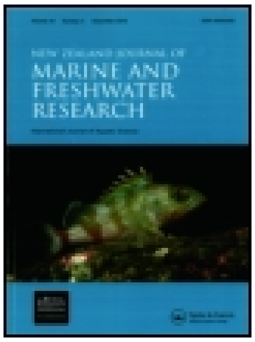

Taylor & Francis
Taylor & Francis Group

New Zealand Journal of Marine and Freshwater Research

ISSN: 0028-8330 (Print) 1175-8805 (Online) Journal homepage: https://www.tandfonline.com/loi/tnzm20

Short-term variations in sea level (2–15 days) in the New Zealand region

Derek G. Goring

To cite this article: Derek G. Goring (1995) Short-term variations in sea level (2–15 days) in the New Zealand region, New Zealand Journal of Marine and Freshwater Research, 29:1, 69-82, DOI: 10.1080/00288330.1995.9516641

To link to this article: https://doi.org/10.1080/00288330.1995.9516641

New Zealand Journal of Marine and Freshwater Research, 1995: Vol. 29: 69–82
0028–8330/95/2901–0069 $2.50/0

Short-term variations in sea level (2–15 days) in the New Zealand region

DEREK G. GORING
National Institute of Water & Atmospheric Research Ltd
P. O. Box 8602
Christchurch, New Zealand

Abstract Sea level data from 15 tide gauges around New Zealand were analysed to assess the effect of meteorological forcing. Many of the data were of poor quality and special care was needed with the data processing to make the data usable. Analyses were carried out in both the time domain and the frequency domain in the frequency band from 1 to $9° h^{-1}$, resulting in the same general outcomes: that sites exposed to the prevailing westerly winds respond to changes in barometric pressure at greater than the conventional inverted barometer response, whereas eastern sites sheltered from the west respond at less than the inverted barometer. At northern sites, sea level generally changes in advance of changes in barometric pressure by 3 to 4 hours; however, for individual events, the reverse may be true. For other sites (from the mid-North Island southwards), sea level generally responds to barometric pressure changes after a few hours. For north-eastern sites, the percentage of the variation in sea level which can be explained by changes in barometric pressure is low and there appears to be no correlation between sea level and regional wind stress, leading to the conclusion that, to a large extent, variation in sea level is caused by waves propagating into the area.

M94022
Received 27 June 1994; accepted 1 December 1994

Keywords sea level; tide gauge; barometric factor; inverted barometer; coastal trapped waves; New Zealand; winds

INTRODUCTION

Barometric pressure is an important cause of short-term sea level variation. In isostatic conditions, sea level variation is related to barometric pressure changes by the inverted barometer (IB) response: 1 hPa change in pressure results in −10 mm change in sea level.

However, isostatic conditions rarely apply (particularly around islands such as New Zealand) and the relative importance of dynamic effects determines how applicable the IB response is. This study addresses this issue by analysing tide gauge records from 15 locations around the New Zealand coast.

Tide gauge records contain a whole spectrum of signatures, from the tide itself—whose influence spans the entire spectrum but is primarily in the range of periods less than 1 day—to secular and global eustatic changes which occur over periods of centuries. In New Zealand, tide gauge records for major ports are analysed in a routine manner by the Royal NZ Navy to identify the tidal constituents and Hannah (1990) analysed the records for the long-term secular changes. The present paper describes a small area in the spectrum between these two extremes, where sea level is primarily affected by meteorological effects arising from weather systems passing across New Zealand. One of the earliest researchers in this field was Doodson (1924) who analysed the meteorological perturbations of sea level at seven sites in the United Kingdom using least-squares analysis in the time domain. He found that barometric pressure and its gradient accounted for most of the variation in sea level once the tides are removed. Hamon (1966) carried out a similar analysis, with regression on barometric pressure only, for 17 sites around Australia. He found considerable variation in the

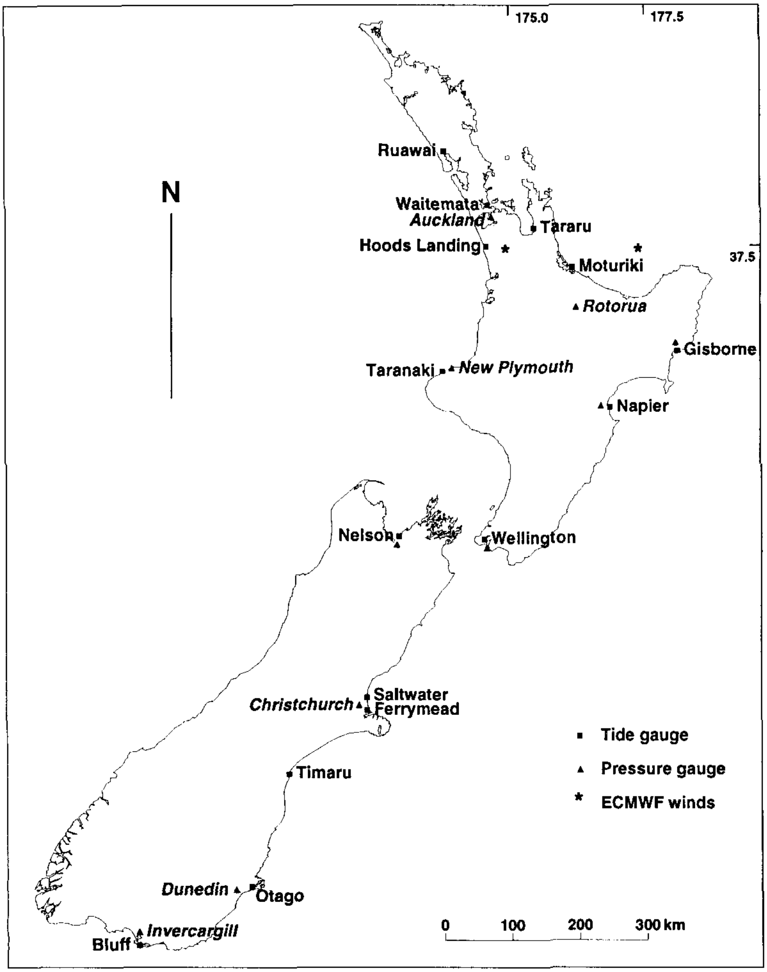

Fig. 1 Map showing locations of tide gauges, barometric pressure gauges, and ECMWF winds in New Zealand.

barometric factor (i.e., the response of sea level to change in barometric pressure) from +4.1 mm hPa^{-1} at Townsville on the east coast to –23.9 mm hPa^{-1} at Geraldton on the west coast. He attributed the wide variation to travelling continental shelf waves. Goring & Bell (1993) analysed a 19-year dataset from the Moturiki Island tide gauge in the Bay of Plenty (see Fig. 1) and found a barometric factor of –6.0 mm hPa^{-1}. Only 33.5% of the overall variation in sea level was explained by barometric pressure, and like Hamon (1966), they found that including pressure gradients or winds from the European Centre for Medium-range Weather Forecasting (ECMWF) model had little effect. There was considerable seasonal variation in both the barometric factor and the coefficient of determination, both being larger in the winter than the summer. The Moturiki record also showed evidence of a secondary peak occurring a day or more after a sea level peak caused by passage of an intense low-pressure system. These were attributed to coastal trapped waves.

