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TOW SPECTRA FROM MODE

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Towed sensor data from the main thermocline in the Sargasso Sea south of Bermuda during the Mid-Ocean Dynamics Experiment are reported and compared with the Garrett and Munk internal wave model. The tows consisted of two sensor suites vertically spaced 11 or 21 m apart; the depth of tow was varied so as to continuously bracket an isothermal surface. Spectral analysis in the wave number band from 0.015 to 5 cycles km^{-1} results in a vertical displacement spectrum of the isopycnal surface that is statistically indistinguishable from earlier estimates in the same area. In this wave number band, agreement with both the 1972 and the 1975 versions of the Garrett and Munk internal wave model is good, though the model predicts a spectral level about one third too high. The vertical coherence spectra obtained from the temperature fluctuations at the two separations describe the horizontal wave number bands over which vertical coherency is lost. The 1975 model underestimates coherency but can be brought into better agreement by reducing the 'mode number scale.'

In a previous paper [Katz, 1973] the results of a series of tows were presented. The observations closely approximated a direct measure of the wave number spectra of the vertical displacement of an isopycnal surface. The tows were made at a variable depth following an isothermal/isopycnal surface, and thus the need for deriving displacement spectra indirectly from temperature variance spectra was eliminated. The region chosen for the observations was in the main thermocline of the Sargasso Sea south of Bermuda at depths greater than 600 m below the surface. This is a region where temperature and salinity are highly correlated (salinity was nonetheless observed) and where the main thermocline is separated from the seasonal thermocline by an intermediate minimum in the Väisälä frequency profile associated with the '18° water' [Worthington, 1959]. From three separate cruises to the area and a variety of tracks (a 550-km reach, an equilateral triangle, etc.), six independent estimates of the displacement spectrum were shown to overlap and combine into a single spectrum. Covering the wave band from 0.02 to 30 cycles km^{-1} , this spectrum is monotonically decreasing with wave number, independent of direction, and stationary.

The displacement spectrum was compared with the appropriate projection of the Garrett and Munk [1972] internal wave model (familiarily called GM72) and with a set of four tow spectra that they had selected to help build up their model. Agreement between the above Sargasso Sea spectrum and the earlier data (as interpreted by Garrett and Munk) was encouraging. Two were overlapped by the Sargasso Sea spectrum: the LaFonds' spectrum derived from near-surface thermistor chain tows off San Diego and Ewart's spectrum derived from temperature data at constant depth in the shallow main thermocline off the state of Washington. The other two observations had parallel spectral slopes but were higher in amplitude. These comparisons are made after weighting energy density by the local Väisälä frequency as suggested by WKB wave solutions [Fofonoff, 1969].

Agreement with the GM72 model was good only for wave numbers smaller than several cycles per kilometer. A high wave number cutoff predicted by the model, as a function of Väisälä frequency, was absent from all of the relevant observations. At best, the Sargasso Sea spectrum, which was the first to bridge the gap between low and high wave numbers, suggested a break in spectral slope: from a power law of -1.55

at wave numbers smaller than 1 cycle km^{-1} to -2.3 at the high wave number end. In an attempt to incorporate this and other discrepancies between new observations and GM72 the modelers adjusted the functional way that they had distributed the energy at a particular frequency across the horizontal wave number axis [Garrett and Munk, 1975]. The high wave number cutoff was replaced by a -2.5 power law, and good agreement between data and the revised model, GM75, was demonstrated [Garrett and Munk, 1975, Figure 3].

A perplexing question facing the interpretation of tow spectra of either vertical displacement or temperature is that of deciding which wavelength band is dominated by which physical process, when one assumes that such dichotomies exist. This has led to attempts to compare recently observed spectral slopes with single process model predictions [McKean and Ewart, 1974; Keunecke and Magaard, 1974]. In the internal wave model of Garrett and Munk, this slope is a parameter of the model, which is only partially constrained by fitting frequency spectra from moored sensors and floats. They have so far been able to adjust the model to obtain better spectral fits. It is when observations from two or more different projections in wave number-frequency space cannot be rationalized by a single internal wave model that the model may help with the identification of the internal wave bandwidth.

