2018

Observations of thermohaline sound-speed structure induced by internal waves and spice in the summer 2015 Canada Basin marginal ice zone

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http://hdl.handle.net/10945/57870

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A. Introduction
In the past few decades there have been substantial changes in the Arctic region including a rapid decline in summer sea ice extent (Stroeve et al., 2012), as well as changes in ocean freshwater content (Rabe et al., 2014) and ocean heat content (Lique and Steele, 2013). These changes have attracted not just scientific interest, but also the attention of commercial organizations, governments, and militaries. Under the sea there are many potential activities that would rely on sound, including navigation (Webster et al., 2015), communication (Freitag et al., 2015), and ocean acoustic tomography (Munk et al., 1995). Each of these applications requires a good understanding of the structure and variability of the ocean acoustic conditions, conditions that appear to be in a state of transition.

The Arctic seas are in a period of transition as they adjust to stimuli from anthropogenic climate change. The acoustic response to this adjustment is of fundamental interest, as acoustics provide an important means for Arctic remote sensing, communication and navigation, and there are important biological implications for marine mammals and other organisms that use sound. The Canada Basin Acoustic Propagation Experiment (CANAPE) is an effort to study Arctic acoustics; this paper reports on ocean sound-speed measurements from a pilot study undertaken between 30 July and 16 August 2015. Moored and shipborne observations of temperature and salinity were made in the upper 600 m of the ocean, allowing analysis along isopycnals (surfaces of constant density) to separate sound-speed structure due to internal-wave-induced vertical displacements from those originating from density-compensated temperature and salinity variations termed spice. Frequency spectra and vertical covariance functions were used to describe the space/time scales of displacements and spice. Internal-wave frequency spectra show a spectral slope much lower than the Garrett-Munk model, with the energy level roughly 4% of the standard Garrett-Munk value. Frequency spectra of spice show a form similar to the internal-wave spectra but with a slightly steeper spectral slope, presumably due to the horizontal advection of the spice by internal-wave currents. The root mean square sound-speed fluctuations from internal waves were small with values less than 0.1 m s\(^{-1}\). Spicy sound-speed fluctuations were much stronger, particularly in the upper 100 m where a maximum of 0.25 m s\(^{-1}\) was observed. Both processes have vertical decorrelation lengths less than 100 m. The observed strong variations in vertical and horizontal sound-speed structure will have significant impacts on acoustic applications, especially in the realm of communications, navigation, and remote sensing.

Keywords: acoustics; observations; Arctic Ocean; Canada Basin; marginal ice zone
The Canada Basin is a deep-water basin north of Alaska and west of the Canadian Arctic Archipelago. To the west of the Canada Basin lies the broad and relatively shallow Chukchi Shelf, which provides input of relatively warm Pacific waters into the Canada Basin. Prevailing winds drive the anticyclonic Beaufort Gyre, which transports sea ice and upper ocean water masses from the central Arctic Ocean in a clockwise direction around the basin. Between 1983 and 2014 sea ice concentration in the Beaufort Sea has decreased at a rate up to 15% per decade, and the annual duration of open water has increased as much as three weeks (Galley et al., 2016). Of significant acoustical consequence, these changes have resulted in the emergence of a large-scale summer marginal ice zone (MIZ) in the Canada Basin, thus changing the dominant processes governing acoustic/ice interactions, air/sea interactions, and changing thermohaline sound-speed structure.

Changes in the mean and fluctuating sound-speed structure in the upper few hundred meters of the ocean are of intense acoustical interest. Below the surface waters around 100-m depth, a temperature maximum has emerged that appears to be increasing in intensity and lateral extent (Jackson et al., 2010; Toole et al., 2010; Steele et al., 2011). One consequence of this feature is a subsurface acoustic duct that can allow long-range acoustic propagation with little energy loss. These waters are of Pacific origin and fill the upper to intermediate depths of the Canada Basin. Coachman and Barnes (1961) named these layers Pacific summer water (PSW) and Pacific winter water (PWW). PSW is characterized as having a temperature maximum greater than –1.0°C (Steele et al., 2004) with salinities of 31–33 (Shimada et al., 2001; Steele et al., 2004). Timmermans et al. (2014) have shown that the PSW has increased in heat content and freshwater content in recent years, with potential impacts to stratification and vertical heat fluxes. Below PSW is the PWW that is generally found below 150 m and can be identified by a temperature minimum and salinities greater than 33 (Coachman and Barnes, 1961). PWW is believed to be formed by ice formation on the Chukchi Shelf during winter months (Pisareva et al., 2015). Although this water mass seems to be fairly consistent in its properties, Steele et al. (1998) found that its lateral extent may be variable in time. Below the PWW, a strong halocline and thermocline marks the transition to water of Atlantic origin, simply called Atlantic Water (AW), which is characterized as warm (T > 0°C) and salty (S > 34.5; Rudels et al., 2004). The cumulative effect of these layered water masses is a highly stratified upper ocean, with strong density gradients and high buoyancy frequencies, especially at the transitions between water masses. Changes in these water masses on time scales from interannual to buoyancy period are of fundamental interest to a broad spectrum of Arctic scientists, including acousticians.

