OBSERVING OCEANIC INTERNAL WAVES: What have we learned? What can we learn?

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ABSTRACT

An incomplete and biased assessment is made of the current state of our understanding of oceanic internal waves. The purpose of this presentation is to remind researchers of some inconsistencies that exist between the explanation and description of certain features of the internal wave field. The goal is to renew interest and guide discussion toward certain observations that may ultimately lead to an improved understanding of the dynamics controlling internal waves.

INTRODUCTION

The oceanic internal wave field has been measured by many researchers for decades. What have we learned? If condensed into a single short answer, it is that the internal wave field is remarkably constant in time and space. If one puts instruments anywhere into the ocean, then it is highly probable to expect that the observed fluctuations will follow certain characteristic spectral shapes and coherence structures. This realization led to the development of an empirical description of the wave field known as the Garrett-Munk model (Garrett and Munk, 1972, 1975; hereafter referred to as GM). This model provides a kinematically consistent framework for comparing different types of observations that may be made at different times and locations. It is actually because this first-order description works so well that it has been difficult to answer basic questions about the dynamics of the wave field, such as what are the important sources and sinks of internal waves. It is difficult to tell from where a particular wave came, and to where it is going, when its identity is obscured by a surrounding random sea of oscillations.

Despite the success of the Garrett-Munk formulation, there are notable omissions from this steady-state, climatological description. For example, waves in the near-inertial frequency band vary dramatically in space and time, and therefore are not easily characterized by a steady-state description. Much effort has gone into studying the transfer of energy from the wind into the near-inertial waves of the upper ocean. The internal tide is also not included in the GM model. The internal tide is omnipresent throughout the ocean and often represents a significant fraction of the total internal wave energy. Deviations from GM are also found near topography; either the topography is acting as a source of waves or the interactions are causing a

perturbation in the universal wave field. In unique environments, such as beneath the Arctic ice pack, dramatic differences in the overall wave energy and spectral shape have been found. Study of atypical systems may provide clues toward understanding the more typical ocean.

The second question in the title: "What can we learn?" really depends upon "What do we want to learn?" The answer will vary depending upon who asks the question; investigators in different specialties will be interested in different aspects of oceanic internal waves. For example, some acousticians may be interested in the internal wave correlation functions that describe the fluctuations of sound speed. Other acousticians may want to know higher order statistics, such as a statistical description of the occurrence of sharp gradients in velocity or sound speed. The specific internal wave information that is useful will depend on the particular acoustic study. High-frequency transmission experiments would be affected by a different scale internal wave than an acoustic tomography experiment.

Researchers studying turbulence and mixing are primarily interested in internal waves for their role in providing small-scale vertical shear. The ability to predict how the waves affect the time/space distribution of the Richardson number would be valuable. Can estimates of turbulent dissipation be made from observations of the internal wave field alone, as has been suggested (e.g., Gregg, 1989)? To determine if this is feasible, an improved description of the space/time variation of the internal wave field is needed.

Some investigators are interested in the remote sensing of internal waves. The initial emphasis in this field has been on detecting solitons and large-amplitude waves that produce a significant surface expression. Attention is also focused on processes that generate these signals, usually interaction of the tide with topography. Clearly, the GM description of the wave field is less important to this group.

And there are those investigators that follow the approach of the mainstream physicist and try to understand the details of the nonlinear energy transfer among the waves. Theoreticians need, at the very least, to have an accurate description of the wave field in time/space or frequency/wavenumber in order to insure relevance to the oceanic environment. Estimates of higher-order statistical quantities would undoubtedly also be of interest.