Garrett and Munk have discussed two other tow spectra to assist in the testing of internal wave models: the coherence between vertically separated towed sensors and the coherence between two tows along the same path (time-lagged coherence). These spectra include the effect of vertical wave number and frequency on horizontal wave number spectra obtained from tows, thereby contributing to a broader understanding of the energy spectrum of ocean variability.

OBSERVATIONS AND DATA ANALYSIS

During April and June 1973 a depth-controlled tow fish was 'flown' for a total of 13 days within 100 km of the center of the Mid-Ocean Dynamics Experiment (29°N, 68°40'W, deep water southwest of Bermuda). A weighted sensor package was suspended from the control fish and towed either 11 or 21 m below it. The sensor package contained temperature, pressure, and conductivity sensors (from the Plessey vertical profiler, model 9007). Mounted on the tow fish above were second matching pressure and temperature sensors. Data were continuously transmitted to a shipboard computer and recorded

every half second. Towing speed varied between 2.1 and 3.0 m s⁻¹ on various legs. Depth of tow varied between 700 and 800 m as the 12°C isotherm was bracketed by the two sets of sensors. The design of the tow fish and the success of its depth control system have been reported by Hess and Nowak [1974].

From the above data set a subset was extracted for spectral analysis. Only periods of towing where the isotherm was firmly bracketed for long straight reaches were analyzed. These data were then averaged by using hourly averages of speed from the good Loran C coverage in the area, to obtain an interpolated isotherm depth along every estimated 100 m of track.

The resolution of the temperature sensor is about 2 mdeg. With the mean vertical temperature gradient being 22.5 mdeg m⁻¹ the resolution leads to a relatively small error in computing the isotherm depth. The error due to the resolution of the pressure sensor is comparatively small. However, the interpolation between the two sensors necessarily assumes a linear gradient. At 10-m separation, error in this interpolation can be estimated by considering the accumulated variance of temperature for vertical wavelengths of 0.05 cycle m⁻¹ to infinity. This variance can be calculated from the MODE density program of STD lowerings reported by Hayes *et al.* [1975]. In the main thermocline, one obtains an rms value of 20 mdeg. High vertical wave numbers can therefore be thought to introduce an error of about 1 m when one interpolates between the two sensors.

Another possible source of error is the use of the isotherm displacement to represent the isopycnal displacement. The ratio of the change of sigma t with temperature to that of sigma t with salinity is 1‰ (4°C)⁻¹ in this region. For the isothermal surface to diverge more than a meter from the isopycnal surface therefore requires the salinity to change more than 0.005‰ at a given temperature. It is not known if intermittent or systematic changes of that magnitude occur in the temperature-salinity correlation over distances of 100 km. In fact, the sensor used is unable to reliably sense rapid fluctuations of salinity less than 0.015‰, and an observed drift of 0.01‰ (100 km)⁻¹ in the sensor masks smaller continuous changes.

Variations in towing speed over less than an hour will tend to blur the spectra at high wave numbers. Sample calculations suggest that this is not particularly worrisome.

The isothermal surfaces have very definite large-scale trends. The full set of data from the tows, which consists of multiple crossings at 120° to one another, has been contoured and will be available in the *MODE Synoptic Atlas* scheduled for publication early in 1975. The mean slope of the isothermal displacement over 100-km track lengths approached values of 1 m km⁻¹ at times. This trend and lower wave number variation were removed from the analysis by rewriting the data series as first differences and then recoloring the spectra.

MODE DISPLACEMENT SPECTRUM

The displacement spectra of eight selected 65-km segments were averaged to obtain the single MODE spectrum shown in Figures 1 and 2 (tows 703/704). The towed sensors were vertically separated by 11 m. The data are from two periods separated by 2 weeks in time and at three different headings. The spectral estimates have been averaged without regard to time or direction as suggested by the earlier results.

