From: OCEAN SEISMO-ACOUSTICS
Edited by Tuncay Akal and Jonathan M. Berkson
(Plenum Publishing Corporation, 1986)

A STUDY OF OCEAN AND SEISMIC NOISE AT INFRASONIC FREQUENCIES

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ABSTRACT

Acoustic noise in the ocean is known to be wind dependent and several mechanisms have been proposed to explain the transfer of energy from the wind to the noise field. Because reliable ambient noise data are sparse at frequencies below 10 Hz it has been difficult to assess the agreement between theory and experiment. The difficulties at these frequencies have arisen through self-noise in the monitoring system and deficiencies in the environmental data. This study has examined correlations of the ocean-wave field and the ocean-induced seismic activity at frequencies below 1 Hz. The quality of the data, the long term nature of the observations and an unique property of the recording environment have helped clarify the nature of wave-induced noise processes. It is concluded that the ocean ambient noise below 5 Hz is controlled by wave-wave interactions.

1. INTRODUCTION

It is nearly one hundred years since a close connection between microseisms and ocean wave activity was first proposed.[1] Since that time a vast literature has appeared as interest in the subject has waxed and waned. Various mechanisms have been proposed to account for the generation of microseisms, most favoured among them being nonlinear interactions between ocean surface waves. Interest in this mechanism has increased in recent years as underwater acousticians have pushed their horizons to lower and lower frequencies. The latest series of papers[2] has however again emphasised that a number of theoretical and experimental questions still require clarification.

The contribution to be reported here has arisen from a major wave-climate investigation, which has been carried out recently in the Cook Strait region of New Zealand.[3] Like the rest of New Zealand this area, shown in Fig. 1, is subject to a regular succession of weather systems which cross the country from west to east. The mountain chain centered on Cook Strait acts as a barrier to the associated air flow and produces a strong, well-defined, bimodal wind regime in Cook Strait. The rapid swing in the wind vector between northwest and southeast has made the region an ideal one for the study of ocean wave processes.

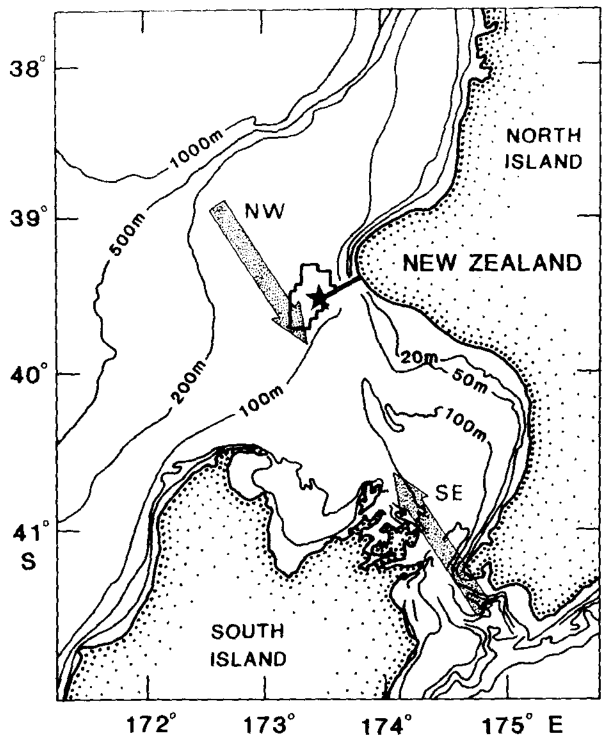

Fig 1. Localities and bathymetry of the Cook Strait and Maui environment.

The general wave-climate study had of necessity to involve the long term recording of wave and related environmental parameters. This fact, coupled with the unique orographic properties of the region, provided an opportunity to extend the basic study and include investigations of various wave related processes. In particular plans were made to address some of the unresolved issues relating to ocean induced microseisms. A full account of this work is given in a thesis submitted for a PhD degree.[4] A number of the important results are being prepared as a series of papers of which this is one.[5-7] It deals specifically with the generation of microseisms and their relation to the low frequency ambient noise field. For details of the instrumentation, analysis procedures used, and a more detailed account of the history of research into microseisms the reader is referred to either the original thesis or References 6 or 7. Suffice it to say here that the wave data were provided by a Datawell Waverider buoy moored in approximately 110 m of water close to the Maui platform. The signal from this unit was received ashore 30 km away. Also recorded were the output of a long period seismometer installed at the receiving site ashore, a time code signal and relevant meteorological parameters. Recordings of the wave and seismic signals of 20 minute duration were initiated automatically every 4 hours. Wave and seismic spectra were produced from the analogue records. Various presentations of the data were developed as required, including the contour plots giving the spectral histories described later.