In each of these examples a different aspect of the internal wave field is emphasized depending upon the objectives of the researcher. Certainly there are overlaps, but the labeling of certain advances in internal waves as *important* may depend on who is doing the labeling.
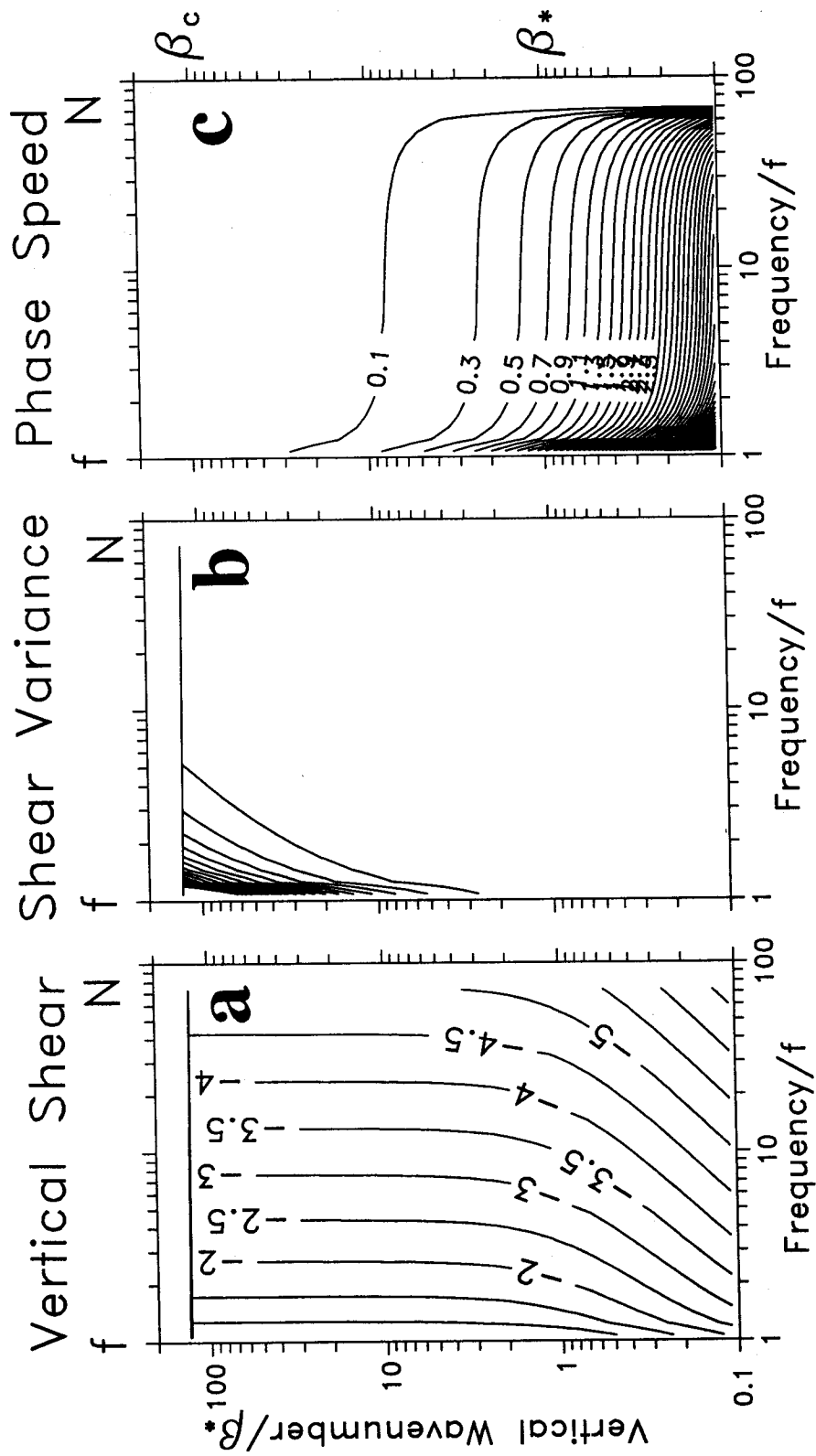
So, where do we go from here? Two possible paths to follow are new measurements and new data, or old observations and new analysis. There are a variety of new

instrumental developments that will be able to measure new quantities of the wave field. Better Doppler sonars, improved neutrally buoyant drifters, acoustic travel-time experiments, and longer time-series observations may provide views of the wave field from different perspectives and lead to an improved description and understanding. However, the remarks here will be confined to the second track--are there different ways to look at the old data? Given the large investment that has been made in obtaining these data it makes sense to spend some effort in exploiting the data to the fullest. Armed with new ideas, a reexamination of our data banks may reveal some interesting results, or possibly, suggest new observations that would be most fruitful. As a step toward this goal, a few topics are reexamined below to provide motivation for continuing the search for new types of analysis and new ways of looking at the data.