This paper extends the work of Goring & Bell (1993) to other tide gauge records around the New Zealand coast and incorporates another 2 years of data from Moturiki. The objectives were to investigate the variation of barometric factors around the New Zealand coast and to determine whether the secondary peaks in sea level observed at Moturiki are evident elsewhere. The paper presents information obtained from analysis of observed data and highlights the anomalies in the information when it is compared with the conventional theory. Some suggestions are made concerning the causes of the anomalies, highlighting the need for extensive modeling to better explain them.

OBSERVATIONS AND METHODS

Sea Level Data

Figure 1 shows the locations of the 15 tide gauges under consideration; Table 1 lists the periods of record available for analysis and the source of the data. Of all the sites under consideration, only Moturiki Island is on the open coast. Most others are in enclosed harbours and several are in rivers. The quality of the data varied considerably, with some records having significant errors in both amplitude and time, as well as gaps of several weeks. Many of these data are collected by port companies for navigation purposes only, and it was never intended that they be used for detailed analysis such as this. However, the paucity of good quality tide gauge records makes it necessary to make the most of these inferior data.

The data from Ferrymead Bridge were of particularly poor quality, being high and low tides, digitised from charts. The time resolution of these data was so inaccurate that it was necessary to use times for high and low tides predicted using the tidal constituents in preference to the digitised times. Hourly data were obtained by interpolating between high and low tides (and between low and high tides) using a cosine function. Goring & Bell (in press) assessed the efficacy of cosine interpolation and showed that for tidal analysis the method is accurate, providing the signal is primarily semi-diurnal and does not contain appreciable energy in the higher modes as a result of compound and over-tides. For Ferrymead, which is at the head of a large estuary, we expect that compound and over-tides *are* significant, so cosine interpolation is not appropriate for tidal analysis. However, for the analysis carried out here, in which we eliminate the diurnal, semi-diurnal, and higher-mode tides, the cosine interpolation is considered to be appropriate. Indeed, it is the only alternative to discarding the data completely.

After plotting the sea level data and removing any obvious errors, the hourly data were processed in the following manner:

(i) the mean and any linear trend were removed;

(ii) the gaps were replaced with tidal predictions;

(iii) the data were band-pass filtered to remove both the tide and long-period effects;

(iv) the gaps were re-introduced;

Table 1 Tide gauge data used in the analyses. The start and finish dates (yymmdd) denote the digitised data available for this study; additional data may have become available subsequently. Elapsed months is the number of months of usable data from the record. NIWA denotes that the data have been collected by NIWA and are archived in digital form on the NIWA Water Resources Archive. Env W, Environment Waikato; WRC, Wellington Regional Council; CRC, Canterbury Regional Council; CCC, Christchurch City Council. Port Co data have been obtained in chart form from the Royal New Zealand Navy Hydrographic Office and digitised, except for Timaru Port Co which supplied digital data directly.

Site	Agency	Start date	Finish date	Elapsed months
N Wairoa at Ruawai	NIWA	690829	740605	52
Waitemata Harbour	Port Co	840104	920229	97
Thames Tide at Tararu	Env W	900525	921101	28
Waikato at Hoods Landing	NIWA	840310	920828	101
Moturiki Island	NIWA	730615	940401	248
Gisborne Harbour	Port Co	841001	910323	65
Napier Harbour	Port Co	860901	881229	27
Taranaki Harbour	Port Co	860212	910501	59
Wellington Harbour at Waterloo Wharf	WRC	900814	921101	26
Nelson Harbour	Port Co	870501	881031	19
Saltwater Creek at Kairaki	CRC	861018	871020	12
Heathcote at Ferrymead Bridge	CCC	740101	881228	161
Timaru Harbour	Port Co	910508	920329	11
Otago Harbour	Port Co	821230	890207	57
Bluff Harbour	Port Co	821228	860621	36

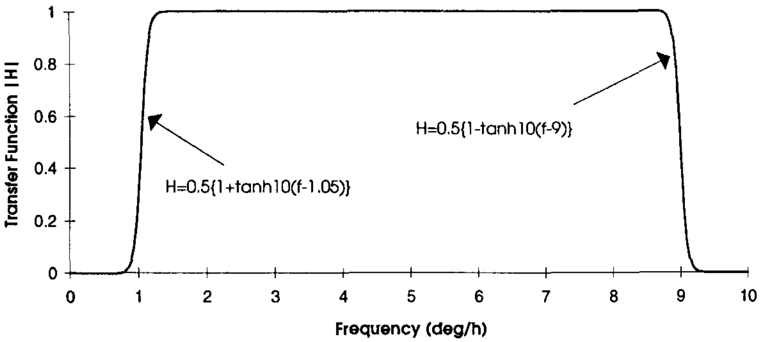

Fig. 2 Transfer function of the boxcar filter with tanh transitions and half amplitude frequencies of 1.05 and 9° h^{-1}.

(v) the hourly data were decimated to 6-hourly data.

Gaps in the record have the potential for introducing errors into the analysis unless they are carefully handled. The procedure adopted here was to fill the gaps with tidal predictions before filtering, but to re-introduce the gaps for analysis in the time domain. An alternative would have been to simply fill the gaps with zeros after removing the mean, but Goring & Bell (in press) showed that for gaps larger than a few days this causes leakage of energy from the semi-diurnal tides into the low-frequency region of the spectrum. The leaked energy is a small proportion of the total energy in the semi-diurnal band but is significant in terms of the relatively lower energy in the low-frequency region.

Goring & Bell (unpubl. data) showed that at Moturiki Island the semi-diurnal tides account for 96.63% of the energy in the signal. These tides must be removed completely, otherwise their energy can spread into lower-frequency bands by aliasing when the data are decimated (Goring & Bell in press). For these reasons a boxcar filter in the frequency domain as shown in Fig. 2 was used. The boxcar has a hyperbolic tangent transition from zero to unity at the low-frequency end and from unity to zero at the high-frequency end. The half amplitude frequencies were 1.05 and 9° h^{-1}, corresponding to periods of 14.3 days and 40 h, respectively. Thus, variations in sea level with periods outside of this range were eliminated.

Decimation to 6 hourly intervals was an arbitrary choice, and data at this interval were used only for plotting. For analysis in the time domain, the data were further decimated to 18 h, giving a Nyquist frequency of 10° h^{-1}. Figure 2 shows that the energy at this frequency and above has been reduced to zero.

Climate data

Figure 1 shows the locations of the airports where the MSL atmospheric pressure data were obtained. For the purpose of analysis, the atmospheric pressure data were converted from hecto-Pascals to an equivalent inverted barometer (IB) sea level in mm using the commonly-used transformation (−10.0 mm hPa^{-1}) and the datum adjusted to yield an overall mean of zero for each record. These derived data will be referred to as IB.

Exactly the same smoothing procedure was employed for the IB data as was described for the sea level data, using the boxcar filter shown in Fig. 2.

