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# Spectral Characteristics of Ocean Waves Undergoing Generation in New Zealand Waters

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## ABSTRACT

A model for predicting the development of ocean wave spectra is derived from wave generation observations off the west coast of the North Island of New Zealand. Fetch-dependent parameters of the JONSWAP function, adapted to the local wave generation observations are used to derive equivalent duration-dependent relationships by means of the fetch-duration duality principle. The duration-dependent relationships form the basis of the spectral development model. Some specific ocean wave generation events, taken from single point observations made both near the Maui A platform and off the east cost of Great Barrier Island, are then compared with the model, and a number of spectral properties of the sea states involved are established.

## INTRODUCTION

The classical Kitaigorodski (1961) approach to the specification of the sea surface during wave generation is to specify the frequency spectrum at each point on the ocean surface, when a turbulent wind with a constant average speed and direction beings to blow over an originally quiescent ocean. When the wind is offshore, the ocean surface can be divided into two regions. Adjacent to the leeward shore, the wave statistics are dependent only on the distance from shore and are independent of time. Further out to sea, the wave statistics are time-dependent and independent of the distance to the shore. In the near-shore zone the waves are steady and are said to be fetch-limited, while those in the offshore zone are unsteady and are referred to as duration-limited. Kataigorodski calls the region between the fetch-limited and duration-limited regimes the steady-state wave front. A third region can exist if the fetch and duration are sufficiently long that wave development ceases. In this case the wave statistics are dependent only on the wind speed, and the sea state is referred to as being fully-developed.

Fetch-limited waves were extensively studied by Hasselmann et al. (1973) in the Joint North Sea Wave Project (JONSWAP). A significant result of the study was the parametric wave spectrum that they ascribed to a growing sea state. The spectrum, which is based on the Pierson and Moskowitz (1964) form for a fully-developed sea, is expressed in terms of two fetch-dependent parameters - the frequency of the peak of the spectrum (the peak frequency , fp) and a parameter corresponding to Phillips (1958) constant (the Phillips parameter, $\alpha$ ). Hasselmann et al. (1973) deduced relationships for these two parameters that enabled a spectral form to be given at any distance down the fetch in the steady region.

The opportunity to investigate properties of ocean waves undergoing generation in an environment quite different from the North Sea, where the JONSWAP research was conducted, arose during an environmental study carried out off the west coast of the North Island of New Zealand (Kibblewhite et al., 1982). Among other things, the study involved the measurement of ocean waves, using a Datawell Waverider buoy, near to a platform (Maui A) associated with an offshore gas field - see Figure 1.

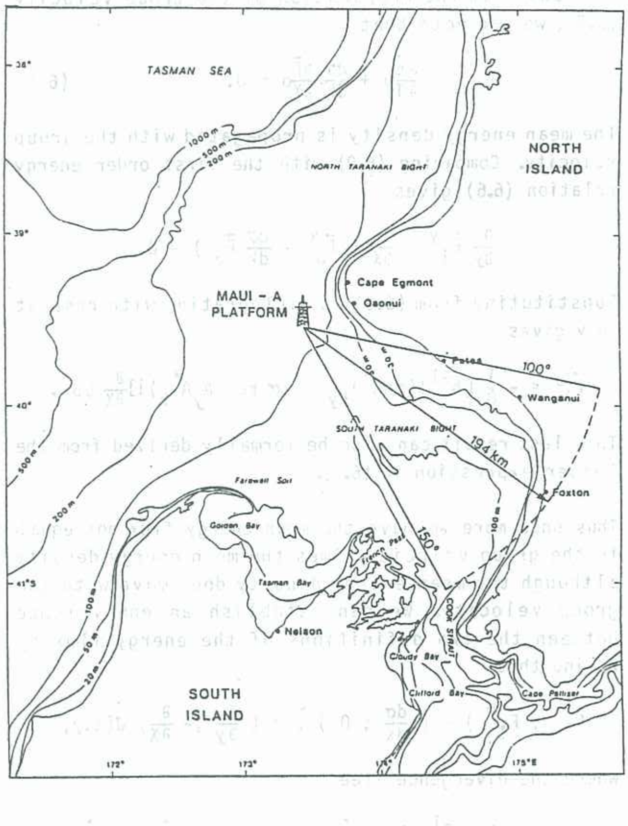


Figure 1. The wave measurement location, and the range of southeasterly bearings.