2. BASIC THEORETICAL PREDICTIONS

Our concern here is with the double frequency (DF) component of the microseism field. For a full account of generation theory the reader is referred elsewhere,[4] but the key relations relevant to this study are summarized below.

As first reported by Miche,[8] consideration of second order terms in the hydrodynamic equations leads to terms representing the generation of low frequency pressure fluctuations by the nonlinear interaction of opposing ocean waves. In contrast to the progressive waves producing them, the distinctive features of these waves are that the pressure effects they produce do not decrease with depth, occur at twice the frequency of the interacting surface waves, and are proportional to their amplitude product. Miche's theory was developed by Longuet-Higgins[9] to account for microseism generation and expanded further by Hasselmann,[10] in particular. Using Hasselmann's terminology the density spectrum of the pressure field arising from interacting surface waves can be written:

$$G_p(\omega) = \frac{\pi\rho^2 g^2 \omega^3}{4c^2} \; G^2(\omega/2) \int_0^{2\pi} H(\omega,\theta)\, H(\omega,\theta + \pi)\, d\theta \tag{1}$$

where ρ is the density of sea water, c the ocean sound velocity, g is the gravitational acceleration, $G(\omega/2)$ the variance density spectrum of the surface wave displacement, and the integral describes the directional properties of the wave field. This form of the pressure spectrum can be shown to be the same as that calculated by Brekhovskikh[11] and Hughes[12] in the context of underwater noise, when minor errors are corrected.[13] For later discussion it will be helpful to express Eq (1) alternatively as:

$$G_p(f_a) = \frac{2\pi^3\rho^2 g^2 f_w^3}{c^2} \; G^2(f_w) \int_0^{2\pi} H(f_w,\theta)\, H(f_w,\theta + \pi)\, d\theta \tag{2}$$

where f_a and f_w are the frequency components of the acoustic pressure and gravity wave fields respectively, and $f_a = 2f_w$.

Equation (1) can be written more conveniently as:

$$G_p(\omega) = K_o\omega^3 G^2(\omega/2).I \tag{3}$$

where K_o is a constant given by $K_o = \pi\rho^2 g^2/4c^2$ and I describes the integrand. Modification of Eq (3) by the transfer function to relate the displacement to the pressure field, and a term K_1 involving the active area of the wave field, leads to the ground displacement variance density spectrum of the microseism field:

$$\overset{n}{G}_\mu(\omega) = K_0 K_1 \overset{n}{T}_\mu(\omega)\omega^3 G^2(\omega/2) I \tag{4}$$

where K_1 is a constant associated with the transfer function. Hasselmann examines the properties of T_μ^n for a particular model and shows that for certain conditions a simple ω dependence of the transfer function will apply. In this case the microseism displacement variance density spectrum becomes:

$$G_\mu(\omega) = K_0 K_1 K_2 \omega^4 G^2(\omega/2) I \quad (5)$$

where K_2 is also a constant. It will be useful to note for later discussion that Eq (2) and Eq (5) are equivalent to Eqs (2) and (4) in Ref. 7, with the integral set at 1/8.

Hence according to theory not only should there be a two-to-one frequency relationship between the seismic and ocean-wave spectra, but the variance density spectral levels of the vertical component of the ground displacement should be proportional to the fourth power of the frequency of the interacting ocean waves, and to the square of the variance density levels of the ocean wave components producing the exciting pressure field. The contribution from the integrand in Eq (5) is difficult to estimate, but for some cases analytical descriptions are available.[14] In this study three cases were considered: (i) Single sea - no opposing swell; (ii) Sea and unidirectional swell propagating at an angle ϕ with respect to the wind; (iii) Two opposing unidirectional swells. In case (iii) the integrand can be shown to have a constant value of 0.5 and to be independent of frequency. In cases (i) and (ii) the integrand has a complex frequency dependence which must be taken into account. We discuss (i) and (ii) briefly later. Ewans[4] provides detail of the analysis.

