Modeled Acoustic Propagation Through an Ice Edge Eddy in the East Greenland Sea Marginal Ice Zone

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A detailed modeling study of the relationship between the various oceanographic features of a cyclonic eddy located at the ice edge off the coast of northeastern Greenland and the eddy's effects on the propagation of acoustic energy is presented. The effects of the eddy on acoustic propagation as a function of location, depth, and frequency of the acoustic source and depth of the receiver for nominal frequencies of 50 Hz and 1 kHz are discussed. Significant differences sometimes greater than 20 dB in the acoustic field were observed for variations in any of the source and receiver parameters. The sound speed structure of the eddy makes propagation loss and acoustic modes very dependent on direction and location. A significant finding is that the interior environment of the eddy can generate a frequency dependence on propagation loss so that 1 kHz sustains a loss as much as 20 dB smaller than does 50 Hz, i.e., dispersion phenomenon. A similar propagation loss anomaly was observed and appears to be due to a combination of marginal ice zone (MIZ) fine structure and interference patterns created by reflections from the sea surface. Such an anomaly can exist in the MIZ with or without the eddy environment. Both of these frequency anomalies are a function of source and receiver depth. Low-frequency (50 Hz) energy in the presence of the eddy can experience stronger downward refraction and thereby possibly suffer greater bottom interaction than high frequencies (1 kHz). As compared to the noneddy environment, propagation in the presence of the eddy, for any of the source and receiver depths studied, can result in changes in the levels and distribution of energy in the acoustic field by more than 10 dB as well as changes in the mode of propagation of some rays (e.g., refracted/surface-reflected to refracted/refracted).

1. INTRODUCTION

Eddies are a very significant physical phenomenon in the ocean and have been the subject of extensive scientific research, particularly in the mid-latitude regions. An excellent survey of the results of recent research is presented by Robinson [1983]. Strong temperature changes often occur in the region of the eddy, causing strong sound speed gradients and consequent anomalous acoustic propagation. A review of recent studies on the acoustic properties of mesoscale eddies is given by Spindel and Desaubies [1983]. Our knowledge of eddies in Arctic regions is sparse [Needler, 1983]; however, during the last several years extensive research on this phenomenon has been undertaken in the marginal ice zone (MIZ). Indeed, a central part of the Marginal Ice Zone Experiment (MIZEX) was focused on ice-ocean eddies: their generation, their propagation, their decay, and their role in affecting the ice edge position [Johannesen et al., this issue, MIZEX Group, 1986; Johannesen et al., 1987]. The system performance of acoustic travel time tomography to resolve mesoscale eddies in the MIZ has been evaluated by Chiu et al. [this issue].

This paper reports on a modeling study of acoustic propagation through one of the ice-ocean eddies observed during MIZEX in the central part of the Fram Strait between Svalbard and Greenland. The first section of the paper considers environmental observations of the ice-ocean eddy selected for the acoustic modeling. The succeeding sections cover the effects of the eddy on low-frequency acoustic propagation, both across the entire eddy and from the center of the eddy outward. The effects of the location, depth, and frequency of the acoustic source and receiver depth are also discussed. Finally, comparisons are made between the acoustic fields produced by various locations of the source.

The influence of the eddy on acoustic propagation can be expected to vary with the oceanographic features of the eddy as well as with the relative geometries of the source and receiver, the source frequency, and the direction of propagation. These factors are addressed in the following sections of this paper.

2. ENVIRONMENTAL OBSERVATIONS

During the summers of 1983–1984 extensive ice-ocean eddy investigations were carried out by ships and helicopters and included Eulerian and Lagrangian measurements in combination with remote sensing observations. An example of the abundance of the ice-ocean eddies is shown by the July 4, 1984, infrared and visual images in Plate 1. (Plate 1 is shown here in black and white. The color version can be found in the separate color section in this issue. The eddies that are numbered 1 to 4 all interact strongly with the ice edge, while eddy 5 is located just off the ice edge. Notice also that warm Atlantic water of 4°–5°C (red and yellow color in Plate 1) associated with the eddies is penetrating the ice edge, causing enhanced melting [Johannesen et al., this issue]. All the eddies in Plate 1 show cyclonic rotation. Eddy 1 started to form on June 26 at approximately 79°15'S and 1°30'W. It was fully developed on June 29 and had moved 10 km/d in a southward direction. From June 30 to July 1, eddy 1 moved slowly south to 78°30'N, 2°W and remained approximately in this position until July 15. An Argos buoy that became trapped in this eddy showed that it started to move southward at 20 km/d. After August 10 the eddy signal in the drift path of the buoy disappeared, indicating a minimum lifetime of 30 days and an orbital velocity of 30–40 cm/s. The subsurface three-dimensional structure of eddy 1 was extensively mapped using...
conductivity-temperature-depth probes (CTDs) from the research vessels R/V H. Mosby and R/V Kvitbjørn. One of these CTD sections from July 12–13 though eddy 1 is shown in Figure 1. Nineteen CTD profiles were taken along this section.

