.29: Acceleration in sea level rise in Wellington's corrected annual mean sea levels 146

Figure 5.30: Significance of signals from Fast Fourier Transform Analysis using Auckland's annual mean sea level values from 1903 until 2007 149

Figure 5.31: Significance of signals from Fast Fourier Transform Analysis using Wellington's annual mean sea level values from 1903 until 2007 149

Figure 5.32: Significant signals within uncorrected annual mean sea level and atmospheric pressure records 151

Figure 5.33: Significant signals within Auckland’s annual mean sea level, atmospheric pressure, and temperature records 152

Figure 5.34: Significant decadal and interdecadal signals present in Auckland's annual mean sea level records 154

Figure 5.35: Auckland's annual mean sea levels with significant decadal and interdecadal signals removed 154

Figure 5.36: No significant decadal or interdecadal signals present in Wellington's annual mean sea level records 155

Figure 5.37: Wellington's annual mean sea levels with no significant interdecadal signal parameters to remove 155

Figure 5.38: Significant decadal and interdecadal signals present in Lyttelton’s annual mean sea level records 156

Figure 5.39: Lyttelton’s annual mean sea levels with significant decadal and interdecadal signals removed 156

Figure 5.40: Significant decadal and interdecadal signals present in Dunedin’s annual mean sea level records 157

Figure 5.41: Dunedin’s annual mean sea levels with significant decadal and interdecadal signals removed 157

Figure 5.42: Changing linear trends in Auckland's annual mean sea levels 159

Figure 5.43: Changing linear trends in Wellington’s annual mean sea levels 160

Figure 5.44: Changing linear trends in Lyttelton’s annual mean sea levels 161

Figure 5.45: Changing linear trends in Dunedin’s annual mean sea levels 162

Figure 5.46: Derived trends within Wellington's uncorrected annual mean sea level records 165

Figure 6.1: Relationship between Auckland's detrended annual mean sea level values and relative differences in local and national atmospheric pressures 173

Figure 6.2: Relationship between Auckland's detrended annual mean sea level values and relative differences in local and global atmospheric pressures 174

Figure 9.1: Auckland's hourly sea level residual values calculated for 2004 using harmonic constituents derived from same year plotted against corresponding sea level atmospheric pressures to find local trend....................203

Figure 9.2: Auckland's monthly sea level residual values from 1916 until 2007 using harmonic constituents derived from 2004 plotted against corresponding monthly average sea level atmospheric pressures to find local trend....................203

Figure 9.3: Wellington's hourly sea level residual values calculated for 2003 using harmonic constituents derived from 2004 plotted against corresponding sea level atmospheric pressures to find local trend....................204

Figure 9.4: Wellington's hourly sea level residual values calculated for 2004 using harmonic constituents derived from same year plotted against corresponding sea level atmospheric pressures to find local trend....................204

Figure 9.5: Wellington's monthly sea level residual values from 1944 until 2007 using harmonic constituents derived from 2004 plotted against corresponding monthly average sea level atmospheric pressures to find local trend....................205

Figure 9.6: Lyttelton's hourly sea level residual values calculated for 2003 using harmonic constituents derived from 2005 plotted against corresponding sea level atmospheric pressures to find local trend 205

Figure 9.7: Lyttelton's hourly sea level residual values calculated for 2003 using harmonic constituents derived from same year plotted against corresponding sea level atmospheric pressures to find local trend 206

Figure 9.8: Lyttelton's monthly sea level residual values from 1924 until 2007 using harmonic constituents derived from 2005 plotted against corresponding monthly average sea level atmospheric pressures to find local trend....................206

Figure 9.9: Dunedin's hourly sea level residual values calculated for 2002 using harmonic constituents derived from 2001 plotted against corresponding sea level atmospheric pressures to find local trend 207

Figure 9.10: Dunedin's hourly sea level residual values calculated for 2002 using harmonic constituents derived from same year plotted against corresponding sea level atmospheric pressures to find local trend....................207

Figure 9.11: Dunedin's monthly sea level residual values from 1913 until 2007 using harmonic constituents derived from 2001 plotted against corresponding monthly average sea level atmospheric pressures to find local trend....................208

Table of Tables

Table 2.1: Spectrum of sea-level "drivers" and responses with timescales (Goring and Bell, 2001) 20

Table 2.2: New Zealand's most significant earthquakes since 1848 (GeoNet, 2010) 29

Table 3.1: Tide gauge station details (Rowe, 2010) 49

Table 3.2: Total records available 61

Table 4.1: Weather stations used to compile hourly sea level atmospheric pressure data for inverted barometer effect investigation (National Institute of Water and Atmospheric Research, 2010)..........71

Table 4.2: Weather stations used to provide periods of monthly average sea level atmospheric pressure values (National Institute of Water and Atmospheric Research, 2010) 80

Table 5.1: Weighted mean local responses to atmospheric pressure variations 115

Table 5.2: Continuous-Time Fourier Series Representation (Baranuik *et al*., 2010).........................126

Table 5.3: Initial approximate linear trends in sea level rise for the Auckland, Wellington, Lyttelton and Dunedin 128

Table 5.4: Approximate linear trends for the four stations using data corrected for the inverted barometer effect..129

Table 5.5: Approximate periods of most significant signals that are contained within Auckland's and Wellington's corrected datasets 131

Table 5.6: Trend results from full dataset acceleration analysis corrected for the inverted barometer effect 133

Table 5.7: Significant signals found within the corrected datasets with 95% confidence intervals 134

Table 5.8: Results from linear trend analysis using segments of Auckland’s data that have been corrected for inverted barometer effect...140

Table 5.9: Results from linear trend analysis using segments of Wellington’s data that have been corrected for inverted barometer effect...141

Table 5.10: Results from linear trend analysis using segments of Lyttelton’s data that have been corrected for inverted barometer effect...142

Table 5.11: Results from linear trend analysis using segments of Dunedin’s data that have been corrected for inverted barometer effect...143

Table 5.12: Accelerating trend in sea level rise within the corrected Auckland dataset.....................145

Table 5.13: Signals within Auckland’s corrected dataset 145

Table 5.14: Accelerating trend in sea level rise within the corrected Wellington dataset 146

Table 5.15: Signals within Wellington's corrected dataset...146

Table 5.16: Accelerating trend in sea level rise within the corrected Lyttelton dataset......................147

Table 5.17: Signals within Lyttelton’s corrected dataset 147

Table 5.18: Accelerating trend in sea level rise within the corrected Dunedin dataset 147

Table 5.19: Signals within Dunedin’s corrected dataset 147

Table 5.20: Approximate periods of significant signals contained within Auckland's and Wellington's corrected datasets...150

Table 5.21: Trend results from full dataset acceleration analysis..153

Table 5.22: Significant signals found within the datasets with 95% confidence intervals 153

Table 5.23: Results from linear trend analysis using segments of Auckland’s data..........................159

Table 5.24: Results from linear trend analysis using segments of Wellington’s data 160

Table 5.25: Results from linear trend analysis using segments of Lyttelton’s data...........................161

Table 5.26: Results from linear trend analysis using segments of Dunedin's data............................162
Table 5.27: Accelerating trend in sea level rise within the Auckland dataset...................................164
Table 5.28: Signals within Auckland's uncorrected dataset...164
Table 5.29: Accelerating trend in sea level rise within the Wellington dataset.................................165
Table 5.30: Signals within Wellington's uncorrected dataset...165
Table 5.31: Accelerating trend in sea level rise within the Lyttelton dataset....................................166
Table 5.32: Signals within Lyttelton's uncorrected dataset 166
Table 5.33: Accelerating trend in sea level rise within the Dunedin dataset.....................................166
Table 5.34: Signals within Dunedin's uncorrected dataset 166
Table 6.1: 95% Confidence Intervals of parameters derived from Wellington's corrected and original annual mean sea level datasets 175
Table 6.2: A posteriori variances of unit weight from corrected and uncorrected datasets 175
Table 9.1: Summary of trends derived for Auckland to provide Auckland's final weighted mean inverted barometer response...209
Table 9.2: Summary of trends derived for Wellington to provide Wellington's final weighted mean inverted barometer response...210
Table 9.3: Summary of trends derived for Lyttelton to provide Lyttelton's final weighted mean inverted barometer response...211
Table 9.4: Summary of trends derived for Dunedin to provide Dunedin's final weighted mean inverted barometer response 212
Table 9.5: Derived harmonic constituents for Auckland using hourly sea level measurements from throughout 2003...214
Table 9.6: Derived harmonic constituents for Auckland using hourly sea level measurements from throughout 2004...216
Table 9.7: Derived harmonic constituents for Wellington using hourly sea level measurements from throughout 2004...218
Table 9.8: Derived harmonic constituents for Wellington using hourly sea level measurements from throughout 2007...220
Table 9.9: Derived harmonic constituents for Lyttelton using hourly sea level measurements from throughout 2003...222
Table 9.10: Derived harmonic constituents for Lyttelton using hourly sea level measurements from throughout 2005...224
Table 9.11: Derived harmonic constituents for Dunedin using hourly sea level measurements from throughout 2000...226
Table 9.12: Derived harmonic constituents for Dunedin using hourly sea level measurements from throughout 2001...228
Table 9.13: Derived harmonic constituents for Dunedin using hourly sea level measurements from throughout 2002...230
Table 9.14: Derived harmonic constituents for Dunedin using hourly sea level measurements from throughout 2003...232
Table 9.15: Derived harmonic constituents for Dunedin using hourly sea level measurements from throughout 2004...234

List of Abbreviations

CI	Confidence interval
ENSO	El Nińo-Southern Oscillation
GIA	Glacial isostatic adjustment
(c)GPS	(continuous) Global Positioning System
HADSLP	Hadley Centre sea level pressure dataset
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
PDO	Pacific Decadal Oscillation
mbar	millibars
mm	millimetres
SLPR2	Sea Level Data Processing On IBM-PC Compatible Computers Version 3.0
TOPEX/Poseidon	Topography Experiment/Positioning Ocean Sea Earth and Ice Dynamics and Orbiting Navigator

1 Introduction

Of growing interest in society today is the quantification of the relative rates of sea level rise in low lying, populated coastal areas. The height of sea level is relevant to many infrastructural aspects of current day societies. The potential of an acceleration in the rate of sea level rise has been a point of major concern for environmentalists and climatologists for some years now (e.g., Holgate and Woodworth, 2004; Church and White, 2006).

The identification of the rate of local sea level rise, whether linear or accelerating, is essential for all coastal or low-lying authorities in order to establish an 'early warning' for what must be accommodated in the future (Woodworth, 1990).

A significant rise in global sea levels is predicted to impact areas around the world with varying levels of severity. Some of the effects that have been identified by the Intergovernmental Panel on Climate Change (2007) include:

- Coastal erosion, which is predicted to increase in both scale and rate,
- Increasing risk to coastal developments and populations,
- Vital infrastructure, settlements, and facilities that support the livelihood of island and low-lying communities are increasingly threatened with increased high tides coinciding with extreme weather events. The numbers affected will be largest in the densely populated low-lying areas of Asia and Africa, while low-lying small islands are also extremely vulnerable. The cost of adaptation for these low-lying coastal areas with large populations could exceed 10% of the local country's gross domestic product. Options for mitigation of these effects are limited; costs for coastal protection must be sized up against costs of land-use, population, and infrastructure relocation, and
- Fresh water supply availability may be severely compromised due to saltwater intrusion into freshwater water tables. This will affect drinking water supply, as well as water supply for irrigation purposes, which may lead to a food shortage crisis.

Due to the obvious inability to stop global sea level rise, mitigation measures are being considered and applied wherever possible to minimise the potentially devastating effects that will be caused by the increasing height of sea level.

Mitigation measures may be considered and implemented with intended functions and lifespans considered relative to the projected rate of sea level rise. Similarly, the rate of sea level rise must be considered for the development or maintenance of essential infrastructural components of any society, namely drainage and freshwater systems, to ensure that the height of sea level will not impair its functionality within its projected lifespan.

1.1 Purpose of this study

This study sets out to investigate if there is a detectable acceleration in the rate of sea level rise around the New Zealand coastline. The investigation utilises New Zealand's long-term sea level records from the tide gauge stations located in Auckland (1899), Wellington (1981), Lyttelton (1901) and Dunedin (1899). There are a number of methodologies that can be used to derive trends in the relative rate of sea level rise (Barnett, 1984), some of which provide significantly differing results.

Other studies investigating the presence of an acceleration in the rate of global average sea level rise have been conducted (e.g., Church and White, 2006). The study conducted by Church and White (2006) utilised tide gauge records as well as short-term Topography Experiment/Positioning Ocean Sea Earth and Ice Dynamics and Orbiting Navigator (TOPEX/Poseidon) satellite altimetry data. Due to the long-term nature of sea level change, long-term records are considered preferable, if not essential, for the accurate derivation of the sea level's behaviour over time (Douglas, 1991, 1992).

In conducting the study outlined in this thesis, meteorological forces and their influences on the height of sea level are investigated. Of particular interest in this study is the effect caused by atmospheric pressure changes in the form of inverted barometer effect. For the purpose of reducing the overall variability of the sea level records from the various tide gauges, a correction for the influence of these atmospheric pressure changes is investigated and tested.

The presence of decadal and interdecadal signals within the sea level records are of great significance to this form of study as these signals may cause biases in derived trends. This study sets out to investigate if there are any such signals that are present in the individual sets of sea level records, to identify the possible drivers of these signals, and to quantify their effects on the respective sea level datasets.

1.2 Significance of this study

As noted earlier, the rise in global sea level can generate significant societal, ecological, and economic hazards concerning the coastal environment. In order to be able to investigate and apply any mitigation measures for these hazards, a precise estimate of the rate of relative sea level rise is required (Mazzotti *et al.*, 2008). The presence of an acceleration in the rate of sea level rise will exacerbate the urgency relating to the impending threat.

TOPEX/Poseidon records from January 1993 until August 2010 indicate that the global average sea level has been rising by around 3.2 ± 0.4 millimetres per year over that period (White, 2010). This suggests that the rate of sea level rise has increased or is increasing with time. However, this behaviour must be isolated from periodic tendencies that may cause increases, and then decreases, in the apparent rate of sea level rise.

A similar study carried out by Church and White (2006) combined tidal records with the TOPEX/Poseidon satellite altimetry data from 1993 until 2004. This study suggests that there is an acceleration in the rate of global average sea level rise as their results indicated an acceleration of 0.013 ± 0.006 mm/yr² between 1870 and 2004. An acceleration of this magnitude will cause sea level to be between 0.60 metres and 1.63 metres above its current level by 2100.

Adaptation measures can be utilised to potentially reduce vulnerability, both in the short and long-term. Societies around the globe have a long history of adaption and reducing their vulnerability to climatic influences such as floods, droughts, and storms. The Netherlands have been adapting to its vulnerability to sea level with water management and water defence since time immemorial. Mounds, dykes, windmills, canals with locks and sluices, the Delta Works and the Afsluitdijk, were all created as a means to confine the rising waters. However, more recently the Netherlands have realised that coexisting with the water is a sustainable option. Water management there has changed accordingly with a movement towards floating cities, seawater inlets, and freshwater basins combined with nature reserves (Peel, 2009).

Adaptation options are available, but more extensive adaptation than is currently occurring is necessary to reduce vulnerability to sea level rise, especially in the event that the sea level rise rate is increasing. There are limitations and significant costs associated with this that are not yet fully comprehended. Local planning initiatives such as coastal defence and disaster risk reduction strategies are being applied as adaptation to this impending future begins (Intergovernmental Panel on Climate Change, 2007). Numerous regional councils and territorial local authorities now have planning procedures that explicitly require sea level rise to be incorporated when designing coastal developments (Bell *et al.*, 2000).

Information relating to the projected future heights of sea level is necessary for local bodies to be able to take appropriate mitigation measures considering projected time frames. The information obtained from this study may be utilised to aid local bodies in the development of suitable mitigation methods that may be realised within the predicted available time intervals.

This study is not intended to identify the causes of sea level rise, nor quantify their respective contributions.

1.3 Structure of this study

There are numerous issues that must be considered in this form of study to ensure that the most representative results of long term sea level behaviours are obtained. Chapter 2 of this paper discusses some of the most relevant issues and their relevance to this study. The issues include:

- The nature of mean sea level and its variability,
- A review of the evidence pertaining to the historical and present-day trends in sea level rise, and
- A review of the non-tidal factors that influence the relative height of sea level at any given tide gauge, including vertical deformation, meteorological drivers (namely atmospheric pressure and temperature changes), the physical properties of the water mass, and long-term signals within the sea level records.

To conduct this study, long-term sea level records were required from New Zealand's four reliable long-term tide gauge stations. The earliest records available extend from 1891 onwards. Chapter 3 documents the sources of the sea level datasets, and details the maintenance records associated with each station to maintain the tide gauges' vertical positions throughout their respective recording periods. The use of the annual mean sea level records in preference to monthly mean sea levels is justified in this chapter, and the standard deviations associated with the annual mean sea level records are also explained.

Chapter 4 details the methodology used to carry out this study. This investigation utilised statistical confidence intervals to establish the statistical significance of the results obtained. Linear trend estimates were required for some of the investigations, and these estimates were improved upon as further information became available. An intensive analysis methodology is utilised to investigate the inverted barometer effect, and the necessary datasets were pursued to allow a correction to the annual mean sea levels for the influence of these pressure variations to be applied. Chapter 4 also details the trend investigations incorporated into Least Squares analyses to identify the parameters of signals within the records simultaneously with the trend of the change in sea level over time.

The Least Squares and Fast Fourier Transform analyses utilised in this study are detailed with the results in Chapter 5. This presents the results of the investigations into the local influences of the inverted barometer effect, and their relevant application in corrections to the mean sea level records. The signals identified using the Fast Fourier Transform analyses are presented, and the results obtained from their incorporation into the trend investigations are summarised with the accelerating trend parameters and their statistical significance.

The implications of the results obtained from this study are discussed in Chapter 6. The assumptions associated with the inverted barometer effect and vertical deformation rates are detailed, and their implications examined.

Finally, Chapter 7 summarises the results obtained in this study and their implications. Future research relating to the inverted barometer effect correction and the isolation of the drivers of the long-term signals present within the sea level records is recommended in this chapter. Further research into the presence of an acceleration in the rate of sea level rise is also encouraged for when further evidence is available.

2 Literature Review

Sea level is a dynamic, constantly changing surface that exhibits extreme variability. The mean height of the sea is used to define a datum relative to which the levels of terrestrial observations can be established. Mean sea levels at any given station will always exhibit variations that are caused by oceanographical, meteorological, and terrestrial sources, superimposed over the measurements' noise (Rossiter, 1972). The mean values are also influenced by the length and completeness of the records used to obtain each mean. Due to the relatively short timescales of many of these influences on sea level, it is convenient to aggregate the sea level data into mean values over some defined period of time. By doing so, it is anticipated that many of the short periodic influences will be averaged while maintaining the integrity of any longer trends. Many studies of long-term sea level changes have used monthly mean sea levels from the Permanent Service for Mean Sea Level database (e.g., Church and White, 2006; Church *et al.*, 2004; Mazzotti *et al.*, 2008), while others have used annual mean sea levels (e.g., Hannah, 1990, 2004; Woodworth *et al.*, 2009).

The 'mean' level of the sea's surface used to be considered as a stable equipotential surface; a fixed surface relative to dry land. Initially, mean sea level was established using 18.613 years of continuous tidal records from an individual station to derive the mean sea level for that area. This duration of records was required as the nodal tide with its period of 18.613 years, caused by the regression of the moon's node, is the longest signal affecting the Earth's tides (Pugh, 1987). These levels were assumed to define the same stable equipotential surface. The only recognised variability in the datum was due to seismic events (Hannah, 1990).

Advances in technology provided evidence that the assumption of stability and uniformity required revision. For example, long-term tidal records demonstrate an increasing trend over time, indicating that the datum is not stable as was once assumed. Additionally, satellite altimetry measurements provided data that revealed a long-term component of sea surface topography that varies between the northern and southern parts of New Zealand (Rapp, 1982).

The aim of this study is to examine New Zealand's long-term sea level records to see if any acceleration can be detected in the well known sea level rise trend. Due to the limited number of stations being considered, the sample size is significantly smaller than those used in similar studies which can be perceived as both an advantage and a disadvantage. By having a smaller dataset, there is greater provision for more intensive local investigations, and the ability to have a more intimate understanding of the histories and natures of the tide gauges being considered. This may benefit the investigations into the influences discussed in this chapter, giving the optimum obtainable result.

This chapter begins by providing details pertaining to the nature of sea level. The areas considered include:

- A review of the factors that influence the annual and monthly sea levels,
- Historic sea level trends, and
- Contributors to sea level rise.

The chapter then proceeds to discuss the various factors that influence the height of sea level relative to the tide gauges that monitor it. These factors include:

- Tectonic deformation,
- Meteorological drivers; namely thermal expansion and the inverted barometer effect, and
- Decadal and interdecadal periodic signals.

2.1 The nature of mean sea level

The sea's instantaneous height is determined, inter alia, by the distribution of densities and currents. Any annual anomalies due to atmospheric pressure, wind-stress, precipitation, and temperature variations must be reflected in the corresponding anomalies in sea level as the Earth's oceans flow to attempt to maintain equilibrium (Rossiter, 1972). The sea's level is also influenced by numerous signals of various amplitudes and frequencies. These influences combine to create complex tidal patterns that contribute to overall variations in the sea's calculated mean level.

Sea level records may be contaminated by local and regional effects including vertical deformation, land settlement or subsidence, sedimentation, oceanic currents, port modifications, and differing regional responses to seasonal weather conditions as well as the El Nińo phenomena. These various factors appear in tidal records and obscure the true tendencies of the sea level over time, causing uncertainties in the derivation of relative and absolute sea level rise (Goring and Bell, 2001).

2.1.1 A review of the factors that influence monthly and annual mean sea levels

The dynamic nature of the sea is caused by the combination of signals and drivers that act upon it. The frequencies of these signals and the magnitudes of their influences can cause significant variations, and potentially errors, in the derived mean levels. Tide gauges are designed to filter out high frequency influences, namely wind-waves and swells. The water level at individual tide gauges is subject to many influences over a variety of timescales, ranging from a few minutes, to decades (Mazzotti *et al.*, 2008). Monthly mean sea levels effectively filter out signals with periods shorter than around one week. This includes the main diurnal and semidiurnal constituents. However, signals with longer periods ranging from fortnightly, to decadal, remain present in the monthly mean sea levels (Mazzotti *et al.*, 2008).

Most tidal signals are filtered out through using annual mean sea levels. Long period spectral lines, such as those associated with the 18.613 and 8.847 year tidal constituents (Hannah, 1990), will be present in the annual mean sea levels (Munk and MacDonald, 1960). Signals from processes such as El Nińo-Southern Oscillation and Pacific Decadal Oscillation with periods ranging from annual to multidecadal in length are also evident in most series. These influences can reach amplitudes of 100 to 150 millimetres (Mazzotti *et al.,* 2008).

Signals with periods in the decadal to interdecadal scale can significantly bias long-term trend estimates if their effect is not removed, or suitably accommodated (Mazzotti *et al.*, 2008). Long-term signals, namely those that have periods in the order of several decades, may be present in lengthy sea level records (Sturges, 1987), and their presence and associated influences may only be identified by continuing to measure sea level to extend the length of the records.

2.1.2 A review of historical sea level trends

The absolute rate of sea level rise around the world cannot be directly ascertained using tide gauge measurements due to the existence of localised vertical land movements. The average values derived for global sea level rise between 1900 and 2000 generally fall within the range of one to two millimetres per year (Intergovernmental Panel on Climate Change, 2007). It is important to note that the range for the rate of rise in sea level is a consensus range considering the numerous studies carried out by various authors whilst generally using the same data set provided by the Permanent Service for Mean Sea Level (Woodworth, 2006).

The 'absolute' rate of sea level rise reflects the true rate of the increase in volume of the Earth's oceans relative to the centre of the Earth. The 'relative' rate of sea level rise is that which is measured with a fixed device whose vertical position may be non-stationary. Such movements are the result of active tectonics, glacial isostatic adjustment, or tide gauge instability.

The differing results can be caused by different analysis methods, with two main areas of variation:

- The global sea level dataset is compiled of records from numerous locations that are unevenly distributed around the globe. Consequently, authors will obtain differing results depending on which gauges they wish to include in their analysis. Obviously this results in different spatial distributions, and hence the spatial variability due to decadal and interdecadal trends will be inconsistent.

- Authors apply different corrections for vertical deformation at each of the tide gauge stations (Woodworth, 2006). Generally the latest glacial isostatic adjustment model, discussed in Section 2.2.1.2, has been applied, but studies by Peltier (e.g., 1995, 2004) have revealed significantly different results between these models, thereby casting doubt on their applicability.

The most recent estimate for absolute sea level rise used by the Intergovernmental Panel on Climate Change (IPCC) is 1.8 ± 0.5 millimetres per year for the period from 1961 until 2003 (Bindoff *et al.*, 2007). This estimate for absolute sea level change is based on the findings from multiple studies carried out using relative sea level data spanning different periods of the twentieth century in numerous locations around the globe, which have been corrected for vertical land movement using postglacial rebound models (e.g., Peltier, 2001).

A global average rate of sea level rise of 3.1 ± 0.7 millimetres per year has been calculated between 1993 and 2003 (Intergovernmental Panel on Climate Change, 2007), and 3.2 ± 0.4 millimetres per year between 1993 and 2010 (White, 2010). However, at this stage it is unclear if this is due to an increased rate of rise, and accelerating rate, or a reflection of decadal variation (Intergovernmental Panel on Climate Change, 2007). Church *et al.* (2001) and Lambeck (2002) support the idea of regional variations in sea level trends. Regional variations may be explained by climate change (whether natural or anthropogenic) as air-sea fluxes of heat, momentum, and freshwater change (Gregory *et al.*, 2001).

The IPCC is an independent panel that reviews published information relating to climate change parameters, including sea level rise trends, to obtain the best evidence and information relating to climate change and its impacts.

In 1990, 1995, 2001, and 2007 the Intergovernmental Panel on Climate Change independently reviewed the published information outlining evidence of changing global temperature trends within sea level records. Their findings indicate that global sea level had risen by ten to twenty centimetres over the past century, with predictions indicating a greater rate of rise by 2100 (Intergovernmental Panel on Climate Change, 1990, 1995, 2001, 2007). The evidence for this was sourced from the analysis of long-term measurements of mean sea level. A high quality tide gauge was found to be able to determine a rate of rise with a standard error of 0.5 millimetres per year if thirty years of data was available (Woodworth *et al*., 1999). However, it is impossible to distinguish vertical land movement from sea level rise using only sea level data. Many of the studies used by the IPCC to establish the global rate of sea level rise have incorporated vertical land movement by using a glacial isostatic adjustment (GIA) model. Unfortunately these models do not account for all of the vertical land movements occurring around the globe, and they do not accommodate active tectonics. GIA models are discussed in more detail in Section 2.2.1.2.

The IPCC utilises historic sea level records from around the globe to aid in the derivation of the rate of sea level rise around the globe.

Geological evidence providing information for the Earth's historical rate of sea level rise, beginning around 24,000 years ago, is detailed in this section. The latest evidence for the current, potentially accelerating, rate of sea level rise is considered later in this section.

2.1.2.1 Evidence of historical sea level trend

Although the rate of sea level rise during the 20th century is believed to be approximately 1.8 ± 0.5 millimetres per year, there is geological evidence that suggests that the historical rate of sea level rise was different to this.

The relative sea level changes during the Quaternary period are generally considered to have been influenced by compounding drivers over varying temporal and spatial timescales. The most significant contributor to sea level change is believed to have been the gradual formation and deformation of continental ice sheets by cyclic glacial-interglacial periods. These periods were resultant of the Earth's orbital variations. It is estimated that the fluctuations in sea level caused by these cycles were in the order of 100 metres in magnitude, over a period of 100,000 years. These fluctuations were superimposed over the vertical movement of the land from both glacial isostatic adjustment and active tectonic processes, as well as the oceanic currents and the shorter-term climate variations that influences the height of sea level (Paulik, 2010).

After the last glacial maximum, eustatic sea level rose rapidly as global ice volumes decreased. Post-glacial eustatic sea level increased from -125 ± 5 metres below current sea level approximately 20,000 to 25,000 years ago, to near present levels about six to seven thousand years ago (Figure 2.1).

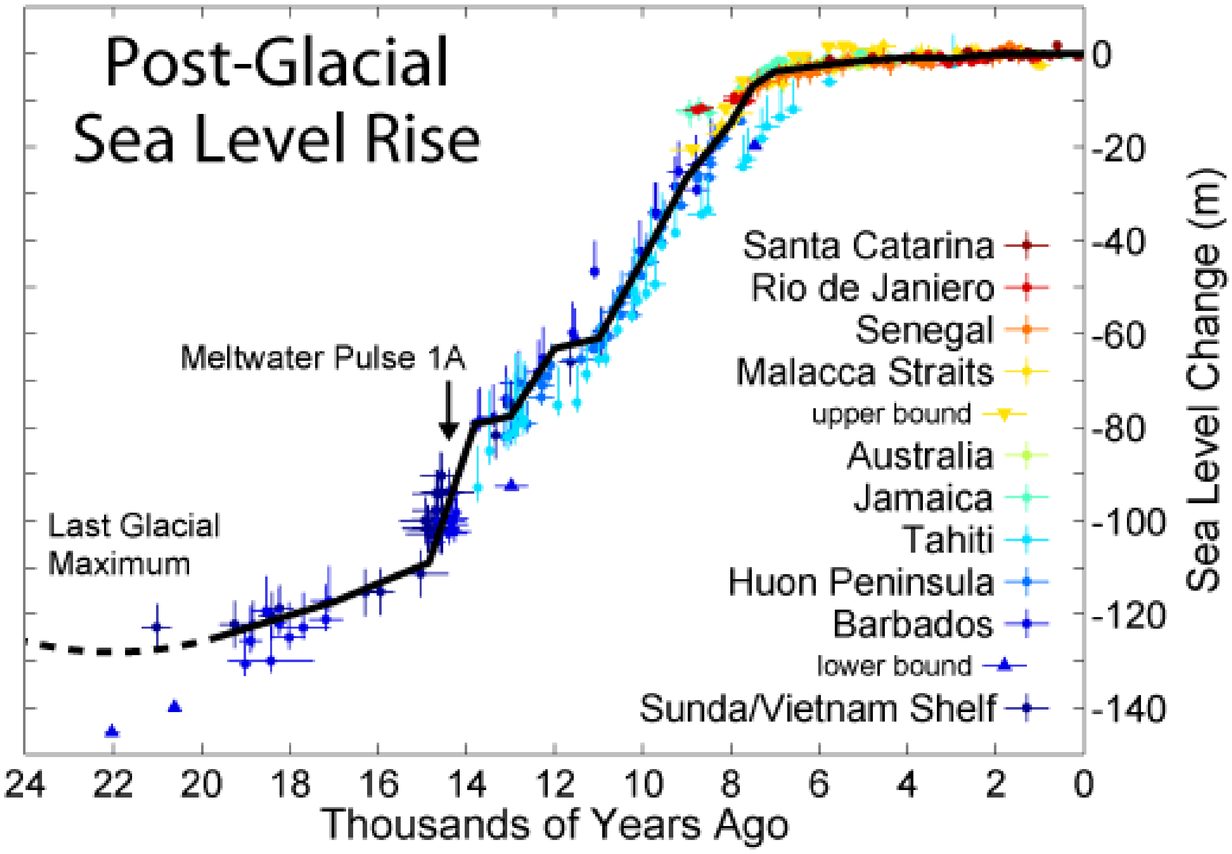

Figure 2.1: The general eustatic sea level trend since the last glacial maximum (Fleming *et al*., 1998; Milne *et al*., 2005)

Gibb (1986) developed a Holocene sea level change trend for New Zealand that demonstrates the general change in trend of sea level rise during the Holocene period (Figure 2.2). Eustatic sea level rose from 33.5 ± 2.5 metres below present level 10,000 years ago, to near current sea level about 6,500 years ago. The sea level initially rose rapidly, with stand-stills occurring around 24 ± 2.9 metres below present level from 9,200 until 8,400 years ago, and again at -9.0 ± 2.8 metres from 7,500 until 7,300 years ago (Paulik, 2010). Subsequently, eustatic sea level oscillations of up to one metre above current sea level occurred from 5,500 to 3,000 years ago along the New Zealand coast (Gibb, 1986).

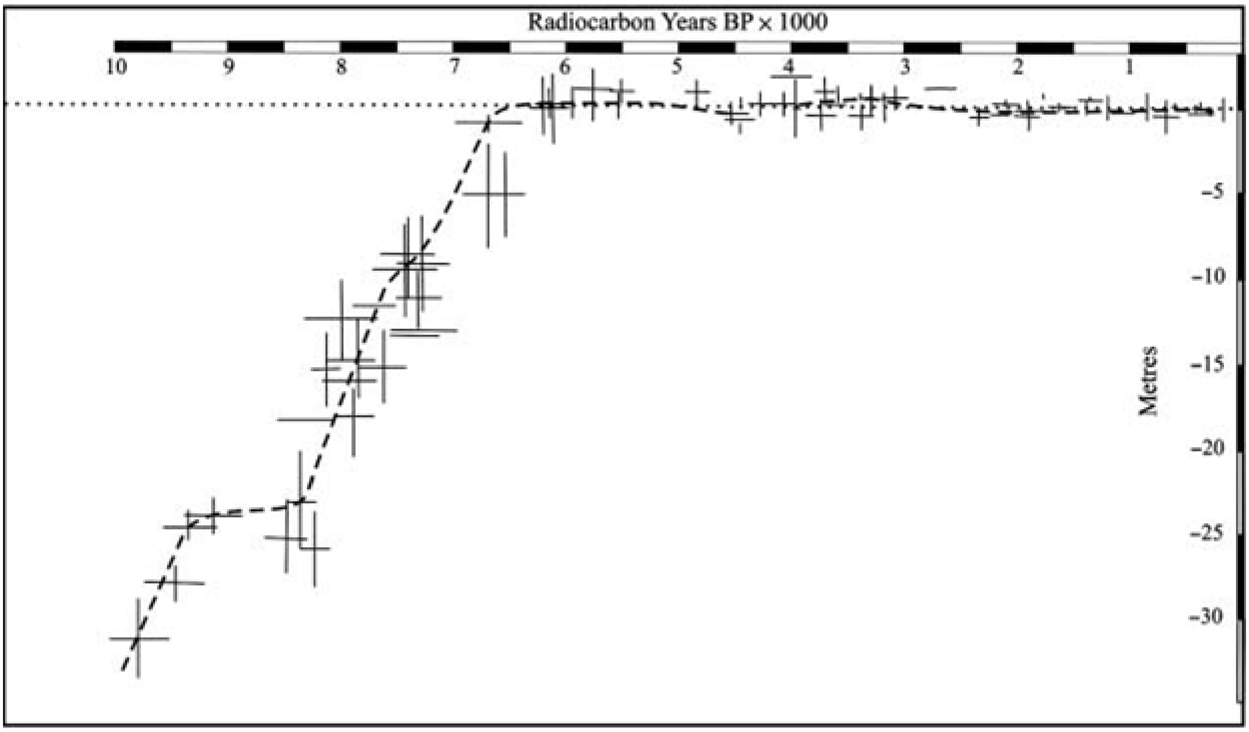

Figure 2.2: The Holocene sea level curve [(Gibb, 1986) *cited in Kennedy, 2008*]

Gehrels *et al*. (2008) utilised geological evidence to investigate the historical trends in sea level rise to further project the trend beyond the historical tidal data available. Core samples from salt marshes at four locations in southern New Zealand were collected between April 2003 and December 2006. The sediments were analysed for foraminiferal content to detect evidence of sea level changes.

Salt-marsh surfaces are positioned roughly between mean high and extreme high water level, where sediments accumulate in the highest water events. Thick salt marsh sediment accumulations are created by rising sea level (Gehrels *et al*., 2008). Salt marsh accumulations in southern New Zealand are rarely thicker than 0.5 metres. This is a reflection of the length of time the water level remained close to its current level through the middle and late Holocene (Gibb, 1986).

The samples indicated that the sea level was rising at a relative rate of 0.3 ± 0.3 millimetres per year between 1500 AD and 1900 AD, and that during the twentieth century the rate of rise increased to 2.8 ± 0.5 millimetres per year. This is approximately in agreement with the instrumental records commencing in 1924 (Gehrels *et al*., 2008), illustrated in Figure 2.3.

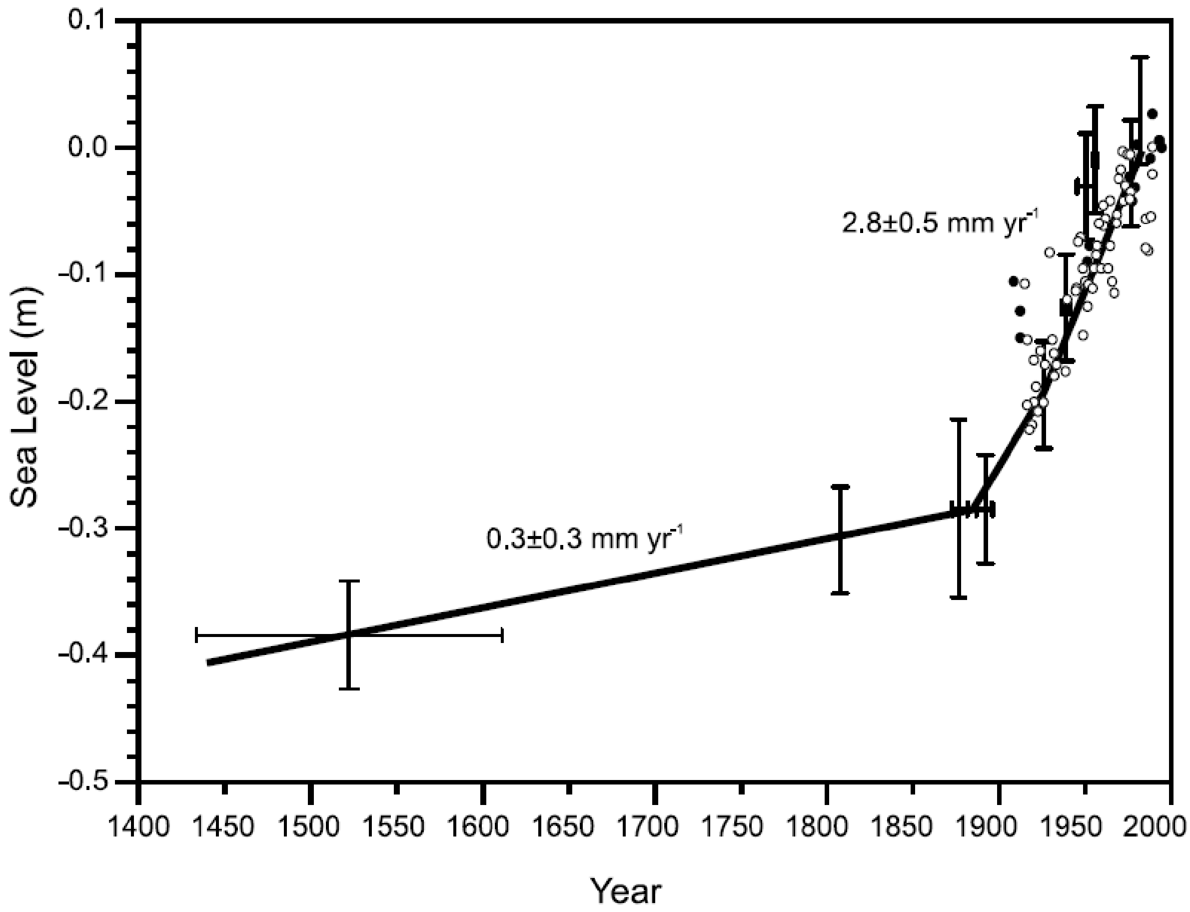

Figure 2.3: Reconstructed sea level changes at Pounawea, southern New Zealand, since 1500 AD. Also shown are Lyttelton tidal records (open dots) and Bluff (black dots) (Gehrels *et al.*, 2008)

Since the last glacial maximum approximately 18,000 years ago, global mean sea level has risen approximately one hundred and twenty metres, but the rate of rise has not been linear. After the Holocene climate optimum, a warm period between 9,000 and 5,000 years ago, the rate of sea level rise has been minimal compared to that during the ten millennia prior (Maul, 1993). The large reduction in land-based ice associated with this caused a massive reduction in earth loading, which has resulted in ongoing vertical movement of the earth's crust and sea surface in response that is known as glacial isostatic adjustment (e.g., Milne *et al.*, 2001). Wanless *et al.* (1988) found that sea level rise in Florida was approximately 2.5 millimetres per year in the Holocene climate optimum period, approximately 0.4 millimetres per year since then, and about 2.3 millimetres per year since the commencement of instrumental records. These figures can only be approximations as vertical deformation rates over these periods cannot be separated from the apparent sea level rise.

Without additional information about the effects of climate change, it is not yet possible to explain if the increased rate of sea level rise is due to recent, anthropogenic change, as sea levels over the past several thousand years may have oscillated on time-scales of one hundred to one thousand years by up to several decimetres (Church *et al.*, 2001).

Geological evidence suggests that the rate of sea level rise has either accelerated or changed in rate since the Holocene climate optimum period. The current rate of rise has been attributed to numerous contributing sources, whose respective contributions may have increased in the Earth's more recent history. Satellite altimetry has been utilised by some analysts to aid in the identification of the current rate of sea level rise.

2.1.2.2 Satellite altimetry in similar investigations

Satellite radar altimeters transmit microwave radiation from the satellite to the sea's surface that is then partially reflected back to the satellite. Provided that the position of the satellite in its orbit is well known, measurement of the time delay for the signal to return can then be used to derive the height of the surface. To obtain the best estimates of sea level rise around the globe, extensive quantities of data is required. This data ideally should be well distributed spatially to provide records of the sea level trends in all locations so that anomalies may be identified and better understood. Furthermore, for the purposes of finding an average trend in the sea level's behaviour over a given period, equal spatial distribution should help to cancel out the regional variations. The advent of satellite altimetry has provided another means of measuring the height of sea level, but unlike conventional sea level measurements, satellite altimetry can measure the height of sea level on a global scale. The launch of the TOPEX/Poseidon mission in 1992 provided an additional data source, believed to be of suitable accuracy (below ten centimetre level) to be suitable for the monitoring of ocean dynamics and sea level change (Cazenave and Llovel, 2010). The variance of the heights measured by satellite altimetry can be easily overestimated, but it is unlikely that these measurements have better standard deviations than those attained by tide gauges.

Using worldwide historic tide gauge records, derived global sea level rise lies between one and two millimetres per year during the past one hundred years (Church *et al*., 2004). Global radar altimetry data over the past fifteen years suggests this rate is closer to three millimetres per year (Cabanes *et al*., 2001; Nerem and Mitchum, 2002; Leuliette *et al*., 2004). The latest sea level rise budget that has been derived using satellite altimetry data also suggests a rate of approximately three millimetres per year between 2003 and 2008 (Cazenave *et al*., 2009). This potentially may be attributed to an acceleration or change in the rate of sea level rise causing this higher rate of rise today. Fifteen years of satellite altimetry measurements may not be long enough in duration to be able to establish long-term trends in sea level rise as the sea level variations contain interdecadal signals (e.g., Douglas, 2001; Cazenave and Nerem, 2004). However, with complete global coverage, especially around the Equator, these signals may cancel out.

Wöppelmann *et al.* (2007) stated that the few years of altimetry records that Church *et al.* (2004) used for the study into the regional distribution in sea level rise is insufficient. The data span used is "*obviously*" too short to calculate a trend for the global rise in sea level on a century timescale.

The study carried out by Holgate and Woodworth (2004) using tidal data from 1948 until 2002 and the available satellite altimetry records found a significantly increased rate of sea level rise in the late 1990s, consistent with the other similar studies, with the lowest rate of rise in the 1980s. This increased rate could be periodic, and hence could be associated with a decadal or interdecadal trend that may be apparent in periods of significant acceleration, as well as periods of significant deceleration. However, Watson (2011-b) noted that "*Although average decadal rates of rise in relative ocean water levels are clearly high during the 1990s, they are not remarkable or unusual in the context of the historical record available for each site over the course of the 20th century. Similar conclusions have been drawn by Holgate (2007) in examining global data and by Hannah (2004) examining long-term sea level records for New Zealand".*

Church *et al.* (2004) combined 1993 to 2001 TOPEX/Poseidon altimeter data with 1950 to 2000 sea level data to generate a global model for absolute sea level rise. Spatial tide gauge coverage at the global scale is poor due to their sporadic locations combined with the large sparse areas of the Earth's oceans. Collocation analysis was applied to combine both the short-term altimeter data and long-term tidal data to vastly improve the global model to obtain an overall average rate of sea level rise of 1.8 ± 0.3 millimetres per year (Church *et al.,* 2004).

The TOPEX/Poseidon altimeter data is collected as part of the Ocean Topography Experiment mission. This mission was a collaboration between National Aeronautics and Space Administration and the Centre National d'Etudes Spatiales of France to obtain sea-surface height measurements around the globe using radar altimetry (National Aeronautics and Space Administration, 1992).

Church and White (2006) combined tidal records dating back until 1870 with the TOPEX/Poseidon altimeter data from 1993 until 2004 to investigate if there is an acceleration in the trend in sea level rise. They found a significant acceleration of sea level rise of 0.013 ± 0.006 mm/yr^2 between 1870 and 2004. The duration of TOPEX/Poseidon altimeter data available by 2004 still failed to fulfil the length of records Wöppelmann *et al.* (2007) believed necessary for deriving a linear trend. Further records are expected to be necessary for studies quantifying a possible acceleration parameter.

Wöppelmann *et al*. (2007) argue that several additional decades of measurements with TOPEX/Poseidon altimetry are necessary to attain definitive conclusions on the low-frequency sea level changes, such as those caused by decadal and interdecadal signals discussed in Section 2.2.4. This length of data must be available before true trends in sea level change can be identified with statistically significant results. The standard deviations of altimetry measurements must be confidently established in order to obtain a trend with a confidence range that reflects the quality of the records used.

The suitability and variances of satellite altimetry measurements must be carefully considered when investigating sea levels for significant trends. The presence of signals within the datasets and meteorological effects combine to cause significant variations in the annual mean sea levels, and hence may affect derived trends. Potential weaknesses associated with satellite altimetry need to be thoroughly understood and accommodated in investigative studies into the changing height of global mean sea level.

Altimetry data is collected at pre-determined grid points once every ten days, with significant post processing of the datasets to correct for systematic errors, including instrumental drift and water vapour. In comparison, tide gauges provide orders of magnitude greater data density, but only for a singular location (Watson, 2011-a).

2.1.3 Contributors to sea level rise

The enigma of sea level rise is the issue relating to identifying the exact cause, or causes, of the gradual increase in mean sea level we have been detecting over the past hundred years (Woodworth, 2006). Melting of parts of ice sheets on polar land combined with the other contributors could potentially cause metres of sea level rise (Intergovernmental Panel on Climate Change, 2007). The recent increase in the rate at which glaciers are melting is believed to have increased its contribution to global sea level rise (Cazenave and Llovel, 2010).

Freshwater is stored in various reservoirs such as rivers and lakes, as well as in ice sheets and glaciers. Land waters are continuously exchanged between the atmosphere and oceans through evaporation, surface and ground runoff, and transpiration of the vegetation. Such freshwater exchanges are an integral part of the global climate system with links and feedbacks influencing surface energy and moisture fluxes between land-water, the atmosphere, and the ocean salinity. Anomalies in salinity content and temperature in the ocean water column change the water's density, which further contributes to sea level variations. If ocean salt content is assumed to remain constant, additional freshwater in the oceans due to increased freshwater supply, namely from melting glaciers and ice sheets, modifies the ocean's salinity. If global records of ocean salinity were available it would be possible to deduce global salinity change, and through that, the rate of global freshwater addition (Cazenave and Llovel, 2010), assuming that the total salt content remains constant.

Changes in the ocean's heat content contribute to sea level change, and this is subject to significant decadal variability (Levitus *et al.*, 2005). Global climate simulations by the Goddard Institute for Space Studies and parallel climate models by the National Centre for Atmospheric Research indicate that these causes are likely to be due to dynamical features, rather than climate forcing (Hansen *et al.*, 2002; Barnett *et al.*, 2001). Interdecadal and multidecadal variability in sea level is most likely connected to the variability of heat transported by the thermohaline circulation; driven by water movement caused by relative temperature and salinity differences (Deser and Blackmon, 1993; Rajagopalan *et al.*, 1998; Rodwell *et al.*, 1999). An increase in the thermal structure of the ocean causes thermal expansion (Knutti and Stocker, 2000).

Water's volume increases as its temperature increases. An increasing global temperature trend over time would cause increases in the Earth's ocean's volume in the order of tens of millimetres per century. As thermal expansion is considered to be a contributor to sea level rise it should not be corrected for in the annual mean sea level datasets. The effects of thermal expansion, and its trend over time, are not necessarily constant. Therefore, components of a changing trend in sea level rise may also be removed when removing this systematic effect from sea level records.

The contributions of freshwater from glacial and land ice melt, combined with the Earth's changing temperature trend, creates a compounding effect that further increases sea level. Freshwater changes the ocean's salinity content, and therefore the volume of the water changes due to the temperature of the water; assuming the atmospheric pressure remains constant. As the temperature of the oceans slowly increases, the water's volume increase is greater than it would with a higher salinity content, and hence higher density.

One of the main periods of sustained rise in global air and sea surface temperatures in the twentieth century occurred between 1920 and 1930 (Jones *et al.*, 2001), which was shortly followed by a high rate of global sea level rise in the 1940s, coinciding with increased glacier melt. Church and White (2006) argue that periods of increased rates of warming would precede an increased rate in sea level rise caused by thermal expansion. Rahmstorf (2007) attempted to derive the relationship between sea level rise and temperature change by assuming a linear relationship between them. This assumption implies that there are no other contributors to sea level change or rise, including the inverted barometer effect, and glacial and ice cap melt. Rahmstorf's analysis has been criticized by Holgate (2007).

Chao *et al*. (2008) suggest that the change in the quantity of impounded water on land could have caused a change in sea level, which is another intriguing possible anthropogenic influence on global sea levels. The impoundment of water on land is believed to have reduced the height of sea level to date by about thirty millimetres, removing about 0.55 millimetres per year over the past half century (Chao *et al*., 2008).

Conrad and Hager (1997), Tamisiea *et al.* (2001), and Mitrovica *el al*. (2001) theorise that the rise in sea level at any given location is a function of the location's distance from the melting glaciers and ice masses. Church *et al.*(2004) further support the case for spatially varying absolute sea level rates through their use of satellite altimetry data. This theory goes against the natural assumption that the sea level is rising at the same rate at all locations around the globe. The rates of absolute sea level rise at the four stations considered in this study are likely to be the same due to the comparatively small geographical separation between the tide gauges used in this study, assuming that there are no other influences causing relative differences. An acceleration in absolute sea level rise is similarly assumed to be identical for all four stations, assuming there are no active tectonics acting on any of the tide gauge stations. Further spatial variations may be caused by local periodic drivers, such as meteorological signals.

2.1.4 Mean sea level summary

A 'stable' height of mean sea level has traditionally been established through using 18.613 years of consecutive sea level observations to incorporate the full cycle of the Earth's gravitational interactions with the sun and the moon. However, longer records provide evidence that mean sea level is rising over time.

The rising sea level is currently being attributed to a combination of likely sources. The effects of sea level rise possibly may be reduced or minimised through first identifying the various drivers. The increasing sea level is likely to have major socio-economic impacts on many peoples, and may threaten lives and livelihoods, thereby providing incentives for governmental authorities to establish timeframes within which they may apply mitigating measures to minimise the impacts.

Furthermore, there is evidence that suggests that the current rate of sea level rise may be significantly different to the historical rate of rise.

Long-term tide gauge records show that there is an increasing trend in the sea's height that is superimposed on numerous signals that cause sea level variations. Historical evidence suggests that the rate at which sea level is rising today is far greater than it was prior to the twentieth century; although it has not been confidently established if the rate of sea level rise has accelerated since then. Alternatively, the rate of sea level rise may have been subject to a secular increase, driven by a sudden change in the nature of a sea level rise driver.

Vertical deformation is a common factor in all investigations into the rate of sea level rise that complicates the accurate identification of the rate at which sea level is rising as it causes the tide gauges to move relative to sea level, causing sea level rise to appear faster or slower than it truly is, depending on the nature of the movement.

2.2 A review of factors that influence monthly and annual mean sea levels

Sea level is universally acknowledged for its extreme variability as it responds to temporal forces and effects that may be non-repetitive, periodic or secular. While the height of sea level is varying constantly due to a variety of influences (see, for example, Table 2.1), the sea level also demonstrates a gradual increasing trend (see Section 2.1). The drivers shown in Table 2.1 and their corresponding approximate timescales over which they influence must be carefully considered when attempting to identify any trend in the rate of rise of sea level as they potentially may cause a bias in the result. Further to that, if the drivers are adequately understood, their influences may be able to be modelled and removed from the dataset to reduce its overall variability.

Spectrum of sea-level “drivers” and responses with timescales		
Driver	**Sea-level response**	**Timescale**
Glacial/Interglacial episodes	Long-term sea-level change	Centuries
Anthropogenic sea level change	Long-term sea-level change	Decades
Interdecadal Pacific Oscillation	Interdecadal oscillations	Decades
El Nińo-Southern Oscillation	Interannual oscillations	Years
Annual temperature cycle	Annual cycle	1 year
Changing atmospheric pressure	Inverted barometer	1 to 7 days
Wind stress	Set-up	1 to 7 days
Gravitational attraction of astronomical bodies	Tides	From 18.613 and 8.847 years, to 24, 12, 8, 6, and 3 hour periods
Chaotic interactions	Seiche	2 to 4 hours
Submarine earthquakes, avalanches and volcanoes	Tsunami	Minutes to 1 hour

Table 2.1: Spectrum of sea-level "drivers" and responses with timescales (Goring and Bell, 2001)

2.2.1 Tectonic deformation

Any vertical movement of a tide gauge relative to sea level distorts the apparent observed trend in sea level rise. The nature of this distortion is dependent on the nature of the vertical shifts; whether they are constant over time, regular, or irregular. Mitrovica *et al*. (2001) emphasised that sea level change may have significantly differing rates in different regions due to gravitational and loading effects. Local land movement in the vertical dimension due to tectonic or other influences can cause significant variation in calculated sea level trends when compared to other locations due to the rate at which the land, and hence also the tide gauge, is moving relative to the ocean’s mean level.

Vertical land motion can occur as a result of natural geological processes such as tectonics, or from anthropogenic causes such as ground water pumping or mining (Woodworth, 2006). Structures that tide gauges are attached to may also move vertically due to settling or subsidence. Without precise levelling records to maintain the integrity of gauges attached to such structures, this motion cannot be corrected and hence may incorrectly be associated with vertical deformation or sea level rise.

Earthquakes may also cause other phenomena that affect the height of sea level in the high frequency domain, namely tsunamis and seiches. Tsunamis are irregular waves caused by the sudden displacement of a large quantity of water. Seiches are standing waves that occur within enclosed or partially enclosed bodies of water, and they may be generated by irregular motions such as earthquakes, tsunamis, or meteorological influences, or may reflect regular waves such as tidal signals.

The determination of an acceleration in sea level rise is hindered by the same problems affecting the determination of a linear trend, with one important exception; vertical crustal movement (Douglas, 1992). Tidal records contain evidence of both the rise in sea level, as well as the vertical movement of the tide gauge relative to the sea level. In regions that do not experience irregular changes in land level due to plate tectonics, a linear vertical motion trend over time is assumed. Evidence for a quadratic trend in sea level rise, should such a trend exist, can be derived from the tidal records independent of the compounded linear trend component of sea level rise superimposed over the vertical deformation (Woodworth *et al.*, 2009). However, vertical deformation trends may not be constant.

Denys *et al.* (2010) used continuous Global Positioning System (cGPS) measurements to measure local relative vertical deformation rates at the four stations being considered in this study. The vertical deformation rates, illustrated in Figure 2.4, mostly show a consistent rate of vertical movement over time. However, the Wellington records suggest that the vertical deformation rate over time has been non-linear. This data cannot isolate whether the tide gauge itself was affected by irregular vertical movement, or the cGPS station that the vertical position is measured relative to.

Figure 2.4 illustrates the full extent of the cGPS measurements that are currently available. The trends in the vertical positions over time demonstrate that the tide gauges cannot be considered to be stationary relative to mean sea level. There is no way of confidently ascertaining from these records the nature of any changes to the respective tide gauges' vertical positions prior to the cGPS records commencing.

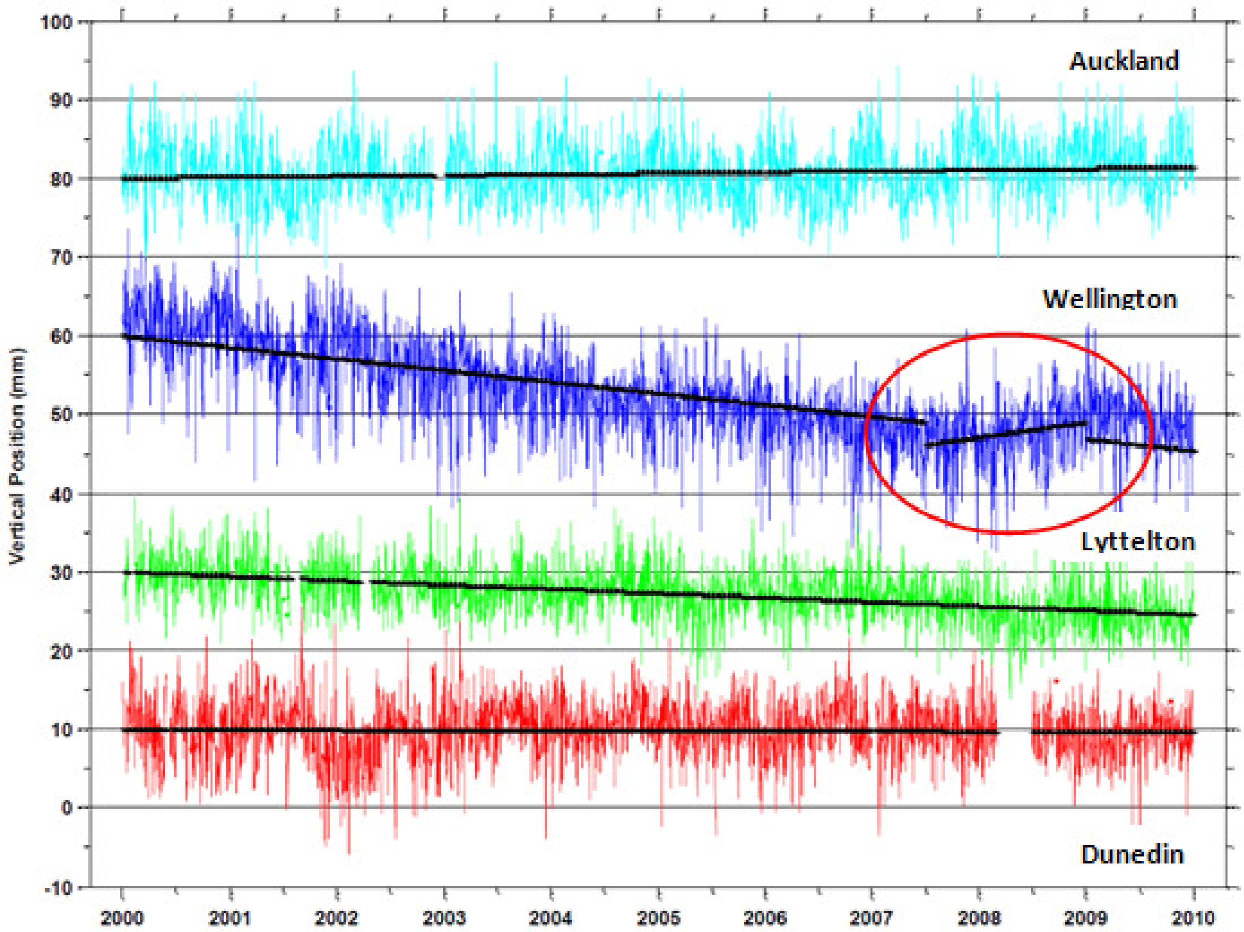

Figure 2.4: Preliminary relative change in vertical positions over time at the Auckland, Wellington, Lyttelton and Dunedin tide gauges (Denys *et al*., 2010)

In order to establish accurately the absolute rate of sea level rise, vertical land deformation must be known and appropriate corrections applied to the observed records. The rate of relative sea level rise, which is change in height of the sea relative to the level of the land, is the result of the combination of absolute sea level change, combined with local vertical motion relative to the centre of mass of the earth. The poor resolution of vertical deformation rates complicates the accurate derivation of relative and absolute sea level rates. The quantification of the rate of local sea level rise relative to the land is necessary for the management of coastal areas (Mazzotti *et al*., 2008).

Douglas (1997) argues that less than 25% of sea level rise rates exhibit consistent trends due to vertical crustal movement. Coherent records are those obtained from tide gauges located in areas absent of tectonic plate boundaries and associated collisions, and which were not subject to a large amount of ice-loading in the last glaciation (Douglas, 1997).

GPS measurements have now reached the level of precision required for validation or comparison of high-precision vertical velocity models such as glacial isostatic adjustment (GIA) models (e.g., Johansson *et al*., 2002; Nocquet *et al*., 2005; Rülke *et al*., 2008), elastic deformation models in active tectonic areas (e.g., Bergeot *et al*, 2009), and tidal measurements (Kuo *et al*., 2004).

Vertical deformation causes varying rates of sea level rise to be observed at different locations. This vertical movement is caused by the behaviour of the Earth's internal components and their influence on the Earth's continental and oceanic crusts. This section goes on to discuss the vertical uplift of the land due to the glacial isostatic adjustment, and lastly this section discusses the potential of biases in the sea level records due to irregular vertical land movements caused by active tectonics.

2.2.1.1 The structure of the Earth

The internal composition of the Earth and the interactions between the inner layers influences the form of the Earth's surface. Radiating outwards from the Earth's centre these internal layers include:

- solid inner core,
- a liquid outer core,
- the mantle that consists of the rigid and inflexible lower mantle,
- the asthenosphere,
- the lithosphere, and
- the Earth's crust.

The asthenosphere is relatively soft and ductile when compared with the characteristics of the lower mantle. This allows the asthenosphere to be able to flow under strain without fracturing. The Earth's crust is the rigid outermost layer whose thickness crust varies considerably. The oceanic crusts that lie beneath the Earth's oceans are approximately six kilometres thick, whereas the continental crusts that include continents and their offshore margins are between twenty to thirty kilometres thick (Aitken, 1996).

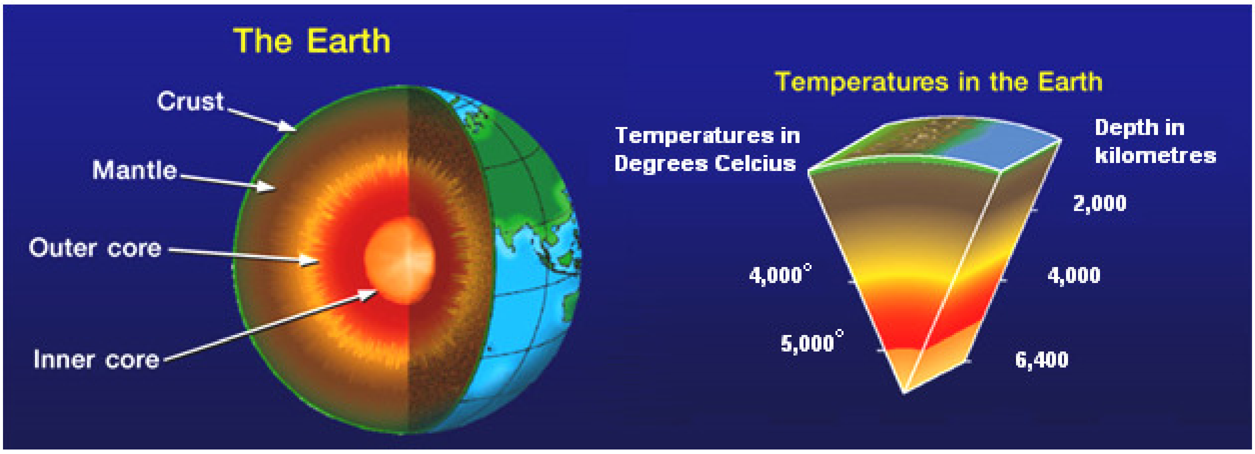

Figure 2.5: Internal Composition of the Earth (edited from Heidtke, 2003)

Tectonic plates are comprised of the lithosphere and areas of both continental and oceanic crust. Due to the differing characteristics of the lithosphere and asthenosphere, the tectonic plates are considered to effectively "float" on top of the asthenosphere. The Earth's surface is broken up into eight major lithospheric plates, and each of these plates is subject to motions of varying degrees and directions due to forces acting on them that are not yet completely understood. Common theories attempting to explain this phenomenon include heated convection currents, or gravity driven plates (e.g., Aitken, 1996).

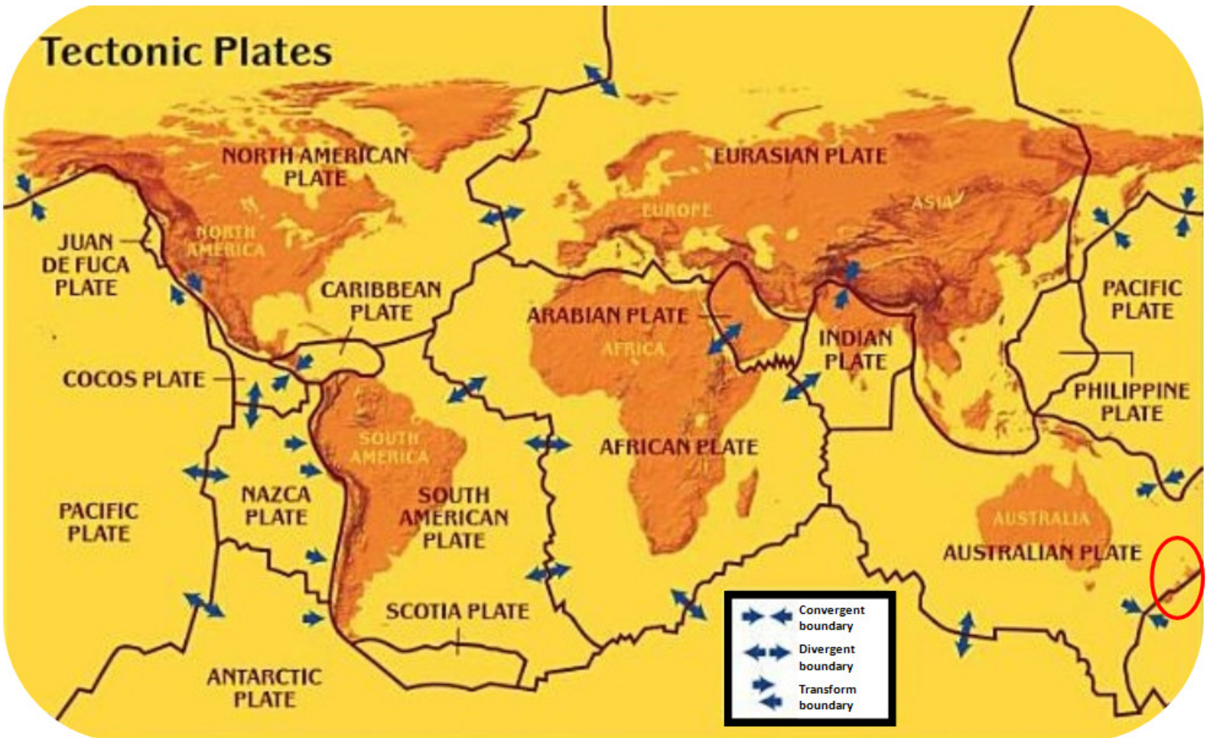

Figure 2.6: Tectonic plates and boundary interactions around the globe (Original Image: Silverstein et al., 2009)

As illustrated in Figure 2.6, New Zealand is positioned along the boundary between the Pacific and Australian tectonic plates. This causes New Zealand to be highly vulnerable to tectonic motion of varying degrees in both horizontal and vertical dimensions. The interactions between these two plates are very complex, largely due to the presence of both oceanic and continental crust on either side of the boundary, combined with the fact that the pole of rotation for these two plates is relatively close to New Zealand (Beaven and Haines, 2001). The New Zealand Geodetic Datum (2000) is a semi-dynamic three-dimensional datum with horizontal deformation velocities around New Zealand incorporated into it. However, it is not yet able to include vertical movement velocities. As the vertical positions are changing at such a gradual rate, cGPS measurements need to provide accurate vertical positions over a length of years to enable the confident derivation of local vertical velocity rates from the observations. Unfortunately, cGPS provides its poorest positional resolution in the vertical dimension (Stevenson, 2009).

2.2.1.2 Glacial isostatic adjustment

The surface of the Earth is presently undergoing vertical reaction at varying rates around the globe in response to the deglaciation event of the last Quaternary Ice Age. The reduction in the weight upon the Earth's land masses is causing the land areas to rebound in a process known as the glacial isostatic adjustment (GIA) (Peltier, 2004) caused by the change in flow in the mantle (Peltier and Jiang, 1997). This changes the relative vertical positions of the co-located tide gauges causing biases in the apparent rates of sea level rise. The change in sea level relative to the tide gauge needs to be corrected for the earth movement over the same period in order to derive the eustatic changes (Church *et al.*, 2004). GIA models are commonly used to correct for these motions. However, measurements of the actual movement over time derived from GPS stations are being used more regularly as their lengthening records begin to isolate long-term land motion trends.

Studies to derive the global rate of sea level change have utilised the near global coverage of tide gauge records of varying durations (e.g., Gornitz *et al.*, 1982; Barnett, 1984; Douglas, 1991, 1997, 2001; Church *et al.*, 2004). In order to isolate the sea level rise from the vertical movement, most studies have applied corrections based on models, namely the GIA models (e.g., Peltier and Tushingham, 1989; Trupin and Wahr, 1990; Douglas 1991, 1997, 2001; Peltier, 2001; Church *et al.*, 2004).

The use of these GIA models to correct for vertical land motion has two clear limitations:

- the postglacial rebound corrections differ depending on which model is used (cf. Peltier, 2004), and

- the corrections do not incorporate other vertical motion processes, such as active tectonics (Mazzotti *et al.*, 2008).

Discrepancies between the predicted glacial isostatic adjustment rate and the velocities detected with GPS observations may be related to tectonic activity that would impact on the observed velocity (Bouin and Wöppelmann, 2010). The thickness of the Earth's crust at a location is another parameter that influences the magnitude of the vertical and horizontal movements caused by these internal mechanisms on the land's surface due to the weight associated with the crust's breadth. The local thicknesses are approximated for incorporation in the GIA models. The melting of glaciers also influences the weight the Earth's inner layers are subject to.

In areas of active tectonics, large earthquakes can cause significant irregular vertical movements, resulting in vertical offsets in the tide gauge data series (e.g., Larsen *et al.*, 2003). Unless these irregular movements are of sufficient magnitude to be detected by GPS measurements, the sudden vertical movements may be incorporated into a linear or quadratic approximation, causing an erroneous trend to be derived.

ICE-3G, ICE-4G (VM1), and ICE-5G (VM2) are consecutively superseding models of the vertical rebound rates around the Earth in response to the removal of glacial weight from the last deglaciation event of the current ice age. These approximate the internal viscoelastic structure of the solid Earth and the detailed spatiotemporal characteristics of the glaciation history (Peltier, 2004). These models assume that there is a steady state of change with time, and thus do not allow for active tectonics.

The ICE-5G model improves upon the underlying assumptions made in the ICE-3G and ICE-4G models. The overall global agreement between the ICE-5G model and GPS observations is good, with discrepancies related either to issues with the local fit, or to active tectonics (Bouin, 2010). ICE-4G was itself a significant improvement upon ICE-3G; utilising relative sea level observations to constrain the ICE-4G model (Peltier, 2004). The quality of the ICE-5G's modelling of the postglacial rebound is still uncertain in relation to its model of the Earth's mantle. Mazzotti *et al.* (2008) believe that it does not take into account the low viscosity of western North America's upper mantle. This arguably results in an over-prediction of rebound velocity of one to two millimetres per year (Mazzotti *et al.*, 2008; cf. Clague and James, 2002).

Despite the fact that the various glacial isostatic adjustment models are qualitatively similar, their present-day rates of vertical deformation contain uncertainties due to limitations in the historic knowledge of the Earth's ice coverage history. Furthermore, there is limited knowledge of three vital geophysical parameters; lithospheric thickness, and upper and lower mantle viscosity. These limitations are additional to the uncertainties associated with the models due to their respective resolutions and parameterisation (Woodworth, 2006). Woodworth (2003) found that different models for the GIA available at the time provided significantly different corrections, varying in both magnitude and sign. The best scientific approach is to measure local vertical movement if one can (Woodworth, 2006), which can be achieved using long-term GPS measurements (Carter *et al.*, 1989; Carter, 1994; Neilan *et al.*, 1998; Blewitt *et al.*, 2006).

The GIA models predict the rate of vertical land uplift following the removal of the immense weights of the glaciers that have melted, or are presently melting. However, further to this there are anthropogenic forces that are increasing the quantity of weight that has been removed in some locations. The extraction of gas and oil resources is a continuing process at numerous locations around the world. Through the removal and transportation of these resources, local crustal loading is reduced as the weights associated with these resources are redistributed, exacerbating the local isostatic adjustments (Denys, 2010).

2.2.1.3 Significant active tectonics in New Zealand

Significant New Zealand earthquakes may potentially cause irregular vertical land movements which change the nature of the apparent rate of sea level rise observed through relative sea level measurements.

Figure 2.7 shows New Zealand's major fault lines and the boundary between the Australian and Pacific tectonic plates. Table 2.2 lists and describes all of New Zealand's most significant earthquakes since 1848, and Figure 2.8 illustrates the locations of these earthquakes, the dates and magnitudes of the events, and the locations of the four long-term tide gauges used in this study.

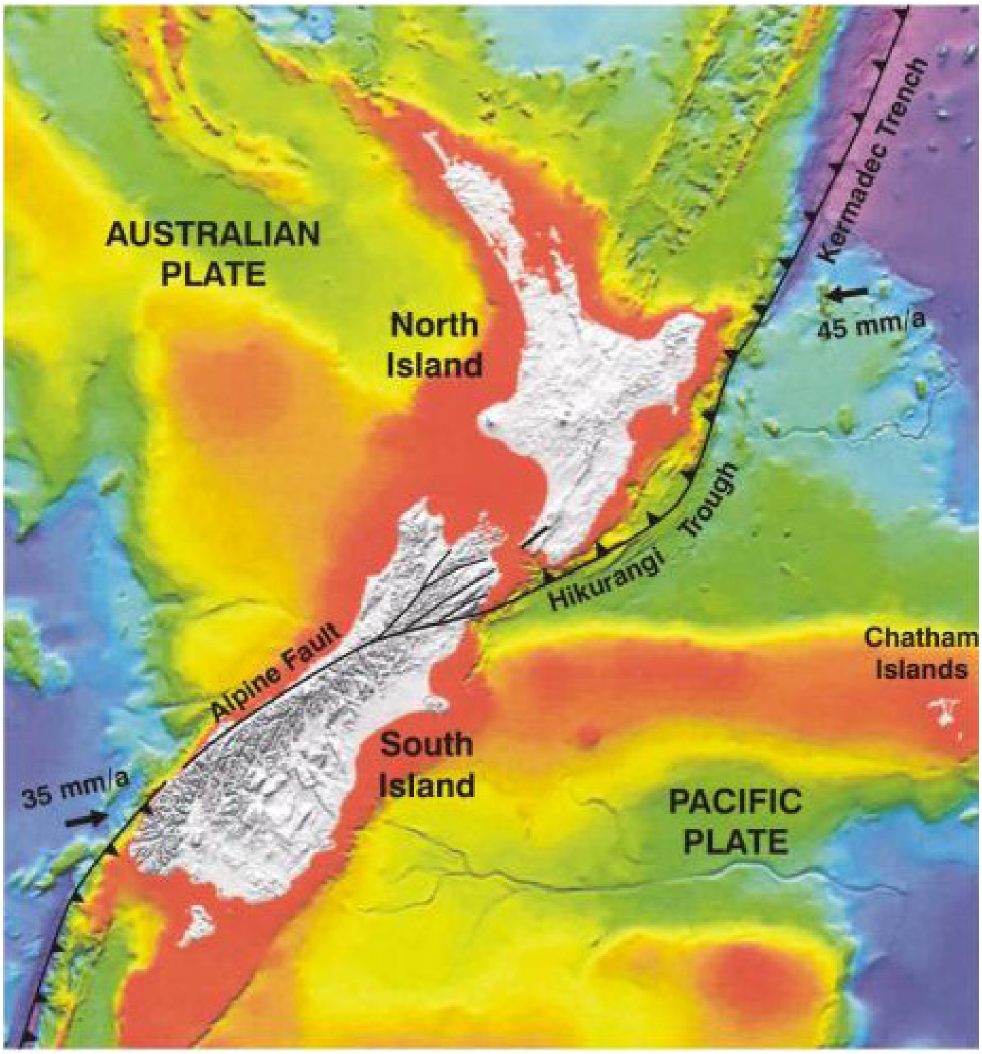

Figure 2.7: Major fault lines in New Zealand the boundary between the Australian and Pacific tectonic plates (National Institute of Water and Atmospheric Research, 2010-b)

New Zealand's most significant earthquakes since 1848			
Magnitude	**Date**	**Location**	**General description**
7.8	October 16 1848	Marlborough	This earthquake was the largest in a series of earthquakes to hit the region that year.
8.2	January 23 1855	Wairarapa	The most severe to have occurred in New Zealand since European colonisation began.
7.1	September 1 1888	North Canterbury	The Amuri District was shaken by a large earthquake causing significant destruction.
7.8	June 17 1929	Buller (Murchison)	The massive rumbling caused by this was heard as far away as New Plymouth.
7.8	February 3 1931	Hawke's Bay	This earthquake caused the greatest loss of life in New Zealand since records began.
7.6	March 5 1934	Horoeka (Pahiatua)	This was felt in both Dunedin and Auckland with its origin in the lower North Island.
7.2	June 24 1942	Wairarapa	The lower North Island was severely rocked, causing extensive damage to local buildings.
7.0	August 2 1942	Wairarapa	The damage caused by this shock was nearly as severe as that caused on June 24.
7.1	May 24 1968	Inangahua	Widespread damage was caused with the shockwaves felt over much of the country.
6.5	March 2 1987	Edgecumbe	The shallow origin of this earthquake made it unusually destructive for its size.
6.8	December 20 2007	Gisborne	This event caused buildings to collapse in the Gisborne central business district
7.8	July 15 2009	Dusky Sound	This earthquake in Fiordland was New Zealand's largest for nearly 80 years.
7.1	4 September 2010	Darfield (Christchurch)	Extensive damage to heritage buildings in Christchurch's Central business damage. Thousands of buildings were condemned.