The general features of the wave measurement programme, including a description of the data acquisition and analysis techniques and some aspects of the general wave climate at the site, have been presented already (Kibblewhite and Ewans, in prep). In addition to the general wave climate results, the study was also particularly productive in providing answers to long standing questions on microseism and low-frequency ambient noise generation. In this paper however we will be concerned only with the ocean wave results; the microseism and ambient noise findings are presented elsewhere (Ewans, 1984; Kibblewhite and Ewans, 1985).

Due to the unique orographic and climatic properties of the Greater Cook Strait region, approximations to the Kitaigorodski ocean wave generation scenario were observed on a number of occasions during south easterly winds at the Maui A platform (Ewans and Kibblewhite, in prep). These conditions allowed the local fetch-dependent relationships for the peak frequency and Phillips parameter to be established and compared with the corresponding JONSWAP relationships.

From these fetch-dependent relationships, duration-dependent relationships were derived and a model for local wave generation established. The predictions of the model were compared with measured data recorded at the Maui site and at a site off the east cost of Great Barrier Island. The comparisons highlighted the presence of fully-developed sea states during a number of events, but only aspects of fetch-limited and duration-limited sea conditions are addressed in this paper.

## FETCH-LIMITED SPECTRAL CHARACTERISTICS

From the two year data base produced in the wave study, only 75 spectra (from the 4000 odd examined) were found to have steady southeast sea components i.e. having constant spectral levels during periods of 4 hours or longer when the wind speed was constant. In only 44 of these could the local sea component be satisfactorily fitted (by the method of least squares) with a JONSWAP spectral form. In the fitting process, the five JONSWAP spectrum parameters, the two scale parameters, fp and $\alpha$, and the three peak shape parameters, $\gamma$, $\sigma_a$ and $\sigma_b$, were varied until specified convergence criteria were met. To ensure that the fitted curves were 'good fits', the convergency criteria were made especially restrictive, as evidenced by the low number of good fits achieved. An example of one of the chosen spectra and its JONSWAP fit is given in Figure 2.

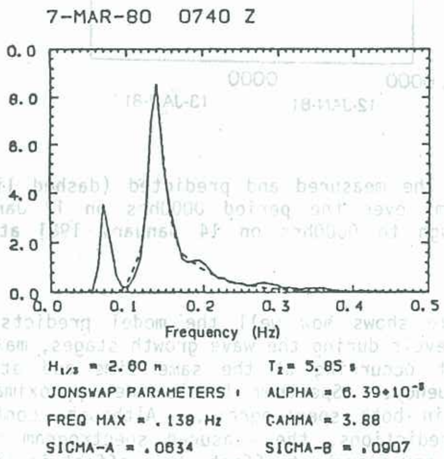


Figure 2. A Maui wave spectrum with a steady south east sea component and its best-fit JONSWAP curve.

The average values of the spectral parameters established for the 44 best fit spectra were: $\alpha = 7.1 \times 10^{-3}$, fp = 0.139 Hz, $\gamma = 2.9$, $\sigma_a = 0.10$, $\sigma_b = 0.13$. The average Phillips parameter is approximately equal to the value of $7.4 \times 10^{-3}$ found by Phillips (1958); the average peak enhancement factor is slightly less than the JONSWAP value of 3.3; and the average left and right peak widths are slightly larger than the equivalent JONSWAP values of 0.07 and 0.09. It appears therefore that the steady local southeast seas in the Maui region are not significantly different from seas measured elsewhere and can be described by a JONSWAP spectrum which has a slightly lower and broader peak than the mean spectrum described by Hasselmann et al. (1973).

Following Hasselmann et al. (1973), the five spectral parameters were assumed to obey a relationship of the form:

$$P = a\tilde{X}^n \qquad (1)$$

where P is the spectral parameter
X is the non-dimensional fetch defined by

$$\tilde{X} = \frac{gX}{U_{10}^2} \qquad (2)$$

where X is the actual fetch (194km for the south east winds at Maui),
g is the acceleration due to gravity,
and $U_{10}$ is the mean windspeed at 10 metres above mean sea level.

