OCEAN VARIABILITY: DECOMPOSITION OF COMPLEX SOUND VELOCITY FIELDS AND ANALYSIS OF THEIR IMPACT ON ACOUSTIC PROPAGATION

A Thesis in
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by
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Abstract

Acoustic propagation in the ocean is driven by the sound velocity profile, which varies in both space and time. These variations are caused by many phenomena, but on the finestructure (10 meters to 1 kilometer) scale, the dominant forces in most areas of the ocean are internal waves and thermohaline intrusions. Internal waves are gravity waves (similar to surface waves) that propagate beneath the surface by displacing the stratified constant density surfaces. Thermohaline intrusions (also referred to as spice) are variations in temperature and salinity which compensate each other in their effect on density. Although spice features are independent of density and therefore have a very minimal effect on ocean dynamics, they do affect the sound velocity in the water, and therefore can be very important acoustically.

This thesis uses data from the Transverse Acoustic Variability Experiment (TAVEX) to study properties of spice in the East China Sea and examine their impact on sound propagation through use of parabolic equation acoustic modeling. A method of separating the effects of internal waves and spice on a sound speed field is presented, followed by several methods of analyzing the form and characteristics of the spice present in the data. Finally, parabolic equation code is used to model acoustic propagation through sound speed fields containing spice, and connections are drawn between the spice contained in a field and its impact on the resulting acoustic field.
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Dedication

This thesis is dedicated to my husband, Anthony, without whose support, encouragement, and willingness to take on absurd amounts of wedding planning from two states away, I could never have finished on time.
Chapter 1

Introduction

1.1 Research Goals

This thesis aims to characterize the effects on the sound velocity field due to spice (variations in temperature and salinity which compensate each other in their effects on density) in the data from the Transverse Acoustic Variability EXperiment (TAVEX) of 2008, and to examine the impact that variability has on shallow water acoustic propagation.

Attention will also be given to sound speed variations due to internal waves (vertical motion of constant density surfaces which can be either random or propagating), as they are extremely common in the East China Sea, and presumed to be responsible for the generation of the thermohaline variation. It is also necessary to consider internal waves when analyzing spice activity in order to separate the effects of the two phenomena.

TAVEX involved the collection of oceanographic data in an approximately 34 by 10-kilometer area of the East China Sea using a towed conductivity, temperature and depth (CTD) chain. The towed CTD data revealed variation in the sound speed profile due to linear internal wave displacements and spice, and several propagating internal waves, all superimposed on an average profile with slight spatial variation.

1.2 Motivation

Acoustics is an important tool both for studying the ocean and for underwater communication because sound waves travel exceptionally well through water, while electromagnetic rays are quickly absorbed. Sound propagation is directly affected by the properties of the medium through which it travels, through the effects that those properties have on the speed of sound. Any variation in the ocean, whether due to internal waves and spice, which dominate the scales of interest in TAVEX, large-scale phenomena such as mesoscale eddies, or small fluctuations such as those caused by turbulence, will have an effect on acoustic propagation, and cause variations
in the received signal. (The relevance of a particular phenomenon to a propagation situation is determined by the characteristic scale of the sound speed variation in relation to the acoustic wavelength and propagation distance.) Advances in our understanding of these effects can lead to improved designs of underwater acoustic systems for both communication and scientific study, and better interpretation of data.

Although there is a large body of literature on the acoustic effects of both linear and nonlinear internal waves, and a respectable volume of oceanographic work on the physics and dynamics of spice creation and dissipation, there is comparatively little literature on the effects of spice on acoustic propagation. One of the primary goals of this thesis is to partially fill that gap.

![Location of TAVEX experiment](image.png)

Figure 1.1: Location of TAVEX experiment. Image from Google Earth.

### 1.3 Thesis Outline

The remaining section of Chapter 1 is a description of the TAVEX experiment which provided the data used for this research. Chapter 2 explains the concepts of internal waves and spice in detail and gives an overview of previous work in these areas. These concepts are applied in Chapter 3 to develop the decomposition process that was used to separate tilt and spice features in the oceanographic data. Chapter 4 discusses several methods for characterizing tilt and spice, and advantages and disadvantages of each. Chapters 5 and 6 are dedicated to acoustic propagation modeling: descriptions of the modeling programs used and basic results from each are included in Chapter 5, while Chapter 6 contains more detailed, quantitative results. Chapter 7 gives a summary of the results of the research presented and provides suggestions for further work in this
area. Two appendices are included for additional information and to facilitate continued work in this area. Appendix A contains plots which describe the spice content in detail for all thirteen sections of the CTD tow that were used for analysis, and Appendix B contains MATLAB code that was developed for this thesis that may be useful to a future researcher.