In Figure 1 the region where a temperature of 3.5°C or higher exists has been shaded to help identify the warm center of the eddy, especially along the sea surface. Of note in the figure is the cold water at the sea surface overlying warmer water to the east and west of the warm center. Note also the domelike pattern of the isotherms directly below the warm center. This pattern extends to within 25 to 50 m of the sea surface at the warm center. Extensive horizontally layered, fine structure can be seen at depths of < 50 m.

Three representative sound speed profiles are presented in Figure 2. The full-scale profiles for three locations are given on the left: one profile for each of the extreme eastern and western edges of the eddy and one from the warm center of the eddy. The three profiles are very similar in overall shape, although significant differences exist above 500 m and especially above 100 m. Profiles for the upper 200 m are given on the right in the figure. Extensive fine structure can be seen on the western and eastern profiles. Horizontal gradients of 15 m/s occur. As will be shown in the next section, these gradients have significant effects on acoustic propagation.

As an indication of their abundance, 13 eddies, most with cyclonic rotation, were studied in the MIZEX ’83 and MIZEX ’84 experiments between latitudes of 78°–81°N [Johannessen et al., this issue]. Typical scales were 20 to 40 km. Several of the eddies were topographically trapped, while others moved as much as 10 to 15 km/d with the mean current. Eddy life was at least 30 days. An inspection of satellite imagery for both the Greenland Sea and the Barents Sea shows the existence of a very dynamic eddy field along the ice edge for all seasons. This implies that ice-ocean eddy phenomena must be included in acoustic studies of these regions.

3. Acoustic Effects

Two widely used but essentially different models of acoustic propagation in the sea were utilized for this study. The models are a ray theory model (Germinating Ray Acoustic Simulation System, or (GRASS) and a wave theory standard parabolic equation (PE) model. Both range-dependent models assess the effects on acoustic propagation of environmental changes of ocean bottom depth and vertical sound speed structure as a function of horizontal position. See Kuperman [1985] for a survey of acoustic propagation models.

The ray theory model [Cornyn, 1973] was used to obtain ray diagrams that yield an informative physical picture of the acoustic field and allow interpretation of propagation loss calculations as generated by a standard PE model [Tappert,
Fig. 1. Temperature cross section through ice edge eddy 1; isotherms are in degrees Celsius. The ice edge is in the west at range 0 km. Approximate sea surface locations are shown of first and second convergence zones for 300-m source depth, east-to-west and west-to-east propagation.

1977]. Results from the standard PE model were compared with those from the wide angle finite difference PE model [Lee and Botseas, 1982; Botseas et al., 1983], and excellent agreement was obtained.

The ray theory model and therefore the ray diagrams do not include diffraction and other wave effects. They do not therefore adequately describe, for example, low-frequency ducted propagation. When necessary, this limitation is noted in the paper.

The purpose of this paper is to investigate the fundamental effects of the eddy on propagation, and not the effects of the complex boundaries for which, in many cases, sufficient environmental and/or acoustic data are not yet available. Such eddies have been observed along the entire coast of northern Greenland, the coast of Norway, and the ice edge of the Barents Sea. They exist in open water (as may be seen in Plate 1) at various sea states, along the ice edge where both open water and ice floes coexist on the surface, and under complete ice cover. Thus the upper (sea surface) and lower (ocean floor) boundary conditions that may exist for such an eddy and their influence on propagation are extremely complex and variable.

Fig. 2. Representative sound speed profiles.

Fig. 3. Ray tracing, west to east, for source depth of 300 m and noneddy environment.

The reflection of underwater acoustic energy at a sea-ice interface, for example, is the subject of extensive ongoing research and is itself a very complex mechanism [Yang and Votaw, 1981]. At the present time, neither of the models used in this study includes the option of under-ice reflectivity. To isolate the effects of the eddy and to investigate its contribution to propagation, the following conditions were assumed. Any ray incident upon the ocean floor is terminated, and any energy in the PE model that is incident upon the bottom is absorbed. Further, the sea surface is considered smooth and perfectly reflective.

For all ray diagrams, the rays between +89ø and -89ø are plotted, and the increment between rays at the source is 1ø. Nominal source frequencies of 50 Hz and 1 kHz are used in the study. Attenuation due to absorption in sea water is included in the GRASS and PE models and is therefore included in the results.