Table 2.2: New Zealand's most significant earthquakes since 1848 (GeoNet, 2010)

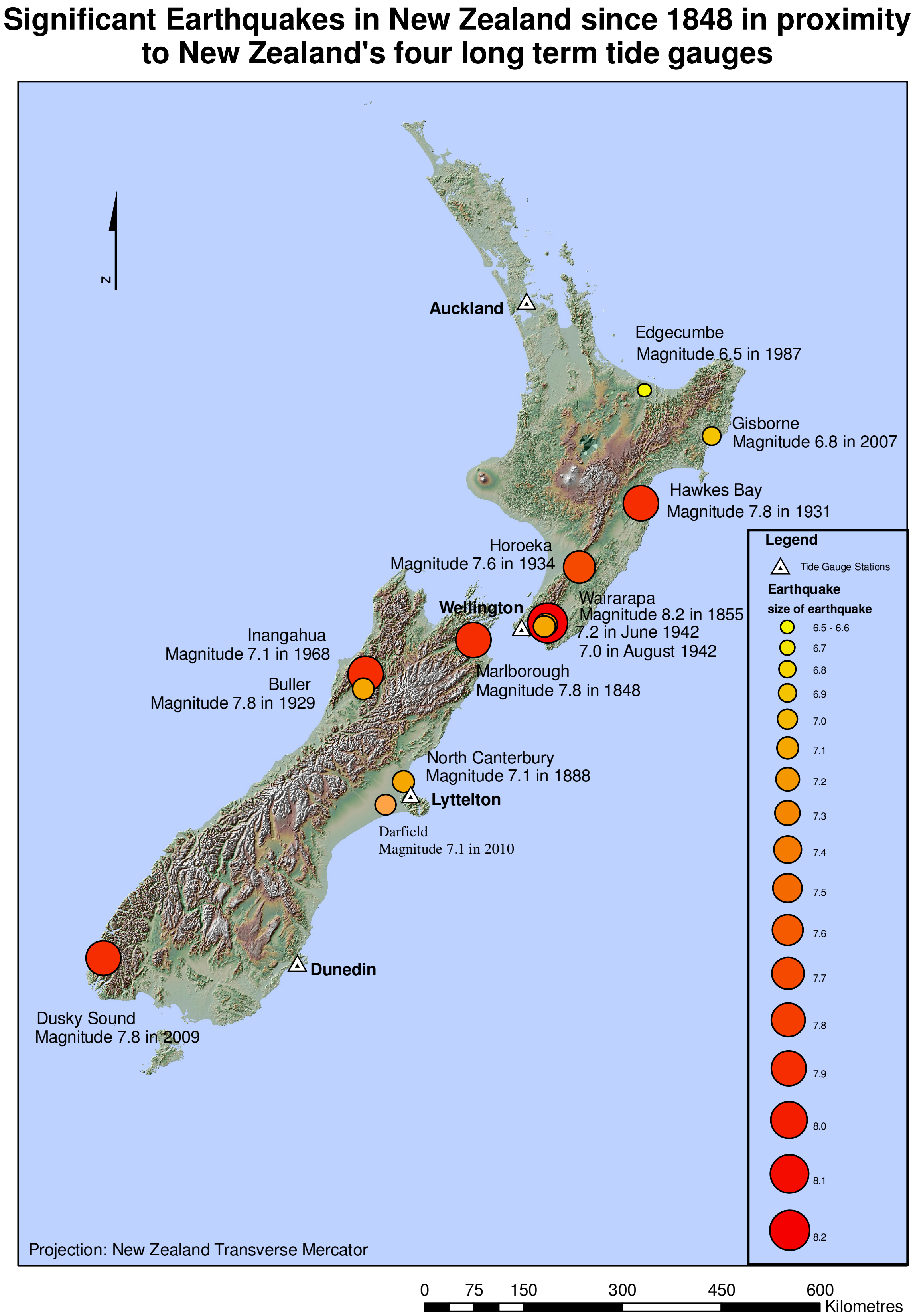

Figure 2.8: Significant Earthquakes in New Zealand since 1848 in proximity to New Zealand's four long-term tide gauges[1]

[1] Note: The sizes of earthquake symbols represent the earthquake's magnitude, not the extent of the areas affected. The positions of the earthquake symbols are not the true epicentres.

The earliest sea level measurements used in this investigation are those from the Wellington tide gauge whose records commenced in 1891. Figure 2.8 shows that the two earthquakes that occurred in the Wairarapa in June and August in 1942. These were the only significant earthquakes that have occurred in close proximity to any of the four tide gauges used in this study during the periods being analysed. The 7.1 magnitude earthquake in Darfield (September 4, 2010), near Christchurch, is likely to have significantly altered the Lyttelton tide gauge's vertical position. This proximity is shown again in Figure 2.9 for improved clarification.

Wairarapa 1942 earthquakes in proximity to Wellington tide gauge

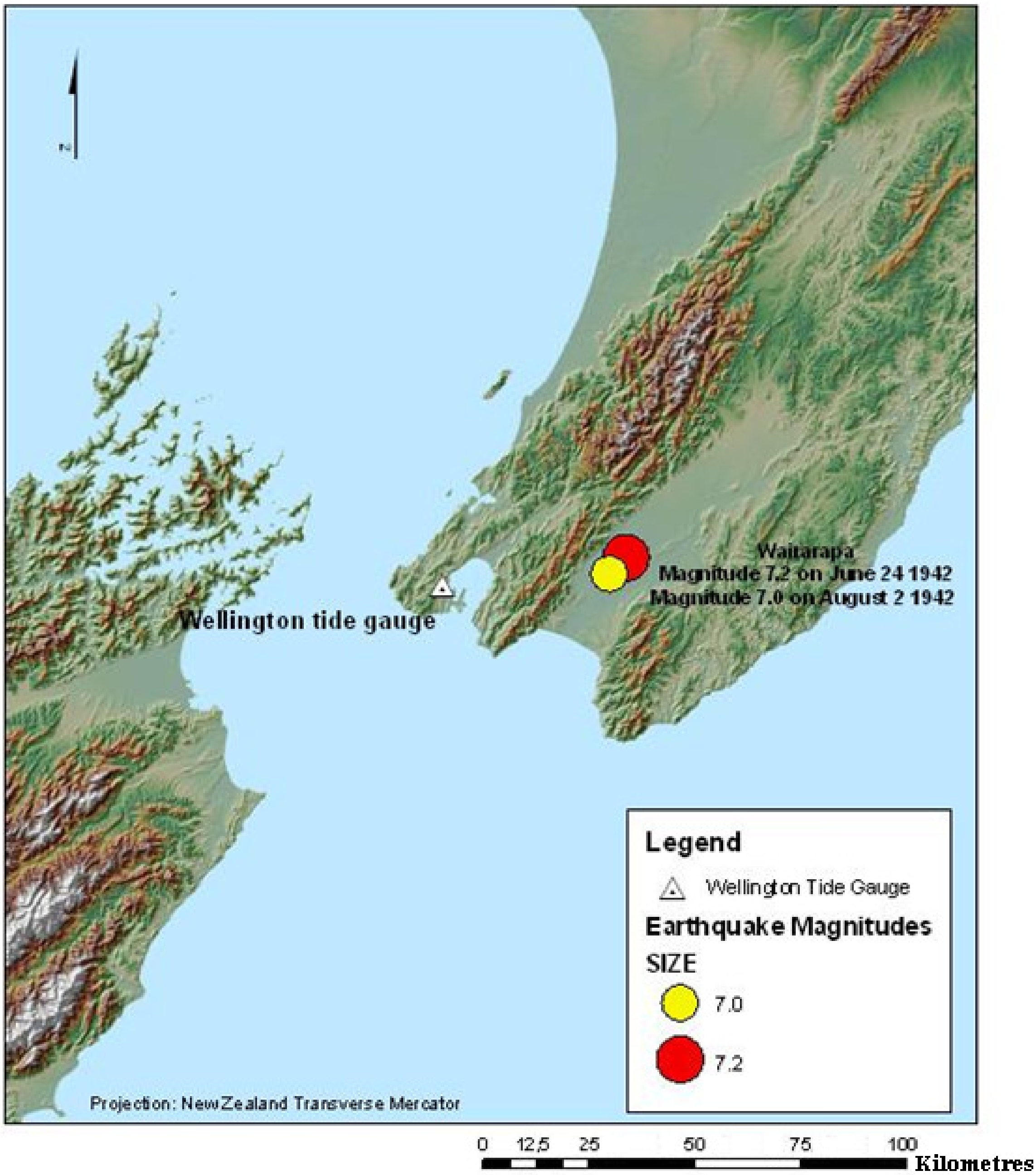

Figure 2.9: Significant 1942 Wairarapa earthquakes in proximity to Wellington tide gauge

Active tectonics within proximity of the tide gauges used in this study may have caused any co-located tide gauges to shift vertically, thereby compromising the gauge's datum continuation. Any circumstances under which this may have occurred must be considered carefully and appropriately incorporated into any mathematical analyses.

2.2.1.4 Tectonic deformation summary

The internal composition of the Earth generally causes slow and imperceptible movements on the Earth's surface. However, sudden releases of immense quantities of built-up energy cause significant land movements to occur, sometimes causing permanent displacements of the land in any dimension. Therefore, earthquakes may cause significant sudden vertical offsets, which will shift the tide gauges used to measure relative changes in the height of sea level. Many similar studies have attempted to accommodate the continuous vertical tectonic motion through GIA models, but these models historically have been found to be inconsistent. Another methodology being increasingly investigated is utilising GPS stations to measure regular vertical land movement; although sudden small-scale movements are still an unresolved issue.

The vertical movement of the land causes variation to the measured height of sea level, introducing difficulties associated with confidently determining the rate of sea level rise, and potentially causing apparent trends in the change in sea level that do not actually reflect the nature of the absolute changes in sea level. Long-term changing behaviours within the sea level records further complicates the accurate resolution of the long-term trend in sea level rise.

2.2.2 Meteorological driver: Thermal expansion

Many meteorological parameters influence the ocean's tides and cause some of the year-to-year variations in annual mean sea levels. These parameters include wind stress, atmospheric pressure change, temperature, precipitation, glacier melt, and river discharge (Hannah, 1990). Variations in precipitation and glacial melting can correspond with variations in river discharge, which is explicitly connected to changes in harbour salinity. Oceanic thermal expansion, discussed in this section, and the inverted barometer effect, discussed in Section 2.2.3, are both functions of water salinity (Wigley and Raper, 1987). These changing conditions cause an inherent change in water properties, and hence the sea level by association.

There is a high interest in the quantification of sea level rise due to its obvious practical impact, and also because of its scientific value as a parameter of global change (Douglas, 1992). An increase in the Earth's temperature would increase the volume of the Earth's oceans concordantly. Thermal expansion causes the volume of the Earth's oceans to increase as the density decreases. Equation 2.1 shows that if the total mass remains constant, the volume must increase if the density decreases (ie, due to thermal expansion).

$$v = \frac{m}{d}$$

Equation 2.1: Volume to density relationship

The Earth's warming throughout the twenty-first century is expected to vary geographically. Average warming should be greater over land masses and greater still at high northern latitudes. The lowest increases in average temperatures are expected over the Southern Ocean, and North Atlantic. In association with this, snow coverage is projected to contract, and sea ice is projected to shrink in both the Arctic and Antarctic (Intergovernmental Panel on Climate Change, 2007). The response to thermal expansion depends on both the extent of warming, and the depth to which the change in temperature penetrates. The temperature of the surface of the ocean responds to changes at an annual timescale, whereas deep ocean water responds in the timeframe of decades, to centuries. The latter would cause the most significant change to the volume of the ocean, and hence the height of sea level around the globe.

Worldwide sea level records suggest that sea level rise is not spatially uniform. This can be attributed to the glacial isostatic adjustment and vertical deformation. However, Cazenave and Llovel (2010) attribute the majority of the spatial variation to thermal expansion. With this in mind, thermal expansion in New Zealand's context must be considered, both in the context of New Zealand's geographical form, and in relation to the harbour locations of the tide gauges used in this study and the changes in water salinities associated with these locations.

2.2.2.1 Temperature trend in New Zealand

New Zealand's temperature records extend back as far as 1853 and demonstrate an increase of approximately 0.7° Celcius between 1900 and 1993 (Folland, 1995), which can be expected to cause a corresponding increase in the height of sea level around the country. Although warming in New Zealand is regional, seasonal fluctuations vary in magnitude and phase because of the country's rugged terrain with high topography and wide latitude range; straddling from 34° to 47° South. New Zealand's climate is also influenced by the ocean currents flowing towards and around the country. Prevailing winds further influence New Zealand's temperatures.

Ocean currents have a significant effect on New Zealand's climate by modifying air masses as they approach New Zealand (Trenberth, 1973). Southern New Zealand lies exposed to the south-western current, thereby exposing the climate to this predominant wind flow (Tomlinson, 1975). The mild East Australian Current flows southwards along Australia's east coast, curves and continues eastwards towards New Zealand's west coast, deflects around the northern end of the country, and then southward along the east coast of the North Island. The cold West Wind Drift flows along the east coast of the South Island, to meet with the south-flowing East Australian Current where it forms the Subtropical Convergence (Salinger, 1979).

The axial ranges of the North and South Islands are oriented approximately north-east to south-west. The Southern Alps of the South Island reach an altitude of 3764 metres, and are over 1000 metres high for over 700 kilometres. The North Island axial ranges do not rise to the same extents as the Southern Alps, but still produce substantial orographic affects with the less frequent easterly winds coming in off the Pacific Ocean. These axial ranges effectively act as barriers to the prevailing westerly winds. Precipitation and temperature changes both cause variability in local thermal expansion effects.

The reliability of most instrumental temperature measurements reduces with earlier records. New Zealand temperature data is no exception. Long temperature records need to be investigated as corrections may be required due to errors in the data caused by non-standard measuring techniques, changes in sheltering over time, and other factors (Salinger, 1979).

2.2.2.2 Thermal expansion effect variability due to salinity changes

Thermal expansion is a function of salinity and temperature. Rainfall and river flow into a harbour increases its freshwater content, thereby reducing its overall density. Equation 2.1 demonstrates that this would cause the overall volume of the water to increase if the total mass remains constant. Furthermore, the reduced water density will cause a greater increase in volume when the water is subject to a temperature increase (ie, through thermal expansion).

With extensive records of water salinity content, the local relationships between temperature and salinity changes and its corresponding influence on sea level may be better modelled. Some researchers have attempted to correct mean sea level values for the effects of thermal expansion to reduce its overall variability, but this may compromise the data.

2.2.2.3 Effect of thermal expansion on derivation of acceleration trend in sea level rise

The aim of this study is to investigate if there is a detectable acceleration in sea level rise using New Zealand's four long-term tide gauges. The Earth's temperature is believed to be increasing over time. This increase in temperature can be expected to result in an increase in ocean volume, and hence a rise in sea level. As a contributing factor to sea level rise, this effect should not be corrected, but instead should be incorporated into the analysis as an important cause of the effect being investigated. The complex nature of thermal expansion in terms of its relationship with water salinity means that it would be difficult to isolate the true effect of thermal expansion on local sea level.

In terms of short-term relative sea level analysis, thermal expansion must be considered to be insignificant as the ocean's responses to local temperature changes are gradual, with minimal annual ocean temperature variation. Short-term meteorological temperature trends are not expected to be reflected in ocean temperatures, and hence are not expected to have a significant influence on the local water volume within this short timeframe (Denys, 2009).

2.2.3 Meteorological driver: Atmospheric pressure

In its simplest form the inverted barometer effect corresponds to the sea surface depressing under atmospheric loads by approximately ten millimetres for every millibar of atmospheric pressure increase. The atmospheric loading causes an isostatic subsidence of the sea surface, essentially compensating for the additional weight the ocean is subject to. Through the ocean responding to the atmospheric loading in this manner, it effectively acts as a buffer for the underlying land, preventing almost all of the normal stress experienced by the ocean surface from affecting the ocean floor (Dickman, 1988). The ocean surface is forced to subside under the atmospheric loading, but the water itself is not compressed; it is displaced (Vennell, 2010).

Atmospheric pressure changes induce change to the height of sea level within hours. However, this effect may be reflected in annual mean sea level values due to the presence of a bias in specific years' weather patterns. This may be reflected with unusually high or low annual mean sea levels, or similarly through increased variations in the year-to-year annual mean sea level values.

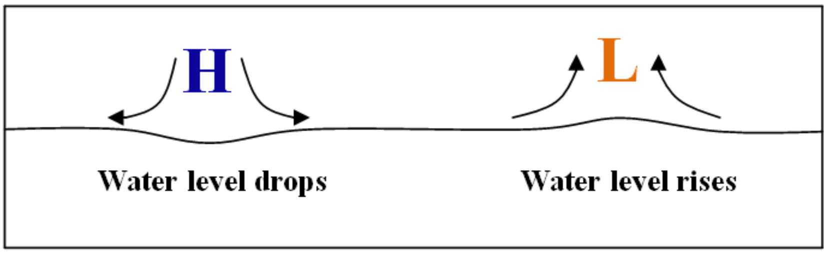

Figure 2.10: Inverted barometer effect

Changes in atmospheric pressure about its mean tend to have a high association with changes in other sea level forcing meteorological conditions. These conditions are namely wind stress and site specific resonance effects (Thomson and Tabata, 1982). Due to these typically non-linear effects combining with the traditionally linear inverted barometer effect (Mazzotti *et al.*, 2008), the basic application of height corrections for changes in water salinity and atmospheric pressure need to be carefully considered.

This section discusses the numerous interrelationships between atmospheric pressure changes and changes to the height of sea level. The magnitude of the inverted barometer effect on sea level is altered by changes in the water's density and the other meteorological drivers associated with pressure systems. Periodic atmospheric pressure systems may cause similar periodic signals within sea level records, providing a potential source of error in derived sea level rise trends. Local atmospheric pressure records theoretically may be utilised to correct sea levels for the inverted barometer effect, providing the records are all relative to the same height reference; namely sea level. The influence of altitude on atmospheric pressure is considered lastly in this section.

2.2.3.1 Water salinity content

The influences of thermal expansion and changes in atmospheric pressure on the height of the sea level are both influenced by the water salinity content. A change in salt content inherently causes a change in density, also known as a 'steric change' (Antonov *et al.*, 2002). A decrease in water salinity corresponds to an increase in volume if the temperature and pressure remain constant. Similarly, a decreasing steric trend will cause a greater depression of water volume with an increase in atmospheric pressure. This effect is central to maintaining the ocean's thermohaline circulation (Warrick *et al.*, 1996).

The variations in water salinity caused by the contributing factors should have a negligible effect on derived annual mean sea levels. The magnitude of the impact a slight salinity change has on the inverted barometer effect is not significant (Vennell, 2010). Due to this and the absence of salinity records for the water bodies being considered, corrections associated with salinity content variations shall not be included in this study.

Long-term atmospheric pressure trends can influence sea level so that the records demonstrate similar trends. Such trends may be harder to detect in the event of large salinity changes for any given year as it may increase or decrease the size of the inverted barometer effect proportionally.

2.2.3.2 Decadal and interdecadal atmospheric signals

Douglas (2008) showed that surface atmospheric pressure variations have a high correlation with low frequency variations such as decadal and interdecadal signals, although not in terms of an isostatic response. The longest-term signals are the most relevant to the accurate detection of sea level rise accelerations (Miller and Douglas, 2007). Long-term signals that are associated with atmospheric pressure changes are discussed in depth in Section 2.2.4.

Significant long-term signals must be carefully considered in this form of study as they may cause biases in the derived trends. If there is a significant signal that is common between both the atmospheric pressure records and the sea level records, it is likely that this signal is substantially governed by this meteorological driver. If an accurate model for the inverted barometer effect can be created, these signals may be effectively removed from the datasets, thereby preventing any bias in the derived trends.

2.2.3.3 Associated influence of wind set-up

Atmospheric pressure variations are inherently associated with other meteorological conditions that may compound or reduce the local effect on ocean height. As discussed in Section 2.2.3, an increase in atmospheric pressure of one millibar is generally believed to cause a decrease in ocean height of ten millimetres. However, this change in height can be increased or decreased depending on the nature of meteorological drivers that the pressure change may be associated with, such as wind systems. The wind affects the water's height due to wind set-up.

The magnitude of the increase or decrease in height for any given wind stress is a function of the length of the water body preceding the tide gauge. Other factors that influence the wind set-up include the depth of the water body along its length and the depth's variability, as well as the topographical layout of the water body concerned. For example, the Dunedin harbour is approximately eleven kilometres in length with hills aligning both sides. Its depth varies due to its natural composition, as well as human intervention in the form of harbour dredging and the construction of the sand bar. The shape of the harbour, illustrated in Figure 2.11, further influences the magnitude of the wind set-up effect caused by prevailing winds.

The Dunedin Harbour is aligned approximately south-west to north-east. The prevailing winds Dunedin Harbour is subject to are south-westerlies, and north-easterlies. Therefore, it is expected that significant wind events will funnel up or down the harbour, amplifying the wind set-up under these circumstances.

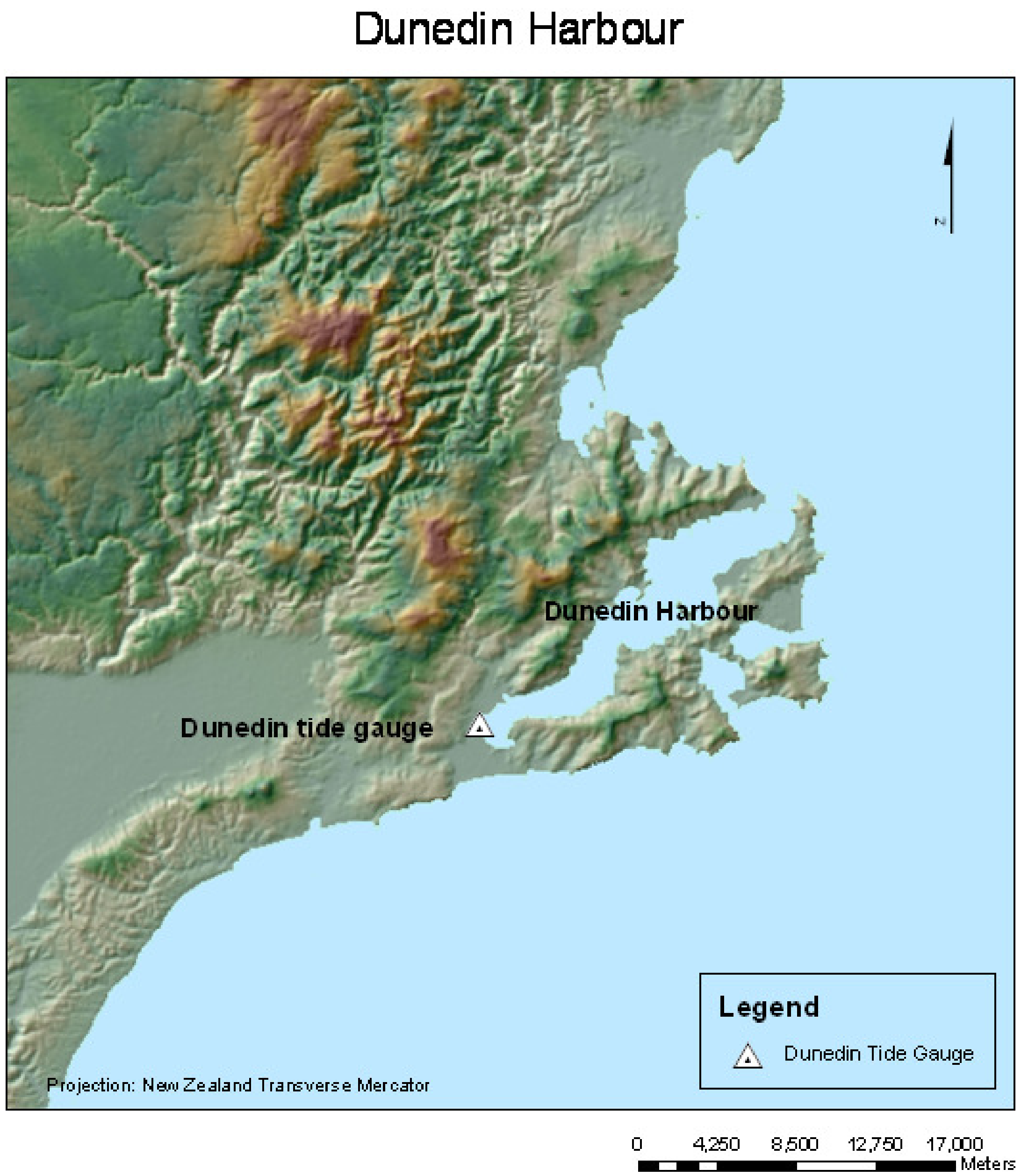

Figure 2.11: Dunedin Harbour

Prevailing winds, especially those that are funnelled towards or away from tide gauge locations, cause significant changes to the height of sea level due to the drag the wind exerts on the water's surface.

Wind set-up is the phenomenon that occurs when wind travels over a water body, exerting a drag force on the water's surface. This creates a slope in the water surface in the direction of the wind stress (Forrester, 1983). Pugh (1987) states that *"the effects of winds on sea levels increases inversely with the water depth and will be most important when the wind blows over extensive regions of shallow water."*

When wind starts to blow across a water surface the wind stress initially causes an acceleration. When the water is no longer accelerating, and hence a steady state has been achieved, the balance of forces must be between the pressure gradient force due to the surface slope, and the bottom stress on the water and on the surface.

Figure 2.12 illustrates the balance of forces in the direction of the wind stress for wind blowing towards shore. Persistent winds are required for a steady state to be reached.

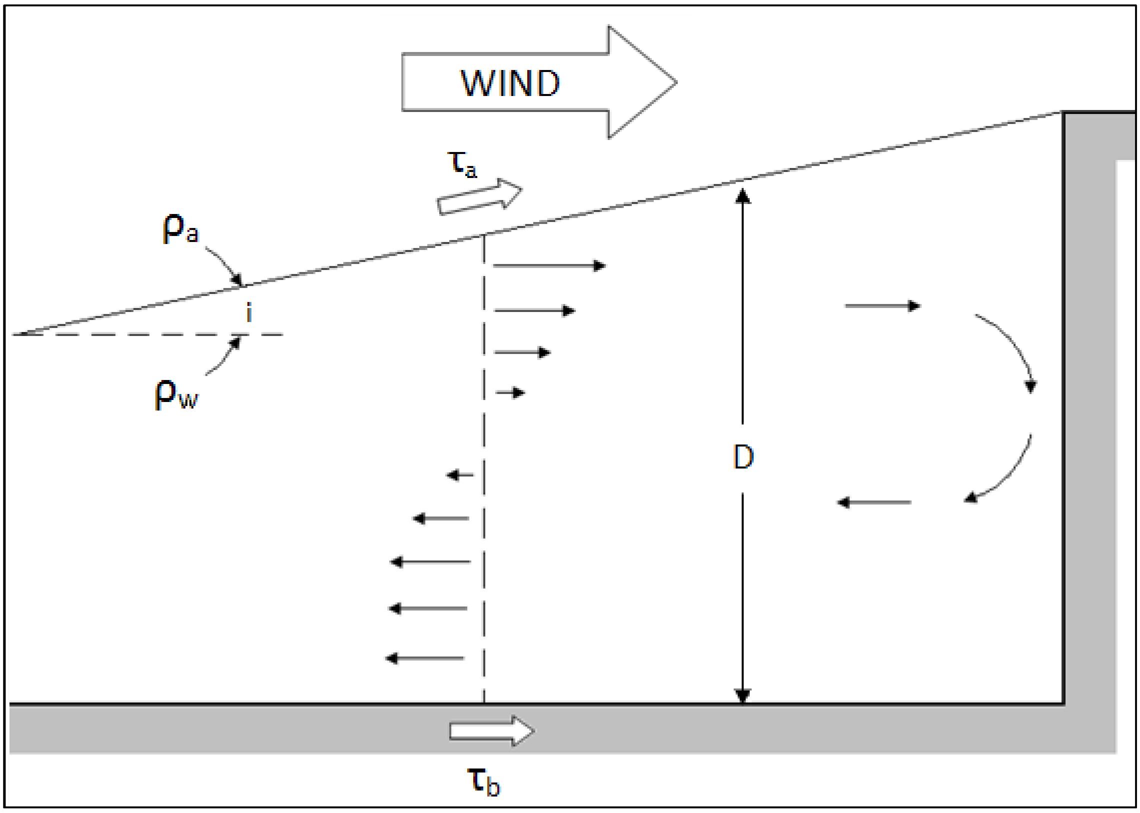

Figure 2.12: Sea level set-up due to wind-stress

The drag force of wind on a water surface can cause an increase in water height in the direction of the prevailing wind. This height change is increased when the wind is channelled through appropriately oriented terrain. Wind anomalies are often associated with significant atmospheric pressure variation events. The pressures related to these events are recorded to obtain mean pressure values, but these pressures must all be in terms of the same reference height.

The wind-set up effect is most prominent in shallow, enclosed harbours, where the water height increases at the leeward end. However, coastal locations are often subject to winds parallel to the coast due to the Coriolis affect. The harbours that contain the tide gauges considered in this study are affected by prominently along-shore winds, reducing the prevalence of winds that funnel directly into the harbours at these locations.

2.2.3.4 Atmospheric pressure measurement corrections

At sea level, the weight of the air presses down upon us with a weight of approximately one kilogram per square centimetre of area. However, at higher altitudes there is less pressure, and hence weight. Therefore, atmospheric pressure measurements taken at altitude must be corrected to bring them in terms of a universal datum; sea level.

Atmospheric pressure decreases inversely with increasing altitude (Davis and Foote, 1956). Figure 2.13, compiled by National Aeronautics and Space Administration, gives an approximation of air pressure change in atmospheres at increasing altitudes. The relationship between units of atmospheres, pascals and millibars is expressed in Equation 2.2.

$$1 \ atmosphere = 100 \ pascals = 1013.25 \ millibars$$

Equation 2.2: Atmospheres to millibars conversion

Fraction of one atmosphere	Average altitude (metres)
1	0
1/2	5,486.3
1/3	8,375.8
1/10	16,131.9
1/100	30,900.9
1/1000	48,467.2
1/10000	69,463.6
1/100000	96,281.6

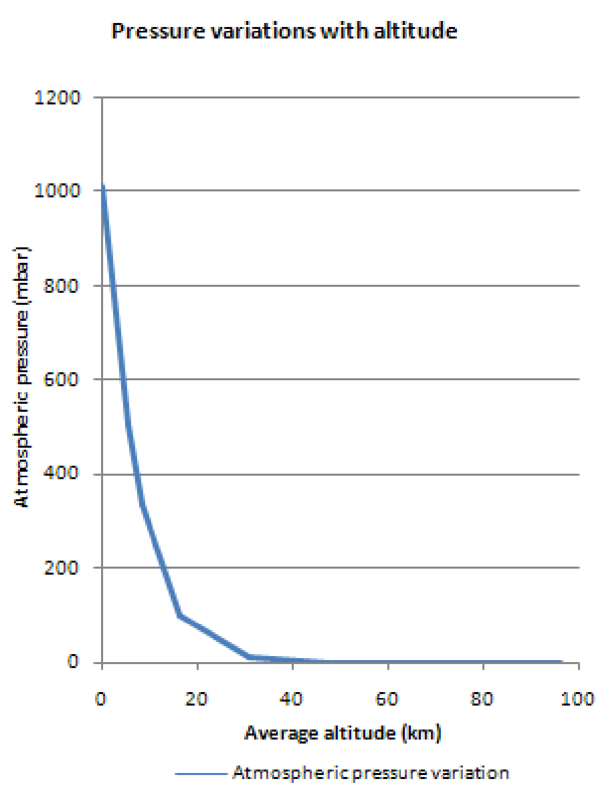

Figure 2.13: Pressure variations with altitude (National Aeronautics and Space Administration, 2010)

2.2.3.5 Inverted barometer effect summary

The influence of changes in annual mean atmospheric pressures and associated meteorological parameters on the height of sea level increases the year-to-year variability of the annual mean sea level records. The variability in the data complicates the identification of trends in the rate of sea level rise, which also incorporates the random noise associated with the records.

If the variability of the datasets may be reduced by identifying the drivers causing changes in the height of sea level and then correcting for these influences, the datasets will become more indicative of underlying long-term trends over time.

2.2.4 Decadal and interdecadal oscillations

Oscillations in sea level correspond to the redistribution of the Earth's oceans without any change to the total ocean volume (Wöppelmann *et al*., 2007). An acceleration in sea level rise will form a low-frequency signal superimposed over decadal and interdecadal variability, causing difficulty in isolating the acceleration from the periodic trends (Douglas, 1992). This weakness is improved upon by analysing longer term sea level records, but severe weaknesses in the analysis still exist. To effectively avoid these signals compromising the data, they should be modelled or removed in the process of trend derivation. Sea level records spanning at least fifty to sixty years are required to produce stable estimates of relative sea level rates because of the strong interdecadal variability contained in the records (Douglas, 1991; 1997).

Numerous mechanisms have been proposed to explain the source of decadal and interdecadal variability in the tropical Pacific (Parker *et al*., 2007). Regional variations in climate are caused by a range of natural models of decadal to interdecadal climate variability, as well as from anthropogenically induced changes in the climate (Mantua and Hare, 2002). The study carried out by Barnett (1984) found that long-term tidal records show temporal and spatial coherence along large sections of the world's coastlines. Inspection of most long-term sea level records reveals variations such as those caused by the El Nińo-Southern Oscillation. It is variations such as this and the Pacific Decadal Oscillation that generates the decadal and interdecadal 'noise', which is a major contributor to the difficulties associated with the definitive derivation of trends in sea level rise.

This section considers the known drivers of decadal signals that may be apparent in long-term sea level records, and then goes on to consider longer period signals and how they would have a greater influence on long-term derived trends in sea level rise.

2.2.4.1 Decadal-scale signals affecting mean sea level

Regional trend patterns in sea level that have been reported by satellite altimetry are mainly due to regional variability in temperature trends and water salinity (e.g., Carton and Giese, 2008). In most regions, thermostatic trend patterns closely resemble observed sea level trend patterns (e.g., Wunsch *et al*., 2007), although in some regions such as the equatorial Pacific and North Atlantic, the effects of temperature and salinity are opposite and effectively cancel out.

Jevrejeva *et al.* (2006) found that 3.5 to 13.9 year oscillations demonstrated an increase in amplitude in the sea level time series since the 1940s in the north-eastern Atlantic, north-western Atlantic, and eastern Pacific. The study did not produce statistically significant results in relation to increasing amplitudes in these oscillations at the New Zealand tide gauge stations.

Sea level oscillations in the 2.2 to 7.8 year period range have been associated with large scale atmospheric circulation signals (Unal and Ghil, 1995; Jevrejeva *et al*., 2005). The processes that generate this sea level response include the direct influence of changes in atmospheric pressure through the inverted barometer effect, changes in wind stress, and storm surges (Jevrejeva *et al*., 2006). The variability in sea level associated with the Indian and Pacific Oceans are mostly attributed to the Southern Oscillation Index signals with periods of 2.2, 3.5, and 5.7 years (Ropelewski and Jones, 1987).

Interannual and decadal variability in sea level around New Zealand is inextricably linked to the Pacific-wide El Nińo-Southern Oscillation (ENSO) response. The results obtained by Bell *et al*. (2000) imply that the ENSO affects sea temperatures, winds, and ocean currents over a wide region around New Zealand, although it has not yet been proven if these effects extend as far south as Christchurch.

Trenberth *et al*. (2002) explored the increases in global surface temperatures accompanying El Nińo events. Most of the delayed warming outside the Tropical Pacific is caused by persistent changes in atmospheric circulation. Some ocean heat is lost to the atmosphere through evaporation; driving teleconnections as latent heating in precipitation. Reduced precipitation in conjunction with an increase in solar surface temperatures in Australia, Southeast Asia, parts of Africa, and northern South America, contribute to warming peaks several months after the El Nińo event (Trenberth *et al.,* 2002). After an El Nińo event, global surface air temperature increases by approximately 0.1 degrees Celcius, at a lag of about 6 months in the Tropics, and a greater lag at higher latitudes (Angell, 2000). An exception to this increase is the increase in global sea surface temperature of more than 0.2 degrees Celcius after the 1997 to 1998 El Nińo event (Trenberth *et al*., 2002).

It has been suggested by Wyrtki (1985) that the timescale of the ENSO is determined by the period required for an accumulation of warm water in the tropics to effectively recharge the weather system, plus the time for the El Nińo event itself to evolve. The quantity of warm water in the Tropics builds up during this period, and is then depleted during the ENSO event (Meinen and McPhaden, 2000). This is supported with both sea level and surface temperature data (Smith *et al.*, 1996; Zhang and Levitus, 1996, 1997).

It is acknowledged that although patterns have been witnessed in climatic records that are inherently affected by the ENSO, the oscillation cycle is not in itself strictly periodic (Zhang *et al*., 1996).

Interannual contributors, namely the ENSO, account for approximately 25% of monthly variance in New Zealand mean sea level records, excluding that caused by tidal influences (Bell *et al*., 2000). A striking feature of Auckland mean sea level records between 1980 and 2000, identified by Bell *et al*. (2000), was that there was a persistence of El Nińo events that had a flow on effect causing a reduction in the rate of sea level rise over that period.

As sea level records increase in length, more evidence of long-term signals within the sea level trend becomes available. With these extended records there is evidence to suggest that there are also significant interdecadal signals affecting sea level records.

2.2.4.2 Interdecadal-scale signals affecting mean sea level

There is a significant amount of variability in annual mean sea levels because of the effects of the El Nińo-Southern Oscillation (ENSO) with cycles between two and five years in duration. The Interdecadal Pacific Oscillation (IPO) is a relatively recently discovered phenomena that operates across the Pacific in twenty to thirty year cycles (Goring and Bell, 2001).

Interdecadal changes in the climate affect many natural systems, including water resources in the Americas, and marine fisheries in the North Pacific. Sea surface temperatures are unusually cool in some areas of the Pacific during warm phases of the Pacific Decadal Oscillation, and unusually warm in others. Sea surface pressures are similarly affected, causing enhanced winds (Mantua and Hare, 2002). Increasing quantities of evidence highlight the tendency for the Pacific Decadal Oscillation to affect the southern hemisphere, causing significant surface climate anomalies in the southern regions of the Pacific Ocean (Mantua and Hare, 2002). By association these meteorological changes influence the height of sea level.

The Pacific Ocean has sea surface temperature oscillations on timescales ranging between a few years, to decades. Patterns of low-frequency fluctuations within the climate and ecological systems in the Pacific Ocean and neighbouring regions is the PDO (Mantua and Hare, 2002), which applies to the north Pacific, or the IPO (Power *et al*., 1999), which is recognised as being the wider Pacific Basin phenomena. An investigation carried out by Folland *et al*. (2002) indicates that the IPO is made up of signals with significantly differing periods over a large timescale range. It needs to be noted that some authors identify the IPO as being separate from the ENSO due to several differences concerning the IPO's symmetry about the equator, and variance in the eastern-most Pacific (e.g., Folland, 2008).

Mean sea level rises more quickly when the IPO is in its negative phase than when it is in its positive phase. The Auckland tidal records illustrated in Figure 2.14 show that it was coming out of the Interdecadal Pacific Oscillation's positive phase in 1998 so it can be expected that the following twenty years would rise faster than it had over the 1976 to 1998 period, before once again resuming its positive phase (Goring and Bell, 2001).

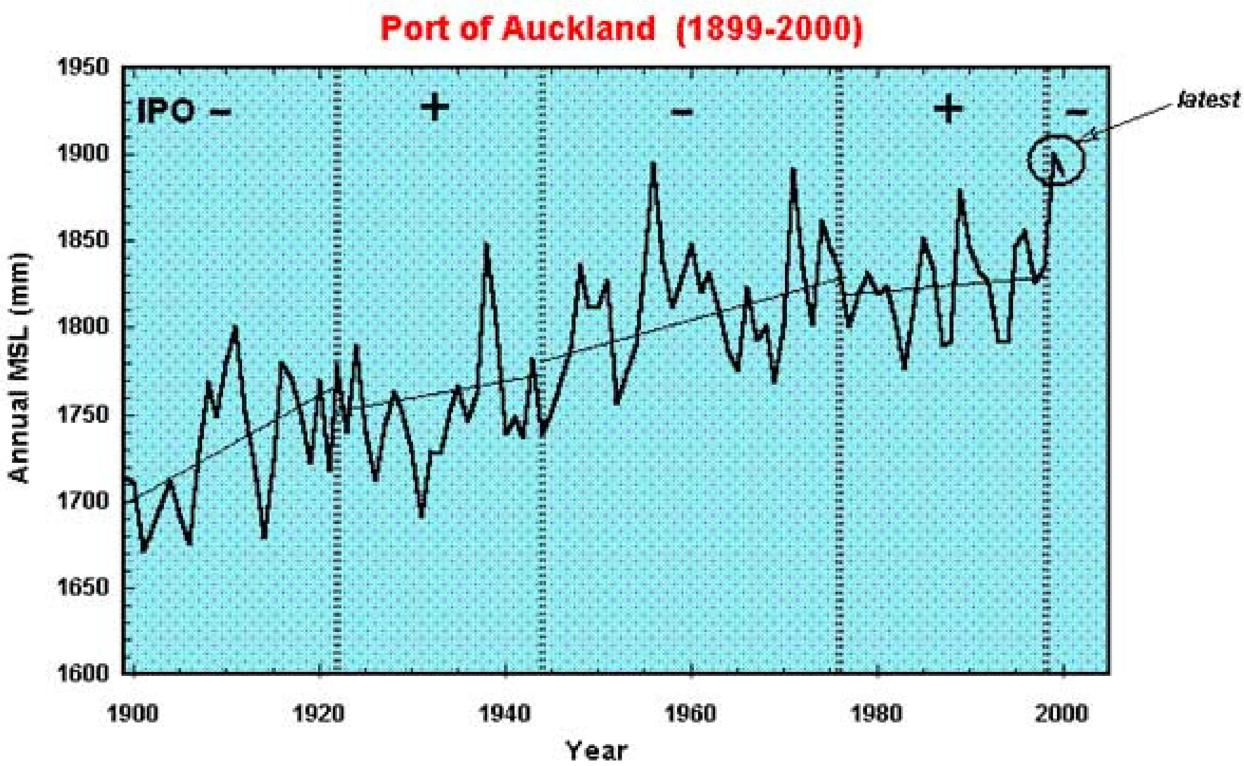

Figure 2.14: Annual mean sea level at the Port of Auckland since 1899. The record is subdivided into phases of the 20 to 30 year cycles of the Interdecadal Pacific Oscillation, accompanied by a piece-wise fit to sea-level rise (Goring and Bell, 2001).

The Interdecadal Pacific Oscillation has almost as much variance in the Southern Hemisphere, as far as 55° South, as in the Northern Hemisphere (Folland, 2008).

The presence of long-term signals in sea level records causes difficulty when attempting to identify the overall trend in sea level over time. This is due to the complex relationship between global warming, long-term signals, and the resulting nature of sea level rise.

2.2.4.3 Relationship between decadal and interdecadal oscillations and sea level rise

Long-term climate records, including annual mean sea levels, and air and sea temperatures, demonstrate continuous fluctuations over various long-term timescales from years to centuries. These fluctuations make it very difficult to determine whether changes in global temperatures are causing an acceleration in sea level rise, causing an increased risk of severe storms, or both (Bell *et al.*, 2000).

An understanding of interannual (year-to-year), interdecadal and potentially multidecadal variability in sea level is required due to the scale of their effects. These larger signals cause variations in the order of 50 to 150 millimetres in annual mean sea level, which may have a significant effect on derived long-term sea level trends. Such trends have magnitudes in the order of only about twenty millimetres, with comparatively short sea level records to derive them from. These fluctuations are caused by varying changes in air temperatures, oceanic currents, and wind patterns over decadal and interdecadal timescales. Unfortunately, there is limited understanding of low-frequency variability in sea level around New Zealand that is caused by these changes in weather patterns. This is due to inconsistent climate records from the more sheltered ports, and a general lack of long-term tide gauges on New Zealand's open coast (Bell *et al.*, 2000).

2.2.4.4 Decadal and interdecadal oscillations summary

The influence of decadal and interdecadal signals on the height of sea level can significantly influence sea level trends over time. To prevent any bias in the result, the signals need to be appropriately incorporated into any analyses.

Meteorological decadal and interdecadal signals influence sea level due to their interrelationships with the ocean. Meteorological changes can also cause proportional changes in the height of sea level through water displacement or by inducing changes in the water's volume.

2.3 Summary of literature review

The rate of sea level rise has changed significantly in nature during the Earth's history. It is essential that the current rate of change is adequately identified so mitigation measures may be taken to prepare low-lying and coastal areas for the future.

To conduct a fully comprehensive investigative analysis into a potential acceleration in the rate of sea level rise, there are numerous factors that need to be considered. Vertical deformation causes the land supporting the mounted tide gauges to shift relative to mean sea level. This movement appears in sea level records by causing the rate of sea level change to appear faster or slower than it truly is. Changes in temperature and atmospheric pressure affect the height of sea level. Increases in the ocean's temperature cause the water to expand, and hence the sea level rises. Atmospheric pressure changes affect the height of sea level with the phenomenon known as the 'inverted barometer effect'. Signals within the historical records of these meteorological influences cause signals in the sea level records through these interrelationships. These signals may be decadal or interdecadal in duration, and their presence and potential influence on ocean water levels need to be understood when investigating trends associated with sea level rise derived from tide gauge data.

3 Analysis datasets

In any study of long-term sea level change, an understanding of the quality of the data is required for assessing the reliability of the derived results. In this chapter, the quality of the records from the four tide gauges used in this study that are located in Auckland, Wellington, Lyttelton and Dunedin, are discussed. The locations of the four tide gauges are illustrated in Figure 3.1.

Reliable datasets are needed for statistical analyses, and so the reliabilities of the tide gauge measurements used in this study must be carefully considered, as discussed in Section 3.3. The criteria used to select which datasets to include in this study are outlined in this section, and the maintenance histories of the tide gauges, with details for relocations, datum shifts, and tide gauge changes, are provided for each gauge.

Hourly, monthly, and annual sea level records were required for the various investigations conducted in this study. The variances associated with these records must be established considering the likely errors associated with the measurements, and any other relevant surrounding circumstances which may affect them.

This chapter begins with a brief discussion of the types of tide gauges used in the data collection process, then describes the way in which hourly, monthly, and annual sea level means were derived. Lastly this section concludes with an overall assessment of quality of the annual mean sea level records.

Figure 3.1: New Zealand's four long-term tide gauges

3.1 Tide gauges used

The sea level measurements utilised in this study were made with forms of float activated tide gauges and acoustic tide gauges, as detailed in Table 3.1. These gauges are used in conjunction with staff tide gauges to ensure the continuity of datum.

All of the raw sea level measurements used to derive monthly and annual sea level values were originally provided by the Auckland, Wellington, Lyttelton and Dunedin Harbour Boards. The derived monthly and annual mean sea level measurements that were used in this study were provided by Land Information New Zealand.

Station Name	Latitude (° ‘ S)	Longitude (° ‘ E)	Periods over which tide gauges were used	
			Time frame	Tide gauge
Auckland	36° 51’	174° 46’	Prior to 1957	Tide gauge unknown
			1957 to August 2000	Munro clock/float
			From March 2000	Vegapuls63 radar unit installed
Wellington	41° 17’	174° 47’	Prior to 1944	Newman float gauge (Adams, 1908)
			1944 until end of 1997	Evershed and Vignoles float gauge with analogue chart
			From 1998	Evershed and Vignoles with digitiser
Lyttelton	43° 36’	172° 43’	Prior to 1955	Tide gauge unknown
			June 1955 until May 1988	Evershed and Vignoles
			June 1988 until 1994	Ellwood Gauge
			From 1994 onwards	Tide gauge type unavailable
Dunedin	45° 53’	170° 30’	Prior to 1917	Tide gauge unknown
			1917 until 1962	Clockwork gauge
			1963 until 1982	Evershed and Vignoles
			1982 until June 1999	Furuno pressure transducer
			From June 1999 onwards	Milltronics Ultrasonic HydroRanger Plus

Table 3.1: Tide gauge station details (Rowe, 2010)

A staff tide gauge consists of a graduated staff with markings typically every 0.1 or 0.01 metres. Staff tide gauges are generally mounted on wharf structures or anchored to the sea floor and are frequently used for short-term surveys, such as tidal datum transfers. Manual observations are required for measurements with these tide gauges (Marshall, 2007). These gauges are used to maintain continuity of datum when establishing a co-located float or acoustic tide gauge in the correct height position

Prior to 1980, most of New Zealand's primary sea level measurements were made using float activated tide gauges, such as that shown in Figure 3.2. A small orifice at the base of the tube allows sea water to flow in and out of the gauge with the influence of the tide. The orifice and the tube act together as a mechanical low-pass filter that eliminates high frequency wave and wake action, as mentioned in Section 2.1.1. As the float rises and falls with the tidal influence, the relative height of the float device is traced out on a paper graph via a mechanical pulley system. The paper graph rotates as it is driven by a mechanical clock. Much of New Zealand's historic tidal records were recorded in this manner (Hannah, 2010-b).

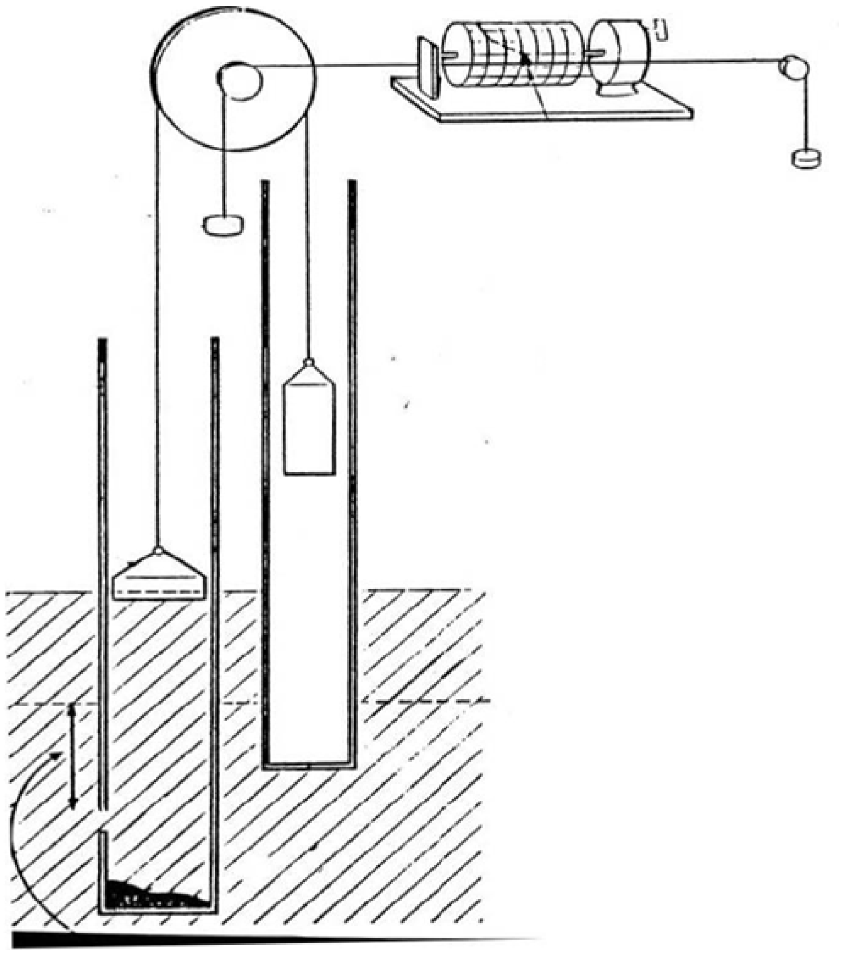

Figure 3.2: Float activated tide gauge (Hannah, 2010-b)

Acoustic tide gauges measure the time taken for a pulse of sound to travel from the source, reflect off the surface of the water and return to the source to calculate the distance travelled. The travel time (t_p) is given by Equation 3.1, where l_z is the distance to be measured, and C_a is the velocity of sound in air. For dry air conditions at 10º Celcius and 1013.7 millibars, the velocity of sound in air is 337.5 metres per second. This means that a change in distance of 0.01 metres causes a change in travel time of 0.000059 seconds. Corrections must be made for the variations of the velocity of sound in air with variations in air temperature, pressure and humidity. If these corrections are not applied it can cause the sea level measurements to be significantly incorrect (Pugh, 1987).

$$t_p = \frac{2l_z}{C_a}$$

Equation 3.1: Acoustic tide gauge signal travel time (Pugh, 1987)

Acoustic tide gauges take ultrasonic measurements at fixed intervals, typically every ten minutes. A burst of observations is taken at a rate of one Hertz for a period of thirty seconds prior to the tenth minute (Marshall, 2007). The standard deviations of the tidal measurements could be established if all of the observations from the bursts taken every ten minutes were available to derive the measurement's average standard deviation.

Submerged acoustic tide gauge measurements may be affected by changes to the water's density from salinity changes due to the velocity of the signal through the water medium changing. A tide gauge near the mouth of a river may have a much lower salinity than tide gauges in harbours without a significant freshwater river flow (Mazzotti *et al.,* 2008). Year-to-year variations in the water's salinity would also be expected due to variations in annual rainfalls.

3.1.1 Errors in the measurement of mean sea level

Tidal records are typically assumed to be of a high quality, and as such the records are rarely subject to question. However, this confidence in the data record can only be maintained through diligent maintenance practices combined with thorough maintenance records. New Zealand's tide gauge maintenance records show that each of New Zealand's primary tide gauges have been renewed, replaced, or changed several times throughout their complex histories that all extend back about one hundred years. These maintenance practices are a common source of error in the sea level records. Further to this, it is not uncommon for tide gauges to malfunction for sometimes very significant periods of time, which may significantly bias the sea level record over that period (Hannah, 2010-b).

There are numerous errors associated with historic graphical tidal records (cf. Rossiter, 1972; Gordon, 1960). The tide gauges that collected the data used in this study were reset approximately once every three weeks, with a reset standard deviation of 0.03 to 0.04 metres. In theory, this resetting practice should eliminate any correlation between the tide gauges. Gordon (1960) suggests that this error combined with expected reading errors produces an annual mean standard deviation of approximately 0.01 metres. Considering this in conjunction with the quality of the tide gauge records and histories, Hannah (1990) decided to assign standard deviations of 0.02 metres to the majority of the historic annual mean sea levels. For the Dunedin mean sea level records prior to 1961, and the Wellington mean sea level records prior to 1944, standard deviations of 0.03 metres were assigned. The standard deviations were increased in the event of incomplete sea level records within an individual year.

The three main sea level measurement devices are staff tide gauges, float activated tide gauges, and acoustic tide gauges. The errors associated with these devices cause errors in the sea level records, which must be incorporated into the variances of the annual mean sea levels.

Staff tide gauge

A staff can usually be read to 0.02 metres from its 0.01 metre graduations, but with increased wave action this standard deviation decreases to 0.05 metres. The perspective of the observer may cause a bias in readings due to parallax error. The use of this form of gauge to maintain the continuation of datum propagates the poor measuring accuracy of the tide staff onto the height accuracy of the primary tide gauge. There may also be further error caused by the staff itself moving from its original position.

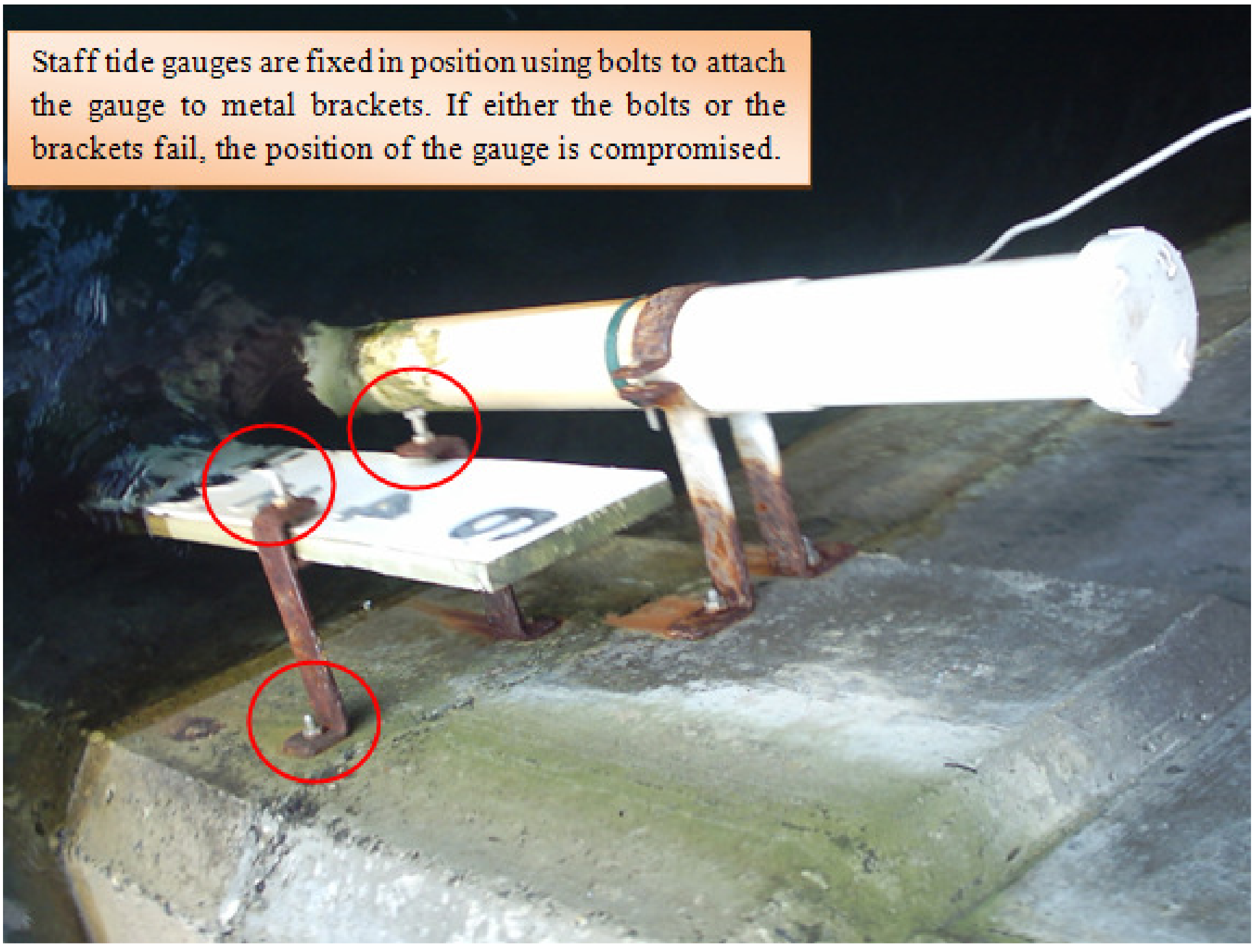

Figure 3.3: Staff tide gauge (photo: Hannah, 2010-b)

Float activated tide gauges

Float activated tide gauges have a number of well known errors. As shown in Figure 3.2, sediment can collect in the bottom of the stilling well. With inadequate maintenance practices this sediment can build up to a point where it prevents the float device from extending to the lowest extents of the tides. Data demonstrating this behaviour is flattened at the lowest points instead of following the typical pseudo-sinusoidal trend. Such data exhibiting this error need to be rejected from the dataset as any mean sea level value derived from measurements containing this error will be subject to significant error.

Excess friction in the stilling well due to inadequate maintenance practices can cause the float mechanism to stick at random locations inside of the tube, causing arbitrary flattening of the tidal curve. Again, any data exhibiting this error must be rejected from the dataset.

The tide gauge's clock may contain errors due to being set incorrectly, or drifting away from the true time over a long period. Errors as large as an hour or more are not unexpected when regular maintenance is neglected.

When float activated tide gauges are installed, fixing the mechanism in the correct height position is often an iterative process. The readings on the graph paper must be aligned to correspond with the correct heights in relation to the local datum (Hannah, 2010-b). Alternatively, an offset between the local datum and the float activated tide gauge can be identified to allow the corrections to be applied in post-processing to ensure that all measurements are in terms of the local datum. However, with this practice comes the potential risk of the offset correction being lost; thereby causing a situation where the measurements are not relative to the local datum and may be deemed useless.

Acoustic tide gauges

Any distance calculated from acoustic tide gauge measurements must be corrected for the gauge's height above its pre-determined zero point. Potential error sources in acoustic tide gauge measurements include susceptibility to temperature and humidity changes, and also through the tide gauge's calibration with external height systems that is considered to be the largest source of error. Calibration with relation to another height system is often very difficult when overhanging wharves or other structures interfere with this process. Such gauges are usually calibrated by manually observing a co-located tide pole (Dewar, 2003). The typical expected standard deviation for sea level heights measured in this manner is 0.01 metres (Dewar, 2003).

Tide gauges are imperfect in their reliability as they can break down due to poor maintenance or bad weather. They may be shut down temporarily for maintenance purposes, or they may break down at random. There are several years of data missing from the Lyttelton and Dunedin sea level datasets in particular. It is not unreasonable to state that there may be a significant bias in the mean sea level value in any one year; especially if the tide gauge is susceptible to breaking down in severe weather events. Severe weather events are associated with significant atmospheric pressure, temperature, and wind changes. These meteorological conditions all affect the height of sea level, and if the heights of sea level are not recorded throughout these events during each year it may have a significant carry-on effect on the derived annual mean.

3.2 Sea level data

The input datasets used in this study were carefully selected so as to obtain the most representative results given the information available. Monthly mean sea levels traditionally provide more data which may be incorporated into the analysis so it is therefore easier to obtain a statistically significant result, as can be seen by considering Equation 5.14. However, the monthly records that are available from the Wellington tide gauge are significantly shorter in duration compared to the annual mean sea levels dataset, as explained below.

It is the length of the Wellington dataset which provides the best evidence of the long-term trend in sea level rise. Annual mean sea level values were utilised for the acceleration analyses undertaken in this study as it was this form of dataset which provided the greatest length of evidence pertaining to sea level change, and the variances of these values could be confidently estimated.

The data used in this study have a wide variety of origins. Much of the data prior to 1990 were derived from float activated tide gauges like that illustrated in Figure 3.2. In principle, these gauges produce a graphical record of the rise and fall of the tide on a slowly rotating mechanical device throughout a period of days. The graphical records from the four tide gauges used here were converted into digital form between 1988 and 1989 (c.f., Hannah, 1990).

The analogue records that were available were digitized to find hourly sea level values, which were then used to derive monthly and then annual mean sea level values. This technique has spectral weaknesses associated with it (cf. Sturges, 1987), but this is the historic methodology used for deriving annual mean sea levels held in archives so all records used in the analyses were derived similarly (Hannah, 1990). In some cases the analogue records were found to be missing, but the annual mean sea levels had been determined some seventy to eighty years earlier and stored in archives. Unfortunately, the monthly mean sea levels associated with these records were mostly unavailable (Hannah, 1990). After being subject to quality control, the records were then converted into monthly mean sea levels (provided there were a minimum of fifteen days of sea level records available, fourteen days for February), and annual mean sea levels.

The exception to the above relates to the records available from the Wellington tide gauge. Wellington's monthly mean sea level records are only available from 1944 onwards, whereas there is annual evidence available demonstrating the nature of the sea level change in Wellington from 1891 onwards, with an unknown change in the standard offset of the gauge relative to mean sea level in either 1942 or 1944. A continuous record of annual mean tide levels is available for the Wellington tide gauge from 1903 to 1970, and another fourteen mean sea level figures prior to 1944 were found. An approximate mean sea level history for the missing years was reconstructed using the annual mean tide level records. However, as the

Wellington tides are not truly symmetrical, this correction can only be considered an approximation [cf. Hydrographer of the Navy (1970) *cited in* Hannah (1990)].

The more recent sea level records have been obtained through using modern acoustic tide gauges in which an electronic signal is typically bounced off the water's surface to measure the height of sea level relative to the distance from the gauge.

Different locations may be subject to different vertical deformation or subsidence motion. With these differing rates of vertical deformation or land subsidence, the rate of observed sea level rise changes accordingly. Therefore, the records analysed in this study should not be considered in isolation as the records from each station are likely to contain vertical shifts from the tide gauges moving vertically during their recording periods. These shifts can be corrected for provided the vertical offsets can be measured and are appropriately recorded.

The figures on pages 57 and 58 show the original, uncorrected annual mean sea level values for Auckland, Wellington, Lyttelton, and Dunedin respectively.

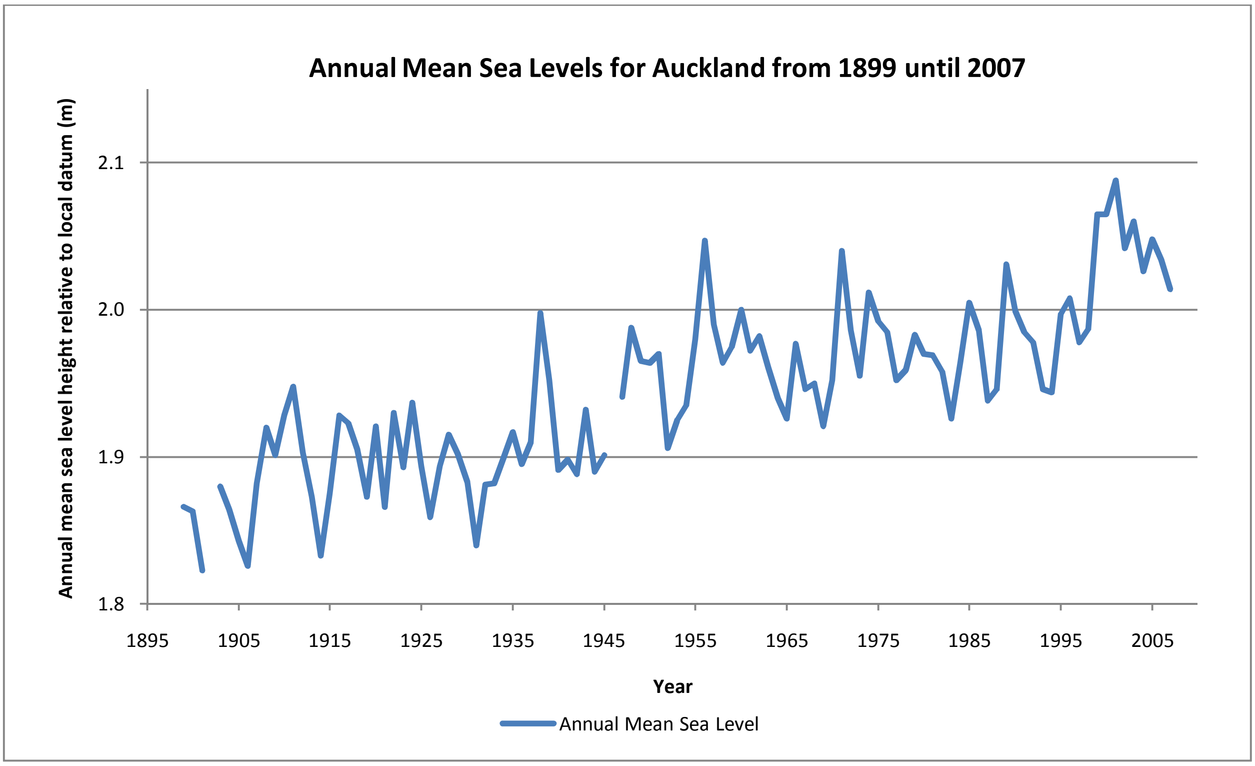

Figure 3.4: Original Annual Mean Sea Levels for Auckland from 1899 until 2007

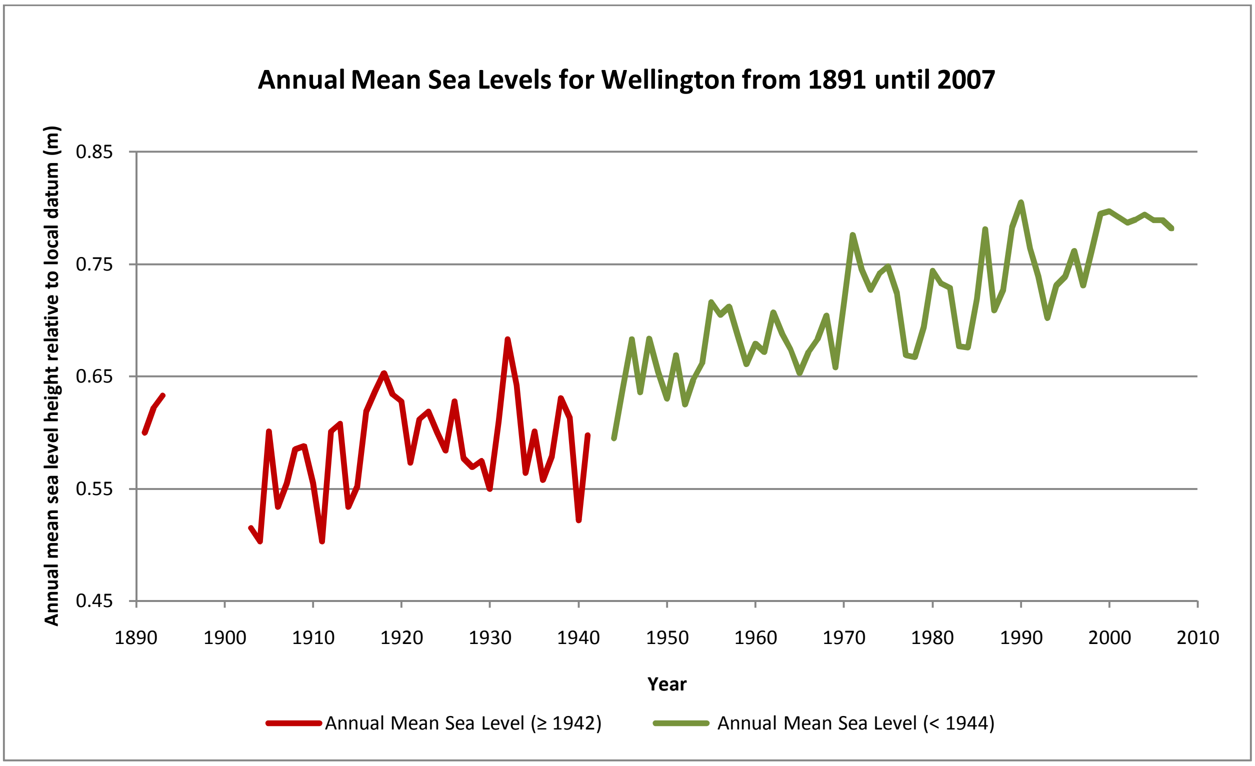

Figure 3.5: Original Annual Mean Sea Levels for Wellington from 1891 until 2007

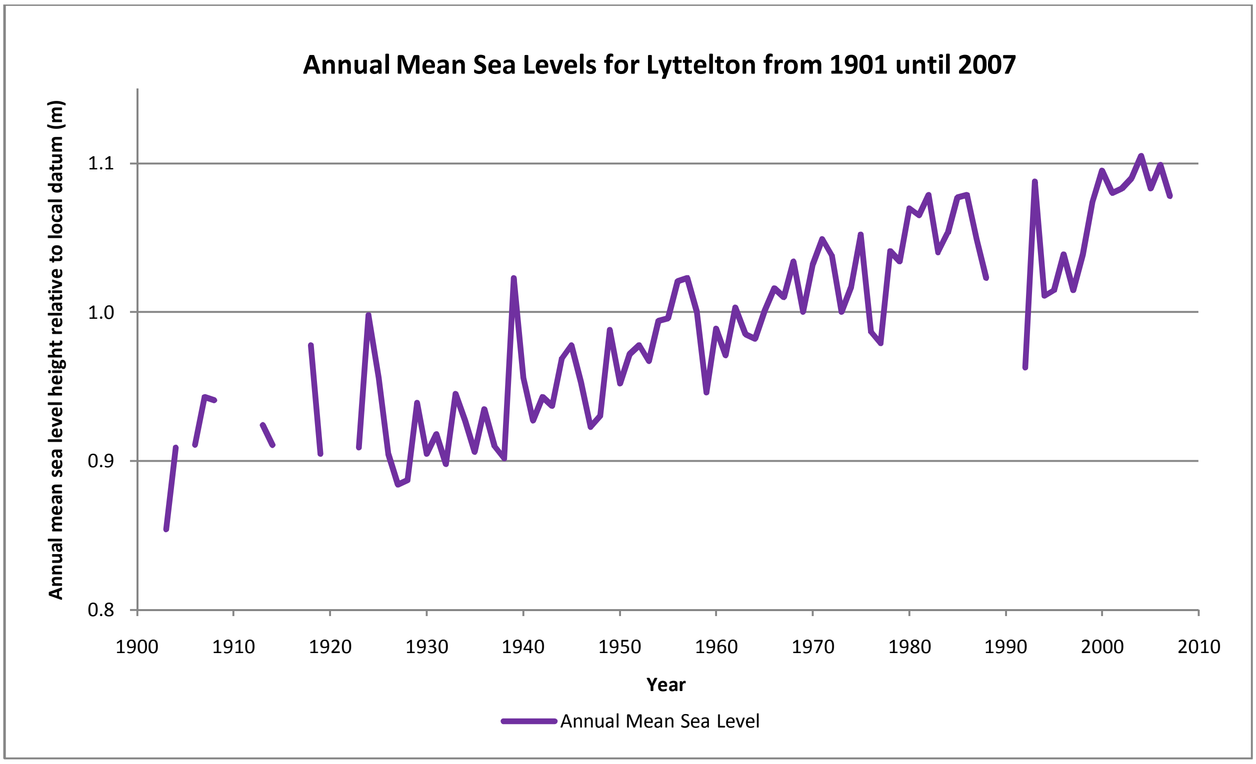

Figure 3.6: Original Annual Mean Sea Levels for Lyttelton from 1901 until 2007

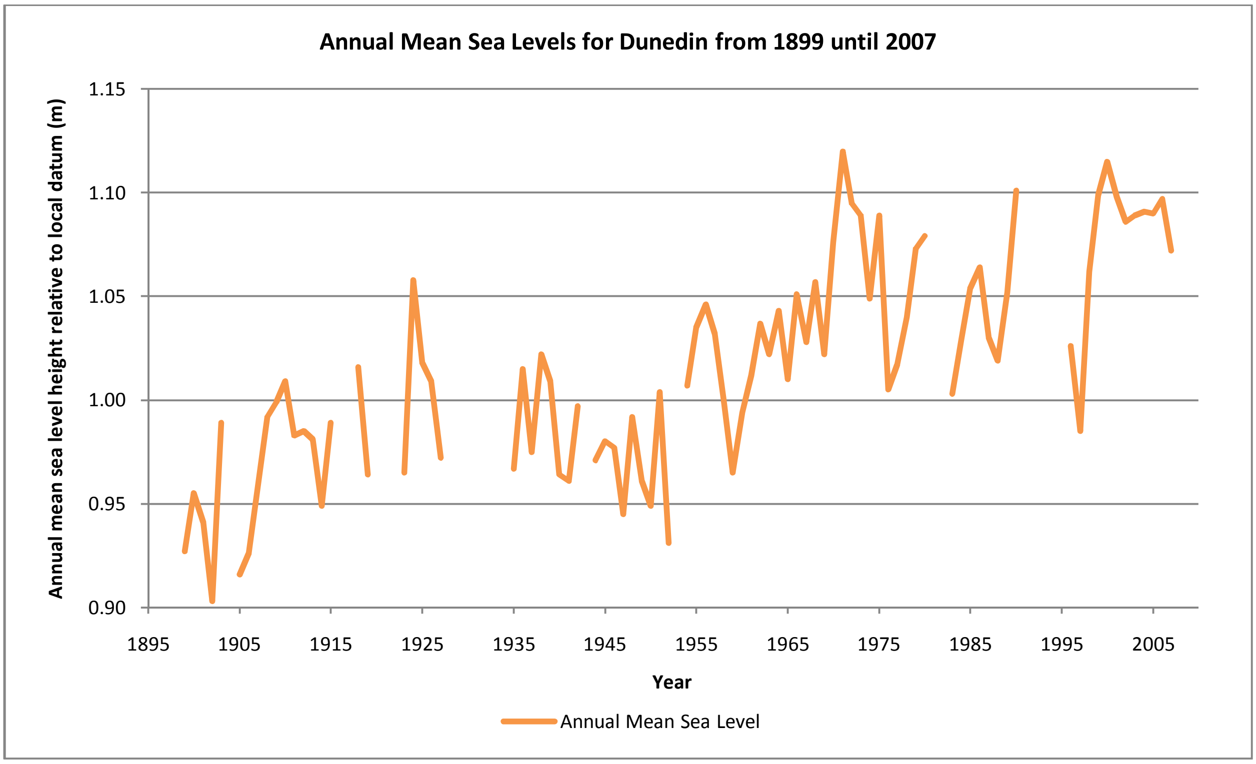

Figure 3.7: Original Annual Mean Sea Levels for Dunedin from 1899 until 2007

3.3 Quality of sea level records

Data quality rests upon four primary factors. Firstly, the maintenance history of the gauge, including the regular care to ensure that the records are referenced correctly with respect to time and with respect to the gauge zero. Secondly, the consistency with which a tide gauge datum has been maintained. Thirdly, the stability of the local wharf structures to which the tide poles and gauges are attached is reviewed, and finally, the stability of the land to which the wharf structures are attached.

The variances of the sea level records must be identified and appropriately incorporated into this analysis for the determination of the true trends in sea level rise. If adequate weighting is not provided for corresponding sea level measurements, an overall result may be found to be inconclusive or incorrect. Furthermore, the data used must be devoid of any significant outliers or errors. Errors may be present in the records due to human measurement errors, or the absence of the relevant maintenance information to isolate the magnitude and timeframe of required data corrections. The data must be considered to be reliable for it to be included in this investigation.

3.3.1 Criteria used for sea level data selection

The investigation carried out by Hannah (1990) isolated which sea level records are considered suitable for this form of analysis of mean sea level data by using the following criteria:

- The data needed forty years of consecutive records for two main reasons. It was considered necessary in order to be able to reasonably separate the sea level trend from the associated noise, and also to cover at least two complete lunar cycles, which have a period of 18.613 years.

- Reasonably well documented maintenance history is required to identify when tide gauges were moved, upgraded, or calibrated. Precise levelling data are required in conjunction with these so that the vertical offsets associated with any recorded movements can be incorporated, and to connect the tide gauge to a local network of stable bench marks.

- Additionally, gauges' proximities to large freshwater rivers were investigated. The data recorded by tide gauges are significantly affected by major rainfall events, increasing the volume of water, especially in harbour basins, and also changing the properties of the water in the harbour due to the changed water salinity.

Douglas (1991) enforced the condition that all records used were required to be at least 80% complete so as to ensure that all low-frequency sea level variations were included. Furthermore, Douglas (1992) detailed that data gaps may also compromise the determination of accelerations in sea level rise.

In contrast to Hannah's (1990) minimum requirement for record duration, Sturges (1987) states that records greater than a minimum of fifty years in length are required in order to distinguish any changes in the rate of sea level rise from long-term influences, such as that caused by decadal and interdecadal oscillations discussed in Section 2.2.4, or background "noise" in the absence of the ability to correct for such effects.

The tidal records from Auckland and Lyttelton are considered to satisfy all of these criteria. Auckland's records are considered to be of very high quality, with the gauge and records being well maintained since 1904. Lyttelton Port has records dating back to 1924 at a site that is considered to be stable. Dunedin records were also selected to be included in the analysis as the breaks in the data in 1953, 1981 and 1982 were considered relatively minor.