The present spectrum and two representative previous spectra are compared in Figure 1. It again confirms that there is a reproducible average displacement spectrum for this area. The

approximation and deviation from an α^{-2} power law is indicated on the figure. No single power law describes the nearly 3½ decades of wave numbers. It is equally correct to speak about a central wave number band with a -2 slope as it is to divide the spectrum into two segments with slopes less than and greater than -2. Where previously a value of -1.55 was suggested for the wave number band 10⁻² to 1 cycle km⁻¹, the equivalent calculation for tow 703/704 yields -1.75. Owing to the improvement of the measuring technique and because tows 300 and 400 used 1 km rather than 100 m spaced data, more confidence is placed in the present estimate.

Also shown in Figure 1 is the MODE spectrum in a variance preserving plot. When a planimeter is applied to the area under the curve, the rms vertical displacement of the surface about its mean slope in the wave number band from 10⁻² to 10¹ cycles km⁻¹ is 7.5 m, giving a measure of the size of the phenomenon being observed. Broken down into decades of wave numbers one obtains the following description:

Wave Number Band	rms Displacement
10 ⁻² –10 ⁻¹ cycle km ⁻¹	6.7 m
10 ⁻¹ –1 cycle km ⁻¹	3.1 m
1–10 cycles km ⁻¹	1.2 m

The displacement in the highest wave number band is of comparable amplitude to our anticipated resolution, and if the uncertainty was all at the higher end of the spectrum, this displacement would be unresolvable. The spectrum does not indicate that this is the case, since it shows no indication of becoming white until it reaches the highest wave numbers, but one should be cautious discussing the slope of the displacement spectrum at $\alpha > 10^{-1}$ cycle km⁻¹. Even more caution is advised when converting temperature spectra to displacement spectra at high wave numbers.

The weighted MODE spectrum is compared with the Garrett and Munk model in Figure 2. In the band compared, only a slight edge can be given to the revised model, because the high wave number cutoff of GM72 only begins to dominate the spectrum at the highest wave number estimates. The greater part of the variance of the vertical displacement is independent of the redistribution of energy that resulted in GM75. There is a suggestion that the models are high in amplitude over the entire band. Both models assume an energy density of 0.382 joule cm⁻² to fit a diverse collection of mooring and tow data. A better fit between the MODE spectrum and GM75 is obtained if the constant is reduced by a third; i.e., $E(\text{dimensionless}) = 4\pi/3 \times 10^{-4}$. Alternatively, the same effect can be achieved by a one-third reduction in the equivalent number of modes at the inertial frequency [Garrett and Munk, 1972, equation 6.22].

VERTICAL COHERENCE SPECTRA

The two temperature sensors bracketing the tracked isotherm provide the data to compute estimates of the vertical coherence spectra. It is only an approximation because the vertical gradient must be assumed to be constant in order to interpret the coherence between temperature signals as the coherence between vertical displacements.

The coherence spectra between the two signals are obtained from their cross spectra and the coherences squared are plotted in Figure 3 as a function of horizontal wave number. The corresponding phase spectra between the quadrature and cospectra estimates are indistinguishable from zero. The data from 11-m separations are from the same eight segments used to obtain the displacement spectrum. For 21 m a single track

Fig. 1. MODE vertical displacement spectrum of the 12° isotherm. The average spectrum from eight 65-km tracks (tows 703/704) compared with earlier tows (401 and 606) in the same area. The energy density of the latter has been increased by the ratio of their Väisälä frequencies, 2.7/2.5. A variance preserving presentation of the MODE spectrum is given in the insert.

of 128-km length observed two months earlier was segmented into five series and analyzed by 50% overlapping of the pieces and then using a Hanning window. The same analysis on a long track from tow 703 (11-m separation) repeats the result shown for the eight separate segments.

