The effects of a dynamic shallow water front on acoustic propagation

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The Effects of a Dynamic Shallow Water Front on Acoustic Propagation.

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Abstract

This paper investigates the effects of a dynamic shallow water front on narrowband (1 kHz) and broadband (50 Hz bandwidth centered at 1 kHz) acoustic propagation. A generic shallow water front is simulated with the Princeton Ocean Model. The sound velocity field is calculated as a function of range, depth and time. A parabolic equation acoustic model is used to simulate acoustic propagation from the warm to the cold side of the front. When the front is in geostrophic balance, acoustic mode coupling is from the higher order, bottom-interacting modes to lower order modes that become trapped in the upper 50 meters of the water column. In the narrowband case, acoustic propagation across the front is enhanced by 10 to 15 dB in the upper 50 meters due to mode coupling. In the broadband case, the coupling from higher order to lower order modes mitigates the multipath, causing the pulse to emerge from the cold side of the front almost undistorted in the upper 50 meters. However when the front becomes unstable and begins to move, acoustic propagation becomes highly variable and the above effects may be observed only intermittently. The study shows that acoustic propagation across a shallow water front can change significantly over a period of hours and hence the need to consider the dynamics of fronts when trying to draw general conclusions about their effects on acoustic propagation.

Introduction

Previous simulations and experiments have shown those coastal fronts along continental shelves and slopes can induce acoustic mode coupling. Work by Jin et al. investigated the sensitivity of mode coupling to the structure of the Barents Sea Polar Front. A CTD transect across the front was used to generate the sound velocity field for acoustic modeling. Acoustic propagation was from the cold side of the front to the warm side causing lower order modes to couple to higher order modes, which exacerbated the multipath propagation. The present study uses the Princeton Ocean Model to simulate a generic coastal front where acoustic propagation is from the warm side of the front to the cold side. For this propagation direction the mode coupling is from the higher order to lower order modes, which mitigates the multipath. However, these effects are shown to be intermittent in nature when the front begins to move. Previous simulations have not addressed the dynamic nature of coastal fronts and the resulting effect on acoustic propagation.

Ocean Model Description and Initialization

A four dimensional, shelf edge front was simulated with the Princeton Oceanographic Model (POM). POM is a 3-d free surface primitive equation, time-dependent coastal ocean circulation model. The prognostic variables are the three components of the velocity field, sea surface elevation, temperature, salinity, and two quantities that characterize the turbulence.

Fig. 1 shows the front at time zero when it is in geostrophic balance. The front separates the cold, neutrally stratified waters on the right (lower sound velocities) from the warm stratified waters on the left (higher sound velocities). The frontal zone is approximately 12 km wide, beginning at 30 km and ending at about 42 km in range. The coastal front simulated here is representative of frontal features that are commonly found along the shoreward edge of the Gulf Stream (e.g. South Atlantic Bight). The POM was configured on a periodic channel 60-km long, 80-km wide and 200 m deep. Initially, the effects of the static front (Fig. 1) on acoustic propagation are studied. To study the effects of the dynamics of the front on acoustic propagation, a small disturbance of amplitude 2-km and wavelength 60-km is superimposed on the front. No external forcing was used. Sound velocity profiles for acoustic modeling were generated every 2-km in range with a 6.67 meter depth resolution.

Acoustic Model Description and Initialization

The range dependent, time independent, velocity field shown in Fig. 1 was input into a parabolic equation acoustic model. The geoaoustic parameters used are characteristic of a silt/clay sea floor with a compressional wave velocity of 1550 m/s, a density of 1.5 gm/cm$^3$, and an attenuation of 0.5 dB/λ. The acoustic source was located at 100 meters depth on the warm, stratified side of the front. Fig. 2 shows the acoustic simulation through the static front at 1000 Hz. Transmission loss is displayed as a function of range and depth.
The acoustic pressure as a function of range and depth is expressed as the sum

$$p(r,z) = \sum_{j=1}^{M} a_j(r) \phi_j(z)$$  \hspace{1cm} (1)$$

where \(a\) and \(\phi\) are the mode amplitudes and local mode functions, respectively. Fixing the range and discretizing the pressure in depth, \(z_i\)

$$p_i \equiv p(z_i), i = 1, M$$ \hspace{1cm} (2)

the following equation is obtained

$$\begin{bmatrix} p_1 \\ \vdots \\ p_M \end{bmatrix} = \begin{bmatrix} \phi_1 & \cdots & \phi_N \\ \vdots & \ddots & \vdots \\ \phi_{M1} & \cdots & \phi_{MN} \end{bmatrix} \begin{bmatrix} a_1 \\ \vdots \\ a_N \end{bmatrix}$$ \hspace{1cm} (3)$$

The left-hand side of equation 3 is the depth vector of pressures, \(p_i\), at a fixed range. The right-hand side consists of a matrix whose columns are the local mode functions, \(\phi_j\), and the second term is a vector of modal amplitudes, \(a_j\). Equation 3 can be solved using singular value decomposition to get a linear least squares solution. The mode functions were calculated by the KRAKEN normal mode program.