INTERNAL WAVE CONTINUUM

One approach to describe the internal wave field is to assume it is composed of a sum of waves from a smooth continuum of frequencies and wavenumbers. This is the basis of the GM model and provides a first-order statistical description of the wave field. This framework allows us to view the wave field in a variety of different spaces. The energy spectrum can be displayed as functions of vertical wavenumber, horizontal wavenumber or frequency. Different vantage points provide different revelations. For example, the spectrum of vertical shear ($\partial u/\partial z$) is plotted as a function of frequency ω and vertical wavenumber β (Figure 1a). The axes are logarithmically scaled, as are the contour levels. The GM shear spectrum is separable in ω-β space and increases with β before leveling off at $\beta > \beta_*$. An *ad hoc* constant upper wavenumber cutoff β_c has been included. One gets an entirely different impression of the spectrum looking at the so-called volume preserving version (Figure 1b). Here equal volumes contribute equally to the total variance. It is clear that more of the shear variance comes from frequencies near f and wavenumbers near β_c. Hence, if one is using the GM model to estimate shear for some mixing parameterization (e.g., Gregg, 1989), then the *ad hoc* choice of β_c is important. Maybe β_c is a function of frequency? Maybe β_c varies in a more complicated way (Duda and Cox, 1989)? How do uncertainties in β_c translate into uncertainties in predicting mixing from models?

Critical layer absorption is a process that is thought by some to play an important role in internal wave dynamics. A critical layer occurs at the depth where the horizontal phase speed of the wave equals the horizontal velocity of the mean flow. To get an idea of the likelihood of this occurring in the internal wave field, the magnitude of the phase speed is plotted in the same region of ω-β space as the shear spectra (Figure 1c). The phase speed is simply ω/α where α is the horizontal wavenumber and is determined from the linear dispersion relationship. Waves with lower phase speeds are more likely to encounter mean flows of comparable speed and be absorbed in critical layers. Considering Figures 1b and 1c together, it seems that the region of ω-

Figure 1. Vertical shear spectrum ($\partial u/\partial z$) given by the Garrett-Munk model is plotted as a function of frequency and vertical wavenumber contoured in units of spectral density (a) and in variance preserving form (b). The horizontal phase speed (ω/α) is contoured in units of meters per second in (c).

β space with the highest shear variance is the most susceptible to critical layer absorption. This realization casts some doubt on the reliability of parameterizing the vertical shear from the GM model--variations of the background shear may lead to variations in wave induced vertical shear. Even if critical layer absorption may not be important in the total energy budget of internal waves, it may be significant in the waves that contain most of the shear.

INTERNAL TIDE

The internal tide is a ubiquitous feature in the world ocean. Its existence has been documented from early in this century. While not included in the GM formulation, the energetic internal tide is important to some investigators, e.g. acousticians, because of its significant contribution to the vertical displacement and straining of the stratified ocean. However, does the internal tide play a role in the dynamics of the wave field?

The internal tide is generated by the interaction of the barotropic tide with topography. The continental shelf break is believed to be a significant source. However, the sea floor as a whole, although much less steep, may actually provide significantly more flux of internal tidal energy into the ocean than the entire continental shelf region (Baines, 1982). There are varying opinions as to whether the internal tide is a significant source of energy to the internal wave continuum. The tide is an attractive candidate for an internal wave source because it is widespread in space and steady in time. This fact is consistent with the observed universality of the internal wave continuum. Also, estimates of the energy flux into the internal tide from the sea floor of order 1 mW m^{-2} are comparable to that needed to maintain the entire internal wave field (Bell, 1975).

But can nonlinear interactions transfer energy out of tidal frequencies at a significant rate? Or does the internal tide propagate passively through the internal wave continuum? One theoretical estimate from weak-interaction theory suggests that the tide could not be a significant source (Olbers and Pomphrey, 1981), however this study was not comprehensive. Perhaps including non-resonant interactions will yield a different result.

It has also been argued that if the tide were a significant source, then there should be a different internal wave spectrum in non-tidal seas. The Mediterranean Sea would provide an interesting testing ground since there are regions where the tide is weak. The author has not yet located convincing evidence (although some may exist) that compares observations there to the GM spectrum. The Black Sea is another nontidal sea; some evidence (albeit limited) indicates that the spectral levels are highly variable and well below GM (Ivanov and Serebryanyy, 1982).