3. CHARACTERISTICS OF THE MICROSEISM-OCEAN WAVE RELATIONSHIP

3.1 General Features

At all times observations in the Maui region gave clear evidence of the marine generation of microseisms in the frequency range 0.05-1.0 Hz. Comparisons of any ocean wave spectrum with its seismic equivalent identified peaks at or very close to a frequency relationship of 2:1. For a detailed examination of the effects observed long sequences of variance density levels established from the 4 hourly spectra were contoured by hand. For ease of comparison the two spectrograms covering periods of interest were included on the same diagram along with time series plots of wind and other parameters. Gaps in the series were brief and interpolations to the spectrograms were made for continuity.

Several typical time histories of characteristic generation events are analysed in detail in other publications.[4-7] Here we reproduce only one of these by way of example - see Fig 2. Details of the presentation format are given in the figure caption. For a full description of the meteorology and generation events of this period the reader is referred to the other sources. We confine comment to a brief statement of the features relevant to the present analysis.

The effect of the succession of weather systems which cross New Zealand is shown clearly in the events of 16 and 24 October. Prior to both dates the meteorology was dominated by anticyclones, and the winds in the Maui region were more or less constant from the north. As the low pressure systems move on to the country the winds swing

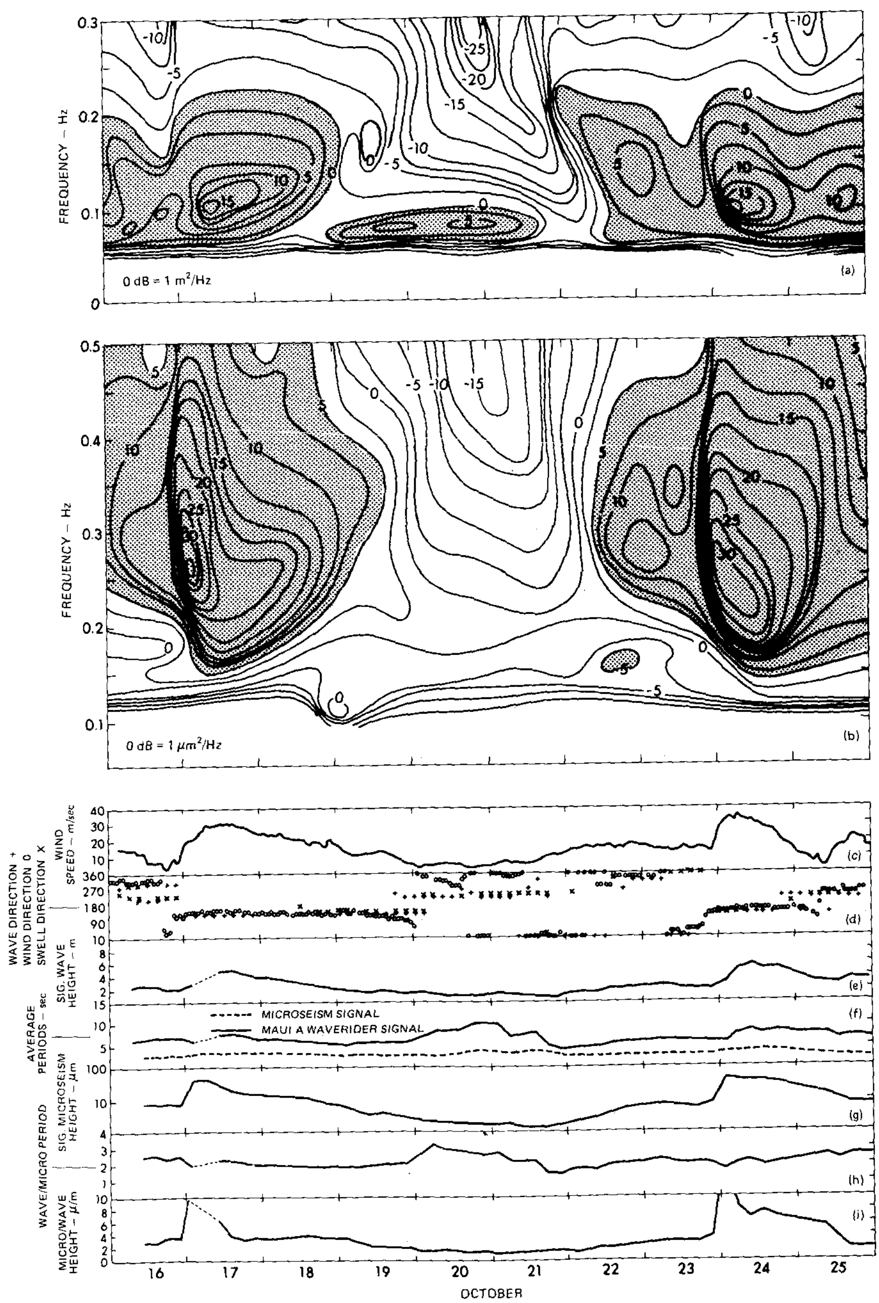

Fig 2. Time series plots of wind, ocean wave and microseism parameters for the period 16-25 October 1981. (a) Ocean wave spectral history; (b) Microseism spectral history; (c) Wind speed, m/sec; (d) Wind, wave and swell directions; (e) Significant wave height, m; (e) Average wave and microseism period; (g) Significant microseism height, microns; (h) Wave/microseism period ratio; and (i) Ratio of microseism to wave height, microns/meter. (From Ref. 7)

rapidly to the southeast and increase in speed to over 30 ms^{-1} before decreasing. Ocean wave spectral levels increase sharply in response to the rapid change in wind speed and bearing. A new low frequency peak is soon established, of sufficient strength to mask the ever present low level southwesterly swell.