The constants a and n are determined by linear regression analysis of log (P) on log $(\tilde{X})$. For this analysis the peak frequency was non-dimensionalised by the Kitaigorodski (1961) scheme of

$$\tilde{fp} = \frac{U_{10} fp}{g} \qquad (3)$$

Also investigated was the relationship for a sixth parameter, the non-dimensional variance $\tilde{\varepsilon}$, defined by

$$\tilde{\varepsilon} = \frac{\varepsilon g^2}{U_{10}^4} \qquad (4)$$

where $\varepsilon$ is the zeroth moment of the variance density spectrum.

The analyses were carried out in terms of $U_{10}$ values using both a neutral and a stability dependent wind profile. The results of the analysis are shown in Table 1.

| JONSWAP SPECTRAL PARAMETER | WIND PROFILE | | | | | |
|---|---|---|---|---|---|---|
| | Neutral | | | Stability Dependent | | |
| | a | n | c | a | n | c |
| Phillips Parameter ($\alpha$) | 0.06 ±0.02 | -0.25 ±0.01 | -0.40 | 0.07 ±0.02 | -0.27 ±0.01 | -0.40 |
| Non-Dimensional Frequency ($\tilde{f}_p$) | 2.98 ±0.04 | -0.30 ±0.01 | -0.93 | 2.59 ±0.04 | -0.28 ±0.01 | -0.90 |
| Peak Enhancement ($\gamma$) | 7 ±1 | -0.1 ±0.2 | -0.24 | 8 ±2 | -0.1 ±0.2 | -0.22 |
| Sigma-a ($\sigma_a$) | 0.04 ±0.02 | 0.08 ±0.02 | 0.09 | 0.04 ±0.03 | 0.08 ±0.02 | 0.08 |
| Sigma-b ($\sigma_b$) | 0.3 ±0.1 | -0.17 ±0.05 | -0.11 | 0.4 ±0.1 | -0.18 ±0.06 | -0.11 |
| Non-Dimensional Variance ($\tilde{\varepsilon}$) | (2.6 ±0.2) × $10^{-7}$ | 0.872 ±0.004 | 0.91 | (5.9±0.7) × $10^{-7}$ | 0.786 ±0.005 | 0.86 |

Table 1. Linear regression parameters of log (P) on log $(\tilde{X})$, where P is a JONSWAP spectrum parameter, for the 44 steady spectra.

In agreement with the results of those from the JONSWAP experiment a strong dependence of the non-dimensional peak frequency and variance on the non-dimensional fetch is apparent; on the other hand the dependence of the Phillips parameter on the non-dimensional fetch is weak and the fetch dependence of the peak shape parameters negligible. In addition, the constants found for the fetch-dependent parameters are similar to those found by Hasselmann et. al. - Viz for fp, a = 3.5 and n = -0.33; for $\alpha$, a = 0.076 and n = -.22; and for $\tilde{\varepsilon}$, a = $1.6 \times 10^{-7}$ and n = 1. The differences between the Maui and JONSWAP values do however suggest that slightly faster spectral growth occurs in the North Sea.

## DURATION-LIMITED SPECTRAL RELATIONSHIPS

In principle, a study analagous to that involving ocean wave generation under steady conditions could be undertaken to determine relationships between the peak frequency and the Phillips parameter and the non-dimensional time parameter, $\tilde{t}$, defined by

$$\tilde{t} = \frac{tg}{U_{10}} \qquad (5)$$

where t is the duration relevant to the "unsteady" region.

In practice however, the onset of the sudden steady wind required to generate the conditions necessary

for such an analysis occur too infrequently to make it practicable. Instead we make use of the fetch-duration duality proposed by Kitaigorodski to determine time dependent spectral parameters from the fetch dependent parameters. The fetch-duration durality principle can be simply stated as follows:
the minimum duration for any stage of build-up in the unsteady region is the time required for some representative group of waves to traverse the fetch in the steady region.