There is some suggestion from observations of a link between internal tide and the continuum (Figure 2). Time series of velocity from the JASIN experiment near
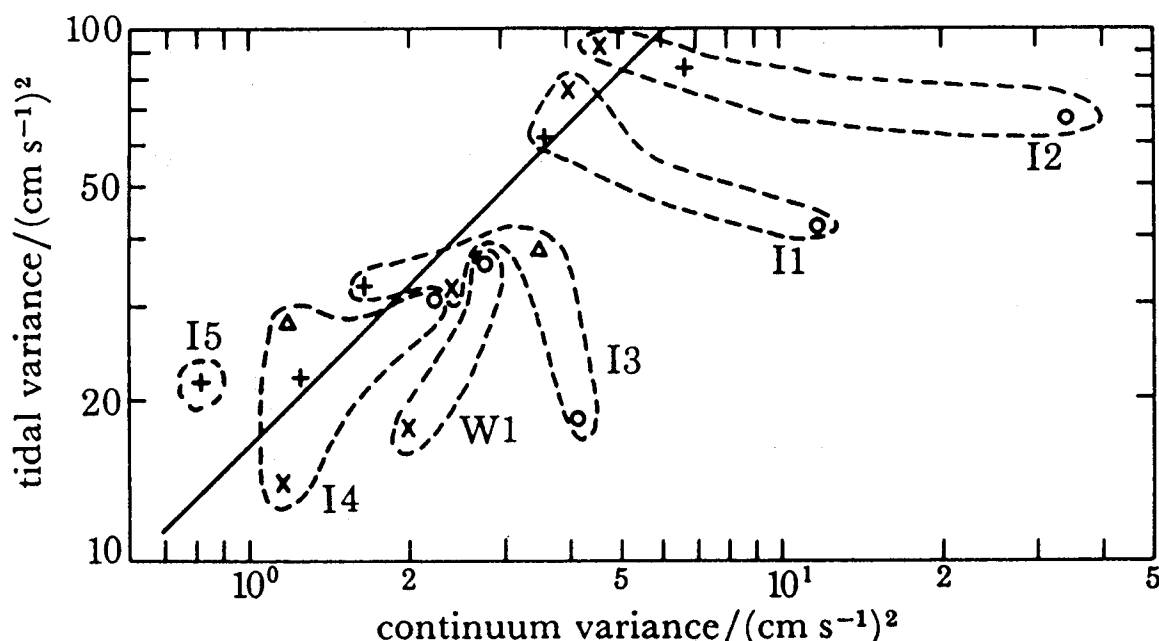
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Figure 2. Variance of horizontal kinetic energy in the continuum (.1 to .3 cph) is plotted against variance in the tidal band (.076 to .090 cph) from nominal depths of 200 (×), 600 (+), 1000 (O) and 1500 m (▲). The straight line indicates a constant ratio of tidal to continuum variance fitted to data at 200 and 600 m. (Adapted from Levine *et al.*, 1983.)

Scotland indicate a correlation between energy in the tidal band and in the continuum. A higher energy internal wave continuum was found with larger internal tides. This correlation, of course, does not prove cause and effect as the higher energy was found near steeper topography. Perhaps the entire internal wave spectrum was enhanced by interaction with topography--the tidal band and continuum could have no dynamic link.

Another interesting set of moored observations from the equator (Eriksen, 1985) suggests that a change in the spectral slope occurs at the semidiurnal frequency (Figure 3). If the tide did not interact with the background wave field, then there is no obvious reason for different spectral slopes above and below the semidiurnal frequency. The persuasiveness of this argument may depend somewhat on one's artistry with pen and ruler.

