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Observations of Internal Gravity Waves Under the Arctic Pack Ice

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Internal gravity waves measured under the Arctic pack ice were strikingly different from measurements at lower latitudes. The total wave energy, integrated over the internal wave frequency band, was lower by a factor of 0.03–0.07, and the spectral slope at high frequency was nearly −1 in contrast to the −2 observed at lower latitudes. This result has implications for theoretical investigations of the generation, evolution, and destruction of internal waves and is also important for other processes, such as the propagation of sound, and the wave-induced turbulent diffusion of heat, plankton, and chemical tracers.

INTRODUCTION

Internal gravity waves are responsible for much of the variability in the ocean at short time scales, from the inertial to buoyancy periods, and at small space scales, from 0.1 to 10 km [*Olbers*, 1983]. These waves transport energy vertically and horizontally and may transform large-scale geostrophic circulations to small-scale turbulent motions. Away from topographic features the internal wave spectrum has been observed to be remarkably steady in time and uniform throughout most of the world's oceans. However, beneath the Arctic pack ice the wave field differs markedly from lower-latitude observations. Results from the Arctic Internal Wave Experiment (AIWEX) indicate that the internal waves are substantially less energetic with a significantly different spectral composition compared with lower-latitude observations. We believe that the measurements made during AIWEX represent one of the best sets of observations of an oceanic internal wave field in which the spectral level and shape are significantly different from the universal Garrett-Munk model [*Garrett and Munk*, 1972, 1975] (hereinafter referred to as GM).

Oceanic measurements over the past two decades reveal that the internal wave field is composed of a wide spectrum of frequencies and wave numbers with statistics that are nearly stationary in time and space. This conclusion allowed GM to derive a universal spectral representation of the wave field that is consistent with observations and linear wave theory. Although the GM model is a simplified view of internal waves, experience has demonstrated that new observations tend to follow the main features of the model.

While the spectral description of the internal wave field has continued to improve, we do not yet understand the physical processes that generate and dissipate internal waves. Theoretical studies have suggested a variety of plausible mechanisms, but verification is difficult. One approach has been to search for deviations from the universal GM description and to attempt to correlate these deviations with fluctuations in external forcing [*Wunsch*, 1975]. Some success has been achieved in correlating wind forcing with the generation of internal waves at near-inertial frequencies [e.g., *Pollard*, 1970; *Fu*, 1981; *D'Asaro*, 1985]. However, establishing a cause and effect relationship between a forcing mechanism and the remainder of the internal wave spectrum has not been as successful. The possibility of topographic forcing is suggested from measurements of enhanced levels of wave energy near significant topographic features such as seamounts [e.g., *Wunsch and Webb*, 1979] and canyons [e.g., *Hotchkiss and Wunsch*, 1982]. Atmospheric forcing appears to produce a seasonal variation in energy from 1/2–1/3 to 2–3 times the mean level in observations made during the Long-Term Upper Ocean Study [*Briscoe and Weller*, 1984]. Further evidence connecting specific forcing mechanisms with variations in the internal wave field will aid in determining the identity of the important sources of internal waves.

It was in the spirit of searching for an anomalous internal wave field that AIWEX was organized. Scant evidence indicated that internal wave energy levels might be low in the Arctic Ocean [*Levine et al.*, 1985]. AIWEX was designed to test this hypothesis by making intensive observations of the internal wave field beneath the polar ice cap. In this paper we present measurements of the internal wave spectra measured during AIWEX and compare these observations with the GM model.

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OBSERVATIONS

The experiment took place at an ice camp established about 350 km north of Prudhoe Bay, Alaska, in the Beaufort Sea, with researchers from Oregon State University, the University of Washington, Scripps Institution of Oceanography, and private industry. During nearly 2 months of occupancy from March to May 1985 the camp difted about 120 km to the west from its origin at 74°N, 143°W. An extensive set of temperature, conductivity, and velocity data were gathered from a variety of instruments. Access to the water was obtained through holes in the 3-m-thick ice. The measurements reported here were made from both fixed and vertically profiling instruments.

To determine the density field through which the internal waves propagate, vertical profiles of temperature and salinity were measured with the Arctic profiling system [*Morison*, 1980]. The buoyancy frequency N was then estimated from the vertical gradient of density. There are significant variations in N in the upper 250 m reflecting the different water masses that compose the upper Arctic Ocean [*Aagaard et al.*, 1985] (Figure 1). Values range from 4 cph to peaks near 12 cph.