Wind vectors at 10 m above sea level derived from the European Centre for Medium-range Weather Forecasting (ECMWF) model were obtained for a node in the Bay of Plenty as shown in Fig. 1. These winds are calculated from analysis of pressure, temperature, moisture, and wind formation, with allowance made for Coriolis force and curvature of pressure gradients. Thus, they provide a better estimate of the regional wind field than the locally measured wind and are more appropriate than the simple pressure gradient used by Doodson (1924), the pioneer paper in this field.

ECMWF model winds are presented as east*ward* and north*ward* winds. Therefore, to avoid confusion, the signs have been reversed for this study so that they become conventional east and north winds. For analysis, the wind velocities were converted to a wind shear stress using the relationships of Wu (1982) and to obtain an estimate of the total force on the sea surface during a particular event, the wind shear was integrated over the duration of the event to produce cumulative wind shear stress, expressed in N h m^{-1}.

Regression analysis

Regression analysis was carried out in both the time domain and the frequency domain. The methods employed are only summarised here.

Time domain

In the time domain, sea level y_i is expressed as a linear function of IB sea level x_i as follows:

$$y_i = h_{i,k} x_i + v_i \qquad (1)$$

where $h_{i,k}$ is the barometric factor and v is a noise term. The subscript i takes values of 0,1,2,...,N, where N is the number of data at 18 h intervals in the record. The additional subscript k in the barometric factor denotes the number of data used in its estimation. Thus, for example, $h_{100,10}$ denotes the barometric factor centred at data point 100, calculated using the data points from 96 to 105. The noise term comprises measurement noise, caused by errors in the data, and model noise, caused by the error associated with using Eq. 1 to represent the physical system.

The literature contains many variations to Eq. 1. For example, Hamon (1966) assumed that the barometric factor was a constant; Crisciani et al. (1987) allowed for lags of up to 80 h between IB sea level and sea level response; Doodson (1924) included the effect of pressure gradients, thus making h and x vectors. However, all researchers solve their equivalent of Eq. 1 using the method of least squares and this technique will be used here also.

Another approach favoured by oceanographers is to assume that the barometric factor is unity and to rearrange Eq. 1 by subtracting the IB sea level from actual sea level to obtain adjusted sea level anomaly. The analysis then involves scrutiny of the noise v to determine which part of it is data error and which part is error associated with model assumptions; and whether the latter contains information about the presence of other factors affecting sea level. In the open ocean, away from the influence of land masses, there are fewer such factors and they are relatively small compared to the IB effect, so this approach is valid. Indeed, Ponte (1994) shows by numerical experiments that in the open ocean the response to pressure change is essentially static and wind-driven sea level signals are relatively small. However, for coastal sea level data the anomaly must be seen in relation to the IB effect to assess its relative importance, so the approach suggested by Eq. 1 is preferred.

Young (1984) describes Eq. 1 as a "moving rectangular window" in which all the data receive equal weight. The numerical technique involves simply stepping through the data, adding a new value and subtracting the oldest value. This generates a time series of barometric factor and coefficient of determination r^2 at 18 h intervals. To obtain an overall estimate of barometric factor the window is enlarged to include the entire duration of the record, with gaps excluded.

An alternative approach is to use a "moving exponential window" in which past data receive a reduced weighting relative to present data. The moving rectangular window tends to smear individual events and is most suitable for analysis of historical sequences. However, for analysis of individual events (and for forecasting sea level a few days ahead), the moving exponential window is more appropriate, as will be demonstrated.

Frequency domain

Analysis in the frequency domain is the method preferred by most researchers (e.g., Garrett & Toulany 1982; Palumbo & Mazzarella 1982; Crisciani & Ferraro 1989). The method involves splitting the time series into a set of N records of equal length, then transforming these to the frequency domain and using least squares techniques to fit the coefficient H_i in:

$$Y_{i,j} = H_i X_{i,j} + V_i \qquad (2)$$

where $Y_{i,j}$ and $X_{i,j}$ represent the Fourier transforms of sea level and IB sea level, respectively, subscript i denotes the i-th Fourier component and subscript j denotes the j-th Fourier series. V_i is the noise term, comprising both measurement and model error, as described earlier. The analysis generates a series of complex numbers H_i, called the transfer function, and real numbers $\gamma^2{}_i$, called the coherence, as a function of frequency. The magnitude, or gain, of the transfer function is equivalent to the barometric factor of time domain analysis and the coherence is equivalent to the coefficient of determination. Frequency domain analysis gives an additional quantity in the form of the phase of the transfer function. Phase, when divided by frequency, gives the time shift between the two signals.

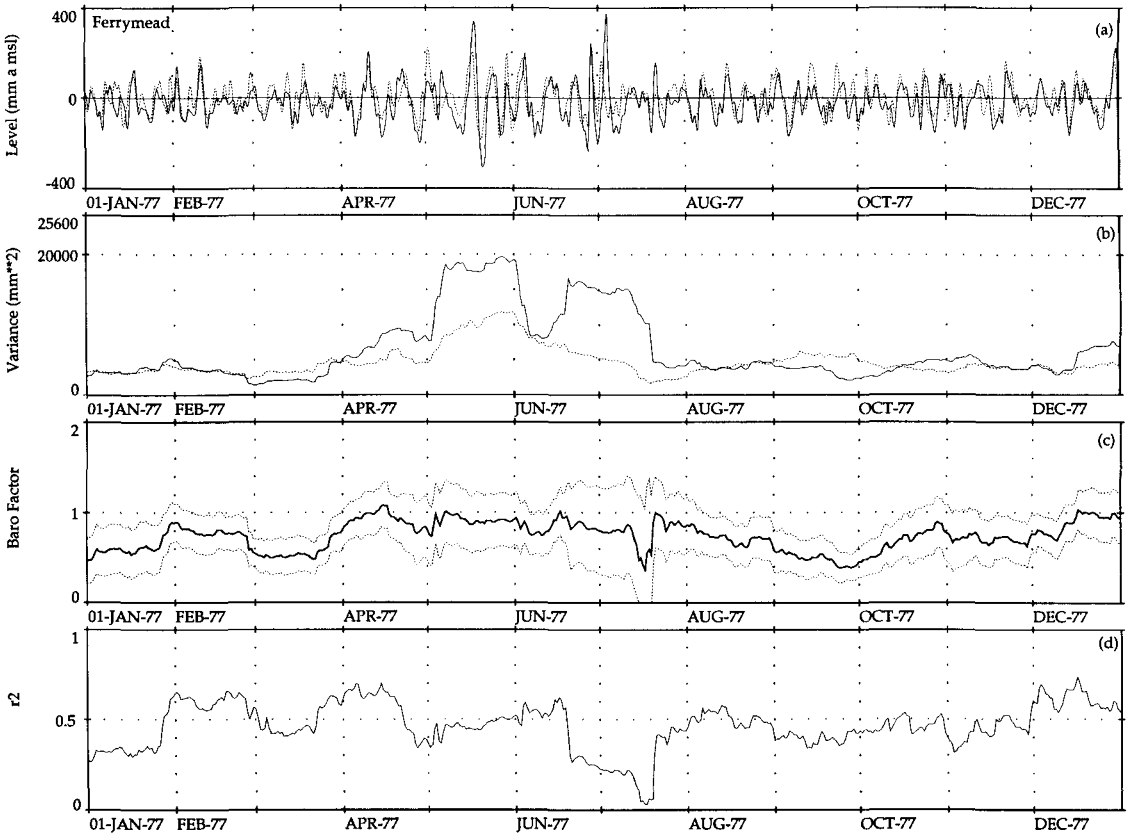

Fig. 3 Typical results of regression analysis in the time domain for Heathcote at Ferrymead Bridge, showing time records of filtered sea level (solid line) and IB (dashed line) (**a**), variances of filtered sea level and IB sea level (**b**), barometric factor with the 95% confidence limits (**c**), and coefficient of determination r^2 (**d**). The analysis used a moving window of 720 h and the calculated quantities are assigned to the centre of the window.