1.4 Description of TAVEX Experiment

The TAVEX experiment was conducted in August of 2008 in the East China Sea, about 100 km southwest of Jeju Island off the southern coast of South Korea. Figure 1.1 shows the location of the experiment. Water column data was collected with a towed conductivity, temperature, and depth (CTD) chain. A bottom-mounted horizontal line array (HLA) also received acoustic signals from a 300 Hz and a 500 Hz source placed 34 km and 20 km, respectively, from the HLA. The arrangement of the sources and horizontal line array and the path that the ship towing the CTD chain followed are shown in Figure 1.2. Bathymetry information was also collected using a depth sounder during the tow, revealing a relatively flat bottom that varies from 70 to 85 meters within the tow area, and from 72 to 80 meters along the acoustic axes [1].

![Figure 1.2: Path of towed CTD and location of sources and receiver used for TAVEX. Red lines indicate tow sections where nonlinear internal waves were observed. The tow area enclosed by the black rectangle is approximately 34 by 11 kilometers. Map provided by Chad Smith of Applied Research Lab at Penn State.](image-url)
1.4.1 Acoustic Data

Acoustic signals were transmitted by two sources, which were placed as shown in Figure 1.2, at a depth of approximately 64 meters. Each produced alternating continuous wave (CW) and linear frequency modulated (LFM) pulses. The LFM pulses had a bandwidth of ±10% of the center frequency. Each pulse lasted approximately two seconds with approximately two seconds of dead time between each pulse [1]. Figure 1.3 shows a spectrogram of a portion of the signal received by one of the hydrophones in the HLA, to illustrate the signals that were used. The pulses were received by a bottom-mounted, 200 meter long horizontal line array consisting of 96 hydrophones placed approximately perpendicular to the acoustic axes. The original goal of this work was to perform acoustic propagation modeling in a way that could be compared with the TAVEX acoustic data to look for agreement. This first required characterizing the spice, and finding a way to realistically model it. As work progressed, it became apparent that spice was an extremely complex phenomenon, and characterizing and modeling it to the degree required for the initial goal was beyond the scope of a master’s thesis. That object has been kept in mind, however, and for that reason much of the acoustic modeling in this thesis has been performed at 300 and 500 Hz.

![Spectrogram of Signal Received by HLA](image)

Figure 1.3: Spectrogram illustrating the transmitted pulses
1.4.2 CTD Data

Oceanographic information was collected over a 36-hour period by towing a chain with 34 CTD fins attached to it behind a ship, which followed the course shown in Figure 1.2. Each fin contained sensors to measure conductivity, temperature, and pressure. Conductivity and pressure were used to calculate salinity and depth, respectively.

The fins were placed on the chain with a variable spacing in order to achieve increased resolution in the thermocline region. Spacing of the sensors along the chain ranged from two to eight feet (0.61-2.44 meters), which translated to a vertical resolution of 0.6 to 2.4 meters when the chain was trailing behind the ship during the tow. Data was recorded every two seconds, resulting in a horizontal resolution of about 3.6 meters as the ship maintained an average speed of about 3.5 knots (1.8 m/s). Figure 1.4 shows a representative sound speed field recorded during TAVEX, with the locations of the actual data points shown as white dots.

Because the CTD sensors were connected by a flexible chain, they do not form a straight line downward from the ship when the ship is in motion, but rather form an arc. Using the ship’s speed, the depth of each fin as measured by its pressure sensor, and the known location of each fin along the chain, the distance each fin lags behind the ship can be estimated. Combining this calculation with GPS data recorded by the ship during the tow and the measured depths, each data point recorded by the CTD chain can be placed in time and space. The temperature, salinity, and pressure can then be used to calculate the sound speed based on the UNESCO formula [2] to create a sound speed field from any section of the tow. An example of such a field is shown in Figure 1.5. Density can also be calculated from the data using the equation of state for seawater.

The CTD data revealed several traveling internal waves, which appear as depressions in the contours of a sound speed field (or a temperature, salinity, or density field, since internal waves are a physical displacement of water from its equilibrium depth), the trajectories of which were calculated by Smith [1]. One such wave can be seen in Figure 1.5, and the locations of the measured waves are marked in red in Figure 1.2.
Figure 1.4: Sound speed field for a portion of one tow section, with CTD sample points super-imposed to show spatial resolution. The curved left edge of the figure is due to the curvature of the chain as it was towed.

Figure 1.5: Sound speed field as recorded by TAVEX CTD tow, which contains a large internal wave depression at 3 kilometers. The black contour lines show 2 m/s increments.
Chapter 2

Internal Waves and Spice: An Overview

2.1 Introduction

The variation in the sound speed field in the TAVEX experiment has been classified for study into three categories: linear (background) internal waves, nonlinear (propagating) internal waves, and density-compensated thermohaline variations (spice). All three of these phenomena are related to the density stratification that occurs naturally everywhere in the ocean, and the dependence of sound speed in water on temperature, salinity, and pressure.

Gravitational force causes seawater with varying density to stratify, with heavier water sinking to the bottom and lighter water floating to the top. Thus gravity creates a restoring force, which causes water that is vertically displaced to oscillate about its equilibrium depth. This restoring force is the basic principle behind both linear and nonlinear internal waves. The same gravitational restoring force also contributes to the creation of thermohaline intrusions. Variations in density equilibrate with their surroundings through vertical motion much faster than the variations in temperature and salinity which cause them can dissipate through thermal conduction or salt diffusion.