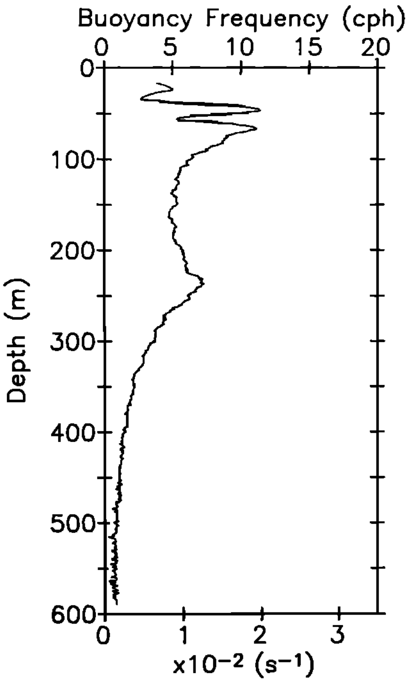

Fig. 1. Vertical profile of buoyancy frequency.

Below 250 m, N decreases nearly exponentially to the bottom at 3700 m.

Time series of temperature were measured by a vertical and horizontal array of temperature sensors (Sea-Bird Electronics, sensor SBE-3). Seven of the sensors were located at 250 m, where the fluctuations in temperature are due primarily to the vertical displacement of the internal waves. The vertical displacement is inferred by dividing the temperature time series by the average vertical temperature gradient. An observed spectrum of vertical displacement from the period March 20 to April 5 is shown in Figure 2. The spectrum decreases as ω^{-1} up to 6 cph, the local value of the buoyancy frequency. Above N there is a sharp break in slope and a steep falloff in energy.

Over the same period a time series of horizontal velocity at 100 m was measured with an electromagnetic current meter (InterOcean S4). Because the ice pack drifts, the observed velocity is the sum of the ice and water motion. The ice motion was removed from the velocity time series using the time history of the camp position determined from a fit to satellite navigation. The method used is due to *McPhee* [1986]. Positions were obtained approximately 40 times per day. The frequency spectra of the two rotary components of horizontal velocity are shown in Figure 2. There is a peak in the clockwise component at the inertial frequency as expected in the northern hemisphere. Above f the clockwise component is higher than the counterclockwise; at high frequency the components are nearly the same and follow ω^{-1}. The falloff above N is not observed because the sampling rate was too low.

Discussion and Conclusions

To compare these observations with those from other oceans, the GM spectrum was calculated; it is a good representation of the internal wave field at lower latitudes away from topography. The GM spectra of vertical displacement S_ζ and of clockwise and counterclockwise rotary velocity S_- and S_+ are given by

$$S_\zeta(\omega) = \frac{2}{\pi} E b^2 N_0 \frac{f}{N(z)} \frac{(\omega^2 - f^2)^{1/2}}{\omega^3}$$

$$S_\pm(\omega) = 4\pi E b^2 N_0 f N(z) \frac{(\omega \mp f)^2}{\omega^3(\omega^2 - f^2)^{1/2}}$$

where we use the same values of the parameters as GM: $E = 6.3 \times 10^{-5}$ (nondimensional energy level), $b = 1300$ m (vertical depth scale of N), and $N_0 = 3$ cph (buoyancy frequency scale). The units of S_ζ and $S_\pm$ are m^2 (cph)$^{-1}$ and m h^{-1} (cph)$^{-1}$ respectively, for frequency specified in units of cycles per hour. The GM description is confined to freely propagating, linear internal waves which are restricted to frequencies between the inertial frequency f and N. The GM spectra are plotted with the observations in Figures 2 and 3. The local value of N is used to scale the level of the spectra. The values of N at 100 and 250 m were taken from Figure 1 and found to be near 6 cph at both depths. At high frequency, $\omega \gg f$, the frequency dependence of the GM spectra of velocity and vertical displacement is ω^{-2}.

The Arctic spectra are strikingly different from lower-latitude observations: The total internal wave energy is significantly lower by a factor of 0.03–0.07, and the spectral slope is substantially less steep, with a frequency dependence near ω^{-1} at high frequency. The total internal wave energy is estimated from the total variance of the velocity or vertical displacement over the internal wave frequency band from f to N. The total energy is lower than GM by a factor of 0.03 based on vertical displacement and a factor of 0.07 based on velocity. However, the spectral density ranges below GM by a factor of 0.6 near N to a factor of 0.01 near f (Figures 2 and 3).

These observations have a potential impact on a variety of

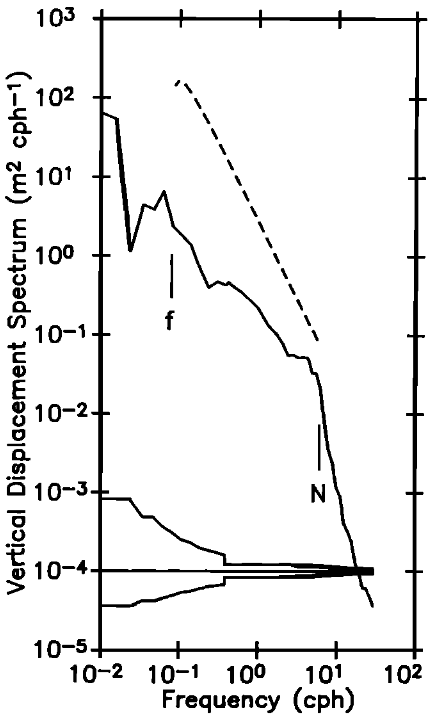

Fig. 2. Spectrum of vertical displacement from 250-m depth (solid line). Vertical displacement was inferred from temperature by dividing by the average vertical temperature gradient of 0.02°C m^{-1}. The Garrett-Munk spectrum is shown for comparison (dashed line). The 95% confidence limits are indicated below.

