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1aAO4. Acoustic propagation characteristics of the estuarine salt wedge

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The estuarine environment often hosts a salt wedge—a layer of denser seawater advected by the rising tide under fresh water discharged by the river. The nature of the stratification is a function of the tide's range and speed of advance, river discharge volumetric flow rate and river mouth morphology. The competing effects of temperature and salinity on sound speed present the question: Is the salt wedge acoustically observable? Using temperature and salinity profiles collected in situ, numerical results show that the salt wedge can impact acoustic propagation. Acoustically, this environment can be approximated by two isospeed layers separated by a thin gradient. While this three-layer very shallow water acoustic waveguide is typically dominated by high angle multipath propagation, refraction occurring in the gradient layer allows low-angle energy from near-surface sources to be trapped above the gradient and creates a shadow zone below the gradient. Energy from near-bottom sources is refracted to higher angles and attenuated more quickly. Acoustic fluctuations observed at an upstream/downstream receiver depend upon the presence/absence of bedforms and the interaction between the advancing/receding tide and the river discharge, which can include the presence of internal waves propagating along the top of the salt wedge.

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INTRODUCTION

The estuarine environment often hosts a salt wedge—denser seawater advected by the rising tide under fresh water discharged by the river. The nature of the stratification is a function of the tide's range and speed of advance, river discharge volumetric flow rate and river mouth morphology. In a summer scenario in which the fresh water is warm relative to the salt water, the competing effects of temperature and salinity on sound speed may create a sound speed gradient too small to cause acoustic refraction. In a winter scenario in which the fresh water is cold relative to the salt water, both temperature and salinity will contribute to create a stronger sound speed gradient compared to that observed during summer. Acoustically, this environment consists of two isospeed layers separated by a gradient. While this three-layer very shallow water acoustic waveguide is typically dominated by high angle multipath propagation, refraction occurring in the gradient layer allows low-angle energy to be trapped in the upper layer and creates a shadow zone in the lower layer. Using temperature and salinity profiles collected in situ, numerical results show that the salt wedge can impact acoustic propagation.

To date, scientific studies have, rightly, focused on geological, thermodynamic and hydrodynamic parameters of the estuarine/riverine environment, such as depth, width, bottom composition and morphology, water temperature and salinity structure, tides, current profiles, turbulence and sediment transport. A complementary acoustical characterization of the estuarine/riverine environment is needed to provide a more comprehensive characterization of the physical environment.

Relatively few acoustical studies have been carried out in the riverine or estuarine environment. Those few studies carried out in confined coastal and inland waterways that are found in the literature have focused on a variety of issues, including acoustic scintillation to estimate current flow (Di Iorio and Farmer, 1994), active sonar systems for biological stock assessment and fisheries management (Xie, 2000), homeland security applications (Stolkin et al., 2006), acoustic communication (van Walree et al., 2007), acoustic monitoring of tidal bores (Zhu et al., 2010), marine mammal surveys (Dong et al., 2011), seasonal trends in a large remote fjord (McConnell et al., 1992), recreational boat noise in waterways (Haviland-Howell et al., 2007), ambient noise in freshwater habitats (Wysocki et al., 2007), high-frequency noise spectra in shallow brackish water (Poikonen, 2010), long-term noise trends in large, industrialized rivers (Vracar and Mijic, 2011), acoustical monitoring of ship traffic (Fillinger et al., 2009), acoustic attenuation properties in a river (Roh et al., 2008), and site-specific acoustic propagation models for the lower Hudson River Estuary (Radhakrishnan, 2009).

As a first step in developing an understanding of mid- to low-frequency acoustic propagation characteristics in the estuarine environment possessing a salt wedge, this paper presents acoustic propagation modeling results for an idealized, yet representative environment.

