Otago extreme sea level analysis

NIWA Client Report: CHC2005-114
August 2005

NIWA Project: ORC06501

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Executive Summary

The Otago Regional Council (ORC) commissioned the National Institute of Water and Atmospheric Research Ltd (NIWA) to determine extreme sea levels with return periods of 2, 5, 10, 20, 50 and 100 years for eight locations along the Otago coastline.

The focus is on extreme sea levels to be used as ocean boundary conditions for river flood modelling.

Long time series of sea levels are available from tide gauges inside Otago Harbour, but the only open-coast gauge outside the Harbour, on Green Island, has only been operational since 2003. Consequently, a storm-surge record was derived using barometric pressure and wind velocity from the Taiaroa Head as surrogates for storm surge. The digital record for the Taiaroa weather station extends back to 1961, which means a much longer time series of storm surge can be derived. Tides can more easily be predicted back through time or well into the future.

Two methods of analysing time series and fitting extreme probability distributions were used. The r-Largest method (Smith, 1986) produced slightly higher extreme sea levels than the revised joint-probability method (Tawn & Vassie, 1989), so were adopted as being more conservative (on higher side).

It has been assumed that the actual mean level of the sea (or MLOS) at all 7 open-coast locations does not vary significantly from that in Otago Harbour for any given period of year(s), in lieu of precise levelling at each location.

Derived values for the extreme sea level start at around 1.4 m above MLOS for a 2-year return period up to 1.7–1.8 m on open coast and 1.9 m in Otago Harbour (Dunedin) for a 100-year return period. These values compare with the maximum high tide (zero storm surge) predicted in the next 100 years for Otago Heads (Spit) of 1.16 m above MLOS and a Mean High Water Spring (MHWS) of 0.8 m above MLOS.

One option to utilise the extreme sea level values in Table 8, as boundary conditions for river models, is to combine a tide time series with amplitude equal to the site mean high water spring (MHWS), with a constant storm surge that is equivalent to the difference between the value of the extreme sea level and the MHWS level. MHWS values for the 8 locations of interest are specified in Table 9.

The computed extreme sea levels, for all required return periods, can be converted approximately to Dunedin Vertical Datum (DVD-1958) by adding 0.12 m to the results in this report.

Recommended extreme sea levels only include the tide and storm surge. They do not include tsunami or several other meteorological and climate components that can substantially increase sea levels at the coastline e.g., wave set-up, wave run-up, seasonal to inter-decadal variations in sea level and finally the projected rise in the mean level of the sea from climate change.

Further improvements in estimating extreme sea levels along the Otago open coast can be made by:

- Obtaining longer measurements of open-coast sea levels at different sites,
- coastal hydrodynamic modelling of storm surge scenarios;
- precise levelling and transfer of mean sea level datums along the coast.

1. Introduction

The Otago Regional Council (ORC) commissioned the National Institute of Water and Atmospheric Research Ltd (NIWA) to determine extreme sea levels with return periods of 2, 5, 10, 20, 50 and 100 years for eight locations along the Otago coastline. The locations of interest, shown in Figure 1, are:

- Oamaru,
- Kakanui River mouth,
- Shag Point,
- Otago Heads (Spit Jetty),
- Otago Harbour (Port of Dunedin),
- Taieri River mouth,
- Clutha River mouth,
- Catlins River mouth.

This information is intended for use by ORC as part of their design ‘standard combination’ for floods and sea level protection works, and for ORC Flood Protection Scheme works in coastal areas.

In this study extreme sea level was considered to be the combination of tide levels and the effects of barometric pressure and winds that result in the generation of storm surge (or set-up of the sea level along the coast). In considering the design level for structures and activities in the coastal zone, predicted future sea level rise, inter-annual sea-level variability, tsunami, and wind-wave and swell set-up and run-up must also be considered. These are not covered in detail in this study.

2. Data and methodology

As only short, reliable, sea level records were available for Otago Harbour and Green Island, a synthetic sea level record was generated for each of the 8 locations of interest along the Otago coastline for use in the extreme sea level analysis. The three components of sea level that were added together to produce a 41-year sea level record at each of the 8 locations were:

1. Tide level (Section 2.1).

2. Inverse barometric effect, i.e. the adjustment of sea level in response to air pressure changes (Section 2.2).

3. Wind set-up, i.e. the elevation of sea levels on the continental shelf due to wind stress piling water up against the coast (Section 2.3).

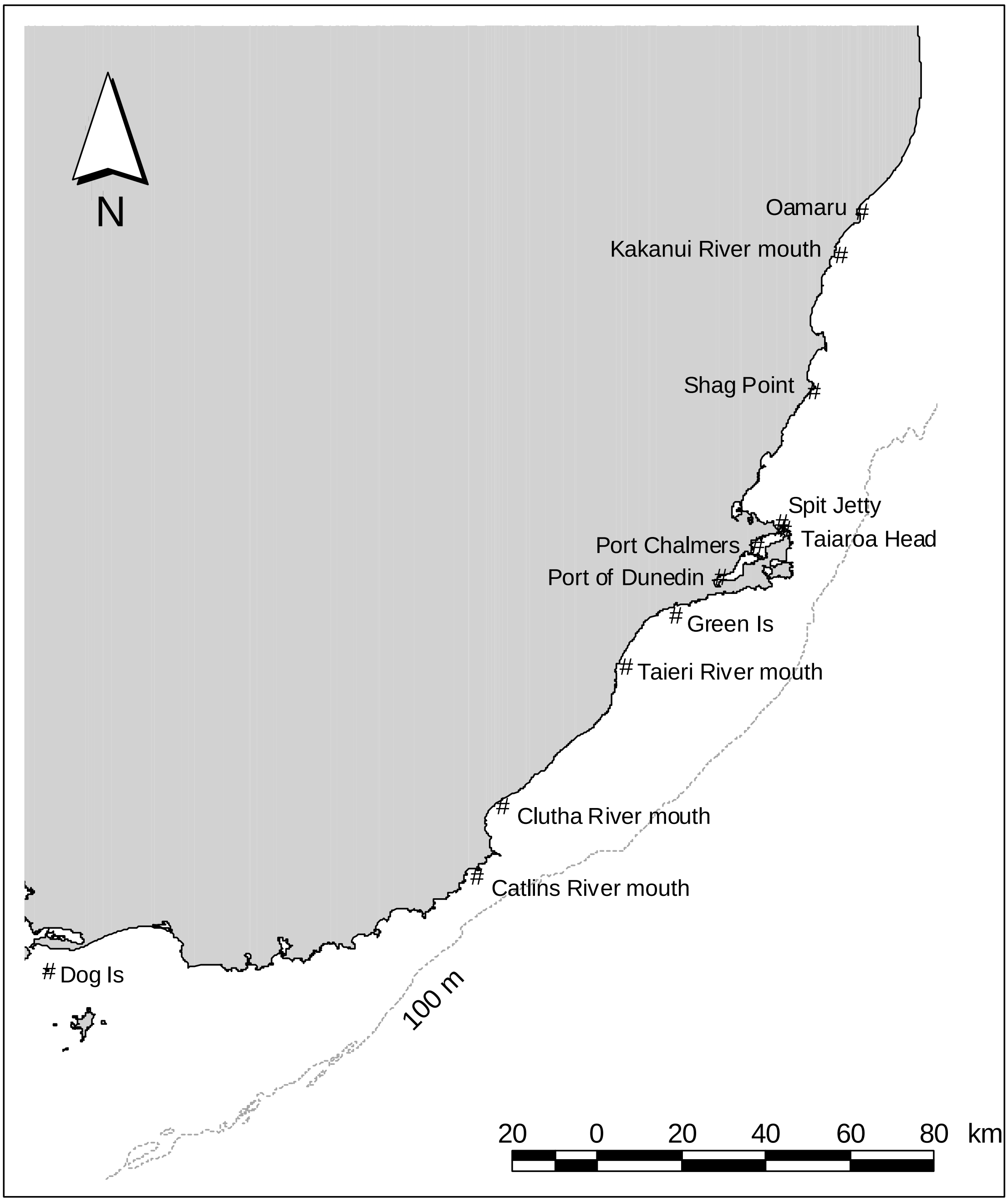


Figure 1: **Locations along the Otago coastline where extreme sea levels are developed.**

Together, components 2 and 3 are called storm surge. However, they have been kept separate for this analysis to utilise wind velocity and barometric pressure as surrogates for storm surge. The reason is that much longer records are available for these weather measurements, than is the case for open-coast sea level measurements.

At the coastline, storm levels are elevated further due to wave set-up and run-up. These are not considered in this report as they are not relevant for setting offshore sea levels for river flood simulations, but they are relevant for setting design levels for open-coast protection works and determining coastal hazard zones.

Along the Otago coastline, sea level, barometric pressure and wind information has been collected at several locations, for varying lengths of time. A summary of the data used in this study is given in Table 1. Data was sourced from the NIWA Climate Database (Taiaroa Head), NIWA open-coast sea-level network (Dog Island), ORC's sea-level gauge at Green Island and Otago Harbour gauge records from Ports of Otago Ltd.

Table 1: Summary of data used for this study

Data type	Location	Site Number	Time period
Sea level	Green Island	74099	4 Dec 2002 – 21 Jul 2005
	Otago Harbour at Spit Jetty	32	17 Aug 1999 – 31 Dec 2004[a]
	Otago Harbour at Port Chalmers	30	17 Aug 1999 – 31 Dec 2004[a]
	Otago Harbour at Dunedin	28	1899 – 2004[b]
Barometric pressure	Green Island	74097	1 Feb 2003 – 21 Jul 2005
	Dog Island	77997	22 Jan 1997 – 25 Jul 2005
	Taiaroa Head	507701	1 Apr 1961 – 19 Oct 2002
	Taiaroa Head	507702	31 Mar 2004 – 13 Jul 2005
Wind speed & direction	Taiaroa Head	507701	1 Apr 1961 – 15 Nov 2002
	Taiaroa Head	507702	18 May 2003 – 13 Jul 2005

[a] large gap in record prior to 17 August 1999
[b] large number of gaps, subsidence of gauge (Hannah, 2004) and location at head of harbour means tide is distorted by shallow-water friction. Port Chalmers record was considered more accurate for tidal analyses.