RESULTS

Analysis in the time domain

Typical results of analysis in the time domain are presented in Fig. 3. The example shows the results for Ferrymead data for the year of 1977. The figure comprises four plots lined up in time. The top plot compares sea level (solid line) with IB (dashed line) and even a cursory inspection shows that although the signals agree well in many places, there are significant events when sea level has much larger amplitude fluctuations than IB (mid-May, for example) and others where sea level has much smaller amplitude fluctuations than IB (March, for example). This is illustrated more clearly in the second plot which shows the variances of the two signals, based on 40 samples at 18 h intervals. The plot shows larger variances in winter than in summer, with the variance of sea level exceeding that of IB by substantially more in winter than in summer. This result was found at all sites and in almost every year.

The third plot shows the time series of barometric factor $h_{i,40}$ with its error bounds, calculated from least-squares analysis of Eq. 1, using a moving window of 720 h, comprising 40 samples at 18 h intervals. This plot needs to be examined in conjunction with the lowest plot which shows the variation of the coefficient of determination r^2 with time: unity implying that IB fully explains the sea level response. In periods when the barometric factor is significantly less than unity (early January, March, September, October, and November), the coefficient of determination is also significantly less than unity, signifying that at these times, factors other than barometric pressure have a significant effect on sea level. However, even when the barometric factor is approximately unity, the coefficient of determination is of the order of 0.6, indicating that 40% of the variance of sea level is caused by other factors.

Notice that the event which occurred at the beginning of May (in which IB greatly exceeded sea level) had almost no effect on the barometric factor. A similar event occurred at the end of May. This is the smearing effect mentioned earlier, caused by using a moving rectangular window for regression. If a moving exponential window had been used for the analysis, the barometric factor would have varied from 0.3 at the start of the month when IB exceeded sea level, to 2.5 for the large sea level event in the middle of the month and back to 0.3 again for the large IB event at the end of the month. Such large swings in barometric factor are important for purposes such as real time forecasting of sea level from IB, but cannot easily be interpreted in the historical analysis being considered here.

Plots such as Fig. 3 were prepared for the entire 82 station-years of sea level data that were available for analysis. The plots were used to identify periods when sea level departed significantly from IB response and to compare response between locations.

For each site, the entire time record (excluding gaps) was analysed for barometric factor and the results are presented in Table 2. A noticeable feature of the table is the way in which the variance of IB varies from south to north, with the maximum at Dunedin Airport and the minimum at Auckland Airport. Variance is analogous to energy, so this implies that the barometric pressure forcing of sea level at Dunedin is greater than at Auckland. To determine whether this was simply a feature of the different periods of record that were analysed, the barometric pressure records at all the airports under consideration were analysed for a common 20-year period from July 1967 to July 1987. The results are presented in Table 3, which lists the variances, and Fig. 4 which compares the probability density functions at Auckland and Dunedin (i.e., the two extremes in variance) with the normal distribution. The analysis confirms the observation made from the data in Table 2 that the variance of barometric pressure decreases from south to north.

The technique described by Crisciani et al. (1987) of lagging IB by up to ±12 h and repeating the regression analysis to determine the lag at which the coefficient of determination is maximised, was found to make little difference to the results. Part of the reason for this can be seen in the top plot of Fig. 3 which shows no consistent lag between IB and sea level: sometimes IB leads sea level and at other times the reverse is true.

Doodson (1924) found that by including gradients of pressure in his analysis, there was an increase in the coefficient of determination r^2 from

Table 2 Results of analysis in the time domain on the entire record (excluding gaps) for each site. σ^2_{IB} is the variance (mm^2) of the band pass filtered inverted barometer sea level, σ^2_{SL} is the variance of the band pass filtered sea level, covar is the covariance, h is the dimensionless barometric factor, ε is the error bound on barometric factor to the 95% confidence limit, r^2 is the coefficient of determination, and N is the number of data (18 h intervals) in the record.

Site	σ^2_{IB}	σ^2_{SL}	*covar*	h	ε	r^2	N
Ruawai	2673	6179	2755	1.0305	0.0051	0.4594	1910
Waitemata	2989	2876	2008	0.6719	0.0023	0.4690	3901
Tararu	3406	3427	2725	0.8000	0.0036	0.6363	1153
Moturiki I.	3020	2572	1987	0.6580	0.0013	0.5083	10021
Hoods Landing	3133	10241	2617	0.8353	0.0050	0.2134	4084
Gisborne	3637	3934	2418	0.6648	0.0031	0.4086	2735
Napier	3334	3018	2640	0.7918	0.0033	0.6926	1047
Taranaki	3260	6369	3740	1.1472	0.0032	0.6737	2438
Wellington	3704	5115	3618	0.9766	0.0040	0.6907	1080
Nelson	3774	3878	2949	0.7815	0.0047	0.5944	754
Saltwater Creek	4233	4795	2874	0.6790	0.0074	0.4070	490
Ferrymead	4833	6138	3456	0.7150	0.0021	0.4025	6608
Timaru	4190	7055	3920	0.9355	0.0091	0.5198	393
Otago	5224	5518	4461	0.8539	0.0024	0.6904	2230
Bluff	4696	11052	6468	1.3020	0.0038	0.7620	1468

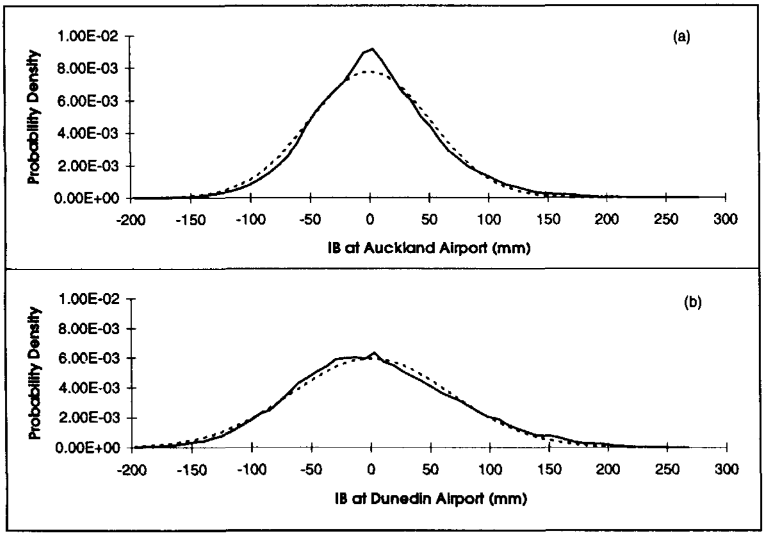

Fig. 4 Comparison of the probability density function for IB at Auckland Airport (**a**) and Dunedin Airport (**b**) with the normal distributions (dashed lines). Data from July 1967 to July 1987 were used in the analysis.