The dynamics of internal waves, both linear and nonlinear, and the effects they have on sound propagation have been very popular topics of research for quite some time, while literature on spice is much more sparse, and studies of its effects on sound transmission even more so. This chapter gives a description of the physical principles behind each of these phenomena and an overview of past literature, both oceanographic and acoustic, on each topic.
2.2 Linear Internal Waves

In order to be gravitationally stable, water must be stratified by density, with the heaviest water sinking to the bottom, and the lightest water rising to the surface. Any water that is displaced in depth, resulting in density inversions in extreme cases, or vertical displacements in the isopycnals (surfaces of constant density) in milder cases, will be restored to its equilibrium by buoyancy forces. The combination of this force and the inertia of the parcel of water in question will create an oscillation around the parcel’s equilibrium depth. Such oscillations are known as internal waves, and are similar in principle to surface waves (surface waves are also caused by density stratification, but a sharp transition from water to air, rather than a gradient).

Internal waves occur virtually everywhere in the ocean. The water column acts as a waveguide for internal waves just as it does for acoustic waves, and resonant interactions between internal wave modes and surface waves, along with other factors such as wind stress and flow over bathymetric features, creates a constant background of fluctuations due to linear (or diffuse) internal waves [4]. This background internal wave activity is so constant, in fact, that a single spectrum, the Garrett-Munk Spectrum (GM79: 79 refers to the year of publication, to distinguish from earlier iterations) [5] can be used to describe linear internal waves in nearly every deep water environment in the world. Internal waves in the deep ocean have been studied extensively over the last century. A summary of this work through the 1970s is given by Munk [4].

Numerical simulation codes exist which will produce random internal wave fluctuations con-
sistent with any environment [6, 7]. Flatté et al developed techniques based on theories of electromagnetic wave propagation for modeling the effects of internal waves on sound propagation in the ocean, focusing particularly on deep water environments and the SOFAR channel [8]. These effects have been studied further, both numerically and experimentally, in shallow and deep water, by many [9, 10, 11, 12, 13, 14].

Levine [15] has presented a modification to the Garrett-Munk spectrum which is more suitable for shallow water. It should be noted, though, that internal waves in shallow water are greatly affected by environmental factors, such as continental shelf breaks, and therefore the use of a single spectrum to describe all shallow water environments is somewhat unrealistic. The Garrett-Munk and Levine spectra are shown in Figure 2.1 along with the spectrum of internal wave activity observed in the TAVEX experiment. This figure is discussed further in Section 4.2. Mingnerney has analyzed the impact of linear internal waves on acoustic propagation during TAVEX [16].

2.3 Nonlinear Internal Waves

Nonlinear internal waves are larger amplitude displacements of isopycnals, which propagate slowly through the water column in "packets" consisting of one or more depressions. These waves are considered nonlinear because they have a definite beginning and end, and because according to the most accepted model for their behavior, the shape of the wave changes from a cosine function at the front of the packet to a Jacobian elliptic function \( cn(x) \), often referred to as a "cnoidal" function, or \( dn(x) \), a “dnoidal” function) at the back. Their form also changes over time, adding more depressions as they propagate [17, 18]. They are generated by flow over bathymetric features such as continental shelf breaks, and therefore their occurrence is usually limited to shallow water. Nonlinear internal waves are extremely common in the East China Sea, where TAVEX was conducted, generated by flow over the continental shelf and around small islands [19]. They are generally much larger than surface waves in both amplitude and wavelength, with typical amplitudes on the order of 10 meters, and wavelengths varying from hundreds of meters to kilometers. The waves observed in the TAVEX experiment had amplitudes between 3 and 5.5 meters, and wavelengths between 450 and 700 meters [1]. The dynamics of nonlinear internal waves were first modeled by Korteweg and deVries [17], and the model was improved upon by Apel [18]. A plot of Apel’s model is shown in Figure 2.2.

Nonlinear internal waves can have very significant effects on acoustic propagation, as the sharp horizontal sound speed gradients they produce can often act as lenses, creating complex horizontal refraction scenarios for acoustic energy propagating parallel to wave crests [20]. Many experiments have been undertaken to study the effects of nonlinear internal waves on sound propagation. These include several that took place on the Northeastern United States coast: Shallow Water 2006 (SW06) [21, 22, 23], Shallow Water Acoustics in a Random Medium (SWARM95) [24, 25, 26], and the Shelfbreak Primer study [27, 28]. SW06 used a large array of moored sensors to collect oceanographic data, including observations of passing nonlinear internal waves, in con-
currence with acoustic propagation data at multiple frequencies. In addition, two ships tracked
individual wave packets while recording temperature and salinity measurements and using current
profilers to record the velocity field induced by the internal waves. Using the SW06 acoustic data,
Duda et al. noted a pronounced decrease in horizontal coherence length when an internal wave
packet crossed the acoustic axis [29], while Katsnelson et al. focused on intensity fluctuations [30].
Several other notable experiments have been carried out in Asian seas, including the Asian Seas
International Acoustics Experiment (ASIAEX) [31, 32, 33], which had components in the South
China Sea and the East China Sea; the South China Sea Oceanic Processes Experiment/Non-
Linear Internal Waves Initiative (SCOPE/NLIWI) [34, 35]; and TAVEX. Primarily theoretical
and numerical studies include Oba and Finette [36], who used a three-dimensional parabolic
equation model to analyze the effects of a wave packet on transmission loss and horizontal co-
herence, Weinberg and Burridge [37], who proposed a system of horizontal ray paths for normal
modes in a stratified medium with slight horizontal variations which has been widely applied to
deal with the horizontal refraction induced by internal waves [38, 39].
Smith [1] documented the propagating internal waves present in the TAVEX CTD data,
calculated their trajectories, and explored their impact on the acoustic data. He found that
there were four distinct internal waves present in the data, two of which were observed twice.
The locations in the tow path where he waves were found and the trajectories of the waves are
shown in Figure 2.3.