If energy at the semidiurnal frequency were being nonlinearly transferred, one might expect spectral peaks at harmonics of the tidal frequency. Indeed, harmonics are often observed in the open ocean in deep water. High resolution spectra suggest that the smooth continuum spectrum may actually consist primarily of harmonics of the tide and near-inertial waves (Pinkel 1981 and 1983).
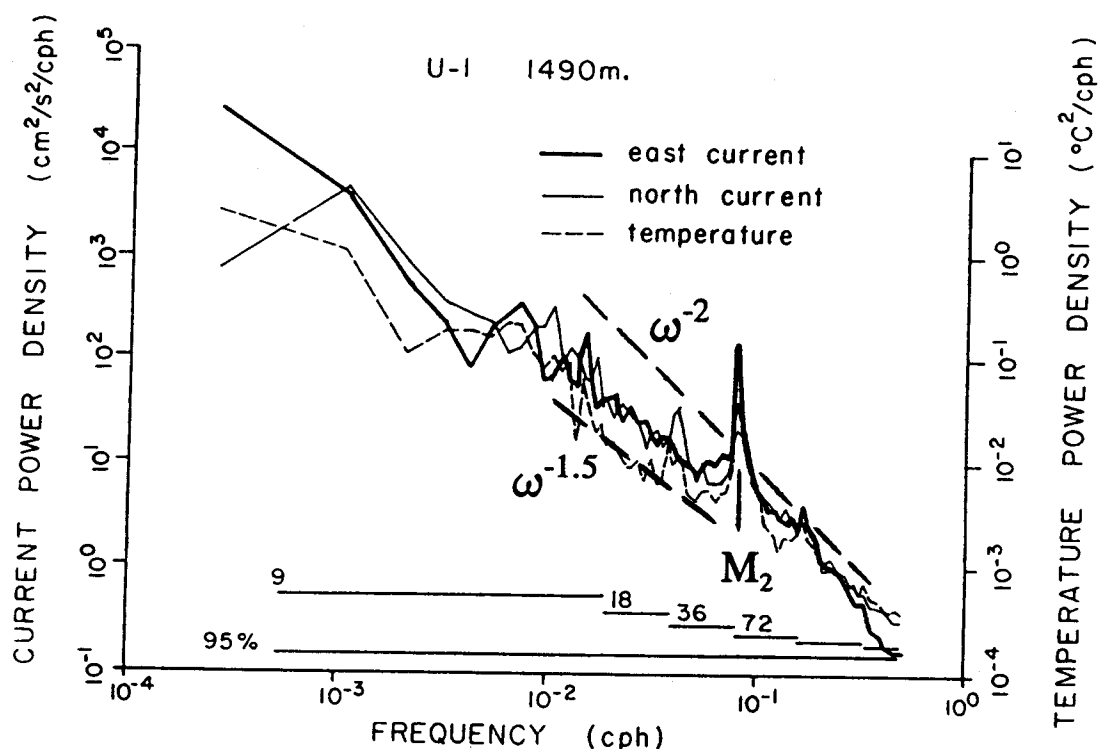
Figure 3. Autospectra of current and temperature from mooring near the equator $(0°20.7'N,144°32.6'W)$. There is an apparent change in the spectral slope at the semidiurnal frequency. (Adapted from Eriksen, 1985.)

Even if the internal tide is not a significant energy source to the continuum, it may be worthy of study as a *test wave*; consider the ocean as a wave tank with the tide acting as a steady wave maker. It might be possible to track the propagation of the internal tide because of its high amplitude and thereby estimate its interaction with other waves. Perhaps theoretical ideas of nonlinear interaction could be tested in this way.

NEAR-INERTIAL WAVES

Waves in the near-inertial frequency band have been studied extensively for decades. Although these waves are included in the universal GM formulation, there is a large amount of space/time variability in the signal. A substantial fraction of the near-inertial energy comes from local generation (Fu, 1981) and has been modeled deterministically by many (e.g., Pollard 1970). Since most of the shear variance comes from the near-inertial band (Figure 1b), it may be risky to use the GM model to estimate vertical shear for purposes of predicting turbulent mixing. Perhaps a better way is needed to express the intermittency of these waves so that a more accurate parameterization of the wave field could be made. Some ideas of intermittency will be explored in the next section.

Can the wind-generated, near-inertial waves be the source of energy for the entire internal wave continuum? Based on a linear model, the overall near-inertial energy flux input estimated from real wind fields in the N.E. Pacific gives ~ 1 mW m^{-2} (D'Asaro, 1985), enough to make a significant contribution to the internal wave continuum. Note that most of the flux occurs in relatively few storm events-- demonstrating the danger of using average values. To check for correlation, the temporal variability of the near-inertial band is compared with the higher frequency continuum in Figure 4. The mean spectrum has been divided out; hence, a contour value of 2 indicates that the spectral level is twice the average value. These observations are from 140 m on a mooring deployed in the N.E. Pacific during the Ocean Storms experiment. It appears that the fluctuations in the continuum are correlated with the near-inertial band, most of the time. Fluctuations in the high-frequency band, from 0.1 to 2 cph, seem to occur at all frequencies by about the same factor. However, the variation of the near-inertial band is usually greater than the high frequencies. It remains to determine if these observations are consistent with the notions of nonlinear interaction. Perhaps it is possible that the increased high-frequency waves are directly forced by the wind by a linear process? Or maybe the increased high-frequency signal is merely the result of the enhanced Doppler shifting of existing waves?

THE RANDOM WAVE FIELD HYPOTHESIS

The description of the internal wave field as a superposition of waves with random phase is a basic tenet of the GM model. The notion of a random wave field is also used extensively by theoreticians when modeling nonlinear interactions. How accurate is this assumption? What if there is significant correlation between some of the waves? What are the ramifications to the description and modeling of the wave field if the assumption of random phase is violated, even slightly?