0.498 to 0.717 for Liverpool and from 0.623 to 0.762 for Newlyn. Nowadays simulated wind fields (e.g., ECMWF) winds are used in preference to gradients of pressure because they take account of other effects such as Coriolis and curvature of the isobars. However, including the ECMWF winds from the node in the Bay of Plenty (Fig. 1) affected only the third decimal place in r^2 for regression analysis of the sites in the vicinity (i.e., Waitemata, Tararu, Moturiki, or Gisborne).

Analysis in the frequency domain

Typical results from analysis in the frequency domain are presented in Fig. 5 for Bluff and Moturiki. Plots such as these were prepared for all the sites under consideration, except for Saltwater Creek and Timaru whose records were too short to make the analysis possible. Bluff and Moturiki were chosen for presentation because they represent two extremes in the results. For each site, five quantities are plotted as a function of frequency. For Moturiki both signals have spectral energy of less than 200 mm^2, but for Bluff the spectral energies are much larger. Furthermore, for Bluff the spectral energy of sea level is much larger than that for IB.

The lower three plots in Fig. 5 show the details of the transfer function, in the form of gain, phase, and coherence, along with their 95% confidence limits. The error bounds for Moturiki are much less than those for Bluff because the transfer function for Moturiki was calculated from 50 samples of 3600 h whereas for Bluff only 5 samples were available. For Bluff the gain is greater than unity indicating that sea level response to barometric pressure is greater than that of the inverted barometer, whereas for Moturiki it is less. The phase is greater than zero for Moturiki and less than zero for Bluff indicating that for Moturiki sea level generally *leads* barometric pressure whereas for Bluff sea level *lags* barometric pressure. The coherence for Bluff is generally greater than it is for Moturiki indicating that for Bluff a larger proportion of sea level variation is explained by barometric pressure than for Moturiki.

In order to compare the overall results of analysis in the frequency domain for all the sites, the quantities displayed in Fig. 5 were further

Table 3 Variances of band pass filtered barometric pressure, converted to inverted barometer, at various airports for the 20-year period from July 1967 to July 1987.

Airport	Variance (mm^2)
Auckland	2631
Rotorua	2887
Gisborne	3210
New Plymouth	2958
Wellington	3533
Nelson	3493
Christchurch	4485
Dunedin	4531
Invercargill	4402

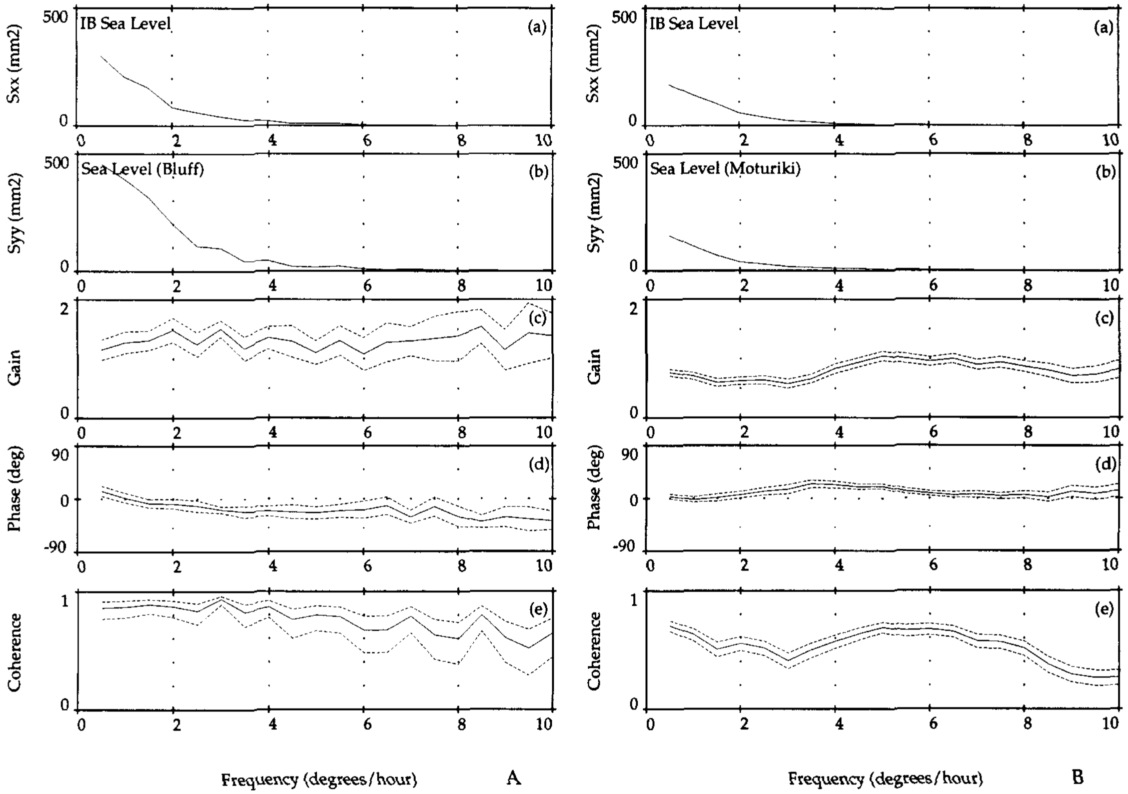

Fig. 5 Typical results of analysis in the frequency domain for Bluff (**A**) and Moturiki (**B**), showing the spectral energy for IB (**a**) and sea level (**b**) and the gain (**c**), phase (**d**), and coherence (**e**) of the transfer function. The dashed lines represent the 95% confidence limits. 3600 h samples were used (i.e., frequency intervals of 0.1° h^{-1}) in the analysis and the spectra were smoothed over five frequency intervals.

Table 4 Summary of results of analysis in the frequency domain, using samples of 3600 h and frequency averaging over 61 terms centred on 5° h^{-1}, thus covering the range from 2 to 8° h^{-1}. S_{xx} and S_{yy} are the spectral energy in mm^2 for IB and sea level respectively, $|S_{xy}|$ is the magnitude of the cross spectral energy. $|H|$ is the gain of the transfer function. Lag is the time in h by which IB lags sea level response, calculated from the phase of the transfer function divided by the central frequency. Negative lag implies that sea level leads IB. γ^2 is the coherence. The quantities preceded by Δ (e.g., ΔH) are the 95% confidence level bounds.