Deep-water sound propagation can be used for many practical applications including remote sensing, navigation, and communication. Of fundamental importance are the features of the water masses (e.g., the sound channel) and their inherent variability due to ocean processes (Colosi, 2016). This variability may be caused by eddies (Cornuelle et al., 1985; Wolfson and Tappert, 2000), internal tides (Dushaw et al., 1995, 2011), internal waves (Colosi, 2016), and spicy thermohaline structure (Dzieciuch et al., 2004; Colosi et al., 2013). Ocean variability translates into acoustic variability, and for any given acoustic system there is a complex relationship between signal stability and randomization and the space/time scales of the ocean (Colosi, 2016). To make progress on this problem requires both deterministic and stochastic ocean models that can then be interfaced with acoustic models. An important example of a stochastic model is the Garrett-Munk internal wave spectrum (Garrett and Munk, 1971).

The goal of this study is to examine two processes that can be considered stochastic, internal waves and spice, and to quantify their space/time scales and contributions to sound-speed variations in the MIZ. Here we present the CANAPE experiment and the observations (Section B),
the frequency spectra of internal waves and sound-speed variability (Section C), and the vertical scales of variability (Section D), concluding with a summary and discussion (Section E).

**B. The experiment**

In the summer of 2015, a field program was carried out in the southern Beaufort Sea to study long-range acoustic propagation and ambient noise in the deep basin. The fieldwork, carried out on the R/V Sikuliaq, was conducted as a pilot study for the Canada Basin Acoustic Propagation Experiment (CANAPE) to be done in 2016 and 2017 in the same region. As part of the 2015 pilot study, detailed moored measurements of the time-evolving and spatially variable ocean sound-speed field were made so that acoustic transmission data could be interpreted in terms of specific oceanic processes such as eddies, internal tides, random internal waves, and spicy thermohaline structure. This experiment is similar to those conducted by Colosi et al. (2012) and Colosi et al. (2013).

**1. Observations**

In the CANAPE pilot study, a 60-hydrophone vertical acoustic receiver array termed the Distributed Vertical Line Array (DVLA) was instrumented with 24 Sea-Bird Electronics models SBE 37-SM and SBE 37 SM MicroCAT conductivity, temperature, depth (CTD) instruments and two Teledyne RDI ADCPs. This mooring collected acoustic and oceanographic data from 30 July through 16 August 2015. The DVLA was located at 73° 10.6691’N, 154° 06.0565’W, where the water depth was 3853 m. The CTD instrumentation on the DVLA (Table 1) was densely arranged in the depth range between 85 and 550 m and made measurements every 30 seconds. The pumped instruments in the upper part of the water column provided the highest quality data. These observations were used to track isopycnal vertical displacements that we denote by the symbol $\xi(\bar{r}, t)$. Vertical displacements perturb the background ocean sound-speed field according to the relation

$$\delta c(\bar{r}, t) = \xi(\bar{r}, t) \left( \frac{dc}{dz} \right)_p (z) \quad \text{(Eq. 1)}$$

where the potential sound-speed gradient, $(dc/dz)_p$ is the important quantity due to the adiabaticity of most ocean processes, including internal waves (Colosi, 2016). Variations in temperature (T) and salinity (S) along isopycnals, called spice, create fluctuations in the sound speed, as density-compensating anomalies in T and S are reinforcing in sound speed (Dzieciuch et al., 2004).

In addition to the CTD sensors, two ADCPs were included on the DVLA mooring (Table 1). These were both placed at approximately 630 m, one looking up and the other looking down, giving an observation depth range of roughly 100 to 900 m. The ADCPs resolved horizontal currents induced by eddies, inertial waves, and internal tides. Because of the weakness of the internal wave field, the ADCP observations were too noisy to be useful and therefore are not analyzed here.