active research areas. Recent theoretical studies have sought to explain the observed spectral composition of the wave field by nonlinear interactions (see *Müller et al.* [1986], for a recent review of the topic). Researchers have typically used a spectrum similar to GM to characterize the oceanic internal wave field. The theories can now be tested with a wave field having a different spectral composition. A successful theory will need to explain both the low-latitude and Arctic measurements. Studies of acoustic propagation have been able to relate amplitude and travel time fluctuations of sound pulses to the fluctuations due to internal waves [e.g., *Flatté*, 1983; *Ewart and Reynolds*, 1984]. The Arctic Ocean, with its unique internal wave environment, provides a valuable laboratory for testing new theoretical ideas in acoustic propagation. The role of internal waves in vertical and horizontal mixing [e.g., *Young et al.*, 1982; *Desaubies and Smith*, 1982] may be elucidated by comparing observations from lower latitude with the Arctic. Differences in mixing could affect the large-scale circulation as well as the diffusion of plankton and chemical tracers.

Why are Arctic internal waves so different from those at lower latitudes? The search for answers to this question is a topic of active research. We can, however, suggest some hypotheses.

It is instructive to examine the physical processes that are unique to the Arctic Ocean. The ice cover acts as a rigid lid to the internal waves. The formation of a turbulent boundary layer below the ice causes increased internal wave dissipation compared to ice free oceans [*Morison et al.*, 1985]. The nature of surface forcing is also quite different in the Arctic. The wind stress usually must be transferred through the ice to reach the water below. This forcing is generally weaker than other oceans because the winds themselves are weaker [*Paulson*, 1980], and some momentum is transmitted through the ice to the coast. Ice keels, which add topographic relief to the underside of the ice, may generate internal waves when the ice moves [*Rigby*, 1976]. Large surface buoyancy fluxes, which occur within leads, may generate internal waves by perturbing the pycnocline at the base of the surface-mixed layer [*Morison*, 1980, 1986]. It is theoretically possible to transfer momentum to internal waves from surface gravity waves [*Olbers*, 1983; *Phillips*, 1977]; this mechanism is not possible in an ice-covered ocean. Another source of energy for the internal wave field may be provided by the spectral transfer of internal tide energy through nonlinear wave-wave interactions [*Bell*, 1975]. The internal tide is an internal wave at tidal frequencies that is generated by the interaction of the barotropic tide with topography, such as continental shelves (see *Hendershott* [1981], for a review of internal tides). In the Arctic Ocean the internal tide is weak due to a small barotropic tide over much of the Arctic Ocean [*Kowalik and Untersteiner*, 1978] coupled with the fact that free internal waves cannot exist at latitudes higher than 75° at the lunar semidiurnal frequency (M_2 tide). Internal waves may also gain energy from low-frequency motions, such as mesoscale eddies and mean geostrophic circulations [*Olbers*, 1983]. The mean circulation in the Beaufort Sea is relatively weak compared to most oceans [*Coachman and Aagaard*, 1974]; however, the basin is populated with intense, long-lived small-scale eddies (10–20 km) [*Manley and Hunkins*, 1985]. Identification of which of the foregoing or other processes are most important in generating, modifying, and dissipating internal waves awaits further investigation.

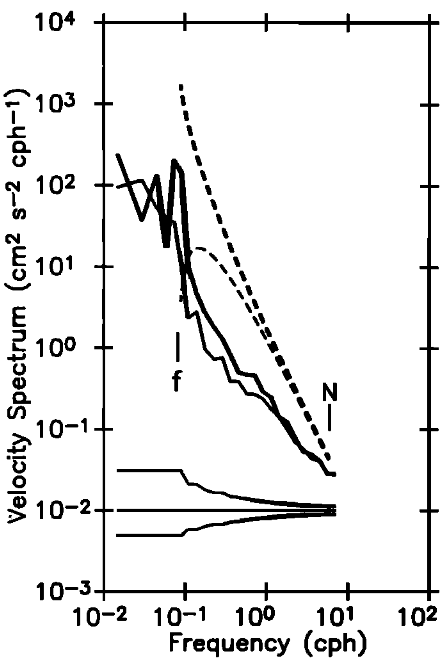

Fig. 3. Spectrum of the clockwise (bold solid line) and counterclockwise (light solid line) components of horizontal velocity at 100-m depth. The Garrett-Munk spectrum is shown for comparison (dashed line). The 95% confidence limits are indicated below.

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