Establishing absolute vertical datum at each of the coastal sites needs precise surveying, but for this report we give extreme sea levels relative to the present mean level of the sea (MLOS) at Dunedin. (Note: this changes with El Niño/La Niña and background sea-level rise.) In the latest tidal datum analysis in 2000, LINZ has set the mean level of the sea to be 1.11 m above Chart Datum at Dunedin (Nautical Almanac, LINZ, 2005). The “fixed” LINZ Dunedin Vertical Datum-1958 (DVD-58) is 0.991 m above Chart Datum, based on BM WW 83 at the Birch St wharf at Dunedin (see Chart NZ6612, LINZ). To tie our extreme sea-level results in with the Dunedin Vertical Datum-1958 (DVD-58) at Dunedin, the difference between the present mean level of the sea (MLOS) and DVD-58 of 0.12 m would have to be added to our results. No allowance has been made for variations in the mean level of the sea along the coast relative to Dunedin.

2.1. Tide levels

Given a set of tidal constituents for any location (i.e., a set of different sine curves of different periods that combine to describe the tide locally), a local ‘predicted’ tide record can be generated for any time period.

Two methods of generating tidal constituents have been used to provide a tidal prediction at each of the eight locations of interest (summary in Table 2). They are:

1. Given an accurate tide record of approximately a year or more, a set of tidal constituents can be generated for that location using tidal harmonic analysis software.

2. If a tidal record is not available, a tidal model of the New Zealand EEZ (developed by NIWA) can be used to generate tidal constituents for any location along the open coastline (Walters, et al., 2001). At Green Island, when the predicted tide generated using the NIWA tide model is compared to the predicted tide generated using 1 above (for data from 2003 to 2005), the generated tide levels are within approximately ± 0.14 m of each other 95% of the time. The difference is partly explained by the amplitude of the tidal constituents, and partly by the phase/timing.

It should be noted that these tidal constituents only provide a ‘prediction’ of the tide due to Moon and Sun and do not incorporate the effects of atmospheric pressure and wind.

The tidal range varies somewhat along the Otago coast, as exemplified by the Mean High Water Spring (MHWS) level in Figure 2. These values are presented as metres above the mean level of the sea (MLOS).

Table 2: **Summary of methods used to generate forecast tide at 8 locations of interest**

Site	Derivation of tidal constituents
Oamaru	NIWA EEZ model
Kakanui River	NIWA EEZ model
Shag Point	NIWA EEZ model
Otago Heads	Spit at Jetty tide record
Otago Harbour	Port Chalmers & Port of Dunedin tide records
Taieri River	NIWA EEZ model
Clutha River	NIWA EEZ model
Catlins River	NIWA EEZ model

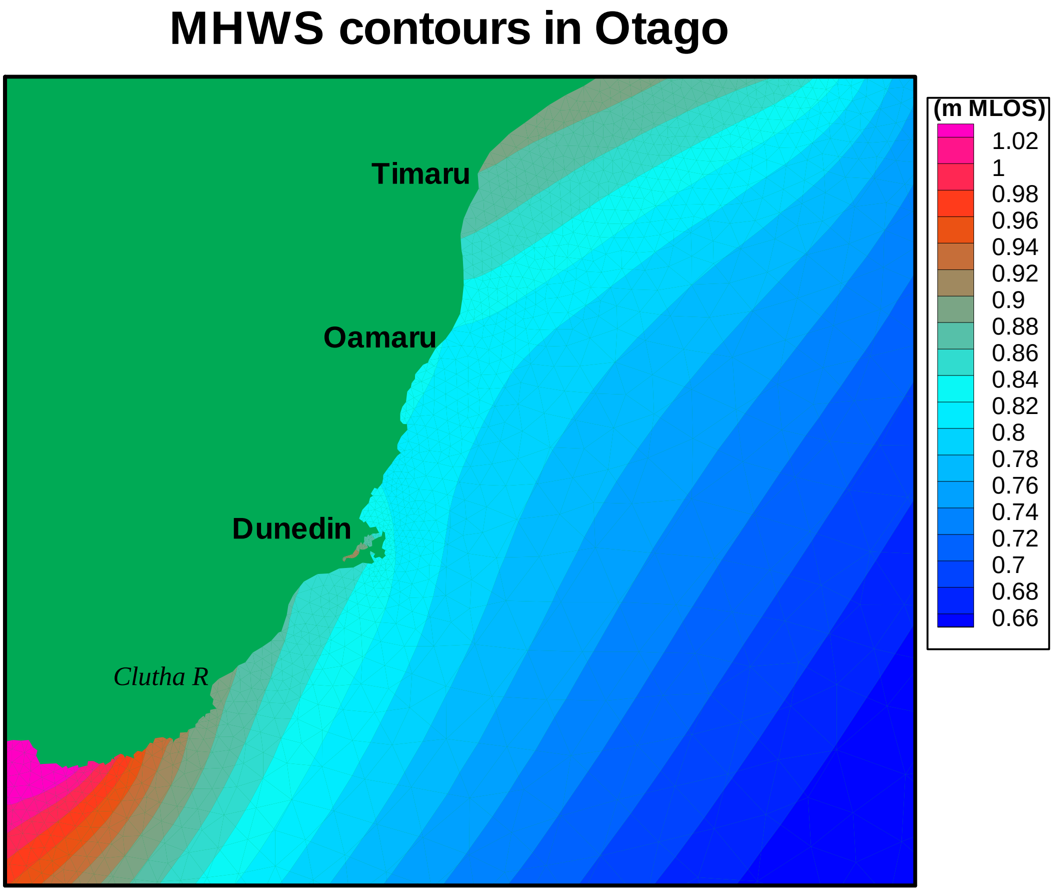


Figure 2: **Distribution of MHWS level in Otago waters in terms of the mean level of the sea based on a tidal model of New Zealand (Walters et al., 2001).**

2.2. Inverse barometric effect

Sea level usually responds to changes in atmospheric pressure over several hours, with the effects observed over a large area of ocean. When atmospheric pressure falls, the mean level of the sea (MLOS) rises, with the amount that sea level increases varying according to location.

In isostatic conditions (e.g., without winds), sea level variation is related to barometric pressure changes by the inverted barometer (IB) response. The theoretical IB response is an increase of 10 mm in sea level for every drop of 1 hPa below the annual-average barometric pressure. However, in reality, sites exposed to a prevailing westerly winds generally respond to changes in barometric pressure at greater than the conventional inverted barometer response (0.01 m.hPa^{-1}), and eastern sites sheltered from the west respond at less than this factor (Goring, 1995).

An equation for calculating the inverse barometer effect is:

$$\eta_{\Delta p} = F\,(a - p) \tag{2.1}$$

where $\eta_{\Delta p}$ = inverted barometer effect (m)
F = barometric response factor (m.hPa^{-1})
a = region's average barometric pressure (hPa)
p = recorded barometric pressure (hPa)

A comparison of recorded barometric pressure at Taiaroa Head, Green Island and Dog Island showed that barometric pressure values were all similar. This enabled the records to be combined to form a barometric pressure record extending from 1 April 1961 to 21 July 2005. This extended record consisted of Taiaroa Heads (1 April 1961 to 22 January 1997) and Dog Island (22 January 1997 to 21 July 2005), with any gaps in the Dog Island record filled with Taiaroa Head data. One gap in the Taiaroa record (12 days from 20 June to 2 July 1980) was unable to be filled. This combined time series gave a mean barometric pressure of a = 1011.4 hPa.

To determine the barometric response factor (F) for the 8 locations of interest, an analysis of storm surge and barometric pressure was undertaken at three sites: Green Island, Otago Harbour at Port Chalmers and Otago Harbour at the Spit jetty (i.e., Otago Heads). The combinations of sea level and barometric pressure data used at each site are summarised in Table 3.

Table 3: **Data used to derive the barometric response factor**

Sites	Sea level site number	Barometric pressure site number	Data range
Green Island	74099	74097	1 Feb 2003 – 21 Jul 2005
Otago Harbour at Spit Jetty	32	77997	17 Aug 1999 – 31 Dec 2004
Otago Harbour at Port Chalmers	30	77997	17 Aug 1999 – 31 Dec 2004

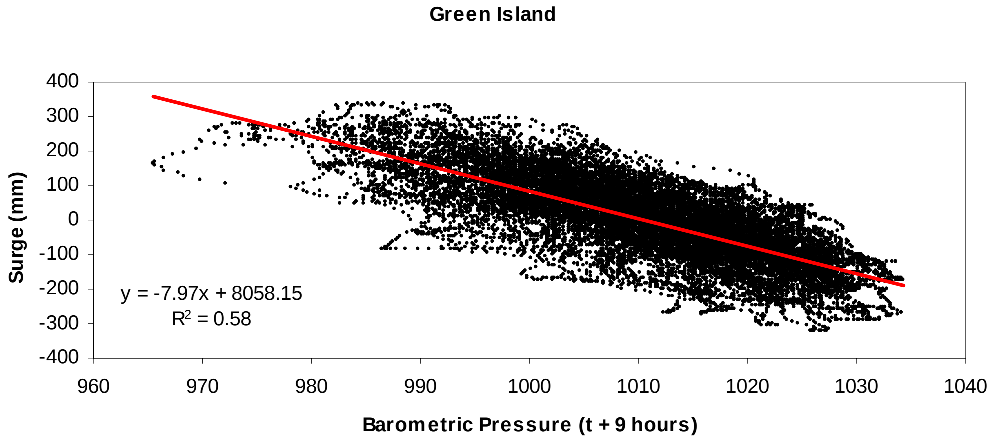
Storm surge (after tide is removed) and inverted barometer were determined for each of the sites in Table 3 using wavelet analyses (Emery and Thomson, 2001) 1x . Comparison plots of storm surge versus inverted barometer (IB) are shown in Figures A1 to A3 of Appendix A for Green Island, Spit Jetty and Port Chalmers, respectively. These figures showed that there is a close relationship between storm surge and IB.