**Table 1:** Oceanographic instrumentation for the DVLA mooring with average depth of each instrument. DOI: https://doi.org/10.1525/elementa.186.t1

| Depth (m) | Instrument* |
|-----------|-------------|
| 82        | SBE 37-SMP  |
| 102       | SBE 37-SMP  |
| 111       | SBE 37-SMP  |
| 120       | SBE 37-SM   |
| 129       | SBE 37-SM   |
| 138       | SBE 37-SM   |
| 147       | SBE 37-SM   |
| 156       | SBE 37-SM   |
| 165       | SBE 37-SM   |
| 175       | SBE 37-SM   |
| 183       | SBE 37-SM   |
| 192       | SBE 37-SM   |
| 210       | SBE 37-SM   |
| 228       | SBE 37-SM   |
| 247       | SBE 37-SM   |
| 265       | SBE 37-SM   |
| 292       | SBE 37-SMP  |
| 320       | SBE 37-SM   |
| 347       | SBE 37-SM   |
| 381       | SBE 37-SM   |
| 418       | SBE 37-SM   |
| 452       | SBE 37-SM   |
| 489       | SBE 37-SM   |
| 525       | SBE 37-SM   |
| 628       | Teledyne RDI 75 kHz ADCP upward lookingb |
| 641       | Teledyne RDI 150 kHz ADCP downward lookingb |

* The primary instruments are Sea-Bird Electronics models SBE37-SM and SBE37-SMP (pumped) MicroCAT CTD instruments. The SBE instruments sampled the ocean at 30-second intervals.  

b The Teledyne RDI 75 kHz ADCP was deployed in the upward looking direction and the Teledyne RDI 150 kHz ADCP was deployed in the downward looking direction.

Depth-time series of potential density referenced to the 300 dbar level and potential temperature are displayed in **Figure 2**, showing the variability observed over the whole two weeks of the experiment. A striking feature of this display is the large mooring “pull-down” event between 01 and 03 August that was likely due to a strong eddy moving over the mooring. (The eddy, located in the Atlantic layer, is clearly seen in the ADCP observations with currents of $\pm 20$ cm s$^{-1}$). Another eddy event of a different nature is seen towards the end of the observation period. Because
Figure 2: Depth-Time series of potential density and temperature. Potential density in kg m$^{-3}$ (top) and temperature in degrees Celsius (bottom) as a function of depth (m) and time (yearday), measured at the DVLA mooring. A few lines of constant potential density (isopycnals) are overlaid in black. DOI: https://doi.org/10.1525/elementa.186.f2

Figure 3: Mean profiles of temperature, salinity, sound speed, buoyancy frequency, potential density, and potential sound-speed gradient. Values derived from the DVLA are shown with circles. Average profiles derived from 3 CTD casts made in the vicinity of the DVLA are shown with dashed lines. DOI: https://doi.org/10.1525/elementa.186.f3
this study is not concerned with eddies, the analysis focuses on the time period 04–15 August (yearday 216 to 228).

Figure 3 shows mean profiles over this shortened time frame for several quantities of oceanographic and acoustical interest, including T, S, sound speed, potential sound-speed gradient, potential density, and buoyancy frequency. These mean profiles were derived from the moored observations and three shipboard CTD casts taken within 75 km of the DVLA. In the upper 600 m there are four distinct water masses. The upper 40 m is characterized by low salinity with values less than 30, and a temperature near –1°C. Below this surface layer is the PSW, a thin layer (about 30 m thick) with salinities between 30 and 32 and relatively warm temperatures between 0 and 1°C. Between 100 and 200 m the PWW is cooler with temperatures below –1°C and salinities between 32 and 33. Below 200 m a thermocline and halocline separate the Pacific-origin waters from Atlantic-origin waters, the core of which is found below 300 m. The Atlantic Water (AW) has a much higher temperature (>0°C) than the overlying Pacific waters, but its high salinity of about 34.8 results in a relatively high density. These water masses are highly stratified, with buoyancy frequencies of around 15 cycles per hour (cph) in the upper 100 m and 7 cph at 250 m. These depths correspond to the upper limit of PSW and lower limit of PWW.