The time, t, for a group of waves of a period, T, to traverse the fetch, is given by

$$t = \frac{X}{Vg} \tag{6}$$

where Vg is the wave group velocity given by

$$Vg = \frac{gT}{4\pi} \tag{7}$$

The choice of T which most represents the sea is some what arbitrary. Inoue (1967) for example, chose the inverse of the peak frequency at the location of interest, but we choose to follow Silvester (1974) and invoke the average speed, $\overline{Vg}$ of the peak frequency group throughout the fetch, where

$$\overline{Vg} = \frac{1}{X}\int_0^X Vg\ dX \tag{8}$$

With appropriate substitution of equations (7), (6) (with Vg replaced by $\overline{Vg}$ ) and (2) into equation (8) we obtain (for details refer Ewans, 1984) the fetch-duration equivalence relationship,

$$\tilde{t} = 4\pi\ a(1-n)\ \tilde{X}^{(1+n)} \tag{9}$$

It is this relationship which allows the fetch-dependent parameters to be rewritten in terms of the non-dimensional time.

## TIME DEPENDENT SPECTRAL MODEL

The duration-dependent relationships, obtained from appropriate substitution of the coefficients a and n into equations (1) and (9), and the mean values of the JONSWAP spectral shape parameters given earlier, were used as a basis of a one-dimensional wave spectrum prediction model. In addition, the spectral parameters in the model were constrained to assume their fetch-limited values when the duration exceeded the time for the steady-state wave front to travel down the fetch and embrace the observation point, and their decay was taken to be linear when either the wind speed or the fetch decreased. No allowance was made for the occurrence of a fully-developed sea, but this possibility is discussed later. For details of the model, reference is made to Ewans (1984).

Comparisons of predictions and measurements for 13 specific wave generation events involving both west and east coast sites (Maui and Great Barrier Island) were made. Input data consisted of the wind speed at 10 metres, derived from a stability dependent model for the Maui site and a neutral model for the Great Barrier Island site; the fetch, estimated from weather maps by the Sverdrup and Munk (1951) method for non-fetch limited situations; and the duration.

In a number of events where the fetch was not limited by the coast, the predicted spectra developed well beyond the measured spectra. In these situations fetch-limiting was artifically imposed through an empirical calculation of the fetch (using equation (1) with P equal to the peak frequency) when the measured spectra became steady, but the sea states involved were identified to have fully-developed properties (Ewans, 1984). For each of the 13 events comparisons were made between the measured and the model spectrograms. Values were established for the significant wave height, Hs, the mean period, Tm, the peak frequency and the Phillips parameter. The significant wave height and the mean period were derived from the moments of the spectra, while the peak frequencies and Phillips parameters were obtained by curve fitting the measured spectra with the JONSWAP spectral form, using the peak shape parameters found earlier- i.e the same values as used in the model.

### Maui Comparisons

The model was evaluated against 10 generation events at the Maui site. An example spectrogram for wave generation from the southeast is given in Figure 3 - the dashed lines are the predicted spectral levels.

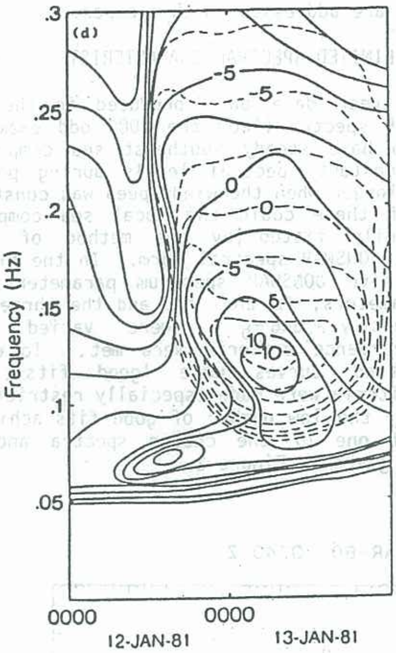


Figure 3. The measured and predicted (dashed lines) spectrograms over the period 0000hrs on 12 January 1981 through to 0000hrs on 14 January 1981 at the Maui site.