The changes in the wind field always produce the characterisic response shown in the microseism spectrogram. Energy which is clearly related in some way to the local sea, appears in the band 0.2 - 1.0 Hz. In this example maximum levels occur on 17 and 24 October some hours before the ocean wave maxima. In both events two distinct periods can be identified in the microseismic response. Activity reaches high levels while the growing southeasterly sea interacts with the northwesterly swell, but the levels drop from the peak as the northwesterly swell is flattened to a lower value, which remains roughly constant until the sea levels fall in response to the decreasing wind field.

3.2 The Two-to-One Frequency Relationship

Comparison of any ocean wave spectrum with its microseism equivalent always identifies peaks at or very close to the two-to-one frequency relationship required by Eq (5). This relationship is expected on the basis of the standing wave generation mechanism originally proposed by Longuet-Higgins and Ursell,[15] but the fact that the microseism levels associated with the local sea are larger than those associated with the southwesterly swell suggests the actual mechanism producing the standing waves must be different.

A primary frequency peak (PF) in the seismic spectra at the same frequency as the sea waves has also been identified, but because its level is two orders of magnitude lower than that of the double frequency (DF) secondary peak it is not routinely observed. It is not discussed further here but an account of it is available elsewhere.[4,7]

3.3. Seismic Spectral Level Dependence on Frequency

For the low level southwesterly swell around 0.07Hz the value of the spectral peak square ratio, (SP^2R - the ratio of the spectral level of the DF peak in the microseism spectrum to its ocean wave equivalent) is typically -5 dB re $1(\mu m/m)^2$. The larger values of this ratio produced by a local sea (10 to 20 dB higher) are shown elsewhere[4,7] to arise from the frequency dependence expressed in Eq (5). According to Eq (5) the SP^2R is proportional to the fourth power of the wave frequency. When allowance is made for this factor the ratios are found to be grouped around certain values, which can be related to the type of wave field responsible for the activity. These factors are explored in more detail elsewhere.[4,7]

3.4 Seismic Level Dependence on Wave Height

According to Eq (5) the seismic spectral levels are also proportional to the square of the levels of the interacting ocean wave spectral components. Evidence confirming this relationship has been presented in other publications.[5,7]