Relevant to ocean acoustics is the vertical structure of the mean sound speed and potential sound-speed gradient profiles. With regards to sound speed, the expected upward refracting surface duct formed by the halocline is seen, but significantly there is a local minimum in sound speed at roughly 120-m depth forming a weak subsurface acoustic duct extending roughly from 75-m to 225-m depth. Sound energy trapped in this duct would experience limited loss because it does not interact with the ocean surface. Furthermore, the potential sound-speed gradient in this subsurface duct is quite small, meaning that internal-wave-induced sound-speed fluctuations are diminished (Equation 1). Thus there is the potential for exceptionally long range, stable propagation in the Arctic at higher frequencies that can be trapped in this duct. This potential is in contrast with areas where the profile is primarily upward refracting resulting in extensive surface interaction and loss by scattering. Because the shallowest instrument on the DVLA was at 85 m and could not observe the surface layer or the core of the PSW, the temporal variability discussed in this paper is restricted to PWW, AW, and the pycnocline between them.

At the low temperatures of the study area, density is determined primarily by salinity, so relatively large changes in temperature can be compensated dynamically by very small changes in salinity. This fact is evidenced by variations in temperature along the first isopycnal overlaid on the temperature time series in Figure 2, especially above 200 m. These variations in isopycnal temperature have significance for spicy sound-speed variability, as density-compensating changes in temperature and salinity are reinforcing in sound speed. When plotted on a T-S diagram, the isopycnal sound-speed variability is readily apparent (Figure 4). Temperature variations in the salinity range above 33.5 lay roughly along the density contours, but resulted in a change in sound speed of up to 5 m s$^{-1}$ at the DVLA (Figure 4, left panel) and 25 m s$^{-1}$ across the 8 CTDs (Figure 4, right panel). The highest variability was associated with Pacific Summer Water.

2. Displacement and spice analysis

The methods used to analyze isopycnal displacement and spicy sound-speed variability are similar to those used in Colosi et al. (2012, 2013). The description of methods presented here will be terse. The reader is encouraged to review Colosi et al. (2012) for a more thorough discussion.

From the moored CTD observations, potential density referenced to the 300-decibar (dbar) level (Talley et al., 2011)

Figure 4: Potential temperature versus salinity measured by the DVLA mooring (left) and ship CTDs (right). The color of each data point indicates the depth of the observation. The dashed lines are contours of constant potential density measured in kg m$^{-3}$; the dot-dashed lines are contours of constant sound measured in m s$^{-1}$; and the solid line is the freezing temperature as a function of salinity. The average CTD temperature and salinity is plotted as black squares for comparison on the left panel. DOI: https://doi.org/10.1525/elementa.186.f4
was computed as a function of instrument depth, $z(t)$, and time $t$; we denote this quantity as $\sigma_{300}(z(t), t)$. Instrument depth here is a function of time due to mooring motion. The depths of 45 isopycnals, $z(t, \sigma_{300})$, between 1026.90 and 1029.36 kg m$^{-3}$ were tracked using depth-linear interpolation, and the specific isopycnals were chosen to give roughly 10-m vertical separation (Figure 5). The advantages and limitations of this technique are discussed in Colosi et al. (2012); the uncertainties associated with this calculation are discussed below. There are several noteworthy aspects of the isopycnal depth-time series shown in Figure 5. First are the energetic deep eddy pull-down event early in the record and the appearance of another weaker near-surface eddy at the end of the record. The increased high frequency variability at depths below 350 m is an artifact of the non-pumped moored CTD instruments on that section that have a lower sensitivity to changing salinity. The small-amplitude displacement

Figure 5: Forty-five tracked isopycnals as a function of depth and time at the DVLA mooring. Isopycnals are roughly separated by 10 m on average. DOI: https://doi.org/10.1525/elementa.186.f5

Figure 6: Root mean square error in tracking isopycnal density (left) and depth (right). DOI: https://doi.org/10.1525/elementa.186.f6
variability is on a super-inertial time scale and falls in the realm of internal waves. A spectral analysis of this variability is presented in Section C.