The example shows how well the model predicts the spectral levels during the wave growth stages, maximum development occurring at the same time and at the same frequency. Spectrum levels are approximately the same in both spectrograms. Although, contrary to the predictions, the measured spectrogram shows no sign of any overshoot effect, this effect is likely to be lost in the hand smoothing of the spectra. However the existance of an equilibrium range, indicated by horizontal variance density contours at the higher frequency compares well with that of the model.

The swell component at around 0.07 Hz has insignificant effect on the comparisons. This result supports the theoretical work of Hasselmann (1963) who showed that wave-wave interactions between swell and local sea, which are widely separated in frequency were insignificant.

As an overall summary of the Maui comparisons, linear regression analyses of the model data on the measured data were carried out for all the parameters. An example plot for the peak frequency is given in Figure 4.

The regression parameters for the peak frequency analysis, with a slope of 1.0 and an intercept of 0 indicate a very good overall agreement between the model predictions and the measured data.
However, poor agreement in the Phillips parameter was found, but this is not surprising in light of its weak fetch dependence. The significant height and mean period do not show the same degree of agreement as the peak frequency, but in both cases

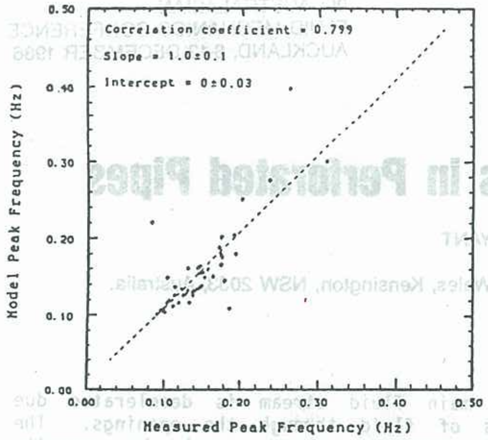


Figure 4. Scatter diagram of predicted and measured peak frequency for all the Maui events. The dashed lines and listed parameters are the results of the linear regression analysis.

the regression line is biassed to a low slope (Hs slope = 0.71, Tm slope = 0.82) and a high intercept (Hs intercept = 0.2, Tm intercept = 0.8) by some anomalous points, a number of which are due to decaying spectra for which agreement between the measurements and the model was in general poor. In spite of this fact, the correlation coefficient, C, for both parameters is still quite high (Hs, C = 0.897; Tm, C = 0.827).

Great Barrier Island Comparisons

The wave climate in the Great Barrier Island region is characterised by wave heights which are generally lower than the Maui region (Ewans and Kibblewhite, 1981). Without the unique orographic features of the Maui region, intense and well-defined ocean wave generation events occur much less frequently - only three Great Barrier Island events are compared.

In contrast to the Maui results, correlation is relatively high for the Phillips parameter (C = 0.757) but low for the peak frequency (C = 0.618), significant biassing occurring in both. The peak frequency analysis is however disadvantaged by the small range of values involved. In contrast the significant wave heights and mean periods show considerable spread but no significant biassing, (Hs slope = 0.93, Tm slope = 0.99). This suggests that although the model was developed for the Maui region, it is also generally applicable to wave generation off the east coast of New Zealand.

## CONCLUSIONS

Fetch-limited ocean wave spectra at Maui obey the general relationships found in the JONSWAP experiment. Differences in the shape of the average JONSWAP and Maui spectra, and in their rate of growth as determined by the fetch-dependent relationships of the peak frequency and the Phillips parameter, are however observed. The Maui spectrum has a slightly lower but broader peak than the mean JONSWAP spectrum, and it develops more slowly than its JONSWAP equivalent.

The fetch-duration duality principle can be applied to derive time dependent relationships which can be used to study temporal development of active seas. The accuracy with which local seas can be described by such simple models that depend only on the local wind speed, indicates the importance of the local wind in determining the characteristics of the local sea. It is believed that this is a consequence of the stabilising influence of non-linear wave-wave interactions on the spectral shape (Hasselman et al. 1973).

The general applicability of the spectral development model to both the Maui region and the Great Barrier Island region suggests that the general conclusions drawn for local sea spectra and their development in the JONSWAP study are, as expected, also applicable to local sea generation in New Zealand waters.

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