The Dunedin gauge is located on a wharf at the end of a narrow harbour approximately twenty kilometres long. The entrance to this harbour was widened and deepened in the 1970s (Vennell, 2010), potentially changing the nature of the tidal signals within the harbour. The quality of the records of the gauge maintenance gives some cause for concern, so the variances of the records are considered poorer in comparison to the other gauges.

The Wellington tide gauge was also included in Hannah's (1990) analysis, and shall be included in this analysis as the gauge has a very good maintenance and site stability history. However, it appears that the continuity of the datum may have been lost in 1944 when a new gauge was installed. Further to this, the Wellington Harbour basin is influenced by the freshwater flows from the Hutt River (Hannah, 1990).

The total length of the annual records that are available are summarised in Table 3.2. However, these records have sporadic gaps in their respective annual mean sea level histories.

Station	Number of years of records	Year records commence
Auckland	107	1899
Wellington	109	1891
Lyttelton	92	1901
Dunedin	90	1899

Table 3.2: Total records available

Despite the stringent criteria that have been used to identify the best stations to incorporate in this study, there are still errors present in the datasets. These errors need to be managed appropriately so that their effects are minimised. Diligent tide gauge maintenance practices reduce the errors in the sea level measurements.

3.3.2 Tide gauge maintenance records

Quality control is required to guarantee that tidal records for a given station remain at the same height relative to the local vertical datum. In particular, corrections for tide gauge relocations, site stability (Mazzotti *et al.*, 2008), and instrument calibration corrections or other instrumental corrections must be diligently recorded and applied accordantly (Pugh, 1987).

Continuing regular maintenance procedures are required for the continuation of unambiguous records. Through regular precise levelling practices in Dunedin it is now apparent that an important reference benchmark relative to the Dunedin tide gauge is gradually sinking over time, whereas the wharf structure itself that the tide gauge is mounted on remains stable (Hannah, 2010-a).

The regular maintenance measures and checks detailed in Hannah (2010) have been applied to the tidal data used for analysis in this study. Tide gauge maintenance records for each of the four tide gauges included in this analysis ideally should ensure that the records are referenced correctly with respect to the relevant tide gauge's zero, and also with respect to time.

Wellington and Auckland mean sea level records were corrected for a significant datum shift associated with changes occurring in relation to the tide gauges' positions. The Dunedin and Lyttelton tide gauges have both had complex histories, and all corrections associated with them have been appropriately incorporated. Unfortunately, as discussed by Hannah (2010-b), there are some circumstances where the maintenance records are found to be lacking, and hence the dates associated with datum corrections, or the quantities concerned, are not precisely known.

The detail and completeness of each tide gauge's maintenance records are obviously inherently related to the quality of the sea level records obtained. The tide gauges used in this study all boast complex histories due to the tide gauges being shifted or reinstated. If the tide gauge is moved without any record of the gauge's change in height, it becomes very difficult to make corrections to ensure that all data are in relation to the same datum. While much greater care has been exercised in the past decade or so with regard to tide pole positioning, a clear and unambiguous historical record remains elusive due to the lack of satisfactory documentation, and also the inconsistent and sometimes inadequate levelling standards that were used at different times (Hannah, 2010-a). Care has been taken to ensure that the records are correctly referenced with respect to time.

Wellington

It is known that the Wellington tide gauge was repositioned in 1944, but unfortunately there are no precise levelling records to show if the gauge's zero was changed, or the quantity of this shift.

A vertical offset correction was calculated using the sea level dataset available at that time by incorporating it as an unknown parameter in the trend analysis process (Hannah, 1990). Unknown vertical offsets must be incorporated into any trend analyses so that errors are propagated appropriately.

Precise levelling records in Wellington have revealed that the tide gauge has been subsiding by 0.15 to 0.20 millimetres per year between 1944 and 2001.

"BM B34P (2H), some 20 m away (from the Wellington tide gauge) *and closer to the shoreline, subsided 4.1 mm* (between 1970 and 2001). *While this trend actually continues through to 2005, between 2005 and 2008 the trend appears to reverse itself such that the 2008 levels are little different from those taken in 2001"* (Hannah, 2010-a).

The reasons for this change are not yet known (Hannah, 2010-a).

Auckland

Maintenance records for the Auckland tide gauge are mostly complete, but with some discrepancy concerning precise levelling records linking the tide gauge zero with the tide gauge bench mark between 2003 and 2010. Fortunately, checks on the tide gauge benchmark and a nearby benchmark between 2000 and 2007 show the wharf structure to be stable, but it cannot be ascertained from this data if the tide gauge zero has remained unchanged over this period (Hannah, 2010-a).

Lyttelton

The history of the tide gauge in Lyttelton has recently been reassessed in Hannah (2010) due to small datum discrepancies in Land Information New Zealand's records. Levelling records to the tide gauge in 1909 compared with 1940 show a discrepancy of 0.02 feet, which has been deemed not significant due to the likelihood of lower levelling standards in 1909. Therefore, the tide gauge has been assumed to be stable over the 31 year interval between these two levelling investigations.

In 1970, levelling revealed that the tide pole zero was 0.04 feet lower than in 1940. Considering that the level of the tide gauge bracket appeared to be stable, it has been assumed that the tide pole was renewed at some unknown date, but not placed in the correct position. Without knowing when this event occurred, the thirty year interval between 1940 and 1970 was separated into two, with the correction of -0.04 feet being applied to the tidal records starting 1956 and carried forward until 1980 when the gauge was renewed. No corrections were applied to the tidal records from 1940 until 1955. The new metric pole installed in late 1980 was found to be 0.08 feet too low in measurements carried out in 1981, and hence corrections have been applied from 1981 until 1986 accordingly. From 1987 until 2002 this correction was applied directly to the tidal data by Mike Day; a representative of the Lyttelton Port Company (Hannah, 2010-a).

In 2003 the tide gauge was once again moved with the new gauge carefully positioned such that the tide gauge zero was returned to its pre-1981 position, and then dropped by 0.293 metres to Chart Datum (Hannah, 2010-a).

There is no evidence of any subsidence occurring in the vicinity of the Lyttelton tide gauge since the commencement of its recording history (Hannah, 2010-a).

Dunedin

The Dunedin tide gauge was positioned with permanent brackets mounted on a wharf pile on the Birch Street Wharf between 1952 and 1963. Connections to the tide gauge zero during this period demonstrated that the gauge was reasonably stable in this location. The position of the tide gauge between 1963 and 1979 was found to be out of position by 0.03 feet relative to the levelling carried out in 1948 and 1952. Furthermore, in 1964 the tide gauge zero was found to be out of position by 0.03 feet, and remained in this position until 1973.

The tide gauge was replaced in 1974 and the tide gauge zero was found to be 0.027 metres too low. Records suggest that this positional error was corrected for, but the exact date of when this correction was applied is uncertain. Levelling records from 1980 relative to a local benchmark suggested that the benchmark itself had subsided by 0.033 feet, while the tide gauge remained stable. This is assumed to have been approximately linear, due to lack of evidence suggesting otherwise, which translates to a subsidence of 0.63 millimetres per year between 1964 and 1979 (Hannah, 2010-a).

In August 1999 the tide gauge was moved to its present location on the Fryatt Street Wharf. Levelling by the University of Otago between the two locations shows consistency of datum through this position change. There has been a suggestion that the tide gauge may have been affected in its new location by subsidence shown to have occurred to local benchmarks, but this evidence is not statistically significant and so has been discounted. This study shall adopt the assumption made by Hannah (2010) that no subsidence has occurred that has affected the tide gauge since 1979.

The Dunedin tide gauge has also been subject to the changing nature of the Dunedin Harbour due to the extensive alterations made to widen and deepen the channel granting large ships access to Otago's ports, and the construction of the harbour's western mole. In 1922 the least centre-line depth of the channel was nineteen feet at low water, and the minimum width between the eighteen foot contour was 130 feet. By 1950 this had changed to a minimum depth of twenty three feet, and a minimum width of 180 feet at the eighteen foot contour. It was estimated that the total reclamation of approximately 280 hectares caused a one-twentieth reduction in the tidal capacity of the harbour, corresponding to the loss of one tide approximately once every ten days (McLintock, 1951). It is worthy of note that this reduction in tidal capacity would not have caused an alteration to mean sea level observed in Dunedin Harbour.

3.3.2.1 Result of tide gauge maintenance investigation

The tide gauges that have been found to be mounted on unstable structures (e.g., Wellington) have been corrected assuming a constant rate of movement over time. All recorded offsets have been accommodated with corresponding corrections applied to the sea level data to ensure the records remain relative to the tide gauge zero.

The only source of discrepancy in the consistency of the sea level records is caused by the apparent omission of the vertical shift of the Wellington tide gauge in its reinstatement in 1944. However, due to the large earthquakes in proximity to the gauge in 1942, the inconsistency of datum around this time must be assumed anyway. Due to the nature of this shift, the new offset may be incorporated into the analysis. There is no degradation of the previous records caused by this movement.

Diligent maintenance of the height of the tide gauges relative to their local datum is essential for the applicability of the tide gauge's records. However, these records may still be subject to other errors relating to the variances in the measurements associated with the device used.

3.4 Summary of the analysis datasets

There are numerous errors associated with float activated and acoustic tide gauges, and staff gauges further contribute to the errors in sea level measurements due to the errors associated with calibrating the gauges to the local datum. Some erroneous data can be identified and removed from the datasets; and the quantity of this invalid data can sometimes become very significant. The removal of the erroneous data may propagate to cause errors in the derived mean sea levels due to the exclusion of important data.

As annual mean sea level measurements make up the primary data used in this study, a comprehensive understanding of the limitations and variances of the records is required. Shifts in the vertical position of the tide gauge and invalid sections of data can severely compromise the applicability of the records for this investigation.

A detailed understanding of the complex histories of each of the tide gauges used in this study is essential. By having an intimate knowledge of these relative histories, biases in specific datasets may be recognised and appreciated. In large-scale investigations that include the records from numerous tide gauges, subtle causes of compromising biases in the datasets are unlikely to be recognised.

4 Methodology

There are a multitude of forces that influence the Earth's seas, causing a combination of short and long-term changes in sea level. These changes compound to create the complex tidal patterns that we observe and cause the variations in the year-to-year annual mean sea levels. By identifying and incorporating the numerous influences on sea level, the variation in the annual mean sea level datasets may be included in the analyses to provide more representative results.

Firstly in this chapter, the methodology used to create a model for the inverted barometer effect is detailed.

This chapter then proceeds to detail the methodologies used to analyse the annual mean sea levels for an accelerating trend over time. Initial linear trend estimate are required to establish the correlations between the four tide gauges' records so that a combined, weighted analysis may be performed. The presence of decadal or interdecadal signals within the sea level records may cause biases in the derived rates of sea level rise. The process used in this study to accommodate these signals in the trend investigations is detailed.

The investigations conducted in this study consider three approaches to the problem. These are:

- An acceleration in sea level rise that is common between all four stations being considered in this study,
- A change in the linear trend in relative sea level rise at each station, and
- Independent relative acceleration trends at each of the tide gauge stations being considered in this study.

Lastly this chapter details the statistical analyses that are used in this study to ascertain the statistical significance of the results obtained.

4.1 Inverted barometer effect investigation

The presence of systematic errors in an analysis' dataset may hinder or prevent the identification of the underlying nature of the dataset. Through the identification and modelling of the inverted barometer effect, these systematic errors may be eliminated, providing 'cleaner' analysis datasets.

This section firstly details how hourly sea level residuals are obtained using Sea Level Data Processing On IBM-PC Compatible Computers Version 3.0 (SLPR2) software.

The section then proceeds to detail the datasets used to generate the residuals utilised in this study.

The local annual mean atmospheric pressures for a given location and the global (oceanic) annual mean atmospheric pressure are required to derive the local relative differences in atmospheric pressure. The source of these required datasets are detailed next in this section.

Finally this section utilises the sea level residuals to identify the local average responses to atmospheric pressure changes, and these responses are incorporated into an overall model for the inverted barometer effect at each tide gauge station considered in this study.

4.1.1 Obtaining sea level residuals using SLPR2 software

The Sea Level Data Processing On IBM-PC Compatible Computers Version 3.0 (SLPR2) package analyses stations' hourly sea level measurements. SLPR2 (Caldwell, 2000) software is a program that uses the Institute of Ocean Sciences Tidal Package (Foreman, 1977) in conjunction with prediction functions for quality control (Caldwell, 2009). The Institute of Ocean Sciences Tidal Package consists of a set of programs, manuals, and test data for analysing and predicting tidal elevation time series data (Foreman, 2009-a).

The tidal heights analysis program analyses extensive datasets containing hourly sea level measurements to calculate the local harmonic and gravitational tidal constituents for the specific tide gauge, which are mostly based on Earth, moon, and sun astronomical configurations. Amplitudes and Greenwich phase lags are calculated using Least Squares analysis, discussed in Section 5.1, coupled with nodal modulation for those constituents that can be resolved given the duration of data supplied. If the time span of the data is insufficient in duration to enable the derivation of important constituents, the inference of the amplitude and phase of these constituents can be sourced from other sets of sea level records from the same station (Foreman, 1977). The harmonic constituents become the input for the sea level prediction function for sea level prediction for any year at that station (Caldwell, 2000). Constituents may be erroneously derived due to incomplete datasets being used, or the dataset containing unusual tidal behaviour.

To obtain the optimum result, the maximum possible number of astronomical and harmonic constituents must be derived and then tested for quality control. Predicted hourly sea levels can be generated for said station for any specified year using these calculated constituents.

The discrepancies between the observed hourly sea levels compared with the predicted tidal patterns provide the sea level residuals.

The residuals are the result of non-periodic drivers; such as meteorological influences and wind-stress changes. The residuals, R, are calculated using Equation 4.1 where H_o is the observed height and H_p is the corresponding predicted height. The residuals show the agreement between the derived sea levels and the observed values, aiding in identifying if any errors lie in the harmonic constituent values. Provided no errors exist, the variations in the derived residuals using different sets of derived constituents for the station can be used to obtain an estimate of the variances of the constituent values.

$$R = H_o - H_P$$

Equation 4.1: Sea Level Data Processing On IBM-PC Compatible Computers Version 3.0 residuals

Hindcasts into the distant past, as far as several hundred years, have been found to still be correct in nature when compared with diary records kept by Captain Vancouver when he explored some of America's coastline in the 1700s (Foreman, 2009-b). Deterioration in the quality of tidal prediction for dates in the distant future relative to the years used to derive the harmonic constituents is not applicable in this study's scenario. The reduction in accuracy caused by the propagation of errors associated with the derived harmonic constituents may only become significant when projecting decades into the future, if not further (Foreman, 2009-b).

The quality control function enables the identification of erroneous constituents through the presence of gross errors, and can be used to separate the non-periodic forcing mechanisms from those that are periodic.

4.1.2 Hourly sea level measurements

Hourly sea level measurements from the Auckland, Wellington, Lyttelton and Dunedin tide gauges from the beginning of the year 2000 until the end of 2007 were provided by The National Climate Database through Land Information New Zealand. Each annual dataset extends from 1.00 a.m. on the first of January for that year until 12.00 a.m. on the first of January the following year. All sea level measurements made over this period using acoustic tide gauges (described in Section 3.1.1) have expected standard deviations of one centimetre. The records from 2000 until 2007 were chosen for this application as the measurements are expected to have lower variances compared with float activated tide gauges.

4.1.2.1 Hourly sea level residuals

The harmonic and gravitational constituents for any given station can be derived using the hourly observations from any given year. Generally, a complete dataset can be analysed to derive more accurate constituents when compared to constituents derived using an incomplete dataset. In theory, the constituents derived from two separate, complete years of hourly sea level observations from a single station should generate identical sea level predictions for a given year. Similarly, if the input datasets are mostly complete, the constituents derived from this data should still provide consistent predicted sea level values. However, in reality this is not necessarily the case.

A source of disagreement between the differing residual values may be caused by the location in question being exposed to unusually complex tides. The tidal analysis cannot fully resolve all constituents due to computation limitations. Using a complete year of hourly measurements as input data, a total of sixty eight constituents can be derived. However, there could be further constituents with sufficient unresolved energy to generate significant variations that are present in the calculated residuals. This has been observed at Balboa, Panama, which has a wide coastal shelf causing complex tides (Caldwell, 2010).

If the timing of the instrument is subject to error, such as clock drift over time, the constituents derived from the tidal analysis based on that year may differ from another. If this error is not resolved, the clock error may propagate through further records, thereby providing inconsistent datasets. However, this form of error is unlikely with modern tide gauges. Very significant differences may be apparent when comparing such sets of residuals.

In theory, residuals should be derived for one year using the constituents from another year for improved redundancy. However, as there is frequently disagreement between the sets of residuals calculated, a further approach that is used in this investigation is to use the residuals from the same year from which the harmonic constituents were derived.

It is the sea level residuals that form the fundamental datasets for the inverted barometer effect investigation. The best quality residuals are required to obtain the optimum indications of the local responses to atmospheric pressure changes.

Monthly sea level residuals

The annual mean sea levels used in this study to investigate if there is a detectible acceleration in the rate of sea level rise have been derived from monthly mean sea level values. The inverted barometer effect is investigated using monthly sea level residuals to potentially obtain an improved model.

The monthly mean residuals are generated through a stepwise methodology. This process assumes that the derived constituents model both short and long-term signals influencing sea level. This proceeds by:

- Generating harmonic constituents from complete datasets of hourly sea level observations throughout the course of one year for each tide gauge station,
- Using the constituents to predict sea levels for every year for which monthly mean sea level records are available for the given station,
- Deriving the mean monthly predicted sea level from the hourly predictions, and then
- Calculating the monthly mean residuals by directly comparing the predicted and observed monthly mean sea levels, and then removing the estimated linear trend in sea level rise from the residuals.

The monthly mean values used for this investigation cover an extensive duration of time. Due to this, the predicted mean sea levels, and hence the residuals, contain errors as they do not incorporate the local trend in sea level rise. The estimated linear trend in sea level rise, discussed in Section 4.1, may be applied to remove this bias in the data for the purpose of this analysis. However, this error is sufficiently small in magnitude that it is swamped by the noise in the data.

4.1.3 Atmospheric pressure data

Specific datasets are required to reduce the year-to-year variability in the annual mean sea level records by applying corrections for the inverted barometer effect. The corrections to the annual mean sea levels for the inverted barometer effect can be investigated and quantified based upon local sea level responses to pressure changes through the comparison of hourly sea level atmospheric pressures with the corresponding sea level residuals.

In order for a relative correction to the annual mean sea levels to be applied, global and local annual mean atmospheric pressures at sea level, and hence the relative differences between them, must be known. Using this information, relevant corrections may be applied to each dataset. The variances of the atmospheric pressure datasets are also required for the purpose of propagating expected errors throughout all data analyses.

4.1.3.1 Local hourly sea level atmospheric pressures

Hourly atmospheric pressure records are required to investigate the local sea level responses to changes in atmospheric pressure. These records must be from weather stations that are in proximity to the tide gauges being investigated in this study. Local monthly mean atmospheric pressures are required for a similar investigation using the monthly mean sea level residuals.

The hourly atmospheric pressure measurements were provided for the years required by the National Institute of Water and Atmospheric Research (2010-a). The weather stations that recorded these meteorological conditions are detailed in Table 4.1. These stations were also used to supply the monthly mean atmospheric pressures, with the exception of Dunedin's monthly mean atmospheric pressure records. The Musselburgh EWS station's records were used for Dunedin's hourly sea level atmospheric pressure datasets. The proximity of the Musselburgh EWS weather station to the Dunedin tide gauge is shown in Figure 4.1.

Standard deviations are established for these hourly atmospheric pressure measurements by considering the records' agreements with overlapping records from other similarly located weather stations. Incomplete datasets do not detract from the overall quality of the hourly datasets as it is the raw observations that are used in the inverted barometer investigation.

Location	Name	Latitude (° ‘ “ S)	Longitude (° ‘ “ E)	Height above sea level (m)
Auckland	Auckland Aero	37° 00‘ 29“	174° 47‘ 19“	33
Wellington	Wellington Aero	41° 19‘ 19“	174° 48‘ 14“	4
Christchurch	Christchurch Aero	43° 29‘ 35“	172° 32‘ 13“	37
Dunedin	Musselburgh EWS	45° 54’ 05”	170° 30’ 53”	4

Table 4.1: Weather stations used to compile hourly sea level atmospheric pressure data for inverted barometer effect investigation (National Institute of Water and Atmospheric Research, 2010)

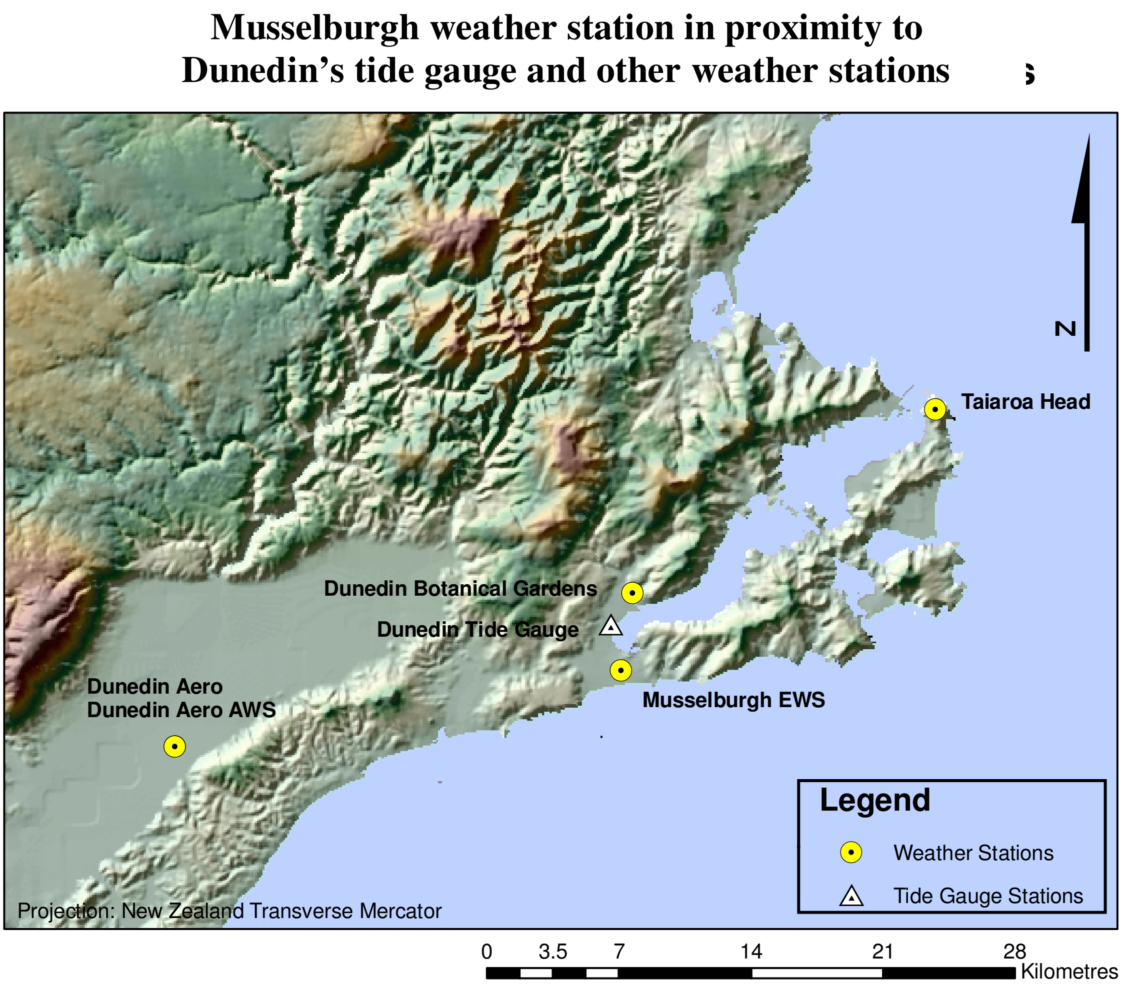

Figure 4.1: Musselburgh weather station in proximity to Dunedin's tide gauge and other weather stations

4.1.3.2 Global average annual sea level atmospheric pressure

The global annual mean atmospheric pressures are required to apply a correction for the inverted barometer effect. The universally acknowledged global average sea level atmospheric pressure is 1013.25 millibars (Cambridge Encyclopedia Vol. 7, 2010). However, the global average sea level atmospheric pressures need to be further investigated as it is likely that there are some year-to-year variations in the atmospheric pressures. The global annual mean sea level atmospheric pressures are investigated in this study using two different datasets, the extended reconstructed sea level pressures dataset and the Hadley centre sea level pressure dataset, to obtain the required information and estimate the standard deviations of the annual mean values.

All global atmospheric pressure records were provided by the National Oceanic and Atmospheric Administration; a federal agency focused on the condition of the oceans and the atmosphere (National Oceanic and Atmospheric Administration, 2002, 2010).

Extended reconstructed sea level pressures

Extended reconstructed sea level pressure datasets provide monthly average sea level atmospheric pressures in a global grid format. Using these global monthly datasets the global (oceanic) average mean sea level atmospheric pressures can be derived.

The extended reconstructed sea level pressure datasets were generated using the most recently available Comprehensive Ocean-Atmosphere Data Set sea level pressure data in conjunction with improved statistical interpolation methods. These interpolation methods enable the stable reconstruction of data over large areas using sparse records from sporadically located weather stations. The Comprehensive Ocean-Atmosphere Data Set was screened using an adaptive quality-control procedure. Land sea level pressures from coastal and island stations were used to supplement the dataset. The locations of these supplementary stations are shown in Figure 4.2.

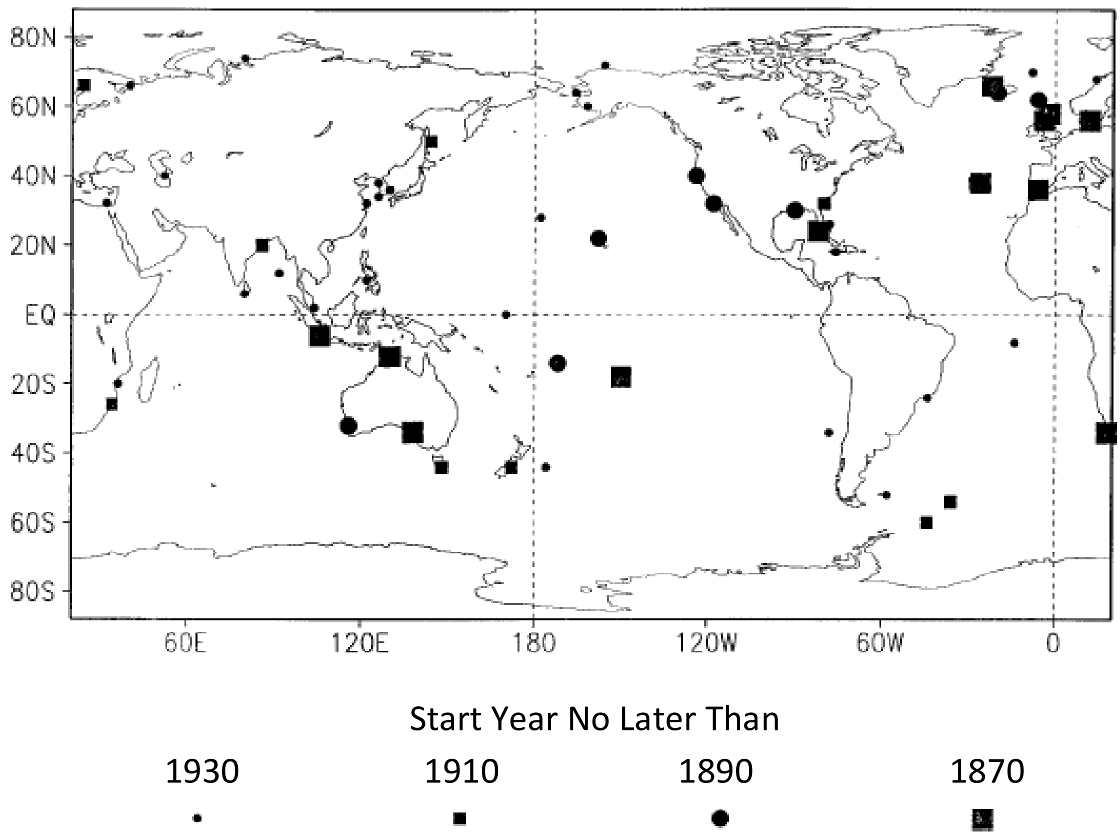

Figure 4.2: Locations of the 58 supplementary coastal and island sea level pressure stations (Smith and Reynolds, 2003)

The monthly datasets are available from January 1854 and extend until December 1997. The atmospheric pressures from the nineteenth century are not considered in this study as the reconstruction appears to underestimate the anomaly amplitudes of the sea level pressures, and the error estimates of the reconstruction are at their maximum during this period (Smith and Reynolds, 2003). After 1900 the reconstruction provides data with improved variances; although there are periods in the first half of the twentieth century when the sampling is of diminished quality, causing the associated variances to increase (Smith and Reynolds, 2003). Spatial correlations investigated to test the reconstruction suggest that the model is most reliable after 1950 (Smith and Reynolds, 2003).

The sea level pressures were generated for a rectangular global grid in 2º by 2º cells, extending from 88º North to 88º South, as illustrated in Figure 4.3. The data was generated using statistics based upon twenty years of assimilated atmospheric reanalysis (Smith and Reynolds, 2003).

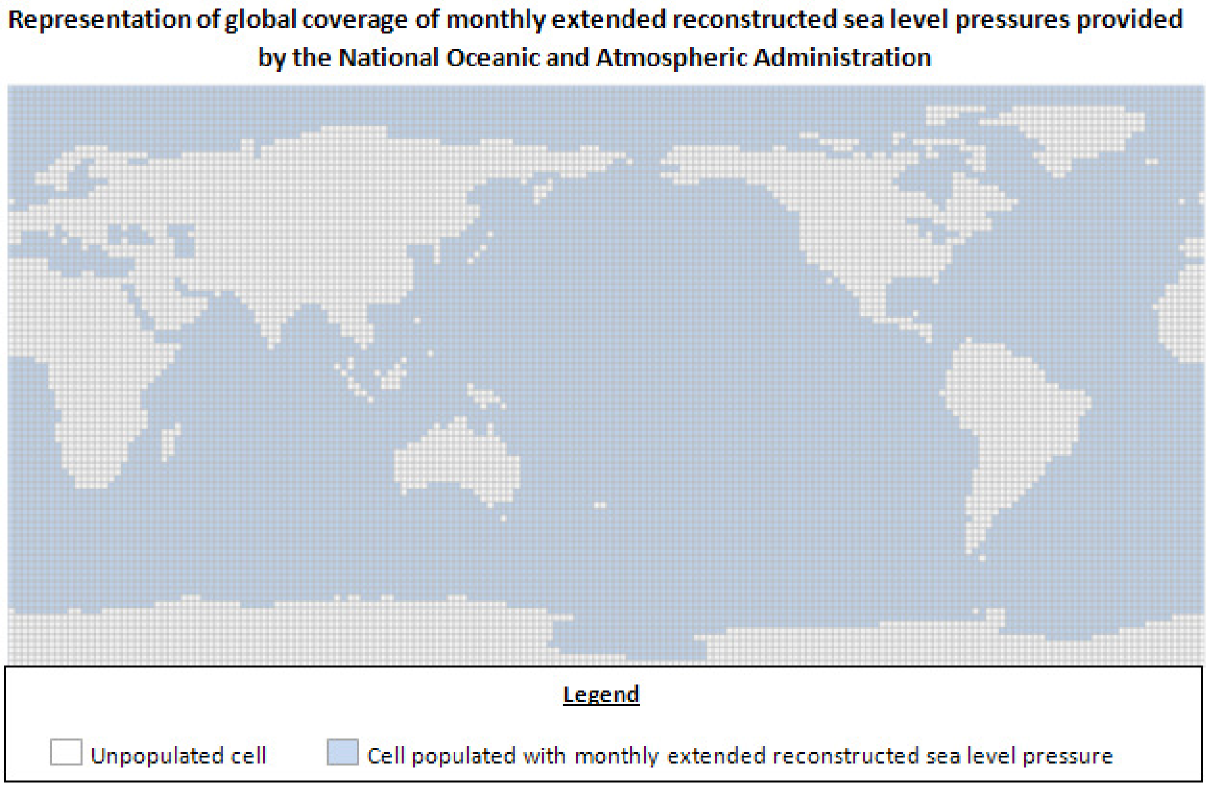

Figure 4.3: Representation of global coverage of extended reconstructed sea level pressures provided by the National Oceanic and Atmospheric Administration (2002), with cells 2° latitude by 2° longitude in dimension on WGS84 projection

Hadley centre sea level pressure dataset

The Hadley Centre sea level pressure (HadSLP2) dataset currently provides data from 1850 until 2010. The dataset uses numerous terrestrial and marine data compilations, all of which were subject to a series of quality control tests. The HadSLP2 dataset was created by combining the processed terrestrial and gridded marine mean sea level pressure data to create a global grid of atmospheric pressure cells. These cells are five latitudinal degrees by five longitudinal degrees in dimension. A total of 2228 stations were incorporated into this dataset, 615 of which had atmospheric pressure data dating back over one hundred years. In contrast however, 275 of the included stations have less than twenty years of observations (Allan and Ansell, 2006). Figure 4.4 illustrates the locations of the stations incorporated into the Hadley Centre sea level pressure dataset.

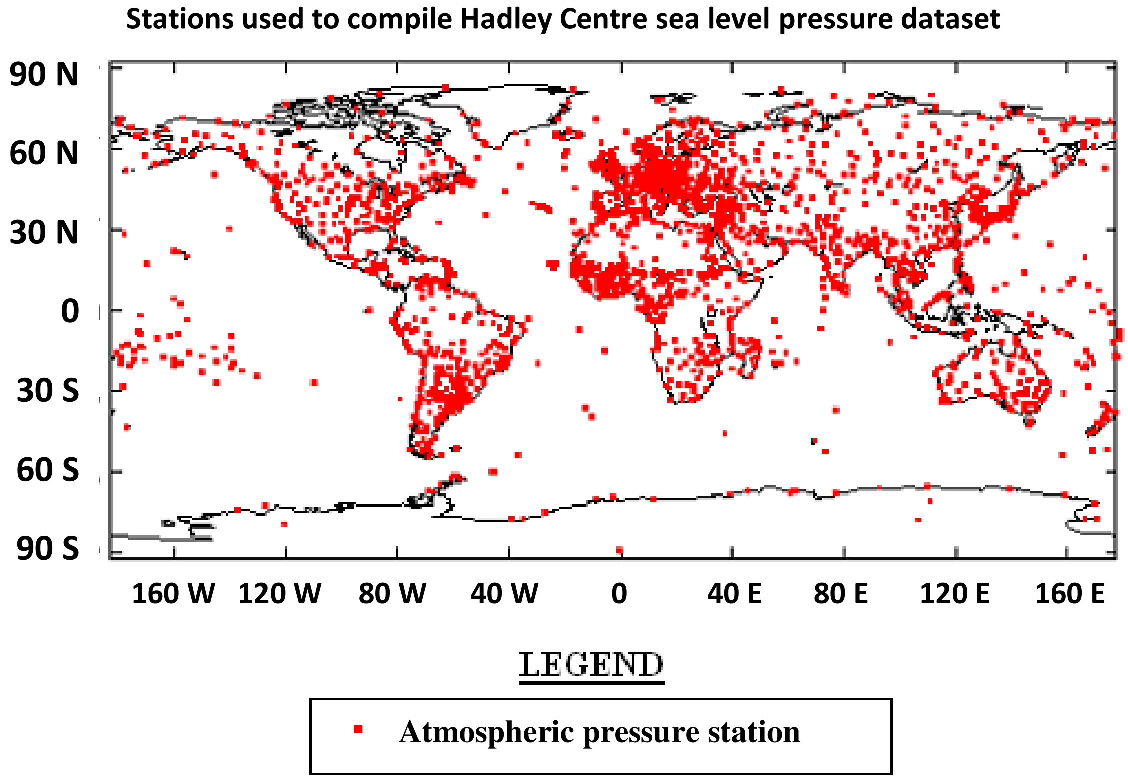

Figure 4.4: Stations used to compile Hadley Centre sea level pressure dataset (Met Office Hadley Centre for Climate Change, 2007)

The dimensions of the monthly mean atmospheric pressure cells are far larger than those produced by the extended reconstructed sea level pressure dataset generation. This is due to the methodology used in creating this datasets that required all of the data values to be provided by pressure stations, and hence no smoothing or infilling techniques were applied (Allan and Ansell, 2006).

The spatial coverage of this dataset extends over all areas of the globe from 70° North to 70° South. Therefore, the data relevant to this study must be extracted from the monthly datasets. All sea level atmospheric pressures located predominantly over land masses were rejected from the dataset, as illustrated in Figure 4.5. The atmospheric pressures over land masses are expected to be higher than those over water bodies due to the land's greater capacity for absorbing and radiating heat, and as such the pressure values must be rejected from the dataset to prevent any bias in the derived oceanic annual mean atmospheric pressures. Only the atmospheric pressures over water bodies are relevant to this investigation as it is local relative pressure differences that cause the inverted barometer effect due to water displacement.

A similar study carried out by Woodworth *et al*. (2009) that utilised the Hadley Centre sea level pressure dataset noted that "*there will be remaining parts of the ocean where computed trends will be very imprecise and where the standard errors determined will not necessarily represent overall uncertainties (southern hemisphere air pressures have many uncertainties even over the last half century, see Jones and Lister, 2007). With this caution in mind, one can see that in the tropics and mid-latitudes the linear trends are of the order of 0.1 mm/year or less and in general will have little influence on studies of secular trends in sea level over these timescales if one assumes that an inverted barometer correction will apply*".

Representation of global coverage of Hadley Centre sea level pressure dataset

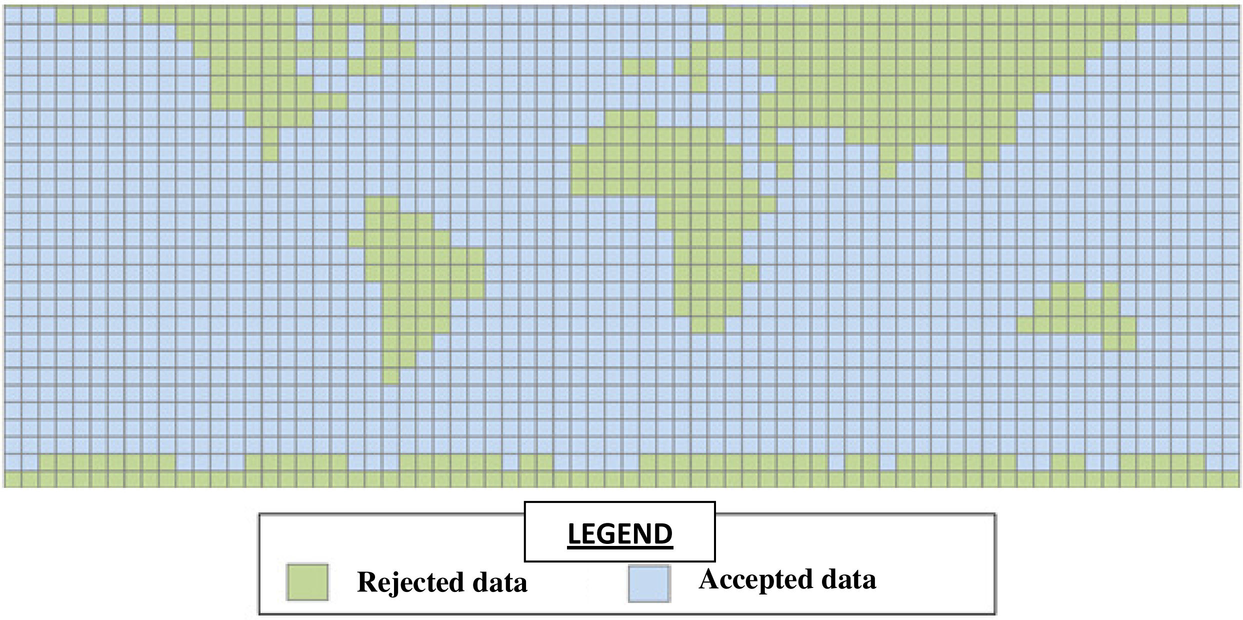

Figure 4.5: Representation of global coverage of Hadley Centre sea level pressure dataset provided by the National Oceanic and Atmospheric Administration (2002), with cells 5° latitude by 5° longitude in dimension on WGS84 projection

Both the HadSLP2 dataset and the extended reconstructed sea level pressure dataset provide atmospheric pressure data in the form of a rectangular representation of the Earth. The true shape of the Earth must be considered to provide representative global average atmospheric pressures.

Extraction of the annual sea level atmospheric pressure data

To derive the global monthly average sea level atmospheric pressures, the pressure values must be considered with proportional weights assigned to them as the Earth is inaccurately represented in the rectangular grid form. The Earth is assumed to be perfectly spherical in shape for the purpose of acquiring weighted global mean atmospheric pressures.

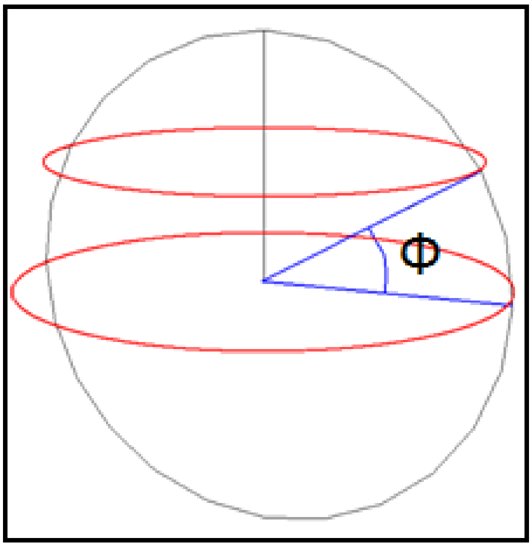

Figure 4.6: Radius of the Earth at a given latitude

Weights were applied to the mean latitudinal sea level atmospheric pressures based upon the ratio of the circumference of the Earth about the given latitude, compared to the circumference of the Earth at the equator, illustrated in Figure 4.6. This is expressed in Equation 4.2, where $W_{\Phi n}$ is the latitude's weight, $C_{\Phi n}$ is the circumference of the Earth at the given latitude, and C_E is the circumference of the Earth at the equator, which is where the Mercator projection intersects the surface of the Earth.

$$W_{\phi n} = \frac{C_{\phi n}}{C_E}$$

Equation 4.2: Weights applied to latitudinal mean sea level atmospheric pressures

The circumference of the Earth at any given latitude is calculated using Equation 4.3, where R is the radius of the Earth that is approximately 6,374,000 kilometres, and Φ is the latitude being considered.

$$C_\Phi = 2\pi R \times \cos \Phi$$

Equation 4.3: Circumference of the Earth at any given latitude

Equation 4.3 assumes that the Earth is perfectly spherical in shape, whereas in reality the Earth more closely resembles an irregular spheroid. For the purpose of establishing monthly weighted average sea level atmospheric pressures, this simplification of the Earth's true form is adequate.

The monthly weighted average sea level atmospheric pressures are derived using Equation 4.4, where P_M is the monthly weighted average pressure, $W_{\Phi n}$ is the weighting for the given latitude, and $P_{M\Phi n}$ is the monthly mean atmospheric pressure at the given latitude.

$$P_M = \frac{\sum_{i=1}^{n} \frac{1}{W_{\Phi n}^2} \times P_{M\Phi n}}{\sum_{i=1}^{n} \frac{1}{W_{\Phi n}^2}}$$

Equation 4.4: Monthly weighted average sea level atmospheric pressures

The final annual mean values are calculated from the twelve months of weighted monthly average sea level atmospheric pressure. This process is performed for both the Hadley Centre sea level pressure dataset and the extended reconstructed sea level pressure dataset to identify the reliability of the datasets, and establish their approximate variances.

Final atmospheric pressure dataset

The Hadley Centre sea level pressure dataset provides sufficient information to establish the annual global average sea level atmospheric pressures for all years that are relevant to this study. It is this dataset that is utilised for the application of corrections for the inverted barometer effect.

The average absolute difference between the reliable data in the two generated annual global average sea level pressure datasets is used to provide a direct estimate of the expected standard deviations associated with the Hadley Centre sea level pressure dataset.

4.1.3.3 Local average annual sea level atmospheric pressure

The corrections to each station for the inverted barometer effect are applied based upon the local annual mean relative differences in atmospheric pressures compared to the global mean. Therefore, the local annual mean atmospheric pressures are required.

The local average annual sea level atmospheric pressures were derived from the compiled dataset of monthly average sea level atmospheric pressure values provided by the National Institute of Water and Atmospheric Research (2010-a). The annual average pressures were generally assigned standard deviations of 0.5 millibars, with increased variances assigned to any annual mean atmospheric pressures that were derived with less than twelve months of monthly mean atmospheric pressures.

The heights of the stations have an influence on the atmospheric pressures they record, as discussed in Section 2.2.3.4. The pressures measured at the weather stations at altitude are corrected to bring them into terms of mean sea level. To identify the quality of the corrected (to sea level) atmospheric pressures from a given weather station, the monthly average atmospheric pressure records were compared against the overlapping corrected average atmospheric pressures provided by another local weather station that is located at a different altitude. This comparison is used to directly establish the standard deviations associated with monthly average sea level atmospheric pressures.

There are no complete sea level atmospheric pressure datasets from appropriately co-located weather stations that cover the full extents of the periods being investigated in this study. Therefore, the monthly, and hence also the annual mean atmospheric pressure values must be compiled from multiple stations, as shown in Table 4.2. The monthly mean atmospheric pressures used to derive the annual mean value in any single year were all provided by one weather station.

The compiled monthly sea level atmospheric pressures for Auckland, Wellington, Lyttelton and Dunedin are illustrated in Figure 4.7, Figure 4.8, Figure 4.9, and Figure 4.10 respectively. These figures show that there are very few gaps in the monthly average atmospheric pressure data records, with the Auckland dataset being the most incomplete. The Dunedin dataset is compiled using four different weather stations, which unfortunately is an unavoidable necessity due to the limited records available at the various local stations. This is a significant weakness in Dunedin's dataset that potentially could introduce errors or inconsistencies into the annual mean pressure values.

The locations of the weather stations used to compile the sea level atmospheric pressure datasets relative to the tide gauge stations are shown in Figure 4.11, Figure 4.12, Figure 4.13, and Figure 4.14 for Auckland, Wellington, Lyttelton, and Dunedin respectively.

Location	Name	Latitude (° ‘ “ S)	Longitude (° ‘ “ E)	Height above mean sea level (m)	Dates of records used Start date	End date
Auckland	Auckland, Albert Park	36° 51‘ 11“	174° 46‘ 01“	49	February 1916	December 1984
	Auckland Aero	37° 00‘ 29“	174° 47‘ 19“	33	January 1985	December 2007
Wellington	Wellington, Kelburn AWS	41° 17‘ 06“	174° 46‘ 05“	125	January 1904	December 1986
	Wellington Aero	41° 19‘ 19“	174° 48‘ 14“	4	January 1987	December 2007
Christchurch	Christchurch Gardens	43° 31‘ 52“	172° 37‘ 08“	7	January 1905	December 1984
	Christchurch Aero	43° 29‘ 35“	172° 32‘ 13“	37	January 1985	December 2007
Dunedin	Dunedin Botanical Gardens	45° 51‘ 36“	170° 31‘ 19“	73	January 1913	December 1936
	Taiaroa Head	45° 46’ 37”	170° 43’ 31”	72	January 1937	December 1962
	Dunedin Aero AWS	45° 55‘ 44“	170° 11‘ 49“	1	January 1992	December 1994
	Dunedin Aero	45° 55‘ 44“	170° 11‘ 46“	1	January 1963	December 1991
					January 1995	December 2007

Table 4.2: Weather stations used to provide periods of monthly average sea level atmospheric pressure values (National Institute of Water and Atmospheric Research, 2010)

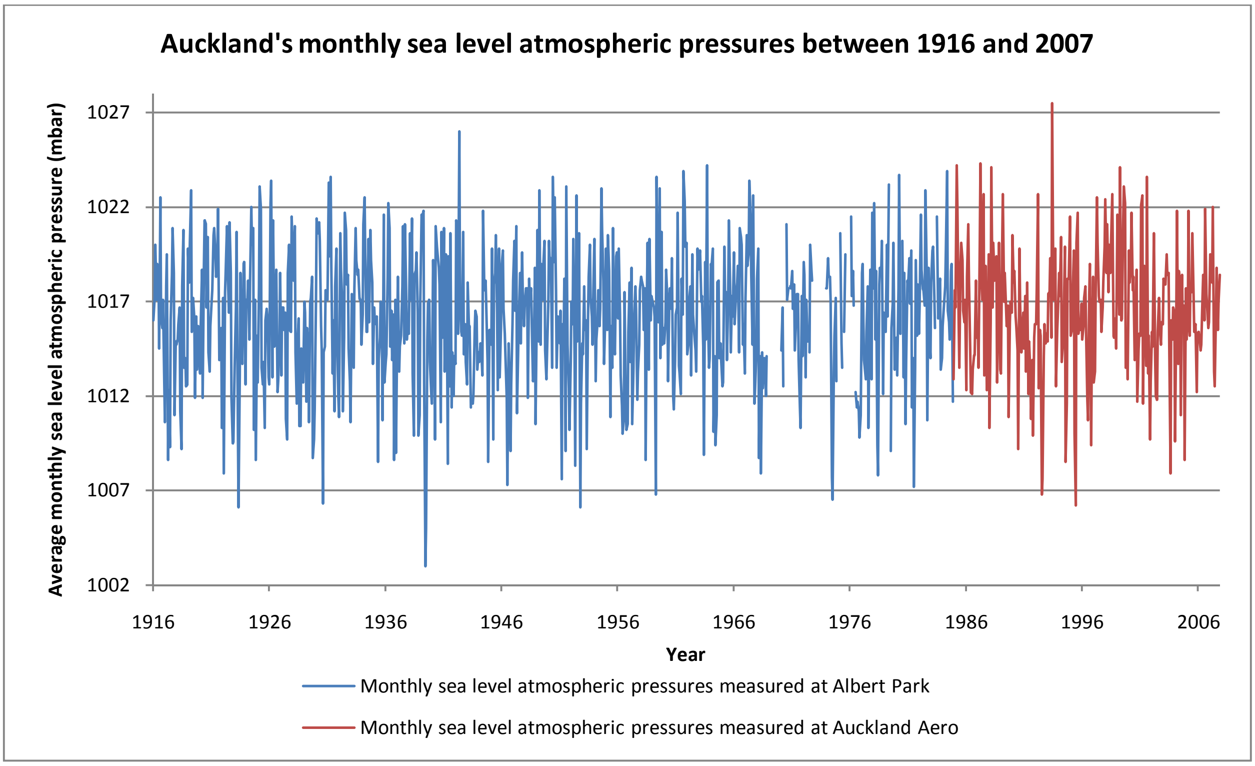

Figure 4.7: Auckland's monthly sea level atmospheric pressures between 1916 and 2007

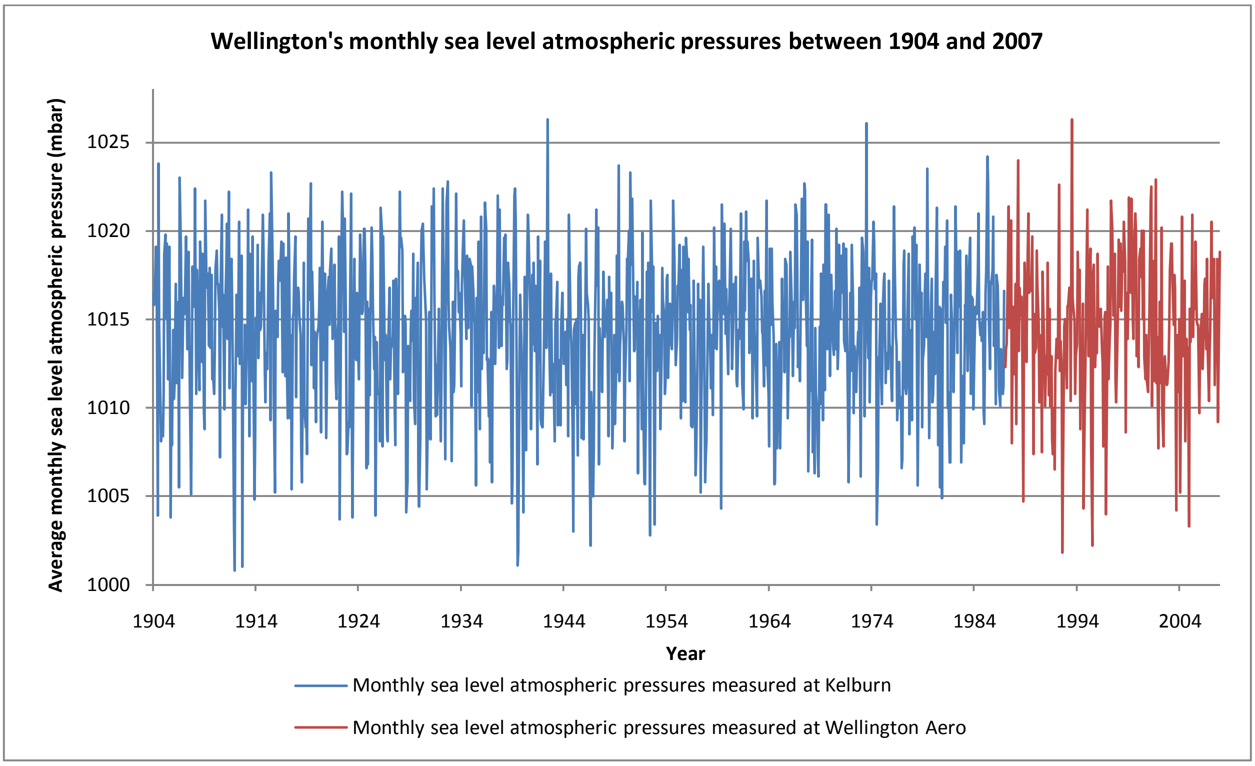

Figure 4.8: Wellington's monthly sea level atmospheric pressures between 1904 and 2007

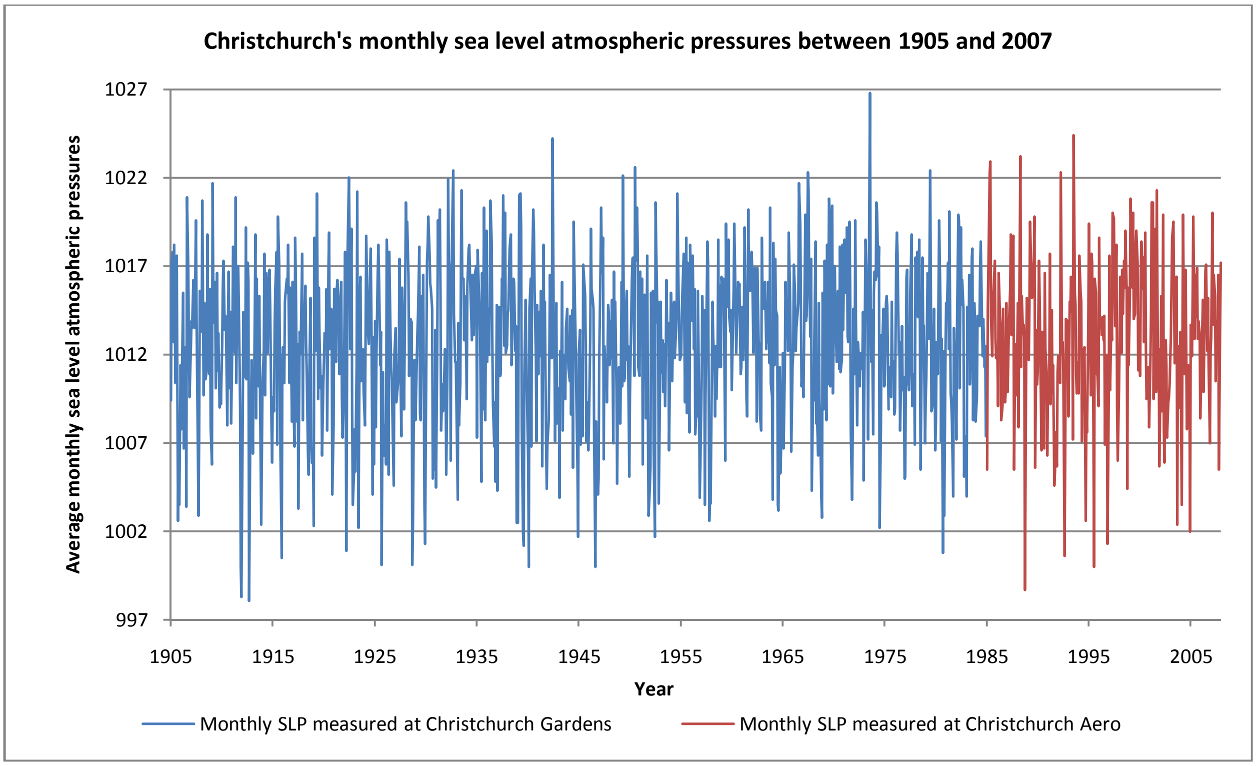

Figure 4.9: Christchurch's monthly sea level atmospheric pressures between 1905 and 2007

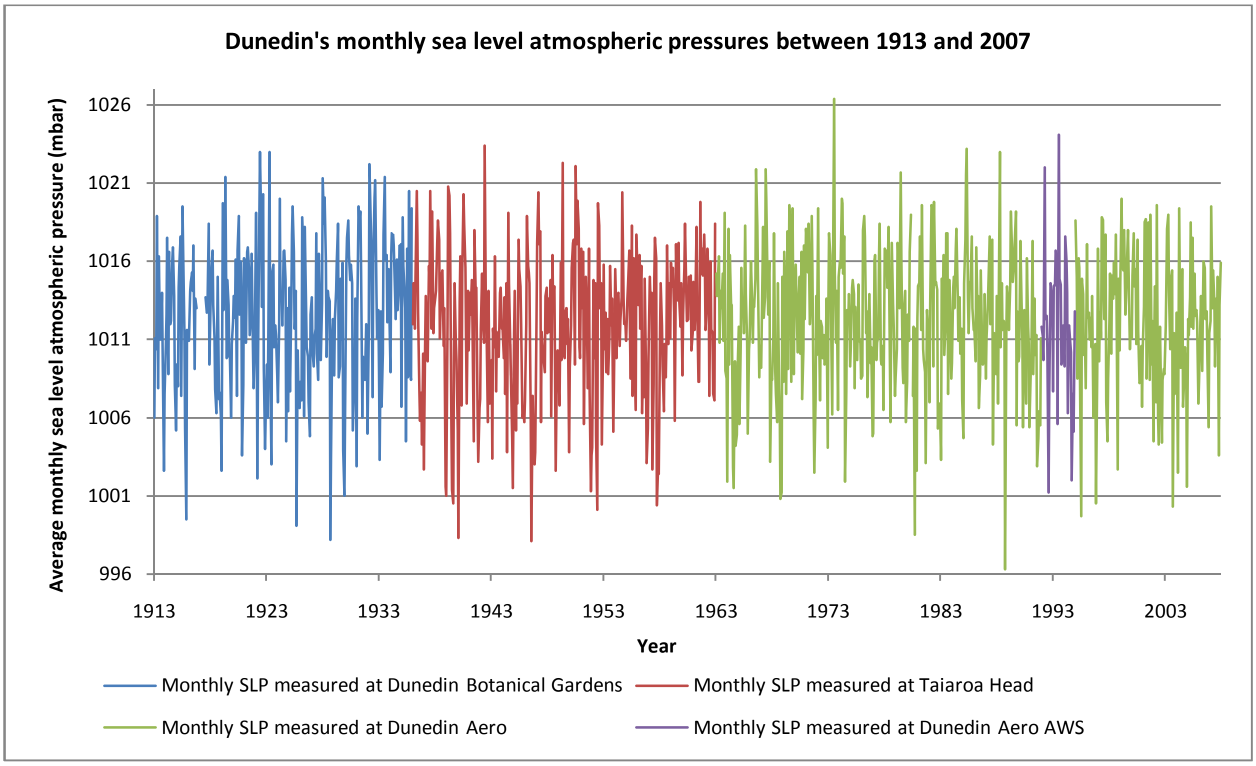

Figure 4.10: Dunedin's monthly sea level atmospheric pressures between 1913 and 2007

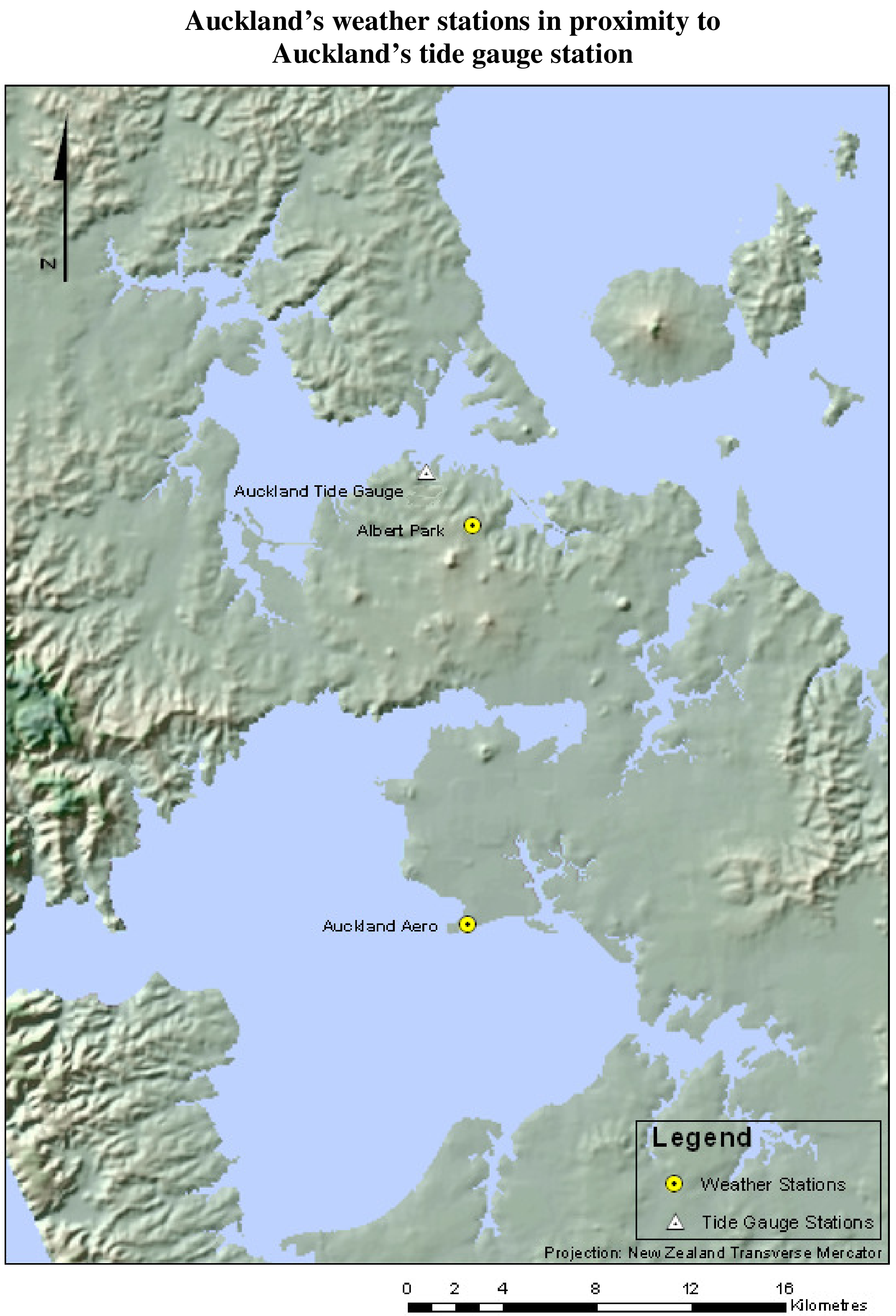

Figure 4.11: Auckland's weather stations in proximity to Auckland's tide gauge station

Figure 4.12: Wellington's weather stations in proximity to Wellington's tide gauge station

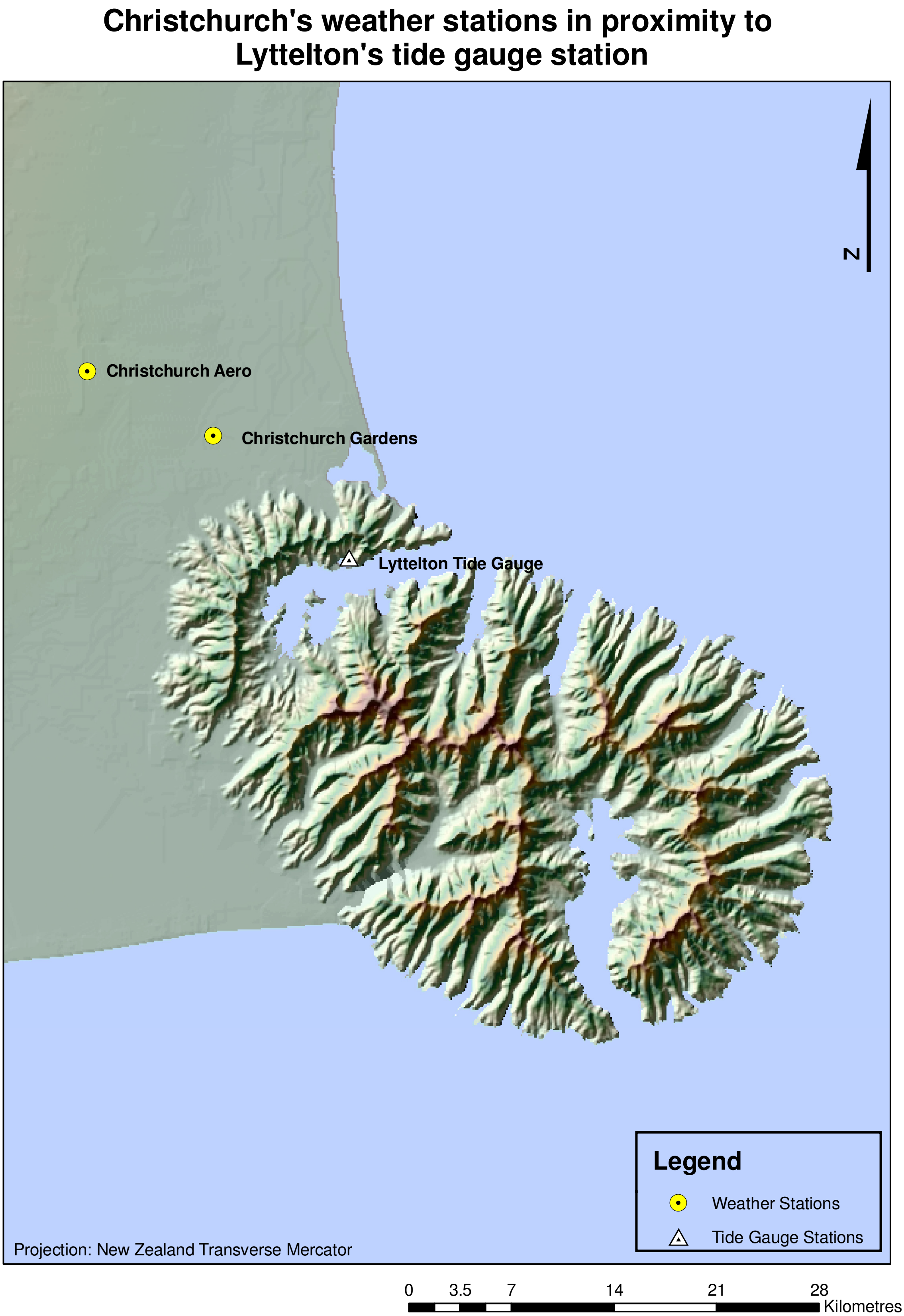

Figure 4.13: Christchurch's weather stations in proximity to Lyttelton's tide gauge station

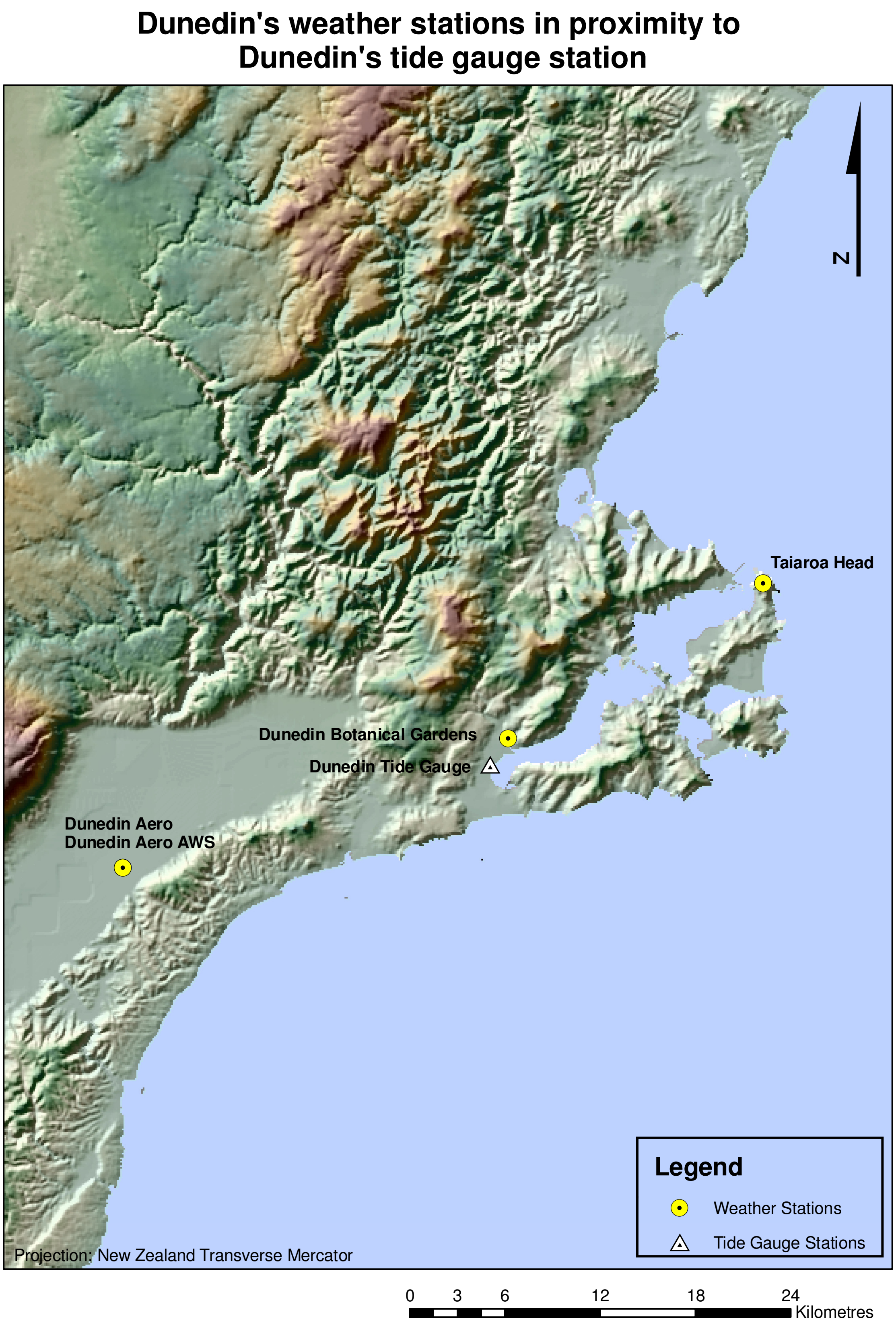

Figure 4.14: Dunedin's weather stations in proximity to Dunedin's tide gauge station

Using the relative differences in local annual mean atmospheric pressures compared to the global means, corrections may be applied the annual mean sea level values, provided the local average responses to atmospheric pressure changes are known.

4.1.4 Inverted barometer trend analysis

As discussed in Section 2.2.3, a change in atmospheric pressure of one millibar causes a negative relative change in height of sea level of approximately ten millimetres. Individual analyses are carried out to better identify the influence such a change in pressure has on the height of sea level in the localities of each of the four tide gauges. To do this the sea level residuals calculated through the methodology outlined in Section 4.1.2.1 are paired with the corresponding atmospheric pressures recorded at that location. The trend between these two variables reveals their interdependencies. Sections 4.1.2.1 addressed the issue of obtaining the best estimates for the hourly and monthly sea level residual values, which are required for obtaining results that accurately represent the relationship between atmospheric pressure variations and the influence on the height of sea level.

By identifying the variables associated with the inverted barometer effect the variability in the annual mean sea levels may be reduced by correcting the data for this systematic effect.

It is worthy of note that the influence of temperature variations, as discussed in Section 2.2.2, are not considered in this analysis. A trend in global temperatures would contribute to global sea level change. An increase in global mean temperature, and hence in the ocean's volume through thermal expansion, could be a continuing effect causing a trend in sea level rise that may be non-linear in nature. The inverted barometer effect causes variation in sea level, but this variation is only about the mean sea level height in order to maintain global equilibrium. Therefore, the inverted barometer effect does not contribute to the trend in sea level rise; it only contributes to the overall variability.

Generally, Equation 4.5 is applied when calculating the change in water height due to changes in atmospheric pressure, where Δh_i is the change in height in millimetres for the time in question, P_{li} is the corresponding local atmospheric pressure, -10 represents the universal approximation for how many millimetres by which the sea level changes for every unit increase in atmospheric pressure (in millibars), and 1013.7 is the universally accepted average sea level atmospheric pressure in millibars. This sea level response may be subject to a time lag that may be apparent when considering hourly data.

$$\Delta h_i = -10(P_{li} - 1013.7)$$

Equation 4.5: Generalised equation for change in sea level due to atmospheric pressure variation

The values for the average sea level response and the average sea level atmospheric pressure have both been investigated further earlier in this chapter. The incorporation of these revised variables into the inverted barometer effect correction is detailed in this section.

4.1.4.1 Relative atmospheric pressure change response

A variation in the average annual atmospheric pressure causes an overall step-up or step-down of the tidal data for that year, which is incorporated into the derived constituents as a standard offset. Therefore the mean pressure for the year from which the harmonic constituents are derived using the Sea Level Data Processing On IBM-PC Compatible Computers Version 3.0 (SLPR2) software must be recorded and used in the analysis of local response to atmospheric pressure changes.

Equation 4.6 represents this relationship, where Δh_i is the change in the height of sea level in millimetres, P_{li} is the simultaneous local atmospheric pressure, η_l is the local response to a change in atmospheric pressure in millimetres, and P_μ is the annual mean atmospheric pressure for the year from which the harmonic constituents were derived.

$$\Delta h_i = \eta_l(P_{li} - P_\mu)$$

Equation 4.6: Change in sea level due to atmospheric pressure variation relative to annual mean value

To ensure reliability and to overcome any possible year-to-year variations if significant wind set-up is present, the analysis is carried out using multiple years of generated sea level residuals and corresponding relative atmospheric pressure differences for each tide gauge to obtain a confident weighted mean result.

4.1.4.2 Impact of atmospheric pressure variations on annual mean sea levels

As noted in Section 2.2.3, a change in atmospheric pressure does not cause the ocean to expand or be compressed; the water is displaced. Therefore, logic dictates that the inverted barometer effect cannot cause an increase in global sea level unless there is a global shift in the mean pressure. Instead, the inverted barometer effect causes variation in the water's height about mean sea level.

To confidently derive the local responses to pressure changes (ie, η_l) Least Squares linear regression analysis is applied. By pairing each sea level residual with its corresponding relative atmospheric pressure change counterpart on the axes shown in Figure 4.15, the relationship between the two variables can be determined using Least Squares linear regression analysis.

$$(SLR_{t0}, \Delta P_{t0}), (SLR_{t1}, \Delta P_{t1}), \dots , (SLR_{tn}, \Delta P_{tn})$$

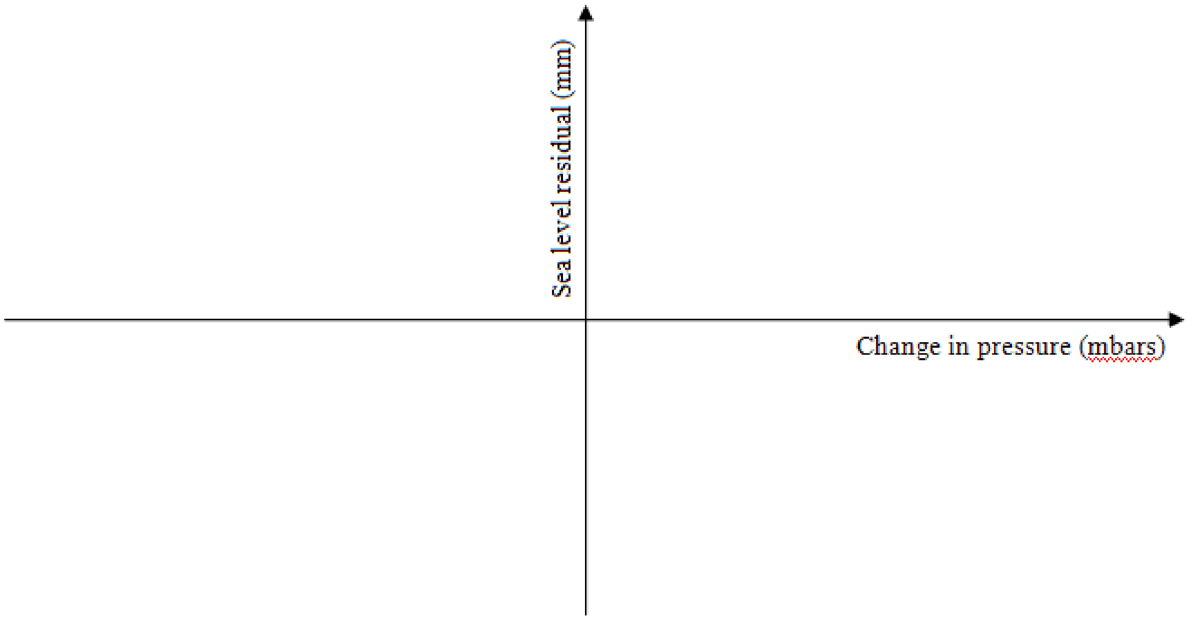

Figure 4.15: Axes of data plot investigating inverted barometer effect

The paired data demonstrates a trend that is associated with the influence of pressure changes on the height of sea level. The data demonstrates natural variation about this trend that is attributed to random errors in the residual generation method. Further variations are caused by other non-periodic drivers; namely wind set-up. The relationship is calculated as a gradient and offset for the apparent trend between the atmospheric pressure changes and the sea level residuals, which is expressed in Equation 4.7.

$$\Delta h = \eta_l(\Delta P) + c$$

Equation 4.7: Linear relationship between pressure variation and sea level change

The gradient (η_l) represents the location's average response of the sea level (Δh) in the given locality per unit change in atmospheric pressure (ΔP) in millibars. The offset (c) has no practical application in this investigation. The derived variance covariance matrices provide the estimated variances associated with the trend components.

This analysis can be performed using the hourly sea level residuals with their corresponding hourly sea level atmospheric pressure observations, and also by using similar datasets on monthly timescales.

For water to be displaced due to an increase in atmospheric pressure in one location, the water level must adjust accordingly to accommodate for this displaced water in another location with lower atmospheric pressure. Equilibrium must be retained around the globe. If this was not the case, water would need to expand, compress, or be created or destroyed as atmospheric pressures change.