MODEL

Figure 1 shows an idealized representation of a salt wedge estuary, consisting of a 4 km long, 20 m deep river mouth; a 16 km long linear 0.125% slope; and an 8 km long, 5 m deep upriver plateau. The basic morphological, physical and acoustical properties of this environmental model are based on the Columbia River (CR) estuary separating Washington and Oregon on the Pacific Northwest coast of the United States. The CR salt wedge is approximated in the present work by a sound speed gradient centered at 12 m water depth (black line) separating well-mixed (isospeed) fresh river water above and well-mixed (isospeed) denser ocean water below. The fresh and salt water sound speeds are 1457.8 m/s and 1473.8 m/s, respectively, and the difference constitutes a 16 m/s gradient spanning 6 m of the water column. The sound speed field was computed using the Chen-Millero equation (Chen and Millero, 1977) from temperature and salinity fields representative of an estuarine salt wedge (Nash et al. (2009); MacDonald and Chen (2012)). The perfectly reflecting sea surface and the river bed are modeled as planar boundaries. The riverbed sediment is composed of fine to medium sand with an average grain size of 2.75φ (Sherwood and Creager, 1990), which corresponds to a sediment sound speed (c), density (ρ) and attenuation (α) at 1 kHz for fine to medium sand of approximately 1620 m/s, 1.83 g/cm³ and 0.365 dB/m (Zhou, Zhang and Knobles, 2009).
The beam tracing model, BELLHOP, was used for the acoustic propagation computations in this paper (Porter and Bucker, 1987). An omni-directional point source is placed at water depths of 2.5 m or 4 m and 18 m, to represent shallow and deep sources above and below the gradient layer. An acoustic frequency of 1 kHz (~1.5 m wavelength) was chosen as it presents high and low frequency behavior in this confined waveguide.

**RESULTS**

Figure 1 shows transmission loss (TL) in dB as a function of range and depth for the 1 kHz source at water depths of 4 m (panel (a)) and 18 m (panel (b)) at the mouth of the river. In the case of the shallow source, the salt wedge sound speed gradient creates an acoustic duct above the layer, as well a shadow zone below between 3 and 10 km. In the case of a deep source, the salt wedge sound speed gradient effectively increases the number of bottom interactions per unit distance, increasing TL per unit distance and thereby limiting the propagation of energy to less than half that range observed for the shallow source.

**FIGURE 1.** Transmission loss (TL) in dB as a function of range and depth for a 1 kHz source at water depths of 4 m (a) and 18 m (b) at the mouth of the river. The black line represents the center of the idealized salt wedge sound speed gradient.

Figure 2 presents raytraces for the first two kilometers in the two cases shown in Fig. 1. Panel (a) shows rays from a shallow source at launch angles of ±1°-9° from the horizontal while panel (b) shows only two rays from a deep source at launch angles of ±1°. In the case of the shallow source, low angle energy (≤ 8°) refracts in the gradient and is concentrated in the upper portion of the water column, while higher angle energy (> 8°) escapes the shallow duct and refracts down-range, resulting in higher skip distances between bottom interactions and less TL per unit distance compared to an isospeed environment. In the case of the deep source, no acoustic energy is trapped above the salt wedge gradient; both low- and high-angle energy encountering the salt wedge from below is refracted to still higher angles, increasing TL per unit distance.

**FIGURE 2.** Example raytraces for the first two kilometers in the two cases shown in Fig. 1. Panel (a) shows rays from a shallow source at launch angles of ±1°-9° from the horizontal while panel (b) shows only two rays from a deep source at launch angles of ±1°. In the case of the shallow source, low angle energy (≤ 8°) refracts in the gradient and is concentrated in the upper portion of the water column, while higher angle energy (> 8°) escapes the shallow duct and refracts down-range, resulting in higher skip distances between bottom interactions and less TL per unit distance compared to an isospeed environment. In the case of the deep source, no acoustic energy is trapped above the salt wedge gradient; both low- and high-angle energy encountering the salt wedge from below is refracted to still higher angles, increasing TL per unit distance.

Figure 3 is a raytrace for the case of the 1 kHz source at 2.5 m water depth on the 5 m deep plateau upriver of the slope with the salt wedge sound speed gradient centered on 12 m water depth. Rays for odd-numbered launch angles between 1° and 23° and launch angle 24° are presented. Rays are scattered to lower angles by the slope before encountering the salt wedge gradient, effectively increasing the number rays that are trapped in the duct above the gradient. In this case, rays for launch angles 1° to 23° are trapped; the first ray that escapes the duct corresponds to a launch angle of 24°. This case of acoustic energy propagating downriver from an upriver source provides a better ducting environment than the earlier case of the shallow source at the mouth of the river; the extent of the difference depends upon the slope angle and the position of the salt wedge relative to the end of the plateau.
FIGURE 2. Raytraces for the first two kilometers for the two cases shown in Fig. 1: rays from a shallow source at launch angles of \(\pm 1^\circ - 9^\circ\) from the horizontal (a), and two rays from a deep source at launch angles of \(\pm 1^\circ\) (b).