2.4 Spice

The density of water is affected by several of its properties, specifically temperature, salinity,
and pressure (though the dependence on pressure can be removed in analysis by using potential
density, or the density that a parcel of water would have if it were moved adiabatically to a
reference depth, rather than in situ density). Because density is a function of both temperature
and salinity, multiple combinations of values can produce the same density. A parcel of water with differing properties (temperature, salinity, and/or density) from its surroundings can move up or down to its “correct” depth much faster than its temperature or salinity can equilibrate, and therefore cause variations in temperature and salinity to occur along isopycnals.

Sound speed is also a function of temperature, salinity, and pressure, but its dependence on these properties is different from that of density; in fact, changes in temperature and salinity which compensate each other in density enhance each other in sound speed. Therefore, such perturbations can cause significant fluctuations in the sound speed field: a change in temperature of 1° Celsius along an isopycnal corresponds to about a 3 m/s change in sound speed. The differing effects that temperature and salinity have on density and sound speed can be illustrated by plotting lines of constant density and sound speed on Temperature-Salinity axes, as shown in Figure 2.4.

Spice structure can come in many forms. Salt fingering occurs at the interface of a layer of warm, salty water over a layer of colder, fresher water, creating vertical “fingers” of the water in the bottom layer to protrude up into the top layer, and vice versa. When the opposite conditions
occur, the result is double diffusive layering, where water near the interface in the top cold layer is heated by the warmer water below and becomes buoyant. As it floats upward in order to compensate its density, it causes turbulent mixing, and this process happens repeatedly, creating several layers of varying temperature and salinity [40]. A vertical front with warm, salty water on one side and cold, fresh water on the other can result in interleaving layers on either side of the front [41]. These are all phenomena with specific structure that are the results of diffusion across sharp transitions between hot, salty and cold, fresh water. The vast majority of the spice structure seen in the TAVEX data is on a smaller scale, and apparently random in nature, present in patches scattered throughout the area. This combined with the dominant presence of large nonlinear internal waves suggests that it is created by turbulent mixing, as described by Hebert [42].

The physical principles behind the formation of this type of spice are illustrated in Figure 2.5 and are as follows: turbulence, often due to an internal wave as shown in Figure 2.5 part a, causes mixing that disrupts the stratification of density, temperature and salinity (parts b and c). Turbulence that is strong and long lasting, will eventually cause the affected parcel of water to become fully mixed and create a layer of which has uniform properties that are an average of the layers from which the water in the patch was taken (part d). The turbulence that is present in the ocean, however, is generally too weak and intermittent to complete the mixing.
process. Instead, the turbulence often dies out before the water is fully mixed, leaving smaller
structure within the patch known as “fossil turbulence”. Density stratification will cause these
patches, which because of the mixing have less density variation in the vertical direction than
the surrounding water, to flatten into layers which are hundreds or thousands of times wider
than they are tall [43]. These layers may be observed as isolated patches, as in the TAVEX
data, or in groups where many patches are stacked on top of one another, creating a “stair-step”
temperature profile [44].

Figure 2.5: A diagram which illustrates the mechanism by which an internal wave creates spice.
Each part shows a schematic of the density stratification at a different point in time as it evolves
from an instability(a-b), to turbulence(c), to spice(d); and the density profile at the cross section
marked by the vertical line (to the right of each figure). Reproduced with permission from Hebert,
©1999, American Meteorological Society.

Such intrusions have no density signature, and therefore do not affect ocean dynamics, such
as internal waves. The only mechanism by which the intrusions can be destroyed is diffusion, and
therefore they tend to be very long-lived. Stommel and Federov [45], Johnson, et al. [46], and
Potter [47], have all suggested slightly different (by constants) expressions for the characteristic
decay time of an intrusion, but all agree that the decay time is proportional to the square
of the intrusion thickness and inversely proportional to the diffusivity constant. The diffusivity
constant can vary by multiple orders of magnitude depending on the degree of turbulence present.
Johnson, et al. estimated that the lifetime of a ten-meter thick intrusion is less than a day during
a turbulent event, but up to six months in very calm conditions where only molecular diffusion
is contributing to the decay.