For every source depth investigated in this paper, receiver depths were investigated for 10, 25, 50, 100, 150, 300, and 1000 m. For brevity, typical results for these receiver depths are presented. In general, the results for all receiver depths produced gradual transitions between those presented.

3.1. Propagation Across Eddy
(Source Depth of 300 m)

Initially, an acoustic source located in the water at the western edge of the eddy and at a depth of 300 m will be con-
considered. To provide a reference, propagation without the eddy present will first be examined. This is simulated in the acoustic models by assuming that the sound speed profiles over the entire propagation range are the same as the one located at the source (i.e., the environment is range-independent). The resulting ray diagram is given in Figure 3. Propagation is west to east. Two convergence zones (CZs) exist; one is located at about 40 km, and the other at about 80 km. A sound channel similar to the deep (SOFAR) sound channel is located near the source depth of 300 m, and is propagating along the entire 110-km range. Note that all the rays in the CZ except those in the SOFAR channel reflect from the sea surface.

The corresponding ray diagram for the eddy environment is given in Figure 4. The most noticeable effect of the eddy is the loss of the SOFAR channel that existed in Figure 3. The two CZs continue to exist at about the same ranges.

It will be useful to follow two of the rays in the diagram to illustrate effects of the eddy on the acoustic field and to aid in interpreting quantitative results given later in the paper. First, the ray indicated by the dotted line is initially refracted upward, vertexing near the 100-m depth at a range of about 5 km. This ray is one of the family of rays that formed the SOFAR channel in Figure 3. The vertex is caused by the warmer surface water that is interrupting this portion of the surface channel. The ray on its downward path is strongly refracted again, this time into a steeper down angle at a range of about 15 km, where it enters a warm water feature shown in Figure 1 by the increase in depth of the isothermal contours at 15 km.

The ray then continues until it vertexes at depth and again near the surface at a range of about 50 km. Note that when the eddy is present, as compared with when it is not, many of the rays such as this one do not reach the surface to reflect from it. The second near-surface vertex occurs at a depth of approximately 50 m, and is a result of the isotherms' domelike pattern (Figure 1), which is similar in configuration to a Gulf Stream cold-core ring. Thus energy from the dissolved SOFAR channel has been added to the CZ. The ray then cycles again at depth and on its last upward path enters and adds to the formation of a shallow SOFAR-type channel at a range of about 90 km. Thus the eddy has had the effect of dissolving the original SOFAR channel of Figure 3 and redistributing it as additional energy in the convergence zone and in the formation of a new, shallow, SOFAR-type channel just beyond the second CZ. The cou-
Corresponding propagation loss predictions, both with and without the eddy present, are given in Figure 5. Propagation loss predictions by the PE model are plotted as a function of range for the 300-m source depth, a nominal frequency of 50 Hz, and a receiver depth of 300 m. The interruption and loss of the SOFAR channel caused by the presence of the eddy can be seen in the range intervals of approximately 10 to 35 km and 55 to 75 km. These ranges correspond to the "shadow zones" (areas of low insonification) seen in the ray trace of Figure 4. The absence of the channel in Figure 5 results in up to a loss 20 dB greater in these range intervals for the eddy environment as compared with the noneddy environment. The difference between the two curves is considerably smaller in the two convergence zones, which are located approximately in 10-km range intervals near 40 km and 80 km. The reason for this is suggested by the ray trace of Figure 4 (for the case of the eddy environment), which shows energy from the dissolved SOFAR channel being refracted, cycled out, and added to the two CZs. Figure 4 also demonstrates the formation of the new, shallow, SOFAR-type channel for ranges beyond the second CZ. This result, in that range interval, is also suggested in Figure 5 by the continued lower propagation losses compared with what is observed in the earlier "shadow zones." In general, for most of the range of transmission, the presence of the eddy has had the effect of increasing propagation loss.

An indication of the dependence of propagation loss on receiver depth when the eddy is present is given in Figure 6. The loss curves shown in this plot were generated by the PE model for a 50-Hz source at a depth of 300 m. Propagation is west to east, and receiver depths are 10, 100, and 1000 m. In general, the shallower the receiver depth, the higher the loss. This results from the warm center of the eddy's restricting the amount of energy reaching the shallower depths. The difference in loss is as much as 10 to 20 dB between the 10-m and 100-m receivers and can be even greater between the 10-m and 1000-m receivers. The loss levels for the 10-m receiver may also be partially due to interference patterns in the underwater acoustic field created when the 50-Hz energy interacts with the sea surface (surface decoupling). The second CZ for the 10-m receiver shows slightly lower loss than is experienced in the first CZ. This is a result of the second CZ's occurring in the range interval with lower near-surface temperatures, as can be seen in the isothermal plot of Figure 1 (the positions of the CZs at the sea surface are indicated). These propagation loss results agree with the effects illustrated earlier in the ray diagram of Figure 4. The ranges of the CZs are also in good agreement.