The difference between the coherence spectra at the two separations is statistically significant. The loss of coherence oc-

curs at wave numbers that are generally thought to be dominated by internal waves. The towed vertical coherence predicted by GM75 is roughly parallel to each curve in Figure 3 but displaced to lower wave numbers. This displacement is indicated in Figure 4, where values of coherence (R) equal to 0.9, 0.7, and 0.5 are compared with the predictions. The 0.7 prediction, for example, predicts a wave number half of that

Fig. 2. MODE spectrum compared with the Garrett and Munk internal wave models. The local Väisälä frequency profile and the average depth of tow is given in the insert. The 1972 model is for a Väisälä frequency of 3 cph.

observed. It appears that the higher vertical wave numbers have been given relatively too energetic a role in GM75.

To force GM75 to fit the observations requires a mode number scale (j_*) near unity in contrast to the value of 6 that they adopted. The physical significance of this scaling factor (which is not straightforward) and several values estimated from vertical and horizontal coherences observed in frequency space are discussed by Garrett and Munk [1975]. The tow spectra yield the lowest value so far but further discussion is best deferred until several recent field programs are reported.

Also included in Figure 4 are the results of McKean and Ewart [1974] as roughly estimated from their coherence curves (their Figures 8b and 8c). The vertical separations are $\frac{1}{2}$ and 1 m and the Väisälä frequency is assumed to be 1.5 cycles h^{-1} (the frequency was not given, but the tows were at 1-km depth, 10 km from a steep seamount in the eastern Pacific). McKean [1974] attributes the drop-off in coherence at his small

Fig. 3. Towed vertical coherence spectra for 11- and 21-m separations. The former is derived from an average of the eight segments used to estimate the MODE displacement spectrum. At higher wave numbers, estimates are averaged over ten adjacent bands as well. The 21-m separation is from a single 128-km track (tow 702), segmented into five pieces and overlapped. At higher wave numbers, estimates are averaged over first three, then ten, adjacent bands. Note that the ordinate is the coherence squared. The bias and confidence bands, are relatively small throughout.

Fig. 4. Towed vertical coherence estimates compared with GM75. The curves are from the model. The data points are from Figure 3 with Y (vertical separation) = 11 and 21 m and $n = 2.7$ cph and after McKean and Ewart [1974] with $Y = \frac{1}{2}$ and 1 m and n estimated at 1.5 cph. Values of α for R (coherence) = 0.9, 0.7, and 0.5 are plotted for each data set.

separations to fine structure contamination, which is outside the scope of GM75. On the other hand, perhaps artificially or perhaps causally, the revised model has been able to do a creditable job of modeling temperature spectra converted to displacement spectra down to horizontal wave numbers in the 10^2 – 10^3 cycle km^{-1} band [Zenk and Katz, 1975]. When one interpolates from Figure 1, the displacement amplitude of this high wave number band is less than 10 cm. Thus the separation is not small in relation to wave amplitude, and the inclusion of their data on Figure 4 cannot be dismissed on a relative amplitude argument. The observations are too widely separated on the figure to connect them, but their relationship to GM75 is consistent. Further observational data, at larger separations as well as intermediate values, are needed.

CONCLUDING REMARKS

Though the observations have been repeatedly applied to a comparison with the Garrett and Munk model, they are obviously useful touchstones for any other internal wave models or theories that wish to explain the vertical displacement field in wave number space. Unlike frequency spectra, where the internal wave frequency band is theoretically bounded by the inertial and Väisälä frequencies, no such natural bounds or signposts can be defined for wave number spectra. Interpretation of wave number spectra is therefore less precise.

With a growing though still small collection of tow spectra having been reported in the literature it appears that they themselves do not as yet clearly differentiate between the various physical processes that one expects they reflect. The more modest objective of a quantitative description of spatial variability is, however, being met.

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