To address the issue of spice, for each isopycnal, potential temperature, \( \theta_{300}(t, \sigma_{300}) \) and salinity, \( S(t, \sigma_{300}) \), were computed using depth-linear interpolation. The along-isopycnal temperature and salinity were then used at the mean isopycnal depth to compute sound speed, \( c(t, \sigma_{300}) \). This sound-speed field holds the mean profile plus spicy fluctuations. Sound-speed variability caused by the fluctuations in isopycnal vertical displacements, like those caused by internal waves, is discussed later. To verify the validity of this linear interpolation scheme, the errors in isopycnal tracking were determined by recomputing potential density from the interpolated potential temperature and salinity, \( \delta\sigma \). The root mean square (RMS) differences between the recomputed and original densities and associated depth errors are listed in Table 2, columns 5 and 6 (also Figure 6). The errors from using linear interpolation are much smaller than those found in the Philippine Sea (Colosi et al., 2013) and New Jersey Continental Shelf (Colosi et al., 2012) experiments, which is likely due to the relatively quiescent nature of the Beaufort Sea when compared to the more dynamic regions of those studies. The largest errors in isopycnal tracking are found between 200 and 400 m deep (Figure 6). Thermohaline staircases of order 1 m in vertical height created by double diffusion are often found in this depth range (Padman and Dillon, 1987; Timmermans et al., 2008) and may explain the enhanced error in linear interpolation.

The time-mean sound-speed profile was subtracted from the sound-speed field, \( c(t, \sigma_{300}) \), to give the spicy sound-speed fluctuations (Figure 7). Variations of over 1 m s\(^{-1}\) were observed in the upper 250 m, with the strongest variations in the upper 150 m. The advection pattern of the passive spicy features past the mooring is complicated, showing both large and small-scale variability.

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**Table 2:** Observed isopycnal statistics for tracked isopycnals. DOI: https://doi.org/10.1525/elementa.186.t2

| \( \sigma_{300} \) (kg m\(^{-3}\)) | \( z \) (m) | \( \theta_{300} \) (°C) | \( S \) (× 10\(^{-5}\) kg m\(^{-3}\)) | \( \delta\sigma_{300} \) (× 10\(^{-5}\) kg m\(^{-3}\)) | \( \delta\theta_{300} \) (× 10\(^{-5}\)°C) | \( \delta S_{300} \) (× 10\(^{-5}\)) | \( \delta c_{rms} \) (× 10\(^{-4}\) m s\(^{-1}\)) |
|----------------|------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 1027.058        | 91.8       | -0.90         | 31.87          | 168            | 113            | 219            | 56             | 504            |
| 1027.324        | 112.4      | -1.22         | 32.19          | 30             | 29             | 121            | 25             | 282            |
| 1027.507        | 132.7      | -1.32         | 32.41          | 5              | 7              | 29             | 6              | 67             |
| 1027.673        | 152.1      | -1.39         | 32.61          | 2              | 2              | 19             | 4              | 43             |
| 1027.829        | 172.1      | -1.45         | 32.8           | 2              | 2              | 18             | 4              | 43             |
| 1028.010        | 191.7      | -1.48         | 33.02          | 20             | 16             | 18             | 4              | 42             |
| 1028.296        | 212.0      | -1.36         | 33.38          | 36             | 25             | 32             | 7              | 74             |
| 1028.594        | 231.7      | -1.17         | 33.76          | 197            | 134            | 103            | 27             | 239            |
| 1028.872        | 251.4      | -0.80         | 34.13          | 272            | 245            | 38             | 14             | 86             |
| 1029.031        | 271.3      | -0.43         | 34.35          | 298            | 479            | 5              | 3              | 11             |
| 1029.136        | 292.5      | -0.11         | 34.50          | 132            | 345            | 4              | 3              | 9              |
| 1029.186        | 311.4      | 0.09          | 34.58          | 105            | 367            | 3              | 2              | 6              |
| 1029.235        | 331.6      | 0.29          | 34.66          | 142            | 676            | 2              | 1              | 3              |
| 1029.276        | 351.4      | 0.48          | 34.72          | 57             | 372            | 3              | 2              | 6              |
| 1029.296        | 370.8      | 0.59          | 34.76          | 50             | 497            | 5              | 4              | 12             |
| 1029.311        | 391.6      | 0.67          | 34.78          | 11             | 172            | 6              | 4              | 12             |
| 1029.320        | 412.0      | 0.71          | 34.80          | 8              | 152            | 6              | 4              | 13             |
| 1029.329        | 431.4      | 0.75          | 34.81          | 3              | 81             | 2              | 2              | 5              |
| 1029.339        | 452.2      | 0.76          | 34.83          | 1              | 22             | 1              | 1              | 3              |
| 1029.345        | 471.8      | 0.74          | 34.83          | 3              | 88             | 1              | 1              | 2              |
| 1029.350        | 492.0      | 0.72          | 34.84          | 2              | 65             | 1              | 1              | 2              |