The propagation loss prediction for the 50-Hz, 300-m source, 10-m receiver, east-to-west propagation is plotted in Figure 8, along with the corresponding west-to-east propagation. The shapes of the curves are similar, although the loss in the "shadow zone" before the first CZ is greater by up to 25 dB for west-to-east propagation. Again, this is caused by the position of the warm center of the eddy, which is closer to the source in the west than it is in the east. The loss levels for the first CZ for the east-to-west propagation are lower than those for west-to-east propagation because of the fact that the first east-to-west CZ reaches the 10-m receiver in water up to 5°C cooler than the first west-to-east CZ. The CZ at 10 m west to east is partially in the surface waters of the warm center at about 5°C, while for the CZ east to west the water is about 0°C. The levels for the outer edges of the second CZ reverse this situation, as indicated by the higher losses for east to west in Figure 8.

Fig. 8. Propagation loss, comparison of west-to-east and east-to-west propagation, for frequency of 50 Hz, source depth of 300 m, and receiver depth of 10 m.
3.2. Propagation Across Eddy
(Source Depth of 10 m)

West-to-east propagation with the eddy present for a shallow (10-m) source located at the western edge of the eddy is illustrated by the ray diagram of Figure 9. For this source depth, ray theory predicts a surface duct that continues until it is obliterated by the warm center of the eddy at a range near 45 km. Energy can be seen to be leaking from the duct over this range interval due to changes in the thickness of the duct. The energy that leaves the duct is refracted at depth and returns to the surface at longer ranges. Some of this energy from the duct and other source-refracted energy approaching the surface from below the warm center are forced to vertex before reaching the shallower depths.

The corresponding propagation losses, with and without the eddy present, are given in Figure 10 for a receiver depth of 10 m and frequencies of 50 Hz and 1 kHz. Surprisingly, the 50-Hz energy experiences far greater loss than does the 1-kHz energy over the entire range of propagation, primarily owing to the inability of the surface duct to contain the energy in the 50-Hz wavelength. The duct is about 46 m thick at the western edge of the eddy; hence the cutoff frequency for transmission is about 575 Hz [Urick, 1983]. The oceanographic feature responsible for this duct is the colder, horizontally layered, fine structure in the 10-m depth interval at the western edge of the eddy, which is too small to contain the 50-Hz energy.

In Figure 1 it can be seen that the temperature at the 10-m source depth is about 0°C, while just 10 m below the source the temperature is ~3°C. Thus in a very short travel distance, the 50-Hz energy enters the influence of this warm water and a very strong downward refracting gradient. In addition to generating a surface duct, the colder, horizontally layered, fine structure also exerts an influence on the nonducted 1-kHz energy. The nonducted 1-kHz energy (1-kHz wavelength ~1.5 m) also "sees" this fine structure and, even though it is not trapped in the duct, will nonetheless have its downward refraction decreased with respect to the 50-Hz energy (50-Hz wavelength ~30 m).

Another significant contribution to this frequency loss anomaly is the creation of interference patterns in the underwater acoustic field by the 50-Hz energy when it interacts with the sea surface. These patterns are caused by constructive and destructive interference between direct and surface-interacting energy when the source or receiver are generally within one wavelength of the sea surface. In Figure 10 the source and receivers for the 50-Hz energy are within one third of a wavelength from the surface, but for the 1-kHz energy, the distance is nearly seven wavelengths. At high frequencies, this result is called the "Lloyd mirror effect". For low frequencies such as 50 Hz, the term "surface decoupling loss" has been used to describe the effect. It has been shown that large losses will occur at frequencies below 100 Hz for source and receiver depths of less than 25 m [Bannister and Pedersen, 1981].

All of the above conditions are true either with or without the eddy present, since the fine structure and surface decoupling loss can exist for both cases. This suggests that the anomalous frequency dependence for propagation loss noted above is not necessarily restricted to waters influenced by an ocean eddy but rather could exist whenever the source and receiver depths are shallow enough to yield a surface decoupling loss and wherever such fine structures exist, such as in frontal zones.

When the eddy is present, however, the environment will change with range as well as with depth. The energy propagating outward from the source at the 10-m depth will enter the warmer surface interior of the eddy, thereby increasing the downward refraction, relative to the noneddy case. This will be especially true for the 50-Hz energy, which enters the warmer interior of the eddy at a range of less than one wavelength from the source. The 1-kHz energy, however, must travel a range equal to 20 of its wavelengths to reach the same gradient.