Site	S_{xx}	S_{yy}	$\|S_{xy}\|$	$\|H\|$	ΔH	Lag	ΔLag	γ^2	$\Delta\gamma^2$
Ruawai	10.69	25.41	11.03	1.031	0.081	-4.3	0.9	0.447	0.042
Waitemata	11.95	12.68	8.74	0.732	0.037	-4.4	0.6	0.504	0.028
Tararu	12.44	16.50	12.05	0.968	0.062	-3.5	0.7	0.707	0.036
Moturiki I.	12.71	13.40	9.54	0.750	0.022	-3.3	0.3	0.534	0.016
Hoods Landing	11.92	29.82	13.18	1.105	0.057	9.1	0.6	0.488	0.028
Gisborne	16.25	17.69	13.43	0.826	0.045	7.0	0.2	0.626	0.032
Napier	15.98	11.69	9.51	0.595	0.056	3.2	1.1	0.484	0.059
Taranaki	15.02	24.58	16.13	1.073	0.050	-1.4	0.5	0.704	0.027
Wellington	16.68	17.67	15.63	0.937	0.043	2.5	0.5	0.829	0.027
Nelson	21.16	14.08	12.94	0.611	0.061	1.4	1.1	0.561	0.062
Ferrymead	24.27	23.12	13.96	0.575	0.032	6.7	0.6	0.347	0.025
Otago	23.26	20.83	15.45	0.664	0.048	0.9	0.9	0.492	0.039
Bluff	21.44	42.16	27.86	1.299	0.055	3.6	0.5	0.858	0.019

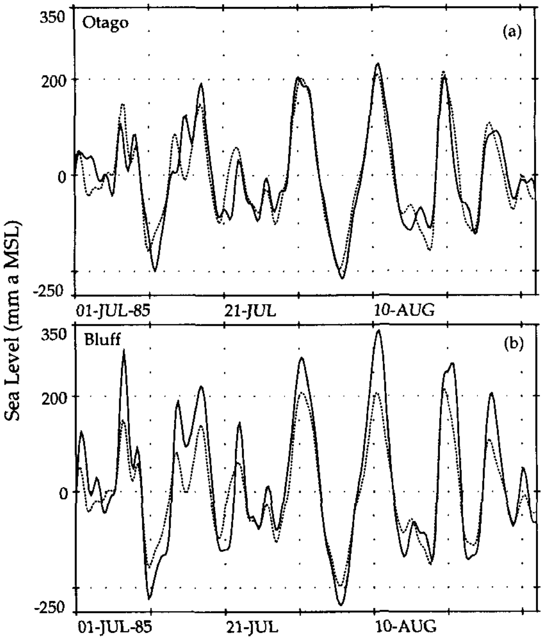

Fig. 6 Comparison of sea level (solid line) and IB (dotted line) for two months in 1985 for Otago (**a**) and Bluff (**b**). For Otago, the IB data are from Dunedin Airport and for Bluff the IB data are from Invercargill Airport.

smoothed in the frequency domain by taking complex means over 61 frequency intervals of 0.1° h^{-1} centred on 5° h^{-1}. This gives a mean quantity which spans the frequency interval between 2 and 8° h^{-1} (corresponding to periods between 45 and 80 h). The results of this analysis are presented in Table 4, which is analogous to the results of analysis in the time domain presented in Table 3. Indeed, in many cases the barometric factor has similar magnitude to the gain of the transfer function, as would be expected because the two methods are equivalent, and if the data were perfect they would give exactly the same result. However, the frequency domain analysis gives an extra piece of information in the form of the phase, which can be converted to a lag between IB and sea level by dividing by the frequency. Table 4 reveals an interesting feature: that for the southern sites IB lags sea level, but for northern sites the reverse is true (except for Hoods Landing and Gisborne). This important result is discussed further below.

The large lag for Hoods Landing may be explained by the location being 12 km up the Waikato River from its mouth, but the reason for the large lag for Gisborne is not so obvious. Poor data quality is a possible explanation.

DISCUSSION

The study has been limited by the lack of concurrent time series. A short period of concurrent data exists for some of the North Island sites, discussed below, but for the South Island sites no such data are readily available. Unfortunately, this situation is not likely to improve in the near future because there is no co-ordination of measurement of sea level in New Zealand. Furthermore, the quality of the data varies considerably, depending on the organisation collecting them. Thus, inferences which are drawn from the results presented suffer from the limitation that site comparisons are generally for different periods of record.

The results indicate a considerable variation in the response of sea level to barometric pressure from one end of the country to the other and from east to west. In the south and in the west (Bluff, Taranaki, Hoods Landing, and Ruawai) sea level responds at greater than the conventional inverted barometer to changes in barometric pressure, whereas in the east the response is less than conventional. Comparing the results from Ruawai with those from Bluff is particularly revealing: although the variance of IB at Invercargill Airport is 1.67 times the variance of IB at Auckland Airport (from Table 3), the sea level response in both cases is greater than conventional and of about the same magnitude. This indicates that being exposed to the prevailing westerly weather is more important for sea level response than the level of variability of barometric pressure changes. This is also shown by comparing the results from Ruawai with those from Waitemata: sites on adjacent harbours, one exposed to the west (Ruawai), the other to the east (Waitemata). For both sites, analysis in the frequency domain indicates that sea level leads barometric pressure by about 4 h and analyses in both the time and the frequency domains indicate that 45–50% of the variation in sea level is explained by variation in barometric pressure. However, sea level at Ruawai responds at greater than conventional to barometric pressure and Waitemata at less than conventional.

Visual inspection of plots such as Fig. 3(a) comparing IB with sea level show qualitatively what Tables 3 and 4 show quantitatively about the

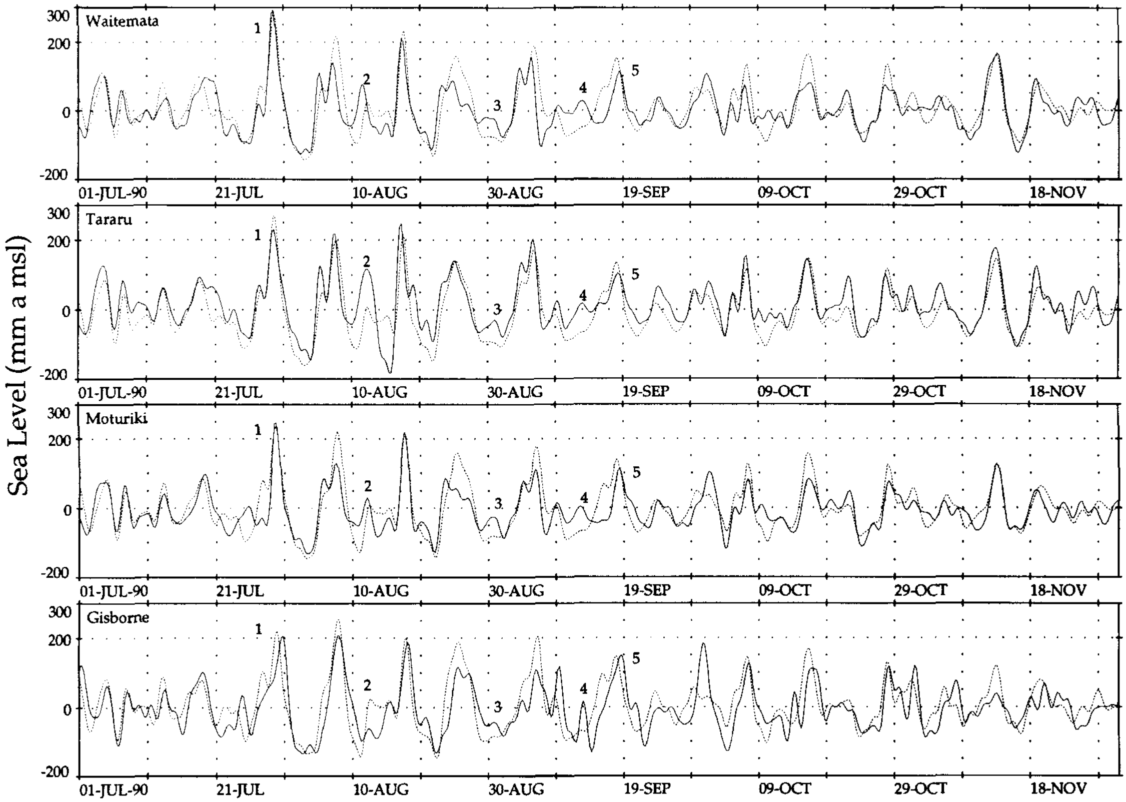

Fig. 7 Comparison of coincident time records for the four north-eastern sites, with sea level plotted as the solid line and IB as the dotted line. The numbers refer to specific events which are described in the text.