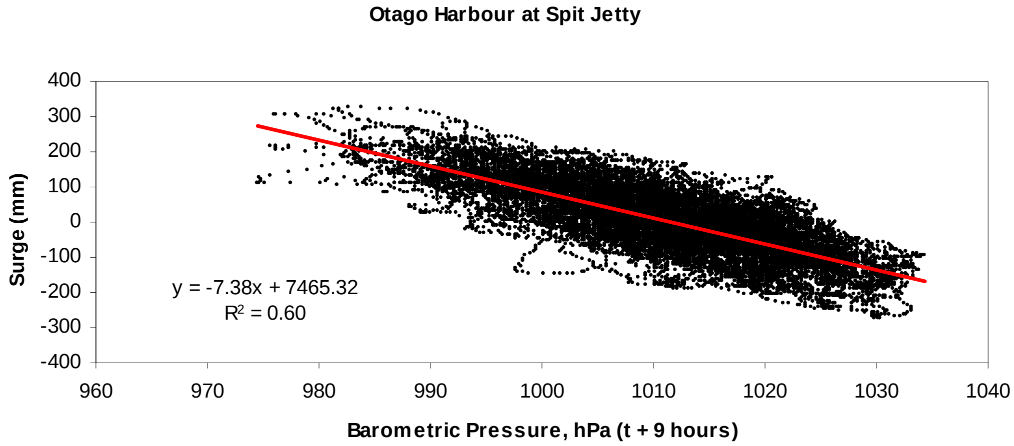
To determine the average barometric response factor for the sites in Table 3, the barometric pressure data was plotted against the derived storm surge. The data was then 'optimised' by moving the barometric pressure time series forward in hourly time steps to represent the lag between changes in atmospheric pressure and the subsequent sea-level response (see Figure 3). The coefficient of determination (R^2) for the 3 sites was between 0.58 and 0.62, indicating that approximately 60% of the variance in storm surge is explained by barometric pressure, but 40% was caused by other factors. Barometric response factors (F) derived in Figure 3 are summarised in Table 4, along with results previously determined for earlier datasets by Goring (1995).

Table 4: **Barometric response factor (F) and coefficient of linear fit (R^2)**

Location	Number of months of data	Time lag (hours)	Barometric response factor, F (m.hPa^{-1})	R^2
Green Island	30	9	0.0080	0.58
Otago Harbour at Spit Jetty	52	9	0.0074	0.60
Otago Harbour at Port Chalmers	52	7	0.0072	0.62
Otago Harbour (at Dunedin) [a]	57	0.9	0.0085	0.49
Timaru [a]	11	[b]	0.0094	[b]
Bluff [a]	36	3.6	0.0130	0.86

[a] Goring (1995). Data gathered by port companies in enclosed harbours.
[b] data series not long enough for analyses.





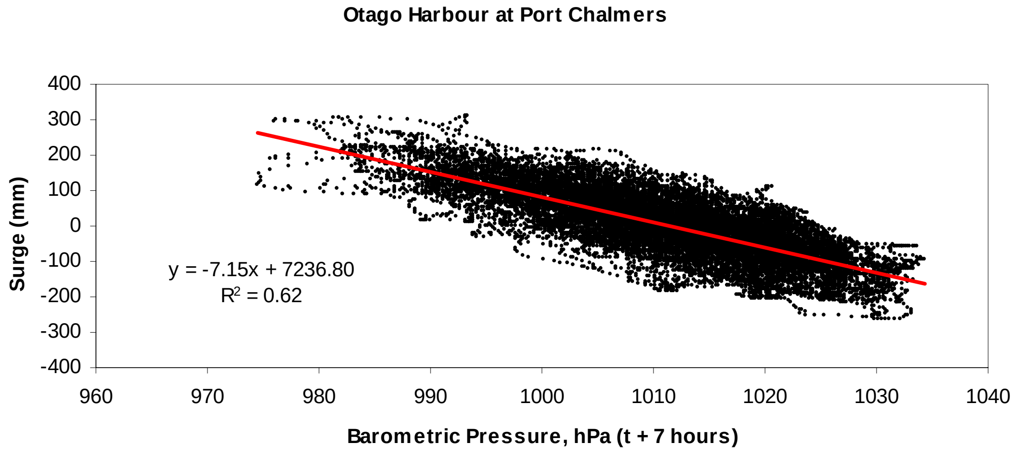


Figure 3: **Barometric pressure (hPa) versus storm surge (mm) for Green Island, Otago Harbour at Spit jetty and Otago Harbour at Port Chalmers. Note that the storm surge time series lags behind the barometric pressure time series.**

To determine the inverse barometric effect, which can be assumed to apply uniformly along the coast (based on the close similarity between barometric pressure data at Taiaroa Heads, Green Island and Dog Island/Foveaux Strait), a barometric response factor of 0.008 $m.hPa^{-1}$ has been used. To give an indication of the sensitivity of this factor in determining extreme sea levels, using the lowest recorded barometric pressure in the post-1961 record of 961 hPa (17-Jan-1980) at Taiaroa Head and the theoretical response value of 0.01 $m.hPa^{-1}$ (instead of the derived 0.008 $m.hPa^{-1}$), would increase the resulting extreme sea level for the 50- and 100-year return period by an additional 0.1 m.

2.3. Wind-stress set-up

Onshore winds (at right angles to the coast) push water across the continental shelf, setting up sea levels at the coast. A similar outcome occurs for winds travelling over the sea with the coast on their left “wing”, which for Otago are winds from the south-west quarter. This latter response occurs due to Ekman flow to the left arising from the Coriolis force on a spinning Earth.

Unfortunately the prediction of wind stress set-up along the coast is more complex than the prediction of inverse barometric effect due to the greater variability in wind velocities over time, their degree of persistence (needs several hours to build up the set-up in sea level), as well as the varying wind directions, passage of fronts and non-uniform water depth and continental shelf width along the Otago coast. Wind data may also be affected by sheltering caused by local topography, while features like Otago Harbour can funnel winds preferentially along the main axis of the harbour.

Silvester (1974) estimated the set-up in sea level caused by wind stress using Equation 2.2.

$$\eta_w = 6.915 \frac{KU_{10}^2 W}{gh_1} \qquad (2.2)$$

where η_w = vertical water level set-up due to onshore wind stress (m)
K = 3×10^{-6}
U_{10} = equivalent steady wind speed 10 m above MSL ($m.s^{-1}$)
W = width of continental shelf (m)
h_1 = depth at shelf edge (m)

The edge of the inner continental shelf was assumed to be at 100 m depth contour where the sea floor drops sharply in the offshore direction.

For the Otago coast, the wind record from Taiaroa Head has been used to determine wind stress as it is the most representative of winds blowing over the shelf waters. The Taiaroa Head climate station is located at the entrance to Otago Harbour at 72 m above MSL. An equivalent 10 m wind velocity reading (U_{10}) has been calculated assuming the empirical altitude relationship from (Beer, 1997):

$$\frac{U}{U_{10}} = \left(\frac{z}{10}\right)^{k} \tag{2.3}$$

where U_{10} = equivalent steady wind speed 10 m above MSL ($m.s^{-1}$)
U = wind speed at Taiaroa Head ($m.s^{-1}$)
z = anemometer height (=72 m for Taiaroa Heads)
k = varies with atmospheric stability with a typical value of 1/7

To provide a conservative estimate of the wind stress effect along the Otago coast, a range of wind directions from 15° to 250° have been assumed to be perpendicular to the coast for each site. This approach is likely to give a slightly higher sea level set-up than expected when the wind is not blowing onshore or alongshore from the SW quarter. Outside of this directional range, the wind stress was set to zero as the wind stress effect is likely to be negligible or produce a set-down at the coast (e.g., offshore winds).

For the waters within Otago Harbour, the storm surge is assumed to be the combined total of the wind set-up at Otago Heads, and an *additional* wind set-up for within the harbour when the wind is blowing from the north-east (i.e. directly down the harbour at an angle of 15° to 75° from north). The additional wind stress set-up within Otago Harbour is calculated using Equation 2.4 (Pugh, 1987).

$$\eta_w = \frac{C_D \rho_A {U_{10}}^{2} w}{\rho g h} \tag{2.4}$$

where η_w = vertical water level set-up due to onshore wind stress (m)
C_D = $(0.63 + 0.066U_{10}) \times 10^{-3}$, $U_{10} \leq 21$ $m.s^{-1}$
= 2.02×10^{-3}, $U_{10} > 21$ $m.s^{-1}$
U_{10} = equivalent steady wind speed 10 m above MSL ($m.s^{-1}$)
ρ_A = density of air = 1.29 $kg.m^{-3}$
ρ = density of seawater = 1025 $kg.m^{-3}$
w = width of shelf over which wind blows (m)
h = average depth (m)

Results produced using Equations 2.2 to 2.4 have been generated using Taiaroa Head wind velocities and directions. This record initially has a recording interval of 6 hours, but changes to hourly data in February 1975. A summary of the parameters used to generate wind stress effect for the Otago coastline and Dunedin is shown in Table 5.

The wind set-up component of storm surge for the Otago coastline used parameters initially derived for Otago Heads. This wind set-up was then applied uniformly at all the other open coast sites. This can be revised in the future if any long-term sea level measurements at other sites, or 3-dimensional storm surge modelling, suggests otherwise. Plots of the resulting wind set-up are shown in Appendix B.

Table 5: Parameters used to determine wind stress set-up for Otago coast sites

Location	Onshore wind direction range (degrees from north)	Continental shelf width (km)	Depth at edge of shelf (m)
Otago coastline	15-250	25	100
Dunedin[a]	15-75[a]	20[a]	10[a]

[a] Otago Heads wind stress effect plus wind stress effect calculated using Pugh (1987) with an average width of shelf over which wind blows of 20km, and an average depth of 10m.

3. Derivation of extreme sea levels for various return periods

Annual Exceedance Probabilities (AEPs) for extreme sea levels were determined using the extreme sea level analysis software package EXTLEV. The approach taken has been to initially estimate the annual exceedance probabilities for the 5 years of recorded sea level data (for Otago Harbour at Port Chalmers and Spit Jetty/Otago Heads).