As is shown in Figure 10, the surface duct for the 1-kHz energy when the eddy is present continues out only as far as the first CZ, as was previously seen in the ray diagram of Figure 9. As before, the influence of the warm center of the eddy on the 1-kHz energy is evident by the sharp increase in loss at the position of the warm center. When the eddy is not present, the surface duct for the 1-kHz energy continues over the entire 110-km range.

In the CZs the 50-Hz energy has greater loss than the 1-kHz energy both with and without the eddy present. This difference is due in part to the lack of surface duct energy and surface decoupling losses; it may also be due to a greater interception (and thus loss) of 50-Hz energy by the ocean floor. As cited earlier, this results from the stronger downward refraction experienced by the 50-Hz energy.
For ranges in the interval between the first and second CZ with the eddy present, the 1-kHz energy continues to have a smaller loss than the 50-Hz energy, even though the surface duct does not exist at these ranges. Energy leaking from the duct and being changed into refracted/surface-reflected (RSR) propagation modes, together with a better coupling of 1-kHz energy into the SOFAR channel, contributes to the 1-kHz signal at these ranges. The improved coupling into the SOFAR channel for the 1-kHz signal reduces the downward refraction effects caused by the eddy. For the second CZ and ranges beyond it, the 1-kHz signals receive the additional contribution of energy refracted from the dissipated surface duct at the eddy's warm center and converted into RSR propagation modes. This effect was seen in the ray diagram of Figure 9. Note that the relative difference between the 50-Hz curves when the eddy is present or absent varies considerably over the range of transmission. At some ranges, the eddy decreases the loss by up to 10 dB; at other ranges, the eddy increases the loss by up to 10 dB. Most often, however, the eddy has had the effect of increasing propagation loss relative to the non- eddy case.

Figure 11 presents propagation loss for the same configurations but with the receiver at the deeper 100-m depth. The propagation, both with and without the eddy, continues to provide a smaller loss at 1 kHz than at 50 Hz for nearly all of the range intervals out to the second CZ. The surface duct does not exist at this depth, but the fine structure in both the eddy and noneddy cases improves the 1-kHz transmission by reducing the downward refraction effects, thereby providing additional energy to the SOFAR mode. The surface decoupling loss is also a factor, increasing the loss for the 50-Hz signal.

The additional downward refraction of the 50-Hz signal caused by the eddy is one of the reasons for the greater difference (up to 20 dB) between the eddy and noneddy propagation loss curves over most of the range in Figure 11. The other reason for the greater difference when the eddy is present is that 1-kHz energy leaking from the duct (Figure 9) is contributing to the energy levels at this and deeper depths. In contrast, beyond the second CZ for the noneddy case, the loss curves for the 1-kHz and 50-Hz signals are more nearly at the same levels. The higher attenuation at 1 kHz is a reason for this result. When the eddy is present, however, it (as was noted for the 10-m receiver) converts energy from the dissolved surface duct into RSR modes, which then contribute additional 1-kHz energy to the ranges beyond the second CZ. This effect is suggested in Figure 11 at these ranges by the smaller loss for 1 kHz compared with 50 Hz.

It can be seen in Figure 11 that with or without the eddy present, the relative difference between the 50-Hz curves and the relative difference between the 1-kHz curves vary considerably over the range of transmission. At some ranges, the eddy decreases the losses by up to 10 dB; at others, it increases the
losses by up to 10 dB. Most often, the presence of the eddy decreased the loss for 1 kHz and increased it for 50 Hz.

At the 1000-m depth (Figure 12), the receivers for both the eddy and noneddy cases are receiving energy from the SOFAR channel for the entire 110-km range. Over most of the transmission range, the 1-kHz energy is continuing to experience a smaller loss than the 50-Hz energy. This is a result of the improved coupling of the 1-kHz signal into the SOFAR channel, the surface decoupling loss for the 50-Hz signal, and the 1-kHz energy from the dissipated surface duct cycling to this depth. For the noneddy case, the frequency loss anomaly is not as great at 1000 m; i.e., the difference between the two curves is smaller than that at 100 m. The upward refraction of the 1-kHz energy due to the fine structure may be retaining more of that energy at the shallower depths, thus yielding a greater difference between the curves at those depths, as was seen for the 100-m receiver. The difference between the frequency loss curves is up to 8 dB greater in the eddy case than in the noneddy case, and this difference increased the loss for 1 kHz and increased it for 50 Hz. In the presence of the eddy, this receiver depth (as with the 10-m and 100-m receiver depths) most often sustained an increase rather than a decrease in loss for the 50-Hz signal compared with the noneddy case. And, like the 100-m receiver, the 1000-m receiver more often experienced a smaller loss for the 1-kHz signal in the eddy case than in the noneddy case. A comparison of the propagation loss levels given in Figures 10, 11, and 12 for the 50-Hz, 10-m source depth with those for the 300-m source depth in Figure 6 shows that the loss decreases with the deeper receivers.