Rather than tracking each wave component in α-β-ω space perhaps it is more efficient to follow the modulation or envelope of the wave field. Of course, if the wave field is modeled as a sum of random waves, then the statistical properties of the envelope can be inferred. But it still may be more straightforward to concentrate on modeling the modulation directly as it is a quantity of real interest--the wave energy. The relationship between individual waves and their envelope has been studied extensively for surface waves by Longuet-Higgins (1984) and has recently been applied to internal waves by Moustafa and Rubenstein (1990). For a random wave field with a given spectral bandwidth, say in frequency, the statistics of the temporal modulation can be predicted. Does the observed modulation of the internal wave field follow the prediction? The analysis by Moustafa and Rubenstein (1990) indicated that the temporal modulation of the internal wave field seemed consistent with the hypothesis of random phase between components. Further analysis of this type with more data and extended to include the spatial dimensions is needed to determine if this behavior is universal.
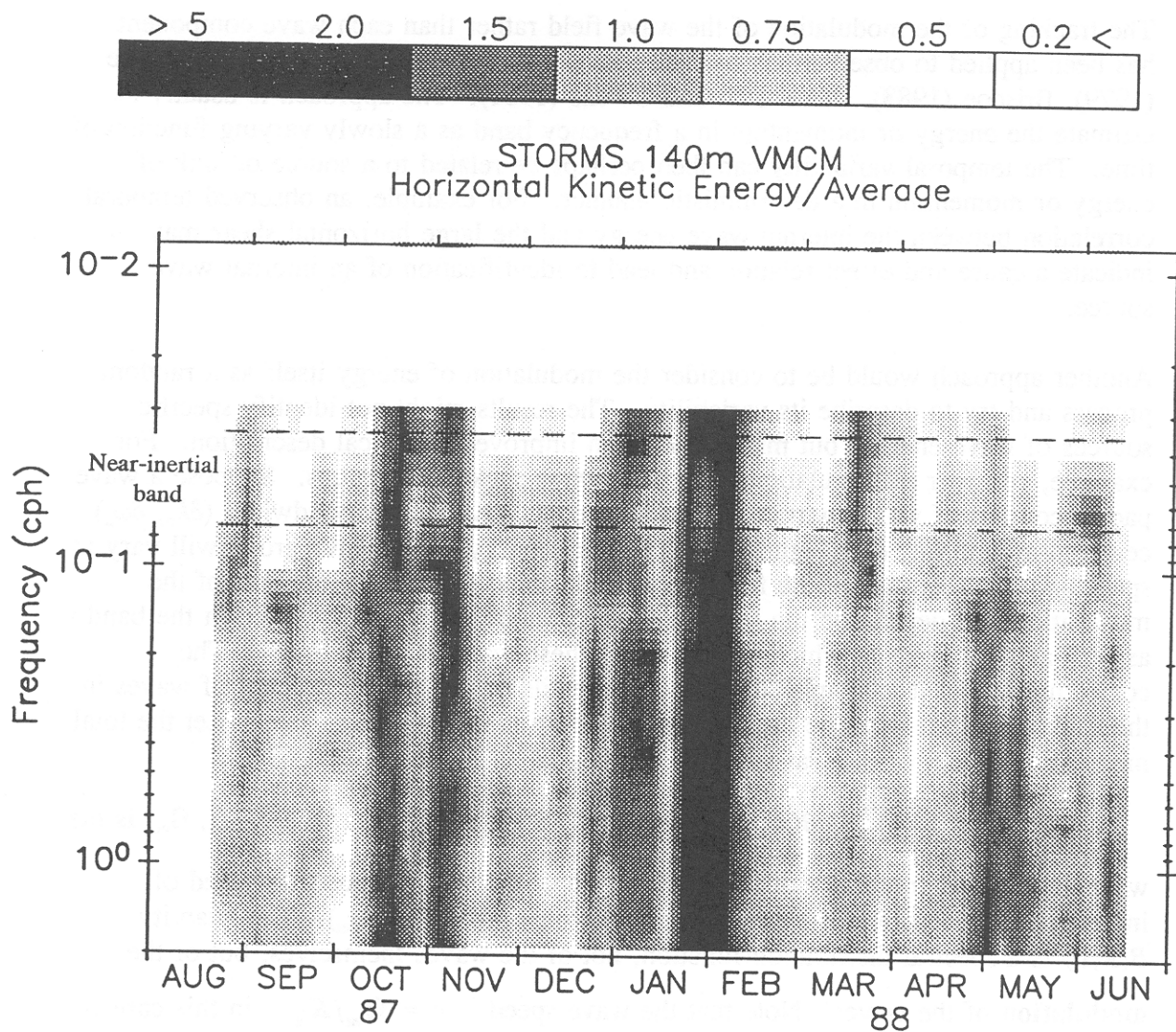
Figure 4. Frequency spectrum of horizontal kinetic energy as a function of time as observed at 140 m during OCEAN STORMS. Plotted values are the ratio of the spectral density divided by the average value. Hence, a value of 2 implies 2 times the average spectral density. The modulation of the high-frequency internal wave field is often correlated with the near-inertial variations. However, there are times, such as in early May when high-frequency waves increase without an associated increase in near-inertial energy.