difference between sites exposed to westerly conditions and those sheltered from it. Fig. 6, comparing records at Otago and Bluff, is typical. At Otago, IB and sea level are quite similar, even for the large event on 10 August. However, at Bluff, variation in sea level almost always exceeds that for IB both for set-down and set-up. Fig. 6 also shows that most fluctuations in sea level occur as a result of fluctuations in IB and this qualitative observation is borne out by the coefficient of determination for these two sites being larger than for many of the others (Table 2).

In contrast, the four north-eastern sites (Waitemata, Tararu, Moturiki, and Gisborne) have many fluctuations which cannot be directly attributed to IB, and this is illustrated in Fig. 7 which shows a period of record for which concurrent data are available from all four sites. Several interesting events occurring in the period are indicated by numbers in the figure. Considering each of the annotated events in turn:

1. In this event, IB and sea level appear to be attuned for all except Gisborne, but the latter may be a data error.
2. Sea level rose in advance of IB and for Tararu to a much larger extent. It seems unlikely that the rise in sea level is related to the rise in IB.
3. Sea level rose while IB was dropping or was level. This may be the signature of a coastal trapped wave. The presence of the wave at Gisborne as well as the Bay of Plenty and Hauraki Gulf sites means that the wave propagates around East Cape. To the accuracy of the data, the wave occurs at all sites simultaneously.
4. This is another example of sea level changing at all sites in a manner which appears to be

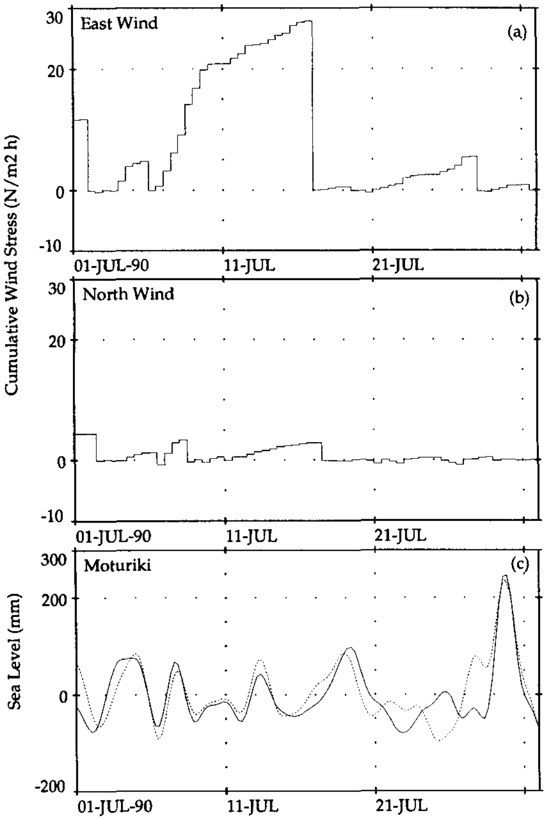

Fig. 8 Time record of a strong easterly wind event and the corresponding sea level variations, in which the upper plots show the cumulative wind shear stress from the easterly (**a**) and the northerly (**b**) directions; (**c**) shows the sea level variation (solid line) and IB (dotted line).

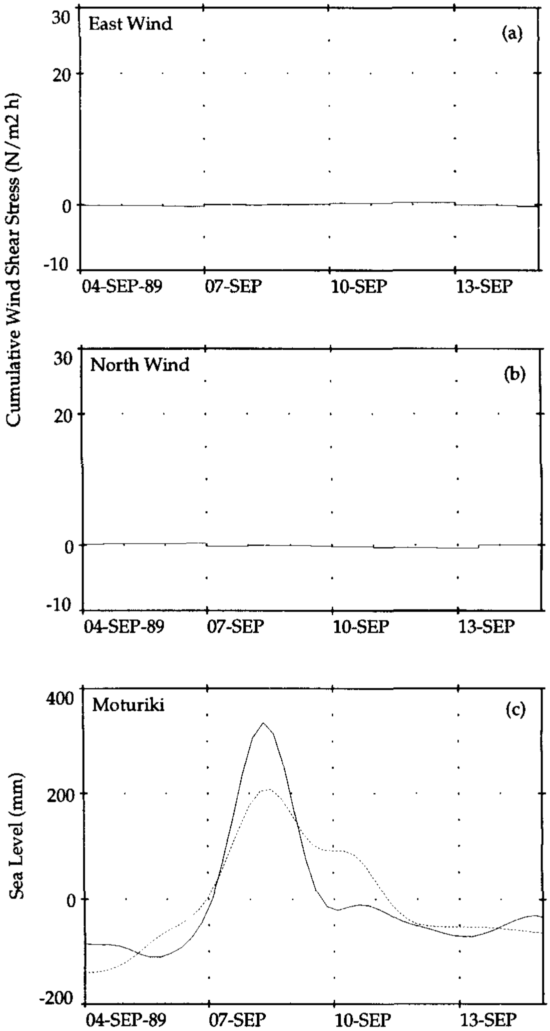

Fig. 9 Time record from September 1989 of the largest sea level rise in the period that ECMWF winds are available, in which the upper plots show the cumulative wind shear stress from the easterly (**a**) and the northerly (**b**) directions; (**c**) shows the sea level variation (solid line) and IB (dotted line).

independent of IB. In concert with Event 3, the peak of the wave occurs at all sites simultaneously.

5. For this event IB preceded sea level change, in contrast to Event 2.

The period shown in Fig. 7 was characterised by relatively low wind activity. The largest wind event by far for the period occurred in the period of relatively low sea level variability in July, as shown in Fig. 8, where from 7 to 17 July there was a sustained easterly wind, yet this appears to have had little or no effect on the sea level at Moturiki. Examination of all the major wind events (such as the one shown in Fig. 8) for the entire period for which ECMWF winds are available (1984–91) revealed a similar result: there seems to be no appreciable correlation between wind and sea level variation in the Bay of Plenty. Another way of approaching this is to examine the major sea level events (i.e., maximum sea level set-ups) and compare the winds. A typical example is presented in Fig. 9. This was the largest sea level rise in the period. Sea level rose 140 mm higher than IB, yet there was essentially no wind. Examination of the synoptic charts for the period under consideration indicates that an eastward travelling low-pressure system passed to the north of New Zealand, with only the southern edge affecting the Bay of Plenty. Thus, we conclude that the surge shown in Fig. 9 must have propagated into the area from the north.