Figure 13 presents a ray diagram for a source located at the eastern edge of the eddy at a depth of 10 m. Transmission is east to west through the eddy environment. The acoustic field, in general, is similar to the west-to-east transmission (Figure 9); however, two important differences exist. First, the surface duct continues in range beyond the first CZ because of the fact that the eddy's warm center (which destroys the duct) lies beyond the first CZ in this direction. Energy is not leaking from the duct (as was seen when propagation was from west to east) since the oceanographic feature (a near-surface lens of cold water) responsible for the duct retains its thickness throughout the range interval.

Second, the vertex depths before the first CZ for the downward refracted rays are all greater than 1700 m. In contrast, for west-to-east transmission, members of the similar family of rays have vertex depths at about 1200 m. This difference is a result of a higher temperature at the 10-m source depth in the east (~4°C in the east versus ~0°C in the west); the higher temperature generates increased vertex depths for rays from the eastern source. Beyond the first CZ, the deep rays are vertexing at shallower depths because of a decrease in the depth of the SOFAR channel axis from ~650 m in the east to ~500 m in the west.

Figures 14, 15, and 16 present a comparison of the 50-Hz and 1-kHz propagation loss (with and without the eddy) for the same 10-m source depth as in the ray diagram of Figure 13. The receiver depths are 10, 100, and 1000 m, respectively. It can be seen in Figure 14 that the surface duct for 1-kHz propagation in this direction continues beyond the range of the first CZ (40 km) and then abruptly dissipates within a range interval of 2 km. The much higher losses for 50-Hz propagation are again evident. All three plots reveal that the internal structure of the eddy can increase or decrease (by up to 10 dB) the propagation loss for both 50-Hz and 1-kHz, as it did for the west-to-east transmission. This shallow (10-m) source, located in the east, is in warm water compared with the water west of it (Figure 1). Thus, 50-Hz energy propagating to the west initially encounters colder water that decreases...
the downward refraction and reduces the loss compared with the noneddy case. A reduction occurs again when the energy enters the colder water in the far west. Figures 15 and 16 show a loss reduction for the 1-kHz energy compared with the noneddy case. This loss reduction is also due to reduced refraction, as well as to improved coupling into the SOFAR channel and the addition of energy from the dissolved surface duct cycling to these depths.

Figure 17 demonstrates the directional sensitivity in propagation when the eddy is present for a 10-m source depth and 1-kHz signal. The east-to-west loss is greater in the region of the surface duct, since the duct is thinner east to west and less able to trap the 1-kHz wavelength. The duct thickness is $\sim 38$ m in the east, with a corresponding $\sim 770$-Hz cutoff frequency; these compare with a $\sim 46$-m thickness and 575-Hz cutoff frequency in the west. Also, the near-surface sound speed gradient in the duct, which refracts energy upward and affects the amount of energy contained in the surface duct, is much stronger in the west ($0.63 \text{ m/s/m}$) than in the east ($0.37 \text{ m/s/m}$). At the first CZ ($\sim 35$ km), the east-to-west transmission continues to experience greater loss, but now the loss results from increased bottom interaction. The stronger downward refraction caused by the higher temperature at the source in the east generates a larger bundle of energy that is incident upon the bottom.

The surface duct east to west extends beyond the first CZ, as was observed in the ray diagram. For ranges greater than the surface duct but less than the second CZ, the west-to-east transmission again yields lower loss. Energy leakage from the surface duct in the west-to-east transmission is refracted and cycled to this depth and range, as was noted in the Figure 9 ray diagram. The second CZ and ranges beyond display a lower loss east to west. Energy from the surface duct is refracted and returns to the 10-m depth at this longer range (Figure 13).

