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6. AUTHOR(S)
Darrell R. Jackson, Michael D. Richardson

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Seasonal temperature gradients within a sandy seafloor: implications for acoustic propagation and scattering

Darrell R. Jackson[1], Michael D. Richardson[2]

[1]Applied Physics Laboratory, University of Washington, Seattle, WA 98105, USA, drj@apl.washington.edu
[2] Naval Research Laboratory, Marine Geosciences Division, Stennis Space Center MS 39529-5004, USA, mike.richardson@nrlssc.navy.mil

Abstract

Seafloor temperatures measured during the SAX99 experiment off Fort Walton Beach, Florida included sharp decreases in response to the passage of cold fronts. Sediment pore water temperatures exhibited an increasing temperature (3-4° C m^{-1}) with depth in the sediment. By fitting a heat conduction model to the gradient data, the thermal diffusivity of the sediment was estimated to be 0.006 cm^2s^{-1}. The effects of seasonal variations of sediment thermal gradients on reflection and scattering from the sediment-water interface are found to be significant at frequencies near 1 kHz but diminish at higher frequencies.

1. Introduction

Shallow water temperate regions often have strong seasonal variations in water temperature. These variations must be taken into account when predicting propagation of acoustic energy through the water column. Seafloor temperatures also vary in response to variations in bottom water temperature and may need to be taken into account when predicting acoustic propagation within, scattering from, and penetration into the seafloor [1]. To account for these effects, water column and sediment temperatures were measured as part of SAX99 (Sediment Acoustics Experiment 1999) [2]. The experiments were conducted in 19-m water depth on a sandy substrate in the northeastern Gulf of Mexico (30° 22.7N; 86° 38.7W) during the fall of 1999 [3]. During the acoustic experiment the meteorological conditions, especially associated with the passage of cold fronts, that strongly affect both oceanographic and seafloor characteristics were monitored. Gradients in sediment temperature are, in part, controlled by diffusive heat flow exchange with the water column and/or heat flow from deep layers within the sediment. If one neglects heat flow from deep in the sediment, the effects of diffusive heat exchange with the water column can be predicted based on seasonal changes in bottom water temperature and thermal diffusivity of the sediment. Differences between the predicted and measured sediment temperature gradients are then a function of advective heat flow from either ventilation due to wave action or advection due to a hydraulic head within underground freshwater aquifers. It should therefore be possible to predict seasonal changes in bottom water temperatures as well as gradients of sediment temperature based on coupled meteorological and oceanographic conditions.

In this paper, we present data on fluctuations in water column and seafloor temperatures measured during the SAX99 experiments (1 October – 10 November 2000). A value of sediment thermal diffusivity is estimated based on the measured sediment thermal gradients and recent variations in bottom water temperature. Seasonal gradients of temperature fluctuations are then determined, based on the sediment thermal diffusivity and average seasonal bottom water temperatures. The modeled gradients allow calculation of seasonal gradients of sediment sound speed. The effects of seasonal variations of sediment thermal gradients and sound speeds on high-frequency reflection and scattering from the sediment-water interface are then modelled. Work supported by the Office of Naval Research (ONR) and Naval Research Laboratory Program Element 061153N.

2. Temperature Measurements

2.1 Methods

Water column temperatures were measured during the SAX99 experiments using a Seabird 911 plus CTD conductivity system (3 casts per day) and continuous monitoring of surface seawater injection systems from the R/V Pelican and R/V Seward Johnson [2]. Air temperatures were continuously measured aboard both ships and compiled from the nearest meteorological station at Eglin AFB. Bottom water temperature and conductivity were measured every 15 minutes from 3 October through 10 November using a bottom-mounted Seabird Microcat.