To accommodate the varying atmospheric pressures around the globe, Equation 4.8 is proposed, where Δh_i is the change in the height of sea level in millimetres for the year in question, $P_{l\mu i}$ is the local annual mean atmospheric pressure, η_l is the local sea level change in millimetres per millibar change in atmospheric pressure, and $P_{g\mu i}$ is the annual average sea level atmospheric pressure over the Earth's oceans.

$$\Delta h_i = \eta_l (P_{l\mu i} - P_{g\mu i})$$

Equation 4.8: Change in sea level due to atmospheric pressure variation relative to global annual mean

Using the derived average local sea level response to atmospheric pressure variations, the local annual mean atmospheric pressures, and the annual mean atmospheric pressure over the Earth's oceans, the annual mean sea level can be corrected for the inverted barometer effect. There are errors associated with this correction and also with the annual mean local and global atmospheric pressure data, especially for those extending far back to the earliest dates used. These errors have been propagated accordingly (ie, Equation 5.15), so the derived results have realistic variances associated with them.

4.2 Sea level trend investigations

The purpose of this study is to identify if there has been an acceleration or change in the rate of sea level rise during New Zealand's sea level recording period. To do this, several trend investigations are conducted.

Firstly, initial trend estimates for the rate of sea level rise at each of the individual gauges must be derived as some of the processing methodologies require datasets with constant mean values. These datasets are applied in the investigations into the correlations between the stations used in this study. The identification of the correlations between the stations allows the combined analysis of the sea level datasets.

The presence of decadal and interdecadal signals is considered in this study as such signals may cause biases in the derived sea level trends. This chapter goes on to discuss the methodology used to isolate the most significant signals within the sea level records, which are then incorporated into the overall trend analyses.

The trend analyses investigate the various sea level datasets, which have not been corrected for the initial linear trend estimates, for the presence of an acceleration or increase in the rate in sea level rise. This process is repeated for the datasets that have been corrected for the inverted barometer effect, as well as those that have not.

4.2.1 Derivation of linear trend first estimate

To obtain sea level values that do not demonstrate increasing trends over time, linear estimates of the rates of sea level rise are made for each station individually. This trend can then be removed from the records, thereby providing a new (detrended) time series dataset that has retained its natural variability, but has a single constant mean value.

Least Squares analysis, discussed in Section 5.1, is applied to obtain these linear trend estimates. Equation 4.9 is used to identify the linear trends in sea level rise using the annual mean sea levels measured by the tide gauges in Auckland, Lyttelton and Dunedin. For all trend analyses, t_0 is 1891, which is the year of New Zealand's earliest annual mean sea level record. These linear estimates are calculated using the full duration of sea level time series records for each of the four stations. The only corrections applied to the mean values are those that are required to ensure continuity of datum, provided such corrections are available. Therefore, the datasets being analysed are subject to the influence of decadal and interdecadal signals, as well as the changes in sea level that are associated with the inverted barometer effect and thermal expansion.

$$y = m(t_i - t_0) + c$$

Equation 4.9: Linear trend

$$y = m(t_i - t_0) + c_{(ti<te)} + c_{(ti \geq te)}$$

Equation 4.10: Approximate linear trend in sea level rise for Wellington

The gradient value represents the average change in height of sea level per year. The offset parameter represents the height of sea level at t_0 relative to the tide gauge zero. Equation 4.10 is applied for Wellington's approximate trend investigation. The offset at the Wellington tide gauge changes in 1944 (t_e). Section 4.2.4.1 discusses the implications of this change and details how the offset is incorporated in this study.

A linear trend estimate is made in preference to a quadratic trend estimate as this methodology preserves the systematic effects within the datasets, enabling them to be identified and potentially eliminated prior to investigating for the presence of an acceleration or change in trend.

As this study is iterative in nature, any parameters that require the approximated linear trends to be removed from the datasets can be recalculated using the improving estimates relating to the nature of the rate of sea level rise as the analysis progresses. Small changes in the estimates of the trends in sea level rise will have negligible effects on the detrended datasets.

4.2.2 Correlation coefficients

As mentioned in Section 5.1, a common weakness in results obtained through Least Squares analyses is the overly optimistic estimates for the variances associated with the derived parameters. This underestimation occurs as a result of the frequently made assumption that all measurements are independent. In relation to this study, this implies that the observations at each tide gauge station are all independent from each other. Under this assumption, all of the covariances in the Least Squares weight matrix are made equal to zero. However, this assumption is not necessarily accurate so it demands further investigation.

Year-to-year annual mean sea levels measured at a single tide gauge are assumed to be independent from each other as the tide gauge is reset approximately once every three weeks. The fact that this process was carried out at least eighteen times each year suggests that any interdependence between consecutive annual mean sea level values has been largely removed.

Pearson's Correlation Coefficient equation (Equation 5.1) is intended to be applied to data with a stationary mean value. Unfortunately, the mean sea level values used in this study display an increasing trend over time. This should not cause any significant errors on a year-to-year basis, but for best practice constant mean values are preferable. To accommodate this, an initial linear estimate for the trend in sea level rise is derived for each individual station, discussed in Section 4.1. The gradients of these trends represent the change in the mean values over time. By removing the trends from the sea level dataset, a new dataset is obtained that demonstrates a singular constant mean value. Through this methodology, the data retains its natural variability about the mean and systematic changes, and as such the standard deviation of the sample can be directly derived from the new dataset.

As this is an iterative study, the results obtained that are indicative of more complex behaviour in sea level rise than simple linear change can be used to reinvestigate the correlations between stations. These recalculated correlations may be applied to obtain improved results for the various parameters investigated.

4.2.3 Analysis of Decadal and Interdecadal trends

The long-term tidal signals that influence annual mean sea levels have periods of 8.847 and 18.613 years. These oscillations are not necessarily in phase between the four tide gauge stations, and therefore models representing these signals must be calculated for each individual station. The signals must be investigated for significance while also considering the presence of other potentially more significant long-term non-tidal signals. Only the most significant signals are incorporated into the analyses to prevent bias in any derived trends from an oscillation's partial phase, while also obtaining statistically significant results. Figure 4.16 shows a theoretical signal with an amplitude of ten millimetres and a period of twenty-five years to illustrate the potential impact that the presence of such signals could have on a trend investigation. The timescales being considered in this study are far greater than those shown in this illustration; but the bias potential remains very significant. The influence of such signals is dependent upon both the amplitude of the signal, and the period being considered. The most effective methodology for managing this potential error is by incorporating the signals into the analysis appropriately.

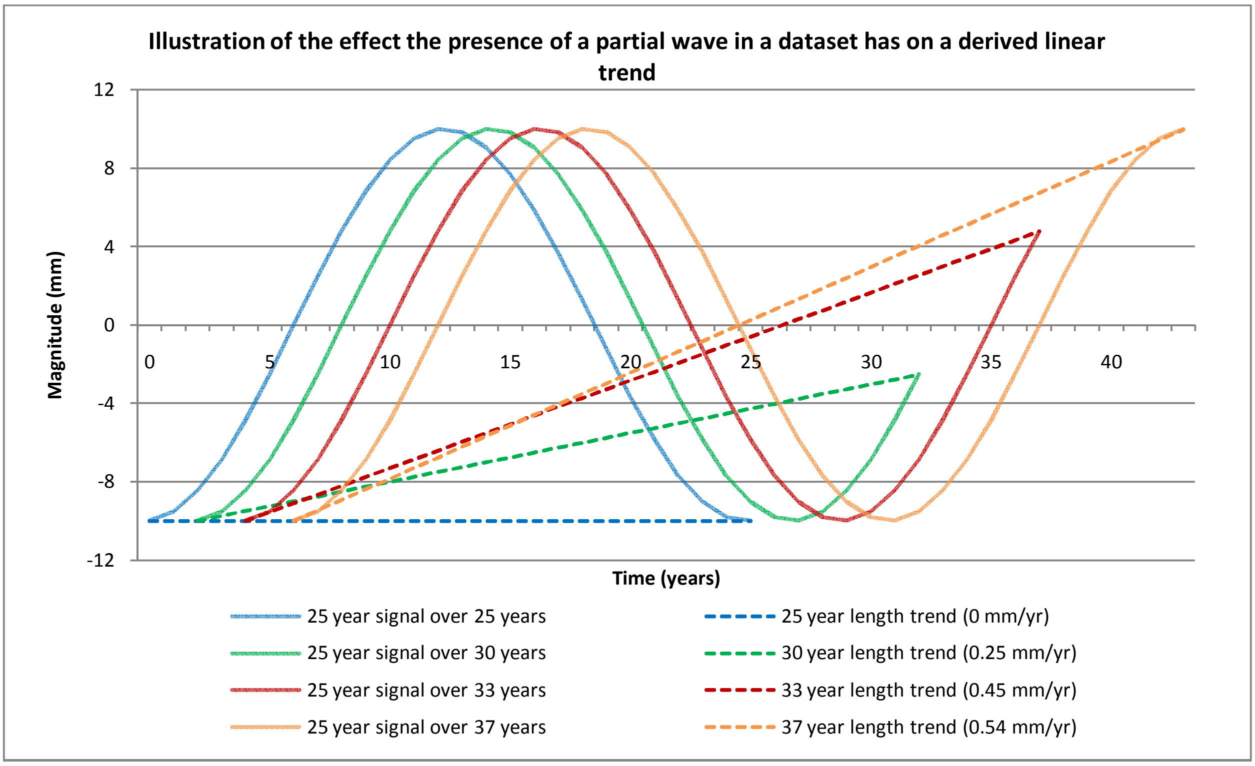

Figure 4.16: Illustration of the effect the presence of a partial wave in a dataset has on a derived linear trend

Equation 4.11 is used in the Least Squares analysis to calculate the combined effects of signals present within the dataset, where α_1, b_1, α_2, and b_2 are the unknown amplitude parameters, and ω_1 and ω_2 are the signals' unknown periods.

$$\sum_{j=1}^{2} A_j \cos(\omega_j t_i - \phi_j) = \alpha_1 \cos \omega_1 t_i + b_1 \sin \omega_1 t_i + \alpha_2 \cos \omega_2 t_i + b_2 \sin \omega_2 t_i$$

Equation 4.11: Equation for derivation of signals present in mean sea level data (Hannah, 1990)

This equation can be extended to include all signals that are indicated as being significant, as represented below in Equation 4.12, using the *α*, *b*, and *ω* parameters to model each individual signal. All signals must be processed in the same analysis to prevent any false aliasing occurring.

$$\sum_{j=1}^{n} A_j \cos(\omega_j t_i - \phi_j) = \alpha_1 \cos \omega_1 t_i + b_1 \sin \omega_1 t_i + \alpha_2 \cos \omega_2 t_i + b_2 \sin \omega_2 t_i + \cdots + \alpha_n \cos \omega_n t_i + b_n \sin \omega_n t_i$$

Equation 4.12: Extended equation for derivation of signals present in mean sea level data

Through the identification of the various statistically significant signals influencing the annual mean sea levels, the influence of the signals may then be incorporated into the analysis. By identifying the approximate periods of these signals they may be incorporated in the Least Squares analysis as observations that have associated variances. The equations utilised in this methodology are detailed in Section 5.3.1.3. Through incorporating Equation 4.12 into the overall trend analysis, the signals are included in the Least Squares model, thereby preventing any bias in the derived result.

4.2.3.1 Datasets used in Fast Fourier Transform signal analyses

In order to apply Equation 4.12, the periods of the signals being modelled must first be estimated to prevent the Least Squares analysis from converging on a less significant signal present in the dataset. The Fast Fourier Transform converts a time-series dataset into the frequency domain. It can be performed using Python's Spyder software, using "*An algorithm for the machine calculation of complex Fourier series*" (Cooley and Tukey, 1965). Through this process it is possible to identify the predominant signals within the records, and isolate the approximate periods of those signals (Andreasen, 2005). The details pertaining to the processing software and the analyses used are provided in Section 9.4 in the Appendix. The effect of the signal on the dataset being analysed is indicated in the data output through the signals' amplitudes and corresponding significance at the 95% confidence interval.

Annual mean sea levels

The input data used for the Fast Fourier Transform investigation must be entirely complete. Both the Lyttelton and Dunedin annual mean sea level datasets have numerous years for which no annual mean sea level record is available. Fortunately, the Auckland annual mean sea levels dataset is complete with the exception of only the mean sea level value for 1946, and the Wellington annual mean sea level dataset is entirely complete from 1903 onwards.

In order to complete the Auckland dataset, linear interpolation was applied. This is expressed in Equation 4.13 that uses the annual mean sea level from the previous year, MSL_{n-1}, and the subsequent year, MSL_{n+1}, to approximate the annual mean sea level value (MSL_n). This methodology is not believed to provide the true annual mean sea level value for 1946, but merely serves to provide an approximation. This is necessary to permit the Fast Fourier Transform analysis to be carried out using Auckland's annual mean sea level dataset. As this approach is only required to approximate one absent mean sea level value, the resulting dataset is considered to be of adequate quality for this investigation. However, if this methodology is applied too often, the dataset obtained no longer reflects the true nature of the mean sea level variations, and hence the signals within the dataset in question may be compromised. The estimated value may be improved upon by considering the likely influence of the annual mean relative difference in atmospheric pressure and the annual mean temperature. This methodology may be suitable when multiple values are required to be estimated, provided the likely influences of these variables are reliably modelled.

$$MSL_n = MSL_{n-1} + \frac{(MSL_{n+1} - MSL_{n-1})}{2}$$

Equation 4.13: Mean sea level linear interpolation

By applying this technique to complete Auckland's dataset, both Auckland and Wellington can be analysed for significant signals that may be modelled using Least Squares analysis through incorporating Equation 4.12. The interpolated mean sea level value for Auckland is only applied for the purpose of this single investigation.

It must be noted that Wellington's annual mean sea level values for 1942 and 1943 must be included in this analysis. The approximate trends in sea level rise, discussed in Section 4.1, must be removed from the input datasets prior to the analysis. The change in standard offset for this trend for Wellington is considered to be 1942 (ie, t_e) for this application.

As mentioned in Section 4.2.3, this analysis is applied to identify the approximate periods of the significant decadal and interdecadal signals within the Auckland and Wellington mean sea level time series datasets. The detected signals are expected to include the Interdecadal Pacific Oscillation, the Southern Oscillation Index, and the El Niño-Southern Oscillation, although the influences of these respective signals may not be statistically significant. All of these oscillations have reduced effects at greater latitudes, and hence the periods calculated for the signals affecting the Auckland and Wellington mean sea levels cannot be directly translated to Lyttelton or Dunedin.

As the effects of the non-tidal decadal and interdecadal signals are believed to decrease as latitudes increase, it is expected that the signals in the Lyttelton and Dunedin datasets are less significant than those contained within Wellington's and Auckland's records.

To incorporate the decadal and interdecadal signals in the Lyttelton and Dunedin datasets into the Least Squares model, the approximate periods obtained for the most significant signals in Auckland's and Wellington's datasets are used as the initial estimates for the periods of the signals within Lyttelton's and Dunedin's records. Through the Least Squares iteration process, the analysis will converge on the true periods of the signals that are present in the datasets. Unfortunately, as the Lyttelton and Dunedin datasets cannot be used in the Fast Fourier Transform analysis, more significant signals of different periods cannot be identified.

Least Squares analysis is limited by its ability to identify signals that are statistically significant. The resolution of the analysis weakens with the inclusion of more unknown parameters, as shown in Equation 5.14. Therefore, the number of signals that are included in this analysis must be limited to only those long-term signals of the greatest statistical significance.

Relative differences in annual mean atmospheric pressures

Atmospheric pressure changes cause the height of sea level to change. By association, that means that if there are signals present within the annual mean relative differences in atmospheric pressure, then similar signals are expected to be present in the annual mean sea level datasets also. The corrections for the inverted barometer effect should theoretically remove these common, pressure driven signals entirely from the mean sea level dataset (e.g., the Southern Oscillation Index). Therefore, the relative differences in atmospheric pressure should also be investigated for significant decadal and interdecadal signals to aid in isolating the sources of the various signals influencing sea levels.

The compiled sea level atmospheric pressure datasets in the localities of the four stations being considered in this study are complete, or nearly complete. Due to this, all sets of relative differences in atmospheric pressures may be analysed for significant signals. Auckland is the only station that requires linear interpolation to approximate one absent annual average sea level atmospheric pressure value.

If there is strong evidence to suggest that the signals present in the annual mean sea level records are also present in the average relative differences in sea level atmospheric pressure datasets, then these two datasets may be combined to improve the resolution of the periods of the signals in question, provided that the inverted barometer effect has not been otherwise removed. This is shown in Equation 4.14, where the signals' periods (ie, ω_1) are common between the two datasets.

$$\sum_{j=1}^{n} A_j \cos(\omega_j t_i - \phi_j) = \alpha_1 \cos \omega_1 t_i + b_1 \sin \omega_1 t_i + c_1 \cos \omega_1 t_i + d_1 \sin \omega_1 t_i + \alpha_2 \cos \omega_2 t_i + b_2 \sin \omega_2 t_i + c_2 \cos \omega_2 t_i + d_2 \sin \omega_2 t_i$$

Equation 4.14: Common periods between mean sea level and atmospheric pressure datasets

If the amplitudes of the signals within the annual mean atmospheric pressure datasets are scaled by the local sea level responses to changes in atmospheric pressure (ie, η), the result should be equal to the amplitude of the signals present in the corresponding annual mean sea level dataset, as shown in Equation 4.15.

$$\sum_{j=1}^{n} A_j \cos(\omega_j t_i - \phi_j) = \alpha_1 \cos \omega_1 t_i + b_1 \sin \omega_1 t_i + \frac{\alpha_1}{\eta_1} \cos \omega_1 t_i + \frac{b_1}{\eta_1} \sin \omega_1 t_i + \alpha_2 \cos \omega_2 t_i + b_2 \sin \omega_2 t_i + \frac{\alpha_2}{\eta_2} \cos \omega_2 t_i + \frac{b_2}{\eta_2} \sin \omega_2 t_i$$

Equation 4.15: Common periods between mean sea level and atmospheric pressure datasets with common amplitude parameters

Through combining the long-term sea level records with the relative differences in atmospheric pressure records, the resolution of the periods (ω) of the decadal and interdecadal signals may be improved through the increased redundancy.

Periodic signals within annual mean temperature records

If annual mean local temperatures have significant long-term signals associated with them, these signals may also be present in the annual mean sea levels; although these signals may not be in phase due to the lagging rate of oceanic thermal uptake. When the temperature of water increases, its volume increases proportionally. Changes in annual mean temperatures cause the temperature of the Earth's oceans to gradually change also, thereby driving changes to the height of sea level. Water masses have a very slow rate of thermal uptake so it cannot be assumed that the year-to-year variations in local mean temperature will be directly reflected in the simultaneous variations in annual mean sea level.

If the temperature records have signals of the same periods as the significant periods within the annual mean sea level records, the two datasets can be combined to improve the redundancy of the Least Squares analysis as there will be more observations available to help refine the period of the common signal or signals. This may be achieved by incorporating both datasets and Equation 4.14 into the trend analyses.

4.2.4 Sea level trend analyses

Time series datasets can be analysed for trend behaviours over time. These forms of datasets provide uniformly separated data values. Unlike normal datasets, time series values may demonstrate a non-constant mean value. When investigating a linear trend within a time series dataset, the gradient (m) and offset (c) parameters in Equation 4.9 are calculated using Least Squares statistical analysis. All data is referenced to the same initial time (t_0) to ensure that all data is included in the analysis in its correct relative time frame location.

If several stations are being investigated for their respective linear trends, a combined analysis should be performed if the stations' measurements are correlated. This relationship must be reflected in the variance-covariance matrix, which applies weightings that are appropriate for the stations' interrelationships. For this form of investigation the parameters in Equation 4.16 are investigated through Least Squares analysis. The linear trend parameters are m_1, m_2, through to m_n. Similarly the station standard offsets are c_1, c_2, through to c_n,.

$$y = m_1(t_i - t_0) + m_2(t_i - t_0) + \cdots + m_n(t_i - t_0) + c_1 + c_2 + \cdots + c_n$$

Equation 4.16: Linear trend in sea level rise with correlations between tide gauges

To investigate an accelerating trend within a single dataset, an acceleration parameter is incorporated into the Least Squares analysis. If the rate of vertical movement for the tide gauge or the land upon which the tide gauge is fixed remains constant over time, then its acceleration will be zero and hence the sea level the acceleration parameter (a) will not be affected. However, this vertical movement relative to sea level will be represented in the linear component of Equation 4.17.

$$y = a(t_i - t_0)^2 + m(t_i - \mathrm{t}_0) + c$$

Equation 4.17: Accelerating trend in a single record

With the assumption that the tide all gauges move at constant vertical rates relative to mean sea level in the absence of other factors such as active tectonic motion, the acceleration observed at all stations should be consistent. Non-constant vertical motion may occur due to a large seismic event. Such an event may be incorporated into the analysis so that the inconsistent vertical motion does not introduce a bias in the overall trend. This is discussed in more detail in Section 4.2.4.1.

A combined analysis may be performed to investigate the presence of an accelerating trend within all of the input datasets, while simultaneously considering the interrelationships between the tide gauges through the covariance values in the weight matrix. This analysis is achieved by investigating the unknown parameters in Equation 4.18.

$$y = a(t_i - t_0)^2 + m_1(t_i - t_0) + m_2(t_i - t_0) + \cdots + m_n(t_i - t_0) + c_1 + c_2 + \cdots + c_n$$

Equation 4.18: Sea level trend using multiple stations and one acceleration parameter

These analyses assume that all of the input datasets maintain continuity of datum, and that there are appropriate variances for all of the mean sea level values. However, the Wellington records do not maintain their continuity of datum, so this must be appropriately incorporated into the analysis.

The datasets analysed in these trend investigations have not been corrected for the initial estimates for the linear trends at each of the stations.

4.2.4.1 Wellington tide gauge correction analysis

Due to the complex histories of the four tide gauges, various vertical offset corrections must be applied to the monthly and annual mean sea level records. These offsets should be quantified by the practices associated with the maintenance of each respective tide gauge. However, due to poor maintenance records it appears that there is an error present in the Wellington time series data due to the tide gauge being shifted at the beginning of 1944 without recording the new vertical offset.

Hannah (1990) quantified this offset by using the mean tide levels records from the Wellington tide gauge prior to 1944 to attempt to model the annual mean sea levels prior to the tide gauge shift. In this analysis the vertical offset was calculated to be in the order of fifteen to thirty millimetres. It must be noted that mean sea levels that are derived from mean tide level records are of reduced quality compared to the mean sea levels, unless the tides are perfectly symmetrical in form.

An improved estimate can now be obtained using the further sea level records that are now available. Equation 4.19 can be applied to quantify this offset using the extended records. This equation incorporates any event that has caused a sudden vertical offset. If the earth, the structure on which the tide gauge is mounted, or the gauge itself moves suddenly relative to mean sea level the movement can be incorporated into the analysis provided that the date of the event is known. All of the Wellington mean sea level data can be combined in a single Least Squares analysis that includes an acceleration parameter to derive the vertical offset for the Wellington tide gauge before 1944 (t_e), and a new vertical offset after 1944. The variance-covariance matrix provides realistic variances for these offset values considering the expected standard deviations of the data used in the analysis.

$$y = a(t_i - t_0)^2 + m_1(t_i - t_0) + m_2(t_i - t_0) + \cdots + m_n(t_i - t_0) + c_{1(ti<te)} + c_{1(ti \geq te)} + c_2 + \cdots + c_n$$

Equation 4.19: Sea level trend with additional offset parameter for significant vertical movement event at a station location

The Wellington tide gauge is believed to have been manually shifted to a new height position relative to mean sea level, but the recording of the vertical offset was neglected. However, natural forces may also cause the tide gauge's vertical position to change.

Earthquake offset at the wellington tide gauge

Sudden earthquakes in proximity to the tide gauges used in this study must be incorporated into the mathematical analyses to prevent any bias in the calculated trend results. Significant earthquake events can potentially cause a sudden vertical offset in the gauge's position by moving the tide gauge relative to the ocean's mean level. At present we cannot confidently quantify an offset of this nature using the measurement technologies currently available. The majority of the significant earthquakes in New Zealand occurred prior to when measurements using Global Positioning System (GPS) became readily available and feasible. Improvements are being constantly investigated to refine the vertical resolution of GPS measurements, but the ability to confidently define sudden vertical movements caused by significant events is currently very limited.

It appears that the Wellington tide gauge may have been reinstated in 1944. Unfortunately, there is no recorded evidence of how much the tide gauge was shifted by from its original vertical position. This may be due to negligence in the maintenance practices, although it is possible that the tide gauge was reinstated in the same vertical position. However, there is another possible explanation or contributing factor for an unrecorded datum shift around this time.

As shown in Section 2.2.1.3, there were two significant earthquakes that occurred in June and August in 1942 in relatively close proximity to the Wellington tide gauge. Both of these earthquakes' epicentres were located in the Wairarapa.

Tectonic deformation, as discussed in Section 2.2.1, can cause imperceptible constant motion over time, or a sudden movement that is associated with the release of an immense amount of energy in the form of an earthquake. It is quite possible that these earthquakes in 1942 caused vertical uplift in the lower North Island area, thereby changing the height position of the Wellington tide gauge. This movement may have been falsely identified as having been associated with the reinstatement of the tide gauge in 1944. It is possible that the continuity of datum was believed to have been maintained through the use of local benchmarks that were also subject to the vertical land movement. With this in mind, the data from 1942 and 1943 should be rejected as it may be subject to datum error due to land movement. Only the data prior to 1942 and from 1944 onwards has been used in the investigation into the vertical offset at Wellington, and also for the overall analysis into the sea level rise trend.

Wellington tide gauge vertical offset analysis

If all rates of vertical deformation are assumed to be linear, a regionally synthesised time series combined dataset may be compiled from which an acceleration in sea level rise may be detected. This methodology allows for the expected variations between stations for the standard offset and linear trend components, but assumes that all stations involved are subject to the same acceleration in sea level rise, as expressed in Equation 4.18.

In the event that a significant vertical offset is suspected at a given station location at event time t_e, an additional vertical offset can be incorporated into the single linear trend analysis by including another parameter for the new vertical offset for the tide gauge, as shown in Equation 4.10. For a combined analysis that considers multiple tide gauge records and their correlations, Equation 4.20 is used in the Least Squares analysis.

$$y = m_1(t_i - t_0) + m_2(t_i - t_0) + \cdots + m_n(t_i - t_0) + c_{1(ti<te)} + c_{1(ti\geq te)} + c_2 + \cdots + c_n$$

Equation 4.20: Linear trend in sea level rise with correlations between tide gauges

As this study is investigating if there is a detectable acceleration in the rate of sea level rise around New Zealand, the vertical offsets must be incorporated into the acceleration analysis. Equation 4.21 is applied to investigate if there is a detectable acceleration present in one sea level time series dataset. Equation 4.22 is applied in the combined analysis.

$$y = a(t_i - t_0)^2 + m(t_i - t_0) + c_{(ti<te)} + c_{(ti\geq te)}$$

Equation 4.21: Single accelerating trend in sea level rise

$$y = a(t_i - t_0)^2 + m_1(t_i - t_0) + m_2(t_i - t_0) + \cdots + m_n(t_i - t_0) + c_{1(ti<te)} + c_{1(ti\geq te)} + c_2 + \cdots + c_n$$

Equation 4.22: Accelerating trend in sea level rise with correlations between tide gauges

Equation 4.20 and Equation 4.22 could both be applied in separate Least Squares analyses to obtain two sets of parameter and variance estimates, from which a weighted mean value for the change in offset at the Wellington tide gauge may be derived. However, this would serve no purpose for this study. The offset must be adequately incorporated to prevent any bias from being introduced to the analysis. The presence of this additional parameter reduces the redundancy of this investigation; but this cannot be avoided.

4.2.4.2 Full dataset analysis

The accelerating trend investigation incorporates all of New Zealand's long-term tide gauges' sea level records in a single, comprehensive analysis. This methodology derives an overall acceleration trend that is common within the four stations' datasets following the assumption that the tide gauges are moving in a constant relative manner over time due to subsidence or tectonic forcing. Linear trend and offset components are derived for each of the individual stations, while considering the correlations between the stations. Least Squares analysis incorporates Equation 4.23 to derive the relevant trend parameters using the long-term records available. To accommodate the vertical shift in the Wellington mean sea level record, two offsets are calculated using 1944 as t_e. Wellington's mean sea level measurements for 1942 and 1943 have been removed entirely from the analysis, as discussed in Section 4.2.4.1.

$$\begin{aligned} y = {} & a(t_i - t_0)^2 + m_1(t_i - t_0) + m_2(t_i - t_0) + m_3(t_i - t_0) + m_4(t_i - t_0) + c_{1(ti<te)} \\ & + c_{1(ti\geq te)} + c_2 + c_3 + c_4 + \alpha_1 \cos \omega_1 t_i + b_1 \sin \omega_1 t_i + \alpha_2 \cos \omega_2 t_i \\ & + b_2 \sin \omega_2 t_i + \cdots + \alpha_n \cos \omega_n t_i + b_n \sin \omega_n t_i \end{aligned}$$

Equation 4.23: Model incorporating accelerating sea level rise trend with decadal and interdecadal signals

Using the periods of the signals that are indicated to be the most significant by the Fast Fourier Transform analysis, the combined influence of the signals can be calculated using Least Squares analysis by incorporating the periods of the signals as observations. The calculated variances derived using Equation 5.15 are used to obtain the 95% confidence interval for the calculated a and b amplitude parameters by applying Equation 4.26. Iteration of the Least Squares analysis is required to converge on the appropriate overall solution, considering the signals' amplitudes and periods, and the overall trend in sea level rise.

The lunar tides (with periods of 18.613 and 8.847 years respectively) are each only to be incorporated in this investigation if the Fast Fourier Transform analysis identifies them as having a significant effect on the annual mean sea level records. In the event that either or both of these signals are incorporated, the periods may be incorporated as parameters as the lunar periods are precisely known.

Through incorporating the most significant signals in the trend investigation, the errors associated with both sets of calculated parameters are propagated accurately, and the false aliasing of parameters is prevented.

4.2.4.3 Changing linear trends analysis

As mentioned in Section 2.2.4, Douglas (1991, 1997) states that mean sea level records spanning a minimum of fifty to sixty years are required to produce stable estimates of the rate of sea level rise because of the strong interdecadal variability contained in the records. With this consideration in mind, a second, independent analysis is applied to investigate if there has been a significant change in the rate of sea level rise at some point within New Zealand's recording history. By carrying out these segmented analyses it can be identified if the trend in sea level rise is changing over time, but not necessarily in a constant or consistent manner at all stations. Such behaviour could be the result of non-regular influences on sea levels.

By analysing blocks of the records (in ten-year shifts) segments of data can be analysed, providing numerous linear trends over the recording period from which a significant change in the rate of sea level rise may be identified. A minimum of fifty years of annual mean sea level records are required for each block to derive each of the progressive linear trends. These analysed blocks of records extend backwards in ten year shifts, starting in 2007, until there is insufficient data to support further trend analysis. Each of these blocks of mean sea level data are analysed for their linear trends using Equation 4.20.

To avoid a bias in the derived linear trend due to decadal and interdecadal signals that are present in the dataset, the lengths of records analysed in each segment are selected based upon the derived periods of the signals discussed in Section 5.4.2. Whole multiples of the most significant periods are considered, analysing segments of records that are greater than fifty years in length. This approach is in keeping with the suggestion made by Douglas (1991) to consider a minimum length of fifty years of data for sea level linear trend investigations. Due to the magnitudes of the standard deviations associated with these periods, trends are calculated using the signals' periods at the extremities of their 95% confidence intervals to identify the natural variation of the derived trends.

There are two possible reasons why an acceleration in sea level rise may be identified by the Least Squares analysis. The rate of sea level rise may be increasing over time, or conversely the rate of sea level rise may have increased at some point during the recording period. Since the beginning of New Zealand's sea level recording history there have been many changes in the use and consumption of resources on Earth. Greenhouse gas emissions are attributed to global warming, which in turn is associated with thermal expansion of the oceans, causing sea level to rise. The production of greenhouse gases has been increasing progressively over time since the dawn of the Industrial Revolution and the creation of affordable automobiles. However, a sudden change in the rate of sea level rise is unlikely; the trend is more likely to have changed progressively over several of years to decades. The segmented analysis identifying the changes in the linear rates of sea level rise may provide an indication how the trend is changing over time. Unfortunately, due to the nature of this analysis and the length of the available datasets, this analysis will have greatest weighting for changes occurring in the middle sixty years of the dataset, namely in the range between 1928 and 1988. This limitation cannot be avoided with this analysis.

4.2.4.4 Non-consistent acceleration rates

The combined analyses detailed in Section 4.2.4.2 assumes that the rates of relative vertical motion of the tide gauges are constant over time at each of the gauges considered in this study, although these linear rates are not necessarily consistent between the gauges. The results of the changing linear trend analysis may indicate if records from stations demonstrate trends which are inconsistent with the other stations. These trend differentials must be considered in this analysis as no single record should be considered without error in isolation.

Non-constant vertical movements relative to mean sea level will distort the apparent rate of sea level rise due to the irregular relative motion of the tide gauge. Irregular vertical movement must be confidently identified to isolate an absolute acceleration in sea level rise from a detected relative acceleration. Considering the potential of irregular vertical movement occurring at any of the tide gauges being considered in this study due to New Zealand's active tectonic nature, the only opportunity to identify if the rate of sea level rise is accelerating is through identifying secular acceleration rates at multiple tide gauges; preferably those that are unlikely to be subject to irregular vertical motion. With this consideration in mind, individual acceleration rates for each individual tide gauge are investigated.

At present there is minimal evidence to identify the nature of the vertical shifts at tide gauges. Through the establishment of long-term continuous Global Positioning System (cGPS) stations, the relative movement of the gauge may be isolated. This form of records is not available for incorporation in this study.

Individual least squares trend investigations need to be carried out using each stations' records through the incorporation of Equation 4.24. By analysing the datasets individually, any biases that may be caused by correlations between close stations can be avoided. Extensive datasets are required to obtain the best evidence of local acceleration trends.

$$y = a(t_i - t_0)^2 + \mathrm{m}(t_i - t_0) + \mathrm{c} + \alpha \cos \omega \mathrm{t} + b \sin \omega \mathrm{t}$$

Equation 4.24: Individual trend and signal

4.2.4.5 Input datasets

The corrections applied to the mean sea level datasets for the inverted barometer effect using the relative differences between the local and global (oceanic) average sea level atmospheric pressures may not successfully remove the systematic effect from the datasets. Therefore, the quality of the results obtained using the annual mean sea levels that have been corrected for the inverted barometer effect using the model created in this study are uncertain. Errors in the model may be due to the assumptions made, which are discussed further in Section 6.2.1. To ensure that this new methodology does not compromise the validity of the result, a separate analysis is carried out using the annual mean sea level values that have not been corrected for the inverted barometer effect.

4.3 Statistical analyses applied in this study

The analyses conducted in this investigation are considered in relation to the calculated variances of the unknown parameters. These analyses illustrate the confidence with which conclusions may be drawn from the derived results. For the purposes of this study, statistical significance is only considered at the 95% confidence interval. These analyses assume that the errors associated with both the input and output datasets are normally distributed about the mean.

For this investigation, the statistical significance of a derived parameter is required to ascertain if a derived parameter is present within the given dataset. A statistically significant difference between two derived parameters is required to identify if there is a significant change in the linear rate of sea level rise.

The variances and covariances associated with variables are considered lastly in this section in their application in error propagation.

4.3.1 Confidence interval of the mean

The establishment of the 95% confidence interval of a derived value to ascertain its statistical significance requires the parameter's derived value and its corresponding standard deviation. This data is applied in conjunction with Equation 4.26, where $\hat{x}$ is the derived parameter, and the standard deviation as obtained from the appropriate variance-covariance matrix is considered to be the standard deviation of the mean ($\hat{\sigma}_m$), expressed in Equation 4.25, where $\hat{\sigma}_s$ is the sample standard deviation. This is substituted into Equation 4.26, to provide Equation 4.27.

$$\hat{\sigma}_m = \frac{\hat{\sigma}_s}{\sqrt{n}}$$

Equation 4.25: Standard deviation of the mean

$$P\left[\hat{x} - \frac{\hat{\sigma}_s}{\sqrt{n}} \times t_{\left(\frac{\alpha}{2},\mathrm{n}-1\right)} \leq \mu \leq \hat{x} + \frac{\hat{\sigma}_s}{\sqrt{n}} \times t_{\left(\frac{\alpha}{2},\mathrm{n}-1\right)}\right] = (1-\alpha)100\%$$

Equation 4.26: Student's t distribution confidence interval of the mean

$$P\left[\hat{x} - \hat{\sigma}_m \times t_{\left(\frac{\alpha}{2},\mathrm{n}-1\right)} \leq \mu \leq \hat{x} + \hat{\sigma}_m \times t_{\left(\frac{\alpha}{2},\mathrm{n}-1\right)}\right] = (1-\alpha)100\%$$

Equation 4.27: Student's t distribution confidence interval of the mean using standard deviation of the mean

If zero does not fall within the confidence range the Alternative Hypothesis (Equation 4.29) is accepted and hence the value is considered to be significant. However, if zero does fall within this confidence range the Null Hypothesis (Equation 4.28) is accepted, and as such the value is not considered to be significant.

$$H_o : \mu = 0$$

Equation 4.28: Confidence of the mean Null Hypothesis

$$H_1 : \mu \neq 0$$

Equation 4.29: Confidence of the mean Alternative Hypothesis

4.3.2 Comparison of two means

When considering two samples, both with independently derived standard deviations ($\hat{\sigma}_{s1}$ and $\hat{\sigma}_{s2}$), it is often necessary to identify if the two samples are significantly different at the 95% confidence interval. Equation 4.31 is applied to obtain the confidence interval of the difference between the two samples, where n and m are the number of observations used in each respective investigation or sample. Equation 4.30 is used to calculate $\mathcal{F}$, which is substituted into Equation 4.31

$$\mathcal{F} = \frac{(\frac{\hat{\sigma}_{s1}^2}{n} + \frac{\hat{\sigma}_{s2}^2}{m})^2}{\frac{\hat{\sigma}_{s1}^4}{n^2(n+1)} + \frac{\hat{\sigma}_{s2}^4}{m^2(m+1)}} - 2$$

Equation 4.30: Fischer-Behren's Equation (Hamilton, 1964)

$$P\left[(\hat{x}_1 - \hat{x}_2) - t_{(\frac{\alpha}{2},\mathcal{F})} \times \sqrt{(\frac{\hat{\sigma}_{s1}}{n} + \frac{\hat{\sigma}_{s2}}{m})} \leq \mu_1 - \mu_2 \leq (\hat{x}_1 - \hat{x}_2) + t_{(\frac{\alpha}{2},\mathcal{F})} \times \sqrt{(\frac{\hat{\sigma}_{s1}}{n} + \frac{\hat{\sigma}_{s2}}{m})}\right]$$
$$= (1-\alpha)100\%$$

Equation 4.31: Student's t distribution confidence interval of the difference between two samples

Zero does not fall within the 95% confidence range if the two samples are significantly different, and hence the Alternative Hypothesis, expressed in Equation 4.33, is accepted. If zero does fall within the range the two samples are not significantly different, the Alternative Hypothesis is therefore rejected and the Null Hypothesis, expressed in Equation 4.32, is accepted.

$$H_o : \ \mu_1 - \mu_2 = 0$$

Equation 4.32: Difference between two means Null Hypothesis

$$H_1 : \mu_1 - \mu_2 \neq 0$$

Equation 4.33: Difference between two means Alternative Hypothesis

This methodology is applied to identify if two similar parameters are significantly dissimilar from each other. Another analysis is required to investigate if two variances are significantly different.

These statistical analyses can be applied to identify statistically significant trends or behaviours within a dataset, or significant changes in parameters' variances. This study focuses on the relationships between meteorological drivers and changes in sea level, for which the identification of statistically significant trends is required.

4.3.3 Error propagation

Error propagation is the effect of the uncertainties of variables on the uncertainty of a function they are subject to. To identify the effect of these uncertainties, the variances and covariances associated with the variables must be considered in Equation 4.34, where A is defined in Equation 5.8, and $\sum_x$ is defined in Equation 4.35.

$$\sum_y = \begin{bmatrix} \sigma_{y1}^2 & \sigma_{y1y2} \\ \sigma_{y2y1} & \sigma_{y2}^2 \end{bmatrix} = A^T \sum_x A$$

Equation 4.34: Error propagation

$$\sum_x = \begin{bmatrix} \sigma_{x1}^2 & \sigma_{x1x2} \\ \sigma_{x2x1} & \sigma_{x2}^2 \end{bmatrix}$$

Equation 4.35: Uncertainties of variables

4.4 Summary

By investigating and modelling the local inverted barometer responses, the year-to-year variability in the annual mean sea levels may be reduced by eliminating this systematic effect to aid in providing more statistically significant results. The local relative differences in atmospheric pressure are required so that this correction may be applied.

Decadal and interdecadal signals must be appropriately incorporated into the analysis to prevent biases in any derived trends.

Several trend investigations are employed in this study to accommodate the potential increasing behaviours in the sea level rise trend. If all of New Zealand's four long-term tide gauges are subject to constant movement over time due to tectonic forces, evidence for an acceleration in the rate of sea level rise would not be affected. However, if the land movements are inconsistent over time, the relative rate of sea level rise will be affected, causing inconsistent trends between the four stations.

Through considering these possible scenarios, two different acceleration analyses are conducted. One investigation considers the tectonic motion to be constant over time, and so one acceleration parameter between the four tide gauge stations is derived. Another analysis considers the potential of inconsistent tectonic trends, and hence individual acceleration parameters are investigated for each set of annual mean sea level records.

Linear trends in the rate of sea level rise are also considered as the rate of sea level rise may have increased at some point, while not increasing constantly over time. Through analysing blocks of annual mean sea level records, a significantly high linear rate of sea level rise may be identified.

5 Analyses and Results

To obtain the most representative and statistically significant results from the data used in this study, intensive analysis methodologies were utilised. The various drivers that influence the height of sea level should be adequately considered and incorporated in this investigation to avoid any bias in the results obtained.

Firstly in this chapter, the annual mean sea level datasets used in this study are briefly detailed.

Secondly, a model is formed to correct the annual mean sea level records for the inverted barometer effect.

This chapter then proceeds to detail the mathematical and statistical analysis methodologies that form the fundamental components of this investigation. Least Squares analysis, discussed in Section 5.3.1, is a statistical analysis method that can be applied to identify trends or behaviours in data, providing the optimum behavioural results considering the observational datasets and their associated variance-covariance matrices.

Fast Fourier Transform analysis was utilised to analyse both the Auckland and Wellington datasets that were corrected for the inverted barometer effect, and those that were not corrected. The Fourier processing technique is explained in Section 5.3.2. The periodic terms derived from the Fourier analyses were then refined through their incorporation into the Least Squares analyses.

The results obtained from the trend analyses are detailed lastly in this section. These investigations also utilised both the datasets that were corrected for the inverted barometer effect, and those that were not. The statistical significances of the derived parameters are provided.

The trend analyses include investigations into a common acceleration between the four stations considered in this study, a change in the linear rate of sea level rise, and individual acceleration rates at each of the four tide gauge stations. The results are provided firstly from the datasets that have been corrected for the inverted barometer effect, and then finally the results from the uncorrected datasets are provided. The signals identified in the datasets were incorporated into the analyses to obtain unbiased estimates of the linear trends in sea level rise throughout each station's recording histories.

5.1 Annual mean sea level datasets

The annual mean sea levels from Auckland, Wellington, Lyttelton and Dunedin were corrected for their recorded datum shifts, discussed in Section 3.3.2, to maintain continuity of datum throughout the historical dataset. Wellington's records from 1944 onwards were considered to have a different datum offset compared to prior to 1942.

Figure 5.1 illustrates the annual mean sea levels measured at New Zealand's four long-term tide gauges since their respective records began. The annual mean sea levels are shown with arbitrary standard offsets for illustration purposes. These records provided the primary datasets used to investigate if there is a detectable acceleration present in the rate of sea level rise.

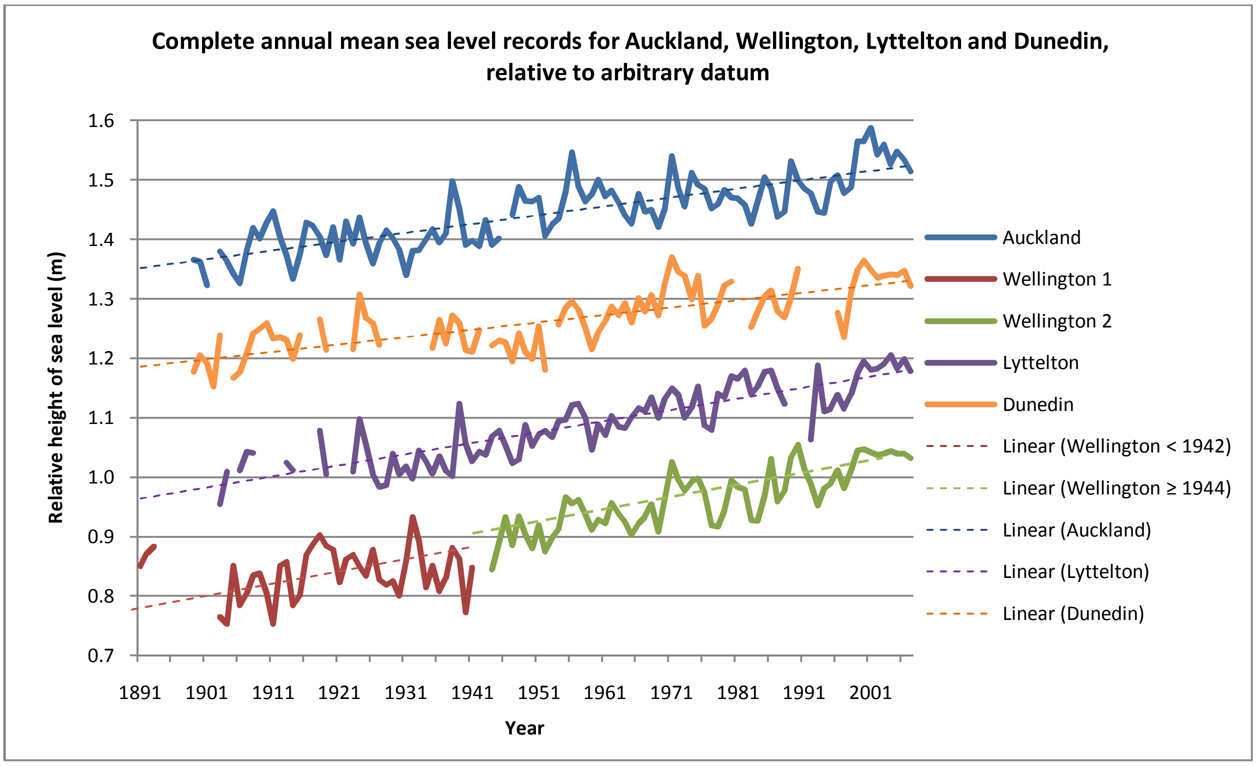

Figure 5.1: Complete annual mean sea level records for Auckland, Wellington, Lyttelton and Dunedin, relative to arbitrary datum

5.2 Influence of inverted barometer effect

To reduce the level of variation in the annual mean sea level datasets from each of the stations used in this study, the local changes to the height of sea level caused by atmospheric pressure variations were investigated. This section goes on to investigate the local relative differences in annual mean atmospheric pressure compared to the global (oceanic) annual mean atmospheric pressure. A corrective model is then formed to remove this systematic effect and thereby reduce the variability of each annual mean sea level dataset.

5.2.1 Local inverted barometer effect responses

The magnitude of the inverted barometer effect on sea level at a given location is dependent upon several factors. The local response to a change in atmospheric pressure is influenced by the local conditions, such as associated meteorological drivers and water salinity. With this in mind, the local responses to atmospheric pressure changes are investigated through the comparison of local hourly sea level residuals with the local observed hourly sea level atmospheric pressures. The relationship between these two variables demonstrates the influence that atmospheric pressure changes have on the height of sea level.

5.2.1.1 Local hourly sea level residuals

Figure 5.2 illustrates the hourly sea levels that were measured during January 2003 in Auckland. The harmonic constituents for the Auckland tide gauge were derived using the recorded hourly sea level measurements from the full duration of 2004. These constituents were then used to predict the hourly sea level heights throughout 2003, and these predictions were compared with the measured heights to obtain the hourly sea level residuals. The predicted hourly sea level heights for January 2003 that were generated using these constituents are shown in Figure 5.3. Both the measured and predicted sea level values are shown in Figure 5.4 to illustrate how the sea level residuals are derived.

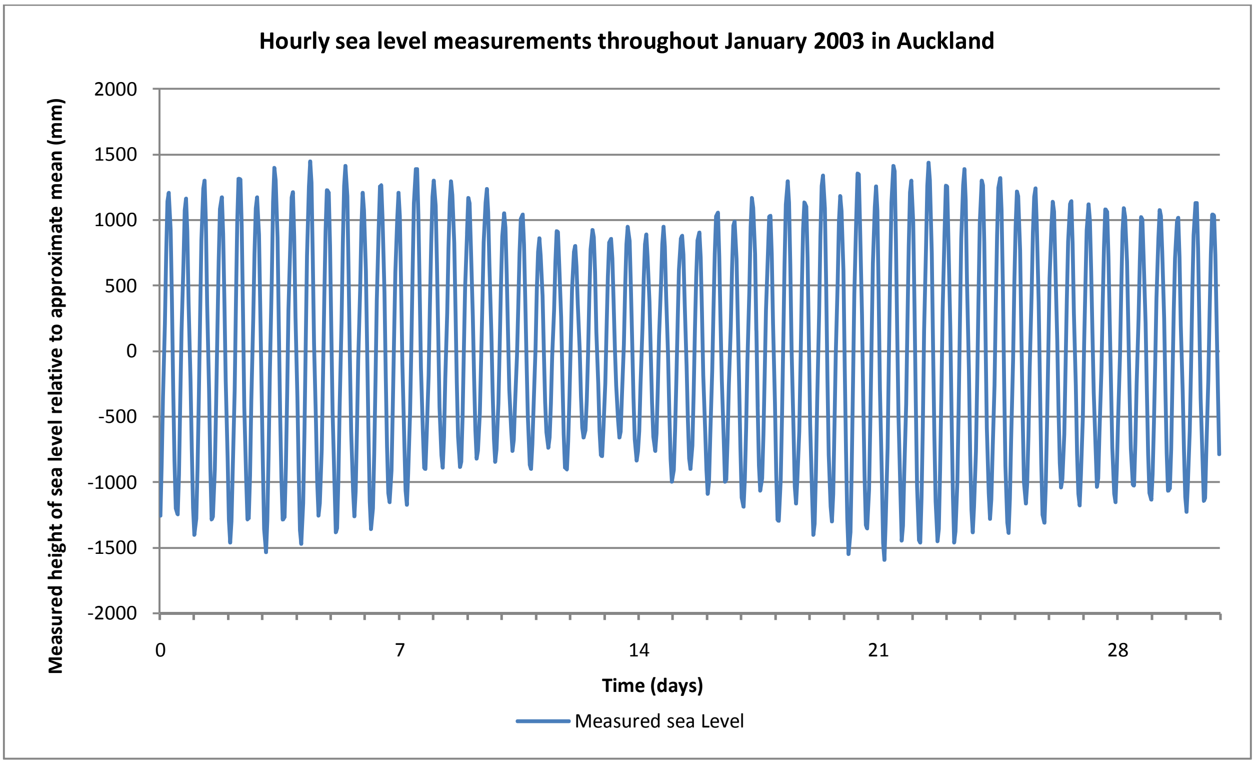

Figure 5.2: Hourly sea level measurements throughout January 2003 in Auckland

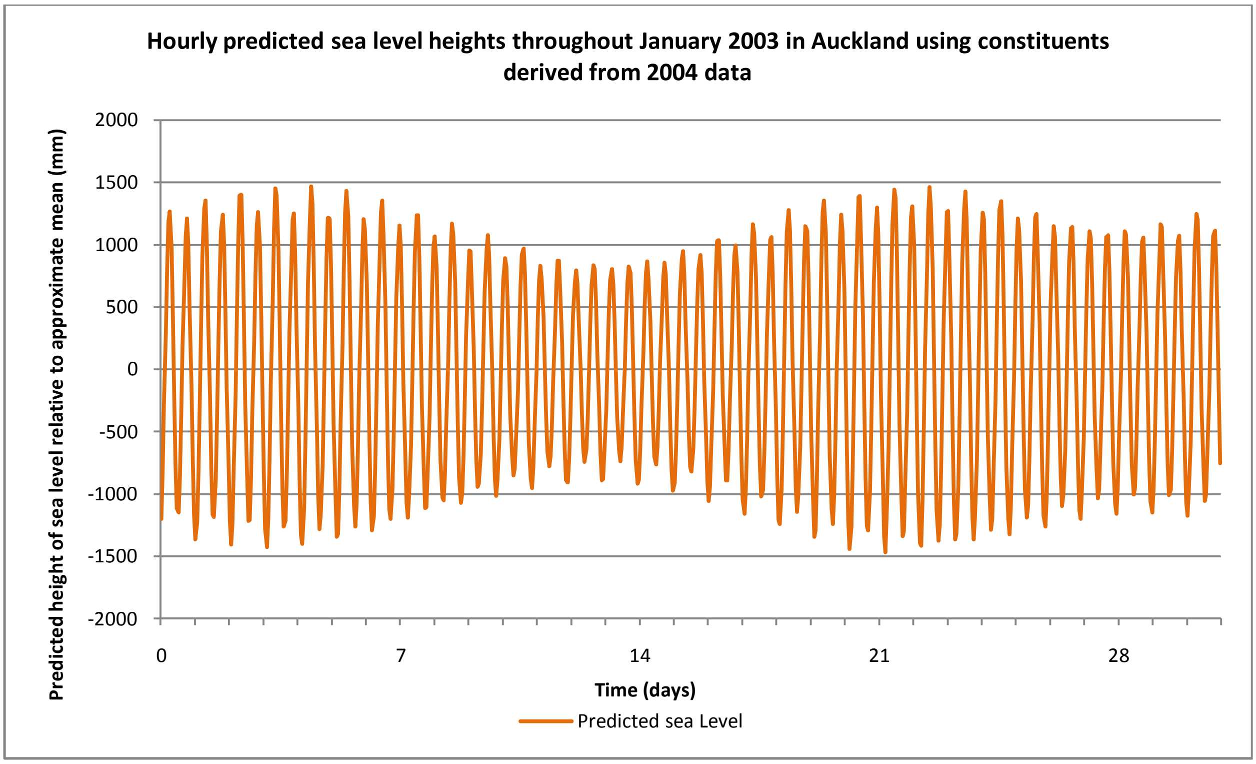

Figure 5.3: Hourly predicted sea level heights throughout January 2003 in Auckland using constituents derived from 2004 data

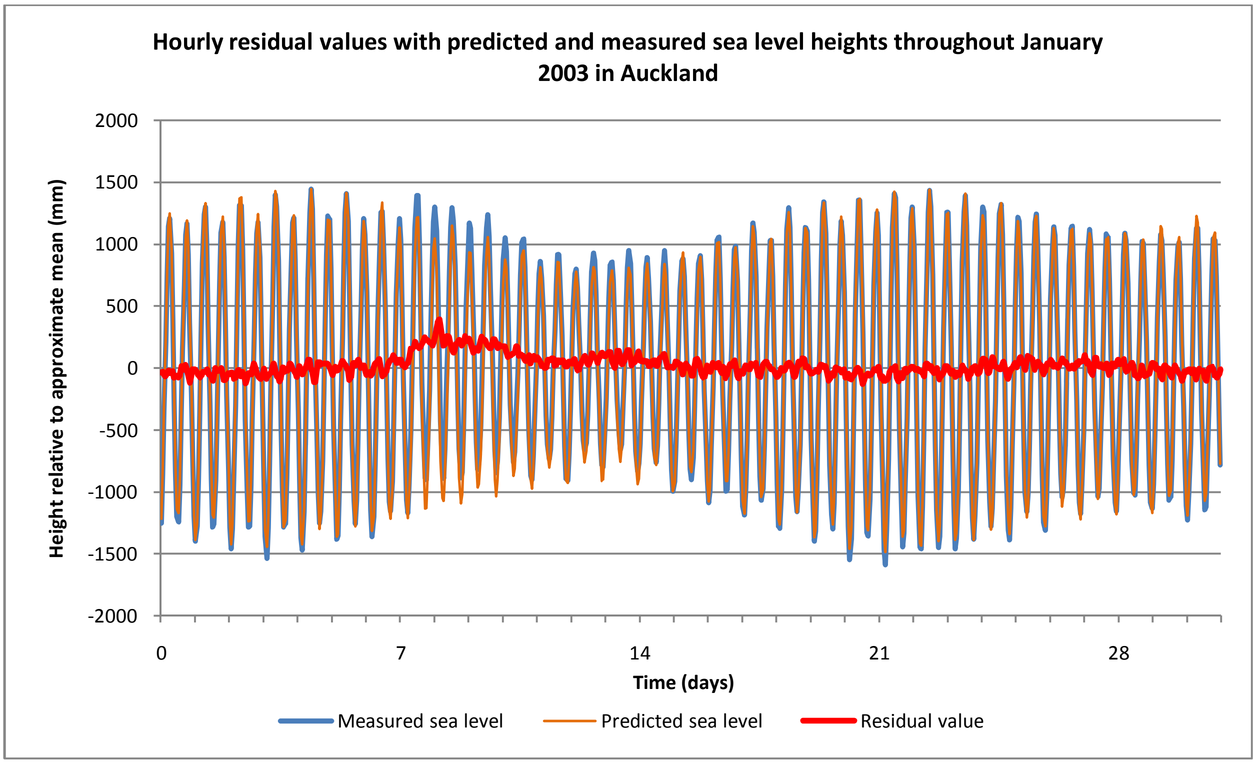

Figure 5.4: Hourly residual values with predicted and measured sea level heights throughout January 2003 in Auckland

5.2.1.2 Local hourly atmospheric pressures

Auckland's hourly sea level atmospheric pressures throughout January 2003 are shown in Figure 5.5 plotted along with the sea level residual values. The atmospheric pressure axis is scaled and reversed to clearly show the relationship between the sea level residuals and relative atmospheric pressure changes. This figure clearly illustrates that although atmospheric pressure changes significantly affect the height of sea level, as reflected in the sea level residual values, they are not the sole cause of unexpected variations in the sea levels. This form of irregular behaviour is clearly illustrated in Figure 5.5, especially between the twenty first and the twenty eighth of January, 2003.

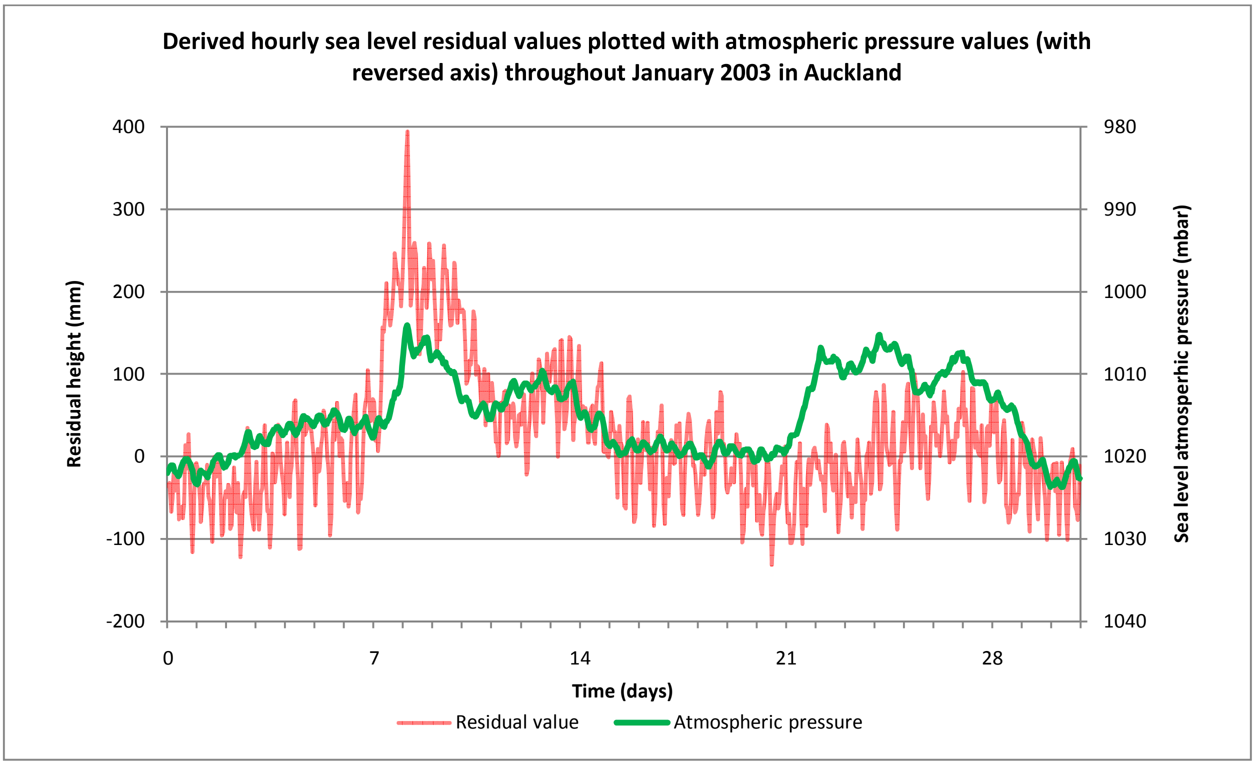

Figure 5.5: Derived hourly sea level residual values plotted with atmospheric pressure values (with reversed axis) throughout January 2003 in Auckland

5.2.1.3 Local atmospheric pressure variation responses

Figure 5.6 shows the hourly sea level residual values calculated throughout 2003 plotted against the corresponding measured hourly sea level atmospheric pressures. The linear trend between the atmospheric pressures and the sea level residuals (parameters detailed in Table 5.7) represents the local responses to atmospheric pressure changes.

Hourly sea level residuals were derived for each station using the harmonic constituents derived from a complete, or near complete, dataset of hourly sea level observations throughout the course of one year. As there were numerous datasets from each of the tide gauge stations that were considered adequate for this form of analysis, the constituents were derived using all of these suitable datasets. This process generated similar residuals for any given year from the different sets of derived constituents, but with some variation due to the errors associated with the constituents. Gross errors were also identified in some datasets. Linear regression analysis was repeated for each station to identify the local sea level responses to atmospheric pressure changes using the residual values calculated using the sets of constituents derived from various years of data, including the same years as those for which the sea levels were being generated. The numerous sets of results for each tide gauge were then utilised to obtain weighted mean local responses for each individual station.

Additionally, the local sea level responses were investigated using monthly relative differences in mean atmospheric pressures paired with the corresponding monthly mean sea level residuals that were corrected for the estimated linear trend in sea level rise.

Further figures illustrating the data used to calculate the local atmospheric pressure change responses are shown in the Appendix, in Section 9.1.

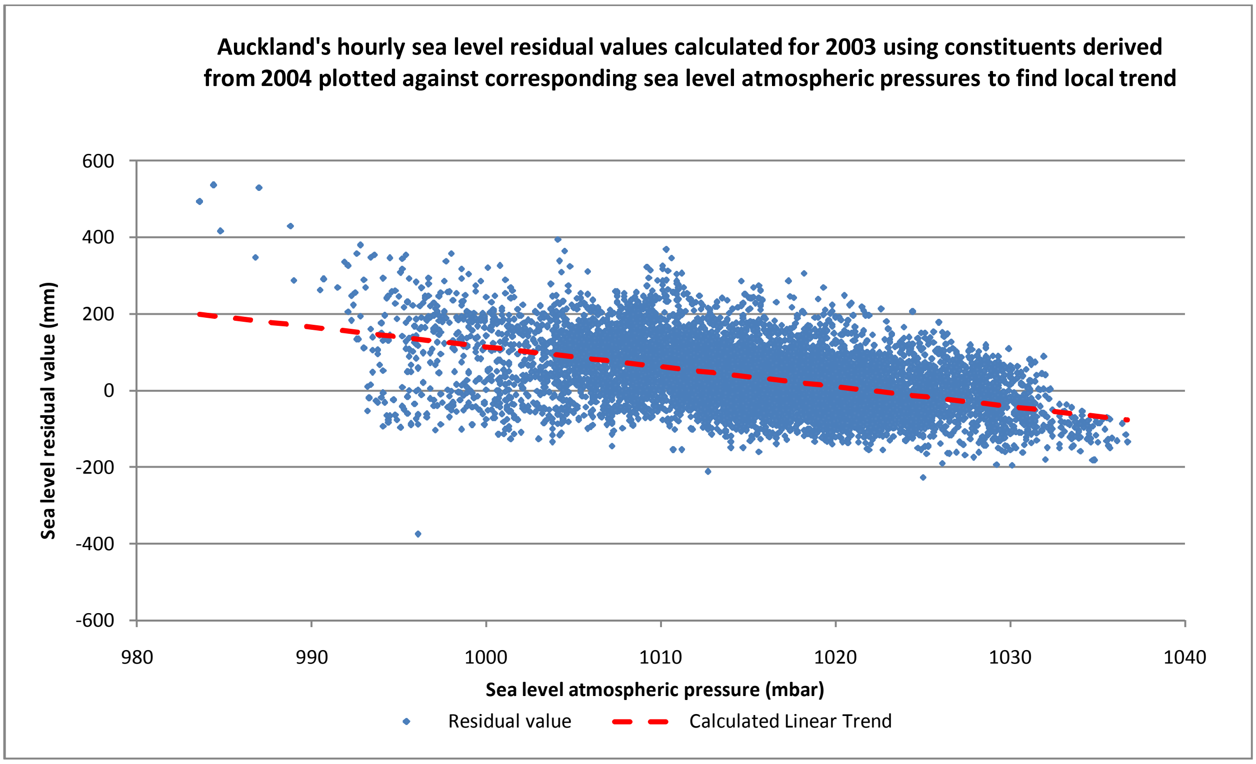

Figure 5.6: Auckland's hourly sea level residual values calculated for 2003 using constituents derived from 2004 plotted against corresponding sea level atmospheric pressures to find local trend

The datasets that were chosen to derive the harmonic and astronomical constituents were carefully considered to ensure that the most representative results were obtained for application. The generated residuals were inspected for consistency; those datasets that contained gross errors or behaviours significantly inconsistent with the other residuals generated for the same period at the given station were excluded from the analysis.

Select results were chosen to be included or excluded and weighted mean local sea level responses to atmospheric pressure changes from the linear trend regression analyses were derived and applied in the corrections to the annual mean sea levels. To derive the local weighted mean sea level responses, the trends calculated from the smallest datasets were generally excluded as these analyses had the lowest redundancy and their overall results had reduced agreement with the calculated trends from the other analyses. The results from the hourly datasets that were considered to be significantly incomplete were excluded. All trends derived from the monthly analyses were excluded as the noise in the residuals was too large to obtain a representative result. The calculated trends and the overall weighted mean results are shown in Section 9.2, in the Appendix and the excluded datasets are highlighted. The final weighted mean local responses to atmospheric pressure changes at each station are summarised in Table 5.1.

Weighted Mean Values	
Station	**Local response (η_l) (mm/mbar)**
Auckland	-5.7
Wellington	-8.7
Lyttelton	-7.2
Dunedin	-7.7

Table 5.1: Weighted mean local responses to atmospheric pressure variations

5.2.2 Relative atmospheric pressure differences

The inverted barometer effect is caused by water flowing from a given location to another location that has a lower relative atmospheric pressure to ensure that equilibrium is maintained. Through using the historic atmospheric pressure records from the localities of the four stations being investigated, the relative differences in local annual mean atmospheric pressures at sea level compared to the global annual means can be realised, allowing corrections for the inverted barometer effect to be applied to the annual mean sea levels. Figure 5.7 shows Auckland's annual mean atmospheric pressure records that extend back to 1916. Figure 5.8 illustrates the global annual mean atmospheric pressures at sea level that have been derived from the Hadley Centre sea level pressure dataset. The difference between these two datasets is shown in Figure 5.9. Auckland's detrended annual mean sea levels are included in this figure for comparison purposes. Similar figures showing the relative differences in atmospheric pressures for Wellington, Lyttelton and Dunedin are provided in Figure 5.10, Figure 5.11, and Figure 5.12 respectively.

The relative differences in atmospheric pressures $\left(P_{l\mu i} - P_{g\mu i}\right)$ are used in conjunction with the weighted mean local responses to atmospheric pressure variations (η_l) in Equation 4.8 to remove the systematic effect from the annual mean sea level datasets, and ideally reduce their overall year-to-year variability.

The variances of the annual mean local atmospheric pressure records were established through the comparison of simultaneous sea level atmospheric pressure measurements at two or more stations in close proximity to each other. Similarly, the expected variances of the sea level atmospheric pressures provided by the Hadley Centre sea level pressure dataset were established by directly comparing the annual mean pressures with those provided over the same period with the extended reconstructed sea level pressure dataset. The errors associated with the two pressure datasets were propagated through the inverted barometer effect corrections using Equation 4.34, thereby increasing the standard deviations of the corrected annual mean sea level datasets appropriately.

The decreasing global annual mean atmospheric pressure trend shown in Figure 5.8 is expected with increasing global average temperatures.

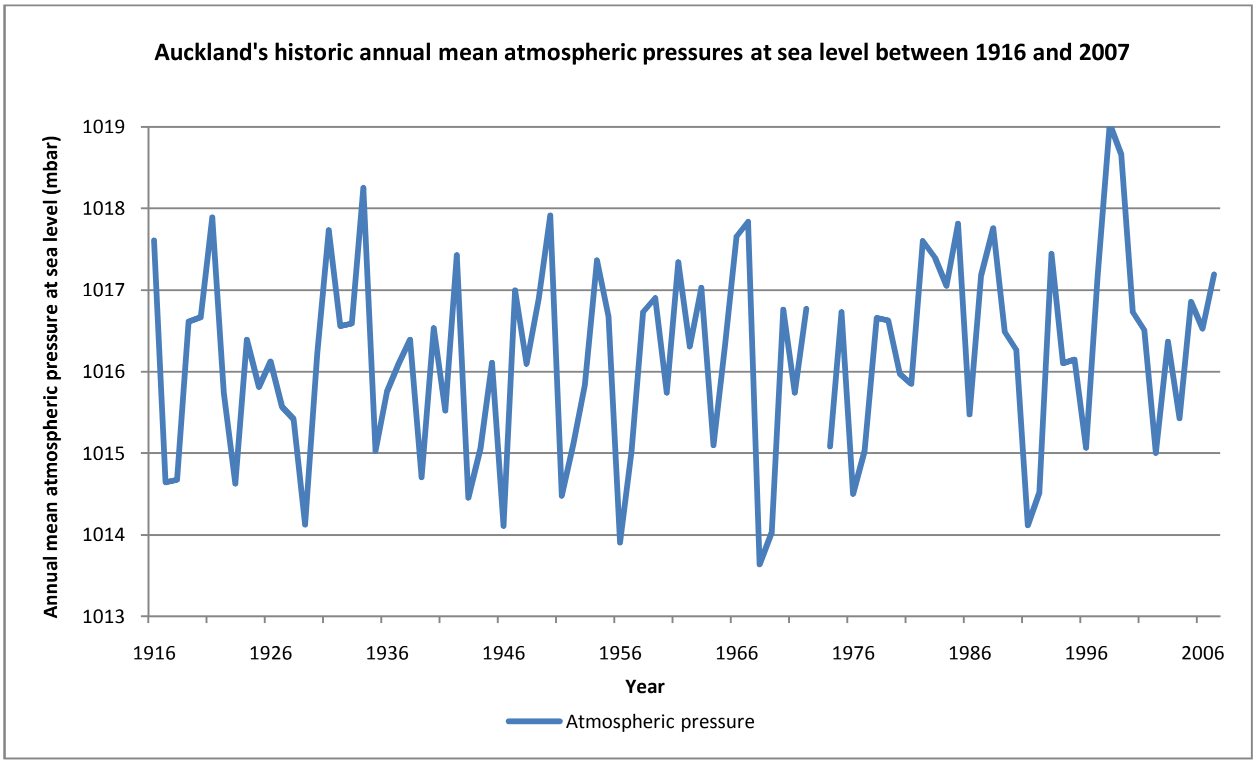

Figure 5.7: Auckland's historic annual mean atmospheric pressures at sea level between 1916 and 2007

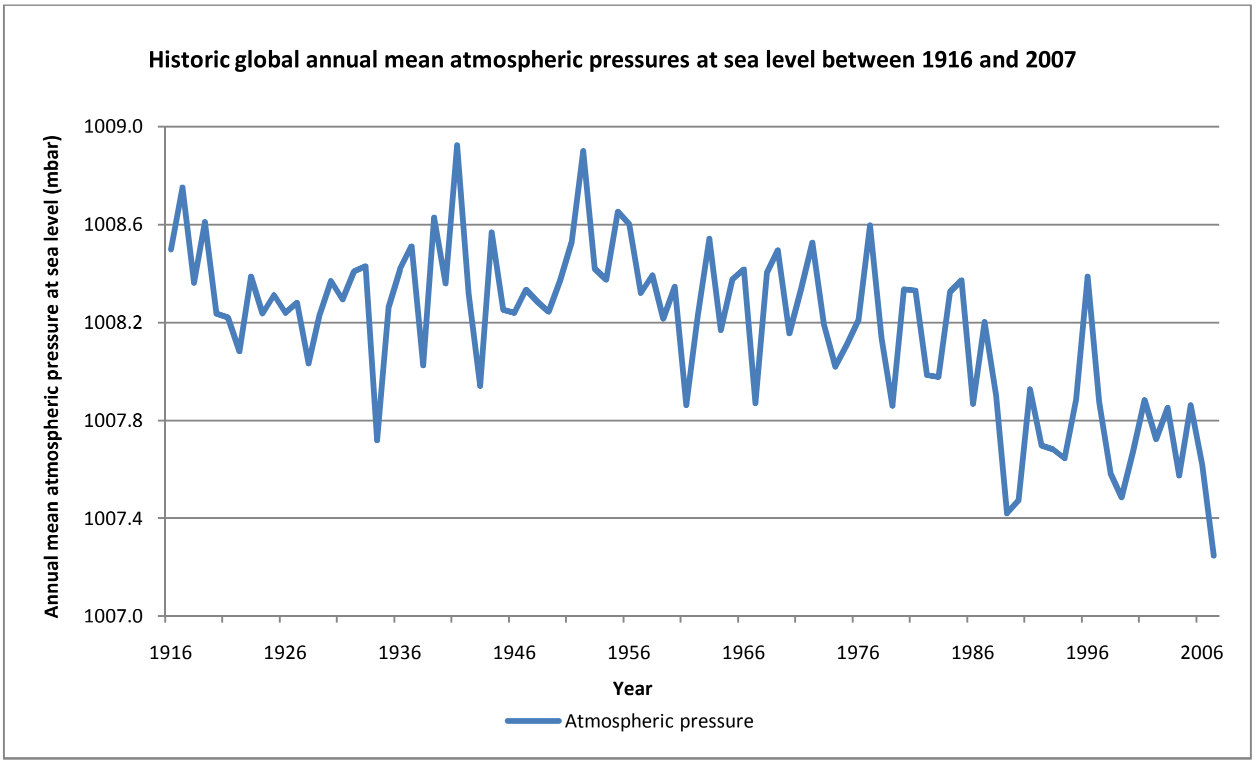

Figure 5.8: Historic global annual mean atmospheric pressures at sea level between 1916 and 2007

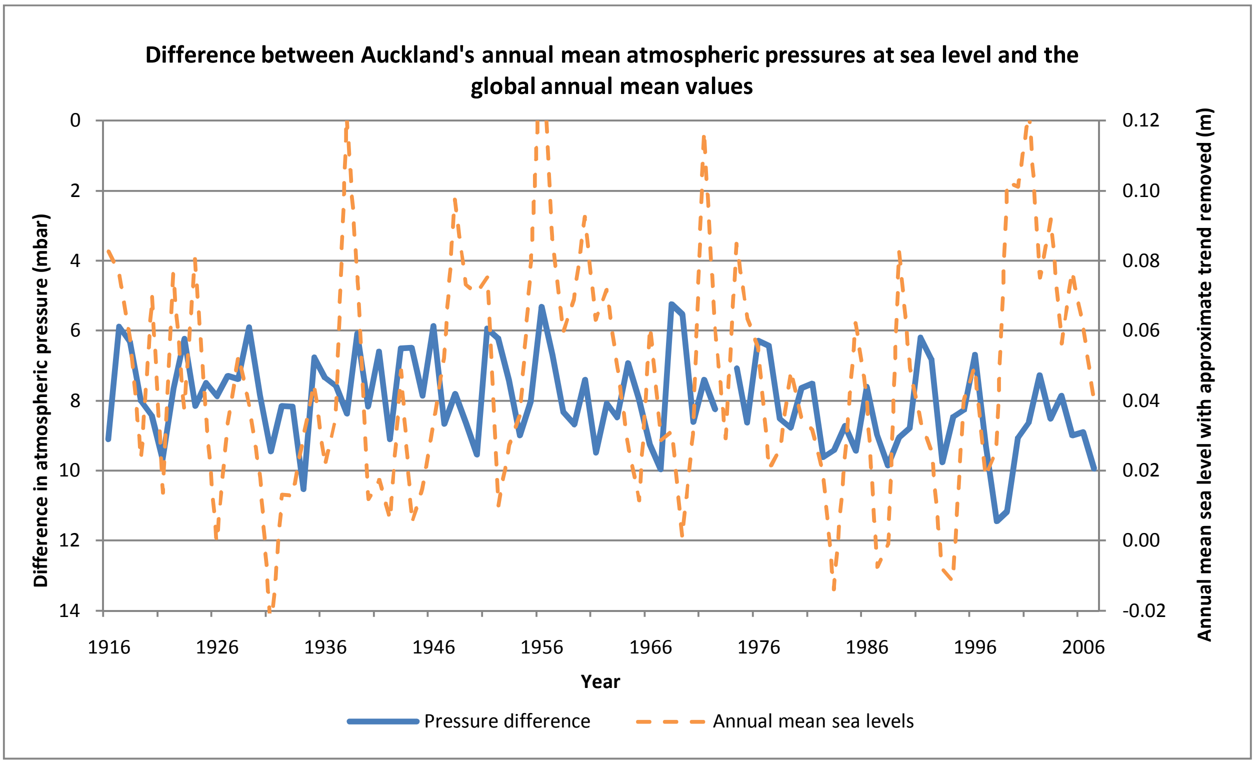

Figure 5.9: Difference between Auckland's annual mean atmospheric pressures at sea level and the global annual mean values

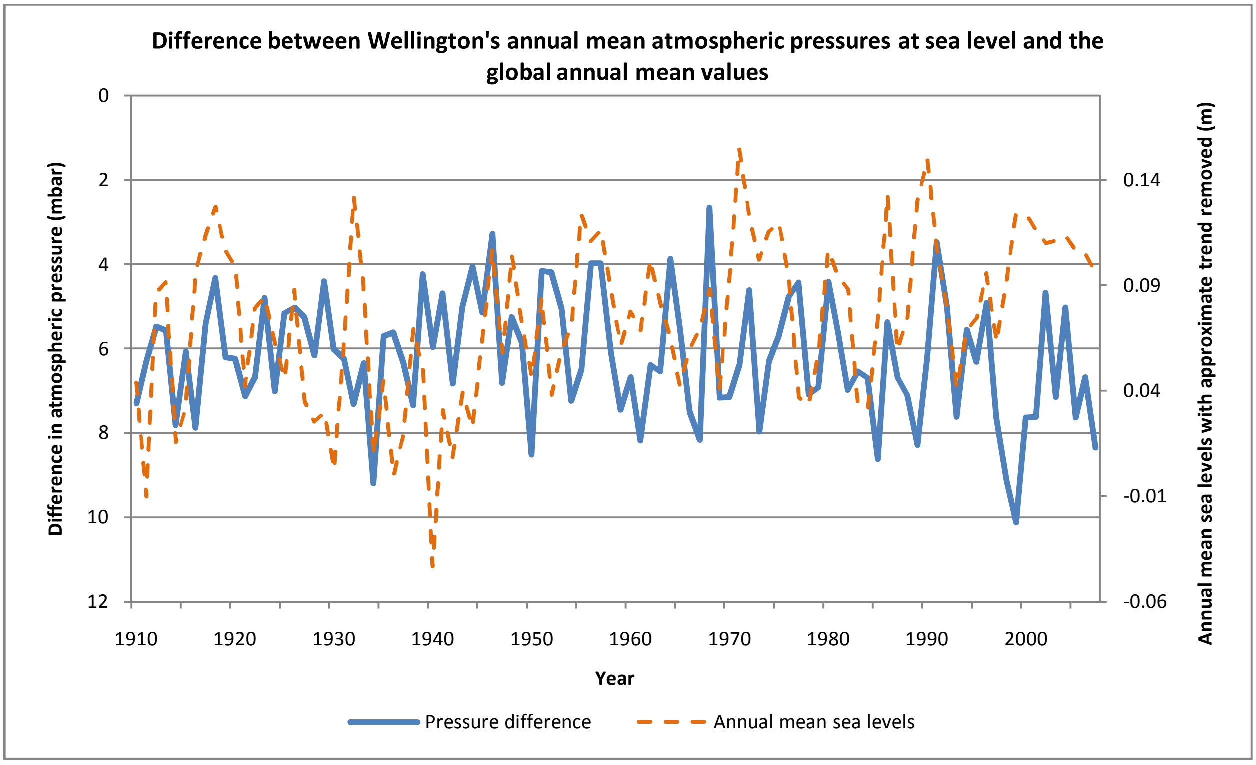

Figure 5.10: Difference between Wellington's annual mean atmospheric pressures at sea level and the global annual mean values

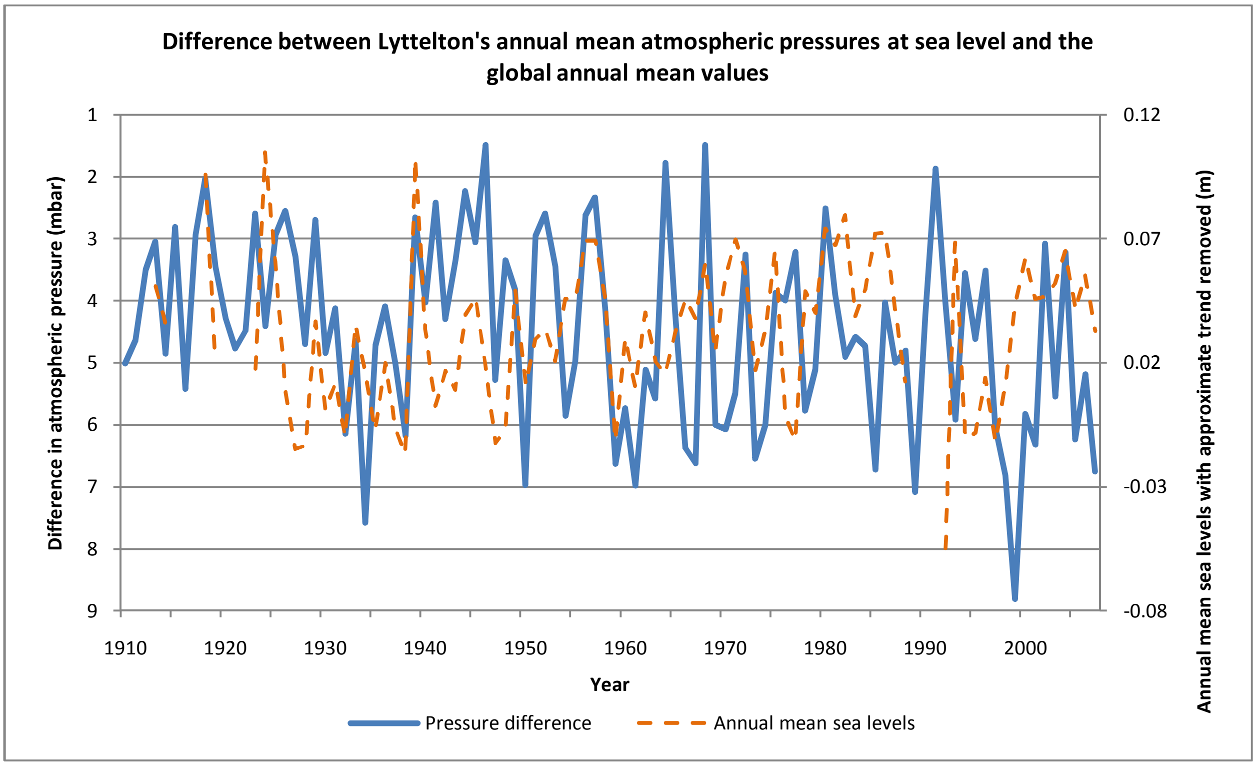

Figure 5.11: Difference between Lyttelton's annual mean atmospheric pressures at sea level and the global annual mean values

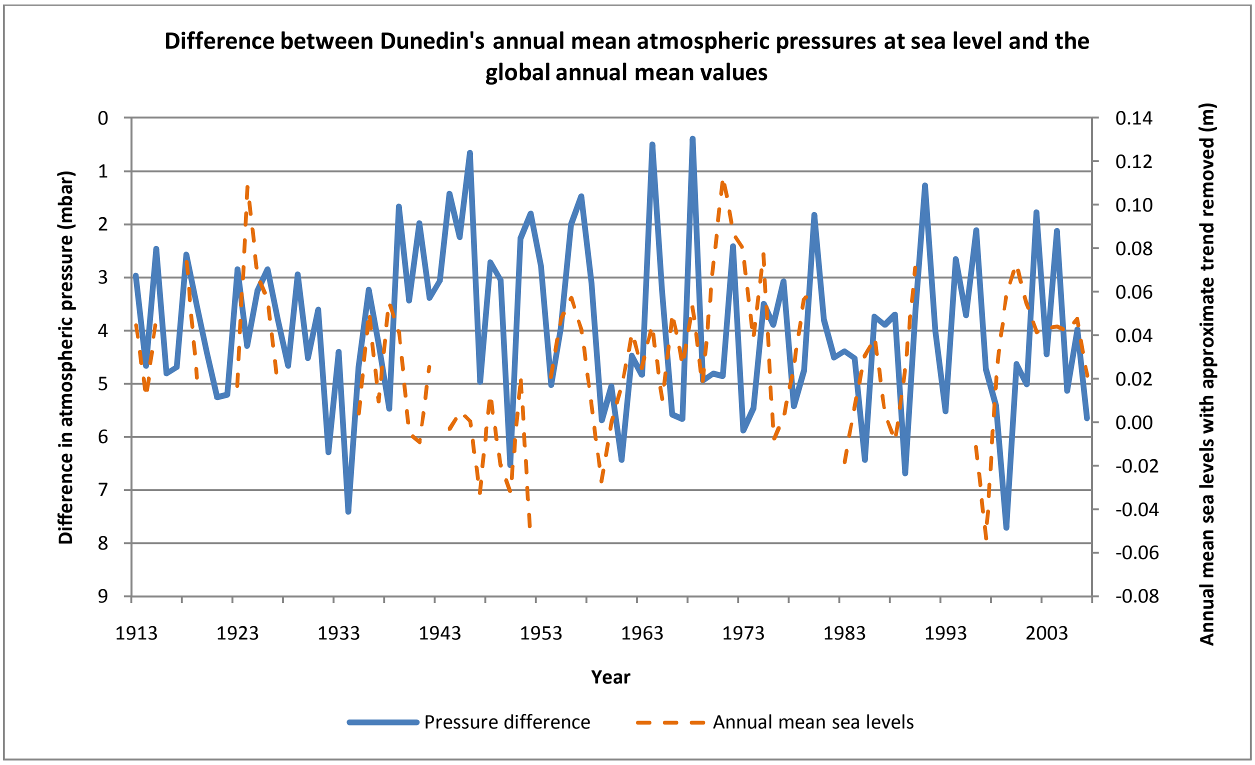

Figure 5.12: Difference between Dunedin's annual mean atmospheric pressures at sea level and the global annual mean values

Although the derived global annual mean sea level atmospheric pressures shown in Figure 5.8 are consistent with those similarly derived from the extended reconstructed sea level pressures, neither dataset is consistent with the academically accepted global average sea level atmospheric pressure of 1013.25 millibars. This figure may be an approximated average pressure value, or may reflect the mean pressure considering both the average oceanic and inland conditions. Higher atmospheric pressures would be expected inland due to the capacity of land masses to absorb and radiate heat, causing comparatively higher atmospheric pressures compared to those measured in open ocean and coastal locations, despite the atmospheric pressures being corrected for altitude above sea level.