3.5 Seismic Level Dependence on Angular Distribution of Wave Energy

The theoretical explanation of microseism generation is based on the production of pressure fluctuations by the interaction of oppositely travelling ocean surface waves. While there has always been difficulty in identifying the precise source of the standing waves recent evidence has confirmed that oppositely travelling waves are present within the fetch itself.[14] The present study has confirmed furthermore most of the predictions of the formalism developed on the concept of standing wave interactions. In particular it has been shown that the microseism height is related to the square of the ocean wave height and that the microseism spectral levels depend to the fourth power on the ocean wave frequency. These results have in turn justified an analysis, based on the spectral peak square ratios, which has allowed comparisons between different generation events by reducing each ratio to an equivalent level at a standard ocean wave frequency by normalising by the factor ω^4 - see Eq (5). The actual normalisations to a standard swell frequency of 0.06 Hz are discussed elsewhere.[4,7] Here we simply note that accepting this normalisation enables other factors to be investigated. In particular, as the constants K_0, K_1, K_2 in Eq (5) will be invariant in the Maui generation area if we confine our attention to winds from one direction (say SE), we can explore the influence of the integrand by careful selection of the spectra.

The analytical expressions for the integral under various wave regimes are examined in detail elsewhere.[4,7] Here we simply note that, some reasonable assumptions accepted, the values of I for the three cases alluded to earlier, and for frequencies close to the spectral peak (below 1.12 f_p), are:

1. Active sea alone $I = 2.65 \times 10^{-2}$
2. Active sea plus swell (ϕ=180°) $I = 0.19$
   where ϕ is the angle between the swell and the wind.
3. Two opposing swell $I = 0.5$

Of particular interest to our next section is that the ratio I/I_{180} = -8.6 dB. For consideration of frequencies above 1.12 f_p the full frequency dependence of the parameters involved must be considered - see later.

4. THE INFRASONIC AMBIENT NOISE FIELD

The application of the observed seismic behaviour to the clarification of the properties of the ambient noise field in the ocean at frequencies below 10 Hz has been discussed in a companion paper.[7] This section reviews that analysis in the light of new data now available.

4.1 Average Spectra vs Wind Speed

Average ocean wave and seismic spectra (in 2.5 ms^{-1} wind speed intervals) are shown as a function of wind speed in Figs 3a, b. These spectra are based on SE winds only and strict criteria were imposed in their selection.[4] The characteristic growth of the wave peak and its migration to lower frequency with increasing wind speed is mirrored in the seismic spectra. The contribution of the everpresent SW swell is evident in both.

4.2 An Analytical Form of the MAUI Spectrum

To examine more clearly the influence of the spreading term in the ocean wave field, and remove the confusion created by the SW swell,

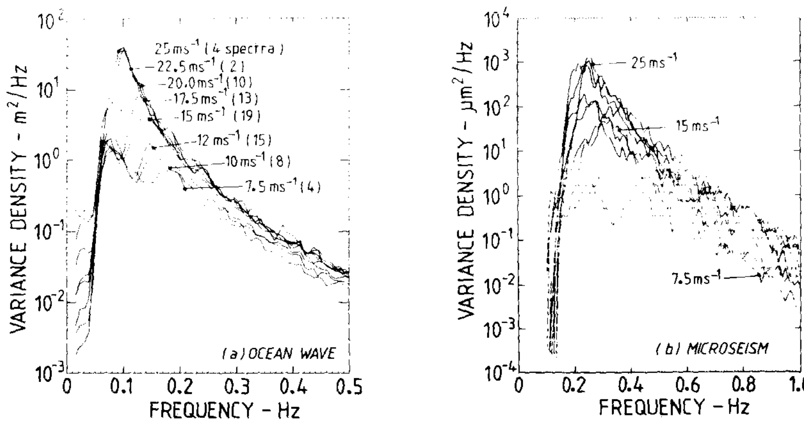

Fig 3. Average ocean wave and seismic spectra in wind speed intervals of 2.5 m/sec.

it is helpful to calculate an analytical form of the ocean wave spectrum based on the JONSWAP function, but using the actual values of the peak enhancement factor and spectral width parameters found relevant to the Maui seas.[4,5] This is traditionally calculated in terms of the peak frequency, but for our purposes a representation in terms of wind speed is more helpful. This transformation has been possible because of other aspects of the overall study.[4,5] The resulting one dimensional MAUI spectra as a function of wind speed are shown in Fig 4a.