As these data sets were limited to 5 years of data, and excluded any information regarding the other locations of interest along the open Otago coastline, the extreme sea level analyses were then completed for the 41-year derived records, and comparisons were made for the sites where both recorded and synthetic data were available (i.e Otago Harbour at Port of Dunedin, Port Chalmers and Spit Jetty) to ensure that the derived time series were calculated correctly.

Methods used were as follows:

- Revised Joint Probability (RJPM) for the 5 years of recorded sea level data.
- Both RJPM and r-Largest for the 41 years of derived sea level data

The RJPM and r-Largest methods are described in Section 3.1. It should also be noted that the results generated by both of these methods (using the extreme sea level analysis software, EXTLEV) give sea levels relative to the mean level of the sea (MLOS).

AEP for the 5-year recorded sea levels are shown in Table 6 and the results from the 41-year derived records are shown in Table 7. To be conservative, the highest extreme levels values obtained at each exceedance probability level were used for the recommended extreme sea levels given in Table 8.

3.1. Extreme sea level analysis methodology

The Revised Joint Probability Method (RJPM) is a refinement of the Joint Probability Method (JPM) that was introduced by Pugh & Vassie (1979), and which has found considerable application in predicting probabilities for extreme sea levels because of its ability to make use of short periods of record. The methodology behind the Joint Probability Method (JPM), Revised Joint Probability Method (RJPM) and r-Largest Method is broadly summarised below, following which the application of the RJPM and r-Largest method to this study is described. Further background reading can be found in Tawn & Vassie (1979, 1990).

Joint Probability Method (JPM)

The JPM, introduced by Pugh & Vassie in 1979, provided estimates of probabilities for extreme sea levels from short periods of sea-level record. Practically, the method consists of the following steps:

1. From knowledge of the principal tidal constituents at the sea-level recorder site, an hourly sequence of tidal predictions over the period of record is obtained and an empirical probability density function for hourly tide is derived

2. The hourly predictions of tide are subtracted from concurrent hourly sea-level values to generate the surge sequence. This is called de-tiding the record.

3. From the hourly surge sequence, an empirical probability density function (pdf) for hourly storm surge is derived.

4. The probability density functions for hourly tide and storm surge are convolved over the tidal range to calculate the density function for hourly (instantaneous) sea level.

5. Assuming the hourly observations of sea level are independent, the distribution function for the annual maxima is derived.

Assumptions made in using the JPM are that the hourly sea-level observations are independent and that the empirical surge pdf can be used instead of the true surge pdf. Given the time-history of the tide, the first assumption is clearly not true. Likewise, due to the short period of record the empirical surge pdf is unlikely to well represent the true surge pdf at the extremes, which are of prime interest. Indeed, because of its use of the empirical surge pdf, the highest level for which a probability estimate can be obtained with the JPM is the sum of highest astronomical tide and the maximum observed surge. It is likely that higher levels could occur and these should be accounted for.

Revised Joint Probability Method (RJPM)

Two principal improvements were introduced into the JPM (Tawn & Vassie, 1989) to remedy the deficiencies described above leading to the RJPM, viz:

1. Dependancy of hourly observations

2. Inadequacy of the empirical storm surge

Dependency of hourly observations

The RJPM applies ideas arising from Leadbetter (1983) concerning local clustering of extreme values to account for the fact that hourly observations of the sea level and storm surge sequences are not independent but tend to cluster as storms. These ideas are implemented in the form of the Extremal Index, $\theta(x)$, a multiplicative factor that varies with level and when multiplied by the number of hourly observations, N, (storm surge or sea level), gives the number of independent observations above a given level, x:

i.e. *Number .of independent observations (storm surge or sea level) above level x is* $\theta(x).N$

The Extremal Index must be calculated for both the sea level and storm surge sequences. Both are required to account for differences in timing between sea-level extremes and peaks in the surge sequence. One problem is that the Extremal Index is required for levels beyond the range of the data, and must therefore be extrapolated. For any given distribution function, F(x), if x is sufficiently large, it can be shown from extreme value theory (Leadbetter, 1983) that $\theta^{-1}(x)$ is invariant to x. Hence the correct function to extrapolate at the extremes is a constant θ^{-1}.

In EXTLEV, the constant θ^{-1} for extreme levels (storm-surge or sea level) is estimated using a weighted least-squares approach on the $\theta^{-1}(x)$ estimates for the data above a minimum threshold level at the extreme.

Inadequacy of the empirical storm surge

In the RJPM method, instead of using the empirical storm surge pdf, a pdf derived by fitting an extreme value distribution is used. This enables probabilities beyond the range of the surge data to be estimated and in addition a smoothing of the tail of the surge distribution function. The method used is the r-Largest method, as described below. The hourly surge probability density function is obtained directly from the extreme value distribution fitted to the event maxima.

r-Largest Method

The r-Largest method is based on the idea of using a fixed number, r, of independent extreme values from each year to provide robust estimates of the parameters of the extreme value distribution from a short period of record. Practically, the method involves 3 steps:

1. Identification of independent extreme events;

2. Selection of a suitable number of independent events from each year of data. The number of events has to be large enough to ensure sufficient data are available to obtain reasonable parameter estimates, but also small enough that the lowest level used still belongs to the extreme tail of the distribution. Typically, the number of events is taken as five.

3. Fitting an extreme value distribution to the selected event maxima.

In EXTLEV, identification of distinct independent events is controlled by specifying a standard storm duration in hours, by means of the Standard Storm Length parameter. Consecutive peaks are taken as independent if they are separated in time by at least the Standard Storm Length, otherwise they are lumped together and treated as a single event. A value between 15 and 80 hours is recommended.

3.1.1. Application of RJPM Methodology

To determine the joint probability of tides and storm surge extremes based on the RJPM, we have assumed that:

- Storm surge acts independently of tide (i.e. the probability distribution of surges is the same for all levels of the predicted tide).
- Extremal probabilities for storm surge have an EV1 (Gumbel) or GEV distribution.
- Extreme storm surge events have a characteristic duration (or Standard Storm Length) of between 20 and 30 hours.

In estimating the storm surge probability density function, we used the 5 largest events per year, giving 25 events over the 5 years of recorded sea-level record and 205 events over the 41 years of derived sea-level record (i.e., this data was used to fit a storm surge distribution). Similarly, the threshold levels for calculating the constant θ^{-1} values for the sea-level and storm surge sequences were chosen by matching the following criterion:

Number of independent exceedances/Number of years of data ≤ 5

This is approximately equivalent to setting the threshold at the level of the 5th largest (sea level or storm surge) event, which is consistent with using the 5 largest events per year for deriving the storm surge pdf.

3.1.2. Application of r-Largest Methodology

To determine the probability of sea level extremes based on the r-Largest method, we have assumed that:

- Extremal probabilities for sea level have an EV1 (Gumbel) or GEV distribution.

- Extreme sea level events have a characteristic duration (or Standard Storm Length) of between 20 and 30 hours.

In estimating the sea level extreme value distribution, we used the 5 largest events per year, over the 41 years of derived record giving 205 events as the basis on which to fit the distribution. Similarly, the threshold levels for calculating the constant θ^{-1} values, for the sea level sequence, were chosen by matching the following criterion:

Number of independent exceedances/Number of years of data ≤ 5

This is approximately equivalent to setting the threshold at the level of the 5th largest sea level event, which is consistent with using the 5 largest events per year for deriving the sea level extreme value distribution.

3.2. Analysis of 5 years of recorded sea level data

Using the RJPM for Otago Harbour at Port Chalmers, for a 20-hour storm, the minimum threshold levels for the surge and tide level were 0.35 m and 1.30 m (above mean level of the sea), respectively. The standard storm length (which is used to distinguish between distinct storm events for the storm surge) was varied from 20 to 30 hours, with the maximum levels being given for a storm length of 20 hours. Results for the 20-hour storm are shown in Table 6. Maximum differences of 10 mm were observed between the various standard storm lengths over the range of maximum sea level for each return period.

Table 6: Estimated extreme sea levels for various return periods (rel. to MLOS Dunedin-2000) in Otago Harbour, using 5 years of sea level record, 5 events per year, a Gumbel (EV1) fit and the RJPM.

Location	**Sea level (m rel. MLOS Dunedin-2000)**					
Return period (y)	**2**	**5**	**10**	**20**	**50**	**100**
Otago Heads (at Spit Jetty)	1.33	1.36	1.39	1.41	1.45	1.47
Otago Harbour (at Port Chalmers)	1.40	1.43	1.46	1.48	1.51	1.53

3.3. Analysis of 41 years of derived sea level data

Since there were no reliable long-term datasets of sea level along the Otago coast, sea-level time series were derived for all 8 locations of interest by combining time series for predicted tide levels (see Table 2) with the estimated storm surge using surrogates of barometric pressure and wind velocity from the much longer weather record at Taiaroa Head. In this case, storm surge is calculated to be inverse barometric effect (time series moved forward by 9 hours) and wind stress effect (no lag), as described in Section 2. To account for other residual meteorological effects, including coastally trapped wave propagation along the coast, and the effects of a moving-storm system, an additional 20% factor has been added to the derived total storm surge for the open coast sites. (From experience, although it is not unusual for a storm surge to be twice the IB set-up, the calculated wind stress component is generally less than the magnitude of the IB set-up).

It should be noted that, as the storm surge components (i.e. barometric pressure and wind set-up) were assumed to be applied uniformly along the open coast, the main difference in extreme sea levels along the open coast will be mainly due to variations in tidal range. This can be revised in the future if any long-term sea level measurements at other sites, or 3-dimensional modelling, suggest otherwise. It was also assumed that the storm surge calculated for Dunedin was relevant for Port Chalmers. This is likely to give a slightly higher than expected storm surge at Port Chalmers.

Comparisons of recorded and derived sea level for Otago Harbour at Dunedin, Port Chalmers and Otago Heads (at the Spit Jetty) are shown in Figures 4a to 4c, respectively. These comparisons show that differences between recorded and derived sea levels, above a MLOS of 1000 mm (1 m), are generally within 200 mm for the Otago Harbour at Port Chalmers and Spit Jetty sites. The Dunedin recorded and derived sea levels are generally within 300mm of each other above MLOS of 1 m, although there is an obvious greater variation at lower sea levels which is likely to be mainly due to the tidal constituents used to derive the tide component of the derived sea level record (Note: the location of this site at the head of the harbour means tide is distorted by shallow water friction). As we have not included wind set-down (i.e. a lowering of the sea level when winds are blowing offshore), our sea levels during periods of exposure to offshore winds will be over-estimated – this is shown by the greater scatter in the points below the 1:1 lines on Figures 4a to 4c. This was not considered important for this study, as we are interested in extreme high sea levels, rather than minimums.