The directional sensitivity, with the eddy present, for transmission to the deeper receiver depths of 100 m and 1000 m can be obtained by comparing Figures 11 and 12 with Figures 15 and 16. It can be seen that for these deeper receivers the loss curve levels and shapes at 50 Hz and 1 kHz are very similar. Significant differences do exist, however, for 1 kHz at ranges less than the first CZ, where the higher temperature at the source in the east generated a stronger downward refraction and a sharper "shadow zone." The "shadow zones" are responsible for this difference. The amount of energy trapped in the fine structure surface duct and the non-surface-ducted energy influenced by weaker fine structure gradients and surface decoupling losses are again responsible for this difference. The amount of energy trapped in the duct is reduced (i.e., the loss is increased) compared with the 10-m source depth. This can be seen by comparing these curves with those in Figure 14 and is a result of the poorer coupling of the 1-kHz energy for the source located below the duct and in warmer water. A comparison of the 50-Hz loss in Figure 19 with that in Figure 14 reveals that the losses for the 150-m source depth are smaller than those for the 10-m source depth. The reduced vertical and horizontal gradients at the

3.3. Propagation Across Eddy
(Source Depth of 150 m)

For a source of 10 m and all receiver depths (10, 100, and 1000 m), the existence of fine structure, the interior eddy environment, and the increased 50-Hz loss due to surface decoupling result in a smaller propagation loss for the 1-kHz energy than for the 50-Hz energy. The effect on propagation loss for an increase in source depth to 150 m is illustrated in the ray diagram of Figure 18. The source is located at the eastern edge of the eddy and is propagating east to west. A surface duct extends to the warm center of the eddy. Rays from the duct are refracted downward and cycle out in range, returning near the surface again at $\sim 90$ km. Energy not trapped in the surface duct is not being refracted downward as strongly as occurred with the shallower (10 m) source previously shown in Figure 13. When Figures 13 and 18 are compared, it is evident that for the 150-m source the rays are vertexing 500 m shallower than for the 10-m source (1200 m versus 1700 m). This results from the downward refracting gradient below the 10-m source, which is stronger (by a factor of 2.5) than that below the 150-m source. To some extent, the $1^\circ$ warmer water at 10 m also contributes to this result.

A quantitative assessment of frequency sensitivity for both the 50-Hz and 1-kHz signals, for a 150-m source depth with and without the eddy present, can be made by comparing the propagation loss curves in Figure 19. The 50-Hz energy continues to exhibit a greater loss over most of the range interval. The 1-kHz energy trapped in the fine structure surface duct and the non-surface-ducted energy influenced by weaker fine structure gradients and surface decoupling losses are again responsible for this difference. The amount of energy trapped in the duct is reduced (i.e., the loss is increased) compared with the 10-m source depth. This can be seen by comparing these curves with those in Figure 14 and is a result of the poorer coupling of the 1-kHz energy for the source located below the duct and in warmer water. A comparison of the 50-Hz loss in Figure 19 with that in Figure 14 reveals that the losses for the 150-m source depth are smaller than those for the 10-m source depth. The reduced vertical and horizontal gradients at the

Fig. 19. Propagation loss, east to west, comparison of 50 Hz and 1 kHz, for source depth of 150 m and receiver depth of 10 m.

Fig. 20. Propagation loss, east to west, comparison of 50 Hz and 1 kHz, for source depth of 150 m and receiver depth of 150 m.
The 50-Hz source depth in Figure 23 is 10 m, and the frequency of 50 Hz, source depth of 1000 m, and receiver depth of 100 given in Figures 23 and 24.

150-m depth are responsible for this occurrence, as was noted in the corresponding ray diagrams.

A comparison of propagation in Figure 19 for the eddy and noneddy cases shows that in the presence of the eddy there is a decrease in loss for the 1-kHz energy. This decrease results from an improved coupling of energy in the surface duct due to an increase in the thickness of the duct (from 38 to 82 m) within 17 km from the source. For the 50-Hz energy, the additional downward refraction caused by the interior of the eddy results in an increase in loss (compared with the noneddy case) over more range intervals than there are decreases in loss.

The levels of the 1-kHz and 50-Hz signals over most of the width of the first CZ in Figure 19 are similar for both the eddy and noneddy cases and result from the improved 50-Hz transmission cited above. The second CZ for the eddy case yields lower losses for the 1-kHz signal due to the return to this depth of cycling non-surface-ducted energy and energy refracted out of the surface duct, as is noted on the ray diagram.

An increase in receiver depth to 150 m, which is well below the influence of the fine-scale structure surface duct and the 50-Hz surface decoupling effect, yields a very different frequency relationship. The loss curves for the eddy and noneddy cases at this receiver depth are given in Figure 20. The 1-kHz energy now suffers higher losses over the entire range of transmission as a result of attenuation and the loss of both the fine structure duct and the refraction generated by the fine structure. In addition, the effect of the eddy on the 1-kHz energy is to now increase loss at these depths compared with the noneddy case. This is a result of the improved coupling of energy into the surface duct, yielding a reduction of energy available for these deeper receivers. The 50-Hz signal continues to sustain an increase in loss when the eddy is present, as it did for the 10-m receiver, for the same reasons. These relationships also continue for a deeper receiver of 1000 m, as can be seen in Figure 21. Thus the frequency dependence of the acoustic field generated by the fine structure, surface decoupling loss, and eddy environment is a function not only of the source depth but also of the receiver depth.

