Ocean Dynamics and Acoustic Fluctuations in the Fram Strait Marginal Ice Zone

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Acoustic waves transmitted over a 100-kilometer path in the Fram Strait marginal ice zone undergo Doppler shifts and fluctuations around these shifts, the former due to quasi-steady motion of both acoustic source and receiver and the latter to unsteady motions of the water column and ice cover. Internal waves and differential Doppler shift usually account for such fluctuations in the deep temperate ocean but only partially explain the results obtained in the marginal ice zone. There the fluctuations are more energetic and may be caused alternatively or additionally by comparably energetic fluctuations in ice-edge eddies or other mesoscale motions.

DURING THE FRAM STRAIT MARginal Ice Zone Experiment (MIZEX-84), an acoustic source was deployed on R.V. *Polarqueen* and a receiving array on R.V. *Kvitbjorn*. The source emitted narrowband tones at carrier frequencies betwen 25 and 200 Hz for a 10-hour period. During this time the two ships, about 100 km apart, were drifting with the ice. Generally upward-refracting but variable sound speed profiles, an undulating bottom (mean depth ~700 m), and a variable ice cover of about two-thirds concentration characterized the overall acoustic environment. Oceanographic data were acquired for the acoustic path (about 80°47′N, 4°19′E to about 80°20′N, 9°12′E) as well as for the surrounding region (*1*).

Acoustic data were analyzed to determine Doppler shift and fluctuations around the shift. The Doppler shift is assumed to be quasi-steady because its various possible causes are inertially set by large-scale effects that evolve slowly in time. More rapid fluctuations can be caused by unsteady motions of the water column, such as internal waves. We now describe both the quasi-steady Doppler shifts and the more rapid fluctuations. Such data, when inverted, can elucidate ocean dynamical properties (such as eddy scale) and, when applied directly, define elements of sonar system design (such as bandwidth).

Under the assumption that the phase and phase rate of each acoustic path are uncorrelated, and that the phase rate changes as an incoherent sum over three or more independent events along the propagation path, several investigators (*2–5*) have shown that the normalized complex correlation function of the signal received versus time is

$$r(\tau) = \exp[-2\pi^2\nu^2\tau^2 - i2\pi f_D\tau] \qquad (1)$$

where τ is the time delay for the correlation, f_D is the Doppler shift frequency, and ν is a fluctuation parameter known as the root-mean-square (rms) single-path phase rate, which is taken to be the same for each of the dominant paths. Equation 1 can be obtained only if acceleration of the source-receiver pair is negligible, which as will be shown was the case in our experiment. The spectral counterpart of Eq. 1 is

$$s(f) = (2\pi\nu^2)^{-1/2}\exp[-(f-f_D)^2/2\nu^2] \qquad (2)$$

which shows that, under these assumptions, the spectrum is a Doppler-shifted Gaussian with spread proportional to ν. This spectrum reasonably fits our observations. From the data we can extract f_D and ν, the former by direct observation of the spectral shift and the latter by the covariance method (*5–8*). This method provides an estimate of ν without the need to estimate the entire spectrum and further enables parameter estimates to be obtained from short records, which in turn separates whatever spreading might be due to quasi-steady shifts in f_D and the intrinsic value of ν.

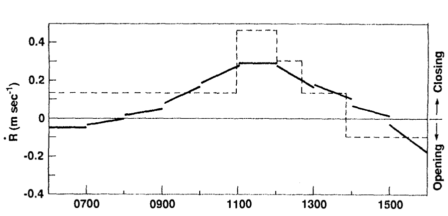

Fig. 1. Range rate $\dot{R}$ obtained from the observed Doppler shift frequency on 19 June 1984. The solid line indicates Doppler data; the broken line indicates satellite data. Time is given as hours Greenwich mean time.