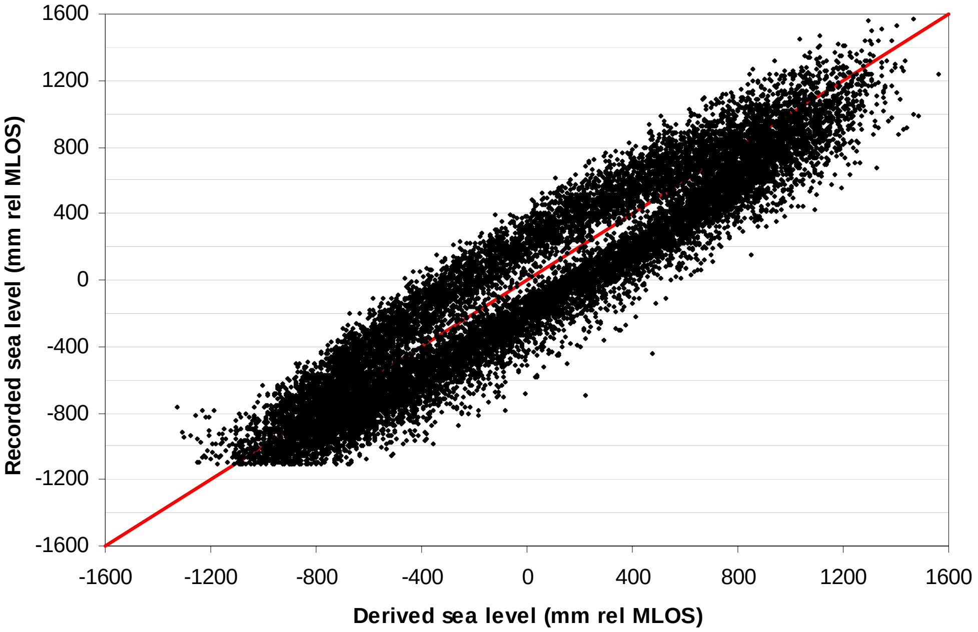


Figure 4a: Comparison of derived (horizontal axis) and recorded (vertical axis) sea level for Port of Dunedin, 17 January 2001 to 15 November 2002. Note: MLOS adjusted to 0 m for comparison.

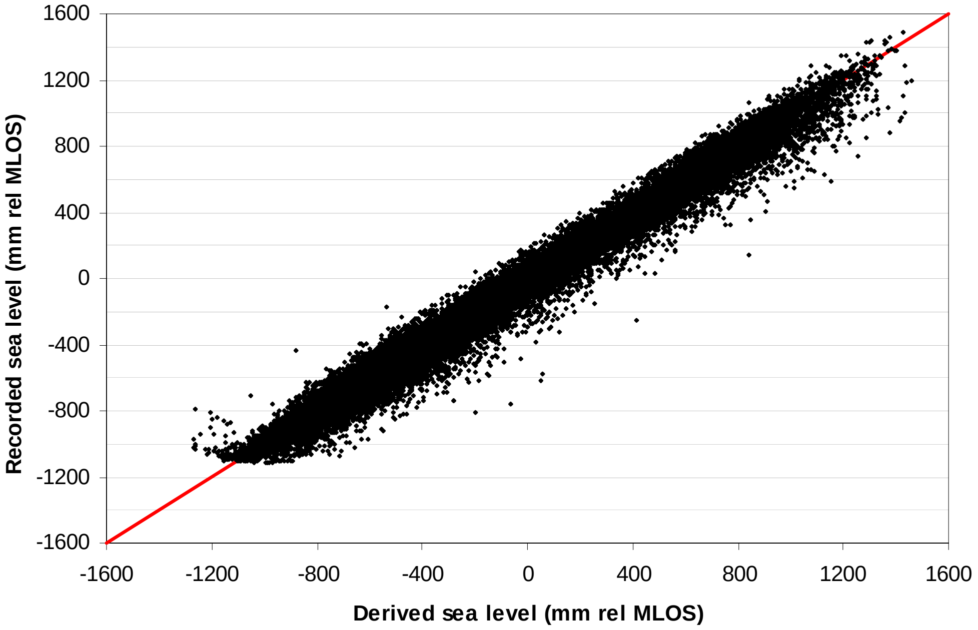


Figure 4b: Comparison of derived (horizontal axis) and recorded (vertical axis) sea level for Port Chalmers, 17 August 1999 to 15 November 2002. Note: MLOS adjusted to 0 m for comparison.

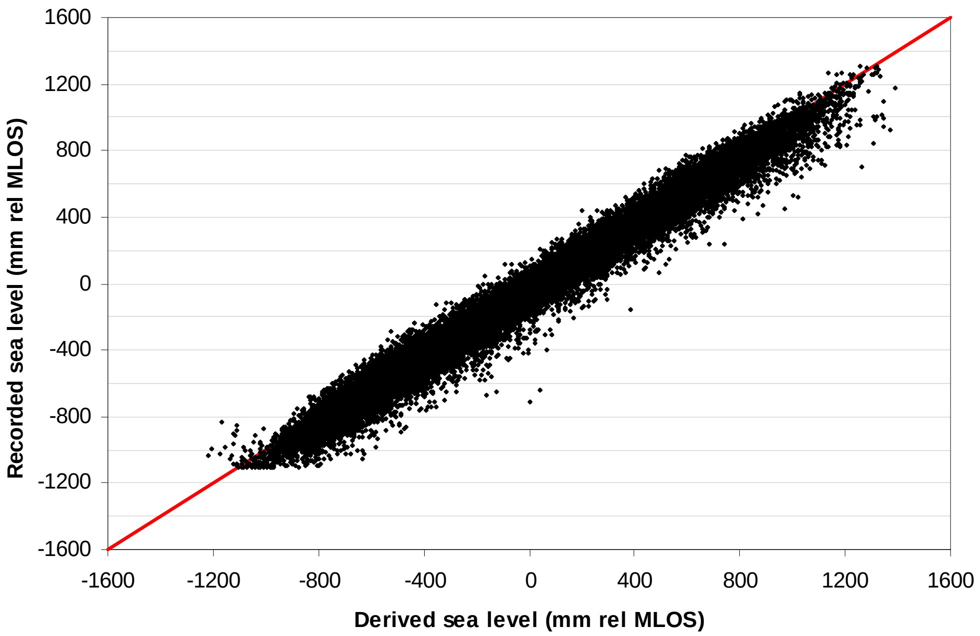


Figure 4c: **Comparison of derived (horizontal axis) and recorded (vertical axis) sea level for Spit Jetty, 17 August 1999 to 15 November 2002. Note: MLOS adjusted to 0 m for comparison.**

The derived time series, extending from April 1961 to November 2002, provided a substitute for 41 years of sea-level data. This 41-year record of combined tides and storm surge was then analysed to determine the joint probability of tides and storm surge based on the Revised Joint Probability Method (RJPM), and the r-Largest method, both using the program EXTLEV. The same assumptions and parameters were used as for the 5-year analysis of the recorded data.

For the Otago Harbour at Port Chalmers and Spit Jetty sites, extreme storm sea levels (with return periods of 2, 5, 10, 20, 50 and 100 years) were calculated using the r-Largest method and the RJPM. These results are summarised in Table 7 for the 41-year record of derived sea levels, with the results for the RJPM given in brackets. From Tables 6 and 7 we can see that the RJPM for the 41-year derived sea-level record gives higher extreme sea levels for each return period for both Port Chalmers and the Spit Jetty – especially at the higher return periods. However, overall, the r-Largest method for the 41 year derived record gave the highest extreme sea levels for each return period for both sites. Therefore, to be conservative, the r-Largest method has been used to calculate the recommended extreme sea levels for the other open coast locations.

The final flood-design extreme sea levels for various return periods (based on the r-Largest method and 41 years of derived data) are summarised in Table 8 and shown in

Figure 5. The values for the extreme sea level start at around 1.4 m above MLOS for a 2-year return period up to 1.7–1.8 m on open coast and 1.9 m in Otago Harbour (Dunedin) for a 100-year return period. These values compare with the maximum high tide (zero storm surge) predicted in the next 100 years for Otago Heads (Spit) of 1.16 m above MLOS and a Mean High Water Spring (MHWS) of 0.8 m above MLOS. It should also be noted that we expect that the extreme sea levels for the various return periods will be accurate to within approximately ±0.3m. This may be able to be more accurately predicted as more data along the coastline becomes available (e.g. preferably more sea level sites with long records of recorded sea level and/or higher resolution bathymetry data for better defining the NIWA tide model together with additional, long weather and sea level records at locations where return periods are required - for calibrating wind set-up and inverted barometer along the coast).

Table 7: **Estimated extreme sea levels for various return periods (rel. to MLOS Dunedin-2000) in Otago Harbour, using 41 years of derived sea level record, a 20-hour storm event, a Gumbel (EV1) fit and the r-Largest method (RJPM in brackets).**

Location	Sea level (m rel. MLOS Dunedin-2000)					
Return period (y)	2	5	10	20	50	100
Otago Heads (at Spit Jetty)	1.41 (1.36)	1.47 (1.41)	1.53 (1.47)	1.59 (1.52)	1.67 (1.58)	1.72 (1.63)
Otago Harbour (at Port Chalmers)	1.48 (1.42)	1.54 (1.48)	1.60 (1.54)	1.66 (1.59)	1.74 (1.65)	1.80 (1.70)

The computed extreme sea levels, for all required return periods, can be converted approximately to Dunedin Vertical Datum (DVD-1958) by adding 0.12 m. It has been assumed that the MLOS at all 7 open-coast locations does not vary significantly from that in Otago Harbour, in lieu of precise levelling at each location.