Stommel was the first to define a variable (which he simply called q) normal to density in
the temperature-salinity plane [48]. His purpose was to explain the absence of variations in the
relationship between temperature and salinity in deep water below the mixed layer, but Veronis
later suggested a similar variable, represented by $\tau$ [49], for the purpose of describing what is now known as spice. Munk used $\pi$ and the name “spiciness”, meaning a measure of how hot and salty (or cold and fresh) water is [4], to represent Veronis’ quantity. The spice variable has often been used both to analyze thermohaline structure [50, 51, 52], and also as a tracer to study general ocean dynamics and circulation [53, 54]. In 1967, Stommel and Federov provided one of the first descriptions of intrusive thermohaline structure, in the form of 5 to 40 meter thick layers of warm, salty water extending up to 20 kilometers horizontally that were observed near Timor and Mindanao [45]. Garrett and Munk discussed the difficulty of computing internal wave spectra from temperature measurements in the presence of “fine-structure” [55] of the type mentioned by Stommel and Federov. Johnson, et al. [46], Cairns [56], Potter [47], and Dzieciuch et al. [57] all developed methods for separating internal wave and intrusive features.

An oceanographic experiment to study spice (the Spice experiment) took place in the north Pacific in the winter of 1997, using a glider to take salinity and temperature measurements along two isobars (constant pressure, and therefore constant depth, surfaces) in the mixed layer. The data achieved a horizontal resolution of 4 meters over an 1100 kilometer track. A study of temperature and salinity variations along these tracks revealed that these variations were nearly perfectly compensated in their effect on density over scales from 20 meters to 10 kilometers [58]. A study by Rudnick and Martin compiled glider data from sawtooth tracks spanning the mixed layer down to depths as deep as 300 meters from the Spice experiment and several similar experiments all over the world. Analysis of the statistics of fluctuations found in all of these data sets showed that compensation in the mixed layer is nearly universal, except in cases of extremely shallow mixed layers or areas with minimal salinity fluctuations. Below the mixed layer, there was a transition to temperature-dominated density fluctuations.

Studies on the acoustic impact of spice are scarce, but there are a few are of note. A 1980 numerical study by Ewart used a Monte-Carlo simulation of internal waves, and found that the addition of a single intrusion similar to one found in the experimental data on which the simulation was based both significantly affected the amplitude of the received signal and increased agreement with the experimental data [59]. Some of the results from this study are reproduced in Figure 2.6, which shows the spectrum of intensity fluctuations in both simulation and experiment for several different frequencies. Two more modern studies use high resolution oceanographic data separated into tilt and spice components (see Chapter 3) as deterministic inputs for numerical propagation models. Dzieciuch et al. used glider data from the Spice experiment in the north Pacific to study the effects of spice on a 1000-km simulated acoustic track in the deep ocean, and found that the first arrivals (the so-called “SOFAR overture”) are highly sensitive to thermohaline variability in the mixed layer, to the extent that the authors suggested that long-range acoustic propagation could be used to monitor seasonal changes in the mixed layer [57]. Lyons used data from a towed CTD chain (similar to TAVEX) taken off the coast of southern California, and simulated propagation over 500-meter sections of the data. Results of the simulation showed increases in the variability of the received signal when propagating through the boundary of an intrusion [60].
Chapter 3

Separation of Tilt and Spice Processes

3.1 Introduction

It is often desirable to examine the separate effects of internal waves and spice on a particular sound speed field. This can be accomplished, as described by Dzieciuch et al. [57], and Lyons [60] by separating the field into two components which represent these two phenomena. Spice is examined by only considering sound speed variations along isopycnals, and internal waves (also called "tilt", in reference to the tilting of isopycnals) is examined by only considering variations in isopycnal depths. An algorithm for tilt and spice separation was developed for this thesis, and is described below. Figure 3.1 is a diagram which illustrates the process conceptually. The top left drawing shows an environment which represents one that might be measured directly by a CTD chain. It contains variation due to vertical stratification, as well as tilt (the displacement of the isopycnals, most likely due to an internal wave) and spice (shown here as a vertical front, but the same concepts apply to all of the types of thermohaline variation described in Chapter 2). In the top right panel, temperature and salinity have been averaged along the isopycnals, removing the front and leaving only the vertical stratification and tilting of isopycnals due to internal waves. In the bottom left panel, the isopycnals have been straightened, removing the internal wave variation while preserving the thermohaline front. In the bottom right panel, both tilt and spice have been removed, leaving only range-independent stratification.