*a* Selected isopycnal densities are listed in the first column, and the second, third, and fourth columns list the mean isopycnal depth, potential temperature, and salinity. The fifth and sixth columns list the RMS errors in isopycnal density and depth tracking (see text for discussion). The seventh, eighth, and ninth columns list the RMS spicy sound-speed variations along the selected isopycnals for temperature, salinity, and sound speed. These last three statistics only include contributions from frequencies between the Coriolis frequency, \( f \), and a typical value of buoyancy frequency, \( N \). For brevity, only every other isopycnal is displayed here.
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Figure 7: Depth-time series of spicy isopycnal sound-speed anomalies. Spicy isopycnal sound-speed anomalies, measured in m s$^{-1}$, are plotted as a function of depth and time, as measured at the DVLA mooring. DOI: https://doi.org/10.1525/elementa.186.f7

Figure 8: Frequency spectra of displacement averaged in three depth bands. The three depth bands are 100–200 m (red), 200–400 m (blue), and 400–500 m (green). The Coriolis frequency, f, and typical buoyancy frequency, N, are indicated with solid vertical lines. Power-law fits (dashed lines) to the random internal wave band of frequencies give the exponents listed. For comparison, the thick black line depicts the GM spectrum at standard energy. DOI: https://doi.org/10.1525/elementa.186.f8
The spice is seen to weaken considerably below 250 m, which coincides with the local maximum in buoyancy frequency.

C. Frequency spectra and analysis of variance

In this section, frequency spectra of displacement and spice variability are analyzed as a function of depth. Spectral shape and depth inhomogeneity of internal wave- and spice-induced sound-speed fluctuations play a major role in acoustic scattering theory (Colosi, 2016). For internal waves the GM spectrum has played a major role in bringing together theory and observation for many mid-latitude experiments, but the acoustics community lacks a similar canonical model for spice.

1. Internal waves

The time series of isopycnal displacements were filtered with a 4-pole Butterworth digital filter prior to spectral analysis to remove signals with frequencies over 20 cph. The full record length of just over 17 days was reduced to 12.4 days to remove data from the mooring pull-down event and to produce a record length of 24 cycles of the $M_2$ tides. After applying a Hanning window, power spectral density (PSD) estimates were computed for each tracked isopycnal, denoted by $S_f(\omega, \Xi(\sigma_{300}))$, where $\Xi(\sigma_{300})$ is the mean depth of the isopycnal, $\sigma_{300}$. Figure 8 shows the depth-averaged PSD estimates for displacements in three depth bands: shallow (100–200 m), mid (200–400 m), and deep (400–500 m). There is decreased energy just below the inertial frequency, followed by increasing low frequency energy associated with the eddy field (spectral gap). At the highest frequencies energy drops off rapidly above the buoyancy frequency cutoff (mostly due to the filter). A spectral peak exists near the inertial frequency. This peak is associated with the nearby $M_2$ and $S_2$ internal tides evident in the horizontal current spectra (not shown). In the continuum band between roughly 3 to 40 cycles per day (cpd), a power law shape is seen with spectral slopes of $p = -1.4 \pm 0.23$ for the depth band of 100–200 m, $p = -1.3 \pm 0.25$ for 200–400 m, and $p = -1.0 \pm 0.30$ for 400–500 m. The deepest spectra show noise problems at high frequency due to the non-pumped sensors. However, in general the observed spectra have a much flatter shape than the GM spectrum, which goes as frequency to the minus two power. Levine et al. (1987) observed internal wave spectra in the Beaufort Sea under pack ice with slope closer to −1.

The strength of internal wave displacement fluctuations depends on depth; in particular, it depends on the stratification, $N(z)$. Here we use RMS displacement to quantify the isopycnal depth fluctuations (Figure 9).

![Figure 9: Root mean square displacement of isopycnals versus depth.](https://doi.org/10.1525/elementa.186.f9)
Vertical covariances and spectra are addressed in Section D. The RMS displacement in the internal wave band is seen to be between 1 and 3 m, increasing with depth. This result is consistent with the Wentzel-Kramers-Brillouin (WKB) depth scaling relation $\langle \xi^2 \rangle^{1/2} = \xi_0 \sqrt{\frac{2}{N_N}}$ (Munk, 1981) using a reference internal wave displacement $\xi_0 = 1.5$ m, $N_0 = 3$ cph, and the mean $N(z)$ from the mooring (see Figure 3). The observed internal wave reference displacement is roughly 20% of the standard GM level of $\xi_0 = 7.3$ m. The effectiveness of the WKB relation implies that there is a rich internal wave vertical spectrum, and that the field is not dominated by a few low order modes. The one eddy event at the end of the record contributes a significant amount of variability to the total RMS displacement. (Note that our analysis does not include the large eddy event at the beginning of the record.)