One option to utilise the extreme sea level values in Table 8 as boundary conditions for river models, is to combine a tide time series with amplitude equal to the site mean high water spring (MHWS), with a constant storm surge that is equivalent to the difference between the value of the extreme sea level and the MHWS level. MHWS values for the 8 locations of interest are specified in Table 9.

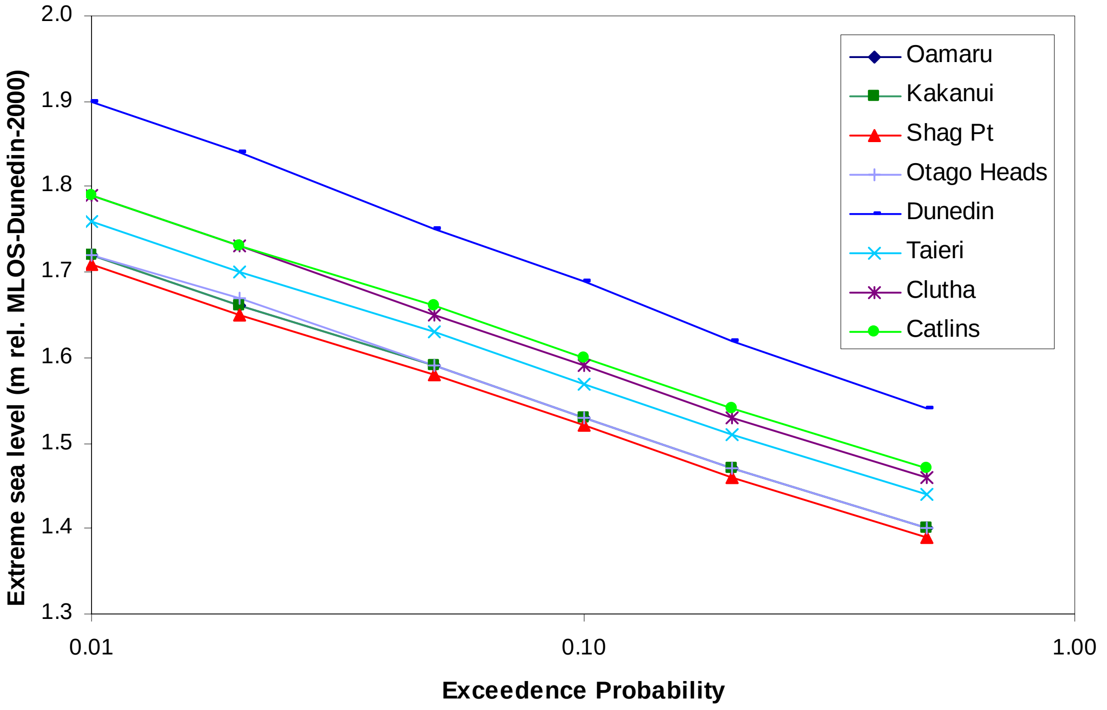


Figure 5: Comparison of recommended extreme sea levels (m rel. MLOS Dunedin-2000) as a function of annual exceedance probability to be used for river-flood modelling purposes. Note: add 0.12 m to put in terms of the LINZ DVD-1958.

Table 8: Recommended extreme sea levels (m rel. MLOS Dunedin-2000) to be used for design purposes to the nearest 0.1 m, with results to two-decimal places in parentheses. Note: add 0.12 m to put in terms of the LINZ DVD-1958.

Location	**Sea level (m rel. MLOS Dunedin-2000)**					
Return period (yr)	**2**	**5**	**10**	**20**	**50**	**100**
Oamaru	1.4 (1.40)	1.5 (1.47)	1.5 (1.53)	1.6 (1.59)	1.7 (1.66)	1.7 (1.72)
Kakanui River	1.4 (1.40)	1.5 (1.47)	1.5 (1.53)	1.6 (1.59)	1.7 (1.66)	1.7 (1.72)
Shag Point	1.4 (1.39)	1.5 (1.46)	1.5 (1.52)	1.6 (1.58)	1.7 (1.65)	1.7 (1.71)
Otago Heads (at Spit Jetty)	1.4 (1.40)	1.5 (1.47)	1.5 (1.53)	1.6 (1.59)	1.7 (1.66)	1.7 (1.72)
Otago Harbour (at Dunedin)	1.5 (1.54)	1.6 (1.62)	1.7 (1.69)	1.8 (1.75)	1.8 (1.84)	1.9 (1.90)
Taieri River	1.4 (1.44)	1.5 (1.51)	1.6 (1.57)	1.6 (1.63)	1.7 (1.70)	1.8 (1.76)
Clutha River	1.5 (1.46)	1.5 (1.53)	1.6 (1.59)	1.7 (1.65)	1.7 (1.73)	1.8 (1.79)
Catlins River	1.5 (1.47)	1.5 (1.54)	1.6 (1.60)	1.7 (1.66)	1.7 (1.73)	1.8 (1.79)

Table 9: **Summary of MHWS at 8 locations of interest**

Site	Mean High Water Spring (MHWS) m
Oamaru	0.82
Kakanui River	0.82
Shag Point	0.82
Otago Harbour at Spit (Heads)	0.80
Otago Harbour at Port Chalmers	0.87
Otago Harbour at Dunedin Port	0.91
Taieri River	0.86
Clutha River	0.89
Catlins River	0.89

It should be noted that the return-period estimates of extreme sea levels do not include tsunami or other meteorological and climate effects. Other smaller sea level contributions that should be noted, and taken into consideration when determining extreme sea levels for ocean boundary conditions for river-flood modelling are (Ministry for the Environment, 2004):

- Seasonal (annual) cycle due to summer heating and winter cooling of ocean waters on the continental shelf. This can add about 0.03 m to the sea level in autumn and a corresponding drop in spring/early summer;

- El Niño/La Niña (e.g., the mean level of the sea can rise by about 0.15 m in strong La Niña conditions, and fall by a similar amount in strong El Niño conditions);

- Interdecadal Pacific Oscillation (IPO) is a longer period El Niño-like phenomenon across the Pacific that cycles every 20-30 years (e.g., when the IPO is in its negative phase, which we are likely to experience over the next 20 to 30 years, the mean level of the sea is likely to be approximately 0.05 m higher);

- Long-term sea level rise due to climate change. Mid-range projections are for a sea level rise of 0.2 m by 2050, and 0.5 m rise by 2100.

These need to be combined where required. For instance, in 50 years time, a period with an El Niño and negative IPO could exhibit a mean level of the sea that is around 0.4 m higher, which includes the projected rise in mean sea level.

None of the extreme sea levels include wave set-up and run-up.

4. Conclusions

Based on available sea level and weather data for the Otago coast, extreme storm sea levels with return periods of 2, 5, 10, 20, 50 and 100 years were estimated for eight locations along the Otago coastline (including Otago Harbour at Dunedin).

Derived values for the extreme sea level are given in Table 8. Extreme sea levels start at around 1.4 m above MLOS for a 2-year return period up to 1.7–1.8 m on open coast and 1.9 m in Otago Harbour (Dunedin) for a 100-year return period. These values compare with the maximum high tide (zero storm surge) predicted in the next 100 years for Otago Heads (Spit) of 1.16 m above MLOS and a Mean High Water Spring (MHWS) of 0.8 m above MLOS.

One option to utilise the extreme sea level values in Table 8 as boundary conditions for river models, is to combine a tide time series with amplitude equal to the site mean high water spring (MHWS), with a constant storm surge that is equivalent to the difference between the value of the extreme sea level and the MHWS level. MHWS values for the 8 locations of interest are specified in Table 9.

The computed extreme sea levels, for all required return periods, can be converted approximately to Dunedin Vertical Datum (DVD-1958) by adding 0.12 m. This assumes that the actual mean level of the sea (or MLOS) at all 7 open-coast locations does not vary significantly from that in Otago Harbour for any given period of year(s), in lieu of precise levelling at each location.

Recommended extreme sea levels only include the tide and storm surge. They do not include tsunami or several other meteorological and climate components that can substantially increase sea levels at the coastline e.g., wave set-up, wave run-up, seasonal to inter-decadal variations in sea level and finally the project rise in the mean level of the sea from climate change.

5. Acknowledgements

We would like to acknowledge assistance received from LINZ who provided tide data for the Port of Dunedin, Port Chalmers and Otago Heads at the Spit Jetty.

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Appendix A

Plots of storm surge (SS) versus inverted barometer (IB)