In the modal analysis the ranges at 20, 30, 36, 40 and 50 km are chosen. The 20 and 30-km ranges are representative of the acoustic energy state before the front, the 36-km range is the state in the front and the 40 and 50-km ranges are the states after the front.

Fig. 3 shows the result of projecting the complex pressures onto the modes for the ranges cited. Mode amplitude is displayed as a function of mode number for each range. Only the first 10 modes are displayed. At the 20 and 30-km ranges (black and blue, respectively), most of the acoustic energy is in mode 7. Within the frontal zone at 36-km (green), mode 7 has coupled to mode 4. At 40 and 50 km (yellow and red, respectively), most of the energy is in mode 2.

Fig. 4 shows the mode amplitude as a function of depth. The curve in black is mode 7 at 20 km and the one in red is mode 2 at 50 km. The figure illustrates that most of the mode 7 energy before the front is below 100 meters in depth. After the front it has been redistributed to the upper 50 meters of the water column in mode 2. Since the higher order modes correspond to high angle multipath, acoustic energy received within the first 50 meters of the water column on the cold side of the front should have fewer multipaths.
The correlation coefficient between the source pulse and the one received at 50 km is 0.95.

Fig. 5a Source pulse, bandwidth: 975-1025 Hz.

Fig. 5b Pulse received at 20-km range, 10-m depth.

Fig. 5c Pulse received at 50-km range, 10-m depth.

Broadband Propagation and Multipath Mitigation

Figs. 5a, 5b and 5c show the results of propagating a 975-1025 Hz pulse across the front. Fig. 5a is the source pulse. The bandwidth was chosen narrow enough to ensure that all frequencies within the band were within the same propagation regime. This means that the previous modal analysis should be valid, at least qualitatively (i.e. higher order modes to low order modes), for all frequencies comprising the pulse. Figs. 5b and 5c are the received pulses at 20 and 50 km in range, respectively. Both are at a depth of 10 meters. Fig. 5b, 20 km, is corrupted by multipath due to higher order bottom-interacting modes. Fig. 5c, 50 km, has reduced multipath due to higher order to low order mode coupling. The normalized correlation coefficient between the pulse received at 20 km and the source pulse is 0.7.
Time Dependent Acoustic Field

The above analysis was done when the front was in geostrophic balance. Fig. 6 shows the sound velocity field of the front as a function of range and time at a depth of 1 meter. The temperature field has a similar structure. The 1-meter depth was chosen to show the surface expression of the front that could be remotely sensed. The time step in the figure is 3 hours and the total time is approximately 10 days. At about 150 hours the front bifurcates. The white dashed line shows the warm/cold water boundary. A transmission loss calculation was done for each snapshot of the front. Fig. 7 shows the transmission loss at 1000 Hz as a function of range and time at a depth of 10 meters. The black dashed line shows a region of low transmission loss. The low loss regions follow the frontal boundary shown by the white dashed line. Acoustic pulses within this boundary, and whose frequencies are within the same propagation regime as 1000 Hz, would experience the multipath mitigation shown in Fig. 5c.

Fig. 8 shows a time slice of the transmission loss from Fig. 7 at the 50-km range, 10-m depth. The initial transmission loss is 80 dB, corresponding to the static front. As time progresses, the transmission loss fluctuates by more than 10 dB as a result of frontal movement. After the front bifurcates, the transmission loss increases from 86 dB at 177 hours to 106 dB at 180 hours. Fig. 9 shows the transmission loss as a function of range and depth at 180 hours (1000 Hz). The point at 10 meters depth and 50 km range has a transmission loss of 106 dB, which is the maximum transmission loss in Fig. 7. Fig. 9 should be compared to Fig. 2, which shows the transmission loss for the static front.

Conclusions

Sound velocity inhomogeneities such as those exhibited by shelf/slope fronts can have both deleterious and salubrious effects on the acoustic field depending on the direction of propagation. For example, in the case studied here the front redistributed acoustic energy from a deep source to the near surface and, for broadband propagation, induced almost distortionless transmission. However, these effects are likely to be intermittent in nature because of the movement of the front. The results will also depend on the acoustic frequency and sea floor properties. The work illustrates the importance of knowing the dynamics of the frontal structure when making acoustic predictions.

Dynamic ocean models like POM, that incorporate realistic boundaries and can be driven with in situ oceanographic and remote sensing data offer the possibility of estimating the space-time sound velocity fields for acoustic predictions. Validating the temperature and salinity fields of these models and the acoustic predic-

\[\text{Fig. 6 The sound velocity field of the front as a function of range and time at a depth of 1 meter.}\]

\[\text{Fig. 7 Transmission loss at 1000 Hz as a function of range and time at a depth of 10 meters.}\]
Fig. 8 Transmission loss vs. time at 50 km range, 10-m depth.

Fig. 9 Transmission loss vs. range and depth at 180 hours (1000 Hz)

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References