2. Spice
The mean sound-speed profile shown in Figure 3 is continuously perturbed by isopycnal displacement as well as spicy sound-speed variability. Vertical isopycnal displacements cause sound-speed perturbations by vertically advecting the background sound-speed structure. Using Equation 1, the RMS sound-speed perturbations can be approximated by multiplying the potential sound-speed gradient (Figure 3, bottom left) by the RMS displacement of isopycnals (Figure 9). The total and internal-wave band RMS sound-speed fluctuation from spice were computed from the observations in Figure 7, and the results are shown in Figure 10. Spice is indeed seen to drop off markedly below 250-m depth. Spice is expected to be the larger contributor to sound-speed variability from the surface to 200-m depth, while internal waves provide the larger contribution below 200 m. Both the internal wave and spice sound-speed fluctuations are small compared to mid-latitude observations (Colosi et al., 2012, 2013). These variations are all small compared to the differences observed between CTD locations. Plotted in black in Figure 10, the RMS differences between the eight CTDs are roughly an order of magnitude larger than the temporal variations observed at the mooring, and the largest variations are found in the upper 100 m. The ship CTD RMS is clearly large because it includes the energetic eddy field in addition to spice and internal waves.

Spectra of spice sound-speed fluctuations were computed using the same methodology as the displacement spectra, with the depth-averaged results shown in Figure 11. These spectra do not show a peak near the inertial/semi-diurnal frequencies. Power-law fits in the
Figure 11: Frequency spectra of sound-speed fluctuations along isopycnals (spice) averaged over three depth bands. The three depth bands are 100–200 m (red), 200–400 m (blue), and 400–500 m (green). Power law fits to the spectra in the frequency range of 3 to 40 cpd are shown (dashed lines). The Coriolis frequency, f, and a typical buoyancy frequency, N, are indicated by vertical solid lines for reference. DOI: https://doi.org/10.1525/elementa.186.f11

Figure 12: Normalized internal-wave displacement covariance matrix (top), and depth-averaged correlation function versus WKB depth lag (bottom). DOI: https://doi.org/10.1525/elementa.186.f12
frequency band between 3 and 40 cpd result in exponents of \(-1.4 \pm 0.21\) for 100–200 m, \(-1.5 \pm 0.23\) for 200–400 m, and \(-1.1 \pm 0.27\) for 400–500 m. These results are similar to what was found in the Philippine Sea and New Jersey shelf experiments (Colosi et al., 2012, 2013), including the decrease in spectral energy with depth, but in these mid-latitude cases the spectral slopes were larger. The relative similarity of the spice spectral slopes to the internal wave slopes is an indication that internal wave currents are a source of spice advection. The higher slopes in the shallower depth band indicate front-like features, which have a slope of \(-2\) (Ferrari and Rudnick, 2000), and the spectra flatten with depth to be more noise-like, though these deep variations are likely at the threshold of our measuring ability, especially with the non-pumped instruments.

D. Vertical scales of variability

The vertical spatial variability of internal waves and spice is addressed here. For internal waves both correlation functions and WKB-stretched vertical wave number spectra are presented. For spice there is no method for handling the depth non-stationarity, and so only correlation functions are analyzed.

1. Internal Waves

Figure 12 shows the internal-wave displacement depth-covariance matrix normalized by the individual variances at each depth, as well as the depth-averaged correlation function. To remove depth non-stationarity, the displacement observations were WKB-stretched and normalized using a reference buoyancy frequency of 3 cph and a reference displacement of \(\xi_o = 1.5\) m (see Figure 9). Displacement correlation decreases rapidly with depth lag, with a typical scale of tens of meters, indicating that the vertical mode structure of the internal wave field is rich in high modes. The slight increase in correlation lengths near 250 m indicates that the halocline just above the AW was perturbed without significantly changing shape; i.e., the halocline as a whole was lifted or depressed.