5.3 Analysis methodologies used

Least Squares analysis was the primary technique used in this study. It has the advantage of allowing estimates of the accuracies of the derived parameters to be obtained. These can then be used to form confidence intervals for the parameters.

Fast Fourier Transform analysis is also used in this study to convert datasets into the frequency domain. This is necessary for this study to isolate the significant decadal and interdecadal signals that are present in the dataset so that they may then be appropriately incorporated into the trend analyses.

5.3.1 Least Squares analysis

The Least Squares analysis method is a form of estimation that obtains the minimum variance unbiased estimator. This is the optimum result given the data used and the variances associated with the data. To achieve this, the analysis process requires the variances and covariances of all observations to obtain the 'best' weighted solution. There are some weaknesses associated with this form of analysis (see Section 5.3.1.1 below) and these need to be minimised to ensure that the most representative results are obtained.

5.3.1.1 Weaknesses associated with Least Squares analysis

Kuo *et al.*(2004) claim that using Least Squares analysis in calculating sea level trends (e.g., Church *et al*, 2001; Nerem and Mitchum, 2002) can produce misleading results if the residuals do not have a random noise spectrum. Additionally, most tidal records show non-uniform trends that cause any trend derived from the data to be sensitive to arbitrarily chosen start and end dates (Jevrejeva *et al*., 2006) unless the signals are removed prior to analysis or are otherwise suitably incorporated.

Mazzotti *et al*. (2008) claim that Least Squares regression analysis is inappropriate for detecting trends in sea level rise as its inherent assumption that variance is random with a normal distribution about the trend is false, as it would be with other geological and geophysical processes.

Woodworth (1990) has investigated sea level acceleration using Least Squares analysis. He assumed that each tide gauge's records were statistically independent. Douglas (1992) argues that this is a false assumption to make, as at low frequencies there is a strong spatial coherence of sea level. Therefore, although tidal records may extend back for very long periods, their records may provide what is effectively a single measurement for interdecadal to centennial sea level variations if they are not sufficiently spatially distributed. If correlations are not appropriately incorporated into the Least Squares analysis, the derived precision estimates are too optimistic (Beavan *et al*., 2007).

The standard errors of sea level trend parameters are generally underestimated due to the assumption that each annual mean is independent, instead of taking into account correlations between the different stations used in the analysis (Douglas, 2001; Nerem and Mitchum, 2002). Decadal and interdecadal signals vary in nature, period, and magnitude in different locations around the globe. However, the signals present in the datasets of stations in close spatial proximity may be highly correlated with each other (Holgate, 2007).

In order to minimise the errors associated with these weaknesses in the Least Squares analysis, the variances and covariances need to be very carefully considered to avoid calculating overly optimistic variances associated with the calculated parameters.

5.3.1.2 Least Squares approach to minimise analysis weaknesses

Considering the limitations in the standard Least Squares analysis approach, a more thorough Least Squares approach is applied in order to minimise the detrimental effects of the common false assumptions. This approach incorporates correlation coefficients to ensure that the standard errors of the trends derived are not underestimated.

Equation 5.1 and Equation 5.2 are used to calculate correlation and covariance values, whereby ρ_{xy} is the correlation coefficient, n is the number of measurements, x_i and y_i are the series of measurements, σ_x and σ_y are the standard deviations of X and Y respectively, and σ_{xy} is the correlation between x and y.

$$\rho_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{(n-1)\sigma_x \sigma_y}$$

Equation 5.1: Pearson's Correlation Coefficient

$$\rho_{xy} = \frac{\sigma_{xy}}{\sigma_x \sigma_y}$$

Equation 5.2: Relationship between correlation and covariance

To calculate the covariances between annual means at any given tide gauge, an approximate linear trend must be removed from the dataset as Equation 5.1 requires a constant mean value.

The variances of all the annual mean sea level values used in this analysis have been carefully considered to ensure that they are not overestimated. This is discussed further in Section 3.3.

5.3.1.3 Least Squares analysis derivation

This section provides the simplified derivation of the Least Squares analysis equations that are used to obtain the minimum variance unbiased estimator. The full derivation is not provided here as it is superfluous to requirements for this study. Least Squares analysis minimises $V^T PV$, where V is the matrix of residuals (random errors) for the observations, and P, shown in Equation 5.4, is the weight matrix. In Equation 5.4, σ_o^2 is the *a priori* variance of unit weight, which is usually equal to 1.0, and Σ_{Lb} is the variance-covariance matrix for all observations used in the analysis, scaled by the *a priori* variance.

$$\sum_{Lb} = \begin{bmatrix} \sigma_1^2 & \cdots & \sigma_{1n} \\ \vdots & \ddots & \vdots \\ \sigma_{n1} & \cdots & \sigma_n^2 \end{bmatrix}$$

Equation 5.3: Variance covariance matrix of observations

$$P = {\sigma_o}^2 \Sigma_{Lb}^{-1}$$

Equation 5.4: Weight matrix

L_a, shown in Equation 5.5, is the matrix of adjusted observations, which is compiled using the best estimates for the true value of the sought parameters. L_b is a matrix of the actual observations made, and V is the matrix of the remaining residuals, or random errors.

$$L_a = F(X_a)$$

Equation 5.5: Adjusted observations

$$L_a = L_b + V$$

Equation 5.6: Adjusted observations in terms of observations and residuals

Expanding Equation 5.5using the Taylor series and considering X_o as the point of expansion we obtain Equation 5.7.

$$L_a = F(X_o) + \left.\frac{\partial F}{\partial X_a}\right|_{X_a = X_o} [(X_a - X_o)] + \cdots$$

Equation 5.7: Expanded expression for adjusted observations

We choose to truncate the series after the first derivative, and we define the terms as follows shown in Equation 5.8, Equation 5.9, and Equation 5.10. A is an n x u matrix, where n is the number of observations made, and u is the number of parameters being calculated.

$$\left.\frac{\partial F}{\partial X_a}\right|_{X_a = X_o} = A$$

Equation 5.8: Definition of the A-matrix

$$\bar{X} = X_a - X_o$$

Equation 5.9: Parameter correction

$\bar{X}$ is the parameter correction to be applied to the prior estimates for the unknown parameters. X_a is the matrix of the adjusted parameters, and X_o is the matrix of our point of expansion. L_o is the matrix of computed observations.

$$L_o = F(X_o)$$

Equation 5.10: Computed observations

From Equation 5.10 we can derive our residuals, V, using in Equation 5.11 in conjunction with Equation 5.12.

$$L = L_b - L_o$$

Equation 5.11: Difference between observations and computed observations

$$V = A\bar{X} - L$$

Equation 5.12: Calculated residuals

If $V^T PV$ is minimized subject to Equation 5.12 as the constraint, we find the Least Squares parameter correction value expressed below in Equation 5.13.

$$\bar{X} = (A^T PA)^{-1} A^T PL$$

Equation 5.13: Adjustment computation to derive parameter corrections

From this we can also derive the *a posteriori* variance of unit weight, expressed in Equation 5.14. This value should be approximately equal to one. There are several causes of large *a posteriori* variance values, which include "*the mathematical model, computational errors, ill-conditioned system, influence of omitted higher order terms, incorrect estimate of a priori variances of observations, and blunders in observations*" (Uotila, 1975).

$$\bar{\sigma}_o^2 = \frac{V^T PV}{n - u}$$

Equation 5.14: *A posteriori* variance of unit weight

The unbiased estimate for the variance-covariance matrix of the adjusted parameters can be derived using Equation 5.15.

$$\sum_{X_a} = \bar{\sigma}_o^2 (A^T PA)^{-1}$$

Equation 5.15: Unbiased estimate variance-covariance matrix of adjusted parameters

Using these equations, the datasets may be analysed to calculate unknown parameters to potentially obtain trend patterns. Appropriate errors that correspond with the derived parameters can also be derived from the use of the same input datasets. The input data may be any form of measurements; including terrestrial or GPS surveying observations, or time series sea level records.

Least Squares analysis with weighted parameters

Approximate values and *a priori* variances associated with parameters being investigated can be incorporated into Least Squares analysis as constraints. The approximate values of the parameters are incorporated as direct observations in Equation 5.16, and the associated a priori variances are incorporated in the weight matrix as shown in Equation 5.17.

$$L_x = X_a$$

Equation 5.16: Direct observation on unknown parameters (Uotila, 1973)

$$P = \begin{bmatrix} P_1 & 0 \\ 0 & P_x \end{bmatrix}$$

Equation 5.17: Weight matrix including *a priori* variances of parameters (Uotila, 1973)

The A_2matrix is defined in Equation 5.18. This matrix has dimensions u × u and has unit element in the diagonal as the weights for the parameters will be non-zero, and all other elements are zero.

$$\frac{\delta F_2}{\delta X_a} = A_2$$

Equation 5.18: Definition of A_2 matrix (Uotila, 1973)

$$L_2 = X_o - L_b^2$$

Equation 5.19: Values of weighted parameters (Uotila, 1973)

The L_2^b matrix has the values of the parameters for which the weights are available. Equation 5.20 provides the solution of the Least Squares analysis.

$$X = -(A_1^T P_1 A_1 + P_x)^{-1}(A_1^T P_1 L_1 + P_x L_2)$$

Equation 5.20: Solution of Least Squares analysis with estimates and a priori variances of unknown parameters (Uotila, 1973)

The corresponding equations associated with this form of analysis are provided in Equation 5.21 and Equation 5.22.

$$V^T PV = V_1^T P_1 V_1 + V_x^T P_x V_x = L_1^T P_1 L_1 + L_2^T P_x L_2 + X^T (A_1^T P_1 L_1 + P_x L_2)$$

Equation 5.21: V^TPV matrix with estimates and a priori variances of unknown parameters (Uotila, 1973)

$$\sum X_a = \sigma_o^2 (A_1^T P_1 A_1 + P_x)^{-1}$$

Equation 5.22: Variance covariance matrix considering estimates and a priori variances of unknown parameters (Uotila, 1973)

5.3.1.4 Least Squares analysis summary

Least Squares analysis can be applied to find the best solution for unknown parameters given a selection of observations. These observations may be repeated sets of measurements to resolve unknown parameters, such as a point's position, or they may be observations taken regularly over time to identify a trend in the time series data. The observations may be annual, monthly, daily, or hourly. Some sea level analysis programs use hourly sea level data to calculate harmonic constituents through a similar mathematical analysis method.

5.3.2 Fourier Function Digital Signal Processing

Fourier analysis is essential for understanding the behaviour of systems and signals. Sine waves are Eigenfunctions of linear, time-invariant systems, so if a particular sine wave is passed through any linear, time-invariant system it will produce a scaled version of that same sinusoid on the output. As Fourier analysis enables us to define any signal through the use of superimposed sine waves, how the given system affects all possible sinusoids needs to be determined to ensure the full understanding of the signal. Furthermore, the passage of any signal from convolution (in time) can be converted to multiplication (in frequency) (Baranuik *et al*., 2010).

One great advantage of expressing a function in terms of sine waves is the inherent simplification of various operations of analysis, including differentiation (Lighthill, 1964).

There are several forms of signal types, and each signal type has an appropriate transform to convert the signal into the frequency domain. Table 5.2 shows the appropriate Fourier transform for this study. The Continuous-Time Fourier Transform works by converting a signal in time into an equivalent signal composed of a combination of sine waves (Baranuik *et al*., 2010).

Transform	Time Domain	Frequency Domain	Convolution
Continuous-Time Fourier Series	$L^2([0,T])$	$l^2(\mathbb{Z})$	Continuous-Time Circular

Table 5.2: Continuous-Time Fourier Series Representation (Baranuik *et al.*, 2010)

The Fourier series provides a means by which a signal can be represented in a general manner; as the composition of sine waves. Below the Continuous-Time Fourier Transform is presented. The radial frequency variable Ω is used in the exponential, where $\Omega = 2f$.

$$\mathcal{F}(\Omega) = \int_{-\infty}^{\infty} f(t) e^{-(j\Omega t)} dt$$

Equation 5.23: Continuous-Time Fourier Transform (Baranuik *et al.*, 2010)

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \mathcal{F}(\Omega) e^{j\Omega t} d\Omega$$

Equation 5.24: Inverse Continuous-Time Fourier Transform (Baranuik *et al.*, 2010)

Equation 5.23 and Equation 5.24 have been derived from the Fourier series and our understanding of its coefficients. The Continuous-Time Fourier Transform integration is utilised to express the aperiodic signals. This is necessary for the Continuous-Time Fourier Transform as it is required to incorporate non-periodic signals, and thus the entire frequency spectrum (Baranuik *et al*., 2010).

The identification of signals within sea level records is vital for the accurate derivation of trends within the datasets as signals potentially may cause a bias in the result. Fast Fourier Transform analysis can be applied to identify the approximate periods of the signals in the records. This information may then be incorporated into further analysis.

5.3.2.1 Application for investigating sea level rise trend

The Fast Fourier Transform was applied in this study using Python software to transform the sea level time-series data into the frequency domain. By doing this, it is possible to identify if any predominant frequencies exist, and approximate what those frequencies are (Andreasen, 2005). Through this investigation to find any periodicity in the data, the periods of any decadal and interdecadal oscillations that might exist may be found, allowing for further investigation into the magnitudes of respective signals.

The Python analysis is limited in its ability to derive the frequency of short period signals when the period is shorter than two units of the time interval of the input data. For example, if annual mean sea levels are used in the input dataset, the shortest period that can be derived is two years. This should not impede the analysis for the purposes of this study as it is the longer period signals that are being investigated because they are considered to have the greatest impact on long-term derived trends.

Another limitation of the Python Fast Fourier Transform analysis is that the data is required to contain no gaps. The mean sea level records for Auckland and Wellington nearly meet this requirement. The Wellington mean sea level records have a significant gap from 1894 until 1900 so only the records from 1900 onwards were considered. Auckland's records have a one year gap in 1902 and another in 1946 that were approximated using linear interpolation.

The nature of sea level records causes difficulties when attempting to apply Fast Fourier Transform analysis techniques. However, if these limitations can be managed suitably the results obtained can be incorporated into the analysis to improve the results.

5.3.2.2 Fast Fourier Transform analysis summary

Fast Fourier Transform analysis identifies the frequencies of signals within datasets with respect to the power spectrum density. These time series records may include sea level records, and temperature and atmospheric pressure records. The presence of such signals can potentially cause biases in the derived trends over time. These signals may be able to be modelled, and potentially removed from the datasets. However, for this to be achieved the datasets must not contain any errors due to tide gauge shifts, or poor maintenance.

5.4 Results obtained from the datasets considered

Two annual mean sea level datasets were considered in this study. These were the annual mean sea levels that were corrected for the inverted barometer effect, and the annual mean sea levels that did not have the correction applied.

Both of these datasets were analysed for the presence of a common accelerating trend between the stations, secular changes in the rate of sea level rise, and site-specific accelerations observed at the individual tide gauges. The presence of significant signals and their approximate periods were investigated in advance of the trend analyses so that the most significant signals could be appropriately incorporated into the models.

5.4.1 Linear trends initial estimates

The methodology for this investigation states that there are several steps in the analysis that require the first estimate of the trend in sea level rise to be removed to obtain a dataset with a constant mean value. The covariances that represent the relationships between the stations must be incorporated into the weight matrix. To obtain these covariances approximate linear trends in sea level rise were investigated for each tide gauge.

Equation 5.1 is used to calculate the correlations between the stations that can then be used to calculate the corresponding covariances. Equation 5.1 assumes that the input dataset has a constant mean value. Therefore, the annual mean sea level values must have their respective estimated linear trends removed to obtain new datasets that have constant mean values. A preliminary trend was obtained using Least Squares linear regression analysis by assuming that the four stations were uncorrelated. This trend was removed from the annual mean sea level datasets, enabling the initial covariances to then be derived.

Improved linear trend approximations were calculated for the four tide gauges by incorporating these covariances into the weight matrix. The calculated estimated trends are detailed in Equation 4.9. These linear trends were not removed from the datasets used to investigate the overall trends in sea level rise at the stations considered in this study.

Station	Gradient (mm/yr)	95% Confidence Interval	Offset (mm)	95% Confidence Interval
Auckland	1.46	± 0.18	1852	± 12
Wellington	2.02	± 0.40	(≤ 1942) 525	± 17
			(>1944) 545	± 35
Lyttelton	1.96	± 0.26	857	± 20
Dunedin	1.28	± 0.22	935	± 15

Table 5.3: Initial approximate linear trends in sea level rise for the Auckland, Wellington, Lyttelton and Dunedin

5.4.2 Corrected annual mean sea level datasets

The annual mean sea levels for Auckland, Wellington, Lyttelton and Dunedin were corrected for the inverted barometer effect using the calculated local relative pressure variations. With this data, new approximate linear trends were derived for all four stations, allowing the covariances between the stations to be revised. The updated linear trends are provided in Table 5.4. The corrected annual mean sea levels for the four stations are shown in Figure 5.13, with arbitrary offsets assigned to the datasets for illustration purposes.

Station	Gradient (mm/yr)	95% Confidence Interval	Offset (mm)	95% Confidence Interval
Auckland	1.41	± 0.19	1810	± 13
Wellington	1.85	± 0.43	(≤ 1942) 478	± 18
			(>1944) 504	± 37
Lyttelton	1.83	± 0.28	833	± 22
Dunedin	1.22	± 0.24	910	± 16

Table 5.4: Approximate linear trends for the four stations using data corrected for the inverted barometer effect

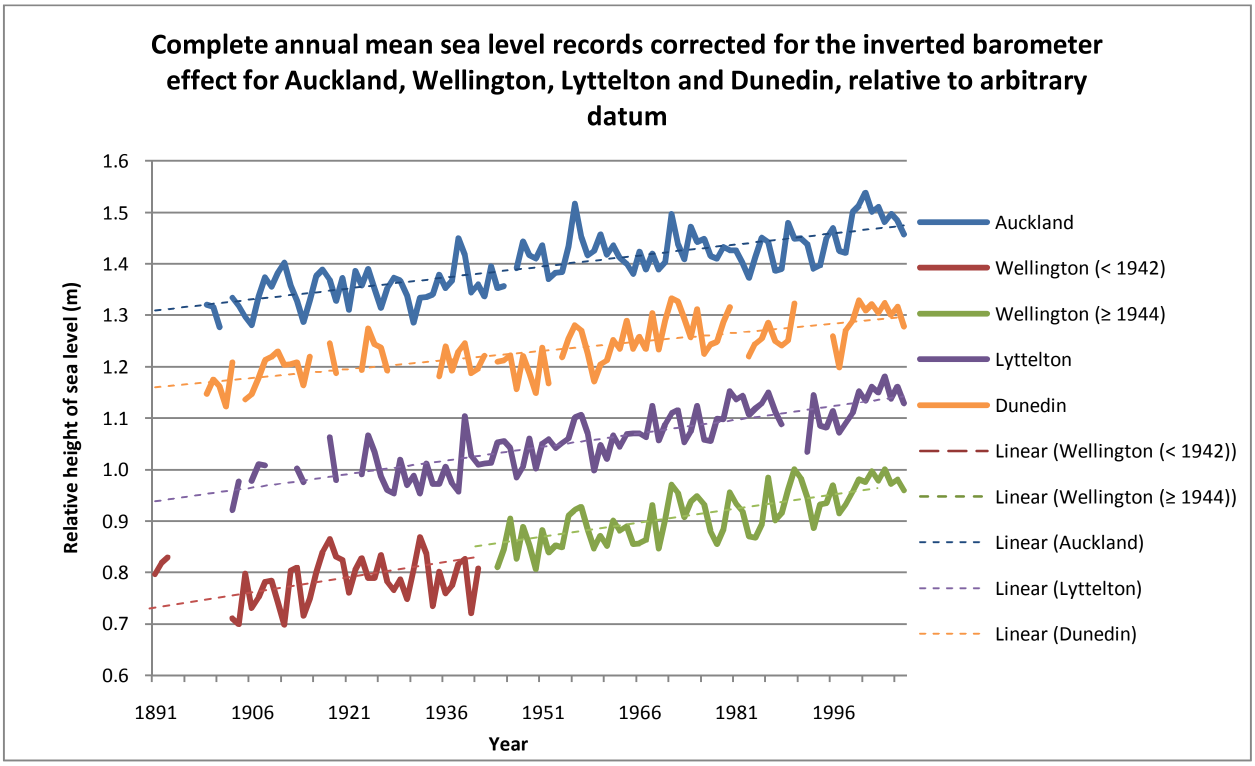

Figure 5.13: Complete annual mean sea level records corrected for the inverted barometer effect for Auckland, Wellington, Lyttelton and Dunedin, relative to arbitrary datum

5.4.2.1 Fourier Function Digital Signal analysis on corrected annual mean sea levels

Decadal and interdecadal signals are believed to be associated with long-term meteorological systems, including atmospheric pressure trends that are inherently associated with them. By correcting the dataset for the inverted barometer effect, any remaining signals that are present in the dataset should not be due to long-term pressure trends. The corrected annual mean sea level dataset was investigated for predominant signals using Fast Fourier Transform analysis. This analysis converts the data into the frequency domain; highlighting the relative significance of respective signals contained within the dataset. Only the Auckland and Wellington datasets could be subject to this analysis as the Dunedin and Lyttelton records are largely incomplete, and the interpolation techniques that would be required to approximate the missing values would be unsuitable at the scale required.

Figure 5.14 shows the periods of signals that are present within Auckland's corrected annual mean sea level dataset, and the corresponding significance of these signals. Similarly, Figure 5.15 illustrates the significance and periods of signals that are present within Wellington's dataset. The signals of greatest significance were included in the Least Squares analysis as observations using Equation 5.20 to calculate the amplitudes and periods of the signals through the incorporation of Equation 4.23. The estimated periods obtained from the Fast Fourier Transform analysis are summarised in Table 5.5. These periods are used as the initial estimates of the period parameters in the modelled signals.

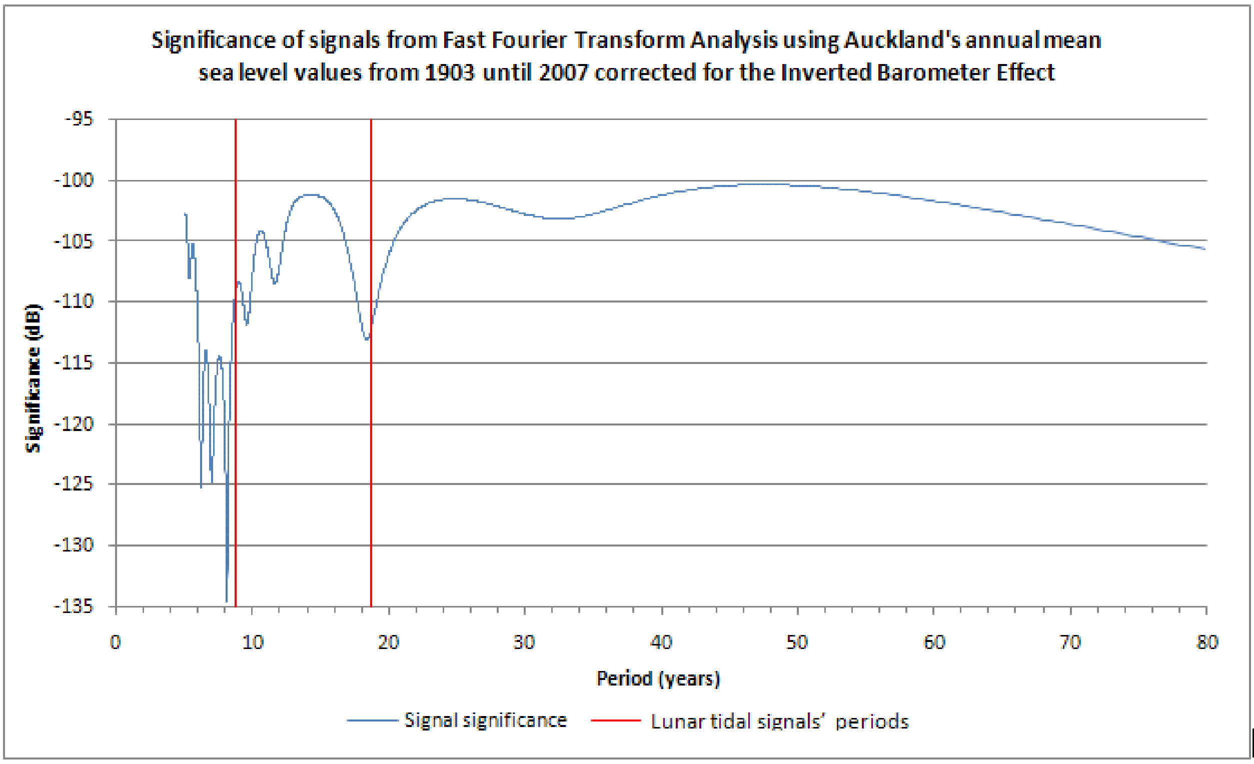

Figure 5.14: Significance of signals from Fast Fourier Transform Analysis using Auckland's annual mean sea level values from 1903 until 2007 that are corrected for the inverted barometer effect

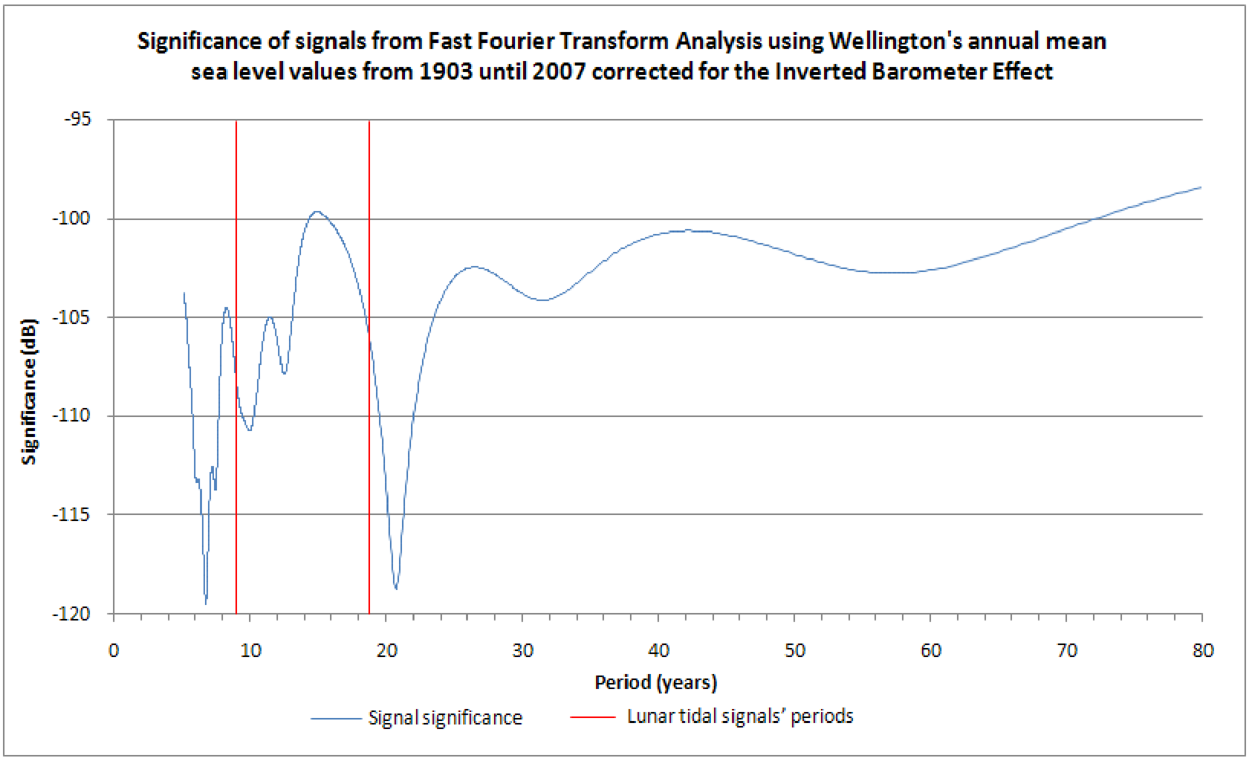

Figure 5.15: Significance of signals from Fast Fourier Transform Analysis using Wellington's annual mean sea level values from 1903 until 2007 that are corrected for the inverted barometer effect

Significant signals' approximate periods	
Station: Auckland	**Station: Wellington**
13-15 years	14-16 years
45-50 years	40-44 years

Table 5.5: Approximate periods of most significant signals that are contained within Auckland's and Wellington's corrected datasets

These signals, shown in Table 5.5, should be considered in this form of analysis to avoid any bias in the derived result. Shorter-term signals theoretically could be averaged out over long term records, but the compounding effect of both the shorter and the longer-term signals and their respective amplitudes should still be incorporated to avoid this potential bias.

Signals from the nodal tides with periods of 18.613 and 8.847 years were expected to have been highlighted as prominent drivers of signals within the annual mean sea level datasets. However, it is not unreasonable to expect these tidal periods to be considered not significant in this regard as their respective influences may have been distorted by the noise in the datasets, compounded with presence of more significant sea level driving signals.

The most significant signals shown in Table 5.5 could be caused by any of a range of drivers. The periods of the lunar tidal signals are shown in Figure 5.14 and Figure 5.15 against the significant periods identified within the datasets. These show that the signals are likely to be the result of other drivers, possibly meteorological (e.g., the Interdecadal Pacific Oscillation) or gravitational. However, as a correction for the inverted barometer effect has been applied, in theory the signals present within the annual mean sea level records should not be driven by atmospheric pressure changes. Figure 5.16 illustrates the significance of the signals present in Auckland's annual mean sea level records against the signals within Auckland's annual mean temperature records.

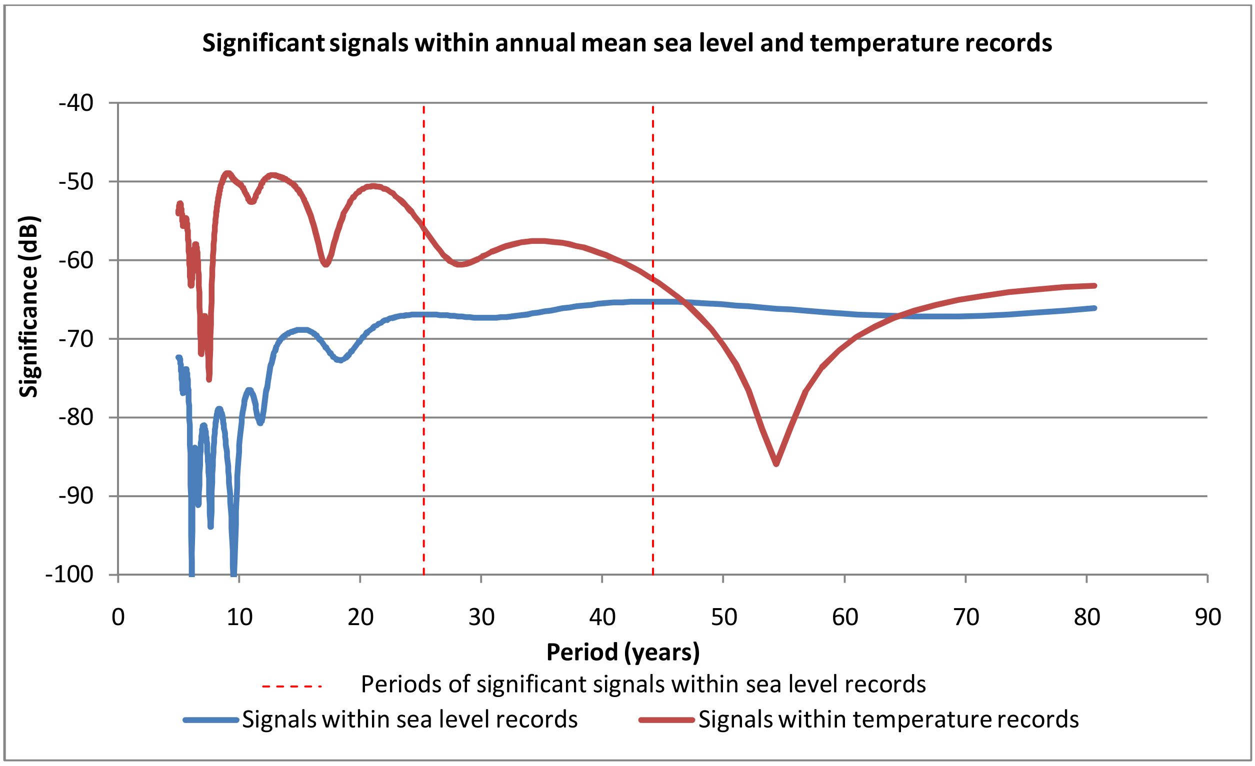

Figure 5.16: Significance of signals within Auckland's corrected annual mean sea level and temperature records

5.4.2.2 Acceleration analyses using data corrected for inverted barometer effect

The annual mean sea level datasets that have been recorded at New Zealand's four long-term tide gauges are subject to significant annual variability due to the multitude of forces acting upon the Earth's oceans. There are limitations to what corrections may be applied to annual mean sea levels to reduce the data's variability due to the complexities of the forces that influence it, and also due to the limited datasets available to investigate and apply further corrections.

Given these limitations, the annual mean sea level datasets were corrected for the inverted barometer effect to reduce the overall variability of the data through utilising the information that is currently available. This technique may provide an improved dataset, which has appropriately propagated errors associated with the annual mean sea level values. This new dataset was then investigated for an accelerating tendency.

The presence of an acceleration in the combined datasets was explored through the application of Equation 4.23 through Least Squares analysis to derive the unknown parameters. The derived covariances and propagated errors associated with the mean sea levels were used to populate the weight matrix for this analysis. The periods of the signals identified in Wellington's and Auckland's datasets were utilised in this analysis, and the same periods were utilised as the initial estimates of the signals present within Lyttelton's and Dunedin's datasets. The Least Squares analysis may therefore converge on a signal that is not the most significant, but this limitation cannot be avoided with this methodology. The results obtained through the combined analysis of the full corrected annual mean sea level datasets are shown in Table 5.6. The table shows that no significant acceleration was found using this complete dataset. Table 5.7 summarises the derived parameters of the signals identified within the datasets. The signals are considered to be not significant in effect if neither amplitude parameter (i.e., a nor b) are statistically significant at the 95% confidence interval.

Station	All	Auckland		Wellington			Dunedin		Lyttelton	
Parameter	a (mm/yr²)	m (mm/yr)	c (mm)	m	c <1942	c ≥1944	m	c	m	c
Value	0.0006	1.4	1806.1	1.9	475.8	496.3	1.2	906.2	1.7	843.4
Standard deviation	0.0022	0.3	8.8	0.4	13.0	25.6	0.3	11.5	0.3	14.0
Significant at 95% Confidence interval	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\bar{\sigma}_o^2$	**1.47**									

Table 5.6: Trend results from full dataset acceleration analysis corrected for the inverted barometer effect

Station	Period (years)	95% CI	*a* (mm)	95% CI	*b* (mm)	95% CI
Auckland	49.3	± 5.3	-14.5	± 11.3	Not significant	
	12.9	± 0.4	-15.2	± 6.8	Not significant	
Wellington	41.7	± 12.1	Not significant		Not significant	
	13.7	± 0.7	12.8	± 12.2	Not significant	
Dunedin	49.9	± 6.3	-20.7	± 11.4	Not significant	
	15.2	± 0.7	Not significant		16.3	± 12.2
Lyttelton	15.9	± 0.9	Not significant		Not significant	
	31.7	± 4.2	Not significant		-15.1	± 14.5

Table 5.7: Significant signals found within the corrected datasets with 95% confidence intervals

A combined analysis investigating both the existence of a possible accelerating trend and decadal and interdecadal signals is necessary as the trend and signal parameters are significantly correlated with each other, and with themselves. By combining these parameters in a single analysis the different behaviours in sea level change over time are all duly considered, to find the most representative overall trends.

The signals detected within each respective dataset are illustrated against the corrected annual mean sea level values that contain the signals in the figures below. The signals and datasets for Auckland, Wellington, Lyttelton and Dunedin are shown in Figure 5.17, Figure 5.19, Figure 5.21 and Figure 5.23 respectively. The gaps in the records are projected into the derived signals in these figures to illustrate the limitations associated with the derivation of the signals using the incomplete datasets. Figure 5.18, Figure 5.20, Figure 5.22 and Figure 5.24 show the corrected annual mean sea level values against the datasets that still contain the significant decadal and interdecadal signals. Approximated linear trends in these corrected datasets are shown in these figures to illustrate the effect that the presence of such signals in the dataset can have on derived trends, although the severity of the influence is dependent on the frequency of the signal and the length of the dataset being analysed, as stated in Section 4.2.3.

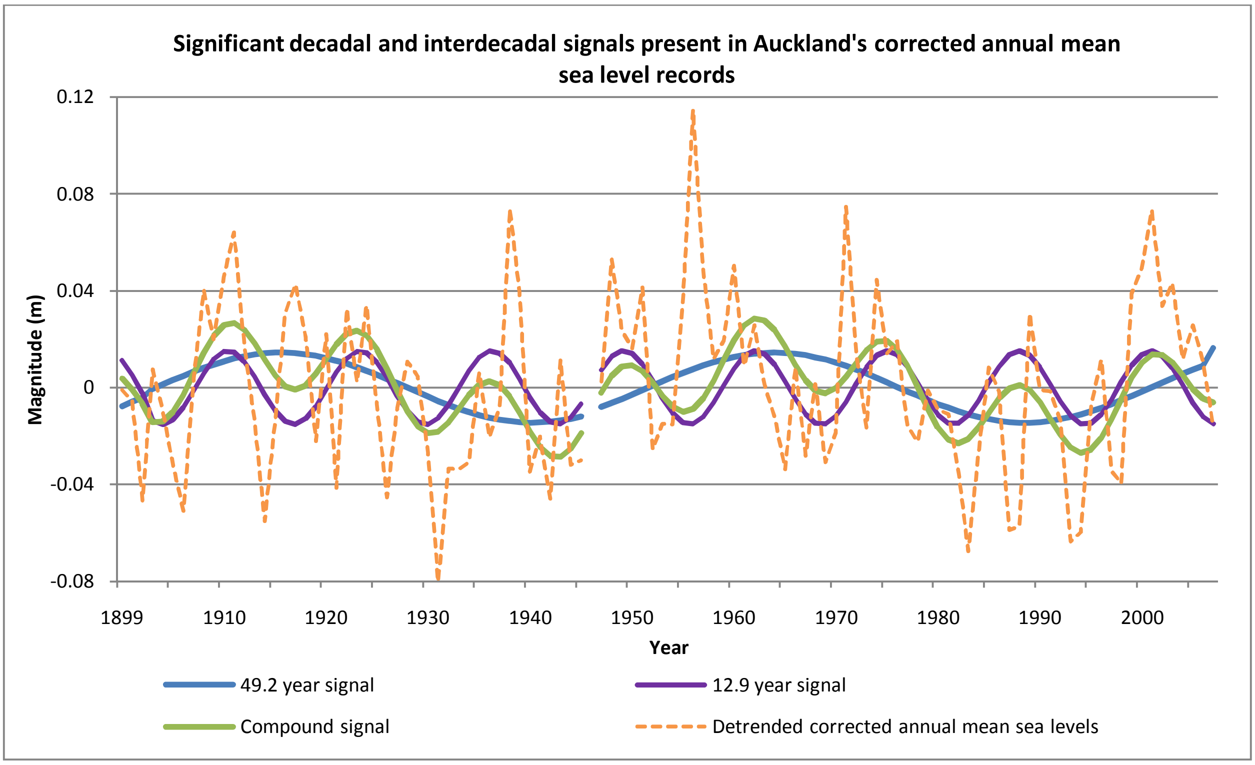

Figure 5.17: Significant decadal and interdecadal signals present in Auckland's corrected annual mean sea level records

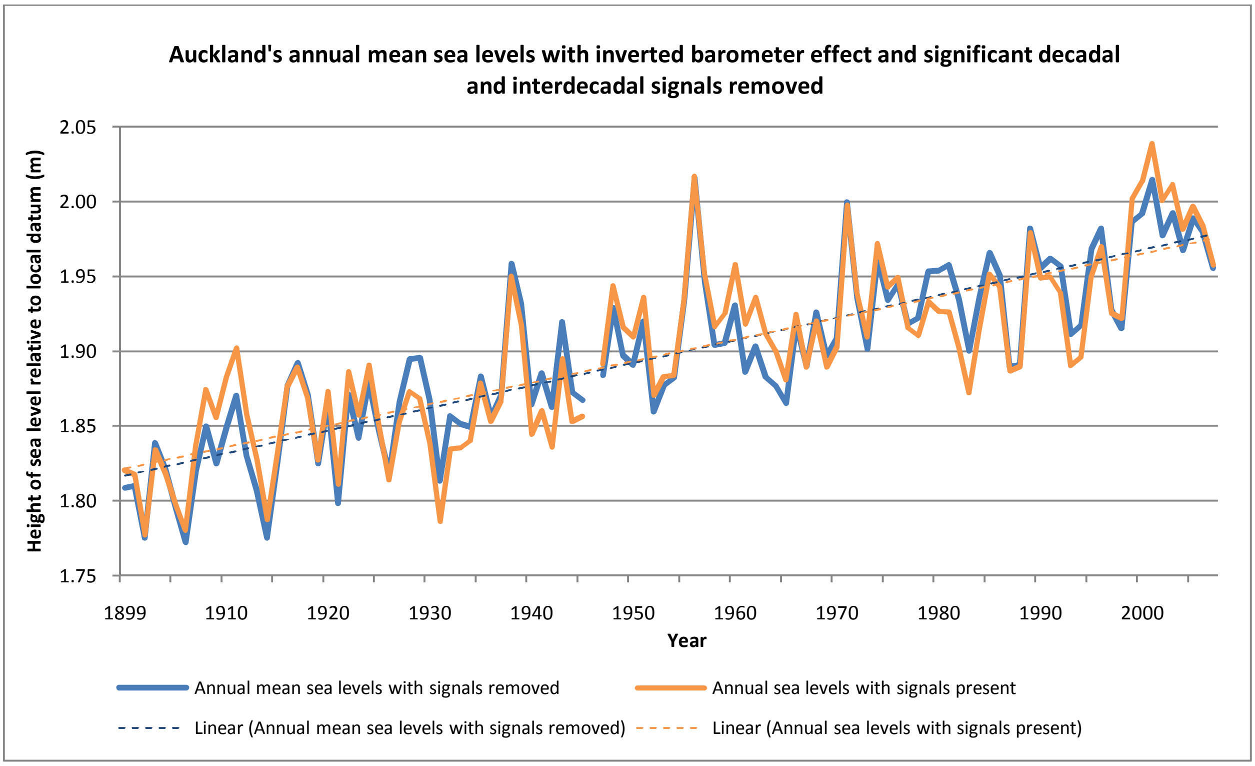

Figure 5.18: Auckland's annual mean sea levels with inverted barometer effect and significant decadal and interdecadal signals removed

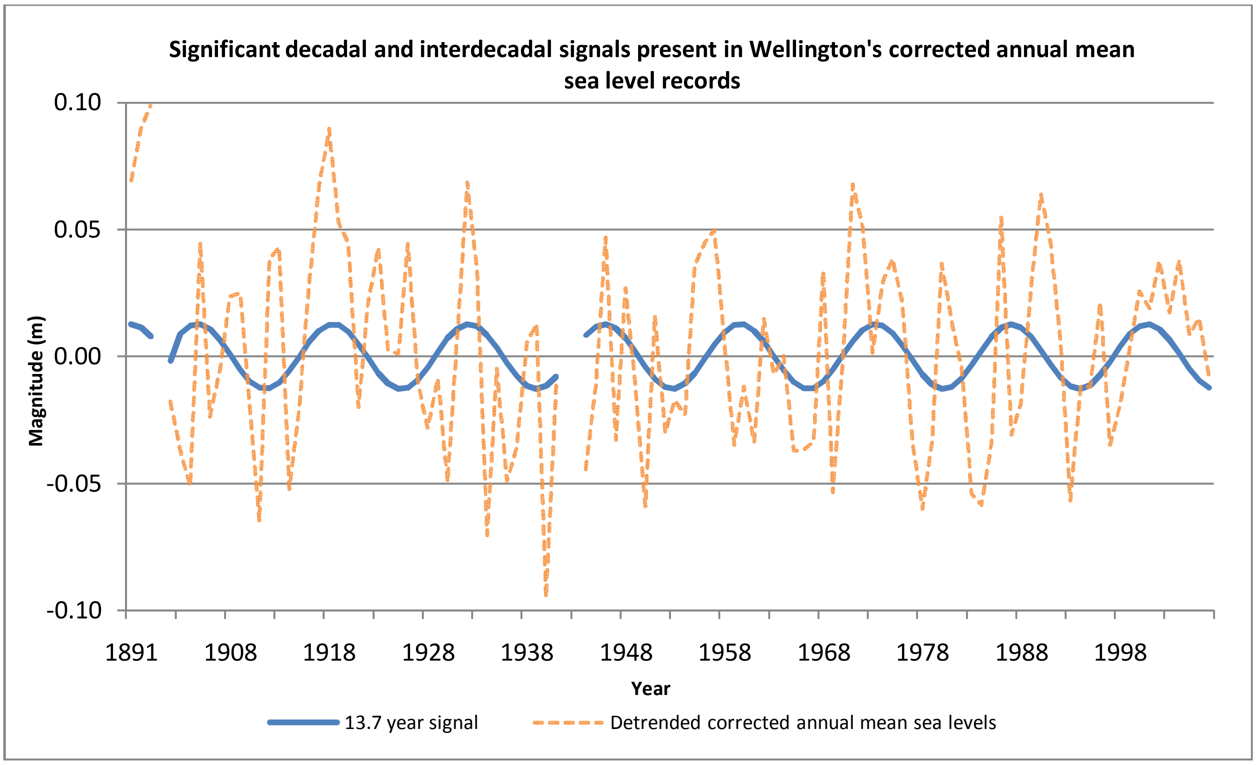

Figure 5.19: Significant decadal and interdecadal signals present in Wellington's corrected annual mean sea level records

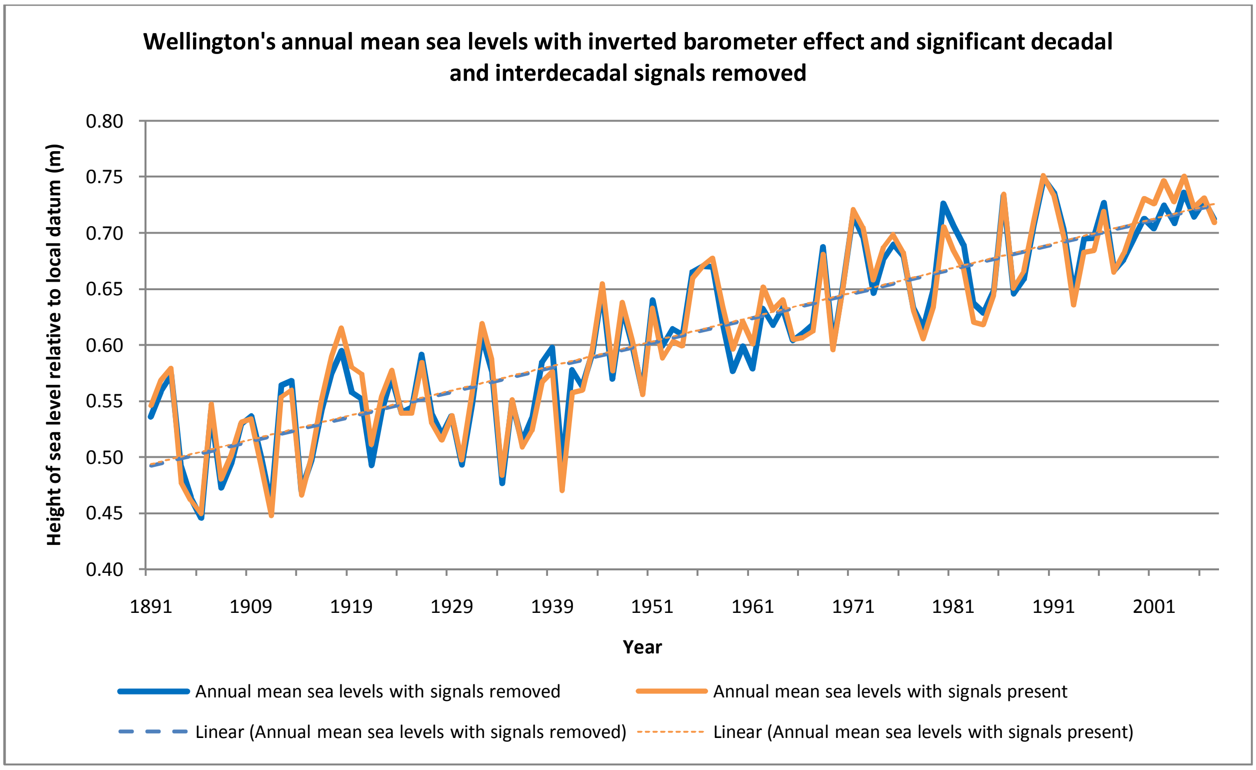

Figure 5.20: Wellington's annual mean sea levels with inverted barometer effect and interdecadal signals removed

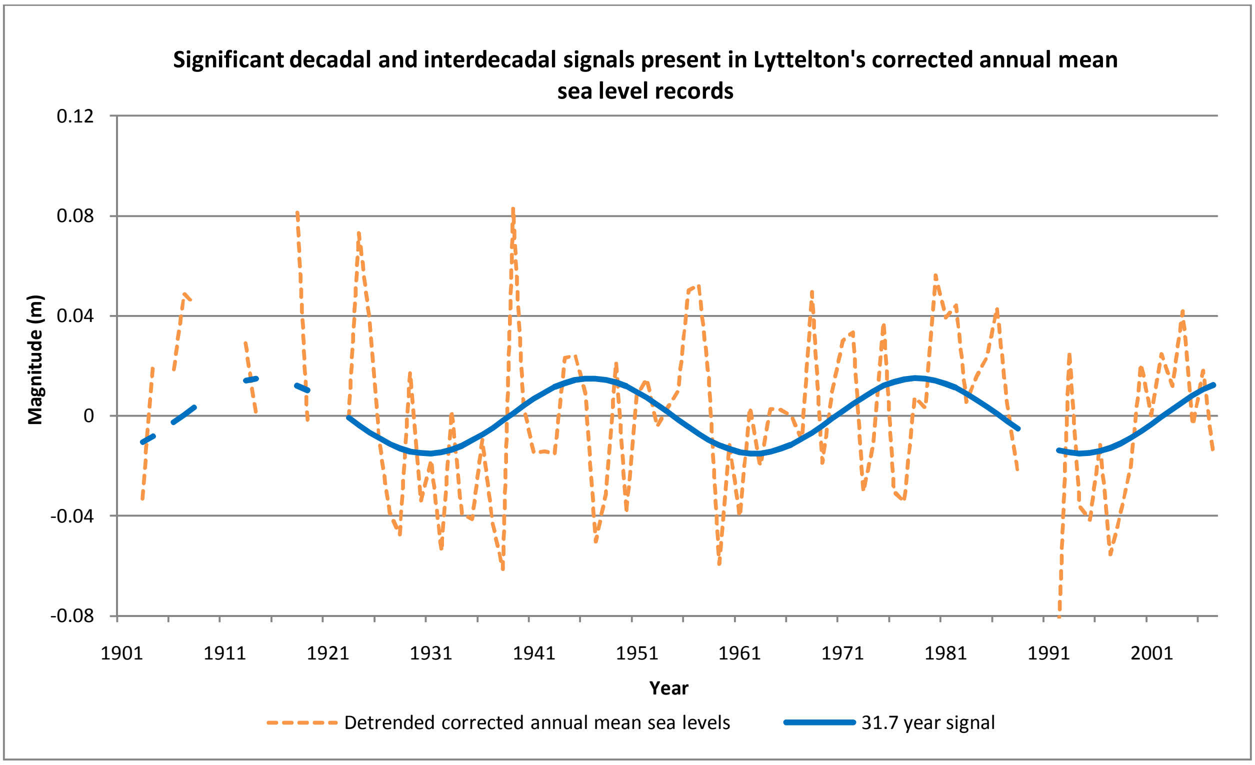

Figure 5.21: Significant decadal and interdecadal signals present in Lyttelton's corrected annual mean sea level records

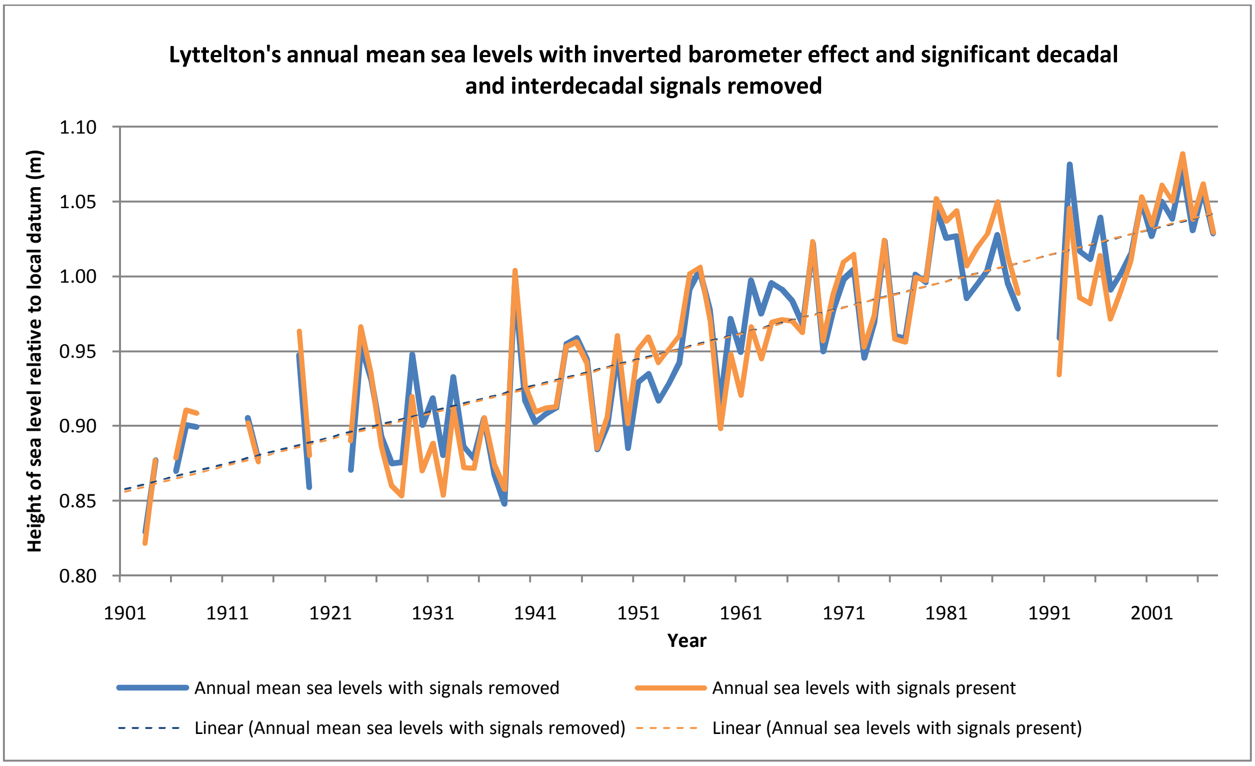

Figure 5.22: Lyttelton's annual mean sea levels with inverted barometer effect and significant decadal and interdecadal signals removed

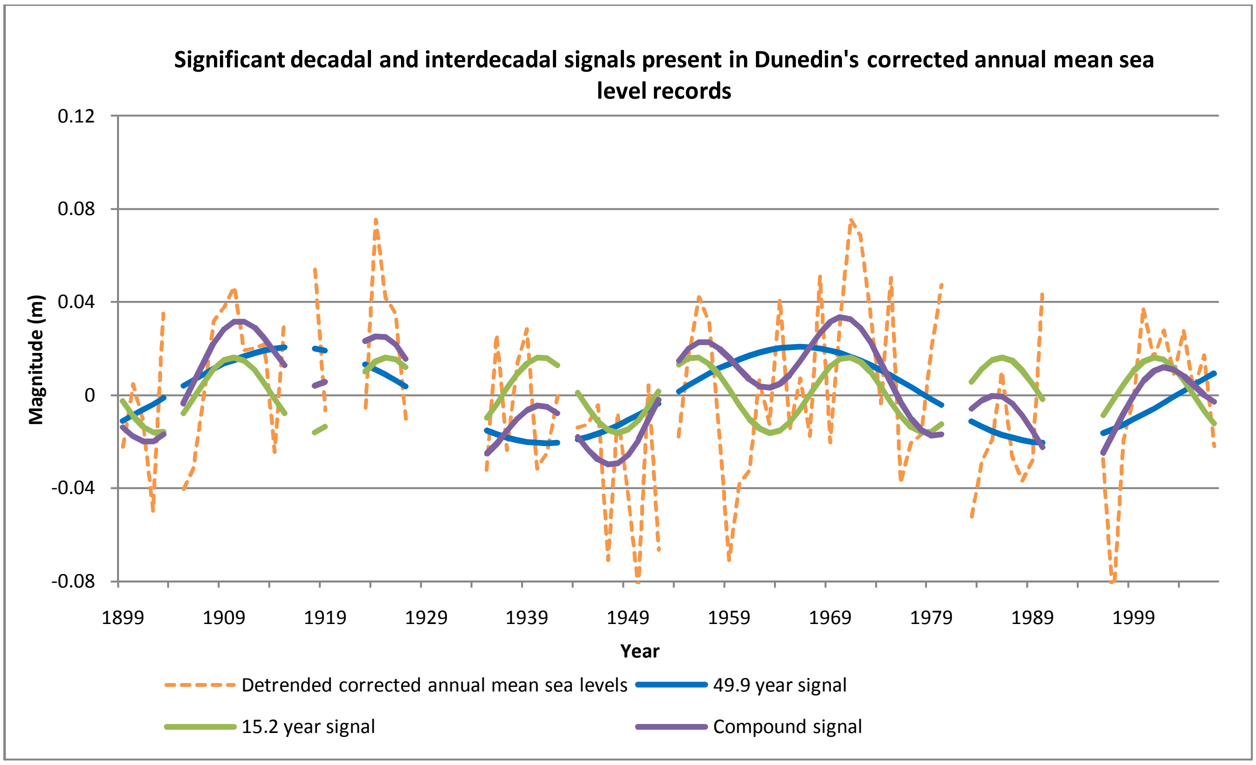

Figure 5.23: Significant decadal and interdecadal signals present in Dunedin's corrected annual mean sea level records

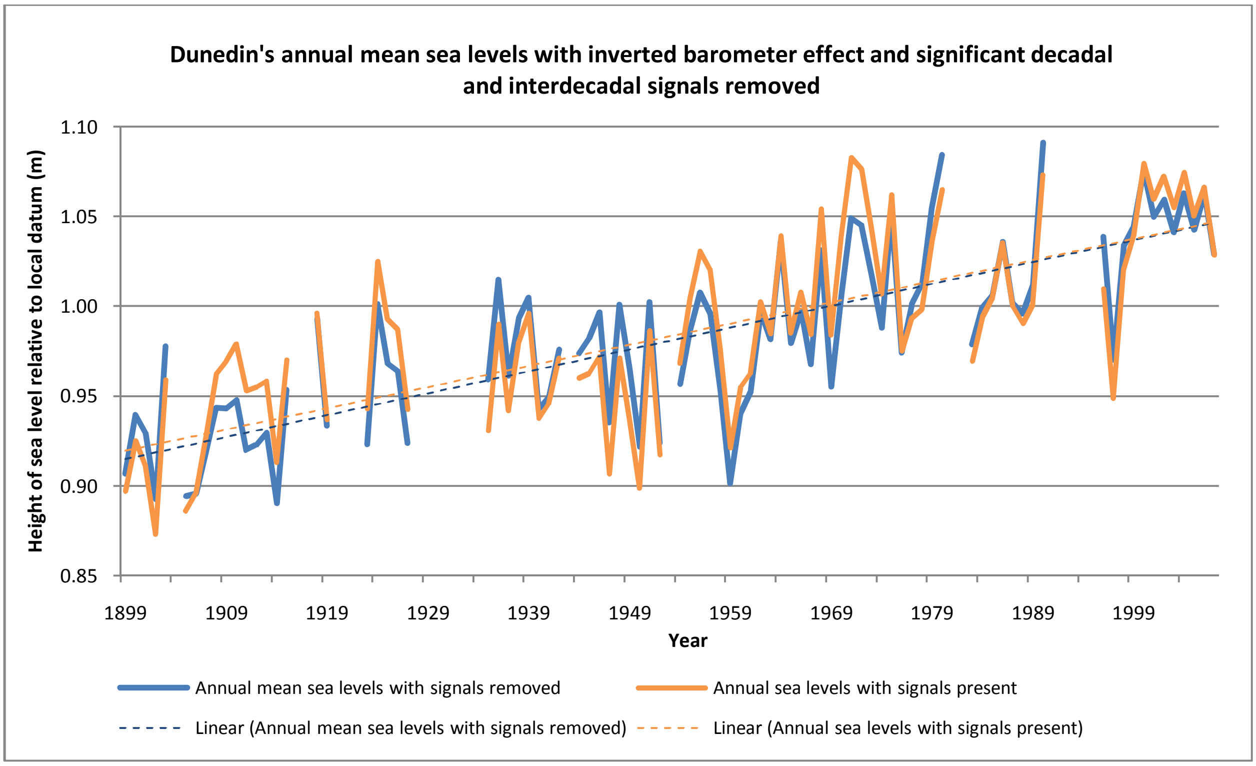

Figure 5.24: Dunedin's annual mean sea levels with inverted barometer effect and significant decadal and interdecadal signals removed

The investigations into the presence of a common accelerating trend in sea level rise between the four stations through the combined analysis of the long-term records from Auckland, Wellington, Lyttelton and Dunedin that have been corrected for the inverted barometer effect and have had parameters incorporated into the analysis to model significant decadal and interdecadal signals. A significant common acceleration in sea level rise was not found in this investigation.

5.4.2.3 Changing linear trend analyses

Linear trends in the rate of sea level rise were calculated over segments of records to reveal if a significant change in the rate of sea level rise has occurred at some point during the course of the recording period. As is the situation with an acceleration in the dataset, if vertical deformation causes the tide gauges to move at a constant rate it will not compromise a test for a change in the rate of sea level rise.

As long-term signals within the annual mean sea level records may cause a bias in the derived trends, the durations of the records analysed in each block are whole multiples of the periods of the most significant periodic signals identified within the datasets. The linear trends derived through the analysis of these segments of data are illustrated in Figure 5.25, Figure 5.26, Figure 5.27, and Figure 5.28 for Auckland, Wellington, Lyttelton and Dunedin respectively.

Considering the standard deviations associated with these periods, which are summarised in Table 5.7, the extreme ranges of the 95% confidence intervals of the derived periods are also similarly incorporated and analysed appropriately in a secondary analysis to glean the natural variability of the linear trends. The fifty year minimum duration recommended by Douglas (1991) was not maintained in this secondary analysis.

Segments of the data were analysed to investigate if a significant secular change in the rate of sea level rise can be found within the dataset, or if the results suggest that the rate of sea level rise is accelerating. The results of the analyses are summarised in Table 5.8, Table 5.9, Table 5.10 and Table 5.11 for Auckland, Wellington, Lyttelton and Dunedin respectively.