Gradients of temperature within the sediments were measured using a hand-held OMEGA K-type digital thermometer with an attached 76-mm long 0.63-mm diameter thermoprobe. The advertised resolution (0.1°C) and accuracy (0.5°C) were confirmed in a water bath. The thermometer was held in a watertight Ikelite case that allowed access to function keys. Divers inserted the thermoprobe into the seafloor 19 times during the SAX99 experiments (22, 26, and 29 October; 5 and 7 November). Measurements were made in 5 cm increments down to 70 cm. The temperature was allowed to stabilize between each successive measurement. Porewater samples were collected with a syringe to measure porewater salinity [2]

2.2 Results

Mean air temperatures decreased from approximately 25°C at the beginning of the SAX99 experiments to near 15°C in early November primarily in response to the passage of three cold fronts (19th and 24th October and 2nd November) (Figure 1, top panel). Both surface and bottom water temperatures averaged 26°C at the beginning of the experiment (1-15 October), followed by a rapid decrease to 23°C in response to the passage of two cold fronts (Figure 1, bottom panel). Temperatures increased again to 24°C by the 31st October in response to warming air temperatures and mixing with the warmer offshore waters; followed by a second rapid decrease in bottom water temperature to 21.5°C after the passage of a cold front on 2nd November. Temperatures in the water column were nearly isothermal during most of the SAX99 experiments suggesting rapid mixing of the water column during to the passage of several cold fronts. Seasonal mean bottom temperatures in shallow waters of the northeastern Gulf of Mexico are approximately sinusoidal with average maximum of 28-30° C in July-September and minimum of 13-15° C in December-March. Bottom temperatures measured during the SAX99 experiments (Figure 2, left panel) are concordant with seasonal variations in bottom water temperatures at 20m-water depth off Panama City Florida (75 km west) suggesting these trends are typical for the northeastern Gulf of Mexico. This seasonal behaviour is approximated in the right panel of Figure 2 by a simple extension of the measured data. This extension consists of a linear term connecting the first and last measured points plus half-cycle and one-cycle sine waves with one cycle spanning the gap in the measured data.

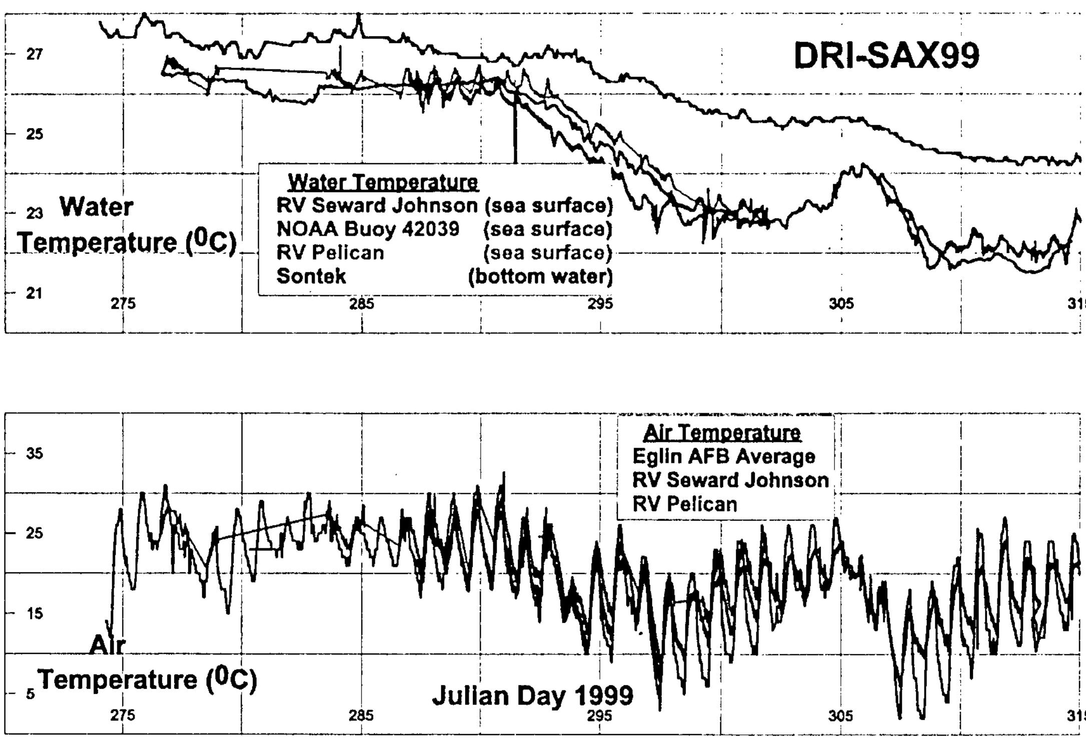

Figure 1. Air, surface, and bottom water temperatures measured during the SAX99 experiments (1 October through 11 November 2000 or Julian dates 274 to 315 in the figures). Air temperatures were measured at Eglin AFB (16 km northeast of the study site) and from the two research vessels while operating in the vicinity of the SAX99 experiment. Water temperatures were measured using a bottom-mounted conductivity probe and from the two research vessels.