FIGURE 3. Raytrace for the case of the 1 kHz source at 2.5 m water depth on the 5 m deep plateau upriver of the slope with the salt wedge sound speed gradient centered on 12 m water depth. Rays for odd-numbered launch angles between 1\(^\circ\) and 23\(^\circ\) and launch angle 24\(^\circ\) are presented.

Figure 4 shows TL (dB) of low-angle (\(\pm 10^\circ\)) energy as a function of range and depth for the 1 kHz source at 2.5 m water depth on the 5 m deep plateau upriver of the slope in the presence (panel (a)) and absence (panel (b)) of the salt wedge. The latter case represents the estuary at low tide during a period of high river discharge. In the very shallow, isospeed water column on the plateau, no ducting occurs while numerous bottom interactions cause significant attenuation of the higher angle energy. For any source sufficiently upriver to allow high-angle energy attenuation, the remaining low-angle energy reaching the salt wedge will be trapped above it (panel (a)). In contrast, in the absence of the salt wedge (panel (b)), energy reaching the slope will proceed to fill the water column as it propagates toward the river mouth.

In order to quantify the extent to which the salt wedge is acoustically observable, Fig. 4 presents BELLHOP’s semi-coherent approximation of the acoustic field. The computations of coherent TL shown in Fig. (1) are illustrative of the propagation physics; however, details of the interference pattern are typically not predictable due to the dynamic nature of the environment and due to environmental uncertainty. Using Fig. 4 as a proxy for what may realistically be observed \textit{in situ}, energy anomaly (EA) can be defined to be the difference between the average acoustic energy distribution above and below (panel (a)), and in the presence (panel (a)) and absence (panel (b)) of, the salt wedge. Energy anomaly between water depths of 2.5 m and 18 m at 22 km in panel (a) is approximately 11
dB, while energy anomaly between the presence vs. absence of the salt wedge is approximately 8 dB (based on TL values at 22 km at water depths of 18 m in panel (a) and 2.5 m in panel (b)) and 2 dB (based on TL values at 22 km at water depths of 2.5 m in panel (a) and 2.5 m in panel (b)).

**FIGURE 4.** TL in dB of low-angle (± 10°) energy as a function of range and depth for the 1 kHz source at 2.5 m water depth on the 5 m deep plateau upriver of the slope in the presence (a) and absence (b) of the salt wedge.

**CONCLUSIONS**

Model results have been presented to investigate the impact of an estuarine salt wedge on acoustic propagation characteristics. An idealized environmental model has been used to represent physical and acoustical properties of the Columbia River estuary. The salt wedge creates a range- and depth-dependent trapping of low-angle acoustic energy from a source above the gradient, while increasing TL per unit distance for high-angle energy from a source above the gradient and for all energy from a source below the gradient. In the case of a source at the river mouth, acoustic energy propagates well up onto the upriver plateau from a shallow source but is heavily attenuated from a deep source. In the case of a source upriver of the slope and salt wedge, higher angle energy is heavily attenuated while the lower angle energy that remains is efficiently trapped in the upper water column by the salt wedge gradient. Energy anomaly values of 11 and 8 dB taken from Fig. 4 in this idealized environmental model demonstrate that the presence of a salt wedge provides a sufficiently refractive environment to be acoustically observable.

Acoustic propagation characteristics of a realistic estuarine environment will depend upon the strength of the salt wedge-induced sound speed gradient, the position of the source and receiver relative to the salt wedge, salt wedge morphology, riverbed sediment acoustic properties and morphology (water depth, bedforms and horizontal curvature) and acoustic frequency. Temporal fluctuations of an acoustic signal observed at an upstream or downstream receiver will depend upon the dynamic interaction between the advancing/receding tide and river discharge, which can include dynamic mixing (weakening of the sound speed gradient), changing slope of the salt wedge gradient, and the presence of internal waves propagating along the salt wedge.

**REFERENCES**