Figure 3.2 shows this same concept using TAVEX data by showing sound speed contours with density contours superimposed on top. Figure a shows the true sound speed field (equivalent to the top left portion of Figure 3.1). Sound speed variation due to both tilt (where the isovelocity contours follow the isopycnals) and spice (where the isovelocity lines deviate from the isopycnals) is visible. In Figure b, which is equivalent to the bottom left panel of Figure 3.1, the depths of individual points have been adjusted to straighten the isopycnals, resulting in a field where all
sound speed variation is due to spice. In Figure c, equivalent to Figure 3.1, top right panel, the temperature and salinity (and by extension, sound speed) values have been replaced with the average value for the isopycnal, so all variation is due to variations in isopycnal depths. This variation is assumed to be due to internal waves, though this is not always the case. The validity and consequences of this assumption are discussed in Section 3.6.

Figure 3.3 uses data from TAVEX to illustrate the effects in a different way, as scatter plots of individual data points on potential density versus depth and sound speed versus potential density axes. The original data, represented by the red dots, lies in a distribution around the mean profile (green line). To create a spice field, all of the data points in Figure 3.3a (density/depth) are moved to the mean profile. The data points after separation are shown by the blue dots. For the tilt field, points in Figure 3.3b (sound speed/density) are moved to the mean profile.

The calculation of each field begins with the isopycnals, and involves several coordinate transformations, illustrated by Figure 3.4. First, the field is converted from depth-range coordinates, with a temperature, salinity, and density value corresponding to each point, to density-range coordinates, where each point has corresponding values of temperature, salinity, and depth. In order to do this, several isopycnals are traced, corresponding to the average density at each depth in the grid. The density values are chosen in this way, rather than using a linear distribution of density values, in order to create a more uniform distribution of points in depth-range coordinates. The temperature, salinity and depth are recorded at each point along each isopycnal, recreating the field in density-range coordinates. An example of the temperature, salinity, and depth along one isopycnal is shown in Figure 3.5b. A combination of temperature, salinity, and depth are replaced with average values before transforming back to the original depth-range grid.
(a) Total sound speed field with isopycnals

(b) Spice sound speed field with isopycnals

(c) Tilt sound speed field with isopycnals

Figure 3.2: Sound speed field (colored contours and black lines) and isopycnals (white lines) before and after applying tilt and spice separation. In the tilt field, the isovelocity contours follow the isopycnals. In the spice field, the isopycnals are flat. The tilt field has been calculated using averages instead of the low-pass filtering technique in order to better illustrate the concept.

Attempting to apply the techniques described below to isopycnals that do not extend all the way across the field is problematic, so these isopycnals are not used, creating areas at the top and bottom of the field with no data. The spice, tilt, and averaged fields each have techniques for dealing with these areas, which are also described.

### 3.2 Spice

In order to create the spice field, the points in density-range coordinates keep their original temperature and salinity values, but the depths are replaced with the average depth of the isopycnal. The field is then re-interpolated back to depth-range coordinates. In Figure 3.5b, the
dark blue curves indicating the original temperature and salinity are used, along with the light green line indicating the average isopycnal depth.

This technique does not yield data above the average depth of the first continuous isopycnal and below the average depth of the last continuous isopycnal. In order to fill these regions, a second spice field is created, using a different technique which does not require continuous isopycnals. The density and average depth of each isopycnal (whether or not it is continuous) is recorded and a polynomial curve fit is used to create an average relationship between density and depth. That relationship is used to assign a new depth to each point in the original field in depth-range space based on its density, and the field is then re-interpolated back to a uniform grid. Points from the second field are then used to fill in the top and bottom of the first field.

3.3 Tilt

The tilt field is created by replacing the temperature and salinity values along each isopycnal in density-range space with the averages for the isopycnal before moving back to depth-range space. This completely removes all thermohaline variation.

The areas above and below the first and last continuous isopycnal are filled using a technique similar to the one used for the spice field. Curves for temperature and salinity versus depth are created and applied to each point in depth-range space that is outside the extent covered by the first technique.

Since the goal of this thesis is to examine the impacts of tilt and spice on acoustic propagation, it is necessary to ensure a reasonable comparison between propagation through the tilt, spice, total, and baseline fields. Ideally, it would be convenient if the impacts on the tilt and spice
Figure 3.4: Grid points in depth-range and density-range coordinates. The depth-range grid is used for initial interpolation of the CTD data. The data in depth-range space is interpolated to density-range space to create the tilt, spice, and averaged fields, and then interpolated back to depth-range space in order to create the RAM input files.

Field added to exactly the impact on the total field (i.e. the difference between the tilt and baseline transmission loss fields plus the difference between the spice and baseline fields is equal to the difference between the total and baseline fields). Of course, this is impossible, most importantly because creating the spice field involves physically moving water up and down, meaning that a spice feature in the spice field will not be acting on the same point in the acoustic field as the same feature in the total field. One way to remedy this is to use $TL_{total} - TL_{tilt}$ instead of $TL_{spice} - TL_{base}$. However, there was still a concern about large variations in sound speed between the tilt and total field (as seen in Figure 3.7c) due to large, slow, variations in temperature and salinity along the isopycnals in larger (up to 10 km) fields. In other words, the average relationships of temperature and salinity versus density are not constant over large
Figure 3.5: An example of how an isopycnal is used to create the tilt, spice and averaged fields. The bottom figures are plots of the salinity, temperature, and depth of the isopycnal that is highlighted in magenta in the upper figure. The light blue mean or filtered temperature and salinity curves are used in the tilt and averaged fields, and the light green average depth line is used in the spice and averaged fields.
(a) Filter coefficients used to calculate a weighted local average of temperature and salinity.