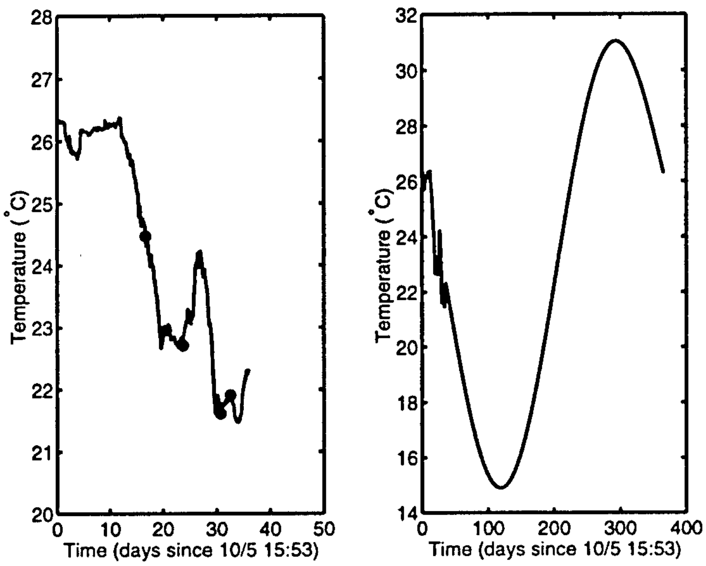

Figure 2 The left panel displays water temperature at the seafloor obtained during the SAX99 experiment. The symbols "o" mark the times at which sediment temperature profile data were taken. The right panel displays a temperature time series spanning one year in which the measured data were supplemented by a simple fit to data from [4].

Sediment temperature profiles show an increasing temperature (3-4° C m^{-1}) with depth in the sediment for all measurement dates (Figure 3). Pore water salinity did not vary and was the same as the water column salinity. The temperature gradient corresponds to an 8-10 m s^{-1} increase in sound speed in the upper meter of sediment. The observed gradients of pore water temperature and time history of bottom water temperature were used to calculate apparent sediment thermal diffusivity. Based on these calculated values of thermal diffusivity and average seasonal bottom water temperatures the effect of changing profiles of temperature on sound speed, acoustic scattering, and reflection loss are predicted in Section 4.

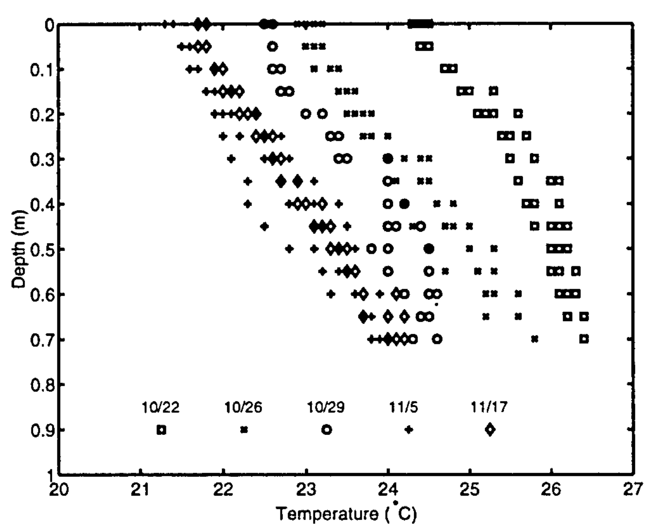

Figure 3. Sediment temperature profile data obtained during SAX99 experiment. Each symbol corresponds to the given date for three or more insertions of the temperature probe. Temperature values at the sediment surface are in agreement with the near-bottom water column temperature of Figures 1 and 2.

3. Heat Conduction

A simple, one-dimensional diffusion model [5] is used to model heat conduction in the sediment. Heat diffusivity is assumed independent of depth in the sediment, and the time- and depth-dependence of sediment temperature is completely determined by the time history of the water temperature at the seafloor, which is assumed to have a yearly period. With these assumptions, the sediment temperature has a yearly period and, at great depths in the sediment, approaches the mean seafloor water temperature. As will be seen, a thermal diffusivity of 0.006 cm^2s^{-1} provides the best fit for the data collected off Fort Walton Beach.