An interesting extension of this approach might be to consider the consequences when all the phases between components are **not** random. Or turning the question around, what does failure of the random phase test imply about the correlation of the phases. This is undoubtedly a complicated problem since there are many ways that waves can be correlated, but only one way they can be uncorrelated.

The tracking of the modulation of the wave field rather than each wave component has been applied to observations by many investigators, e.g. Frankignoul and Joyce (1979), Briscoe (1983), and Brown and Owens (1981). The approach is usually to estimate the energy or momentum in a frequency band as a slowly varying function of time. The temporal variability can then perhaps be related to a source or sink of energy or momentum in a deterministic manner. For example, an observed temporal correlation between the internal wave energy and the large horizontal shear may indicate a cause and effect relation and lead to identification of an internal wave source.

Another approach would be to consider the modulation of energy itself as a random process and try to describe its variability. The results might not identify specific sources of wave energy, but might lead to an improved statistical description. For example, consider a formulation that tracks wave packets or groups. Suppose a wave packet consists of waves within a small frequency/wavenumber bandwidth $(\delta k_n, \delta \omega_n)$ centered around (k_n, ω_n) (Figure 5a). The total energy of the wave group will vary in space and time because of the finite bandwidth. The statistical properties of the modulation will depend on the relative magnitudes of the waves included in the band as well as the degree to which the phases of these waves are correlated. The conjecture is that it is simpler to ignore the details of the infinite number of waves in the packet and just describe the time space variation of the packet itself. Let the total modulation $M(x,t)$ of the wave field be written as

$$M(x,t) = \sum_n \sum_m B(K_n, \Omega_m) \exp[i(K_n \cdot x - \Omega_m t)] \quad \text{where } (K_n, \Omega_m) \text{ is the}$$

wavenumber and frequency of the **modulation** of the wave packet composed of individual waves with frequency/wavenumber centered at (k_n, ω_m). The quantity $B(K,\Omega)$ is a spectral distribution function, not of the waves themselves, but of the

modulation of the waves. Note that the wave speed $c = \Omega_m / K_n$ in this case is

the **group** velocity, not the phase speed, since it is the speed of the wave packet or energy. Perhaps a universal, statistical model of the wave energy can be formulated with this approach in a spirit similar to the GM framework. That is, observed spectra and coherences of the **modulation** would be used to define $< B(K,\Omega) B'(K,\Omega) >$, just as observed spectra and coherences were used by GM to establish $E(k,\omega)$. As an example, an estimate of the spectra of the modulation of vertical displacement in the 1 to 4 cph frequency band is given in Figure 5b. This spectrum can be characterized by an $\Omega^{-1.5}$ dependence with a hint of a few peaks. These observations are from a month-long time series recorded during AIWEX (Arctic Internal Wave Experiment). Is this universal, and what does it tell us? The feasibility and usefulness of employing this approach remains an open question.