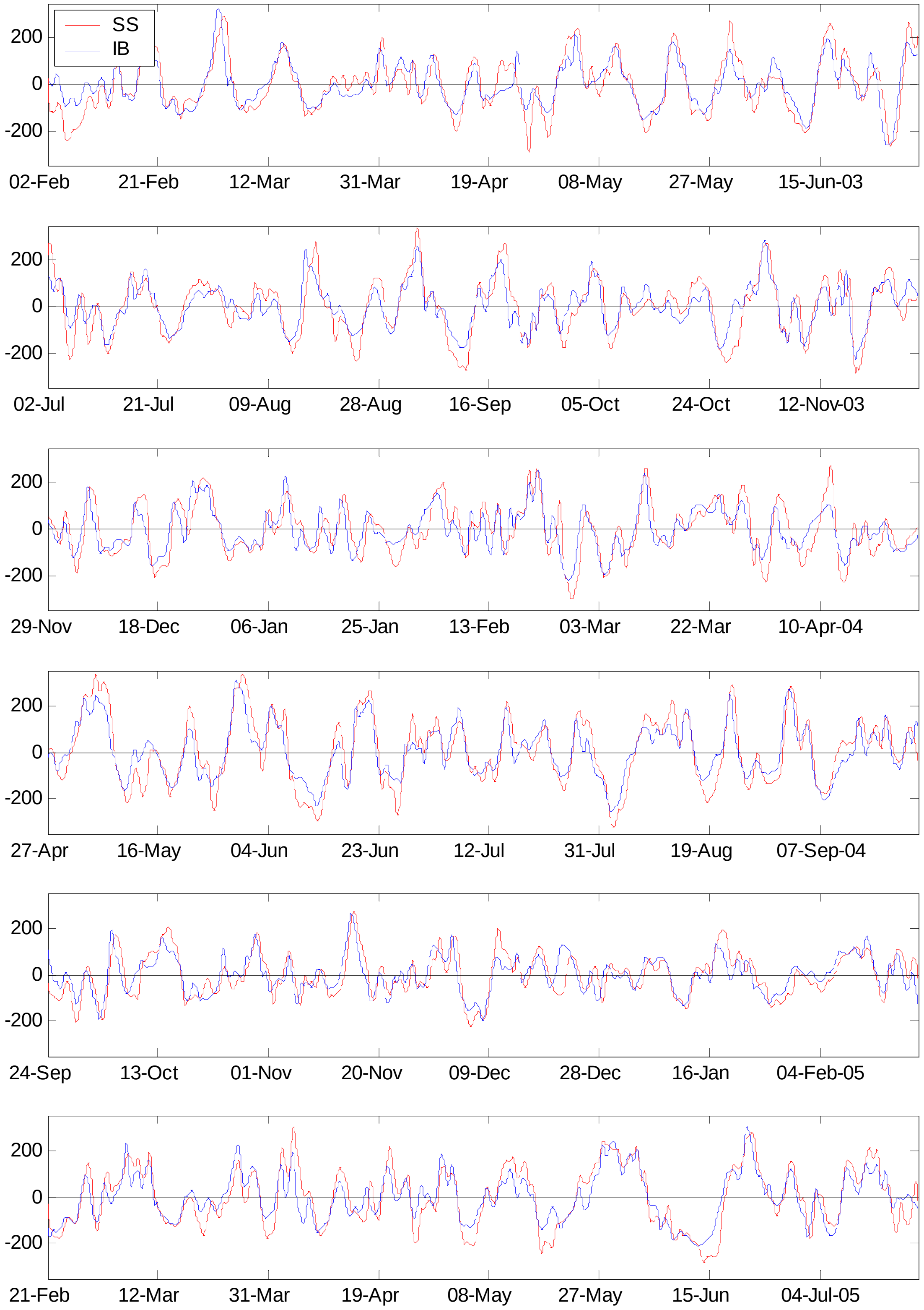

Figure A1: **Green Island storm surge (red) and inverted barometer (blue) from 2 February 2003 to 21 July 2005. Levels are in mm.**

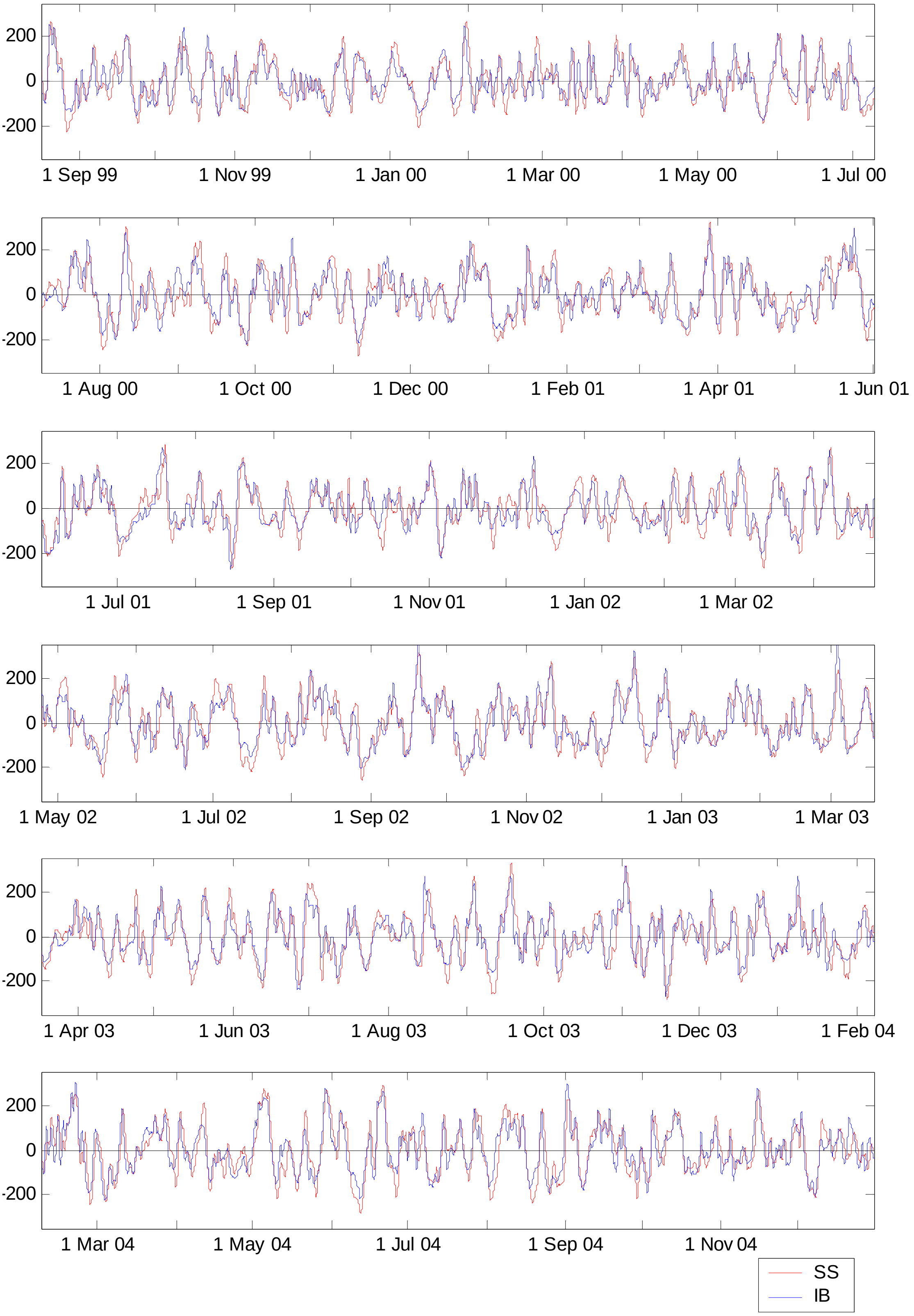

Figure A2: Spit Jetty storm surge (red) versus inverted barometer (blue) from August 1999 to December 2004. Levels are in mm.

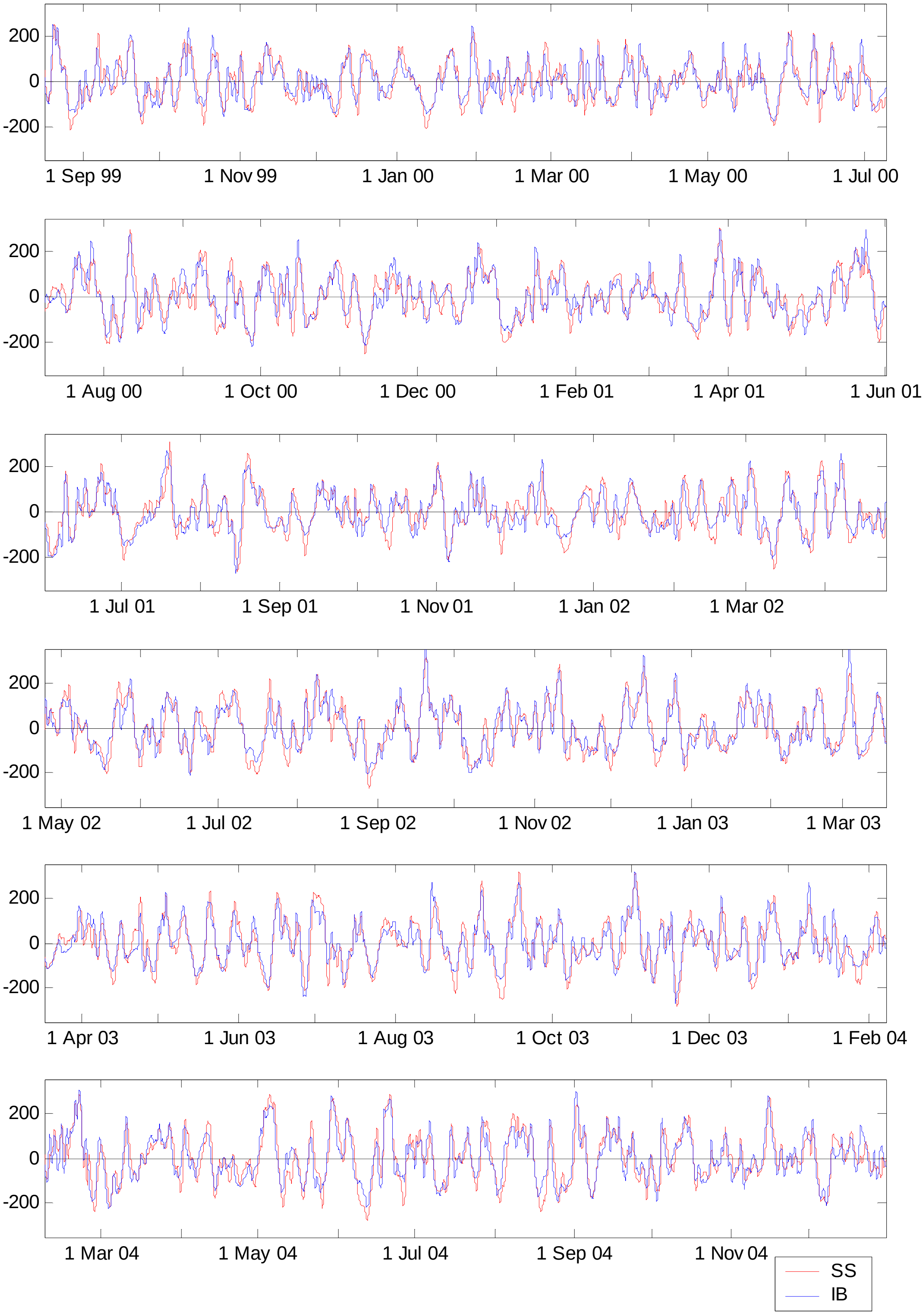

Figure A3: Port Chalmers storm surge (red) versus inverted barometer (blue) from August 1999 to December 2004. Levels are in mm.