4.3 The Pressure Field Arising from Wave-Wave Interactions

From the spectra of Fig 4a the pressure field produced by nonlinear interactions can be calculated using Eq (5). In Figs 4c, d respectively we present the variance density spectra for the pressure field produced by a single sea in which the angular distribution of wave energy inherent in the fetch produces the interactions, and those associated with an active sea with an opposing swell aligned 180° with respect to the wind. We note in particular that overall, the pressure levels are about 10 dB higher when there is an opposing swell present, and recall that the difference predicted theoretically on the basis of the spreading factor is approximately 9 dB, the levels for the sea plus opposing swell again being higher - see Section 3.5.

4.4 Seismic Spectra for Single and Opposing Seas

The measured seismic spectra for single and opposing seas can be obtained from the composite plot of Fig 3b. The separated spectra, after some minor smoothing, are presented in Figs 4e, f. Attention is again drawn to the difference of around 10 dB in the peak levels but also to the overall similarity to the equivalent spectra of the exciting pressure field presented in Figs 4c, d.

4.5 The Pressure Field Derived from the Seismic Spectra

Given the form of the transfer function in Eq (5) it is possible to work back from the seismic spectra and establish the pressure field

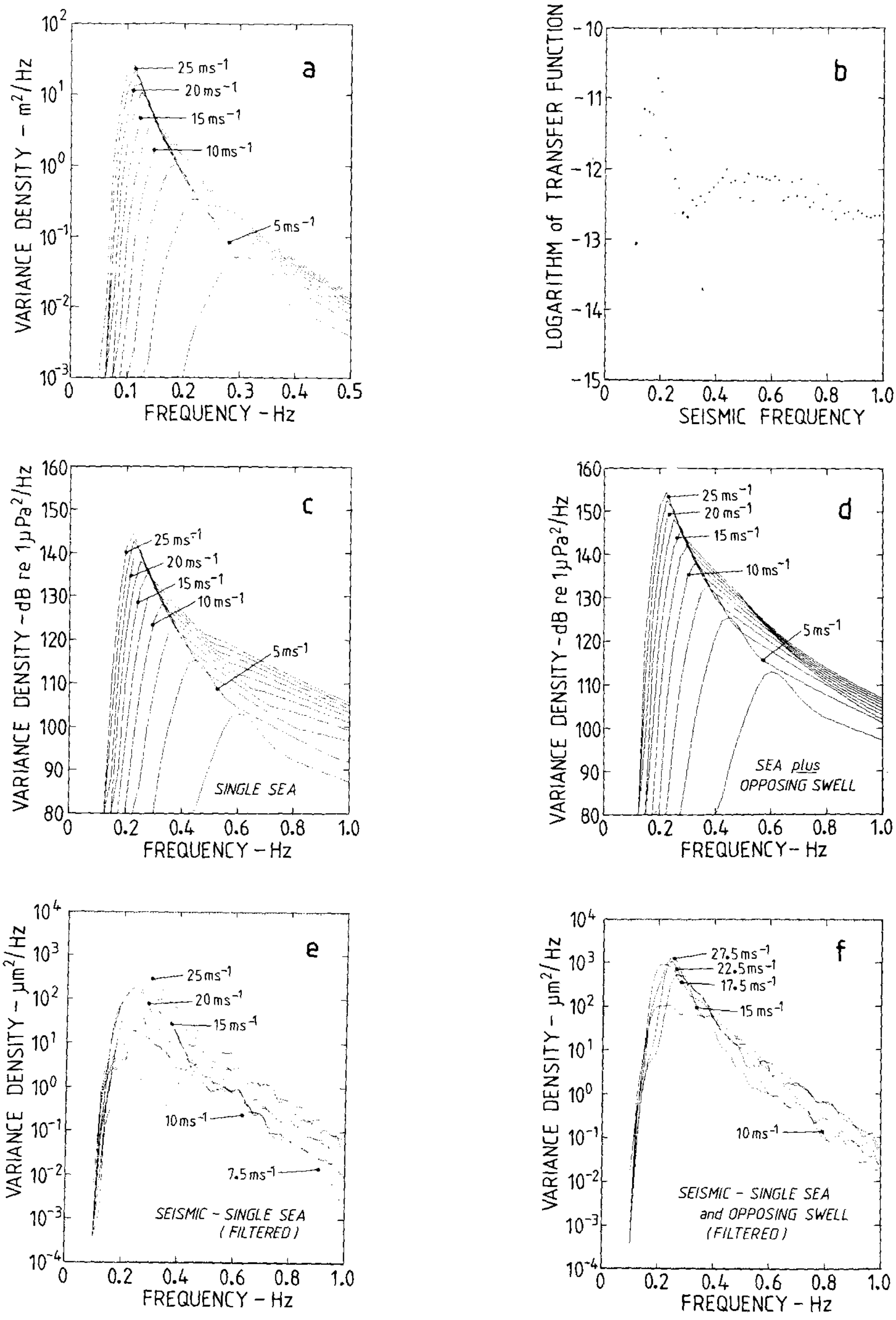

Fig 4.(a) The MAUI spectra (based on the JONSWAP function with parameters relevant to the Cook Strait region) as a function of wind speed; (b) The transfer function derived from the pressure spectra based on the observed ocean wave data, and the observed ground displacement spectra; (c) Variance density spectra of the wave induced pressure field - single sea; (d) Variance density spectra of the wave induced pressure field - sea plus opposing swell; (e) Measured seismic spectra - single sea; (f) Measured seismic spectra - sea plus opposing swell.

at the sea bed responsible for the microseism levels observed. In the absence of such information a simple transformation was used in the earlier comparison of the deduced levels with published ambient noise data derived from hydrophone measurements - see Fig 8 of Ref 7. Inspite of the frequency independence in the transfer function this implied, the close agreement with other data was striking.

Evaluating the transfer function directly from the observed wave and seismic spectra (Figs 3a and 4e, f) suggests however that the frequency dependence may be more complex than the simple linear relation assumed earlier - see Fig 4b. That this might be the case was noted in Ref 7 when attention was drawn to the inflexion in the deduced ambient noise curves around 0.5 Hz, evident in Fig 8 of that paper. However both the angular spreading integral and the transfer function could be involved. This effect is currently the subject of further investigation.