Figure 3.6: Filter coefficients and response for the low-pass filter used on the temperature and salinity to create slowly-varying local averages. The filter is a local average over 1000 meters weighted by a Hanning window.

In order to create a filtered tilt field, a low-pass filter is applied to the temperature and salinity along each isopycnal, instead of replacing all values with an average. This technique eliminates small-scale fluctuations associated with spice created by turbulent mixing, but preserves local averages. The filter is a local average over 1000 meters (or any other desired distance) weighted by a Hanning window. Figure 3.6 shows a plot of the filter coefficients and the response of the filter. In Figure 3.5c, the light blue filtered temperature and salinity curves are used with the dark green true depth curve.

The large-scale variations also need to be accounted for in the upper and lower-portions of the field. This is accomplished by splitting the original field into 1000-meter (or whatever cutoff wavelength is being used) sections. In each section, the same polynomial fitting technique described above is used to find expected temperature and salinity values for several densities ranging from the minimum in the field to the first continuous isopycnal, and from the last continuous isopycnal to the maximum density in the field. Two tables are created with temperature and salinity values corresponding to each combination of these density values and the ranges of the sections. These tables are used to find new temperature and salinity values at each point outside the continuous isopycnals. This technique still allows for variation on the same scale as the low-pass filter, but the variations are not as smooth.
(a) Total (true) sound speed
(b) Spice sound speed
(c) Total sound speed minus tilt sound speed, calculated using averages
(d) Spice sound speed minus averaged sound speed, calculated using averages
(e) Total sound speed minus tilt sound speed, calculated using a 1000-m low-pass filter
(f) Spice sound speed minus averaged sound speed, calculated using a 1000-m low-pass filter

Figure 3.7: Plots showing the difference between sound speed fields with and without spice, calculated using averages method (middle) and using a 1000-m filter (bottom). The variations in the middle row of figures represent sound speed fluctuations due to spice, but are dominated by large variations in local averages of temperature and salinity. The features in the lower figures show sound speed variations due to smaller fluctuations in temperature and salinity. Both pairs of plots show the same variations, but on the right side, they have been moved by the process of removing the effects of internal waves. The total and spice sound speed fields are also shown for reference.
3.4 Averaged Field

In order to study the effects of tilt and spice on acoustic propagation, a baseline field is needed for comparison from which tilt and spice have both been removed. The filtered or averaged, as appropriate, temperature and salinity along each isopycnal and the average depth of each are all used to create a field which is range-independent in density, and is either range independent or slowly varying with range in sound speed. The top and bottom sections outside of the continuous isopycnals are filled by applying the low-pass filter or a constant average value to the temperature and salinity of the spice field.

3.5 Effects of Spice on the Sound Velocity Field

The effects of spice on the sound velocity field can be examined by either subtracting the average sound speed field from the spice field, or the tilt field from the total field. The results of both of these operations for one section of data, with and without the use of a filter for temperature and salinity values, are shown in Figure 3.7. Without the filter (Figures 3.7c and 3.7d), large sound speed variations are visible, while in Figures 3.7e and 3.7f, these large variations have been filtered out, leaving only smaller-scale effects. Similar features are revealed by subtracting the tilt sound speed from the total sound speed or the averaged sound speed from the spice sound speed, but because the removal of internal waves from the spice and averaged fields involves vertically displacing the data points in order to straighten the isopycnals, many of the features are moved to different depths and distorted in Figures 3.7d and 3.7f. Because of this distortion, subtracting the tilt field from the total field is concluded to be a more accurate representation of spice, and is preferred for analysis.

3.6 Shortcomings of the Separation Process

The process of separating tilt and spice makes the assumption that all distortions in the density field are due to internal waves, and therefore classified as tilt. In most cases, this is a good assumption, but since intrusions take a finite time to compensate gravitationally (generally assumed to be close to the Brunt-Väisälä period), some will affect the shapes of isopycnals. Figure 3.8 shows the salinity, temperature, density, sound speed, tilt sound speed, and spice sound speed for a section of the TAVEX data to illustrate the unwanted effects on the tilt and spice sound speed field that can be caused by such intrusions. These effects are amplified by the fact that salinity has a much greater effect on density than on sound speed. The section used here is in an area that IW2/3 has passed through. It is labeled U (for uncompensated) in Figure 4.1.