Station	Auckland		
	Derived gradient (mm/yr)		
Years analysed	4x Mean period = 51.6 years	4x (Mean – 95% CI) = 50 years	4x (Mean + 95% CI) = 53.2 years
2007 -	1.3	1.1	1.8
1997 -	0.3	0.6	0.1
1987 -	0.9	1.1	0.6
1977 -	2.0	1.9	1.8
1967 -	1.8	1.8	2.1
1957 -	1.5	1.7	2.1

Table 5.8: Results from linear trend analysis using segments of Auckland's data that have been corrected for inverted barometer effect

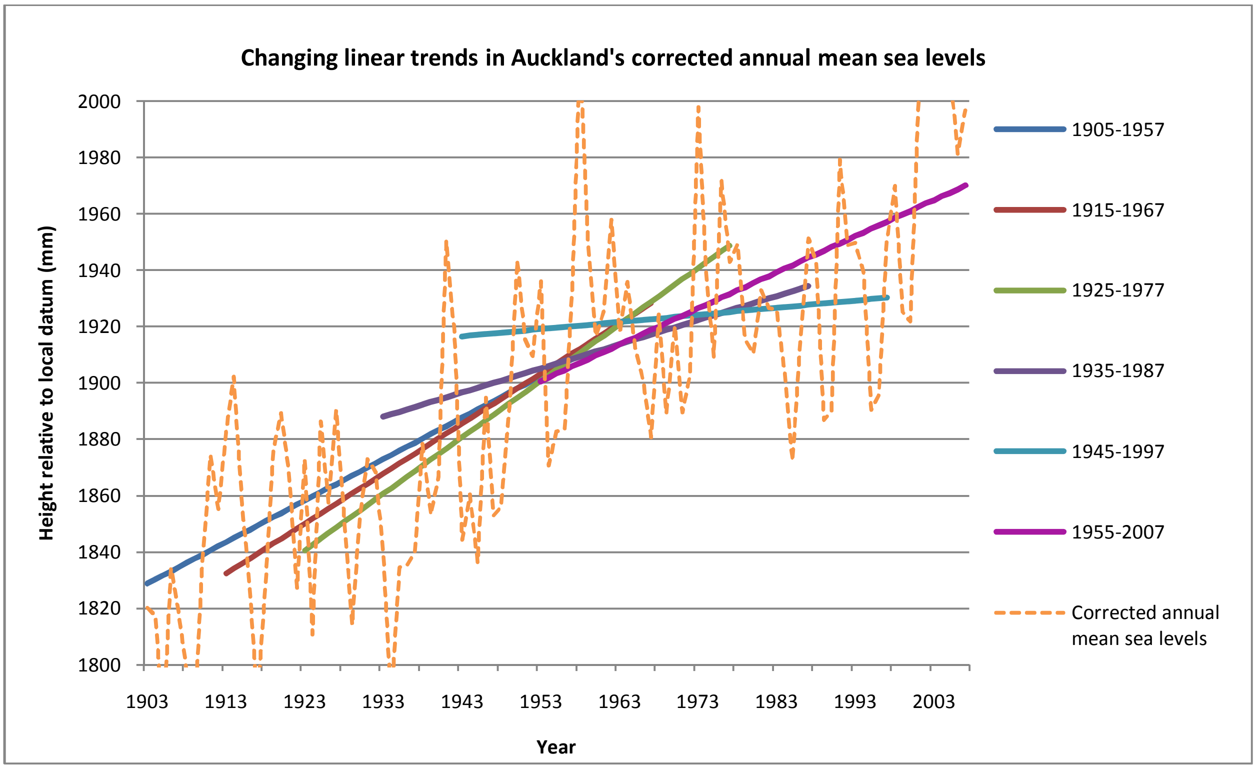

Figure 5.25: Changing linear trends in Auckland's corrected annual mean sea levels

Station	Wellington		
	Derived gradient (mm/yr)		
Years analysed	4x Mean period = 54.8 years	4x (Mean – 95% CI) = 52 years	4x (Mean + 95% CI) = 57.6 years
2007 -	2.0	1.9	2.0
1997 -	1.8	1.8	1.7
1987 -	1.5	1.8	1.3
1977 -	1.5	2.2	1.6
1967 -	0.9	0.2	1.0

Table 5.9: Results from linear trend analysis using segments of Wellington's data that have been corrected for inverted barometer effect

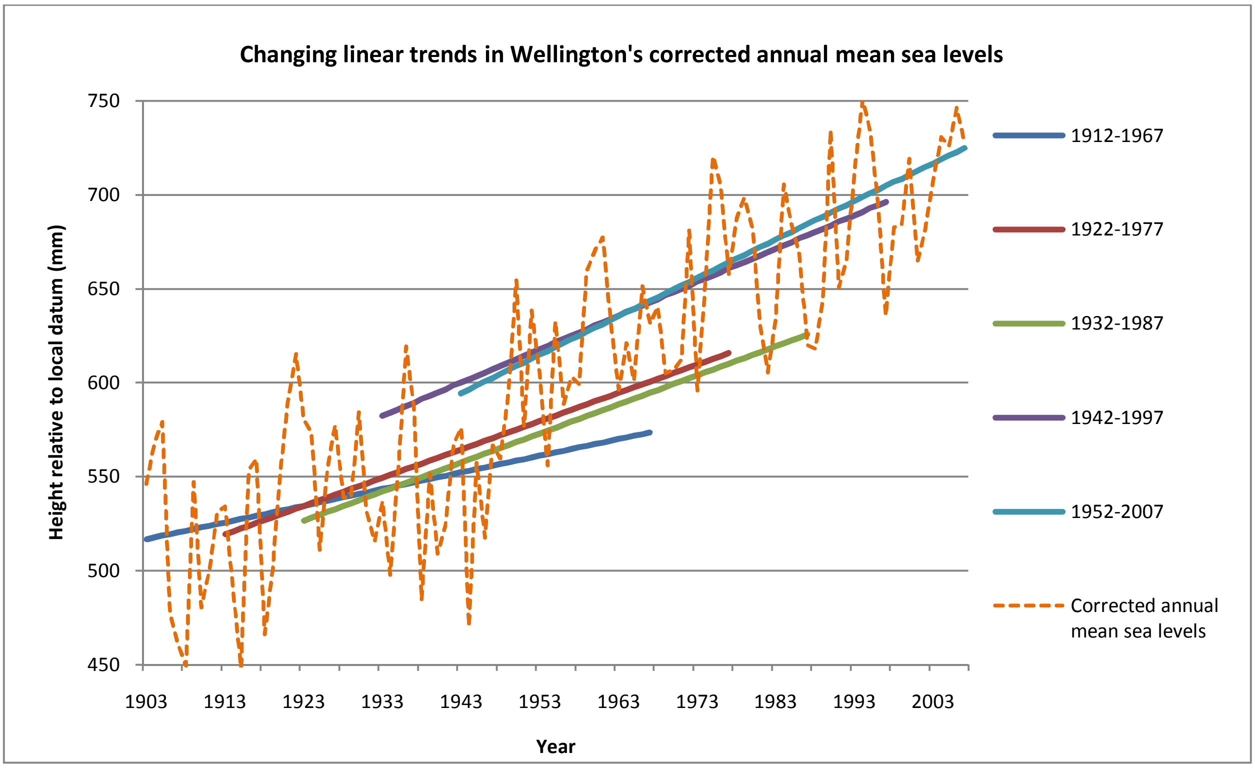

Figure 5.26: Changing linear trends in Wellington's corrected annual mean sea levels

Station	Lyttelton		
	Derived gradient (mm/yr)		
Years analysed	**2x Mean period = 63.4 years**	**2x (Mean – 95% CI) = 55.0 years**	**2x (Mean + 95% CI) = 71.8 years**
2007 -	2.1	1.7	1.8
1997 -	1.7	1.6	1.8
1987 -	2.2	2.5	2.5
1977 -	2.1	2.0	2.0
1967 -	2.0	2.0	1.7

Table 5.10: Results from linear trend analysis using segments of Lyttelton's data that have been corrected for inverted barometer effect

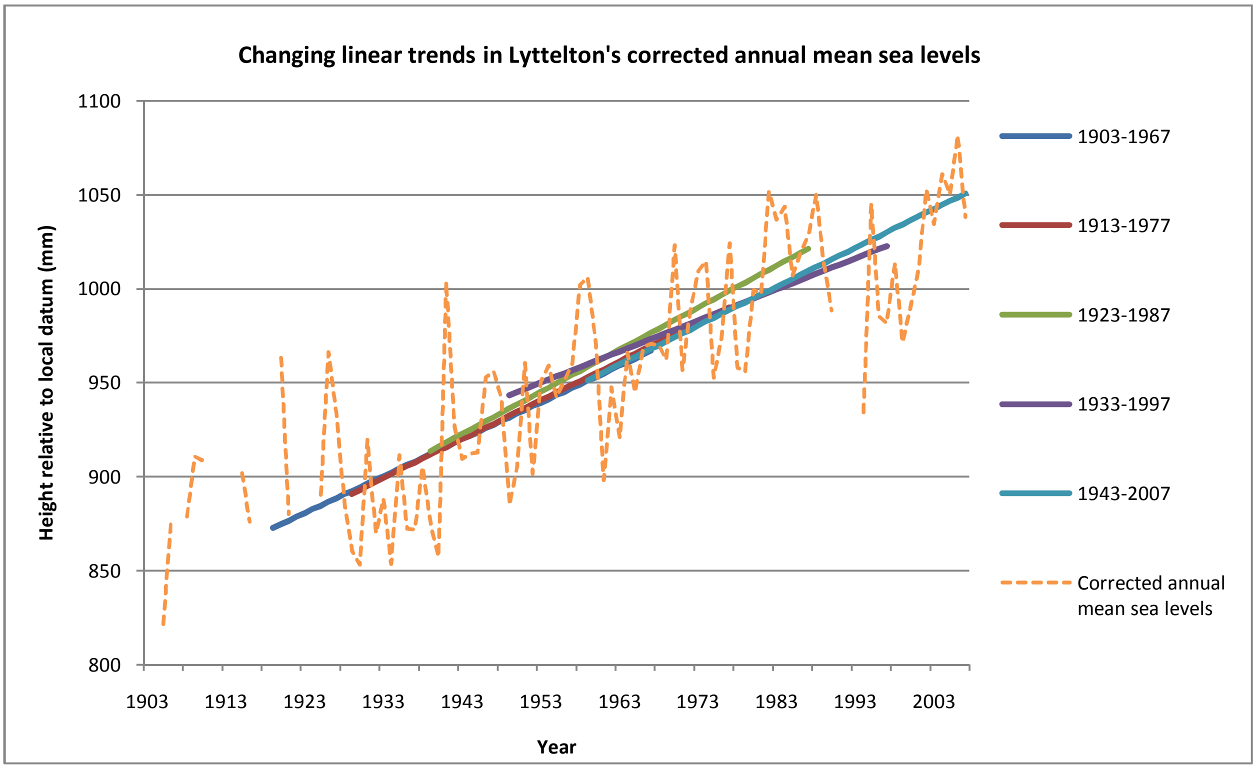

Figure 5.27: Changing linear trends in Lyttelton's corrected annual mean sea levels

Station	Dunedin		
	Derived gradient (mm/yr)		
Years analysed	1x Mean period = 49.9 years	1x (Mean – 95% CI) = 43.6 years	1x (Mean + 95% CI) = 50.2 years
2007 -	1.0	0.7	1.1
1997 -	0.8	0.1	1.2
1987 -	1.5	1.5	1.7
1977 -	2.4	2.4	1.8
1967 -	1.2	1.0	0.9
1957 -	0.4	0.6	0.8

Table 5.11: Results from linear trend analysis using segments of Dunedin's data that have been corrected for inverted barometer effect

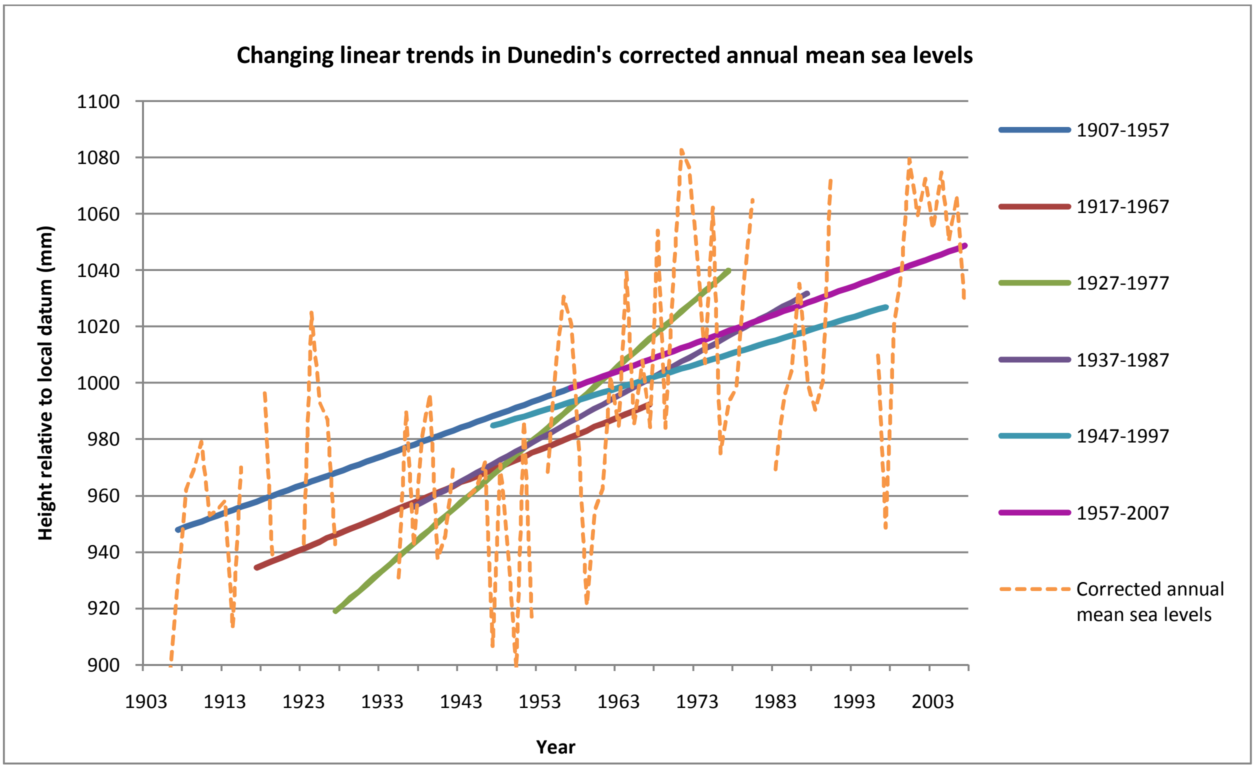

Figure 5.28: Changing linear trends in Dunedin's corrected annual mean sea levels

Figure 5.25, Figure 5.26, Figure 5.27, and Figure 5.28 illustrate that the nature of the linear trends derived using the segments of annual mean sea level records do not indicate any significant changes in the linear rate of sea level rise, or any accelerating tendencies. The

Dunedin records show greatest inconsistency between the derived trends, which may be caused by the incomplete nature of the input dataset. Wellington is the only station to demonstrate an increasing trend over time, although the magnitudes of these progressive changes are not statistically significant.

As stated in Section 4.2.4.3, this form of analysis gives greatest weighting to the mid-range datasets, which is a weakness of the methodology used.

5.4.2.4 Non-consistent acceleration rates

The annual mean sea level datasets that have been corrected for the inverted barometer effect are also analysed to identify if there is evidence of an acceleration in the rate of sea level rise that is specific to the tide gauge. Therefore, individual acceleration parameters were derived for the Auckland, Wellington, Lyttelton and Dunedin sea level records. The trend results from this investigation are summarised in Table 5.12, Table 5.14, Table 5.16, and Table 5.18 respectively. The periodic signals identified within the respective datasets are detailed in Table 5.13, Table 5.15, Table 5.17, and Table 5.19 respectively.

Auckland			
Parameter	***a*** **(mm/yr²)**	***m*** **(mm/yr)**	***c*** **(mm)**
Value	0.0049	2.09	1789.7
95% Confidence interval (CI)	± 0.0083	1.05	28.7
Significant at 95% CI	×	✓	✓
$\bar{\sigma}_o^2$	**1.75**		

Table 5.12: Accelerating trend in sea level rise within the corrected Auckland dataset

Station	Period (years)	95% CI	*a* (mm)	95% CI	*b* (mm)	95% CI
Auckland	48.2	6.1	-16.8	± 13.7	Not Significant	
	13.0	0.5	-14.7	± 8.9	Not Signifiant	

Table 5.13: Signals within Auckland's corrected dataset

Wellington				
Parameter	a (mm/yr²)	m (mm/yr)	c <1942 (mm)	c ≥1944 (mm)
Value	0.0142	-0.04	518.0	572.3
95% Confidence interval (CI)	± 0.0105	± 1.66	± 40.9	± 71.0
Significant at 95% CI	✓	×	✓	✓
$\bar{\sigma}_o^2$	**0.96**			

Table 5.14: Accelerating trend in sea level rise within the corrected Wellington dataset

Station	Period (years)	95% CI	a (mm)	95% CI	b (mm)	95% CI
Wellington	44.4	± 8.0	Not Significant		-13.4	± 10.1
	13.7	± 1.0	Not Significant		Not Significant	

Table 5.15: Signals within Wellington's corrected dataset

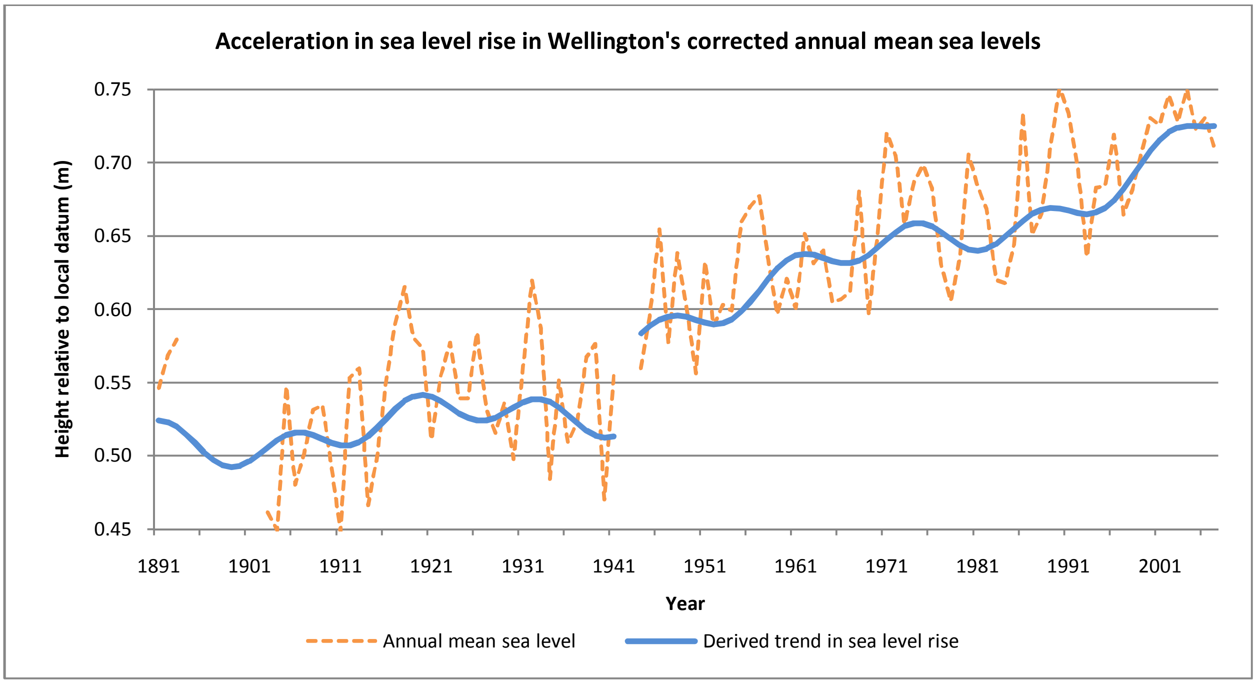

Figure 5.29: Acceleration in sea level rise in Wellington's corrected annual mean sea levels

Lyttelton			
Parameter	***a*** **(mm/yr²)**	***m*** **(mm/yr)**	***c*** **(mm)**
Value	0.0024	1.20	856.0
95% Confidence interval (CI)	± 0.0087	± 1.06	± 33.2
Significant at 95% CI	×	✓	✓
$\bar{\sigma}_o^2$	**0.66**		

Table 5.16: Accelerating trend in sea level rise within the corrected Lyttelton dataset

Station	Period (years)	95% CI	*a* (mm)	95% CI	*b* (mm)	95% CI
Lyttelton	15.9	± 0.8	15.5	± 9.5	Not Significant	
	31.9	± 3.3	Not Significant		-15.3	± 10.7

Table 5.17: Signals within Lyttelton's corrected dataset

Dunedin			
Parameter	***a*** **(mm/yr²)**	***m*** **(mm/yr)**	***c*** **(mm)**
Value	0.0028	0.875	913.6
95% Confidence interval (CI)	± 0.0079	± 1.006	± 28.0
Significant at 95% CI	×	×	✓
$\bar{\sigma}_o^2$	**0.80**		

Table 5.18: Accelerating trend in sea level rise within the corrected Dunedin dataset

Station	Period (years)	95% CI	*a* (mm)	95% CI	*b* (mm)	95% CI
Dunedin	49.5	± 5.6	-20.1	± 10.8	Not Significant	
	15.2	± 0.6	Not Significant		16.0	± 10.3

Table 5.19: Signals within Dunedin's corrected dataset

These results demonstrate a relative acceleration in the rate of sea level rise within Wellington's corrected annual mean sea level records. This accelerating trend may be caused by the active tectonics in the Wellington area, which is discussed in further detail in Section 6.1. The records from the Auckland, Lyttelton and Dunedin tide gauges do not demonstrate accelerations that are statistically significant.

5.4.3 Uncorrected annual mean sea level datasets

As the inverted barometer effect corrections are based upon ideal-Earth assumptions, which are discussed in detail in Section 6.2, the corrections have inherent weaknesses and errors associated with them that may propagate into the datasets used to derive sea level rise trends. Considering this, the investigation into the presence of an acceleration in the rise of sea level can also be performed while incorporating datasets that have not been subjected to the inverted barometer correction.

5.4.3.1 Fourier Function Digital Signal analysis on uncorrected annual mean sea levels

The Fast Fourier Transform analysis was used to convert the uncorrected annual mean sea levels dataset into the frequency domain to isolate the significant signals that are present in the Auckland and Wellington datasets.

Figure 5.30 and Figure 5.31 show the periods of signals of greatest significance within Auckland's and Wellington's records. The approximate periods of the most significant periods are summarised in Table 5.20. These estimations are incorporated into the Least Squares analysis to converge on the most significant signals through its iterative computational process.

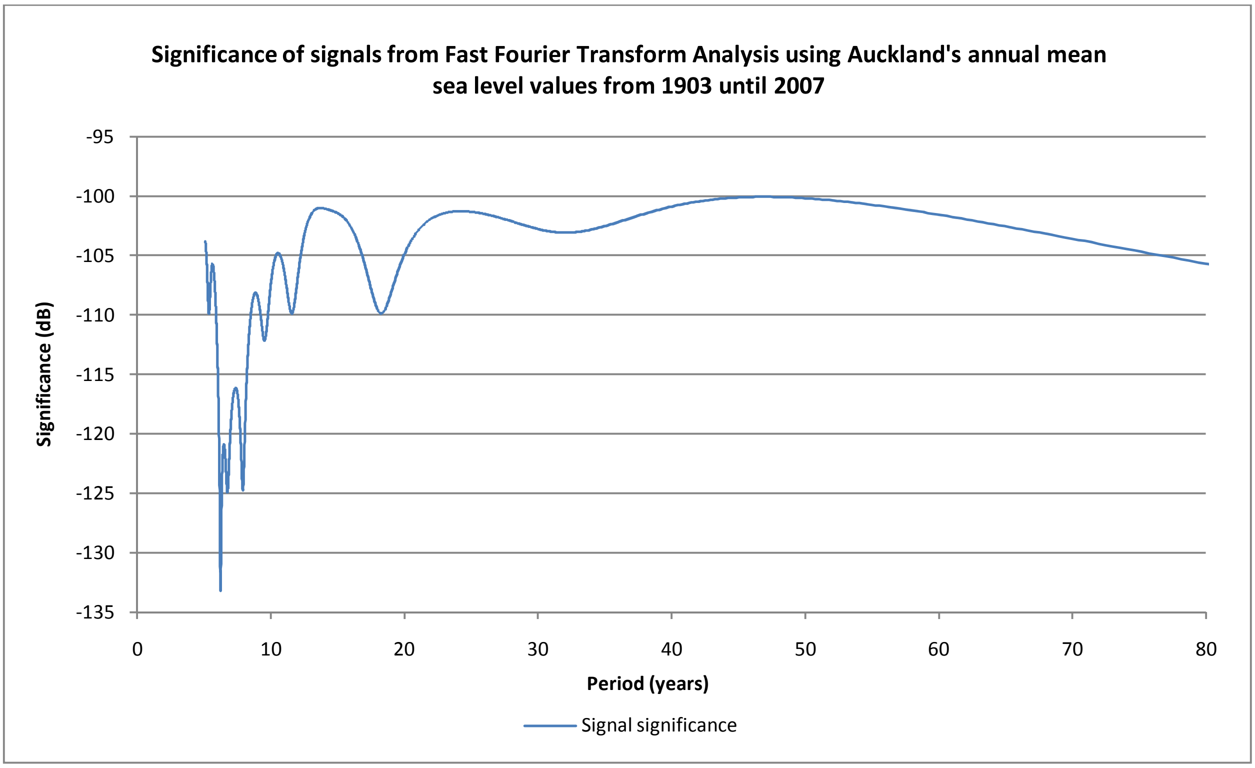

Figure 5.30: Significance of signals from Fast Fourier Transform Analysis using Auckland's annual mean sea level values from 1903 until 2007

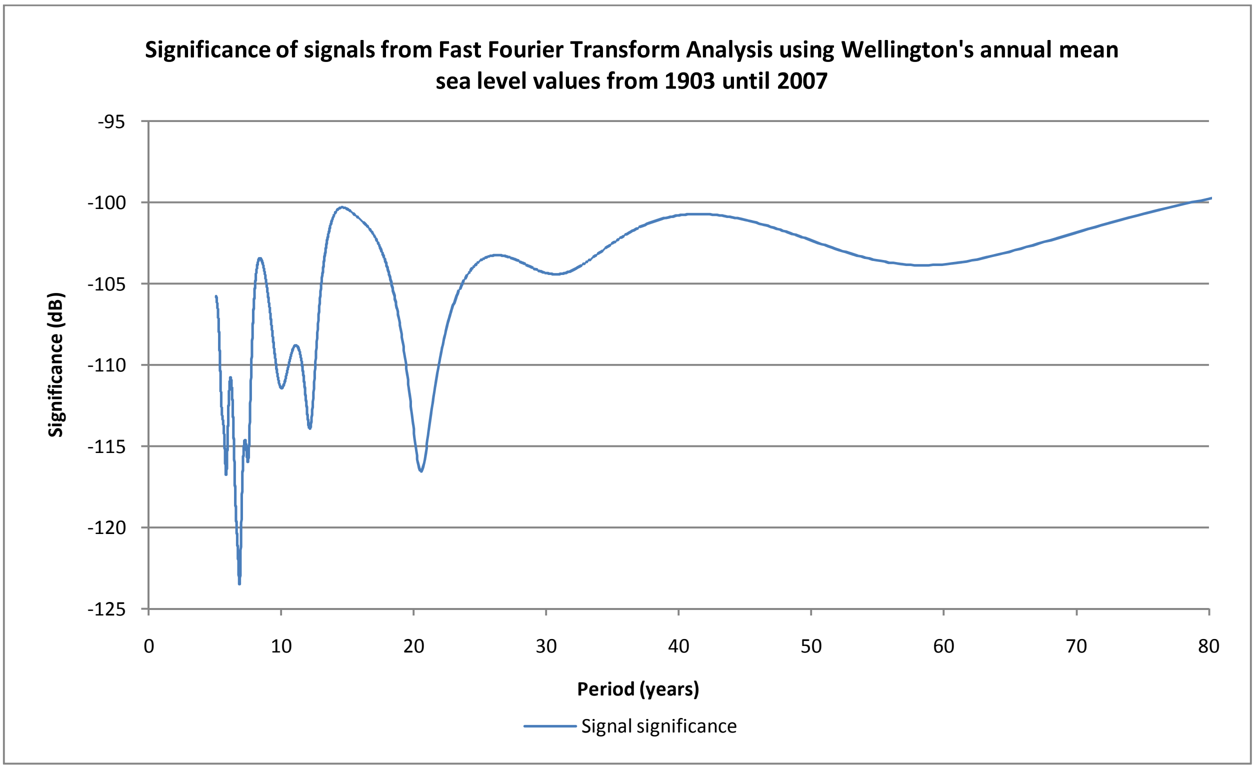

Figure 5.31: Significance of signals from Fast Fourier Transform Analysis using Wellington's annual mean sea level values from 1903 until 2007

Significant signals' approximate periods	
Station: Auckland	**Station: Wellington**
13-15 years	14-16 years
24-26 years	40-44 years

Table 5.20: Approximate periods of significant signals contained within Auckland's and Wellington's corrected datasets

Atmospheric pressure signals

The resolution of significant periods that are not driven by atmospheric pressure changes should improve if the inverted barometer effect is accurately modelled. Periodic signals driven by atmospheric pressure changes would be removed with the removal of the inverted barometer effect, thereby providing a lower variability dataset from which other signals may be isolated.

If, however, the inverted barometer effect is not removed, the presence of signals within the pressure records can still be utilised to aid in the resolution of trends in sea level rise through the combination of the two datasets to resolve the common unknown parameters. Section 4.2.3 discussed the potential combination of the annual mean atmospheric pressure and mean sea level records to aid in the resolution of the long-term signals that are common between the two datasets. This combined approach cannot be applied in this study as the results obtained from the Fast Fourier Transform analysis results, shown in Figure 5.32, illustrate that the most significant signals' periods were not consistent between the two datasets.

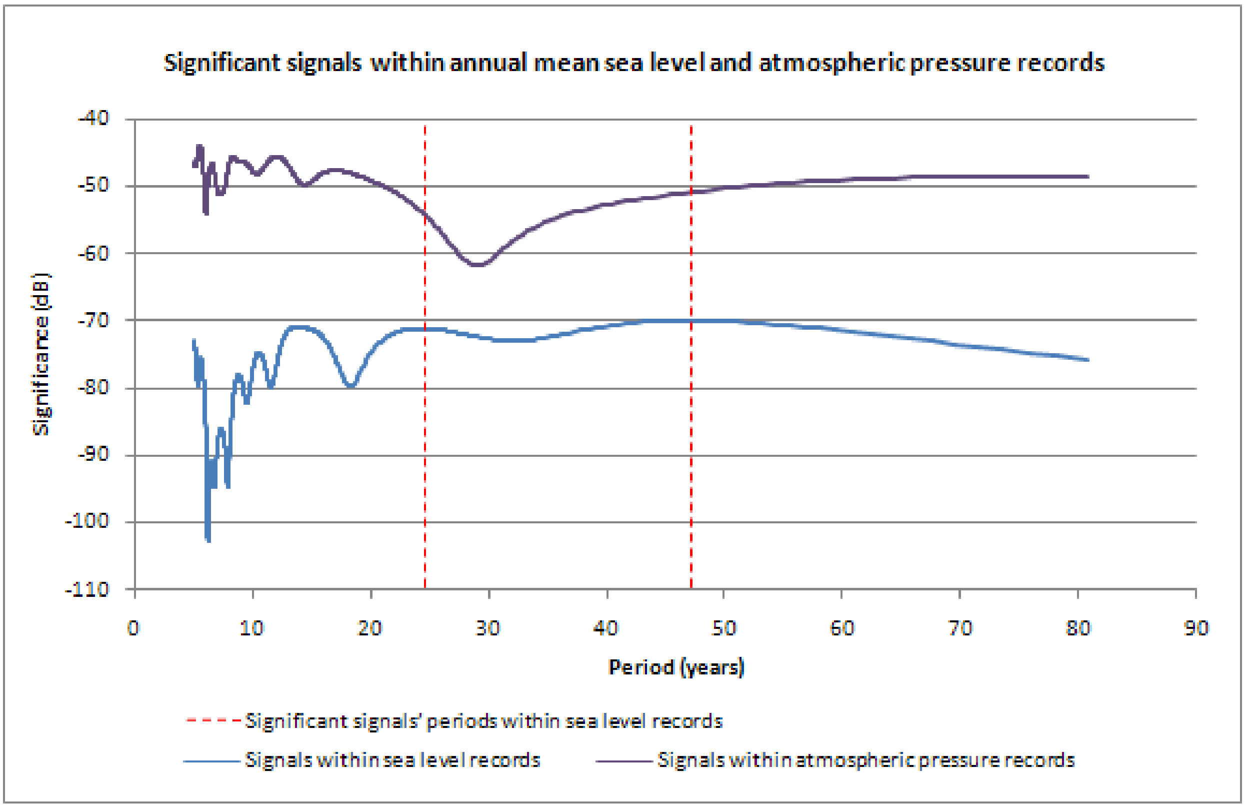

Figure 5.32: Significant signals within uncorrected annual mean sea level and atmospheric pressure records

However, if an investigation was to be considered that included signals that are common between the annual mean sea level and atmospheric pressure datasets, the methodology discussed in Section 4.2.3 would be applicable. Further to this, the trends identified within the annual mean local temperature records may be applied to aid in the resolution of the signals, and potentially could also be used to identify the average influence that thermal expansion has on the height of sea level.

Signals within the temperature records

The significances and periods of the signals that are present within the annual mean sea level, atmospheric pressure, and temperature records are illustrated below in Figure 5.33. If the most significant signals were consistent between the datasets, the temperature and pressure records could be incorporated into the analyses to improve the redundancy of the investigation into the common decadal and interdecadal signals. This would improve the redundancy of the acceleration investigation concordantly, and may simultaneously be used to establish the contribution of thermal expansion to changes in the height of sea level.

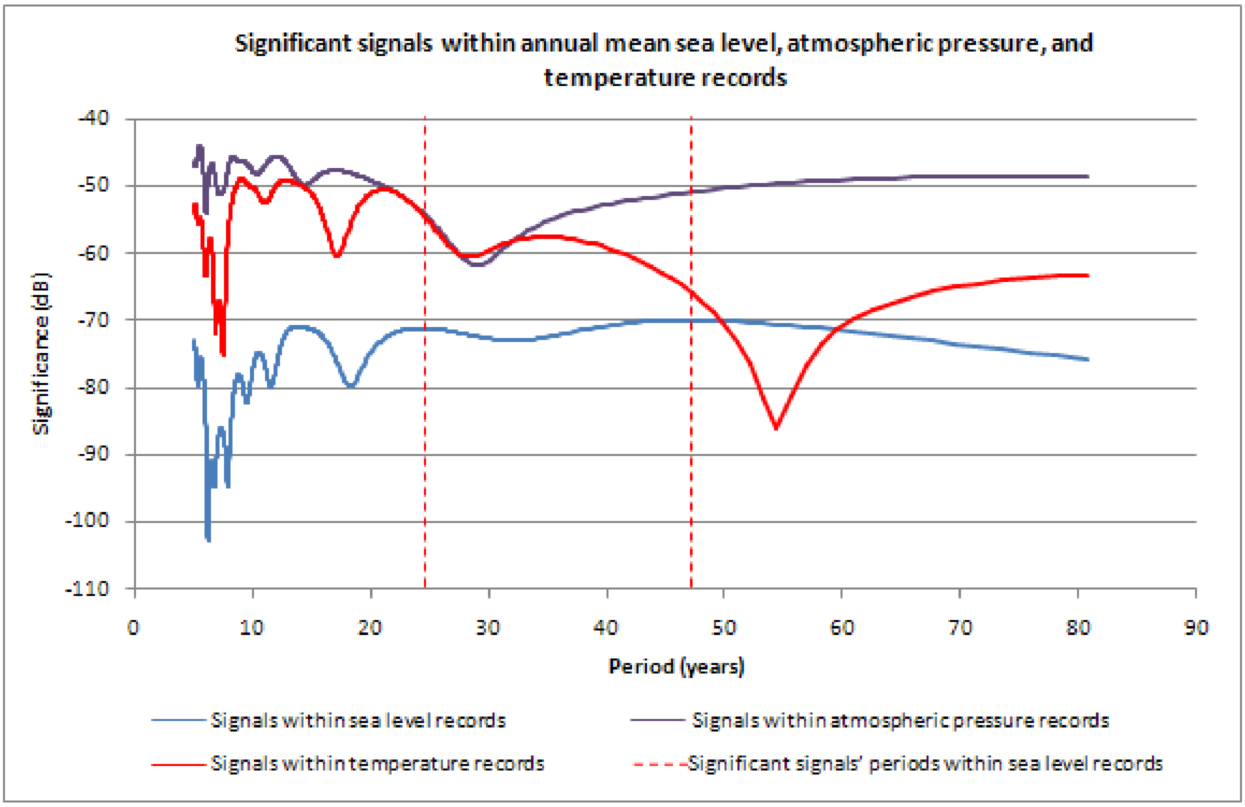

Figure 5.33: Significant signals within Auckland's annual mean sea level, atmospheric pressure, and temperature records

Sea level datasets should not be corrected for the influence of temperature changes as thermal expansion theoretically may contribute to sea level rise. This analysis can only be used to identify the relationship between the two variables, and aid in modelling the common decadal or interdecadal signals present in the both the temperature and mean sea level records.

5.4.3.2 Acceleration analyses using data corrected for interdecadal signals

The annual mean sea levels being analysed here have not been corrected for any short-term variations in the form of the inverted barometer effect. The results from the analysis of the complete datasets are provided in Table 5.21 and Table 5.22. Table 5.21 shows that no significant acceleration has been identified within the dataset.

Station	All	Auckland		Wellington			Dunedin		Lyttelton	
Parameter	*a* (mm/yr²)	*m* (mm/yr)	*c* (mm)	*m*	*c* 1	*c* 2	*m*	*c*	*m*	*c*
Value	0.0024	1.2	1854.1	1.8	527.4	539.6	1.0	936.7	1.5	875.3
Standard deviation	0.0021	0.3	8.2	0.4	12.1	24.2	0.3	10.6	0.3	12.8
Significant at 95% Confidence interval	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\bar{\sigma}_o^2$	**1.24**									

Table 5.21: Trend results from full dataset acceleration analysis

Station	Period (years)	95% CI	*a* (mm)	95% CI	*b* (mm)	95% CI
Auckland	49.0	± 4.9	-14.4	± 10.3	Not significant	
	12.9	± 0.3	-16.6	± 6.3	Not significant	
Wellington	43.0	± 9.6	Not significant		Not significant	
	13.5	± 0.5	Not significant		Not significant	
Dunedin	50.3	± 5.8	-20.8	± 10.6	Not significant	
	15.2	± 0.7	Not significant		15.8	± 10.4
Lyttelton	15.9	± 0.8	16.5	± 11.1	Not significant	
	22.4	± 1.8	Not significant		Not significant	

Table 5.22: Significant signals found within the datasets with 95% confidence intervals

The signals identified within the records from Auckland, Wellington, Lyttelton and Dunedin are illustrated below in Figure 5.34, Figure 5.36, Figure 5.38 and Figure 5.40. The original datasets for the four stations are shown against the corrected datasets in Figure 5.35, Figure 5.37, Figure 5.39 and Figure 5.41.

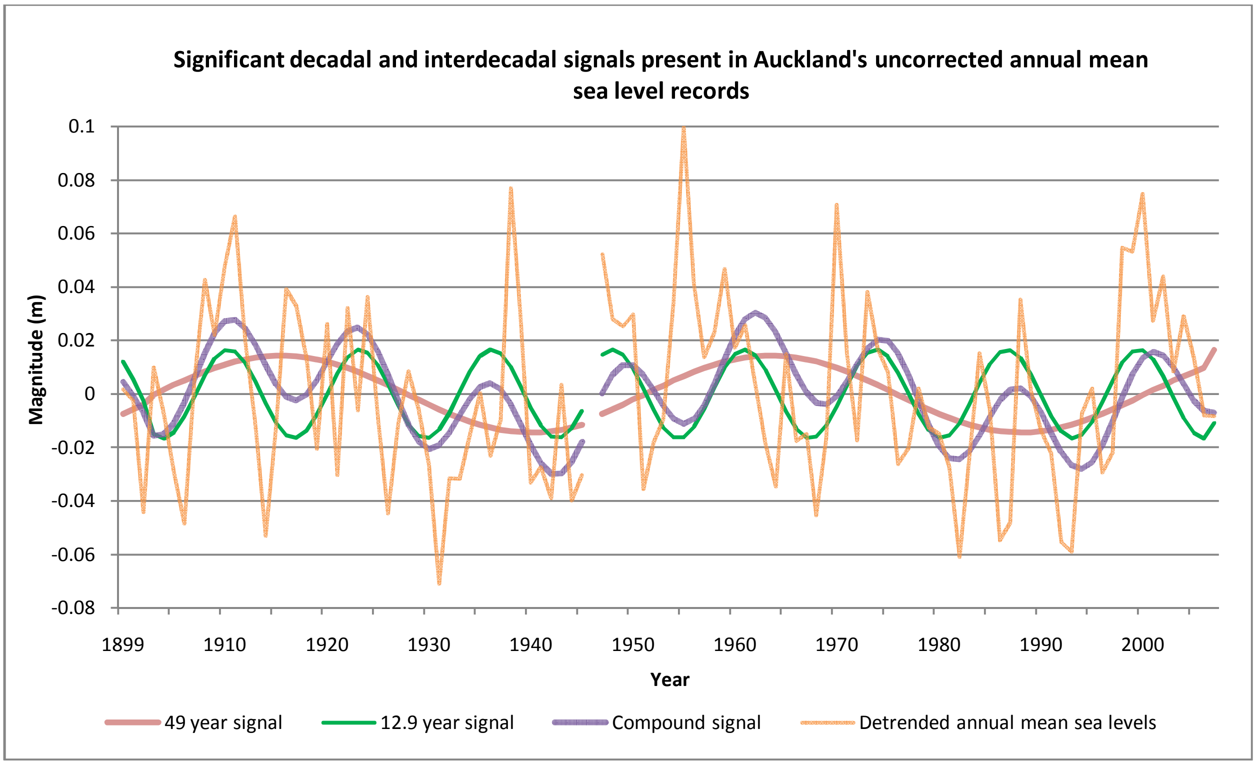

Figure 5.34: Significant decadal and interdecadal signals present in Auckland's annual mean sea level records

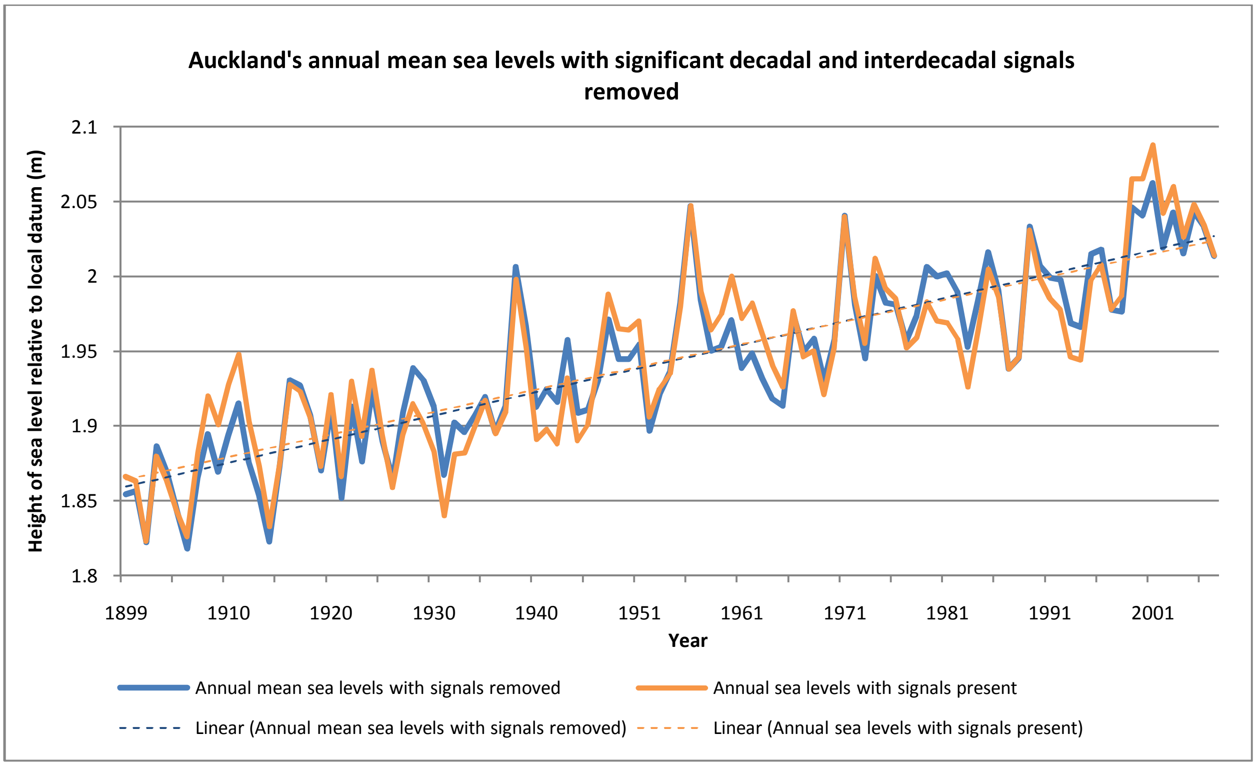

Figure 5.35: Auckland's annual mean sea levels with significant decadal and interdecadal signals removed

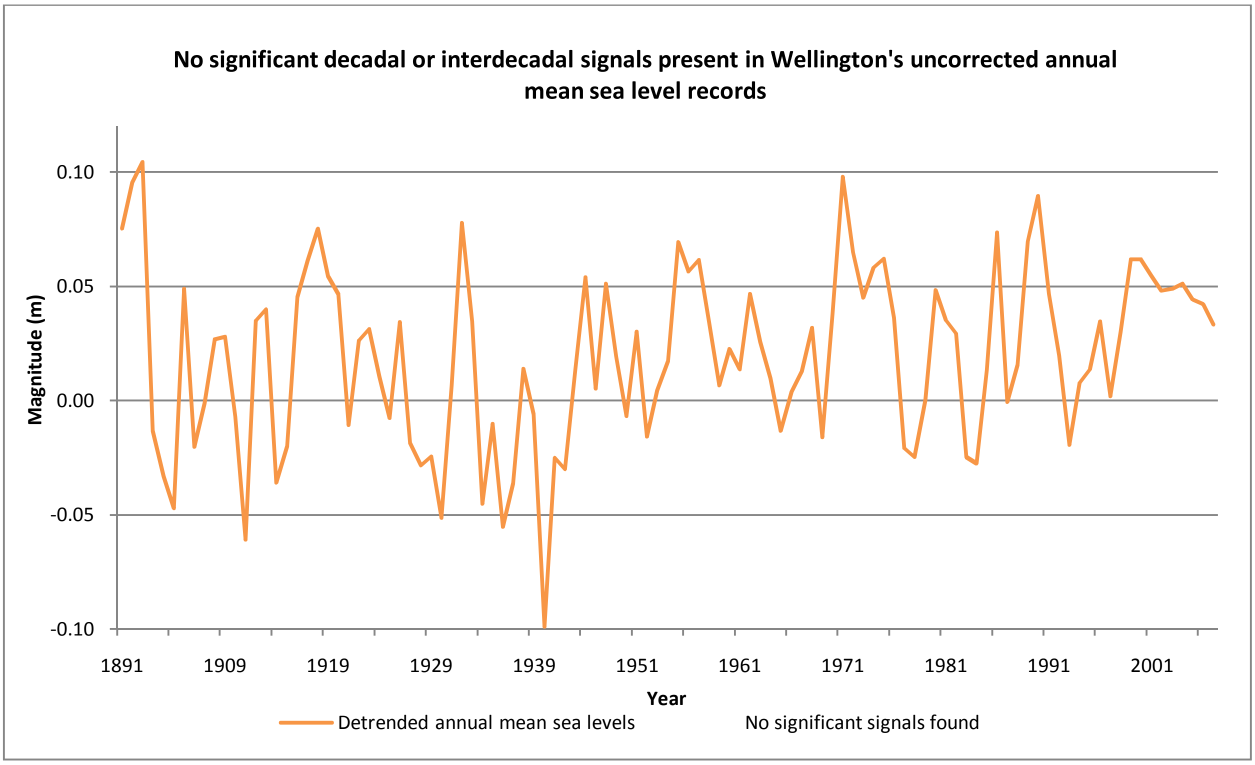

Figure 5.36: No significant decadal or interdecadal signals present in Wellington's annual mean sea level records

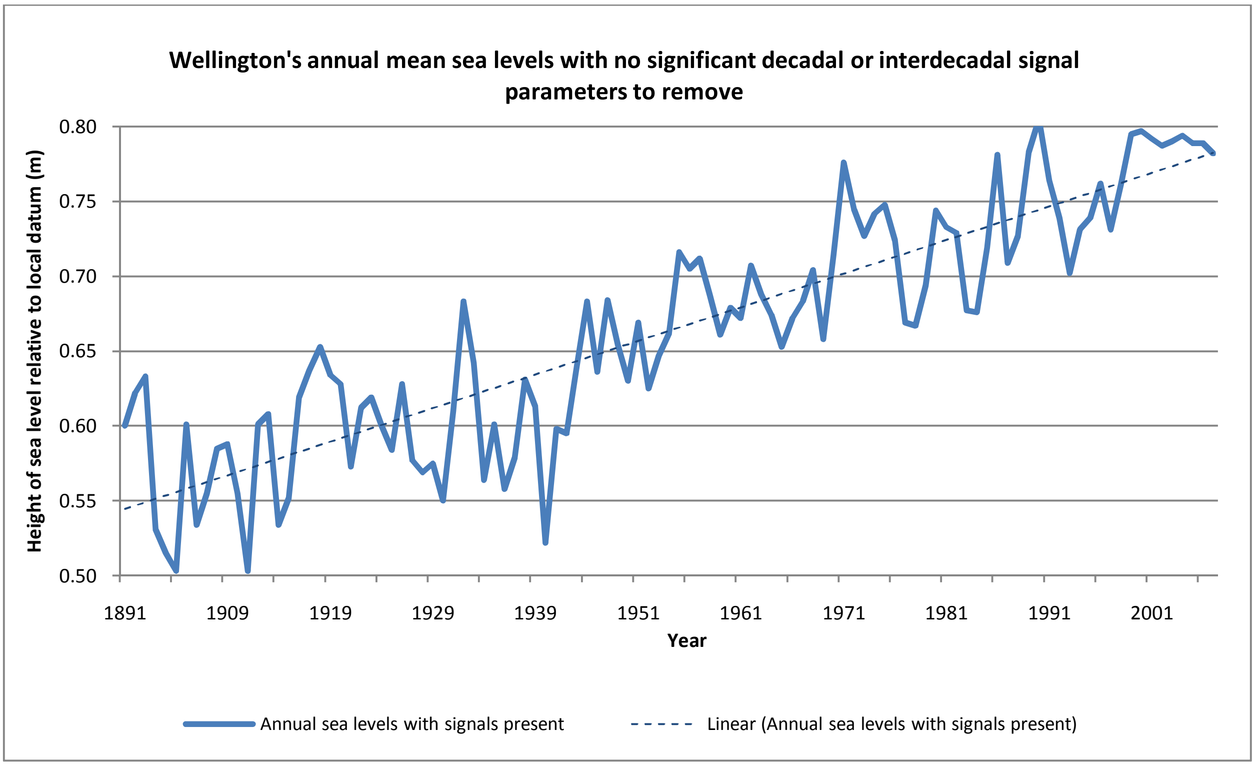

Figure 5.37: Wellington's annual mean sea levels with no significant interdecadal signal parameters to remove

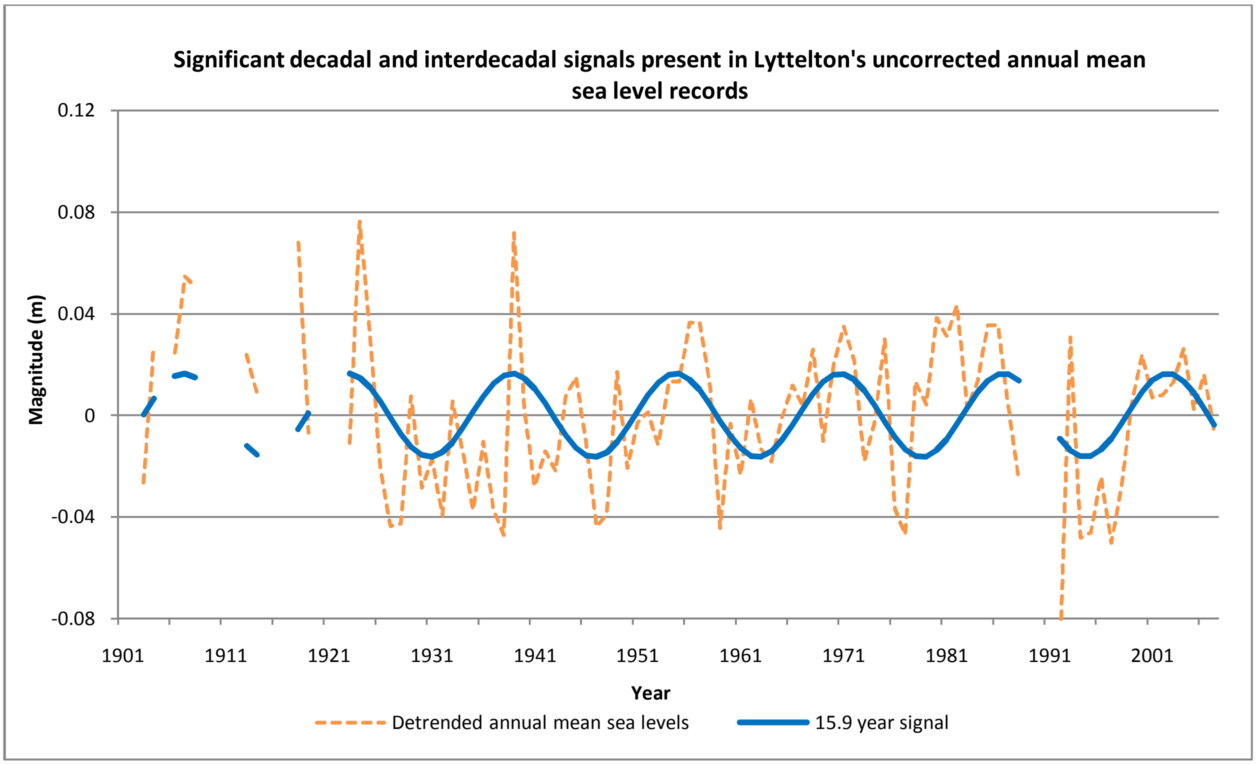

Figure 5.38: Significant decadal and interdecadal signals present in Lyttelton's annual mean sea level records

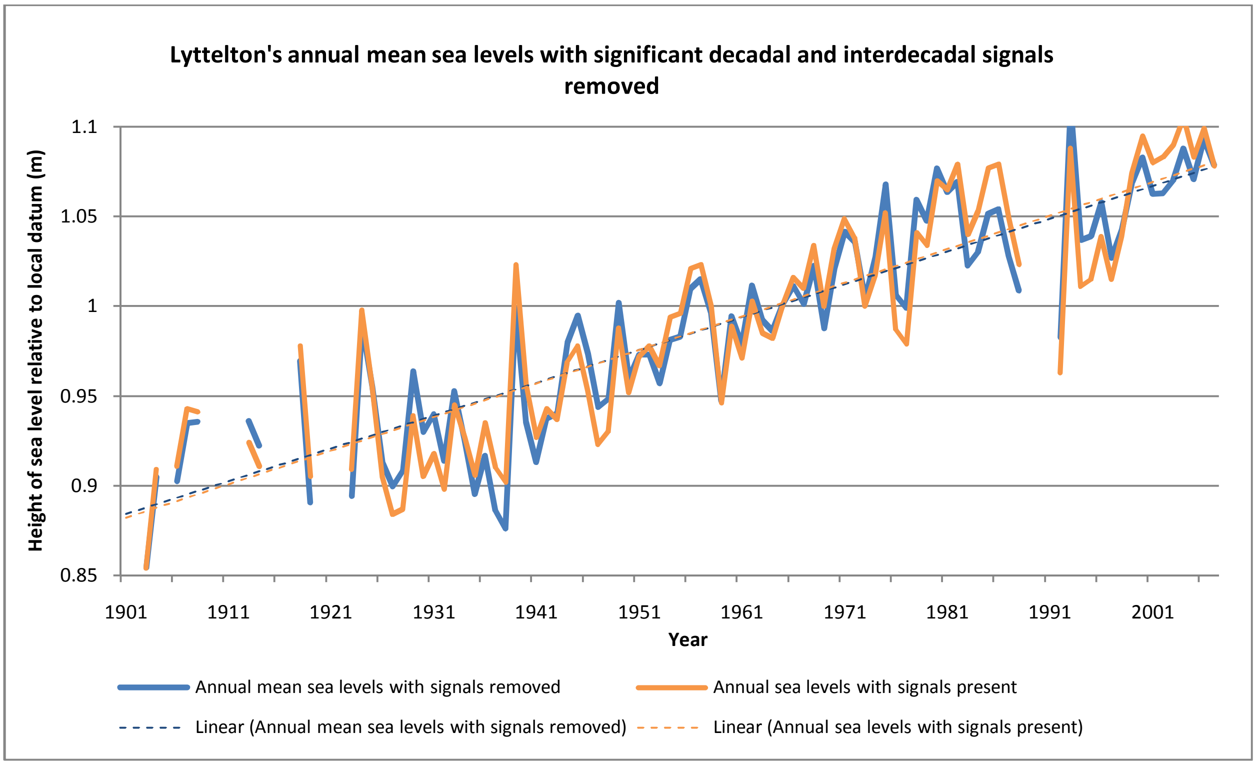

Figure 5.39: Lyttelton's annual mean sea levels with significant decadal and interdecadal signals removed

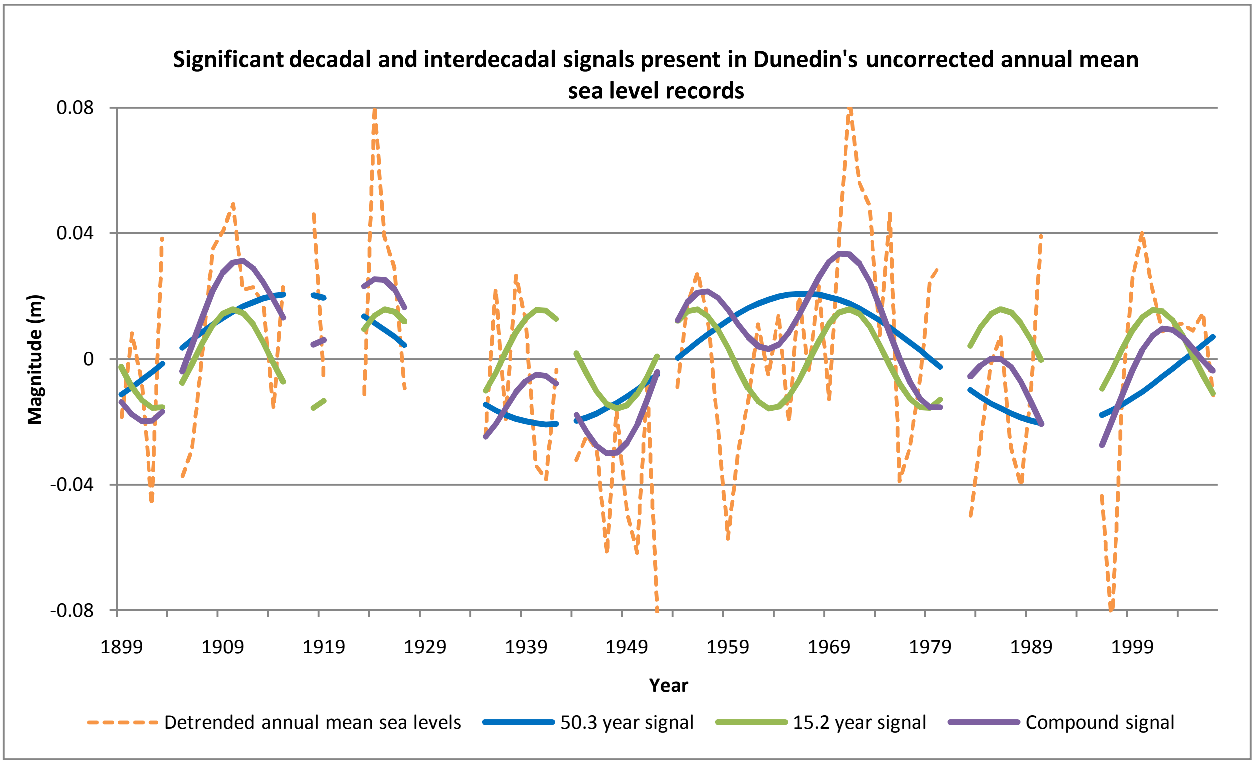

Figure 5.40: Significant decadal and interdecadal signals present in Dunedin's annual mean sea level records

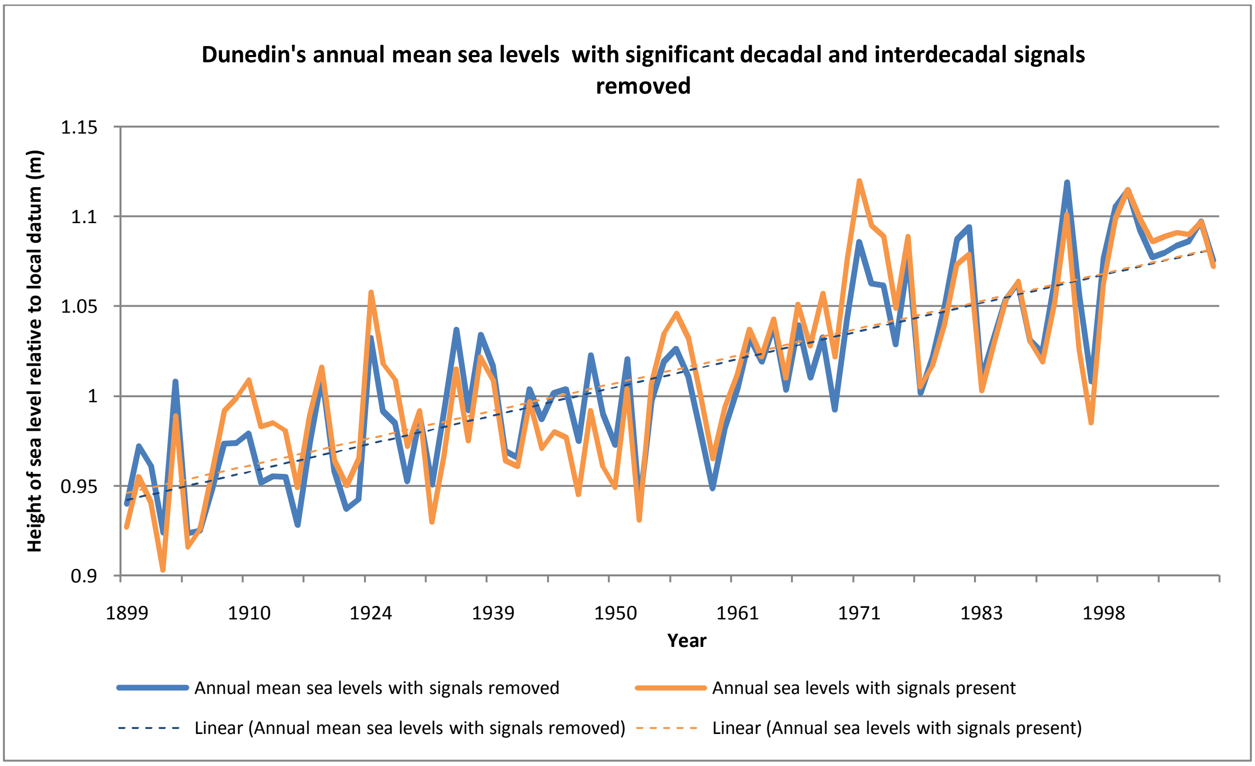

Figure 5.41: Dunedin's annual mean sea levels with significant decadal and interdecadal signals removed

The investigations into the presence of an accelerating trend within the datasets from Auckland, Wellington, Lyttelton and Dunedin with significant decadal and interdecadal signals incorporated, did not find a significant acceleration.

Exclusion of Wellington's potentially compromised records

Considering the nature of the active tectonics in the Wellington area and the potential of these tectonics to have compromised Wellington's annual mean sea level records, combined analyses were also carried out while excluding Wellington's annual mean sea level records. The results obtained from this analysis were not significantly different from those obtained through the complete combined analyses.

5.4.3.3 Changing linear trend analyses

To reveal if a change in rate of sea level rise has occurred within the annual mean sea levels' records, linear trends were again calculated using segments of the records. The same methodology used in Section 5.4.2.3 was applied here to avoid any bias in the derived linear trend due to interdecadal signals that are present in the datasets. Segments of the data were analysed to investigate if any significant secular change in the linear trend can be found within the dataset, or to reveal if the data suggest that the rate of rise is increasing over time. The results of the analyses are summarised in Table 5.23, Table 5.24, Table 5.25, and Table 5.26 for Auckland, Wellington, Lyttelton and Dunedin respectively.

Station	Auckland		
	Derived gradient (mm/yr)		
Years analysed	**4x Mean period = 51.6 years**	**4x (Mean – 95% CI) = 50.4 years**	**4x (Mean + 95% CI) = 52.8 years**
2007 -	1.5	1.6	1.2
1997 -	0.3	0.4	0.5
1987 -	0.9	1.1	1.1
1977 -	2.0	2.0	2.0
1967 -	2.0	2.0	1.8
1957 -	1.4	1.6	1.6

Table 5.23: Results from linear trend analysis using segments of Auckland's data

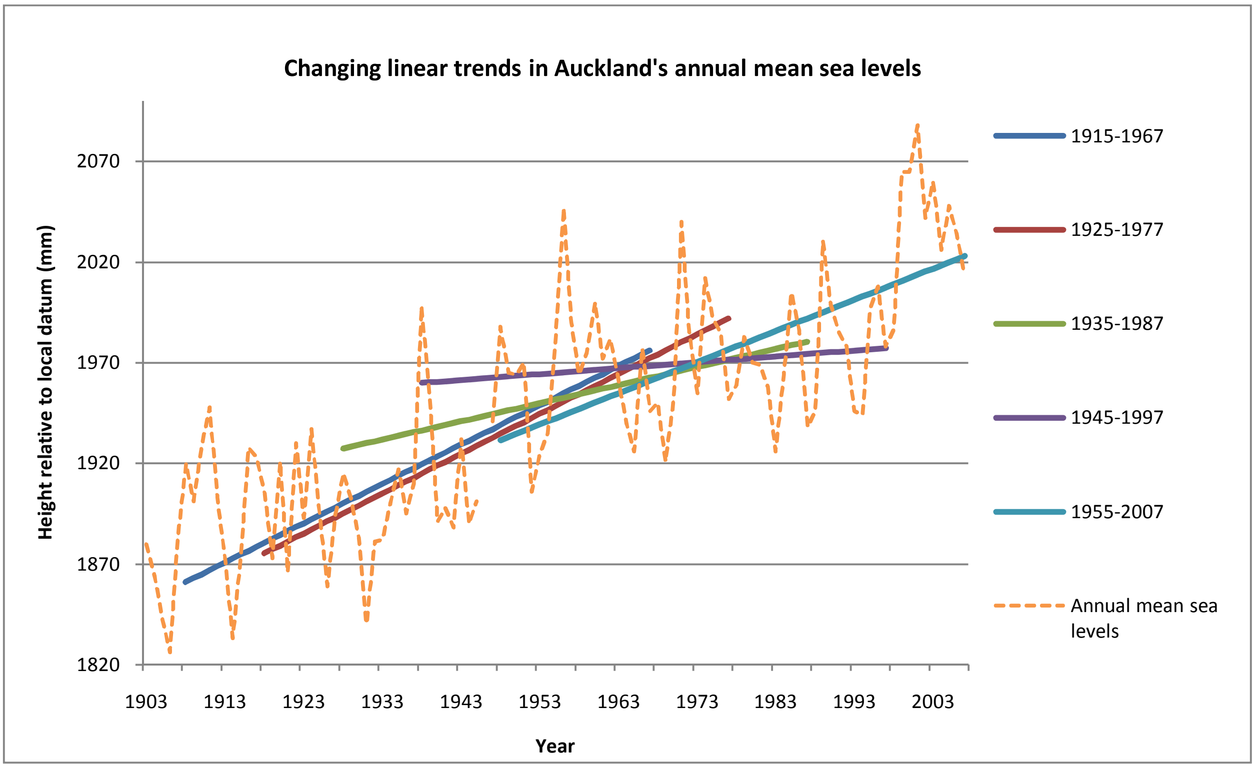

Figure 5.42: Changing linear trends in Auckland's annual mean sea levels

Station	Wellington		
	Derived gradient (mm/yr)		
Years analysed	4x Mean period = 54.0 years	4x (Mean – 95% CI) = 52.0 years	4x (Mean + 95% CI) = 56.0 years
2007 -	2.3	2.3	2.3
1997 -	1.9	1.9	1.9
1987 -	1.7	1.9	1.5
1977 -	1.5	1.8	1.4
1967 -	1.0	0.7	1.2

Table 5.24: Results from linear trend analysis using segments of Wellington's data

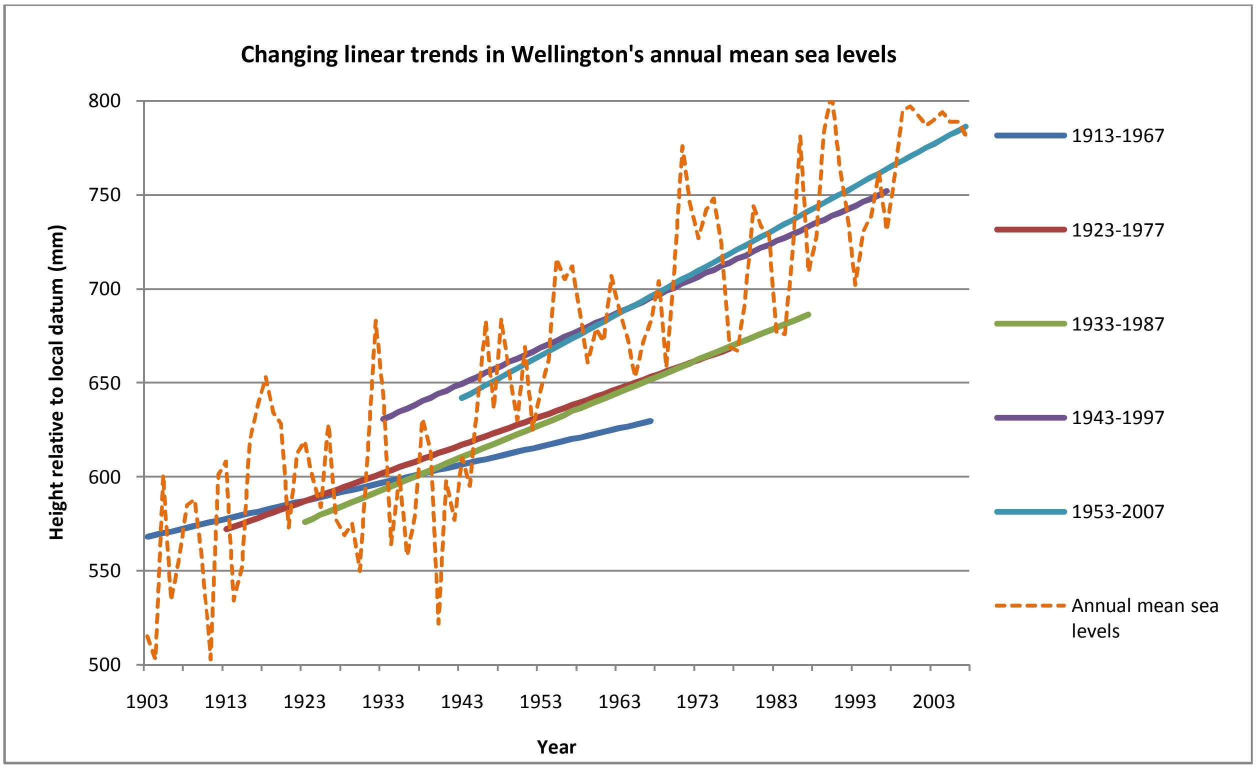

Figure 5.43: Changing linear trends in Wellington's annual mean sea levels

Station	**Lyttelton**		
	Derived gradient (mm/yr)		
Years analysed	**4x Mean period = 63.6 years**	**4x (Mean – 95% CI) = 60.4 years**	**4x (Mean + 95% CI) = 66.8 years**
2007 -	2.0	1.9	2.0
1997 -	2.0	1.9	1.8
1987 -	2.6	2.5	2.5
1977 -	2.2	2.2	2.2
1967 -	1.9	1.9	1.9

Table 5.25: Results from linear trend analysis using segments of Lyttelton's data

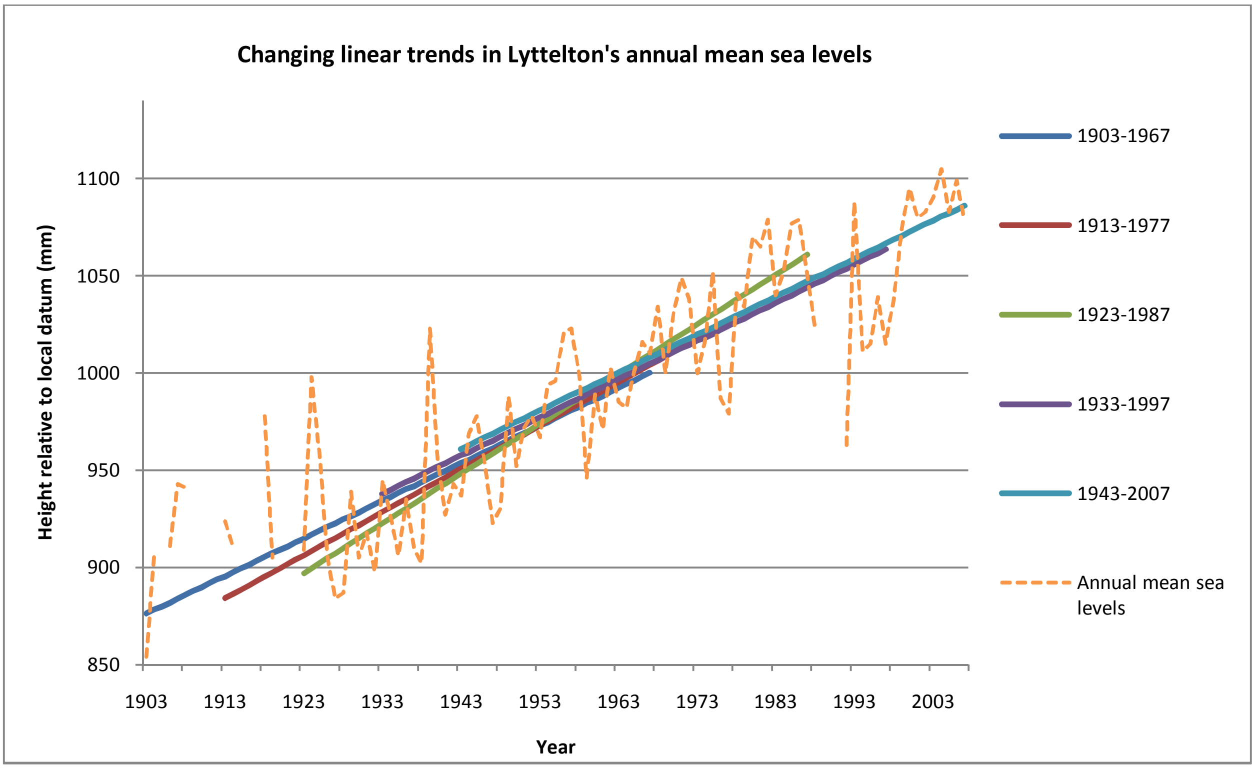

Figure 5.44: Changing linear trends in Lyttelton's annual mean sea levels

Station	Dunedin		
	Derived gradient (mm/yr)		
Years analysed	Mean period = 50.3 years	Mean – 95% CI = 47.3 years	Mean + 95% CI = 53.3 years
2007 -	0.4	1.0	1.1
1997 -	2.0	1.0	1.1
1987 -	2.6	2.0	1.9
1977 -	1.0	2.7	2.5
1967 -	0.4	1.1	1.1
1957 -	0.6	0.2	0.2

Table 5.26: Results from linear trend analysis using segments of Dunedin's data

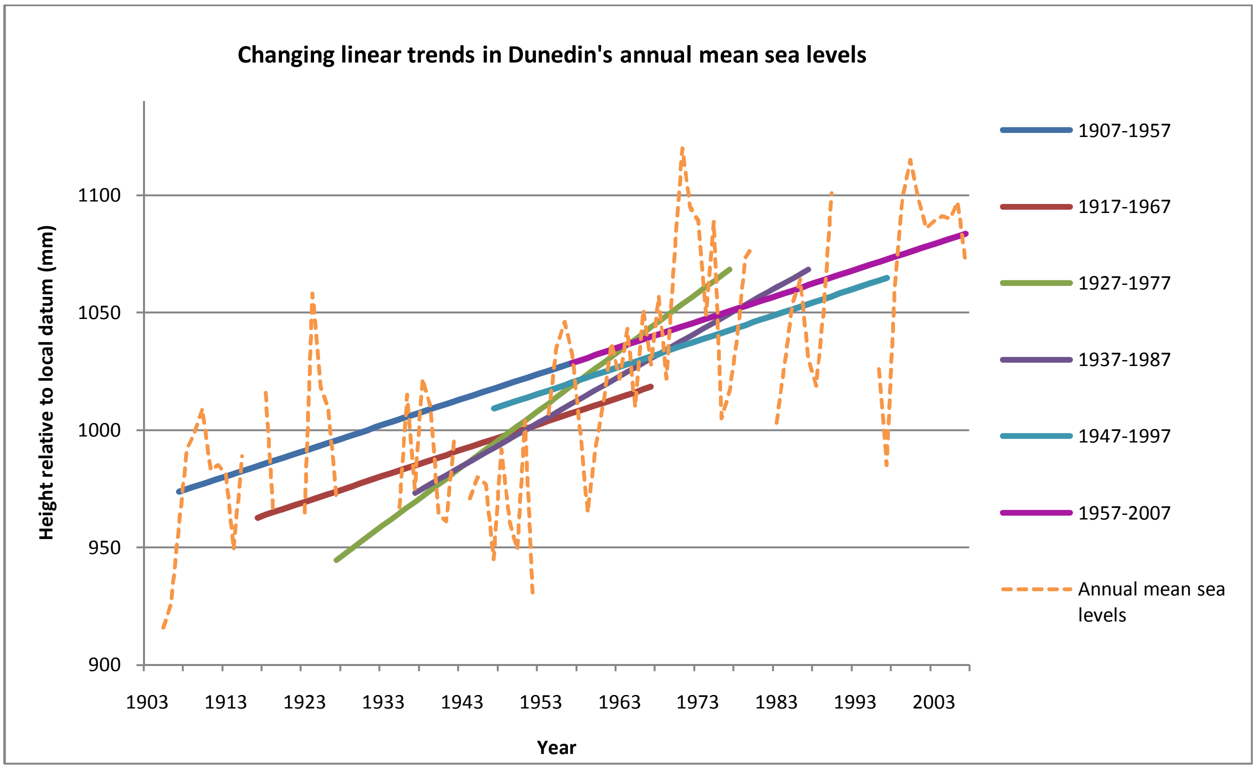

Figure 5.45: Changing linear trends in Dunedin's annual mean sea levels

The results from the changing linear trend analyses are consistent with those obtained in Section 5.4.2.3.

The Dunedin annual mean sea levels show unusual behaviour between 1940 and 1970, indicating a very high rate of sea level rise, but this rate is not consistent throughout the records. Considering the complex history of the Dunedin tide gauge and the unusual vertical movements that have affected its position, or compromised the reliability of the local benchmarks, it is possible that this increased trend over this period has been caused by the gauge's zero being non-constant in its position. Due to the location of this increased rate of rise, all derived linear trends that include these years are significantly influenced by it. The segments from 1907 until 1957 and from 1957 until 2007 are least influenced by this period, and Figure 5.45 illustrates that the trends calculated from these segments are consistent with each other.

The decelerating tendency in the mid-range of Auckland's records is likely to be due to the complex nature of the significant long-term signals influencing the height of sea level at that location. The deceleration is shown to be non-constant in nature, and hence is likely to be due to the influence of a periodic driver. Hannah and Bell (2010) consider that positive phases of the Interdecadal Pacific Oscillation have occurred between 1921 and 1944, and again between 1977 and 2000. The positive phase causes the sea level to be slightly depressed, which may explain the cause of the decreases in the height of mean sea level in Auckland during those periods.

The results obtained from the linear trend analyses performed are generally consistent with the overall findings of the analyses performed on the datasets that were corrected for both the inverted barometer effect as well as decadal and interdecadal signals. While the trends themselves differ due to the presence of the interdecadal signals in the datasets, the overall tendencies remain the same inasmuch as the linear trends do not share any demonstration of significant changes in behaviour, or suggest an accelerating trend overall.

In contrast to this, the trends derived using Wellington's uncorrected datasets are the only trends that demonstrate an increasing rate over time.

5.4.3.4 Non-consistent acceleration rates

Given the results of the changing linear trend analyses in Section 5.4.3.3 above, the datasets from the stations used in this study were analysed for individual accelerations to isolate if there are individual rates of acceleration in the various sea level records. The results detailing the trends in the rates of sea level rise for Auckland, Wellington, Lyttelton and Dunedin that were identified in the datasets are provided in Table 5.27, Table 5.29, Table 5.31 and Table 5.33 respectively. The signals identified in the records in this analysis are similarly summarised in Table 5.28, Table 5.30, Table 5.32 and Table 5.34. The overall accelerating trend within Wellington's long-term sea level records, including the decadal and interdecadal signals, is illustrated against the annual mean sea level records in Figure 5.46.

Auckland			
Parameter	***a*** **(mm/yr²)**	***m*** **(mm/yr)**	***c*** **(mm)**
Value	0.0027	1.87	1838
95% Confidence interval (CI)	± 0.0079	± 1.00	± 27
Significant at 95% CI	×	✓	✓
$\bar{\sigma}_o^2$	**2.14**		

Table 5.27: Accelerating trend in sea level rise within the Auckland dataset

Station	Period (years)	95% CI	*a* (mm)	95% CI	*b* (mm)	95% CI
Auckland	48.2	± 5.9	-16.6	± 13.0	Not significant	
	12.9	± 0.4	-16.2	± 8.6	Not significant	

Table 5.28: Signals within Auckland's uncorrected dataset

Wellington				
Parameter	***a*** **(mm/yr²)**	***m*** **(mm/yr)**	***c*** **<1942 (mm)**	***c*** **≥1944 (mm)**
Value	0.0126	0.3	562.2	594.0
95% Confidence interval (CI)	± 0.0092	± 1.5	± 37.2	± 64.9
Significant at 95% CI	✓	×	✓	✓
$\overline{\sigma}_o^2$	**0.98**			

Table 5.29: Accelerating trend in sea level rise within the Wellington dataset

Station	**Period (years)**	**95% CI**	***a*** **(mm)**	**95% CI**	***b*** **(mm)**	**95% CI**
Wellington	44.9	± 7.8	Not significant		-10.9	± 8.9
	13.4	± 0.5	Not significant		Not significant	

Table 5.30: Signals within Wellington's uncorrected dataset

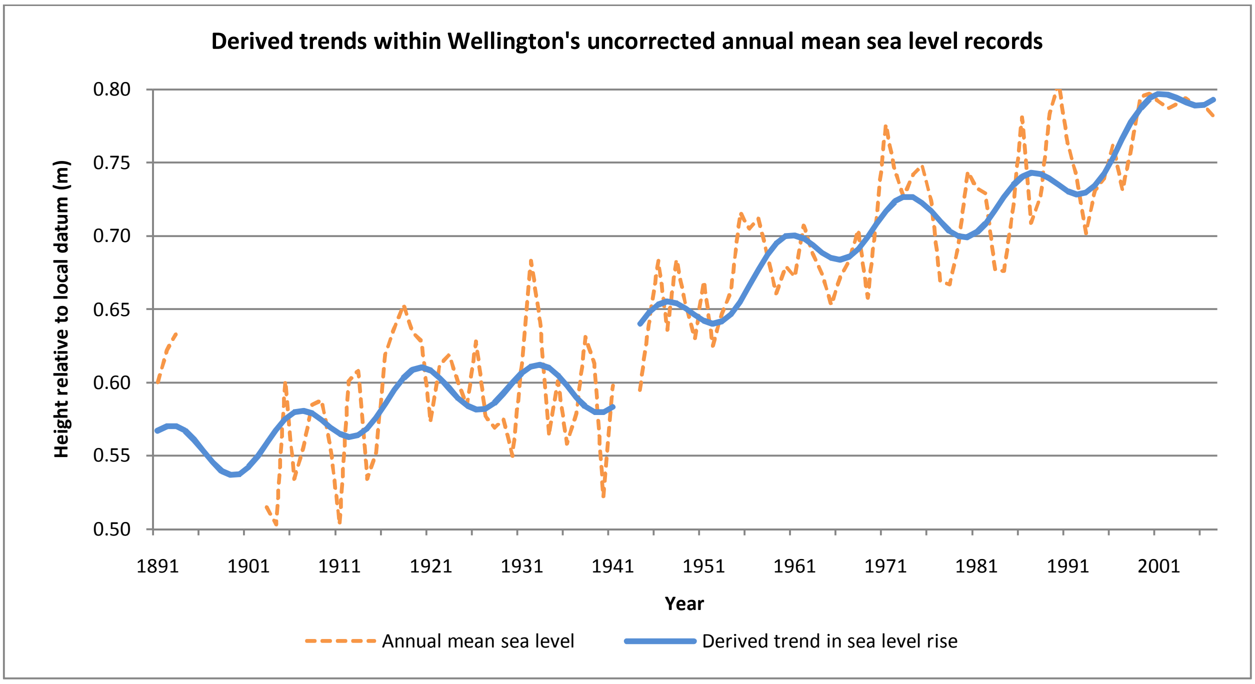

Figure 5.46: Derived trends within Wellington's uncorrected annual mean sea level records

Lyttelton			
Parameter	***a*** **(mm/yr²)**	***m*** **(mm/yr)**	***c*** **(mm)**
Value	0.0035	1.46	874
95% Confidence interval (CI)	± 0.0087	± 1.18	± 36
Significant at 95% CI	×	✓	✓
$\bar{\sigma}_o^2$	**0.87**		

Table 5.31: Accelerating trend in sea level rise within the Lyttelton dataset

Station	**Period (years)**	**95% CI**	***a*** **(mm)**	**95% CI**	***b*** **(mm)**	**95% CI**
Lyttelton	16.0	± 0.7	13.1	± 12.7	Not significant	
	36.9	± 5.7	Not significant		14.8	± 13.0

Table 5.32: Signals within Lyttelton's uncorrected dataset

Dunedin			
Parameter	***a*** **(mm/yr²)**	***m*** **(mm/yr)**	***c*** **(mm)**
Value	0.0059	0.56	947
95% Confidence interval (CI)	± 0.0069	± 0.88	± 25
Significant at 95% CI	×	×	✓
$\bar{\sigma}_o^2$	**0.84**		

Table 5.33: Accelerating trend in sea level rise within the Dunedin dataset

Station	**Period (years)**	**95% CI**	***a*** **(mm)**	**95% CI**	***b*** **(mm)**	**95% CI**
Dunedin	49.8	± 4.7	-20.5	± 9.8	Not significant	
	15.2	± 0.6	Not significant		15.2	± 8.7

Table 5.34: Signals within Dunedin's uncorrected dataset

These results demonstrate that there is a statistically significant acceleration in the rate of sea level rise that has been observed in Wellington. The irregular movement that is believed to have occurred between 1942 and 1944 has been incorporated through the inclusion of an additional vertical offset parameter to prevent that specific movement from compromising the annual mean sea level records. However, recent continuous Global Positioning System measurements provide evidence of irregular vertical land movements in the Wellington area (Denys *et al.,* 2010), and as such the relative acceleration in the rate of sea level rise may be resultant of tectonic signals. The duration and completeness of the records greatly improves the redundancy of the analysis, although the unknown offset still significantly weakens the dataset. There were no significant individual trends of underlying acceleration present in the sea level records from any of the other tide gauges considered in this study.