Appendix B

Plots of wind stress set-up

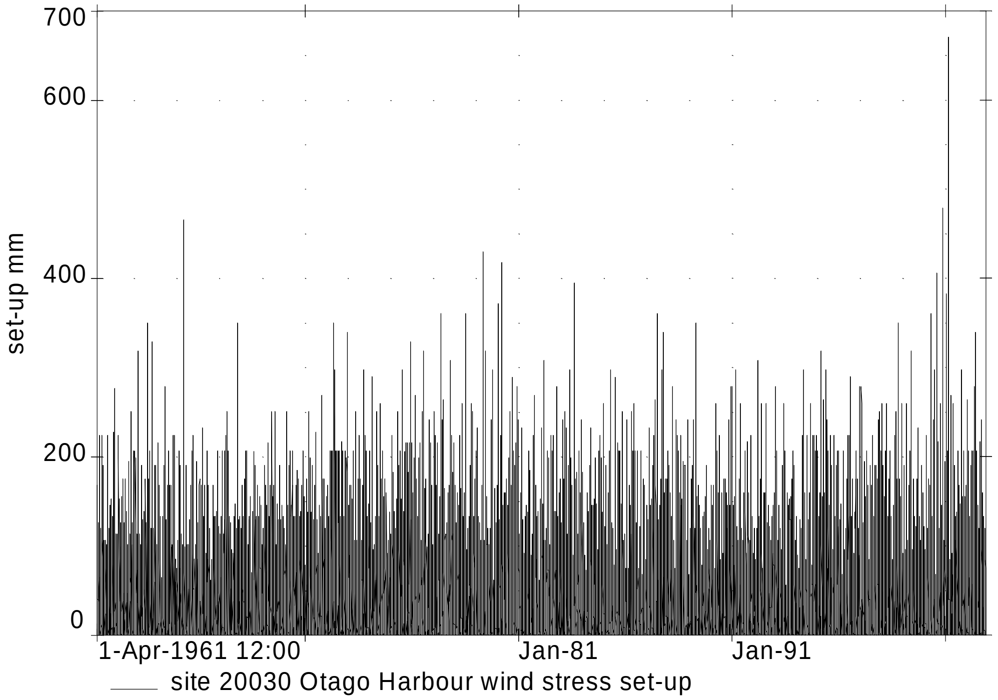

Figure B1: **Increase in sea level (mm) due to 'onshore' wind set-up (i.e. wind stress) for Otago Harbour (Dunedin and Port Chalmers).**

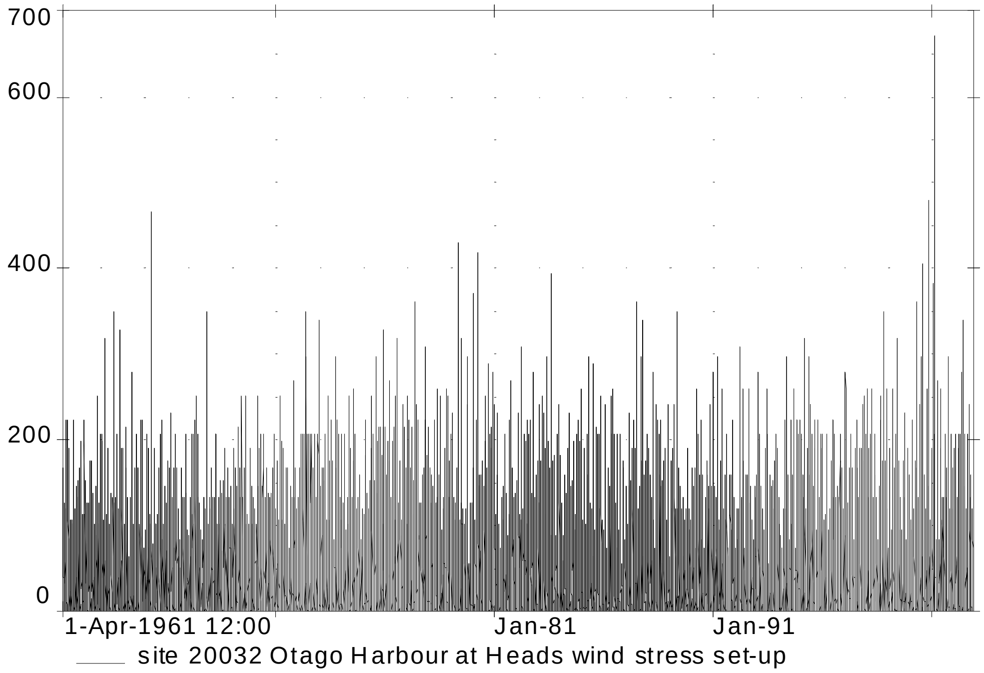

Figure B2: **Increase in sea level (mm) due to 'onshore' wind set-up (i.e. wind stress) for Otago Harbour at Heads and other open coast sites.**

Appendix C

Plots of storm surge (including 20% factor for other storm-surge components e.g., coastally-trapped waves and effects of a moving storm system)

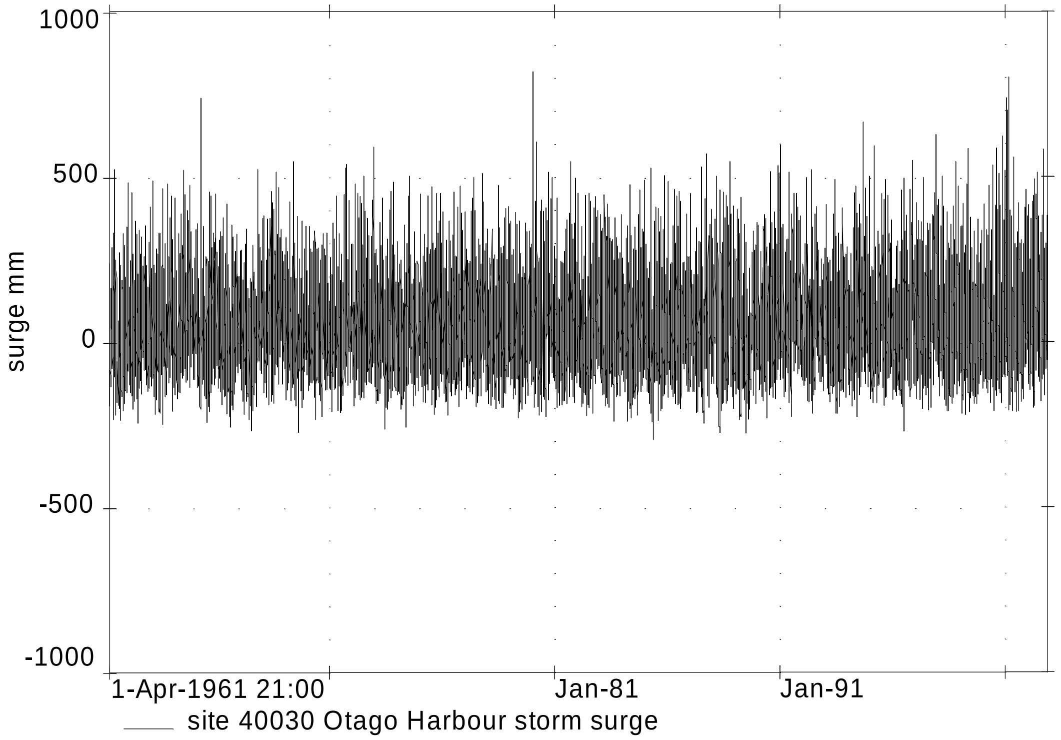

Figure C1: Storm surge for Otago Harbour (Dunedin and Port Chalmers)

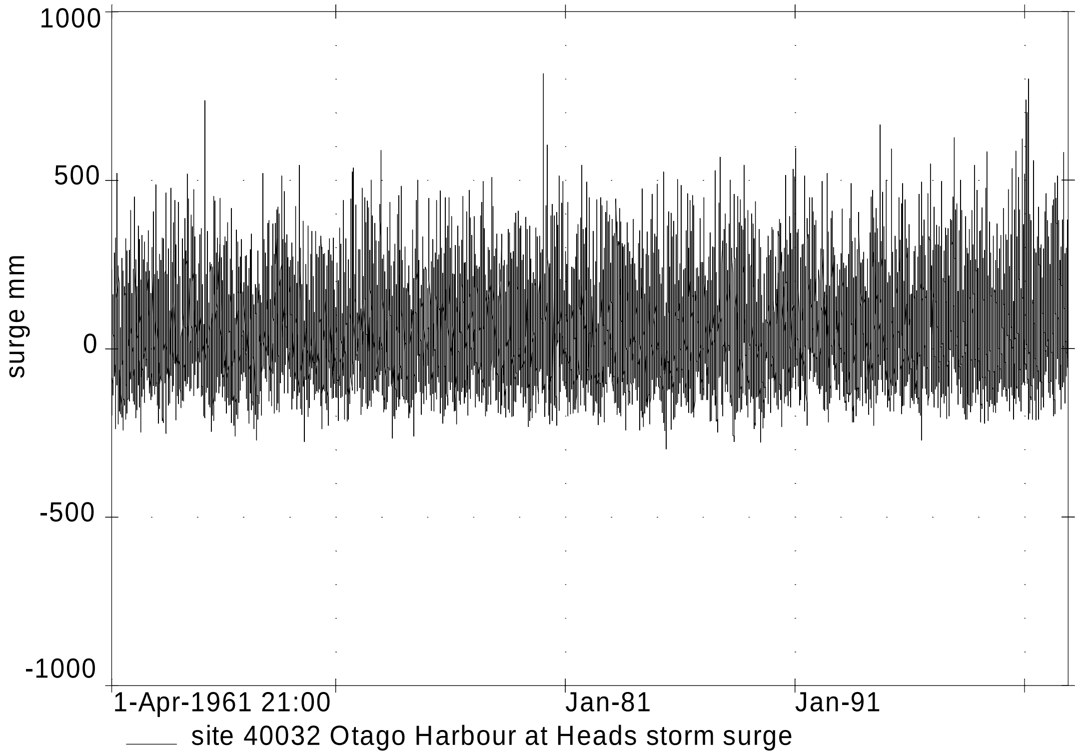

Figure C2: Storm surge for Otago Harbour at Heads and other open coast sites