Figure 1 shows the range rate $\dot{R}$ as determined from f_D in each hourly period. The quasi-steady Doppler shift is approximated in each period by a linear variation; the assemblage of such linear segments is an approximation to a continuous curve that we believe to be a close rendition of the actual motion. Satellite data gave only six simultaneous positions of the two ships; these provide a stepped approximation to the quasi-steady continuous motion and, even though sparse, are reasonably consistent with the continuous Doppler data.

Fluctuations around the quasi-steady phase shifts are given in Table 1 for each of several carrier frequencies f_c. These data yield

$$\nu/f_c \approx 1.15 \times 10^{-5} \pm 24\% \qquad (3)$$

with the spread being 1 standard deviation (σ) on either side of the mean.

Should acceleration have been dominant in the frequency spread, the signal phase would have been $2\pi(f_c - f_D)t + \pi\alpha t^2$, where α is the Doppler shift rate and t is time. The spectral density (Eq. 2) would then be modified by convolution with a rectangular function of frequency width $|\alpha|T$, where T is the sampling window (we used a value of 200 sec). We compare this width with the half-power width of Eq. 2 to test the assumption that such acceleration-induced frequency spreading can be neglected. From the maximum slope in Fig. 1 we obtain

$$|\alpha|T = \frac{2f_c}{c}\left|\frac{\partial\dot{R}}{\partial t}\right|T \lesssim 8 \times 10^{-6}f_c \qquad (4)$$

where c is the sound speed ($\approx$1450 m sec^{-1}). From Eqs. 2 and 3 the measured half-power width is $2.35\nu \approx 3 \times 10^{-5}f_c$, which is substantially larger than Eq. 4. Thus we conclude that range-rate acceleration can be neglected. Furthermore, accelerations caused by drift through marginal ice zone (MIZ) velocity gradients and source and receiver suspension motions relative to the ships can also be neglected. Noise effects can also be ignored: the signal-to-noise ratio was high (>20 dB), which yields a negligible bias in ν (<10%). Thus the values in Table 1 can be ascribed to a quasi-static process with fluctuations around the mean Doppler shift.

Acoustic fluctuations in the temperate ocean are caused by internal waves for fixed or slowly drifting source-receiver pairs (*2, 9*) and by differential Doppler shift for rapidly drifting pairs (*10, 11*). It is therefore reasonable to test these mechanisms for the MIZ, even though such measurements in the temperate ocean rarely encompass the dynamical complexity of the MIZ. Measurements of the fluctuations due to internal waves can be represented (for the deep temperate ocean) by (*2, 9, 11*)

$$\nu \approx 2 \times 10^{-8} R^{1/2}f_c \qquad (5)$$

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Table 1. Observed fluctuations over a 100-km path on 19 June 1984. Symbols: f_c, carrier frequency; ν, rms phase rate.

f_c (Hz)	ν (mHz)
25	0.4
65	0.8
105	1.2
125	1.1
165	1.4
200	2.4

with range R in meters. To scale to the MIZ, we take the accepted model (*2*) and adjust Eq. 5 by the ratios of stability profile scale depth ($\approx 5.2 \times 10^{-2}$), surface stability frequency (≈ 2.3), acoustic axis stability frequency (≈ 12), inertial frequency (≈ 2.0), and sound speed change induced by vertical internal wave displacement (≈ 0.2), each of which appear in the model in various algebraic combinations. In choosing these ratios we are guided by internal wave measurements previously made in the same location and season in the MIZ (*12, 13*). The result (scaled to the MIZ) is

$$\nu \approx 2 \times 10^{-9} R^{1/2} f_c \qquad (6)$$

which for $R = 100$ km becomes $\nu \approx 6 \times 10^{-7} f_c$. This prediction falls more than one order of magnitude below our measurement (Eq. 3), and thus internal wave motion is not a plausible explanation for acoustic fluctuations in our measurements, although it is remotely possible given the uncertainties inherent in scaling from nonconcurrent internal wave data.