4.6 The Ambient Noise Field

As stated earlier the pressure field deduced from the seismic data of Figs 4e, f and presented in Fig 8 of Ref 7, agreed well with other experimental hydrophone data. However, the character of the transfer function shown in Fig 4b suggests that the closeness of the agreement may have been somewhat fortuitous. Further work is in hand to explore the interdependence of the spreading and transfer functions and the significance of any bottom amplification effects. It is clear nevertheless that while noise levels below 0.5 Hz can be influenced by any residual swell that may be present, as is observed in the New Zealand environment, outside this range and at modest wind speeds the local sea is the dominant noise source. Furthermore wave-wave interactions appear to account for the acoustic and seismic effects produced.

SUMMARY

It has been confirmed that microseisms are generated by ocean waves. It has been established further that:

i. The microseisms in the band 0.1 to 1 Hz have spectral components with peaks at double the frequency of the associated peaks in the wave field.
ii. The interference of opposing waves is responsible for the generation of the pressure field which produces the microseisms, in accordance with theory.
iii. The levels generated have a strong frequency dependence, higher frequency seas producing larger activity than lower frequency ones. The pressure and seismic fields display a frequency dependence close to f^3 and f^4 respectively, as predicted by theory.
iv. If allowance is made for this frequency dependence ground displacement levels (and by implication pressure levels) are found to be proportional to the square of the wave height, but a dependence on the wave regime has also to be considered.

v. The influence of the wave regime is embodied in the angular distribution of wave energy. In the case of a single sea the natural angular distribution of waves creates the opposing interactions necessary for microseism generation. (This fact explains why both onshore and offshore winds are equally effective in producing seismic activity.)

vi. The nonlinear interactions are the dominant source of the infrasonic ambient noise levels in the ocean below 10 Hz. In this range the noise level is roughly proportional to the square of the wind speed and has a negative slope of around 18 dB per octave.

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