5.5 Summary of results from analyses

Least Squares and Fast Fourier Transform analysis methodologies were applied for the purposes of this investigation into the presence of an acceleration in the rate of sea level rise. The study utilised long-term annual mean sea level records from Auckland, Wellington, Lyttelton and Dunedin, and subjected these datasets to progressive, intensive analyses.

The local responses to relative atmospheric pressure changes were investigated and utilised to form a model to remove the systematic inverted barometer effect from the annual mean sea level datasets. The combined analysis using the annual mean sea level records that were corrected for the inverted barometer response did not provide statistically significant evidence of an acceleration in the rate of sea level rise using the records from the four stations used in this study.

The similar analysis using the sea level records that were not corrected for the influence of atmospheric pressure changes also did not provide evidence of a significant acceleration in the rate of sea level rise.

Segmented trend analyses using both of these input datasets were performed to investigate if the records demonstrate behaviour indicating a secular change in the rate of sea level rise or an accelerating nature. These trends were affected by complex long-term signals present in the records, and they were also subject to potential bias from the mid-record annual mean sea levels. These investigations demonstrated an increasing rate of sea level rise in Wellington, but this trend was not shared between the other stations.

Using the annual mean sea level values that were recorded at Wellington that were corrected for the inverted barometer effect, the dataset was investigated for the presence of a statistically significant acceleration in the rate of sea level rise. This analysis presented statistically significant results, with a calculated acceleration of 0.014 ± 0.01 mm/yr^2, with an *a posteriori* variance of unit weight of 0.96. A similar investigation was carried out using the annual mean sea levels that were not corrected for the inverted barometer effect. The Wellington records demonstrated a significant relative acceleration of 0.013 ± 0.01 mm/yr^2, with an *a posteriori* variance of unit weight of 0.98.

6 Discussion

An acceleration in the rate of sea level rise has significant implications for all coastal and low-lying areas around the globe. This study did not find statistically significant evidence of a common acceleration in the rate of sea level rise through the combined analyses using New Zealand's long-term sea level records from Auckland, Wellington, Lyttelton and Dunedin. However, a relative acceleration was identified within Wellington's annual mean sea level records. The implications of the results obtained in this study are discussed firstly in this chapter.

Secondly, this chapter discusses the limitations associated with the model created in this study to correct the annual mean sea level records for the inverted barometer effect.

Finally, this chapter discusses the possible drivers of the long-term signals present within the annual mean sea level records.

6.1 Implications of the trend results

This section reviews the results obtained from the analyses carried out in this study. These analyses included investigations into:

- An acceleration in sea level rise that is common between the four tide gauge records,
- Differing rates of acceleration for each individual tide gauge, and
- A secular change in the rate of sea level rise.

These investigations were carried out using the relative sea level records that were corrected for the inverted barometer effect, and again using the annual mean sea levels that did not have this correction applied.

6.1.1 Combined analyses' results

The investigations into the presence of an acceleration in the rate of sea level rise that is consistent between New Zealand's four long-term tide gauges did not provide statistically significant results.

The Auckland and Wellington records are both extensive in duration and have comparatively few absent annual mean sea level values. The unknown offset within Wellington's recording period is a significant weakness in the dataset, but fortunately this does not compromise the dataset's applicability to this form of investigation. Due to the incomplete nature of the annual mean sea level datasets from Lyttelton and Dunedin, the statistical quality of the trends identified using these records are likely to be significantly reduced.

The failure to determine a statistically significant acceleration in the rate of sea level rise may be due to several possible reasons. These include:

- The rate of sea level rise not accelerating over time,
- Land deformation changing the relative position of the respective tide gauges in a non-constant manner over time,
- The acceleration in sea level rise being small in magnitude, which causes difficulties in confidently quantifying the changing trend, or
- By other unknown or unquantifiable factors.

Given the results obtained in this investigation, evidence currently available does not suggest that the rate of absolute sea level rise is increasing over time, nor is there evidence that the rate of sea level rise has been subject to a significant change in the linear rate of sea level rise at some point during the recording period.

6.1.2 Acceleration within Wellington's sea level records

The analyses investigating non-consistent rates of acceleration in sea level rise at each tide gauge provided statistically significant evidence of an accelerating relative trend in Wellington's sea level record. This significant result may be reflective of the influence of the extended length of the records available from Wellington on this form of investigation. Conversely, this significant acceleration may be due to local influences that affect the relative sea level change.

For the purpose of the common acceleration rate investigation in this study, vertical land movement was assumed to be constant over time. This behaviour would cause the rate of acceleration in sea level rise measured at any given station being unaffected by tectonic movements. However, there is some evidence which suggests that the vertical movement at the Wellington tide gauge may not be constant over time. This is demonstrated in Figure 2.4, where there appears to be a change in the relative vertical movement of the Wellington continuous Global Positioning System (cGPS) station. This irregular motion was occurring between mid-2007 and early 2009. Unfortunately, there are no records available to allow the assessment of the consistency of the vertical deformation occurring in Wellington during the timespan of Wellington's sea level records that were used in this study.

There is some ambiguity surrounding the consistency of the Wellington tide gauge's vertical position relative to the local benchmarks, detailed in Section 3.3.2. This coincides with the period of irregular vertical behaviour identified by cGPS measurements, shown in Figure 2.4. The non-consistent vertical trend identified using the cGPS measurements potentially could be associated with this relative movement.

An absolute acceleration in sea level rise, if physically occurring, would be expected to be seen at all four stations considered in this study, provided they are not subject to any irregular vertical movement that has not been incorporated in the investigation. Considering this, common accelerations in the rate of sea level rise need to be identified between multiple stations, preferably at stations that are considered to be in stable, non-tectonic areas, to be considered indicative of an absolute acceleration in the rate of sea level rise. An acceleration in sea level rise may not be representative of an absolute acceleration if such a trend is identified in an active tectonic area as differing irregular vertical deformation behaviours will cause different apparent accelerations. Inconsistent relative vertical movements of the tide gauges need to be identified (ie, with cGPS or precise levelling) and isolated or removed to obtain unbiased evidence of an accelerating trend. Auckland, Lyttelton and Dunedin were also investigated for the presence of any significant acceleration in their respective records, but no statistically significant accelerations were identified.

This study supports the recommendation made in 1988 by the International Association for Physical Sciences of the Ocean Commission on Mean Sea Level and Tides. This association reviewed the necessity of fixing the positions of tide gauge bench marks in a global reference frame (Carter *et al.*, 1989). The Committee recommended that the tide gauges should be monitored through episodic GPS campaigns. In the years which followed this recommendation there were significant advances in GPS technology; making available cheaper and more accurate receivers, completing the satellite constellation, and the establishment of the International Global Positioning System Service (Zumberge *et al.*, 1997). In 1993 the International Association for Physical Sciences of the Ocean Committee recommended that cGPS stations should be installed at about one hundred tide gauges worldwide (Teferle *et al.,* 2006).

Despite the fact that the core network the International Association for Physical Sciences of the Ocean Committee hoped for was not fully realised (Teferle *et al.,* 2006), the data from those cGPS stations which have been set up since the 1988 and 1993 recommendations may now be extensive enough so that they can be used in time series regression analysis to investigate if there is a significant vertical trend detected by the measurements. Co-located cGPS stations are recommended to be established for all tide gauge stations that are utilised for the ongoing monitoring of sea level change trends, if they do not already exist (Teferle *et al.,* 2006).

6.2 Meteorological influences on sea level

To reduce the overall variability of the annual mean sea levels datasets, corrections were applied to correct the sea levels for the inverted barometer effect. Both atmospheric pressure and temperature changes influence the height of sea level. The relationships between these drivers and sea level changes may aid in the improved modelling of signals and systematic effects that are present in the datasets.

6.2.1 Atmospheric pressure and the inverted barometer effect

The corrections for the inverted barometer effect that were applied to the annual mean sea level values assume that the magnitude of the effect is directly proportional to the location's relative difference in annual mean atmospheric pressure compared to the global (oceanic) mean. The timeframes associated with this displacement effect are not significant when considering the respective influences on an annual basis.

The Earth's oceans are very complex in nature. The ocean water level measurements at a particular location are resultant of an extremely complex combination of drivers, including but not limited to:

- The physical properties of the water mass (pH, temperature and density),
- Meteorological process (wind patterns, atmospheric pressure changes, and temperature and pressure signals),
- Oceanographic processes (tidal influences, waves, and inshore and offshore currents), and
- Local responses (harbour seiching and localised freshwater flooding) (Watson, 2011-a)

A correction to the annual mean sea levels based upon the relative differences in annual mean atmospheric pressures compared to the national mean was investigated for its consistency and applicability. This investigation assumed that all changes to the height of sea level that were caused by drivers not modelled in the Sea Level Data Processing on SLPR2 software, with the exception of the inverted barometer effect, average out in the datasets analysed. The nature of these other drivers should be further investigated for biases in the nature of the effects if an improved model for the inverted barometer effect is to be created.

The consistency of the model created in this study should be indicated by the trend between the atmospheric pressure differences and the detrended sea level values, such as that demonstrated in Figure 5.6. The results of the relative national differences and relative global differences are shown in Figure 6.1 and Figure 6.2 respectively.

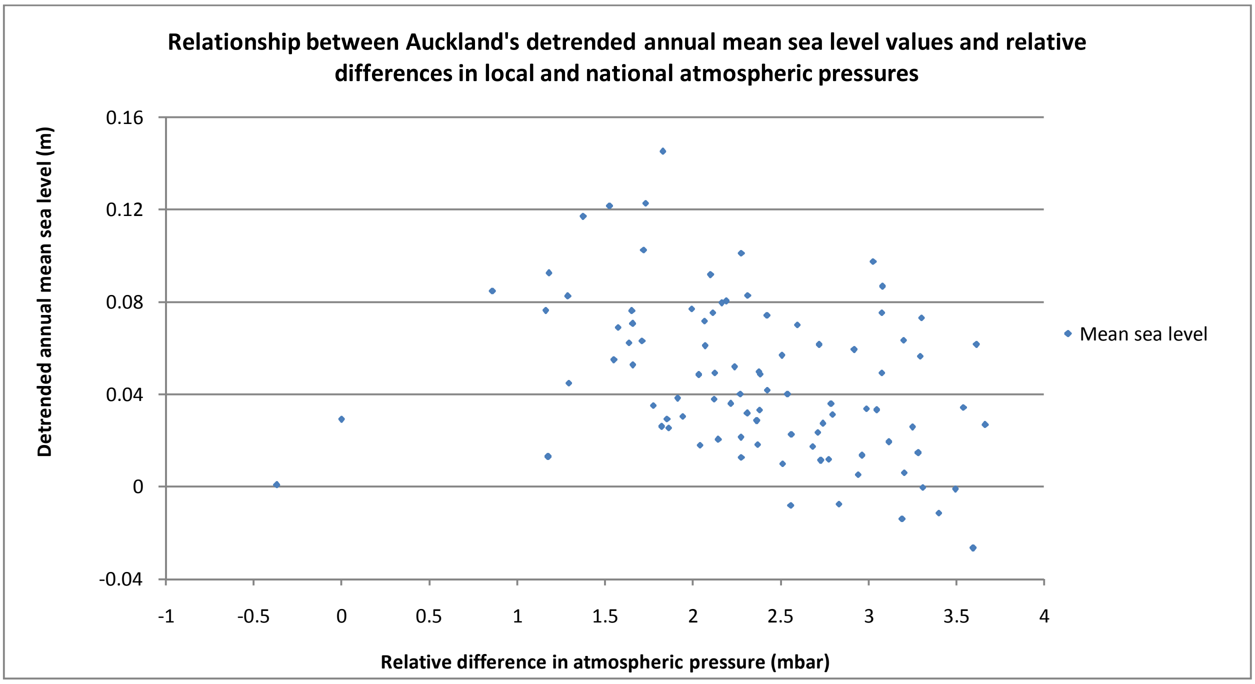

Figure 6.1: Relationship between Auckland's detrended annual mean sea level values and relative differences in local and national atmospheric pressures

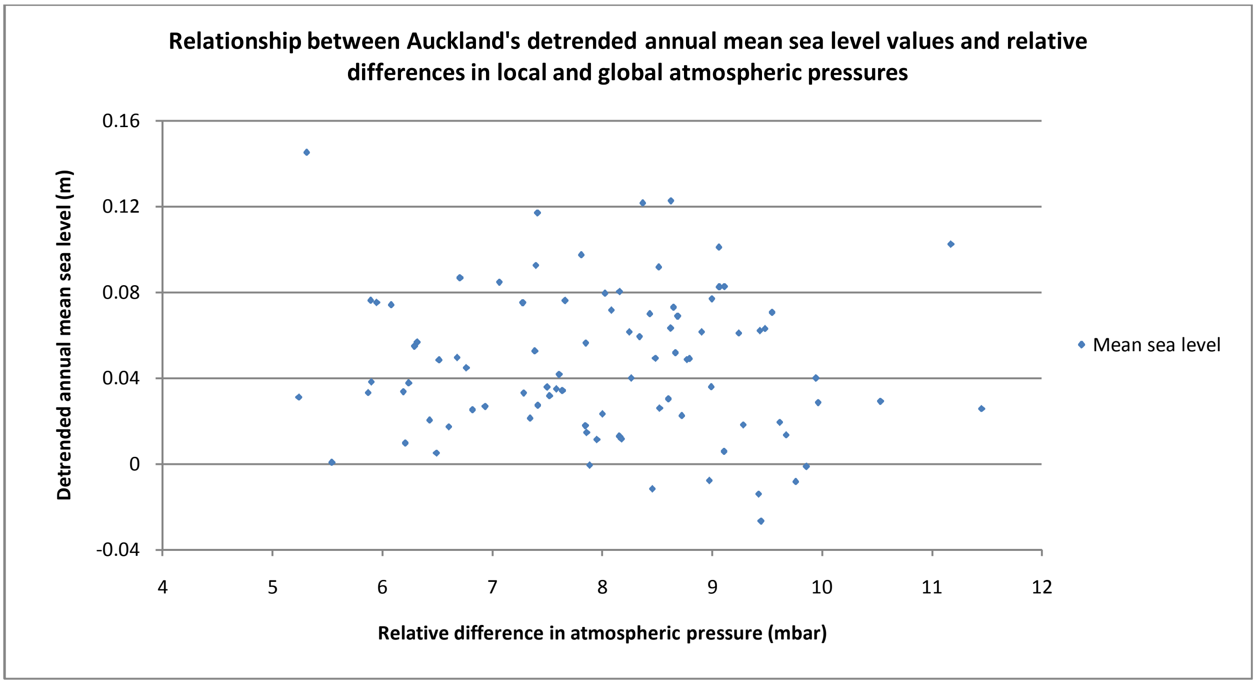

Figure 6.2: Relationship between Auckland's detrended annual mean sea level values and relative differences in local and global atmospheric pressures

These figures demonstrate that there is no evidence to suggest that the local relative differences in atmospheric pressure compared with the national mean pressures are any more applicable than the global relative atmospheric pressure differences.

The direct comparison of the 95% confidence intervals of the various trend parameters derived in this study using the corrected and non-corrected annual mean sea level datasets indicate that the corrections for the inverted barometer effect that were applied to the annual mean sea levels did not significantly reduced the variability of the datasets. The 95% confidence intervals of the parameters derived from the individual acceleration investigations using Wellington's corrected and original datasets are summarised below in Table 6.1. The direct comparison of the *a posteriori* variances of unit weight, shown in Table 6.2, also demonstrate that the values from the uncorrected datasets are generally closer to 1.0 compared to the corresponding corrected dataset's results. The inverted barometer effect model created in this study did not significantly reduce the variability of the annual mean sea level datasets. Therefore, the correction may be disregarded and the analysis performed without applying any correction for this systematic effect.

Parameter	Derived 95% CI using corrected datasets	Derived 95% CI using original datasets
Acceleration (a)	± 0.0105 mm/yr^2	± 0.0092 mm/yr^2
Gradient (m)	± 1.66 mm/yr	± 1.5 mm/yr
Offset (c < 1942)	± 40.9 mm	± 37.2 mm
Offset (c ≥ 1944)	± 71.0 mm	± 64.9 mm
Period (P_1)	± 8.0 yr	± 7.8 yr
Amplitude (b_1)	± 10.1 mm	± 8.9 mm
Period (P_2)	± 1.0 yr	± 0.5 yr

Table 6.1: 95% Confidence Intervals of parameters derived from Wellington's corrected and original annual mean sea level datasets

Investigation	$\bar{\sigma}_o^2$ using corrected datasets	$\bar{\sigma}_o^2$ using uncorrected datasets
Common acceleration	1.47	1.24
Acceleration at Auckland	1.75	2.14
Acceleration at Wellington	0.96	0.98
Acceleration at Lyttelton	0.66	0.87
Acceleration at Dunedin	0.80	0.84

Table 6.2: A posteriori variances of unit weight from corrected and uncorrected datasets

Future research into the nature of the ocean's response to changes in atmospheric pressure is required to confidently isolate what the displacements are relative to, and if these can be modelled for applications such as in this form of study. The spatial extents and velocities of atmospheric pressure systems should be investigated in conjunction with this future research as these parameters may influence the magnitude of this effect.

The atmospheric pressure trends occurring today may be influenced by atmospheric warming by it inducing an overall decrease in average atmospheric pressure with atmospheric thermal expansion. However, such a decrease in pressure would not cause an increase to global mean sea level, or cause greater variation in the year-to-year annual mean sea levels.

6.3 Drivers of significant decadal and interdecadal signals in sea level records

The records from the tide gauges used in this study indicate the presence of long-term decadal and interdecadal signals. These signals appear to be consistent between most of the stations. The periods of the longest signals influencing the height of sea level are generally difficult to define confidently.

Figure 5.33 illustrates that the significant signals that are present in Auckland's annual mean sea level records are not consistent between the atmospheric pressure and temperature records, which are both drivers of changes in the height of sea level. Therefore, there must be other drivers which cause these various signals. As the significant signals are not common between the datasets, the datasets could not be combined in this investigation to improve the resolution of the periods of the signals within the annual mean sea level records.

The magnitudes and periods of the significant signals within the records utilised in this study are summarised in Table 5.22. Any signals associated with gravitational influences would be expected to be consistent between the stations. The longest signals in the uncorrected annual mean sea level records are consistent at the 95% confidence interval between all stations, with Lyttelton being the only exception. Lyttelton's exception to this may be due to the incomplete nature of Lyttelton's annual mean sea level dataset, causing difficulty in the resolution of the long-term influence.

The magnitudes and periods of the signals identified in the annual mean sea level datasets directly relate to the maximum potential bias in derived trends. The signals identified in this study indicated that some of the amplitudes of the signals present in the datasets are in the range of 20 ± 10 millimetres.

It is unlikely that the long-term signals that influence the height of sea level are caused by meteorological drivers. Atmospheric pressure and temperature changes are considered to be the most influential meteorological drivers on the height of sea level, and Figure 5.33 illustrates that the long-term signals are not likely to be the result of these influences.

6.4 Discussion summary

The results obtained using annual mean sea level records do not demonstrate a statistically significant acceleration in the rate of sea level rise. However, Wellington's records do demonstrate a relative acceleration in the rise of sea level. To aid in identifying an absolute acceleration in sea level rise, further records and co-located cGPS observations are required to obtain absolute sea level rise information.

The assumptions associated with the model created in this study for the inverted barometer effect may have been inappropriate or poor approximations. The quality of the inverted barometer effect model created could not be confidently ascertained, and as such its effectiveness in reducing the overall year-to-year variability in the annual mean sea level records has been deemed to be not significant.

The decadal and interdecadal signals present in the annual mean sea level records do not appear to be driven by meteorological forces. The identification of the drivers will aid in obtaining more statistically significant results pertaining to an accelerating trend in sea level rise.

7 Conclusions and Recommendations

7.1 Conclusions

The investigation was carried out by analysing of New Zealand's long-term annual mean sea level records. These records were sourced from four tide gauge stations that are located around New Zealand in Auckland, Wellington, Lyttelton and Dunedin.

A model was tested in this study to correct the annual mean sea levels for the inverted barometer effect. This study's findings suggest that further development of this correction is required.

Pursuing the assumption that all tide gauges around New Zealand are subject to constant vertical trends, combined analyses were carried out investigating any acceleration in the rate of sea level rise that is constant between all four of New Zealand's long-term tide gauge stations. This investigation did not identify a significant acceleration in the rate of sea level rise.

The identification of the drivers of the periodic signals present in the annual mean sea level datasets has not been specifically pursued in this study, although signals with periods in the range of fourteen to sixteen years may be associated with the Interdecadal Pacific Oscillation. The identification of these drivers may enable improved resolution of the period parameters.

The investigations into an increase in the linear rate of sea level rise indicated an increase in the linear rate within Wellington's sea level records. The magnitude of the change in rate was not statistically significant.

Wellington's annual mean sea level records, which extend from 1891 until 2007, provided statistically significant evidence of an accelerating relative trend over time. This acceleration is 0.013 ± 0.009 mm/yr^2 within the dataset that has not been corrected for the inverted barometer effect, and 0.014 ± 0.011 mm/yr^2 in the records that have been corrected for this systematic effect. However, this relative acceleration should not be considered as indicative of an absolute acceleration in sea level rise as the trend may be resultant of irregular local movement. Further research must be conducted to identify an absolute acceleration in sea level change.

There is currently limited evidence available to aid in the identification and quantification of vertical movements of the land, and hence the tide gauge, relative to mean sea level. Long-term continuous Global Positioning System (cGPS) stations need to be established and maintained at tide gauge stations to provide evidence of the gauges' relative movements over time. These records may be incorporated into similar future studies to isolate the vertical shift of the tide gauge from the trend in sea level rise over time. Denys (2010) has utilised cGPS records from the last ten years to monitor the vertical movement of New Zealand's four long-term tide gauges. Figure 2.4 illustrates that irregular movement at the Wellington tide gauge caused by local subduction has been detected through cGPS measurement.

The long-term annual mean sea level records from Auckland, Lyttelton and Dunedin that were considered in this study did not demonstrate statistically significant accelerations.

7.2 Recommendations

As sea level records extend in length, improved investigations into the rate of sea level rise may be conducted and obtain statistically significant results. This investigation into the potential presence of an acceleration in the rate of sea level rise has uncovered some relevant issues that have not been adequately explored as it is beyond the scope of this study. The relevant issues that should be further examined in future studies to improve the likelihood of obtaining results of statistical significance and relevance are as follows:

- The nature of vertical deformation at the tide gauges considered,
- The creation of an improved model for the inverted barometer effect, and
- Isolation of the drivers of the decadal and interdecadal signals within the datasets.

7.2.1 Further investigations into the trend in sea level rise

As sea level records extend in duration, more evidence may be utilised in investigations into the rate of sea level rise. The extending records provide further evidence of the nature of sea level rise and improve the statistical significance of the investigations performed through the increased redundancy of the investigation.

The nature of vertical deformation or other drivers of vertical movement of tide gauges should be carefully considered in this form of analysis. There is minimal evidence currently available relating to the movement of the land upon which tide gauges are fixed. Assumptions made pertaining to the nature of gauges' vertical movements must be carefully considered in relation to the influence that such movements may have on the observed rates of sea level change. Continuous Global Positioning System (cGPS) stations at tide gauges may be utilised to isolate non-constant vertical movements at the tide gauge site, which may then be incorporated into this form of investigation. This becomes very apparent when studying recent cGPS records from Wellington (ie, Denys, 2010).

Tide gauge records from areas that are not affected by active tectonics should be given greater weighting in investigations into sea level trends.

Any future investigations into the trend in sea level rise should incorporate long-term signals in the analysis to avoid any bias in the derived result. Potential improvements upon the methodology used to accommodate for the signals in this study are discussed in further detail in Section 7.2.3.

7.2.2 Improvements to the inverted barometer effect model

As mentioned in Section 6.2, changes to the height of sea level that are caused by the inverted barometer effect need to be further investigated to create an adequate model for this systematic effect. For this study, the relative differences in atmospheric pressure between the local and the global (oceanic) annual mean values were considered. However, the corrections applied in association with these relative differences have not removed the systematic effect from the datasets.

Improvements to this model may be achieved by identifying what the inverted barometer displacements are relative to. However, due to the complexities of the Earth's oceans, a linear correction may not be realistic.

Given the relevance of the inverted barometer effect to investigations into long term sea level change, the establishment and maintenance of barometers at the tide gauges is recommended as this valuable, site-specific data, will be available and spatially relevant for any future studies.

7.2.3 Isolation of the decadal and interdecadal drivers

If the drivers of the signals within the sea level records are identified, the models for the long-term trends in sea level rise may be improved.

Further investigation is required to identify the drivers of these signals, and their expected consistency over the globe. By identifying the respective periods of these signals, the investigations into linear or quadratic trends in sea level rise may be significantly improved as biases in the result may be avoided through the utilisation of improved models incorporating the long-term signals within the records.

7.2.4 Summary of future research

A relative acceleration in the rate of sea level rise has been identified in Wellington's annual mean sea level records. Further research using long-term cGPS may isolate if there is evidence of an absolute acceleration.

Continuing research into the nature of sea level rise is required to identify trends with statistical significance as the analyses' redundancies improve with the increasing number of observations available.

Other similar studies may be significantly improved through accurately modelling the inverted barometer effect. The studies will also be improved through the identification of the drivers of the significant decadal and interdecadal signals present within the sea level datasets as the incorporation of additional datasets may improve the resolution of the periods of these signals, and by association increase the redundancy of the trend investigations.

8 References

Adams, C. E. (1908), The Wellington Tide-gauge, M. Sc., A. I. A. (London), F.R.A.S., *Read before the Wellington Philosophical Society*, 1st July, 1908. pp. 406-410.

Aitken, J. J. (1996), Plate tectonics for Curious Kiwis. Institute of Geological and Nuclear Sciences Limited, Lower Hutt, New Zealand.

Allan, R., and T. Ansell (2006), A new globally-complete monthly historical gridded mean sea level pressure data set (HadSLP2): 1850-2004, Hadley Centre, Med Office, United Kingdom, *J. of Climate*, 19, pp. 5816-5842.

Andreasen, A. (2005), Python for scientific use, Part II: Data analysis, *Linux Gazette*, 115, http://linuxgazette.net/115/andreasen.html, *accessed 18 May 2010.*

Angell, J. K. (2000), Tropospheric temperature variations adjusted for El Nińo, 1958-1998, *J. Geophys. Res.*, 105, pp. 11,841-11,849.

Antonov, J. I., S. Levitus, and T. P. Boyer (2002), Steric sea level variations during 1957–1994: Importance of salinity, J. Geophys. Res., 107(C12), 8013, doi:10.1029/2001JC000964, 2002.

Baranuik, R., Fite, B., Gjendemsjø, A., Haag, M., Johnson, D., Jones, D. (Ed.), Nowak, R., Radaelli-Sanchez, R., Romberg, J., Scott, C., Selesnick, I., and M. Selik (2010), Digital Signal Processing: A User's Guide, *Connexions*, Rice University, Huston, Texas. http://cnx.org/content/col10372/1.2/.

Barnett, T. P. (1984), The Estimation of "Global" Sea Level Change: A Problem of Uniqueness. Journal of Geophysical Research. Vol. 89, NO C5, pp. 7980-7988.

Barnett, T. P., D. W. Pierce, and R. Schnur (2001), Detection of anthropogenic climate change in the world's oceans, *Science*, 292, pp. 270-274.

Beavan, J., Ellis, S., Wallace, L., and Denys, P. (2007). Kinematic constraints from GPS on oblique convergence of the Pacific and Australian plates, Central South Island, New Zealand, in Okaya, D., Stern T., and F. Davey (Eds.), A Continental Plate Boundary - tectonics at South Island, New Zealand (pp. 75-94). Washington, DC: American Geophysical Union.

Beaven, J., and J. Haines (2001), Contemporary horizontal velocity and strain rate fields of the Pacific-Australian plate boundary zone through New Zealand. *J. Geophys. Res.,* 160, pp. 741-770.

Bell, R. G., Goring, D. G., and W. P. de Lange (2000), Sea-level change and storm surges in the context of climate change, *Institute of Professional Engineers New Zealand Transactions,* 27(1), Gen: 1-10.

Bergeot, N., Bouin, M. N., Diament, M., Pelletier, B., Régnier, M., Calmant, S., and V. Ballu (2009), Horizontal and vertical interseismic velocity fields in the Vanuatu subduction zone from GPS measurements: Evidence for a central Vanuatu locked zone, *J. Geophys. Res*., doi:10.1029/2007JB005249.

Bindoff, N. L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., LeQuéré, C., Levitus, S., Nojiri, Y., Shum, C. K., Talley L. D., and A. Unnikrishnan (2007) Observations: Oceanic Climate Change and Sea Level, in: *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. and Miller, H. L., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007

Blewitt, G., Altamimi, Z., Davis, J., Gross, R., Kuo, C., Lemoine, F., Neilan, R., Plag, H.-P., Rothacher, M., Shum, C. K., Sideris, M. G., Schöne, T., Tregoning, P., and S. Zerbini (2006), Geodetic observations and global reference frame contributions to understanding sea level rise and variability. Proceedings of the WCRP Workshop "Understanding Sea-Level Rise and Variability." UNESCO, Paris, pp. 145-170. 6-9 June (2006).

Bouin, M. N., and G. Wöppelmann (2010), Land motion estimates from GPS at tide gauges: a geophysical evaluation, *Geophys. J. Int.*180, pp. 193-209.

Cabanes, C., Cazenave, A., and C. Le Provost (2001), Sea level rise during past 40 years determined from satellite and in situ observations, *Science,* 294, pp. 840-842.

Caldwell, P. (2000), Sea Level Data Processing On IBM-PC Compatible Computers Version 3.0 *(Year 2000 Compliant)*. Joint Archive for Sea Level of the National Oceanographic Data Centre and University of Hawaii Sea Level Centre.

Caldwell, P. (2009),Pers. Email, National Oceanic and Atmospheric Admistration Data Centre Hawaii Liason, Department of Oceanography, University of Hawaii at Manoa, Honolulu, Hawaii, *26 August 2009*.

Caldwell, P. (2010), Pers. Email, National Oceanic and Atmospheric Admistration Data Centre Hawaii Liason, Department of Oceanography, University of Hawaii at Manoa, Honolulu, Hawaii, *18 June 2010.*

Cambridge Encyclopedia Vol. 7 (2010), Standard atmospheric pressure, Mean sea level pressure (MSLP or QFF), Altitude Atmospheric Pressure Variation, State University, http://encyclopedia.stateuniversity.com/pages/2061/atmospheric-pressure.html, *accessed 16 August 2010*.

Carter, W. E., Aubrey, D. G., Baker, T. F., Boucher, C., Le Provost, C., Pugh, D. T., Peltier, W R., Zumberge, M., Rapp, R. H., Shutz, R. E., Emery, K. O., and D. B. Enfield (1989), Geodetic fixing of tide gauge benchmarks. *Woods Hole Oceanographic Institution Technical Report*. WHOI-89-31, p. 44. *Cited in Wöppelmann et al. (2007).*

Carter, W. E. (Ed.) (1994), Report of the Surrey Workshop of the IAPSO Tide Gauge Bench Mark Fixing Committee. Report of a meeting held 13-15 December 1993 at the Institute of Oceanographic Sciences Deacon Laboratory. NOAA Technical Report NOSOES0006. p. 81. *Cited in Wöppelmann et al. (2007).*

Carton, J. A., and B. S. Giese (2008), A reanalysis of ocean climate using Simple Ocean Data Assimilation (SODA). *Month. Weather Rev.,* 136, pp. 2999-3017.

Cazenave, A., and R. Nerem (2004), Present-day sea-level change: observations and causes, *Rev. Geophys.,* 42, RG3001, doi:10.1029/2003RG000139.

Cazenave, A., Dominh, K., Guinehut, S., Berthier, E., Llovel, W., Ramillien, G., Ablain, M., and G. Larnicol (2009), Sea level budget over 2003-2008: A reevaluation from GRACE space gravimetry, satellite altimetry and Argo, *Global and Planetary Change*, 65, 1-2, doi:10.1016/j.gloplacha.2008.10.004.

Cazenave, A., and W. Llovel (2010), Contemporary Sea Level Rise, *Annual Rev. of Marine Science*, Vol 2, pp. 145-173.

Chao, B. F., Wu, Y. H., and Y. S. Li (2008), Impact of artificial reservoir water impoundment on global sea level, *Science*, 320, doi:10.1126/science.1154580, pp. 212-214.

Church, J. A., Gregory, J. M., Huybrechts, P., Kuhn, M., Lambeck, C., Nhuan, M. T., Qin, D., and P.L. Woodworth (2001). Changes in sea level, in: J.T Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. Van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.) (2001), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press (Cambridge, New York), pp. 639-694.

Church, J. A., White, N. J., Coleman, R., Lambeck, K., and J. Mitrovica (2004), Estimates of the regional distribution of sea level rise over the 1950-2000 period, *J. clim.,* 17, pp. 2609-2625, doi:10.1175/1520-0442(2004)017<2609:EOTRDO>2.0.CO;2.

Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea level rise, *Geophys. Res. Lett.*, 33, L01602, doi:10.1029/2005GL024826.

Clague, J. J., and T. S. James (2002), History and isostatic effects of the last ice sheet in southern British Columbia, *Quat. Sci. Rev.*, 21, pp. 71-87, doi:10.1016/S0277-3781(01)00070-1.

Conrad, C. J., and B. H. Hager (1997), Spatial variation in the rate of sea level rise caused by the present-day melting of glaciers and ice sheets, *Geophys. Res. Lett.,* 24, pp. 1503-1506.

Cooley, J. W., and J. W. Tukey (1965), An algorithm for the machine calculation of complex Fourier series, *Math. Comput.*, 19, pp. 297-301.

Davis, R. E., and S. Foote (1956), Surveying: Theory and Practice, *International Student Edition*, Fourth Edition, McGraw-Hill Book Company, Inc., London

Denys, P. (2009), Pers. Con., Department of Land Surveying. University of Otago, New Zealand, *23 July 2009*.

Denys, P., Hannah, J., and J. Beavan (2010), Tide gauge-cGPS Measurements in New Zealand, GNSS Vertical Rates Symposium, Newcastle.

Deser, C., and M. L. Blackmon (1993), Surface climate variations over the North Atlantic Ocean during winter: 1900-1989, *J. Clim., 6*, pp. 1743-1753.

Dewar, P. (2003), The Accuracy of Tidal Datum Transfer Procedures Using the Dunedin Wharf and Port Chalmers as a Case Study, *A dissertation submitted for the Bachelor of Surveying (Honours) degree*, School of Surveying, University of Otago, New Zealand.

Dickman, S. R. (1988), Theoretical Incestigation of the Oceanic Inverted Barometer Response, *J. Geophys. Res.,* 93(B12), pp. 14,941-14,946.

Doodson, A. T. and H. D. Warburg, (1941),Admiralty Manual of Tides*,* H. M Stationary Office, London.

Douglas, B. C. (1991), Global sea level rise, J. Geophy. Res., 96, pp. 6981-6992, doi:10.1029/91JC00064.

Douglas, B. C. (1992), Global Sea Level Acceleration, *J. Geophys. Res.*, 97(C8), pp. 12,699–12,706.

Douglas, B. C. (1997), Global sea level rise: a redetermination. *Surv. Geophys. Res*. 18, pp. 279-292.

Douglas, B. C. (2001), Sea level change in the era of the recording tide gauge. In: Douglas, B., Kearney, M., Leatherman, S. (Eds.), Sea Level Rise: History and Consequences. Int. Geophys. Ser. vol. 75. Academic, San Diego, pp. 37-64. chap. 3.

Douglas, B.C. (2008), Concerning evidence for fingerprints of glacial melting, *Journal of Coastal Research*, 24(2B), West Palm Beach (Florida), ISSN 0749-0208, pp. 218-227.

Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck K., and J. Chappell (1998), Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth and Planetary Science Letters* **163** (1-4): 327-342. doi:10.1016/S0012-821X(98)00198-8

Folland, C. K., and M. J. Salinger (1995), Surface temperature trends and variations in New Zealand and the surrounding ocean, 1871-1993, *Int. J. of Clim.,* Vol 15 (11), pp. 1195-1218, doi: 10.1002/job.3370151103.

Folland, C. K., Renwick, J. A., Salinger, M. J., and A. B. Mullan (2002), Relative influences of the Interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone, *Geophys. Res. Lett., 29(13)*, p. 1643, doi:10.1029/2001GL014201.

Folland, C. (2008), Interdecadal Pacific Oscillation Time Series, Met Office Hadley Centre for Climate Change, Exeter, United Kingdom.

Foreman, M. G. G. (1977),*Manual for Tidal Heights Analysis and Prediction*. Pacific Marine Science Report 77-10, Institute of Ocean Sciences, Patricia Bay, Sidney, B.C. Canada, (2004 Revision).

Foreman, M. G. G. (2009-a), Fisheries and Oceans Canada. IOS Tidal Package, http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/tidpack/tidpack_e.htm, *accessed 20 May 2010*.

Foreman, M. G. G. (2009-b), Pers. Email, Institute of Ocean Sciences, *9 October 2009*.

Forrester, W. D. (1983), Canadian Tidal Manual, Department of Fisheries and Oceans, Canadian Hydrographic Service, Ottawa, Ont.

Gehrels, W. R., Hayward, B. W., Newnham, R. M., and K. E. Southall (2008), A 20th century acceleration in sea-level rise in New Zealand, *Geophys. Res. Lett.,* 35, L02717, doi:10.1029/2007GL032632.

GeoNet (2010), Historic Earthquakes: New Zealand's Top Earthquakes, *Earthquake Commission and GNS Science,* http://www.geonet.org.nz/earthquake/historic-earthquakes/, *accessed 6 April 2010.*

Gibb, J. G. (1986), A New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movement, *R. Soc. N. Z. Bull.*, 24, pp. 377-395. *Cited in Gehrels et al. (2008).*

Gordon, D. L. (1960), The accuracy of automatic tide gauges, *Bull. Geod.,* 55, pp. 59-63. *Cited in Hannah (1990).*

Goring, D., and R. Bell (2001), The Modern Ocean: Sea level on the move? *National Institute of Water and Atmospheric Research: Water & Atmosphere*, 9(4).

Gornitz, V., Lebedeff, S., and J. Hansen (1982), Global sea level trend in the past century. Science 215, pp. 1611-1614. *Cited in Barnett (1984).*

Gregory, J. M., Church, J. A., Boer, G. J., Dixon, K. W., Flato, G. M., Jackett D. R., Lowe, J. A., O'Farrell, S. P., Roeckner, E., Russell, G. L., Stouffer, R. J., and M. Winton (2001), Comparison of results from several AOGCMs for global and regional sea-level change 1900-2100. *Climate Dyn.,* 18, pp. 225-240.

Grinsted, A., Moore, J.C., and S. Jevrejeva (2007), Observational evidence for volcanic impact on sea level and the global water cycle, *Proceedings of the Nat. Acad. of Sciences of the U.S. of A.*, Vol, 104, 50, doi:10.1073/pnas.0705825104, pp. 19730-19734.

Hamilton, W. C. (1964), Statistics in Physical Science: estimation, hypothesis testing, and Least Squares, Brookhaven National Laboratory, The Ronald Press Company, New York, p. 93.

Hannah, J. (1990), Analysis of Mean Sea Level Data From New Zealand for the Period 1899-1988, *J. Geophys. Res.,* 95, B8, pp. 12,399-12,405.

Hannah, J. (2004), An updated analysis of long-term sea level change in New Zealand, *Geophys. Res. Lett.*, 31, L03307, doi:10.1029/2003GL019166.

Hannah, J. (2010-a), A New Updated Sea Level Trend Analysis for New Zealand, School of Surveying, University of Otago, Dunedin, New Zealand.

Hannah, J. (2010-b), The Difficulties in Using Tide Gauges to Monitor Long-Term Sea Level Change, TS 101 – Vertical Reference Frame, *FIG Conference 2010: Facing the Challenges – Building the Capacity*, Sydney, Australia, 11-16 April 2010.

Hannah, J., and R. Bell (2010), Sea Level Change in the Auckland Region, *Report prepared for the Auckland Regional Council*, University of Otago, National Institute of Water and Atmospheric Pressure, Auckland Regional Council, New Zealand, pp. 26.

Hansen, J., Sato, M., Ruedy, R., Kharecha, P., Lacis, A., Miller, R., Nazarenko, L., Lo, K., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, S., Baum, E., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Cohen, A., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Jonas, J., Kelley, M., Kiang, N. Y., Koch, D., Labow, G., Lerner, J., Menon, S., Novakov, T., Oinas, V., Perlwitz, Ja., Perlwitz, Ju., Rind, D., Romanou, A., Schmunk, R., Shindell, D., Stone, P., Sun, S., Streets, D., Tausnev, N., Thresher, D., Unger, N., Yao, M., and S. Zhang (2002), Climate forcings in Goddard Institute for Space Studies SI2000 simulations, *J. Geophys. Res., 107*(D18), 4347, doi:10.1029/2001JD001143.

Heidtke, E. (2003), Geothermal Energy, University of Wisconsin-Eau Claire, United States of America, http://academic.evergreen.edu/g/grossmaz/heidtken.html, *accessed 23 April 2010.*

Holgate, S. J., and P. L. Woodworth (2004), Evidence for enhanced coastal sea level rise during the 1990s, *Geophys. Res. Lett.,* 31, L07305, doi:10.1029/2004GL019626.

Holgate, S. J. (2007), On the decadal rates of sea level change during the twentieth century, *Geophys. Res. Lett.,* 34, L01602, doi:10.1029/2006GL028492.

Hydrographer of the Navy (1970), *Admiralty Manual of Hydrographic Surveying,* vol. II, Tanton, Somerset. *Cited in Hannah (1990).*

Intergovernmental Panel on Climate Change (1990), Scientific assessment of climate change. Cambridge University Press.

Intergovernmental Panel on Climate Change (1995), Climate Change 1995: the science of climate change. Cambridge University Press.

Intergovernmental Panel on Climate Change (2001), Climate Change 2001: the scientific basis. Cambridge University Press.

Intergovernmental Panel on Climate Change (2007), Climate Change 2007: the physical science basis. Cambridge University Press.

Jevrejeva, S., Moore, J. C., Woodworth, P. L., and A. Grinsted (2005), Influence of large scale atmospheric circulation on the European sea level: Results based on the wavelet transform method, *Tellus, Ser. A, 57,* pp. 129-149.

Jevrejeva, S., Grinsted, A., Moore, J. C., and S. Holgate (2006), Nonlinear trends and multiyear cycles in sea level records, *J. Geophys. Res.,* 111, C09012, doi:10.1029/2005JC0032290.

Johansson, J. M. Davis, J. L.. Scherneck, H. -G., Milne, G. A., Vermeer, M. J., Mitrovica, X., Bennett, R. A., Jonsson, B., Elgered, G., Elósegui, P., Koivula, H., Poutanen, M., Rönnäng, B. O., and I. I. Shapiro (2002), Continuous GPS measurements of postglacial adjustment in Fennoscandia: 1. Geodetic results, *J. Geophys. Res*., 107(B8), p. 2157, doi:10.1029/2001JB000400.

Jones, P. D., Osborn, T. J., Briffa, K. R., Folland, C. K., Horton, E. B., Alexander, L. V., Parder, D. E., and N. A. Rayner (2001), Adjusting for sampling density in grid box land and ocean surface temperature time series, *J. Geophys. Res.* 106: 3371-3380.

Kennedy, D. M. (2008), Recent and future higher sea levels in New Zealand: A review, *New Zealand Geographer*, 64, doi:10.1111/j.1745-7939.2008.00132.x, pp. 105-116.

Knutti, R., and T. F. Stocker (2000), Influence of the thermohaline circulation on projected sea level rise, *J. Clim. 13,* pp. 1997-2001.

Kuo, C., Shum, C., Braun, A., and J. X. Mitrovica (2004), Vertical crustal motion determined by satellite altimetry and tide gauges data in Fennoscandia, *Geophys. Res. Lett.,* 31, L01608, doi:10.1029/2003GL019106.

Lambeck, K. (2002), Sea-level change from mid-Holocene to recent time: An Australian example with global implications. *Ice Sheets, Sea Level and the Dynamic Earth,* J. X. Mitrovica and B. L. A. Vermeersen, Eds., Geodynamics Series, Vol. 29, pp. 33-50. *Cited in Church et al. (2004).*

Larsen, C. F., Echelmeyer, K. A., Freymueller, J. T., and R. J. Motyka (2003), Tide gauge records of uplift along the northern Pacific-North America plate boundary, 1937 to 2001, *J. Geophys. Res*., 108(B4), p. 2216, doi:10.1029/2001JB001685.

Leuliette, E. W., Nerem, R. S., and G. T. Mitchum (2004), Calibration of TOPEX/Poseidon and Jason Altimeter Data to Construct a Continuous Record of Mean Sea Level Change, Marine Geodesy, 27:1, pp. 79-94.

Levitus, S., Antonov, J. I., and T. P. Boyer (2005), Warming of the world ocean, 1955-2003, *Geophys. Res. Lett., 32,* L02604, doi:10.1029/2004GL021592.

Lighthill, M. J. (1964), Introduction to Fourier Analysis and Generalised Functions, *Students' Edition,* Cambridge University Press.

Mantua, N. J., and S. R. Hare (2002), The Pacific Decadal Oscillation, *J. Oceanographer, 58*, pp. 35-44.

Marshall, A. (2007), Water Level Measurement and Tidal Datum Transfer using High Rate GPS Buoys, *A dissertation submitted for the Bachelor of Surveying (Honours) degree*, School of Surveying, University of Otago, New Zealand.

Maul, G. A. (1993), Sea level rise at Key West, Florida, 1846-1992: America's longest instrumental record? *Geophys. Res. Lett.,* Vol. 20, No. 18, pp. 1955-1958.

Mazzotti, S., Jones, C., and R. E. Thomson (2008), Relative and absolute sea level rise in western Canada and northwestern United States from a combined tide gauge-GPS analysis. Journal of Geophysical Research, Vol. 113, C11019, doi:10.1029/2008JC004835.

McLintock, A. H. (1951), The Port of Otago, Whitcombe & Tombs Ltd., Dunedin, New Zealand.

Meinen, C. S., and M. J. McPhaden (2000), Observations of warm water volume changes in the equatorial Pacific and their relationship to El Nińo and La Nińa, *J. Clim.,* 13, pp. 3551-3559.

Met Office Hadley Centre for Climate Change, Allan, R. [maintenance] (2007), Hadley Centre Sea Level Pressure dataset (HadSLP2)*,* http://hadobs.metoffice.com/hadslp2/, *accessed 15 June 2010.*

Miller, L., and B. C. Douglas (2007), Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise, *Geophys. Res. Lett.,* 34, L16602, doi:10.1029/2007GL030862.

Milne, G. A., Davis, J. L., Mitrovica, J. X., Scherneck, H. –G., Johansson, J. M., Vermeer, M., and H. Koivula (2001), Space-geodetic constrains on glacial isostatic adjustment in Fennoscandia. *Science,* 291, pp. 2381-2385.

Milne, G. A., Long, A. J., and S. E. Bassett (2005). Modelling Holocene relative sea-level observations from the Caribbean and South America. *Quaternary Science Reviews* **24** (10-11): 1183-1202. doi:10.1016/j.quascirev.2004.10.005.

Mitrovica, J. X., Tamisiea, M., Davis, J. L., and G. A. Milne (2001), Recent mass balance of polar ice sheets inferred from patterns of global sea-level change, *Nature*, 409, pp. 1026-1029.

Munk, W. H., and G. J. F. MacDonald (1960), The Rotation of the Earth, Cambridge University Press, New York.

National Aeronautics and Space Administration (1992), Topex/Poseidon, NSSDC ID: 1992-052A, http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1992-052A, *accessed 17 May 2010*.

National Institute of Water and Atmospheric Research (2010-a), The National Climate Database, http://cliflo.niwa.co.nz/, *accessed 31 May 2010.*

National Institute of Water and Atmospheric Research (2010-b), NIWA, Taihoro Nukurangi, National Institute of Water and Atmospheric Research, http://www.niwa.co.nz/.

National Oceanic and Atmospheric Administration (2002), Sea Level Pressure (SLP) Datasets: *Extended Reconstructed SLP data provided by the NOAA/OAR/ESRL PSD, National Climatic Data Center, Asheville, North Carolina,* http://www.esrl.noaa.gov/psd/, *accessed 4 June 2010.*

National Oceanic and Atmospheric Administration (2007), Sea Level Pressure (SLP) Datasets: *HadSLP2 data provided by the NOAA/OAR/ESRL PSD,* Boulder, Colorado, United States of America, http://www.esrl.noaa.gov/psd/, *accessed 16 June 2010.*

Neilan, R., Van Scoy, R. A., and P. L. Woodworth (Eds.) (1998), Proceedings of the Workshop on Methods for Monitoring Sea Level : GPS and Tide Gauge Benchmark Monitoring, GPS Altimeter Calibration. Workshop Organised By the IGS and PSMSL, Jet Propulsion Laboratory, 17-18 March 1997. p. 202. *Cited in Wöppelmann et al. (2007).*

Nerem, R., and G. Mitchum (2002), Estimates of vertical crustal motion derived from difference of TOPEX/Poseidon and tide gauge sea level measurements, *Geophys. Res. Lett.* 29(19), p. 1934, doi:10.1029/2002GL015037.

Nocquet, J. -M., Calais, E., and B. Parsons, (2005), Geodetic constraints on glacial isostatic adjustment in Europe. *Geophys. Res. Lett.,* 32, L06308, doi:10.1029/2004GL022174.

Parker, D., Folland, C., Scaife, A., Knight, J., Colman, A., Baines, P., and B. Dong (2007), Decadal to multidecadal variability and the climate change background, *J. Geophys. Res., 112*, D18115, doi:10.1029/2007JD008411.

Paulik, R. (2010), A Geological Perspective on Millennial Scale Sea Level Changes in the Auckland Region, in Hannah, J., Bell, R., and R. Paulik (2010), Sea Level Change in the Auckland Region, *Report prepared for the Auckland Regional Council*, University of Otago, National Institute of Water and Atmospheric Pressure, Auckland Regional Council, New Zealand, pp. 10-15.

Peel, C. (2009), Facing Up to Rising Sea Level, Institution of Civil Engineers, www.buildingfutures.org.uk/projects/building-futures/facing-up.

Peltier, W. R., and Tushingham, A. M. (1989), Global sea level rise and the greenhouse effect: might they be connected? Science 244, pp. 806-810. *Cited in Douglas (1992).*

Peltier, W. R. (1995), VLBI baseline variations from the ICE-4G model of postglacial rebound, *Geophys. Res. Lett.,* 22, 4, pp. 465-468.

Peltier, W. R., and X. Jiang (1997), Mantle viscosity, glacial isostatic adjustment and the eustatic level of the sea, *Surveys in Geophys.*, *Kluwer Acad. Publishers*. 18, pp. 239-277.

Peltier, W. R. (2001), Global glacial isostatic adjustment and the modern instrumental records of relative sea level history, in *Sea Level Rise, History and Consequences*, edited by B. C. Douglas, M. S. Kearney, and S. P. Leatherman, pp. 65-95, Academic, San Diego, Calif.

Peltier, W. R. (2004), Global glacial isostasy and the surface of the Ice Age Earth: The ICE-5G (VM2) model and GRACE, *Annu. Rev. Earth Planet Sci.*, 32, pp. 111-149, doi:10.1146/annurev.earth.32.082503.144359.

Power, S., T. Casey, C. Folland, A. Colman, and V. Mehta (1999), Interdecadal modulation of the impact of ENSO on Australia, *Clim. Dyn., 15*, pp. 319-324.

Pugh, D. T. (1987), Tides, Surges, and Mean Sea Level: A Handbook for Engineers and Scientists. John Wiley & Sons, Chichester, p. 047191505X.

Rahmstorf, S. (2007), A semi-empirical approach to projecting future sea-level rise. *Science*, 315, doi:10.1126/science.1135456, pp. 368-370.

Rajagopalan, B., Y. Kushnir, and Y. M. Tourre (1998), Observed decadal midlatitude and tropical Atlantic climate variability, *Geophys. Res. Lett., 25, pp.* 3967-3970.

Rapp, R. H. (1982), A global atlas of sea surface heights based on the adjusted SEASAT altimeter data, *Rep. 333,* 65 pp., Dep. of Geod. Sci. and Surv., Ohio State Univ., Columbus. *Cited in Hannah (1990).*

Rodwell, M. J., Rowell, D. P., and C. K. Folland (1999), Oceanic forcing of the wintertime North Atlantic Oscillation and European climate, *Nature, 398,* pp. 320-323.

Ropelewski, C. F., and P. D. Jones (1987), An extension of the Tahiti-Darwin Southern Oscillation Index, *Mon. Weather Rev.,* 115, pp. 2161-2165.

Rossiter, J. R. (1972), Sea-level observations and their secular variation, *Philos. Trans. F. Soc. London, Ser. A*, 272, pp. 131-139.

Rowe, G. (2010), Pers. Email, Senior Tidal Officer, Land Information New Zealand, *21 June 2010.*

Rülke, A., Dietrich, R., Fritsche, M., Rothacher, M., and P. Steigenberger (2008), Realization of the terrestrial reference system by a reprocessed global GPS network, *J. Geophys. Res*., 113, B08403, doi:10.1029/2007JB005231.

Salinger, M. J. (1979), New Zealand Climate: The Temperature Record, historical data and some agricultural implications, *Climate Change*, 2, Dept. of Geography, Victoria University of Wellington, New Zealand. D. Reidel Publishing Company.

Silverstein, A., Silverstein, V., and L. Silverstein Nunn (2009), Plate Tectonics: *Revised Edition,* Science Concepts: Second Series, Twenty-First Century Books, Lerner Publishing Group, Inc., Minneapolis, United States of America, p. 12.

Smith, T. M., Reynolds, R. W., Livezey, R. E., and D. C. Stokes (1996), Reconstruction of historical sea surface temperatures using empirical orthogonal functions, *J. Clim*., 9, pp. 1403-1420.

Smith, T. M., and R. W. Reynolds (2003), Reconstruction of Monthly Mean Oceanic Sea Level Pressure Based on COADS and Station Data (1854–1997), National Climatic Data Center, Asheville, North Carolina, *J. of Atmos. and Oceanic Tech.,* 21, pp. 1272-1282.

Stevenson, M. (2009), The compilation of a preliminary vertical deformation map of New Zealand from GPS time series, *A dissertation submitted for the Bachelor of Surveying (Honours) degree*, School of Surveying, University of Otago, New Zealand.

Sturges, W. (1987), Large-scale coherence of sea level at very low frequencies, *J. Phys. Oceanogr.*, 17, pp. 2084-2094.

Tamisiea, M. E., Mitrovica, J. X., Milne, G. A., and J. L. Davis (2001), Global geoid and sea level changes due to present-day ice mass fluctuations, *J. Geophys. Res.,* 109, pp. 30,849-30,863.

Teferle, F. N., Bingley, R. M., Williams, S. D. P., Baker, T. F., and A. H. Dodson (2006), Using continuous GPS and absolute gravity to separate vertical land movements and changes in sea level at tide gauges in the UK, *Philosophical Transactions of the Royal Society,* 364: pp. 917-930, doi:10.1098/rsta.2006.1746.

Thomson, R. E., and S. Tabata (1982), Baroclinic oscillations of tidal frequency at Ocean Weather Station P, *Atmos. Ocean*, 20, pp. 242-257.

Tomlinson, A. I. (1975), Section on climatic change, In *New Zealand Atlas*, Ward, I. (Ed.), Government Printer, Wellington, pp. 82-89. *Cited in Salinger (1979).*

Trenberth, K. E. (1973), Possible sea surface temperature influences on short term climate in New Zealand, N.Z. Met. Service Tech. Note 218. *Cited in Salinger (1979).*

Trenberth, K. E., Caron, J. M., Stepaniak, D. P., and S. Worley (2002), Evolution of El Niño-Southern Oscillation and global atmospheric surface temperatures, *J. Geophys. Res.,* 107, D8, 4065, doi:10.1029/2000JD000298.

Trupin, A., and J. Wahr (1990), Spectroscopic analysis of global tide gauge sea level data. Geophys. J. Int. 100, pp. 441-453.

Unal, Y. S., and M. Ghil (1995), Interannual and interdecadal oscillation patterns in sea level, *Clim. Dyn., 11*, pp. 255-278.

Uotila, U. A. (1973), Sequential Solutions with Observation Equations, Department of Geodetic Science, The Ohio State University, Columbus, Ohio, United States of America.

Uotila, U. A. (1975), Statistical Tests as Guidelines in Analyses of Adjustment of Control Nets, Department of Geodetic Science, The Ohio State University, Columbus, Ohio, United States of America.

Vennell, R. (2010), Pers. Con., Department of Marine Science. University of Otago. New Zealand, *April 6 2010*.

Wanless, H. R., Tedesco, L. P., Rossinsky, V. Jr., and J. J. Dravis (1988), Carbonate environments and sequences of Caicos platform with an introductory evaluation of south Florida, AGU. *28th Int. Geol. Congr. Trip Guidebook*, T374. *Cited in Maul (1993).*

Warrick, R. A., Le Provost, C., Meier, M. F., Oerlemans, J. and Woodworth, P. L. (1996) 1996: Changes in sea level. In Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K. (eds.) (1995) Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 359-405. (CEARSPub-96-9-IPCC-1)

Watson, P. J. (2011-a), Pers. Email, Principal Coastal Specialist, Coast and Flood Policy Unit, *Waters, Wetlands and Coastal Division*, NSW Government: Environment, Climate Change & Water, *11 March 2011*.

Watson, P.J, (2011-b), Is there evidence yet of acceleration in mean sea level rise around mainland Australia? *Journal of Coastal Research*, 27(2), 368-377, West Palm Beach (Florida), ISSN 0749-0208.

White, N. (2010), Historical Sea Level Changes: Last two decades, Sea Level Rise; Understanding the past – Improving projections for the future, *National Research Flagships, Wealth from Oceans,* http://www.cmar.csiro.au/sealevel/sl_hist_last_15.html, *accessed 18 October 2010.*

Wigley, T. M. L., and S. C. B. Raper (1987), Thermal expansion of sea water associated with global warming, *Nature*, 330, pp. 127-131.

Woodworth, P. L. (1990), A search for accelerations in records of European mean sea level, *Int. J. of Climatology*, 10, pp. 129-143.

Woodworth, P. L., Tsimplis, M. N., Flather, R. A., and I. Shennan (1999), A review of the trends observed in British Isles mean sea level data measured by tide gauges, *Geophys. J. Int.*, 136, pp. 651-670.

Woodworth, P. L. (2003), Some comments on the long sea level records from the Northern Mediterranean. J. Coast. Res. 19 (1), pp. 212-217.

Woodworth, P. L. (2006), Some important issues to do with long-term sea level change, *Phil. Trans. R. Soc. A.,* 364, pp. 787-803.

Woodworth, P. L., White, N. J., Jevrejeva, S., Holgate, S. J., Church, J. A., and W. R. Gehrels (2009), Review: Evidence for the accelerations of sea level on multi-decade and century timescales, *Int. J. of Climatology*, 29, pp. 777-789.

Wöppelmann, G., Martin Miguez, B., Bouin, M. N., and Z. Altamimi (2007), Geocentric sea-level trend estimates from GPS analyses at relevant tide gauges world-wide, *Global Planet. Change*, 57, doi:10.1016/j.gloplacha.2007.02.002, pp. 396-406.

Wunsch, C., Ponte, R. M., and P. Heimbach (2007), Decadal trends in sea level patterns: 1993-2004. *J. Clim. Res.,* doi:10.1175/2007JCLI1840.1, 20, pp. 5889-5911.

Wyrtki, K. (1985), Water displacements in the Pacific and the genesis of El Nińo cycles, *J. Geophys. Res.,* 90, pp. 7129-7132.

Zhang, R. –H., and S. Levitus (1996), Structure and evolution of interannual variability of the tropical Pacific upper ocean temperature, *J. Geophys. Res.,* 101, 20,501-20,524.

Zhang, Y., Wallace, J. M., and D. S. Battisti (1996), ENSO-like Interdecadal Variability: 1900-93, *J. of Climate*, Vol. 10, pp. 1004-1020.

Zhang, R. –H., and S. Levitus (1997), Interannual variability of the coupled tropical Pacific Ocean-atmosphere system associated with the El Nińo Southern Oscillation, *J. Clim.,* 10, pp. 1312-1330.

Zumberge, J. F., Fulton, D. E., and R. E. Neilan (eds) (1997), International GPS Service for Geodynamics 1996 Annual Report. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, JPL-Publication 97-020. *Cited in Teferle (2006).*

9 Appendix

9.1 Sea level residuals versus sea level atmospheric pressure plots

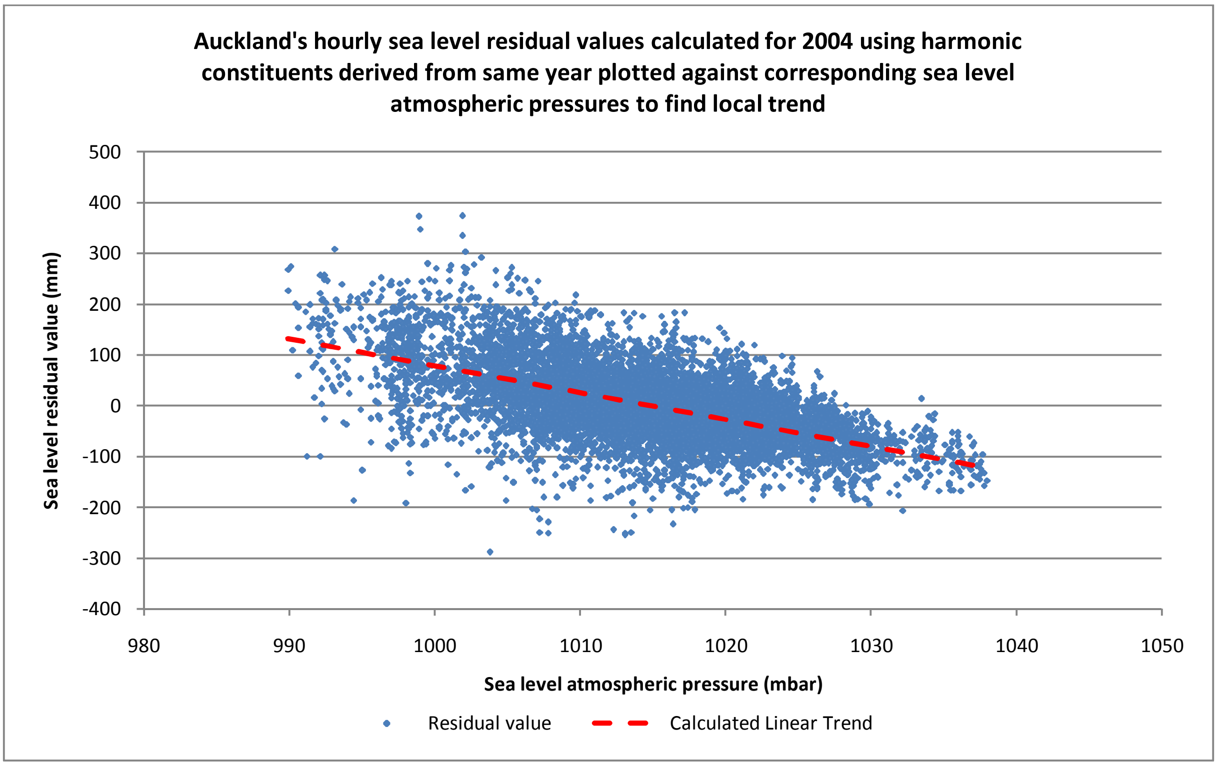

Figure 9.1: Auckland's hourly sea level residual values calculated for 2004 using harmonic constituents derived from same year plotted against corresponding sea level atmospheric pressures to find local trend

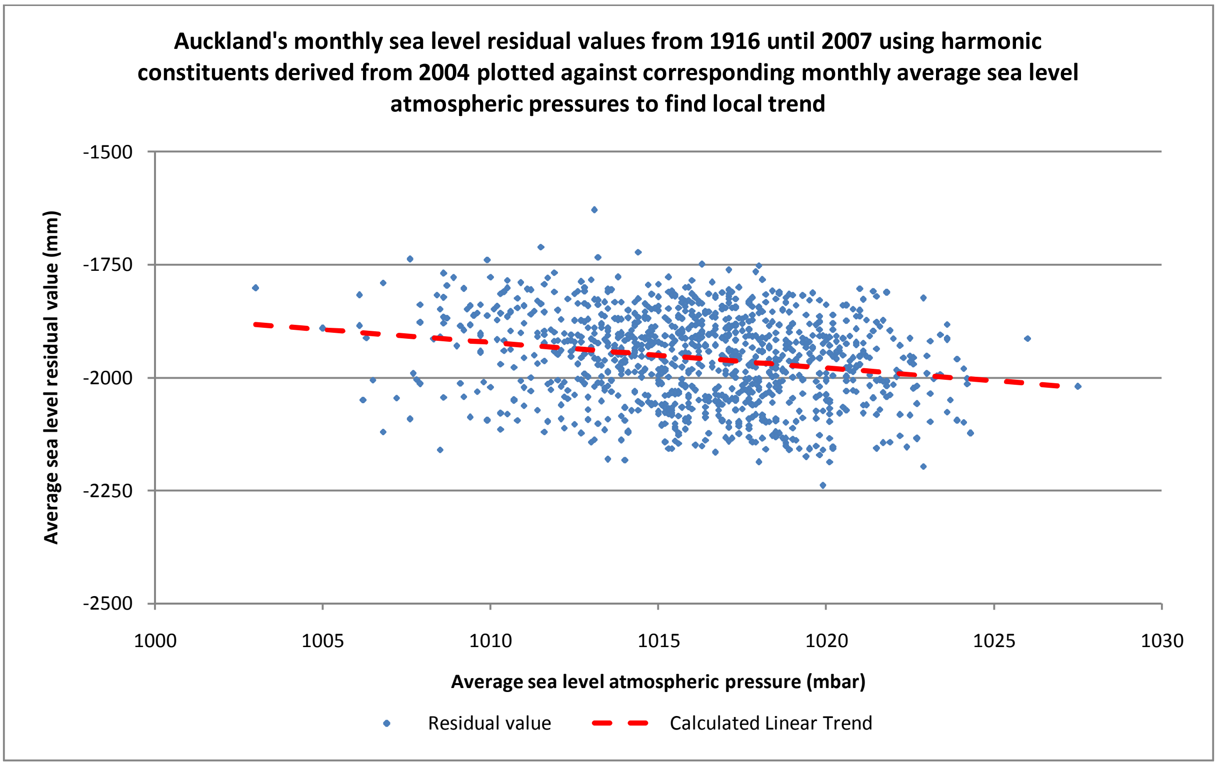

Figure 9.2: Auckland's monthly sea level residual values from 1916 until 2007 using harmonic constituents derived from 2004 plotted against corresponding monthly average sea level atmospheric pressures to find local trend

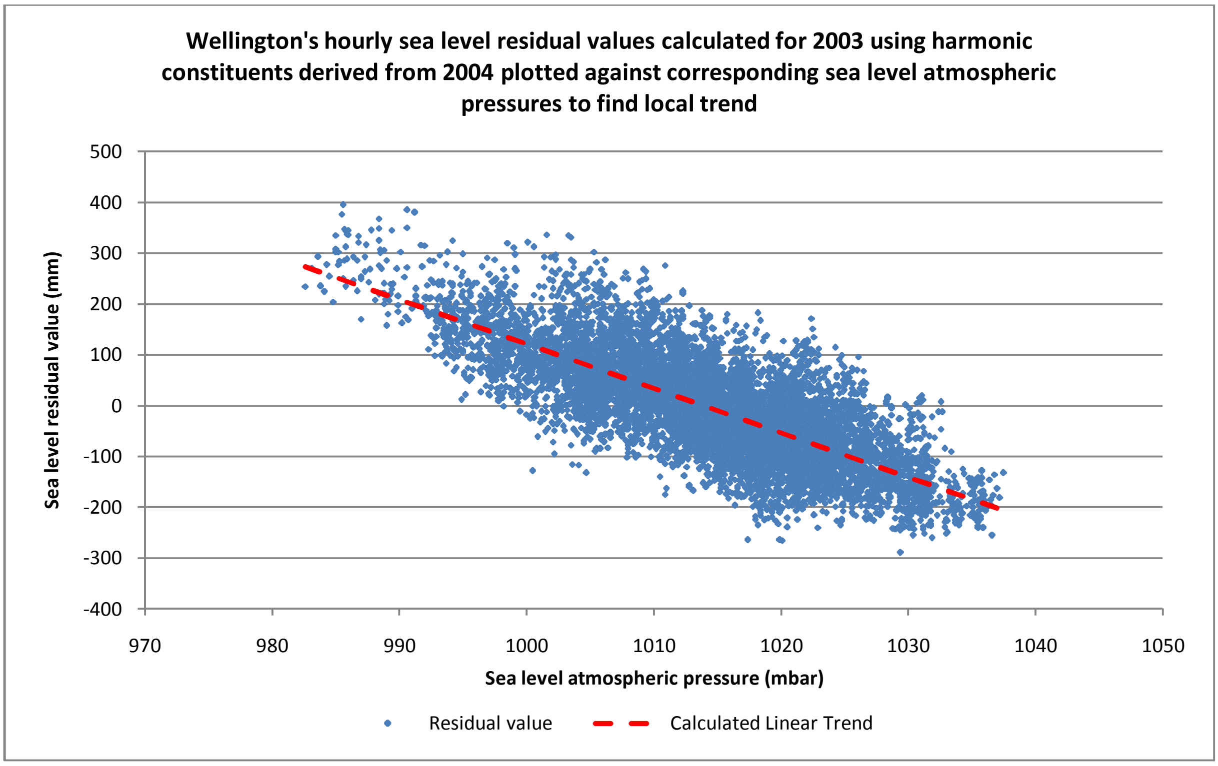

Figure 9.3: Wellington's hourly sea level residual values calculated for 2003 using harmonic constituents derived from 2004 plotted against corresponding sea level atmospheric pressures to find local trend

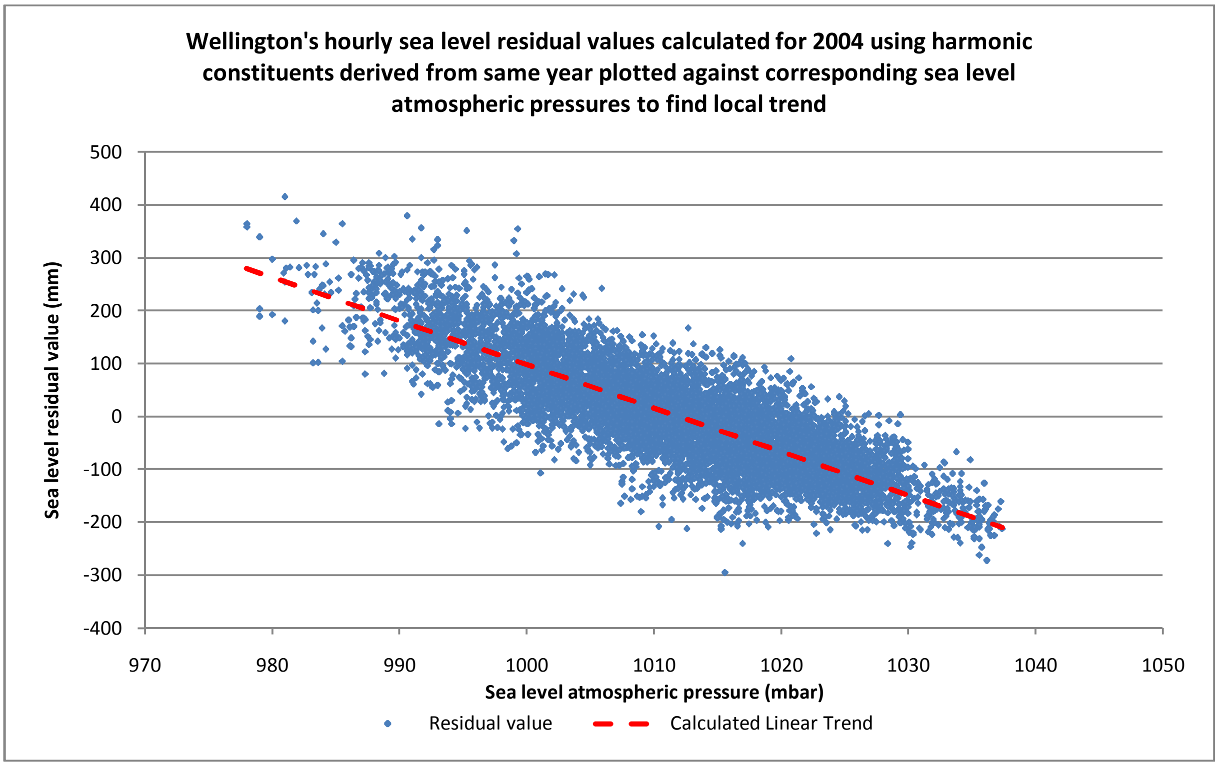

Figure 9.4: Wellington's hourly sea level residual values calculated for 2004 using harmonic constituents derived from same year plotted against corresponding sea level atmospheric pressures to find local trend

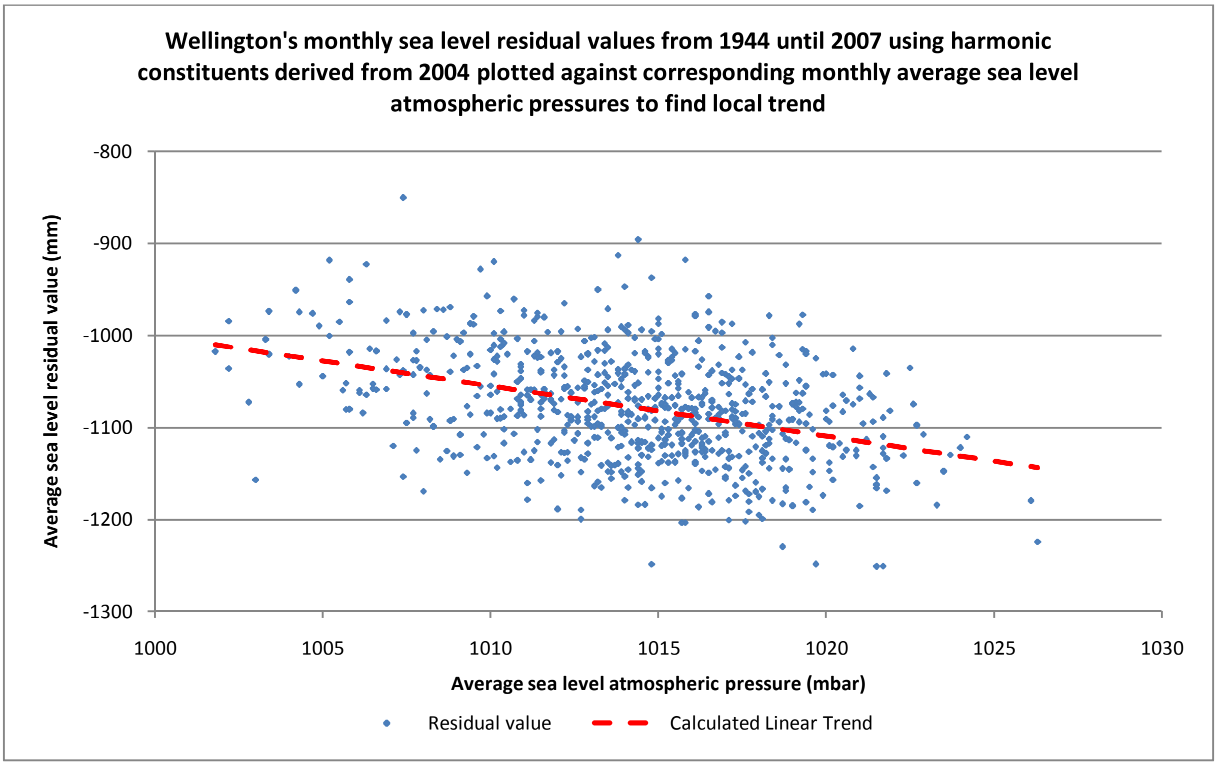

Figure 9.5: Wellington's monthly sea level residual values from 1944 until 2007 using harmonic constituents derived from 2004 plotted against corresponding monthly average sea level atmospheric pressures to find local trend