3.4. Propagation Across and Outward From Eddy Center (Source Depth of 1000 m)

The acoustic fields for deep (1000 m) source depths, below the axis of the SOFAR channel, were examined and exhibited the classic ray diagrams for such deep sources. The near-surface portion of the CZs split into two half-zones, and the insouification at shallow depth and mid-depth improved relative to that for shallow sources [Urish, 1965].

The 50-Hz transmission loss with the eddy present for a 1000-m source (100-m receiver depth) is given in Figure 22. Results for the following three locations of the source are given: sources located at the eastern edge and western edge of the eddy and a source located near the center of the eddy at a range 50 km east of the western edge (transmission for both directions). All four curves show losses smaller than spherical spreading over most of the range interval and are therefore among the lowest losses of all source and receiver combinations previously presented when the eddy is present. The CZs for all four curves exhibit the split (or the beginning of the split) of the zones into half-zones. Ray diagrams (not presented in this paper) also confirm this result. The similarity of the transmission loss for all three source locations is a result of the very similar shape of the sound speed profiles (Figure 2). These results were found to be essentially true for all source and receiver combinations. Representative loss curves are given in Figures 23 and 24.

The 50-Hz source depth in Figure 23 is 10 m, and the
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4. CONCLUSIONS

This paper shows that fine-scale and mesoscale features in the oceanographic parameters of a cyclonic ice edge eddy can exert a very significant influence on acoustic propagation. Variations in propagation loss of greater than 20 dB were observed for changes in (1) the direction of acoustic propagation, (2) the location of the source on either side of the eddy or at its center, and (3) source and receiver depths from shallow (10 m) to moderate depth (100 m, 150 m, or 300 m) or deep depths (1000 m).

These oceanographic features were of such magnitude and/or nature that they destroyed acoustic propagation modes (e.g., a surface duct) and converted them into other preexisting modes or used the energy to generate new modes. In addition, a warm surface feature (whose source was originally the underlying warmer saline Atlantic return water) at the center of the eddy restricted the energy reaching shallower depths so that the second CZ located beyond the warm center contained the same or slightly higher energy at a 10-m receiver depth than did the first CZ located in the warm center.

The considerable variation in the environment of the eddy with respect to range resulted in significant effects on propagation loss. Compared with the noneddy case, the eddy can cause an increase in loss for some intervals of the transmission range and a decrease in loss for others. Differences as great as 20 dB were realized for both 50 Hz and 1 kHz and for any of the source and receiver geometries investigated. Most often for 50 Hz, the additional downward refraction caused by the interior of the eddy resulted in an increase in loss rather than a decrease. This increase is due to energy being refracted below the depth of the receivers and/or an increase in bottom interaction. The exception to this occurred for a shallow (10 m) source located in the relatively warmer water to the east. For this case, the energy propagating west initially encounters colder water that decreases the downward refraction and makes the loss smaller than that in the noneddy case. For 1 kHz, the interior of the eddy caused a decrease in loss over more range intervals than an increase. Exceptions to this occurred (1) when received energy from a surface duct or channel that existed without the eddy was dissipated when the eddy was present and (2) when the insonification of a surface duct improved with the presence of the eddy, resulting in a reduction of energy reaching receivers located at depths below the duct.

A significant finding was that eddy fine structure can generate a frequency dependence for selectively affecting propagation loss so that 1 kHz yields a loss more than 20 dB smaller than does 50 Hz. This result was produced by fine-scale refraction gradients and surface ducts. Such fine structure existed extensively in the upper 100 m, suggesting that ambient noise generated by the ice floes located at the edge of the eddy and/or circulating within the eddy might exhibit such a frequency dependence. Similar fine structure exists in ocean frontal zones and other eddies, indicating that the anomalous frequency-dependent propagation loss may also occur there.

In summary, the presence of an ice-ocean eddy and its unique structure significantly affects many of the characteristics of the acoustic field. The close proximity of these eddies to each other and the ice edge, their large numbers, and their ubiquitous nature all indicate that they can be a very important factor in acoustic propagation in the marginal ice zone.

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REFERENCES

MIZEX Group, MIZEX East 83-84: The summer marginal ice zone program in the Fram Strait/Greenland Sea, Eos Trans. AGU, 57(23), 513-517, 1986.

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