Stanton (in press) found that on the west coast of New Zealand, from the Taranaki Bight south, the variations in sea level can be largely explained in terms of wind-forced, coastal trapped waves. He found strong correlation between alongshore winds and adjusted sea level anomaly (i.e., sea level after IB had been removed) and thus used long wave theory with windstress forcing to model the behaviour on the shelf. The above findings indicate this approach would not be satisfactory for the north-east of the North Island.

Lappo et al. (1978) show by means of a simple mathematical model that, in the deep ocean, for a weather system moving eastward with speed U and wave number k, the ratio between the actual sea level displacement η and the displacement corresponding to the inverted barometer response η_{IB} is gven by:

$$M = \frac{\eta}{\eta_{IB}} = \frac{1-\beta_t/Uk^2}{1-\beta_t/Uk^2-\left(\Omega^2-U^2k^2\right)/c^2k^2} \qquad (3)$$

where Ω is the Coriolis parameter, $\beta_t = \Omega/h\ \mathrm{grad}(h)$ (in which h is the depth) and $c = \sqrt{gh}$. For the event shown in Fig. 9, the weather system was travelling eastward along latitude 30°S ($\Omega = 7.3 \times 10^{-5}$ rad s^{-1}) at $U = 8$ m s^{-1}. Using Eq. 3, the IB response occurs for $k = \Omega/U$, corresponding to a wavelength of 690 km. For waves shorter than 690 km the response is greater than IB and for waves longer than 690 km the response is less than IB. Therefore, we can infer that the storm generated waves with lengths less than 690 km and these propagated into the Bay of Plenty.

Ponte et al. (1991) used a more sophisticated mathematical model to determine the response to large-scale pressure disturbances. Their finite difference model of the southern Pacific had New Zealand as the only isolated land mass. For the node off Napier their model produced a response which was less than 1% different from IB over several months of simulation. However, neither their model nor the simplified model of Lappo et al. (1978) takes account of shallow-water effects on the continental shelf and it is likely that some of the amplification of sea level response to pressure changes illustrated in Fig. 9 results from effects on the shelf. Further research work is planned in this area using data from current meters that have been moored in the Bay of Plenty since 1992. In the first instance, we will attempt to model the momentum transfer across the shelf using the linear systems analysis model of Burrage et al. (1991).

CONCLUSIONS

Around New Zealand the response of sea level to meteorological forcing varies according to exposure to the predominant westerly wind conditions. In general, for sites exposed to the west, sea level responds to changes in barometric pressure at a higher level than indicated by the inverted barometer; for sheltered eastern coasts, sea level responds to barometric pressure changes at a lower level than indicated by the inverted barometer. However, for particular events, sea level at eastern sites may respond at greater than the IB response. Wind may have some effect in these events, but analysis of the global winds from the ECMWF model for the Bay of Plenty showed no significant correlation either in overall behaviour or even for specific events.

For sites at the north of the North Island, sea level generally changes in advance of pressure changes (3 to 4 h), implying that waves are propagating into the area ahead of the weather system. For sites south of the mid-North Island, sea level responds to changes in pressure within a few hours.

Sea levels in the north-east of the North Island area (Poverty Bay / Bay of Plenty / Harauki Gulf) often display a secondary peak after the passage of a low-pressure system and this may be the signature of a coastal trapped wave. What initiates these waves is unclear, but it does not appear to be alongshore winds as have been found in other parts of New Zealand.

Analysis of sea level around New Zealand is limited because of the lack of concurrent data and the poor quality of much of the data that have been and are being collected. Exceptions are the handful of sites which are being maintained by regional councils and NIWA and archived in the national archive of freshwater data. Furthermore, there is a shortage of open coast sea level sites, with all except one current site being in sheltered harbours or on rivers.

ACKNOWLEDGMENTS

Thanks go to the organisations which supplied data: Environment Waikato, Wellington Regional Council, Canterbury Regional Council, Christchurch City Council, Timaru Port Co, and the Royal New Zealand Navy. I am grateful to Dr Rob Bell of NIWA Hamilton for reviewing the manuscript and making very useful suggestions. This work was funded under FRST Contract CO1212.

REFERENCES

Burrage, D. M.; Church, J. A.; Steinberg, C. R. 1991: Linear systems analysis of momentum on the continental shelf and slope of the central Great Barrier Reef. *Journal of geophysical research, 96(C12)*: 22169–22190.

Crisciani, F.; Ferraro, S. 1989: The role of some meteorological factors in the long period modulation of the sea level in the Gulf of Trieste. *Bollettino di oceanologia teorica ed applicata V, 4*: 307–335.

Crisciani, F.; Ferraro, S.; Mosett, F. 1987: Evidence of the inverted barometer effect in the Gulf of Trieste. *Bollettino di oceanologia teorica ed applicata V, 2*: 85–93.

Doodson, A. T. 1924: Meteorological perturbations of sea-level and tides. *Monthly notices of Royal Astronomical Society, geophysical supplement,* April, 124–147.

Garrett, C.; Toulany, B. 1982: Sea level variability due to meteorological forcing in the Northeast Gulf of St Lawrence. *Journal of geophysical research 87 (C3)*: 1968–1978.

Goring, D. G.; Bell, R. G. 1993: Effect of barometric pressure on sea level in the Bay of Plenty, New Zealand. *Proceedings of the 11th Australasian Conference on Coastal and Ocean Engineering, Townsville. National Conference Publication 93/4,* The Institution of Engineers, Australia, Canberra.

Goring, D. G.; Bell, R. G. in press: Distilling something from patchy tide-gauge records: the New Zealand experience. *Marine geodesy, special issue on sea-level networks and applications.*

Hamon, B. V. 1966: Continental shelf waves and the effects of atmospheric pressure and wind stress on sea level. *Journal of geophysical research 71*: 2883–2893.

Hannah, J. 1990: Analysis of mean sea level data from New Zealand for the period 1899–1988. *Journal of geophysical research 95(B8)* : 12399–12405.

Lappo, S. S.; Likhacheva, O. N.; Skripnik, A. V. 1978: The inverse barometer problem. *Doklady akademii nauk SSSR, 244(6)*: 1475–1478 (translated in *Oceanology 1981*).

Palumbo, A.; Mazzarella, A. 1982: Mean sea level variations and their practical applications. *Journal of geophysical research 87 (C6)*: 4249–4256.

Ponte, R. M.; Salstein, D. A.; Rosen, D. A. 1991: Sea level response to presssure forcing in a barotropic numerical model. *Journal of physical oceanography 21*: 1043–1057.

Ponte, R. M. 1994: Understanding the relation between wind- and pressure-driven sea level variability. *Journal of geophysical research 99(C4)*: 8033–8039.

Stanton, B. R. in press: Sea level variability on the west coast of New Zealand. *Journal of physical oceanography.*

Wu, J. 1982: Wind-stress coefficients over sea surface from breeze to hurricane. *Journal of geophysical research 87*: 9704–9706.

Young, P. 1984: Recursive estimation and time-series analysis. Berlin Springer-Verlag, 300 p.