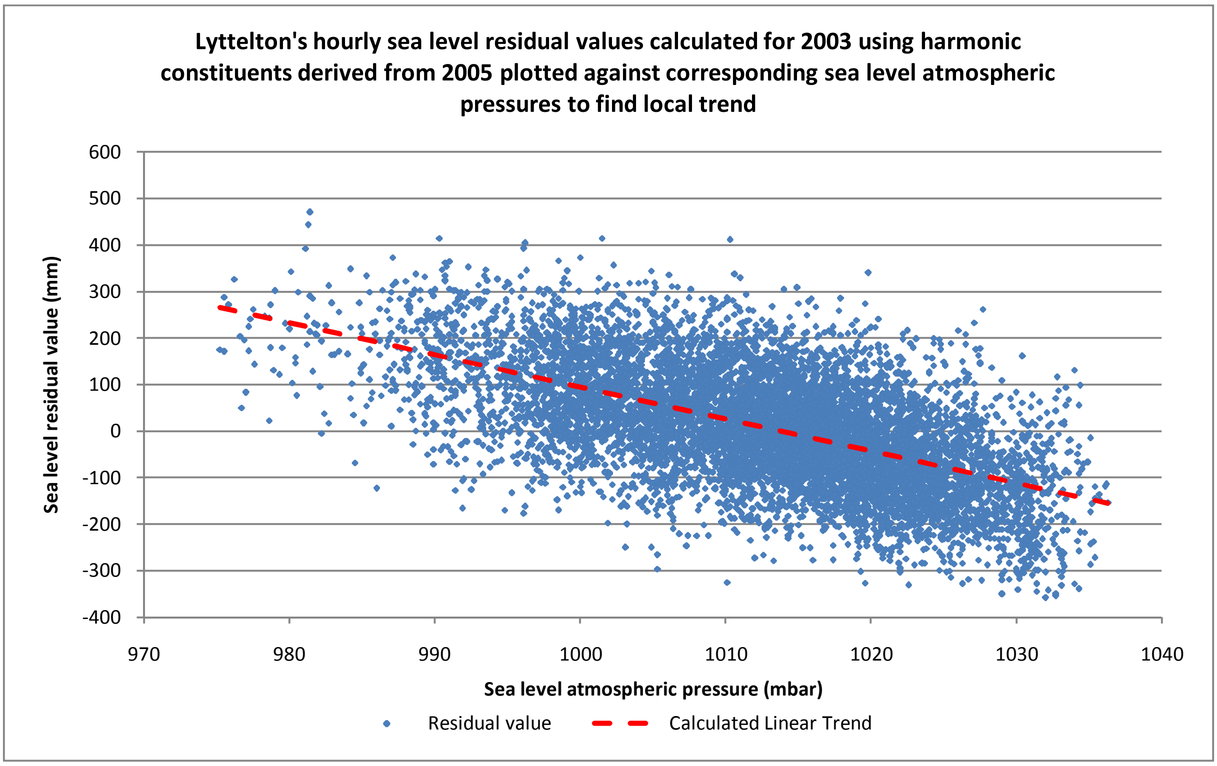

Figure 9.6: Lyttelton's hourly sea level residual values calculated for 2003 using harmonic constituents derived from 2005 plotted against corresponding sea level atmospheric pressures to find local trend

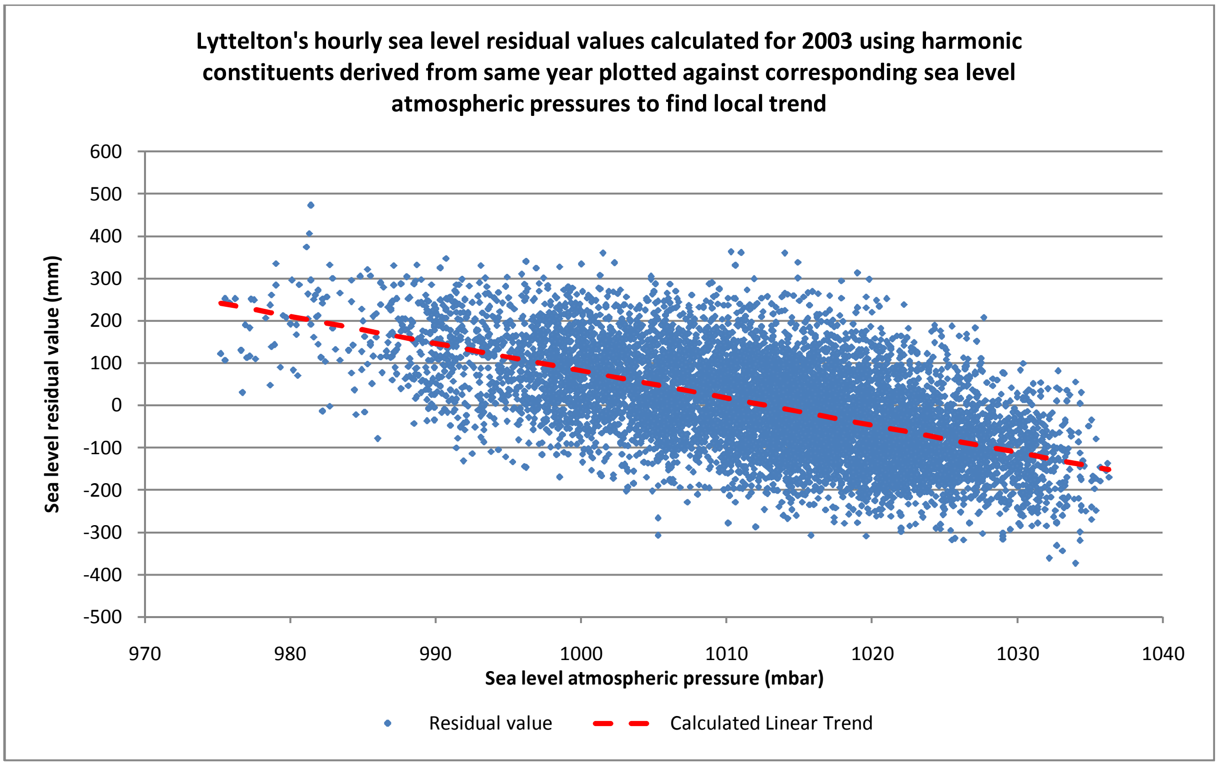

Figure 9.7: Lyttelton's hourly sea level residual values calculated for 2003 using harmonic constituents derived from same year plotted against corresponding sea level atmospheric pressures to find local trend

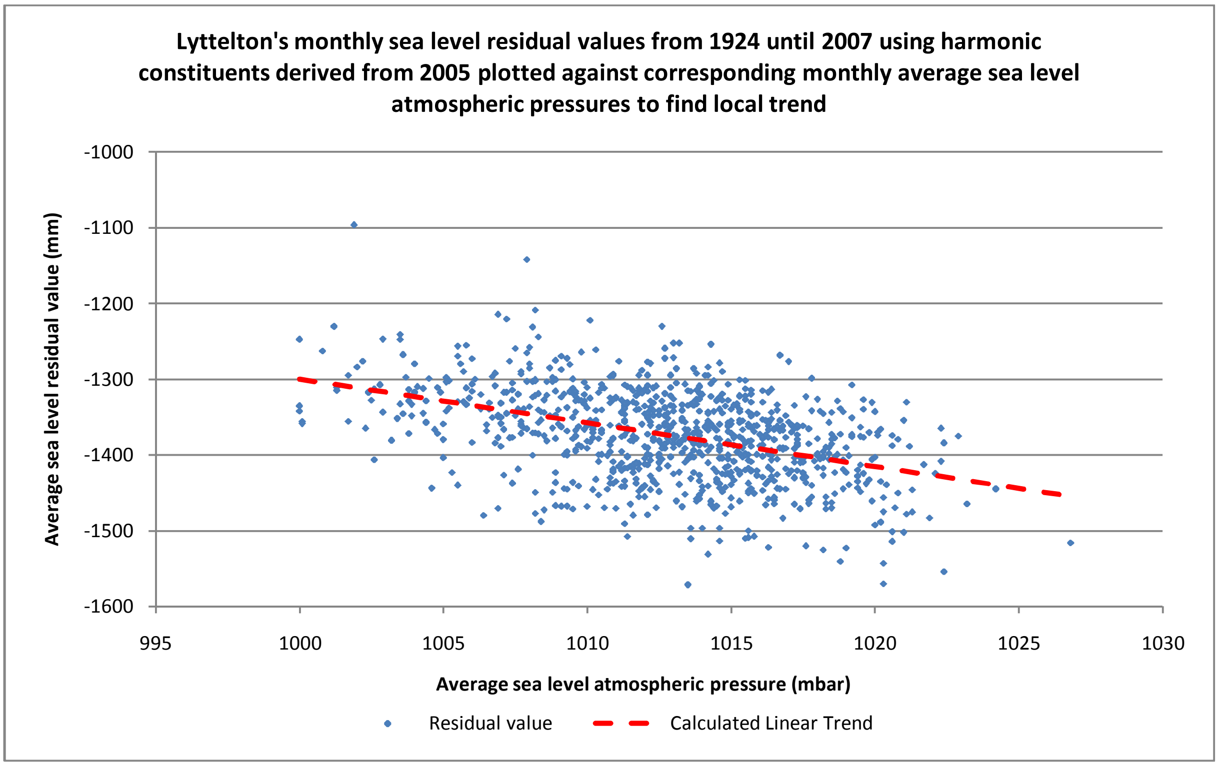

Figure 9.8: Lyttelton's monthly sea level residual values from 1924 until 2007 using harmonic constituents derived from 2005 plotted against corresponding monthly average sea level atmospheric pressures to find local trend

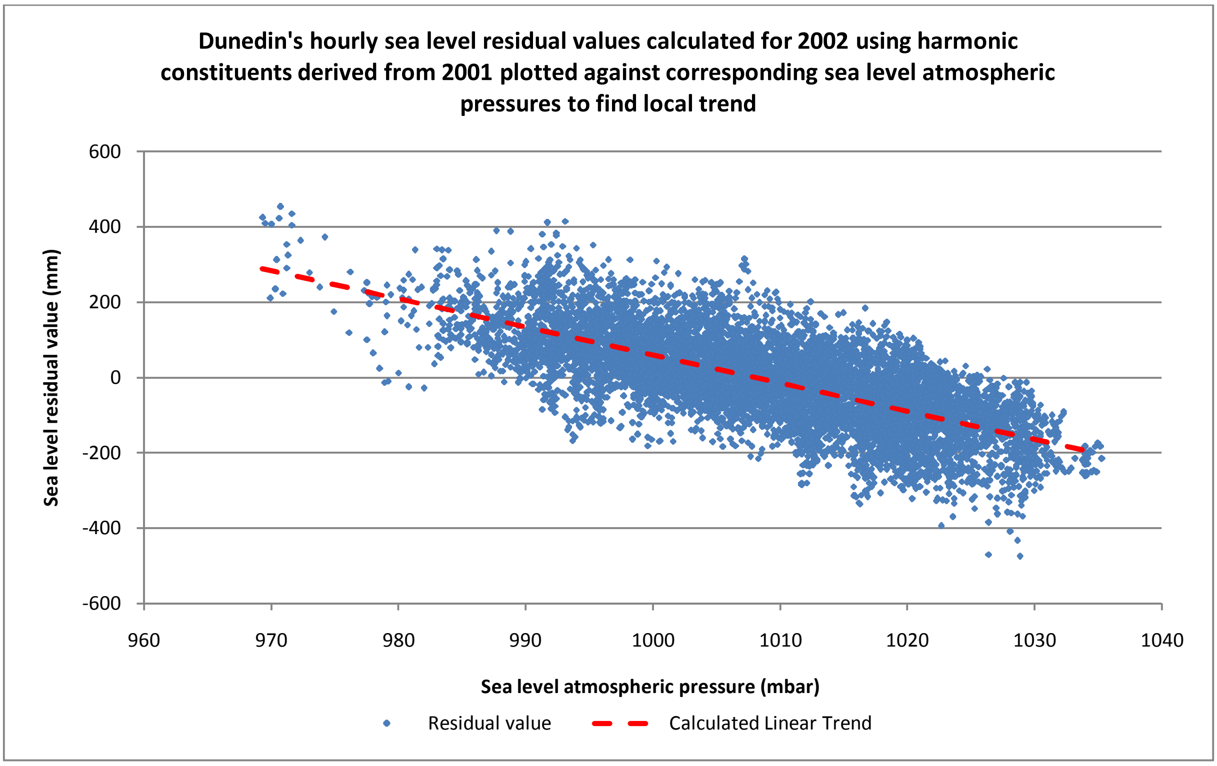

Figure 9.9: Dunedin's hourly sea level residual values calculated for 2002 using harmonic constituents derived from 2001 plotted against corresponding sea level atmospheric pressures to find local trend

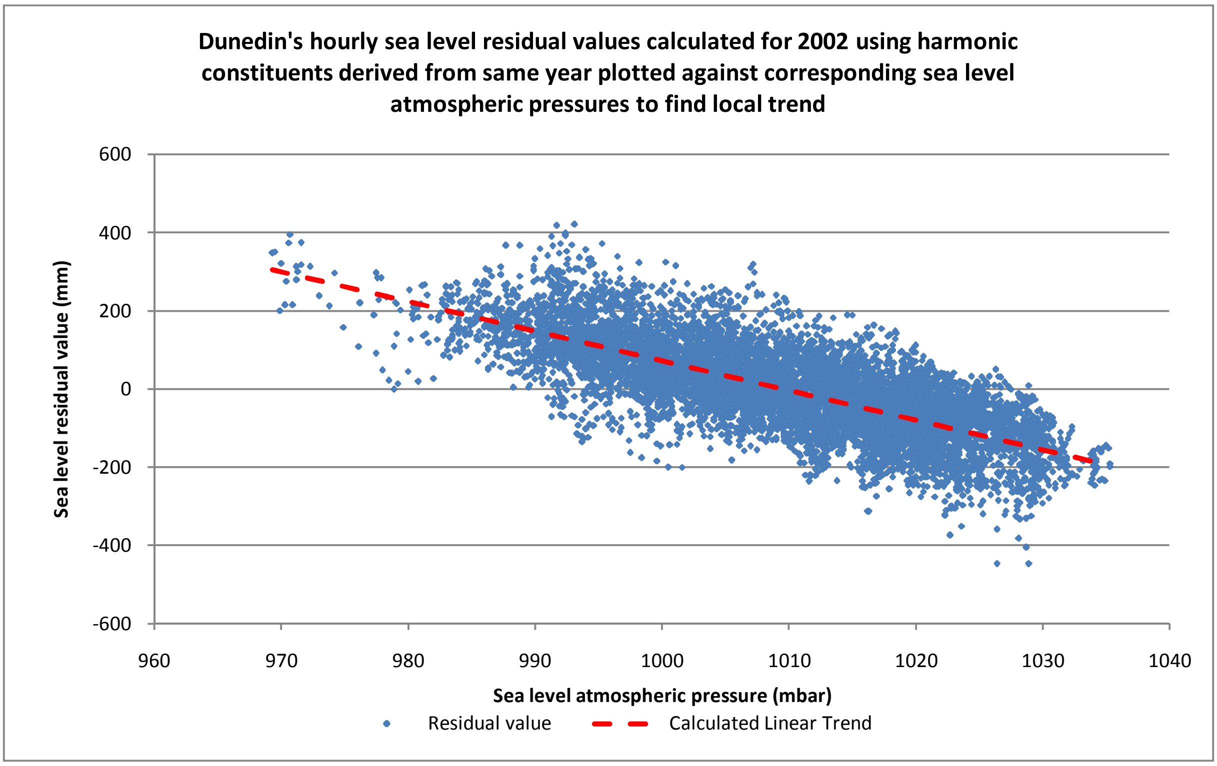

Figure 9.10: Dunedin's hourly sea level residual values calculated for 2002 using harmonic constituents derived from same year plotted against corresponding sea level atmospheric pressures to find local trend

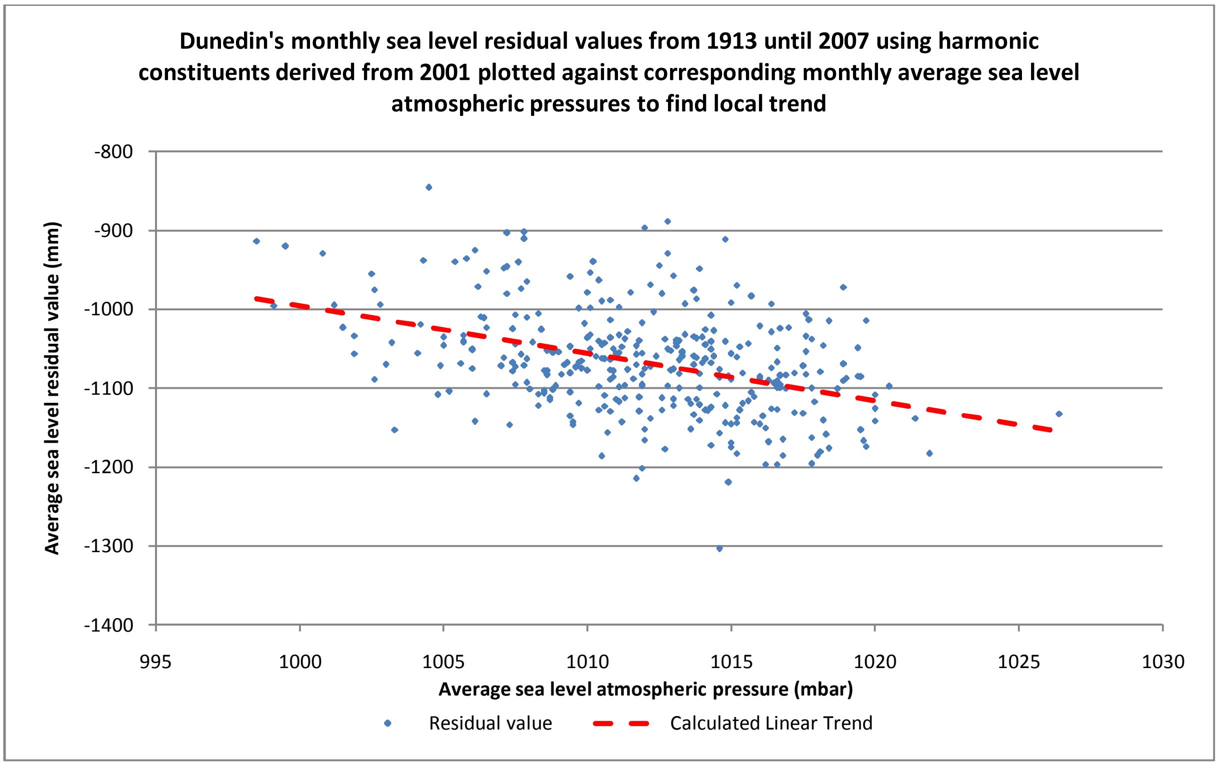

Figure 9.11: Dunedin's monthly sea level residual values from 1913 until 2007 using harmonic constituents derived from 2001 plotted against corresponding monthly average sea level atmospheric pressures to find local trend

9.2 Calculated trends

Auckland				
Year used to calculate harmonic constituents	**Year(s) residuals were calculated for**	**Derived response (m/mbar)**	**95% Confidence Interval**	**Number of observations**
2003	*2001*[*]	*-0.00602*	*± 0.00050*	*8544*
	2002	-0.00645	± 0.00054	8710
	2004	-0.00526	± 0.00050	8784
2004	*2001*	*-0.0063*	*± 0.00050*	*8544*
	2003	-0.00661	± 0.00053	8695
2003	2003	-0.00509	± 0.00053	8695
2004	2004	-0.00524	± 0.00050	8784
2004	*1916-2007*	*-0.00566*	*± 0.00173*	*1024*
Weighted Mean		**-0.0057**		

Table 9.1: Summary of trends derived for Auckland to provide Auckland's final weighted mean inverted barometer response

[*] Note: Italicised data has been rejected from the derivation of the weighted mean

Wellington				
Year used to calculate harmonic constituents	**Year(s) residuals were calculated for**	**Derived response (m/mbar)**	**95% Confidence Interval**	**Number of observations**
2004	2003	-0.00874	± 0.00045	8752
	2005	-0.00869	± 0.00045	8547
2007	2001	-0.00921	± 0.00043	8728
	*2006**	*-0.00985*	*± 0.00050*	*8074*
2004	2004	-0.00825	± 0.00040	8766
2007	2007	-0.00861	± 0.00044	8751
2004	*1944-2007*	*-0.00545*	*± 0.00176*	*740*
Weighted Mean		**-0.00869**		

Table 9.2: Summary of trends derived for Wellington to provide Wellington's final weighted mean inverted barometer response

* Note: Italicised data has been rejected from the derivation of the weighted mean

Lyttelton				
Year used to calculate harmonic constituents	**Year(s) residuals were calculated for**	**Derived response (m/mbar)**	**95% Confidence Interval**	**Number of observations**
2003	2001	-0.00782	± 0.00041	8338
	2002[*]	*-0.00785*	*± 0.00039*	*8169*
2005	2003	-0.00688	± 0.00040	8740
	2004	-0.00763	± 0.00037	8644
2003	2003	-0.00643	± 0.00040	8740
2005	2005	-0.00729	± 0.00042	8732
2005	*1924-2007*	*-0.00576*	*± 0.00147*	*899*
Weighted Mean		**-0.00721**		

Table 9.3: Summary of trends derived for Lyttelton to provide Lyttelton's final weighted mean inverted barometer response

[*] Note: Italicised data has been rejected from the derivation of the weighted mean

Dunedin				
Year used to calculate harmonic constituents	**Year(s) residuals were calculated for**	**Derived response (m/mbar)**	**95% Confidence Interval**	**Number of observations**
2004	2003	-0.00911	± 0.00038	8757
	2005	-0.00808	± 0.00042	8757
2001	2000	-0.00847	± 0.00041	8722
	2002	-0.00748	± 0.00036	8731
2000	2000	-0.00761	± 0.00010	8722
2001	2001	-0.00684	± 0.00040	8724
2002	2002	-0.00759	± 0.00036	8731
2003	2003	-0.00772	± 0.00038	8738
2001	*1913-1984*[*]	*-0.00601*	*± 0.00238*	*338*
Weighted Mean		**-0.0077**		

Table 9.4: Summary of trends derived for Dunedin to provide Dunedin's final weighted mean inverted barometer response

[*] Note: Italicised data has been rejected from the derivation of the weighted mean

9.3 Derived Harmonic Constituents

NO	NAME	FREQUENCY	A	G	AL	GL
1	Z0	0	190.6228	0	190.6228	0
2	SSA	0.00022816	2.4175	320.49	2.4175	120.24
3	MSM	0.00130978	0.2842	52.62	0.2842	249.39
4	MM	0.00151215	0.1585	10.05	0.1585	98.03
5	MSF	0.00282193	0.3772	279.73	0.3772	204.48
6	MF	0.00305009	2.1443	231.38	2.1443	315.88
7	ALP1	0.03439657	0.073	299.41	0.0803	4.32
8	2Q1	0.03570635	0.2679	27.04	0.2911	290.2
9	SIG1	0.03590872	0.0583	287.98	0.0647	81.3
10	Q1	0.0372185	0.1933	89.04	0.2128	79.5
11	RHO1	0.03742087	0.136	106.77	0.1535	350.25
12	O1	0.03873065	1.6526	142.53	1.8409	220.39
13	TAU1	0.03895881	0.0633	85.7	0.0569	141.77
14	BET1	0.04004043	0.1315	215.45	0.1497	307.95
15	NO1	0.04026859	0.2154	173.45	0.2825	98.93
16	CHI1	0.04047097	0.0522	161.78	0.0586	325.57
17	P1	0.04155259	2.3557	182.35	2.3414	193.06
18	K1	0.04178075	6.9874	189.39	7.4876	186.12
19	PHI1	0.04200891	0.1999	282.16	0.193	70.9
20	THE1	0.04309053	0.0547	49.31	0.0622	246.41
21	J1	0.0432929	0.4766	189.62	0.5098	276.17
22	SO1	0.04460268	0.1549	283.18	0.1727	205.2
23	OO1	0.04483084	0.2582	243.49	0.388	350.82
24	UPS1	0.04634299	0.1238	198.32	0.1806	29.25
25	OQ2	0.07597494	0.3161	151.93	0.2766	332.85
26	EPS2	0.07617731	0.8544	169.36	0.8043	237.17
27	2N2	0.0774871	2.5435	174.05	2.317	81.27
28	MU2	0.07768947	3.2524	184.1	3.1542	337.31
29	N2	0.07899925	21.8918	201.11	21.3893	190.26
30	NU2	0.07920162	4.4835	201.51	4.3599	81.45
31	M2	0.0805114	114.4609	233.08	112.156	310
32	MKS2	0.08073957	0.599	98.42	0.693	349.37
33	LDA2	0.08182118	1.1136	249.26	1.0875	343.5
34	L2	0.08202355	3.3345	282.96	3.1298	287.06
35	S2	0.08333334	17.6369	305.28	17.6559	305.16
36	K2	0.08356149	4.2433	295.36	5.0045	109.28
37	MSN2	0.08484548	0.2188	120.93	0.2097	208.57
38	ETA2	0.08507364	0.2541	276.96	0.3005	178.02
39	MO3	0.1192421	0.7267	70.5	0.7932	225.27
40	M3	0.1207671	1.2752	252.15	1.2379	7.84
41	SO3	0.122064	0.0535	147.85	0.0597	225.59
42	MK3	0.1222921	0.1856	126.3	0.1949	199.94
43	SK3	0.1251141	1.3229	13.97	1.4192	10.59
44	MN4	0.1595106	0.7989	168.33	0.7648	234.39
45	M4	0.1610228	2.6908	174.01	2.5835	327.83

NO	NAME	FREQUENCY	A	G	AL	GL
46	SN4	0.1623326	0.1116	197.45	0.1091	186.48
47	MS4	0.1638447	1.2768	277.66	1.2524	354.45
48	MK4	0.1640729	0.4005	262.42	0.4629	153.25
49	S4	0.1666667	0.5883	61.61	0.5895	61.37
50	SK4	0.1668948	0.2747	338.88	0.3243	152.69
51	2MK5	0.2028036	0.094	270.6	0.0967	61.16
52	2SK5	0.2084474	0.0154	323.3	0.0165	319.79
53	2MN6	0.240022	0.6079	331.75	0.5703	114.72
54	M6	0.2415342	1.1719	13.82	1.1025	244.56
55	2MS6	0.2443561	0.501	24.3	0.4816	178.01
56	2MK6	0.2445843	0.1618	11.97	0.1833	339.72
57	2SM6	0.2471781	0.2029	89.09	0.1993	165.77
58	MSK6	0.2474062	0.0583	57.19	0.0675	307.91
59	3MK7	0.2833149	0.0814	303.38	0.0821	170.85
60	M8	0.3220456	0.4436	352.57	0.4089	300.22

Table 9.5: Derived harmonic constituents for Auckland using hourly sea level measurements from throughout 2003

NO	NAME	FREQUENCY	A	G	AL	GL
1	Z0	0	187.2449	0	187.2449	0
2	SA	0.000114	4.6412	123.16	4.6412	305.8
3	SSA	0.000228	2.7099	231.44	2.7099	30.69
4	MSM	0.00131	0.7089	225.03	0.7089	245.61
5	MM	0.001512	1.35	170.17	1.35	162.89
6	MSF	0.002822	0.5193	27.81	0.5193	41.11
7	MF	0.00305	0.1432	271.93	0.1432	84.48
8	ALP1	0.034397	0.0644	347.08	0.0733	152.26
9	2Q1	0.035706	0.1293	94.95	0.1441	281.09
10	SIG1	0.035909	0.1992	309.59	0.2304	107.96
11	Q1	0.037219	0.1287	146.74	0.1466	325.55
12	RHO1	0.037421	0.1712	244.1	0.2061	35.1
13	O1	0.038731	1.6313	146.59	1.8932	318.28
14	TAU1	0.038959	0.133	148.58	0.105	295.73
15	BET1	0.04004	0.0474	331.85	0.0563	342.75
16	NO1	0.040269	0.2596	152.48	0.2189	344.37
17	CHI1	0.040471	0.1411	175.14	0.1636	331.71
18	PI1	0.041439	0.1229	218.94	0.1221	226.95
19	P1	0.041553	2.3085	180.03	2.2938	10.78
20	S1	0.041667	0.1751	82.76	0.1197	55.22
21	K1	0.041781	7.036	188.69	7.7008	3.18
22	PSI1	0.041895	0.0687	90.29	0.0697	83.21
23	PHI1	0.042009	0.152	200.08	0.1385	165.89
24	THE1	0.043091	0.2711	183.53	0.3062	22.04
25	J1	0.043293	0.5864	209.54	0.6522	18.85
26	SO1	0.044603	0.1362	185.25	0.1583	13.49
27	OO1	0.044831	0.2797	239.06	0.4132	242.46
28	UPS1	0.046343	0.0212	240.32	0.0327	234.93
29	OQ2	0.075975	0.3721	142.42	0.3007	153.35
30	EPS2	0.076177	0.6475	155.44	0.5827	138.31
31	2N2	0.077487	2.996	165.03	2.5554	168.67
32	MU2	0.077689	3.2337	184.28	3.0803	159.22
33	N2	0.078999	22.046	198.94	21.4318	194
34	NU2	0.079202	4.3445	202.29	4.1827	169.86
35	H1	0.080397	0.8914	152.87	0.8375	136.98
36	M2	0.080511	114.6012	233.44	111.1031	221.41
37	H2	0.080625	0.4296	175.67	0.4223	345.79
38	MKS2	0.08074	0.1076	157.93	0.1312	315.46
39	LDA2	0.081821	1.0098	245.21	0.9746	74.13
40	L2	0.082024	3.7151	275.22	4.8442	81.22
41	T2	0.083219	1.4179	347.7	1.4179	165.06
42	S2	0.083333	17.7577	305.88	17.784	305.8
43	R2	0.083447	0.3978	257.55	0.4851	254.81
44	K2	0.083561	4.4642	295.78	5.6102	105.24
45	MSN2	0.084845	0.2654	140.95	0.2505	133.8
46	ETA2	0.085074	0.0996	289.7	0.1195	93.92
47	MO3	0.119242	0.6845	56.36	0.7702	216.02

NO	NAME	FREQUENCY	A	G	AL	GL
48	M3	0.120767	1.4104	248.95	1.3486	231.07
49	SO3	0.122064	0.0546	212.58	0.0635	24.19
50	MK3	0.122292	0.1388	156.65	0.1472	319.12
51	SK3	0.125114	1.1707	16.91	1.2832	191.32
52	MN4	0.159511	0.6155	167.32	0.5801	150.35
53	M4	0.161023	2.9544	179.87	2.7768	155.83
54	SN4	0.162333	0.1851	146.49	0.1802	141.47
55	MS4	0.163845	1.3739	274.61	1.3339	262.51
56	MK4	0.164073	0.4666	273.58	0.5684	71.03
57	S4	0.166667	0.5403	65.74	0.5419	65.58
58	SK4	0.166895	0.2411	338.71	0.3035	148.1
59	2MK5	0.202804	0.1153	275.88	0.1186	66.32
60	2SK5	0.208447	0.0281	185.07	0.0308	359.4
61	2MN6	0.240022	0.7132	335.46	0.6517	306.48
62	M6	0.241534	1.1896	11.56	1.0839	335.5
63	2MS6	0.244356	0.5051	28.32	0.4755	4.2
64	2MK6	0.244584	0.1337	352.21	0.1579	137.63
65	2SM6	0.247178	0.1231	58.48	0.1197	46.3
66	MSK6	0.247406	0.0222	170.17	0.027	327.53
67	3MK7	0.283315	0.1034	8.77	0.1031	147.19
68	M8	0.322046	0.4362	339.61	0.3854	291.53

Table 9.6: Derived harmonic constituents for Auckland using hourly sea level measurements from throughout 2004

NO	NAME	FREQUENCY	A	G	AL	GL
1	Z0	0	110.9783	0	110.9783	0
2	SA	0.000114	2.1697	51.14	2.1697	233.78
3	SSA	0.000228	4.1662	228.16	4.1662	27.41
4	MSM	0.00131	0.395	16.96	0.395	37.55
5	MM	0.001512	1.908	331.3	1.908	324.02
6	MSF	0.002822	2.6081	32.74	2.6081	46.04
7	MF	0.00305	2.5061	175.38	2.5061	347.93
8	ALP1	0.034397	0.1772	318.1	0.2007	123.27
9	2Q1	0.035706	0.2821	9.14	0.3108	195.38
10	SIG1	0.035909	0.2639	5.93	0.3047	164.3
11	Q1	0.037219	1.0127	20.37	1.1468	199.24
12	RHO1	0.037421	0.2607	20.95	0.3143	171.96
13	O1	0.038731	3.2642	42.77	3.7896	214.46
14	TAU1	0.038959	0.2172	79.94	0.173	227.14
15	BET1	0.04004	0.1185	320.94	0.1406	331.84
16	NO1	0.040269	0.1777	25.29	0.1547	216.6
17	CHI1	0.040471	0.1075	121.03	0.1247	277.6
18	PI1	0.041439	0.0485	328.44	0.0483	336.46
19	P1	0.041553	0.9726	88.33	0.9665	279.08
20	S1	0.041667	0.0638	96.22	0.0436	68.68
21	K1	0.041781	2.6973	107.47	2.9523	281.96
22	PSI1	0.041895	0.0078	120.4	0.0079	113.32
23	PHI1	0.042009	0.1803	55.98	0.1644	21.79
24	THE1	0.043091	0.0286	115.15	0.0323	313.63
25	J1	0.043293	0.3611	190.18	0.3952	359.33
26	SO1	0.044603	0.0582	299.16	0.0677	127.39
27	OO1	0.044831	0.1826	265.34	0.2707	268.68
28	UPS1	0.046343	0.0766	290.69	0.1175	285.3
29	OQ2	0.075975	0.2529	32.94	0.2003	43.99
30	EPS2	0.076177	0.3693	73.27	0.3297	56.23
31	2N2	0.077487	1.7413	78.5	1.4646	82.3
32	MU2	0.077689	1.8349	96.62	1.7445	71.59
33	N2	0.078999	11.624	122.6	11.3002	117.66
34	NU2	0.079202	2.3849	128.75	2.2946	96.32
35	H1	0.080397	0.5089	160.38	0.4781	144.49
36	M2	0.080511	49.1288	165.9	47.6254	153.87
37	H2	0.080625	0.7626	105.88	0.7497	275.99
38	MKS2	0.08074	0.1273	244.04	0.1554	41.55
39	LDA2	0.081821	0.1418	140.94	0.1368	329.85
40	L2	0.082024	1.3286	229.89	1.7323	35.89
41	T2	0.083219	0.758	342.86	0.758	160.22
42	S2	0.083333	2.5755	22.49	2.5793	22.41
43	R2	0.083447	0.1679	156.39	0.2047	153.66
44	K2	0.083561	0.9121	53.23	1.1466	222.69
45	MSN2	0.084845	0.2084	335.64	0.1967	328.48
46	ETA2	0.085074	0.1676	116.91	0.1979	280.98
47	MO3	0.119242	0.4357	37.48	0.4903	197.14

NO	NAME	FREQUENCY	A	G	AL	GL
48	M3	0.120767	0.6659	225.33	0.6367	207.46
49	SO3	0.122064	0.2992	135.77	0.3479	307.38
50	MK3	0.122292	0.3152	188.92	0.3345	351.39
51	SK3	0.125114	0.4271	260.43	0.4682	74.84
52	MN4	0.159511	0.2837	265.9	0.2673	248.93
53	M4	0.161023	0.9372	309.51	0.8808	285.46
54	SN4	0.162333	0.1321	322.3	0.1286	317.27
55	MS4	0.163845	0.4681	11.31	0.4545	359.21
56	MK4	0.164073	0.1271	7.94	0.1549	165.38
57	S4	0.166667	0.1367	296.89	0.1371	296.73
58	SK4	0.166895	0.0752	215.36	0.0947	24.74
59	2MK5	0.202804	0.0614	330.92	0.0631	121.36
60	2SK5	0.208447	0.1529	256.56	0.1678	70.89
61	2MN6	0.240022	0.2834	147.38	0.2589	118.39
62	M6	0.241534	0.5178	190.45	0.4717	154.38
63	2MS6	0.244356	0.4661	250.51	0.4387	226.39
64	2MK6	0.244584	0.1326	252.11	0.1566	37.52
65	2SM6	0.247178	0.0193	236.88	0.0188	224.7
66	MSK6	0.247406	0.0224	195.66	0.0273	353.02
67	3MK7	0.283315	0.0447	137.94	0.0446	276.36
68	M8	0.322046	0.1435	190.19	0.1268	142.09

Table 9.7: Derived harmonic constituents for Wellington using hourly sea level measurements from throughout 2004

NO	NAME	FREQUENCY	A	G	AL	GL
1	Z0	0	109.8297	0	109.8297	0
2	SSA	0.000228	1.6085	85.89	1.6085	245.58
3	MSM	0.00131	1.4466	195.85	1.4466	59.2
4	MM	0.001512	2.0076	277.86	2.0076	357.88
5	MSF	0.002822	1.5514	187.11	1.5514	130.49
6	MF	0.00305	1.5089	314.6	1.5089	57.67
7	ALP1	0.034397	0.1215	174.8	0.1447	220.33
8	2Q1	0.035706	0.2134	325.7	0.2568	232.88
9	SIG1	0.035909	0.2224	7.32	0.2608	133.78
10	Q1	0.037219	0.8774	31.44	1.0414	19.97
11	RHO1	0.037421	0.07	43.99	0.0801	251.64
12	O1	0.038731	3.162	40.82	3.6998	110.84
13	TAU1	0.038959	0.1128	129.04	0.0882	185.47
14	BET1	0.04004	0.0704	192.36	0.0856	306.15
15	NO1	0.040269	0.258	52.21	0.354	338.09
16	CHI1	0.040471	0.0957	27.78	0.1131	150.18
17	P1	0.041553	1.0324	99.77	1.0215	109.8
18	K1	0.041781	2.5323	104.17	2.8053	91.4
19	PHI1	0.042009	0.1043	344.17	0.1008	136.93
20	THE1	0.043091	0.0401	50.7	0.0466	261.84
21	J1	0.043293	0.3151	177.1	0.3742	247.59
22	SO1	0.044603	0.1461	248.4	0.1714	178.43
23	OO1	0.044831	0.1667	229.24	0.3019	317.32
24	UPS1	0.046343	0.0144	96.41	0.0255	262.05
25	OQ2	0.075975	0.199	92.73	0.2115	260.07
26	EPS2	0.076177	0.4186	80.63	0.4231	109.21
27	2N2	0.077487	1.4957	102.2	1.5625	351.39
28	MU2	0.077689	1.9641	98.58	1.9171	210.03
29	N2	0.078999	12.8443	125.18	12.404	100.86
30	NU2	0.079202	2.4316	131.78	2.3583	324.67
31	M2	0.080511	49.0591	166.3	47.4048	222.27
32	MKS2	0.08074	0.0735	301.9	0.0923	152.09
33	LDA2	0.081821	0.3333	148.29	0.3193	247.35
34	L2	0.082024	1.7569	123.12	1.5284	101.17
35	S2	0.083333	2.6199	20.04	2.6257	20.08
36	K2	0.083561	0.9755	55.85	1.2648	210.1
37	MSN2	0.084845	0.1022	318.93	0.0956	39.27
38	ETA2	0.085074	0.1041	49.89	0.1624	289.39
39	MO3	0.119242	0.1628	357.07	0.1841	123.05
40	M3	0.120767	0.8256	215.08	0.782	118.85
41	SO3	0.122064	0.3887	134.34	0.4558	204.4
42	MK3	0.122292	0.3436	178.09	0.3679	221.29
43	SK3	0.125114	0.4247	269.39	0.4715	256.66
44	MN4	0.159511	0.3775	268.87	0.3522	300.52
45	M4	0.161023	0.9973	312.56	0.9312	64.51
46	SN4	0.162333	0.1879	314.44	0.1818	290.17
47	MS4	0.163845	0.4898	16.1	0.4743	72.12

NO	NAME	FREQUENCY	A	G	AL	GL
48	MK4	0.164073	0.1651	19.25	0.2068	229.48
49	S4	0.166667	0.1391	282.22	0.1397	282.31
50	SK4	0.166895	0.0466	244.14	0.0606	38.44
51	2MK5	0.202804	0.0238	340.89	0.0246	80.06
52	2SK5	0.208447	0.1824	285.38	0.203	272.7
53	2MN6	0.240022	0.2601	136.81	0.2345	224.43
54	M6	0.241534	0.5364	188.56	0.484	356.47
55	2MS6	0.244356	0.5235	248.18	0.4899	0.17
56	2MK6	0.244584	0.1264	231.42	0.1531	137.62
57	2SM6	0.247178	0.1128	284.56	0.1095	340.63
58	MSK6	0.247406	0.0221	185.37	0.0277	35.64
59	3MK7	0.283315	0.0939	138.14	0.0938	293.29
60	M8	0.322046	0.2655	186.01	0.2314	49.89

Table 9.8: Derived harmonic constituents for Wellington using hourly sea level measurements from throughout 2007

NO	NAME	FREQUENCY	A	G	AL	GL
1	Z0	0	139.5414	0	139.5414	0
2	SSA	0.000228	2.4216	159.46	2.4216	319.22
3	MSM	0.00131	1.7198	148.72	1.7198	345.48
4	MM	0.001512	1.2564	358.22	1.2564	86.2
5	MSF	0.002822	3.7334	121.24	3.7334	45.98
6	MF	0.00305	3.0277	245.8	3.0277	330.29
7	ALP1	0.034397	0.0706	14.29	0.0772	79.47
8	2Q1	0.035706	0.2675	353.48	0.2877	257.42
9	SIG1	0.035909	0.3298	41.02	0.3655	194.42
10	Q1	0.037219	0.9258	56.59	1.0148	47.44
11	RHO1	0.037421	0.1992	123.13	0.2253	6.73
12	O1	0.038731	2.724	68.3	3.0356	146.18
13	TAU1	0.038959	0.0651	334.02	0.059	29.71
14	BET1	0.04004	0.1584	232.25	0.1803	324.75
15	NO1	0.040269	0.1598	31.15	0.2125	314.82
16	CHI1	0.040471	0.136	64.27	0.1526	228.06
17	P1	0.041553	1.3115	125.43	1.3037	136.15
18	K1	0.041781	4.6993	108.14	5.036	104.87
19	PHI1	0.042009	0.0996	23.6	0.0961	172.34
20	THE1	0.043091	0.0456	289.69	0.0521	126.65
21	J1	0.043293	0.1772	171.58	0.187	257.04
22	SO1	0.044603	0.0872	127.08	0.0973	49.08
23	OO1	0.044831	0.1697	181.07	0.2557	288.16
24	UPS1	0.046343	0.0358	261.6	0.0519	92.23
25	OQ2	0.075975	0.3357	44.34	0.289	226.57
26	EPS2	0.076177	0.7573	57.03	0.7088	125.38
27	2N2	0.077487	2.6434	77.78	2.3851	345.96
28	MU2	0.077689	3.0679	87.6	2.9705	240.94
29	N2	0.078999	18.7714	116.93	18.3406	106.07
30	NU2	0.079202	3.8972	120.13	3.7869	0.03
31	M2	0.080511	86.3123	152.66	84.5686	229.56
32	MKS2	0.08074	0.4202	30.11	0.4863	281.02
33	LDA2	0.081821	0.6511	176.71	0.6359	270.95
34	L2	0.082024	2.2735	228.61	2.1339	232.72
35	S2	0.083333	5.6587	179.55	5.6646	179.43
36	K2	0.083561	1.9017	148.69	2.2435	322.58
37	MSN2	0.084845	0.1064	62.98	0.102	150.61
38	ETA2	0.085074	0.3328	159.58	0.3891	59.59
39	MO3	0.119242	0.4099	41.87	0.4476	196.64
40	M3	0.120767	0.3875	183.16	0.3762	298.85
41	SO3	0.122064	0.2786	118.33	0.3108	196.09
42	MK3	0.122292	0.2748	127.56	0.2885	201.18
43	SK3	0.125114	0.5177	317.3	0.5554	313.91
44	MN4	0.159511	0.2241	184.25	0.2146	250.29
45	M4	0.161023	0.4017	162.24	0.3857	316.03
46	SN4	0.162333	0.0827	249.67	0.0809	238.69
47	MS4	0.163845	0.3172	199.55	0.3111	276.33

NO	NAME	FREQUENCY	A	G	AL	GL
48	MK4	0.164073	0.087	185.86	0.1006	76.66
49	S4	0.166667	0.2751	307.82	0.2757	307.58
50	SK4	0.166895	0.2684	247.19	0.317	60.97
51	2MK5	0.202804	0.0687	238.3	0.0707	28.82
52	2SK5	0.208447	0.2939	252.13	0.3156	248.61
53	2MN6	0.240022	0.3992	101.28	0.3744	244.22
54	M6	0.241534	0.8559	168.58	0.8051	39.26
55	2MS6	0.244356	0.7412	248.08	0.7123	41.76
56	2MK6	0.244584	0.1295	250.52	0.1467	218.21
57	2SM6	0.247178	0.034	161.69	0.0334	238.35
58	MSK6	0.247406	0.1156	110.45	0.1338	1.12
59	3MK7	0.283315	0.252	104.15	0.254	331.56
60	M8	0.322046	0.4361	203.82	0.402	151.41

Table 9.9: Derived harmonic constituents for Lyttelton using hourly sea level measurements from throughout 2003

NO	NAME	FREQUENCY	A	G	AL	GL
1	Z0	0	138.78	0	138.78	0
2	SSA	0.000228	1.1283	42	1.1283	200.73
3	MSM	0.00131	0.3412	127.88	0.3412	332.28
4	MM	0.001512	3.0396	5.23	3.0396	262.7
5	MSF	0.002822	2.8775	115.8	2.8775	217.67
6	MF	0.00305	0.1748	27.41	0.1748	288.02
7	ALP1	0.034397	0.0248	108.69	0.0288	14.33
8	2Q1	0.035706	0.3514	1.34	0.3971	110.87
9	SIG1	0.035909	0.2493	12.67	0.2923	176.19
10	Q1	0.037219	0.8864	70.92	1.0256	78.6
11	RHO1	0.037421	0.3888	50.31	0.4633	109.68
12	O1	0.038731	2.645	68.03	3.1196	333.65
13	TAU1	0.038959	0.0772	331.31	0.0598	211.89
14	BET1	0.04004	0.1138	87.82	0.1385	17.57
15	NO1	0.040269	0.354	70.62	0.4074	149.72
16	CHI1	0.040471	0.0729	279.52	0.0863	68.32
17	P1	0.041553	1.3299	113.31	1.3181	124
18	K1	0.041781	4.6432	107.91	5.1471	99.76
19	PHI1	0.042009	0.1361	163.47	0.1267	307.08
20	THE1	0.043091	0.2186	174.79	0.2517	11.31
21	J1	0.043293	0.4398	157.79	0.485	49.08
22	SO1	0.044603	0.1005	155.73	0.1188	250.08
23	OO1	0.044831	0.1038	204.35	0.177	99
24	UPS1	0.046343	0.0503	253.58	0.0843	49.39
25	OQ2	0.075975	0.4452	72.72	0.3654	271.42
26	EPS2	0.076177	0.6024	64.81	0.5393	321.31
27	2N2	0.077487	3.1671	85.31	2.7085	184.19
28	MU2	0.077689	3.077	90.14	2.9126	246.39
29	N2	0.078999	19.6813	114.68	19.0714	116.19
30	NU2	0.079202	3.7152	120.06	3.5655	174.84
31	M2	0.080511	86.1619	154.04	83.0686	52.99
32	MKS2	0.08074	0.04	45.86	0.0505	108.95
33	LDA2	0.081821	0.6385	179.72	0.6115	103.11
34	L2	0.082024	2.9519	205.12	3.4083	164.36
35	S2	0.083333	5.7115	179.67	5.7224	179.64
36	K2	0.083561	1.7962	152.88	2.3451	316.99
37	MSN2	0.084845	0.1477	318.27	0.1383	215.68
38	ETA2	0.085074	0.2998	116.2	0.3776	184.98
39	MO3	0.119242	0.3415	15.62	0.3883	180.19
40	M3	0.120767	0.5317	187.82	0.5034	36.11
41	SO3	0.122064	0.3006	117.44	0.3552	23.03
42	MK3	0.122292	0.264	130.24	0.2822	21.04
43	SK3	0.125114	0.4781	322.31	0.531	314.13
44	MN4	0.159511	0.2487	181.01	0.2323	81.47
45	M4	0.161023	0.4047	156.92	0.3762	314.82
46	SN4	0.162333	0.1707	180.15	0.1657	181.63
47	MS4	0.163845	0.2166	196.71	0.2092	95.63

NO	NAME	FREQUENCY	A	G	AL	GL
48	MK4	0.164073	0.0787	207	0.0991	270.06
49	S4	0.166667	0.2437	294.45	0.2446	294.39
50	SK4	0.166895	0.2361	281.98	0.3089	86.06
51	2MK5	0.202804	0.0482	162.74	0.0497	312.5
52	2SK5	0.208447	0.1866	267.43	0.2076	259.22
53	2MN6	0.240022	0.4259	94.9	0.3836	254.31
54	M6	0.241534	0.6849	162.58	0.6137	219.43
55	2MS6	0.244356	0.9126	241	0.8499	38.87
56	2MK6	0.244584	0.2572	256.64	0.3122	218.65
57	2SM6	0.247178	0.0609	136.68	0.0589	35.57
58	MSK6	0.247406	0.0327	195.44	0.0413	258.47
59	3MK7	0.283315	0.1547	133.26	0.1537	181.97
60	M8	0.322046	0.2502	253.71	0.2162	209.52

Table 9.10: Derived harmonic constituents for Lyttelton using hourly sea level measurements from throughout 2005

NO	NAME	FREQUENCY	A	G	AL	GL
1	Z0	0	111.444	0	111.444	0
2	SA	0.000114	1.898	219.17	1.898	41.77
3	SSA	0.000228	1.1501	210.94	1.1501	10.25
4	MSM	0.00131	0.9039	349.85	0.9039	343.85
5	MM	0.001512	2.0366	142.91	2.0366	143.59
6	MSF	0.002822	1.5746	322.03	1.5746	316.71
7	MF	0.00305	3.7659	169.64	3.7659	323.62
8	ALP1	0.034397	0.1254	39.11	0.1204	229.51
9	2Q1	0.035706	0.2185	32.31	0.2135	216.01
10	SIG1	0.035909	0.2765	9.22	0.264	199.52
11	Q1	0.037219	0.7072	61.19	0.6765	245.54
12	RHO1	0.037421	0.3194	57.66	0.3153	246.69
13	O1	0.038731	2.8095	71.73	2.6478	256.63
14	TAU1	0.038959	0.0542	36.56	0.0573	201.31
15	BET1	0.04004	0.1127	55.91	0.1043	52.81
16	NO1	0.040269	0.6772	214.47	0.2815	32.43
17	CHI1	0.040471	0.0479	86.83	0.0453	276.14
18	PI1	0.041439	0.1483	261.22	0.1488	269.36
19	P1	0.041553	0.6579	130.22	0.6617	321.15
20	S1	0.041667	1.3617	252.2	0.9749	224.84
21	K1	0.041781	2.5122	112.04	2.4176	290.23
22	PSI1	0.041895	0.0952	148.54	0.0945	141.79
23	PHI1	0.042009	0.2	162.58	0.1991	128.76
24	THE1	0.043091	0.0811	36.87	0.0767	214.96
25	J1	0.043293	0.3329	173.75	0.3399	356.55
26	SO1	0.044603	0.1889	228.44	0.1779	43.43
27	OO1	0.044831	0.8145	200.72	0.5246	199.53
28	UPS1	0.046343	0.2299	295.5	0.1753	297.16
29	OQ2	0.075975	0.4079	74.32	0.4928	81.46
30	EPS2	0.076177	0.2132	101.65	0.2316	113.61
31	2N2	0.077487	2.7844	93.35	3.1457	99.59
32	MU2	0.077689	1.6114	118.28	1.6675	130.87
33	N2	0.078999	18.5279	120.28	18.7487	126.95
34	NU2	0.079202	3.7474	118.88	3.8249	132.3
35	H1	0.080397	0.5524	53.36	0.5825	57.15
36	M2	0.080511	80.8896	143.37	82.24	150.63
37	H2	0.080625	0.1174	169.74	0.1186	358.78
38	MKS2	0.08074	0.1414	218.1	0.1279	41.35
39	LDA2	0.081821	1.5567	111.95	1.5878	293.55
40	L2	0.082024	4.0738	118.76	5.0174	305.91
41	T2	0.083219	0.2823	282.38	0.2823	99.78
42	S2	0.083333	9.4602	161.02	9.4521	160.91
43	R2	0.083447	0.0409	318.78	0.0505	315.58
44	K2	0.083561	3.518	158.54	3.1325	334.43
45	MSN2	0.084845	0.4245	341.37	0.4364	341.85
46	ETA2	0.085074	0.128	326.05	0.1271	150.75
47	MO3	0.119242	0.2225	98.15	0.2132	290.3

NO	NAME	FREQUENCY	A	G	AL	GL
48	M3	0.120767	0.0675	201.36	0.0692	32.2
49	SO3	0.122064	0.3674	160.5	0.3459	345.29
50	MK3	0.122292	0.3082	143.14	0.3015	328.58
51	SK3	0.125114	0.6768	3.15	0.6508	181.22
52	MN4	0.159511	3.0697	193.97	3.1582	207.89
53	M4	0.161023	7.102	207.74	7.3412	222.25
54	SN4	0.162333	0.1745	253.12	0.1765	259.67
55	MS4	0.163845	1.9389	235.14	1.9696	242.28
56	MK4	0.164073	0.7046	241.99	0.6378	65.14
57	S4	0.166667	0.3888	353.1	0.3881	352.87
58	SK4	0.166895	0.3189	331.53	0.2837	147.3
59	2MK5	0.202804	0.1183	9.76	0.1176	202.46
60	2SK5	0.208447	0.1	225.68	0.0961	43.64
61	2MN6	0.240022	1.1322	38.99	1.1843	60.17
62	M6	0.241534	2.1159	74.24	2.2237	96.01
63	2MS6	0.244356	0.524	82.32	0.5411	96.71
64	2MK6	0.244584	0.2595	36.42	0.2388	226.82
65	2SM6	0.247178	0.1068	57.3	0.1084	64.32
66	MSK6	0.247406	0.1238	19.39	0.112	202.42
67	3MK7	0.283315	0.0969	56.02	0.0979	255.98
68	M8	0.322046	0.546	121.89	0.5834	150.91

Table 9.11: Derived harmonic constituents for Dunedin using hourly sea level measurements from throughout 2000

NO	NAME	FREQUENCY	A	G	AL	GL
1	Z0	0	109.7298	0	109.7298	0
2	SSA	0.000228	2.8372	124.57	2.8372	283.37
3	MSM	0.00131	3.1209	54.1	3.1209	231.92
4	MM	0.001512	1.4056	312.18	1.4056	217.6
5	MSF	0.002822	3.1898	40.74	3.1898	123.98
6	MF	0.00305	1.4157	94.46	1.4157	336.5
7	ALP1	0.034397	0.4817	41.8	0.4867	331.03
8	2Q1	0.035706	0.107	136.99	0.1117	244.22
9	SIG1	0.035909	0.2724	33	0.2741	226.19
10	Q1	0.037219	1.1045	51.6	1.1259	63.24
11	RHO1	0.037421	0.2148	356.46	0.2087	92.28
12	O1	0.038731	2.8566	73.12	2.8625	349.37
13	TAU1	0.038959	0.0917	294.79	0.0977	187.13
14	BET1	0.04004	0.1381	281.28	0.1383	193.46
15	NO1	0.040269	0.2262	113.61	0.2209	180.8
16	CHI1	0.040471	0.2404	265.84	0.2429	91.49
17	P1	0.041553	0.9014	121.99	0.9018	133.16
18	K1	0.041781	2.32	116.64	2.3251	114.91
19	PHI1	0.042009	0.0502	347.43	0.0518	131.84
20	THE1	0.043091	0.0409	299.75	0.0397	119.71
21	J1	0.043293	0.0729	251.34	0.0777	156.07
22	SO1	0.044603	0.1624	236.35	0.1627	319.97
23	OO1	0.044831	0.1612	280.84	0.1593	179.51
24	UPS1	0.046343	0.0557	210.76	0.0564	20.25
25	OQ2	0.075975	0.3058	65.38	0.3468	275.85
26	EPS2	0.076177	0.2226	99.79	0.2363	32.69
27	2N2	0.077487	2.2226	104.21	2.4472	216.36
28	MU2	0.077689	1.4252	108.08	1.4523	304.46
29	N2	0.078999	18.4026	119.58	18.4729	132.79
30	NU2	0.079202	3.5209	115.02	3.5699	215.88
31	M2	0.080511	81.6984	142.7	82.1007	61.53
32	MKS2	0.08074	0.3592	176.29	0.3547	271.72
33	LDA2	0.081821	1.0371	112.07	1.043	29.19
34	L2	0.082024	4.0445	121.82	4.2793	112.47
35	S2	0.083333	9.7435	158.46	9.7427	158.33
36	K2	0.083561	3.4932	149.07	3.4331	325.53
37	MSN2	0.084845	0.6933	336.4	0.6993	241.89
38	ETA2	0.085074	0.1452	309.79	0.1619	34.63
39	MO3	0.119242	0.2497	109.68	0.2515	304.76
40	M3	0.120767	0.07	139.48	0.0706	197.81
41	SO3	0.122064	0.3728	168.97	0.3735	85.08
42	MK3	0.122292	0.3238	147.38	0.3261	64.49
43	SK3	0.125114	0.6557	6.08	0.6571	4.22
44	MN4	0.159511	3.166	189.07	3.1938	121.11
45	M4	0.161023	7.3601	206.22	7.4328	43.88
46	SN4	0.162333	0.329	265.98	0.3303	279.06
47	MS4	0.163845	1.9397	230.06	1.949	148.76

NO	NAME	FREQUENCY	A	G	AL	GL
48	MK4	0.164073	0.6549	217.56	0.6468	312.86
49	S4	0.166667	0.419	19.06	0.419	18.8
50	SK4	0.166895	0.2389	304.69	0.2347	121.03
51	2MK5	0.202804	0.1113	5.11	0.1126	201.05
52	2SK5	0.208447	0.1235	219.87	0.1237	217.88
53	2MN6	0.240022	1.1868	34.11	1.2031	244.98
54	M6	0.241534	2.1288	70.09	2.1604	186.58
55	2MS6	0.244356	0.4735	71.03	0.4781	268.57
56	2MK6	0.244584	0.2499	50.45	0.2481	64.58
57	2SM6	0.247178	0.0906	100.36	0.091	18.93
58	MSK6	0.247406	0.0981	31.59	0.0969	126.76
59	3MK7	0.283315	0.12	36.51	0.122	151.28
60	M8	0.322046	0.5597	112.92	0.5708	148.25

Table 9.12: Derived harmonic constituents for Dunedin using hourly sea level measurements from throughout 2001

NO	NAME	FREQUENCY	A	G	AL	GL
1	Z0	0	108.643	0	108.643	0
2	SSA	0.000228	2.2636	89.06	2.2636	248.33
3	MSM	0.00131	1.2299	33.01	1.2299	40.3
4	MM	0.001512	1.8693	59.67	1.8693	236.37
5	MSF	0.002822	1.5014	29.28	1.5014	213.27
6	MF	0.00305	0.4085	230.63	0.4085	213.9
7	ALP1	0.034397	0.4602	41.86	0.4847	218.97
8	2Q1	0.035706	0.2512	17.58	0.27	204.01
9	SIG1	0.035909	0.5618	50.1	0.5919	43.11
10	Q1	0.037219	0.9799	47.24	1.0459	48.71
11	RHO1	0.037421	0.2993	126.43	0.3023	297.31
12	O1	0.038731	2.7558	76.06	2.9137	252.7
13	TAU1	0.038959	0.1862	25.34	0.191	178.84
14	BET1	0.04004	0.2038	79.72	0.2191	81.55
15	NO1	0.040269	0.069	257.4	0.0999	72.76
16	CHI1	0.040471	0.1146	112.1	0.1228	107.41
17	P1	0.041553	0.6639	119.93	0.6609	130.9
18	K1	0.041781	2.5562	116.44	2.6586	114.31
19	PHI1	0.042009	0.1998	282.62	0.2059	69.59
20	THE1	0.043091	0.1217	145.96	0.13	152.93
21	J1	0.043293	0.0961	281.69	0.1019	95.53
22	SO1	0.044603	0.2176	264.99	0.2301	88.21
23	OO1	0.044831	0.1451	326.37	0.2001	330.53
24	UPS1	0.046343	0.0992	261.21	0.128	81.74
25	OQ2	0.075975	0.053	165.76	0.0531	185.03
26	EPS2	0.076177	0.1514	71.36	0.1521	253.27
27	2N2	0.077487	1.5388	98.49	1.5705	290.86
28	MU2	0.077689	1.5654	106.6	1.5567	101.89
29	N2	0.078999	17.9414	118.02	17.8462	119.49
30	NU2	0.079202	3.7835	117.26	3.7598	287.38
31	M2	0.080511	82.6194	142.18	81.9988	320.13
32	MKS2	0.08074	0.1355	189.89	0.1458	184
33	LDA2	0.081821	1.3495	115.12	1.3369	120.94
34	L2	0.082024	4.2481	107.4	3.0365	277.27
35	S2	0.083333	9.8345	157.23	9.8403	157.1
36	K2	0.083561	3.2711	147.66	3.5453	323.69
37	MSN2	0.084845	0.2112	310.82	0.2086	127.16
38	ETA2	0.085074	0.3007	210.66	0.3521	202.08
39	MO3	0.119242	0.285	109.26	0.2991	103.84
40	M3	0.120767	0.2188	346.12	0.2163	73.31
41	SO3	0.122064	0.3845	168.07	0.4068	344.57
42	MK3	0.122292	0.315	161.49	0.3252	337.31
43	SK3	0.125114	0.7559	3.59	0.7867	1.33
44	MN4	0.159511	3.1698	190.81	3.1293	10.24
45	M4	0.161023	7.2838	204.36	7.1748	200.25
46	SN4	0.162333	0.1126	352.87	0.1121	354.21
47	MS4	0.163845	1.9994	230.27	1.9855	48.08

NO	NAME	FREQUENCY	A	G	AL	GL
48	MK4	0.164073	0.5041	212.71	0.5423	206.69
49	S4	0.166667	0.3374	27.9	0.3378	27.63
50	SK4	0.166895	0.3069	298.74	0.3328	114.64
51	2MK5	0.202804	0.134	357.82	0.1373	351.59
52	2SK5	0.208447	0.0841	229.71	0.0876	227.31
53	2MN6	0.240022	1.2166	34.61	1.192	31.98
54	M6	0.241534	2.1435	67.32	2.0955	241.16
55	2MS6	0.244356	0.5363	69.33	0.5286	65.09
56	2MK6	0.244584	0.2223	75.8	0.2374	247.73
57	2SM6	0.247178	0.0662	86.38	0.0658	264.05
58	MSK6	0.247406	0.1042	6.75	0.1121	0.6
59	3MK7	0.283315	0.0567	37.93	0.0577	209.65
60	M8	0.322046	0.554	106.46	0.5376	98.25

Table 9.13: Derived harmonic constituents for Dunedin using hourly sea level measurements from throughout 2002

NO	NAME	FREQUENCY	A	G	AL	GL
1	Z0	0	108.7935	0	108.7935	0
2	SSA	0.000228	1.9384	180.51	1.9384	340.26
3	MSM	0.00131	1.3841	146.59	1.3841	343.36
4	MM	0.001512	0.9259	17.76	0.9259	105.74
5	MSF	0.002822	3.7142	94.36	3.7142	19.1
6	MF	0.00305	3.9385	244.01	3.9385	328.51
7	ALP1	0.034397	0.2252	183.31	0.2458	248.57
8	2Q1	0.035706	0.0673	344.44	0.0721	248.63
9	SIG1	0.035909	0.4936	33.66	0.5467	187.08
10	Q1	0.037219	1.1102	49.97	1.2152	40.94
11	RHO1	0.037421	0.4254	44.77	0.4814	288.41
12	O1	0.038731	2.9796	72.54	3.3208	150.42
13	TAU1	0.038959	0.402	273.04	0.3655	328.62
14	BET1	0.04004	0.0599	223.45	0.0681	315.95
15	NO1	0.040269	0.1136	354.93	0.1518	278.07
16	CHI1	0.040471	0.0324	9.17	0.0364	172.95
17	P1	0.041553	0.7129	156.42	0.7087	167.15
18	K1	0.041781	2.5454	114.07	2.7278	110.79
19	PHI1	0.042009	0.0367	211.09	0.0354	359.83
20	THE1	0.043091	0.0987	96.66	0.1126	293.57
21	J1	0.043293	0.0705	41.89	0.0741	127.01
22	SO1	0.044603	0.2176	276.27	0.2428	198.26
23	OO1	0.044831	0.0631	327.64	0.0951	74.65
24	UPS1	0.046343	0.1918	293.91	0.2776	124.44
25	OQ2	0.075975	0.2002	334.65	0.1715	157.3
26	EPS2	0.076177	0.2115	120.89	0.1976	189.42
27	2N2	0.077487	1.9951	64.83	1.7948	333.32
28	MU2	0.077689	1.3338	110.9	1.2908	264.28
29	N2	0.078999	17.725	116.57	17.3181	105.71
30	NU2	0.079202	3.8919	118.69	3.7809	358.58
31	M2	0.080511	82.4136	142.18	80.7471	219.07
32	MKS2	0.08074	0.1177	272.61	0.1362	163.51
33	LDA2	0.081821	1.3525	106.57	1.3208	200.81
34	L2	0.082024	2.2904	119.65	2.1497	123.75
35	S2	0.083333	10.2006	159.97	10.2113	159.85
36	K2	0.083561	3.1214	148.47	3.6829	322.36
37	MSN2	0.084845	0.7242	310.27	0.694	37.9
38	ETA2	0.085074	0.1857	238.57	0.2164	138.24
39	MO3	0.119242	0.4873	104.86	0.5321	259.63
40	M3	0.120767	0.1371	330.59	0.1331	86.28
41	SO3	0.122064	0.2374	175.51	0.2648	253.28
42	MK3	0.122292	0.3108	166.33	0.3263	239.94
43	SK3	0.125114	0.6492	8.45	0.6965	5.05
44	MN4	0.159511	3.0305	189.87	2.9011	255.91
45	M4	0.161023	7.4522	205.92	7.1539	359.7
46	SN4	0.162333	0.1835	271.4	0.1794	260.42
47	MS4	0.163845	2.0655	234.65	2.0259	311.42

NO	NAME	FREQUENCY	A	G	AL	GL
48	MK4	0.164073	0.5354	223.23	0.6189	114.02
49	S4	0.166667	0.3404	25.29	0.3412	25.05
50	SK4	0.166895	0.2018	302.63	0.2383	116.4
51	2MK5	0.202804	0.1315	10.6	0.1353	161.1
52	2SK5	0.208447	0.0854	230.65	0.0917	227.13
53	2MN6	0.240022	1.1338	29.52	1.0634	172.45
54	M6	0.241534	2.1962	66.66	2.0656	297.33
55	2MS6	0.244356	0.6009	67.92	0.5774	221.58
56	2MK6	0.244584	0.2304	81.52	0.261	49.2
57	2SM6	0.247178	0.0732	107.34	0.0719	183.99
58	MSK6	0.247406	0.0568	32.27	0.0658	282.94
59	3MK7	0.283315	0.0735	49.46	0.0741	276.86
60	M8	0.322046	0.5154	112.36	0.475	59.92

Table 9.14: Derived harmonic constituents for Dunedin using hourly sea level measurements from throughout 2003

NO	NAME	FREQUENCY	A	G	AL	GL
1	Z0	0	108.984	0	108.984	0
2	SA	0.000114	2.9077	69.08	2.9077	251.72
3	SSA	0.000228	3.315	215.32	3.315	14.57
4	MSM	0.00131	0.6717	32.66	0.6717	53.25
5	MM	0.001512	1.7745	304.17	1.7745	296.89
6	MSF	0.002822	3.9864	18.79	3.9864	32.09
7	MF	0.00305	2.4482	169.26	2.4482	341.81
8	ALP1	0.034397	0.2602	3.24	0.2933	168.39
9	2Q1	0.035706	0.0833	138.33	0.0908	324.67
10	SIG1	0.035909	0.6412	18.74	0.7394	177.1
11	Q1	0.037219	1.1628	72.13	1.3104	251.05
12	RHO1	0.037421	0.0905	69.19	0.1092	220.22
13	O1	0.038731	2.6885	72.88	3.1222	244.58
14	TAU1	0.038959	0.3154	250.59	0.2533	37.84
15	BET1	0.04004	0.3318	57.37	0.3938	68.27
16	NO1	0.040269	0.317	14.49	0.2838	205.31
17	CHI1	0.040471	0.1052	327.65	0.1221	124.21
18	PI1	0.041439	0.1147	169.84	0.114	177.86
19	P1	0.041553	1.1418	134.45	1.1347	325.2
20	S1	0.041667	1.0003	284.48	0.6837	256.94
21	K1	0.041781	2.2497	117.89	2.4625	292.38
22	PSI1	0.041895	0.1178	134.2	0.1196	127.12
23	PHI1	0.042009	0.2504	219.94	0.2282	185.75
24	THE1	0.043091	0.2314	236.4	0.2624	74.87
25	J1	0.043293	0.2881	237.02	0.3107	46.02
26	SO1	0.044603	0.0617	76.52	0.0717	264.75
27	OO1	0.044831	0.2133	350.26	0.3172	353.56
28	UPS1	0.046343	0.1725	286.83	0.2634	281.43
29	OQ2	0.075975	0.7789	70.26	0.6048	81.43
30	EPS2	0.076177	0.5121	101.25	0.4537	84.3
31	2N2	0.077487	3.7344	78.85	3.0983	82.82
32	MU2	0.077689	1.6688	109.64	1.5836	84.62
33	N2	0.078999	17.7281	115.46	17.2342	110.52
34	NU2	0.079202	3.8187	116.55	3.6716	84.12
35	H1	0.080397	0.8564	112.25	0.8046	96.37
36	M2	0.080511	82.3657	143.22	79.8388	131.19
37	H2	0.080625	0.9079	79.53	0.8925	249.64
38	MKS2	0.08074	0.253	192.82	0.3089	350.33
39	LDA2	0.081821	1.3704	110.67	1.3225	299.59
40	L2	0.082024	2.8049	152.05	3.6574	318.05
41	T2	0.083219	0.1561	287.64	0.1561	105
42	S2	0.083333	9.8121	158.72	9.8263	158.64
43	R2	0.083447	0.1933	234.55	0.2357	231.81
44	K2	0.083561	3.3955	154.35	4.27	323.81
45	MSN2	0.084845	0.7339	321.53	0.6925	314.37
46	ETA2	0.085074	0.4143	166.75	0.4819	330.66
47	MO3	0.119242	0.4261	97.27	0.4796	256.94

NO	NAME	FREQUENCY	A	G	AL	GL
48	M3	0.120767	0.1714	309.83	0.1638	291.95
49	SO3	0.122064	0.2653	182.41	0.3085	354.02
50	MK3	0.122292	0.2698	153.96	0.2863	316.42
51	SK3	0.125114	0.6469	11.25	0.7091	185.66
52	MN4	0.159511	2.7134	192.49	2.5569	175.51
53	M4	0.161023	7.3262	208.35	6.8836	184.29
54	SN4	0.162333	0.203	262.2	0.1976	257.17
55	MS4	0.163845	2.0694	233.01	2.0088	220.9
56	MK4	0.164073	0.6543	229.16	0.7976	26.6
57	S4	0.166667	0.3664	17.38	0.3674	17.23
58	SK4	0.166895	0.225	322.2	0.2834	131.58
59	2MK5	0.202804	0.1592	16.23	0.1637	166.66
60	2SK5	0.208447	0.1073	214.38	0.1178	28.71
61	2MN6	0.240022	1.2505	27.18	1.1422	358.18
62	M6	0.241534	2.3447	72.13	2.1355	36.04
63	2MS6	0.244356	0.6298	73.14	0.5926	49.01
64	2MK6	0.244584	0.2237	46.92	0.2643	192.33
65	2SM6	0.247178	0.0832	82.12	0.0809	69.93
66	MSK6	0.247406	0.08	359.6	0.0977	156.95
67	3MK7	0.283315	0.0822	11.05	0.082	149.46
68	M8	0.322046	0.5299	115.07	0.4678	66.96

Table 9.15: Derived harmonic constituents for Dunedin using hourly sea level measurements from throughout 2004

9.4 Spyder Fast Fourier Transform Processing

Python 2.6.2 (r262:71605, Apr 14 2009, 22:40:02) [MSC v.1500 32 bit (Intel)] on win32

```
# -*- coding: utf-8 -*-
"""
Spyder Editor

This temporary script file is located here:
xxx.py
"""

import matplotlib
from matplotlib.pyplot import close,figure,ylabel,title,show
print "using MPL version:", matplotlib.__version__
from scipy.io import loadmat
#from os import chdir
#import pylab
from dateutil.rrule import rrule, MO, TU, WE, TH, FR, SA, SU
from datetime import datetime
from matplotlib.dates import
DayLocator,YearLocator,MonthLocator,date2num,num2date,DateFormatter,WeekdayLocator
#from matplotlib.dates import WeekdayLocator,RRuleLocator
from matplotlib.pyplot import setp,xlabel,axis
from matplotlib.pyplot import psd
from numpy import reshape, ndfromtxt
#from scipy import *

fname='name2'

name=ndfromtxt('E:\scripts\name.txt')
time=name[:,0]
height=name[:,1]
np.save('name3',name)

#FFT analysis

fig2 = figure(figsize=(14.88,8.38),dpi=100)
```

```
ax4=fig2.add_subplot(111)


(y,x)=ax4.psd(height,NFFT=2500,Fs=1)
xlabel('Frequency (cycles/year)')
title('PSD of Tidal Heights')
#axis([0.0, 50.0, -60.0, 120.0])
show()

savetxt('freq_'+fname+'.txt',x)
savetxt('power_'+fname+'.txt',y)
```

psd(self, x, NFFT=256, Fs=2, Fc=0, detrend=<function detrend_none at 0x0251D5F0>, window=<function window_hanning at 0x0251DEF0>, noverlap=0, pad_to=None, sides='default', scale_by_freq=None, **kwargs) method of matplotlib.axes.AxesSubplot instance call signature:

psd(x, NFFT=256, Fs=2, Fc=0, detrend=mlab.detrend_none, window=mlab.window_hanning, noverlap=0, pad_to=None, sides='default', scale_by_freq=None, **kwargs)

The power spectral density by Welch's average periodogram method. The vector *x* is divided into *NFFT* length segments. Each segment is detrended by function *detrend* and windowed by function *window*. *noverlap* gives the length of the overlap between segments. The :math:`|\mathrm{fft}(i)|^2` of each segment :math:`i` are averaged to compute *Pxx*, with a scaling to correct for power loss due to windowing. *Fs* is the sampling frequency.

Keyword arguments:

NFFT: integer

The number of data points used in each block for the FFT.

Must be even; a power 2 is most efficient. The default value is 256.

Fs: scalar

The sampling frequency (samples per time unit). It is used to calculate the Fourier frequencies, freqs, in cycles per time unit. The default value is 2.

detrend: callable

The function applied to each segment before fft-ing, designed to remove the mean or linear trend. Unlike in matlab, where the *detrend* parameter is a vector, in matplotlib is it a function. The :mod:`~matplotlib.pylab` module defines :func:`~matplotlib.pylab.detrend_none`, :func:`~matplotlib.pylab.detrend_mean`, and :func:`~matplotlib.pylab.detrend_linear`, but you can use a custom function as well.

window: callable or ndarray

A function or a vector of length *NFFT*. To create window vectors see :func:`window_hanning`, :func:`window_none`, :func:`numpy.blackman`, :func:`numpy.hamming`, :func:`numpy.bartlett`, :func:`scipy.signal`, :func:`scipy.signal.get_window`, etc. The default is :func:`window_hanning`. If a function is passed as the argument, it must take a data segment as an argument and return the windowed version of the segment.

noverlap: integer

The number of points of overlap between blocks. The default value is 0 (no overlap).

pad_to: integer

The number of points to which the data segment is padded when performing the FFT. This can be different from *NFFT*, which specifies the number of data points used. While not increasing the actual resolution of the psd (the minimum distance between resolvable peaks), this can give more points in the plot, allowing for more detail. This corresponds to the *n* parameter in the call to fft(). The default is None, which sets *pad_to* equal to *NFFT*

sides: ['default' | 'onesided' | 'twosided']

Specifies which sides of the PSD to return. Default gives the default behavior, which returns one-sided for real data and both for complex data. 'onesided' forces the return of a one-sided PSD, while 'twosided' forces two-sided.

scale_by_freq: boolean

Specifies whether the resulting density values should be scaled by the scaling frequency, which gives density in units of Hz^-1. This allows for integration over the returned frequency values. The default is True for MatLab compatibility.

Fc: integer

The center frequency of *x* (defaults to 0), which offsets the x extents of the plot to reflect the frequency range used when a signal is acquired and then filtered and downsampled to baseband.

Returns the tuple (*Pxx*, *freqs*).

For plotting, the power is plotted as :math:`10\log_{10}(P_{xx})` for decibels, though *Pxx* itself

is returned.

References:

Bendat & Piersol -- Random Data: Analysis and Measurement

Procedures, John Wiley & Sons (1986)

kwargs control the :class:`~matplotlib.lines.Line2D` properties:

alpha: float (0.0 transparent through 1.0 opaque)

animated: [True | False]

antialiased or aa: [True | False]

axes: an :class:`~matplotlib.axes.Axes` instance

clip_box: a :class:`matplotlib.transforms.Bbox` instance

clip_on: [True | False]

clip_path: [(:class:`~matplotlib.path.Path`, :class:`~matplotlib.transforms.Transform`) |:class:`~matplotlib.patches.Patch` | None]

color or c: any matplotlib color

contains: a callable function

dash_capstyle: ['butt' | 'round' | 'projecting']

dash_joinstyle: ['miter' | 'round' | 'bevel']

dashes: sequence of on/off ink in points

data: 2D array

drawstyle: ['default' | 'steps' | 'steps-pre' | 'steps-mid' | 'steps-post']

figure: a :class:`matplotlib.figure.Figure` instance

fillstyle: ['full' | 'left' | 'right' | 'bottom' | 'top']

gid: an id string

label: any string

linestyle or ls: ['-' | '--' | '-.' | ':' | 'None' | ' ' | ''] and any drawstyle in combination with a linestyle, e.g. 'steps--'.

linewidth or lw: float value in points

lod: [True | False]

marker: ['+' | '*' | ',' | '.' | '1' | '2' | '3' | '4' | '<' | '>' | 'D' | 'H' | '^' | '_' | 'd' | 'h' | 'o' | 'p' | 's' | 'v' | 'x' | '|' | TICKUP | TICKDOWN | TICKLEFT | TICKRIGHT | 'None' | ' ' | '']

markeredgecolor or mec: any matplotlib color

markeredgewidth or mew: float value in points

markerfacecolor or mfc: any matplotlib color

markersize or ms: float

markevery: None | integer | (startind, stride)

picker: float distance in points or callable pick function ``fn(artist, event)``

pickradius: float distance in points

rasterized: [True | False | None]

snap: unknown

solid_capstyle: ['butt' | 'round' | 'projecting']

solid_joinstyle: ['miter' | 'round' | 'bevel']

transform: a :class:`matplotlib.transforms.Transform` instance

url: a url string

visible: [True | False]

xdata: 1D array

ydata: 1D array

zorder: any number