Instead of resorting to a Fourier representation for $M(x,t)$, it may be useful to try an entirely different representation. For example, a wavelet transform of the modulation
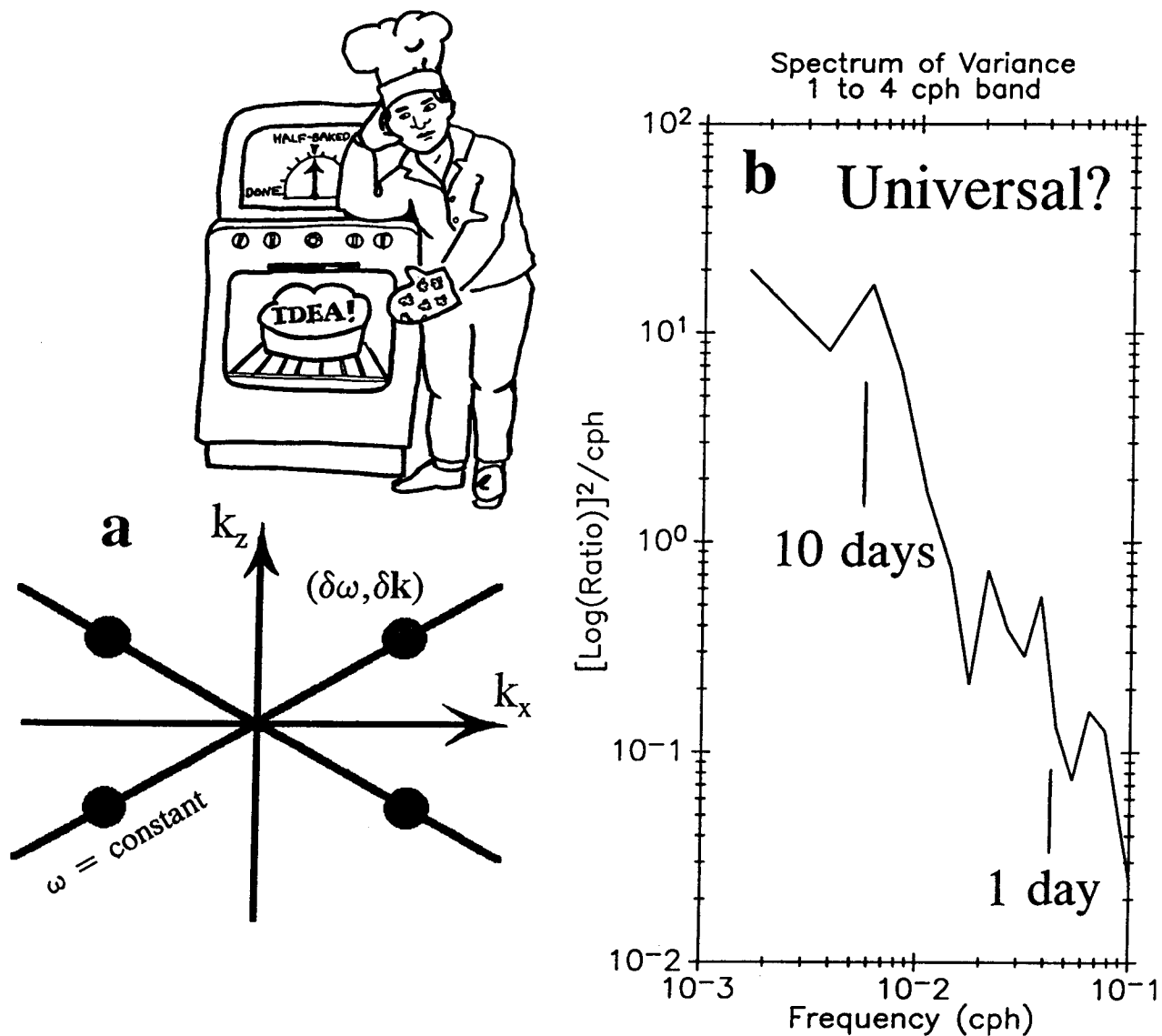
Figure 5. Schematic diagram in wavenumber space (a) of a group of waves with bandwidth (δω,δk). Spectrum of the temporal modulation of the vertical displacement variance of waves is in the 1 to 4 cph band. The spectral density is expressed as the log of the ratio relative to the average variance. These data were recorded for 1 month during AIWEX (Arctic Internal Wave Experiment) in the Beaufort Sea at 257 m depth.

field may provide insight. This transform would express the modulation time series as a sum of localized "packets" of varying length. Of course, any representation of the wave field must also behave somewhat like the GM model, at least to the extent that the GM statistics mimic observations. However, a different representation may lead to significant differences in determining higher-order statistics, estimating the consistency relationships, and modeling nonlinear interactions.

CONCLUSIONS

Theoretical studies of the dynamics of oceanic internal waves rely on a description of the oceanic internal wave field. The more accurate the description, the better the chance for a realistic theory. The GM model has provided the first order statistical formulation of the wave field. However, effort is needed to improve the description of aspects of the wave field that do not follow GM. Features of the non-GM wave field that need further study include internal tides, near-inertial motion and the random wave assumption. While these areas of research are not new, they need to be updated and refined to incorporate new data and theoretical ideas.

Acknowledgments

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