Phase rate fluctuations can be caused in a quiescent ocean by source-receiver motion through differential Doppler shift among the various acoustic paths, since each can be related to a differential angle with respect to the horizontal. Such differential Doppler fluctuations are observed in many experiments with drifting sensors (*10*) and, when large enough, can cause fluctuations that overwhelm those caused by ocean dynamics. We can estimate this phase rate as (*14*)

$$\nu' = a\, k_c\, \dot{R}\, (\Delta c/c)/2\pi \qquad (7)$$

where a is a constant dependent on the shape of the sound speed profile (estimated to be 0.5 for the Arctic), k_c is the carrier wave number, and $\Delta c/c$ is the incremental sound speed relative to the total sound speed defining the channel carrying the acoustic waves. For the MIZ we estimate $\Delta c/c$ to be about 10^{-2} and, from the observed range rate (≤ 0.3 msec^{-1}), find that ν' is less than approximately $10^{-6} f_c$. This is at least one order of magnitude less than our result; thus differential Doppler shift is also an unlikely mechanism for acoustic fluctuation.

If not internal waves or differential Doppler shift, and not drift accelerations or noise, then what is the cause? We have no answers, only hypotheses about possible ocean dynamical mechanisms. In addition to internal waves, the MIZ has dynamical structure associated with eddies, fronts, currents, and meanders (*1, 15*); we hypothesize that one or more of these can contribute to or dominate the phase rate. A crude model for fluctuations caused thereby is

$$\nu \approx \mu \theta^{-1} k_c R^{1/2} L^{1/2} \qquad (8)$$

where μ is the rms spatial contrast in index of refraction associated with the dynamical the corresponding structure, θ is characteristic time, and L the characteristic radius. Equation 8 is obtained from the phase fluctuations for Fresnel forward scattering (*16*), with θ as the most energetic period in the interval of observation. For the MIZ we estimate a value for μ of 4.9×10^{-3}, and with the observed value for ν we find that any other dynamical mechanism must have

$$2L/\theta^2 \approx 44 \text{ km day}^{-2} \qquad (9)$$

to fit the crude model.

If a mesoscale feature oscillates with the inertial period $\theta_i \approx 0.5$ day, then its scale $2L$ from Eq. 9 is 11 km, which is about that observed for underice eddies in the region of the acoustic experiment (*1*). Our observation period (0.42 day) is too short, and our model too crude, to conclude with confidence that eddy oscillations at the inertial period are indeed the most significant contributors. Instead we hypothesize that eddies or other mesoscale motions of comparable scale are important in determining acoustic fluctuations in the MIZ.

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17. We thank F. DiNapoli and O. Diachok for the source and vertical receiving array; G. Kudlak, D. Hicks, and R. Dicus for technical assistance; and E. Scheer and J. Polcari for providing programs for the primary data reduction. Supported by the Office of Naval Research, Arctic Programs.

19 May 1986; accepted 20 January 1987

Physical Properties of Sea Ice Discharged from Fram Strait

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It is estimated that 84 percent of the ice exiting the Arctic Basin through Fram Strait during June and July 1984 was multiyear ice and that a large percentage of this ice is ridged or otherwise deformed. While freeboard and thickness data, together with salinity measurements on cores, usually sufficed to distinguish between first and multiyear floes, preliminary identification could usually be made on the basis of snow cover measurements with snow cover being much thicker on multiyear ice. Cores from the top half meter of multiyear floes were generally very much harder and more transparent than cores from first-year floes. Age estimates of multiyear floes, based on petrographic and salinity characteristics of cores, did not exceed 4 to 5 years for any of the floes that were observed exiting Fram Strait.

DURING JUNE AND JULY 1984, INvestigations of the physical properties of sea ice were conducted from the German icebreaker *Polarstern* as part of the Marginal Ice Zone Experiment (MIZEX-84). A large area within the Fram Strait was traversed by *Polarstern* and provided an opportunity to obtain core samples from 40 separate floes that had likely originated in different parts of the Arctic Basin. Fram Strait is located between the East Greenland coast and Spitsbergen and is the

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