Lovell [6, 7] measured thermal conductivity of sands over a range of porosities in the laboratory. Based on those measurements, he proposed a simple geometric model to predict sediment thermal conductivity (k_b) from sediment fractional porosity (n) and thermal conductivities of the pore fluid (k_s) and solids (k_f),

$$k_b = k_s^{(1-n)} k_f^n .$$

A least squares fit of his measurements yielded thermal conductivities values of 8.58 $Wm^{-1}K^{-1}$ for the solid phase and 0.64 $Wm^{-1}K^{-1}$ for the pore water. These values are in close agreement with handbook values of thermal conductivities of quartz, the major solid constituent in his and our samples, and seawater. Given a sediment fractional porosity of 0.37, the predicted sediment thermal conductivity based on Lovell's regression is 3.28 $Wm^{-1}K^{-1}$. Sediment thermal diffusivity (α^2), which is calculated for our data, is a function of sediment thermal conductivity (k_b), specific heat (S) and bulk density (ρ),

$$\alpha^2 = k_b / s\rho .$$

Given the estimated thermal conductivity of 3.28 $Wm^{-1}K^{-1}$, and handbook values of specific heat for quartz (1.97 x 10^6 $Jm^{-3}K^{-1}$) and seawater at 24°C and 35 ppt (4.09 x 10^6 $Jm^{-3}K^{-1}$) and the measured density of 2040 kgm^{-3}, the predicted thermal diffusivity is 0.012 cm^2s^{-1}. This value is higher than the thermal diffusivity obtained from our temperature profiles. Variations in fractional porosity (0.35-0.40) or temperature (20-25°C) used to calculate sediment thermal conductivity or specific heat yield a range of values of thermal diffusivity (0.011-0.013 cm^2s^{-1}) that are all higher than the thermal diffusivity calculated value from our temperature profiles. This suggests that minor temporal changes or variatibility in porosity or temperature do not account for the difference in calculated and predicted thermal diffusivities. One might be tempted to compare the values of thermal diffusivity used in this paper with those used by Rajan and Frisk [1] in their study of effects of seasonal variations in temperature on sediment compressional wave speed in the Gulf of Mexico. Their estimates of sediment thermal diffusivity (0.0022 cm^2s^-1) however are appropriate for muddy sediments where the solid phase of sediments is composed of clay minerals with bound water with much lower thermal conductivity (1.56 $Wm^{-1}K^{-1}$) and a higher porosity. At the present time no probable explanation is given to explain the greater than expected gradients of sediment temperature. Advective mixing of bottom and pore waters by ventilation, forced by gravity wave induced bottom pressure fluctuations, would tend to decrease the slope of the sediment temperature gradients. This is the opposite of what we observed (Figure 3). Upward advection colder pore water due to a hydraulic head within underground freshwater aquifers would tend to increase the slope of the gradients of sediment temperature during periods of bottom water-cooling but we have no evidence to support this hypothesis. Additional long-term measurements of bottom and sediment temperatures might resolve the apparent differences calculated and predicted sediment diffusivity. For the purpose of this paper we will use a value of thermal diffusivity based on the measured sediment temperature profiles.

3.1 Solution of Heat Diffusion Equation

Using a value of thermal diffusivity of 0.006 cm^2s^{-1} and with the temperature time series of Figure 2 forcing the one-dimensional diffusion equation, the predicted time-depth dependence of sediment temperature is as shown in Figure 4. The largest temperature gradients occur in the fall and spring when seafloor temperature undergoes the most rapid change. It should be noted that lower values of heat conductivity give rise to larger temperature gradients.