The GM spectrum is of the form \(j^2 + j^2\), where \(j^2\) is the modal bandwidth parameter, typically 3 for mid-latitude deep ocean conditions (Munk, 1981). The vertical wave-number spectrum can be computed directly from the WKB-scaled displacements (Figure 13). The spectrum shows some deviations from the GM form with a modal bandwidth factor, \(j^2\), close to 6 but with a steeper slope.

2. Spice

The covariance analysis discussed in the previous paragraph was applied to the spicy sound-speed structure, but without applying WKB depth scaling. The normalized spice covariance matrix and average correlation function are shown in Figure 14. Spice is seen to decorrelate in depth somewhat more rapidly than the internal waves, a result of the common front-like structure of spice (Ferrari and Rudnick, 2000; Dzieciuch et al., 2004). The larger correlation lengths seen at the deeper depths are likely not significant because spice was so weak in these areas.

Figure 13: Internal wave vertical wavenumber spectrum. WKB stretched displacement vertical wavenumber spectrum using a reference buoyancy frequency of 3 cph (blue line), and the GM spectrum with \(j^2 = 6\) (dashed line). DOI: https://doi.org/10.1525/elementa.186.f13
E. Summary and conclusions

In this work the temporal and vertical scales of sound-speed fluctuations caused by internal waves and spicy thermohaline structure in the southern Beaufort Sea during the summer of 2015 were quantified by tracking the vertical displacement of isopycnals and fluctuations of temperature and salinity along them. Large variations in temperature, especially in the upper 150 m, were observed that produce strong spicy isopycnal sound-speed anomalies. The spectral shapes of isopycnal displacements were flatter than predicted by GM theory, with power law slopes of \(-1.0\) to \(-1.4\). An internal wave reference displacement of 1.5 m was observed, which is roughly 20% of the GM level. Analysis of the vertical structure of internal waves showed a modal bandwidth parameter, \(j^*\), value of 6 to 10 as opposed to the typical value of 3 for mid-latitudes. The low internal wave energy means that signals even up in the kilohertz range should suffer weaker randomization effects, though calculations using fluctuation models need to be done. Of particular note is the weakness of the sound-speed variability in the subsurface duct which suggests very stable propagation for trapped acoustic energy. The wider vertical bandwidth of the internal waves, indicated by the \(j^*\) value, means that the Beaufort Sea has more small-scale structure than the mid-latitude case. This typically means less phase fluctuation, which is sensitive to large scales and more intensity fluctuation which is sensitive to smaller scales (Colosi, 2016).

Spicy sound-speed variability is also low, but accounts for significant sound-speed variations in the upper 200 m. Of interest is that scattering in the upper 100 m from spice could inject additional acoustic energy into the subsurface duct. Again, acoustic fluctuation models need to be run to examine effects like this. A noteworthy aspect of the vertical structure of spice is that spice features appear to be strongest near the surface and slump downwards in time (Figure 7). In the marginal ice zone, these spice features could be generated locally at the surface by episodic wind-forcing events, or they may be advected from upstream, neither of which can be determined from this data set.

Although horizontal sampling by shipborne CTDs was limited, a sound-speed minimum consistently appeared in the PWW layer. Therefore, it is likely that some acoustic energy could become trapped in this subsurface sound channel and suffer less attenuation due to surface scattering and absorption by sea ice. However, strong differences were found in the thermohaline and sound-speed structures between CTDs spaced less than 100 km apart, and significant temporal variability was observed in this depth range. These strong variations in vertical and horizontal sound-speed structure will have significant impacts on acoustic applications, especially in the realm of communications and sensor performance predictions. The results of this oceanographic analysis will be used to analyze and understand the acoustic data collected during the same experiment.

Data Accessibility Statement

CANAPE 2015 environmental (CTD, Sea-Bird MicroCAT, ADCP) data can be made available by contacting Peter Worcester, Scripps Institution of Oceanography, University of California, San Diego, at pworcester@ucsd.edu.
Acknowledgements
This work was supported by the Office of Naval Research. The authors would also like to extend a deep gratitude to the crew of the R/V Sikuliaq and embarked scientists and engineers who worked tirelessly to enable this experiment.

Authors contribution
- Contributed to conception and design: DD, JC, PW, MD
- Contributed to acquisition of data: DD, JC, PW, MD
- Contributed to analysis and interpretation of data: DD, JC, AP, JJ, PW, MD
- Drafted and/or revised the article: DD, JC, AP, JJ, PW, MD
- Approved the submitted version for publication: DD, JC, AP, JJ, PW, MD

Competing interests
The authors have no competing interests to declare.

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