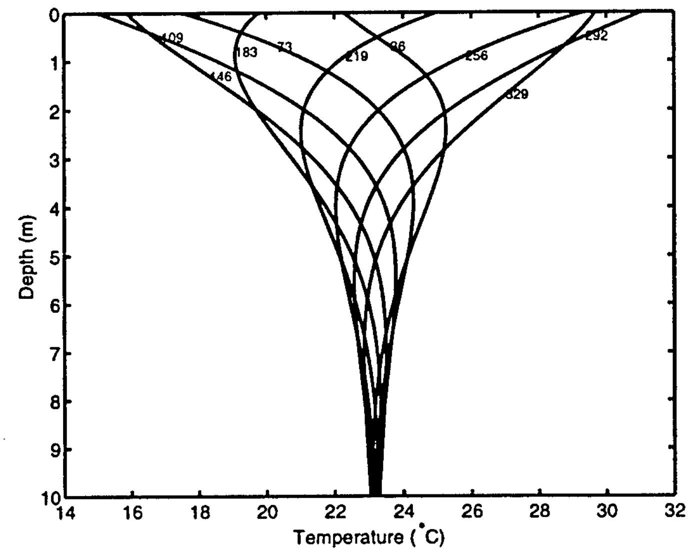

Figure 4. Synthetic temperature profiles obtained by solving the one-dimensional heat diffusion equation with diffusivity 0.006 cm^2s^{-1}. The curves are labelled by the time (in days) from the beginning of the water temperature time series of Figure 2.

3.2 Comparison with Data

Figure 5 shows a comparison of predicted temperature profiles with the probe data. The assumed diffusivity is 0.006 cm^2s^{-1} with an uncertainty of ±0.002. This value was obtained by trial-and-error fitting of the model to the temperature profile data. Although not obvious by inspection, the two prominent cold front events seen in Figure 2 have a definite impact on the model predictions. When these events are smoothed over, the model profiles corresponding to times immediately after the events have gradients substantially smaller than the data.

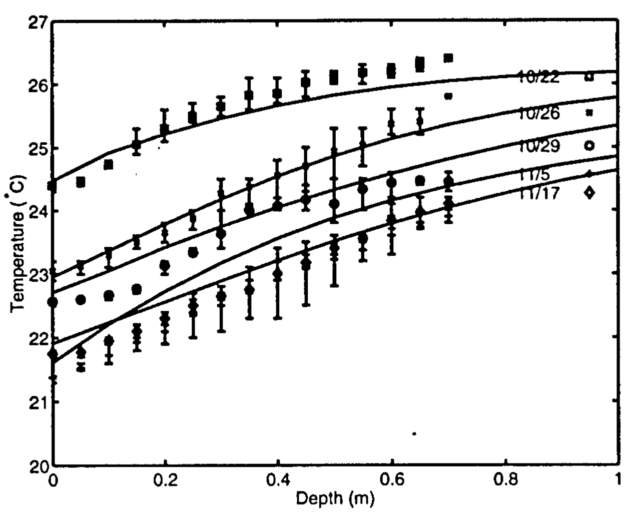

Figure 5. Comparison of sediment temperature profile data (mean values, with extremes shown as error bars) with the heat conduction model. The five model curves are labelled with the measurement date and the corresponding symbol used in data plotting.

4. Acoustic Effects

As evident from the data and model results presented, long- and short-term variations in seafloor water temperature give rise to significant gradients in sediment temperature. As sound speed is dependent upon temperature, there will be corresponding gradients in sound speed, even when the seafloor is otherwise homogeneous. Rajan and Frisk [1] found that such gradients can have a substantial effect upon low-frequency sound propagation; our focus, however, is on high frequencies where these effects are expected to be small owing to increased acoustic absorption, which limits the depth of penetration of sound. For the sandy sediment of the SAX99 site, the dominant cause of acoustic scattering is seafloor roughness [8], but gradients in sound speed can effectively alter the acoustic contrast of the interface and thus alter sound scattering and reflection. The sound speed depth profile is computed using the Chen-Millero equation [9] to determine pore water sound speed and the sediment sound speed is obtained using the assumption that sediment sound speed has a fixed ratio with the water sound speed [1, 10]. We compute the acoustic reflection coefficient using a straightforward geoacoustic model that fits the sound speed profile with a series of thin, homogeneous layers. Finally, this resulting reflection coefficient is used in the scattering approximation of Moe and Jackson [11] to determine acoustic backscattering strength. The inputs required for these calculations are the sediment-water sound speed and density ratios (1.158 and 1.97, respectively), the sediment loss parameter (0.01), and the roughness spectrum strength and exponent (0.012 cm^4 and 3.0, respectively). These values were obtained from a preliminary examination of SAX99 measurements [2, 3].

The result of these calculations is seafloor reflection loss and backscattering strength as functions of time and grazing angle. Figure 6 shows the predicted extremes of the reflection loss and backscattering strength for a low diffusivity case (0.0014 cm^2s^{-1}, approximately equal to the diffusivity of water) for an acoustic frequency of 1 kHz with the seafloor temperature time series of Figure 2. These parameters were chosen to accentuate the time variation of reflection and scattering. As diffusivity increases, temperature gradients decrease, and acoustic time variation diminishes. Likewise, as frequency increases, the penetration depth of the acoustic field decreases, and acoustic time variation decreases as the field "sees" less depth variation in sound speed. Figure 7 illustrates these properties. Note that, for the preferred diffusivity value, time variation is significant at 1 kHz but negligible at 40 kHz.

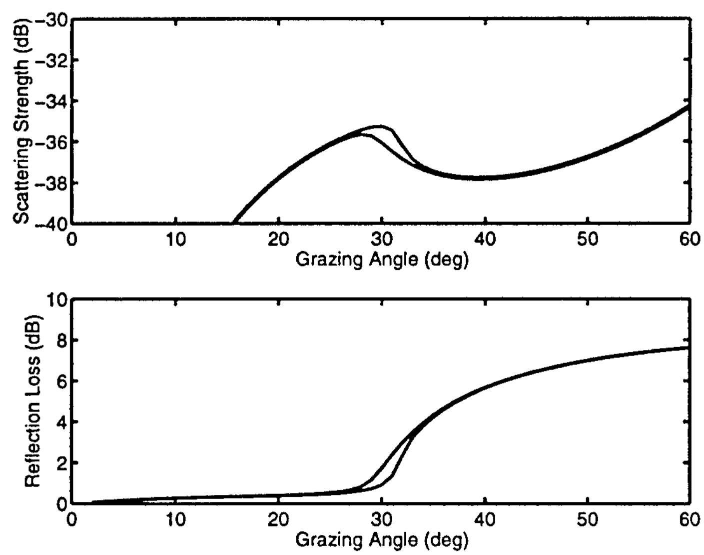

Figure 6. The predicted extremes of the seasonally dependent seafloor backscattering strength and reflection loss at 1 kHz with diffusivity 0.0014 cm^2/day.

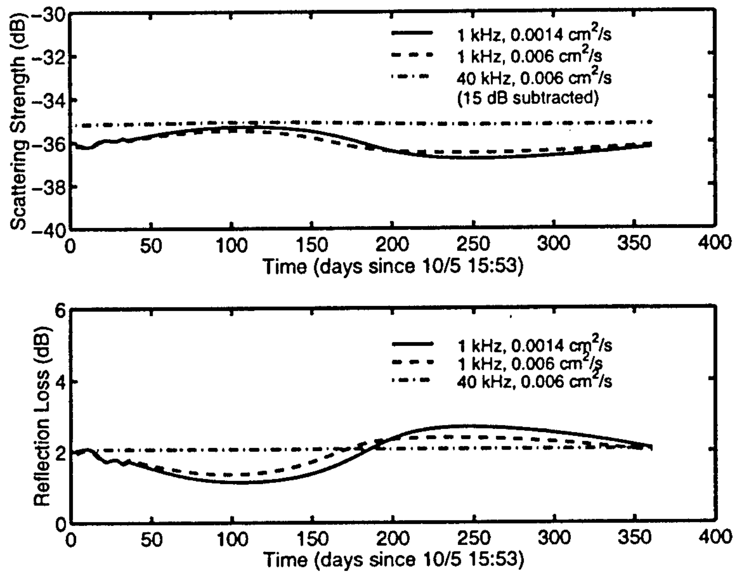

Figure 7. Predicted time dependence of seafloor backscattering strength and reflection loss at 31° grazing angle.

5. Conclusions

The value of sediment diffusivity (0.006 cm s^{-1}) determined from sediment temperature profiles was lower than predictions based on the laboratory measurements of Lovell (0.012 cm s^{-1}). Advective heat flow from either ventilation due to wave action or advection due to a hydraulic head within underground freshwater aquifers does not explain these differences and suggests that long-term field experiments coupled with laboratory measurements of sediment thermal conductivity are required to develop predictive models of sediment thermal gradients in sandy sediments. Acoustically, the sound speed gradients induced by seasonal temperature change have negligible effect at high frequencies, but can be important at frequencies of the order 1 kHz and lower.

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