The salinity field shows a large anomaly (circled in white) which does not appear to be internal wave-related. There is no corresponding anomaly in the temperature field, however, so the density is uncompensated. Since salinity has very little effect on sound speed, this anomaly is absent from the true sound speed field. Eventually this intrusion will sink down to its equilibrium
depth, eliminating the feature from the density field and becoming visible in the temperature and sound speed fields, but that had not yet occurred at the time the data was taken. Creating tilt and spice fields involves altering the sound speed field based on the shapes of the isopycnals, so features which are present in the density field but not the sound speed field create artificial anomalies in the tilt and spice sound speed fields. This phenomenon also occurs on smaller, less noticeable scales throughout the data, and is assumed to be the reason that sound speed spectra (discussed in Section 4.4.1) sometimes show higher levels of variation in the tilt or spice field than in the total field. It is also most likely the cause of the much greater than expected high wavenumber content in the internal wave spectrum calculated from TAVEX data, as discussed in Section 4.2.
Figure 3.8: CTD tow data that illustrates an unresolved issue with the tilt/spice separation process. The circled area of high salinity is not mirrored in the temperature field, which creates a much greater effect on the density field than on the sound speed field. This large, non-internal wave density fluctuation causes unrealistic variations to appear in the tilt and spice sound speed fields. Mean profiles appear to the left of each figure.
Chapter 4

Characterization of Tilt and Spice

4.1 Introduction

This chapter describes several different methods for characterizing the water column variability present in the TAVEX environmental data. Section 4.2 describes a standard method for describing linear internal waves: the displacement spectrum. Section 4.3 is a summary of work done by Smith [1] to identify several important characteristics of the nonlinear internal waves. Because much less prior work has been focused on spice, and the mechanisms of its creation and dissipation are not as well understood as the physical principles of internal waves, the largest section of this chapter is devoted to describing several methods (some used previously, particularly by Colosi et. al. [23], and some new) of describing spice. These methods are attempts to reflect as clearly possible the ways in which spice activity varies in magnitude, physical scale, and spatial distribution in both range and depth.

For this chapter, and the remainder of this thesis, 13 specific portions of the TAVEX CTD data will be analyzed, each six kilometers in length. These sections are divided into three groups: The first group consists of sections which contain the four nonlinear internal waves that were observed within a straight section of data at least six kilometers in length. These are named IW1, IW3, IW5, and IW6, following the names assigned by Smith [1]. The second group contains sections where internal waves have recently passed through, which were determined based on the speed and direction of travel of the internal waves and the times when the data were recorded. These sections are named T1a through T1c, and T2a through T2d. T indicates that the sections trail an internal wave, and the numbers refer to which wave the section is trailing (IW1 or IW2/3). Finally, there is a group of three "calm" sections, named C1 through C3, where no (known) internal wave has passed by recently. Section U is used to illustrate an uncompensated intrusion in Section 3.6, but is not used for further analysis because of this issue. The locations of these sections are shown in Figure 4.1.
4.2 Spectrum of Linear Internal Waves

The linear (random background) internal waves observed in TAVEX have been characterized by Mignerey [3] using a wavenumber spectrum for several sections of the tow where no large nonlinear internal waves (described in Section 2.3) were present. Each section of data from the curved CTD chain was interpolated to form a uniform grid, and the average density profile was found. Then that profile was subtracted from the actual density at each point to find the density fluctuations. These fluctuations were then converted to displacements using

$$\zeta(x, z) = \frac{g}{\bar{N}^2} \frac{\delta \rho(x, z)}{\bar{\rho}}$$

where $\bar{N}$ is the depth-averaged buoyancy frequency. The power spectrum of $\zeta(x)$ at each depth was then computed, and averaged over depth, then averaged again over all of the tow sections being used. The results of this calculation are shown in Figure 4.2 along with the Garrett-Munk and Levine Spectra, and the spectrum of waves produced using an internal wave modeling code. This figure was provided by Mignerey and Turgut [3], who suggested that the large deviation from both the standard analytic spectra and the model-predicted spectrum at high wavenumbers
is due to uncompensated salinity fluctuations as discussed in Section 3.6. No attempt was made to separate linear from nonlinear internal waves, except visually based on the much larger amplitude and more distinctive shape of the nonlinear waves. Instead, it was assumed that where a nonlinear wave was visible, its amplitude would be large enough to make linear waves insignificant in comparison, and in the absence of nonlinear waves, all density fluctuations were due to linear internal waves.

### 4.3 Nonlinear Internal Waves

Six nonlinear internal wave events were observed in the TAVEX CTD data, which were found by Smith [1] to be four separate internal waves. The locations and trajectories of these waves are plotted in Figure 4.3, and several key properties of the waves are listed in Table 4.1.

### 4.4 Spice

Because the behavior of spice variations have been studied much less extensively than internal waves, spice was the most difficult element to characterize. Several methods were attempted,
Figure 4.3: TAVEX tow path with observed nonlinear internal waves marked in red, and trajectories of the waves shown as black arrows. Arrows connecting two internal wave observations indicate where the tow path crossed the same waves more than once. Map provided by Chad Smith of Applied Research Lab at Penn State.

Table 4.1: Properties of the internal waves observed during TAVEX: wavelength, travel speed, maximum displacement amplitude, angle with respect to acoustic axes, and time in hours (relative to the beginning of the experiment) when the wave was crossing each acoustic axis. All data from [1].

| IW1 | 526  | 0.97 | 5.3  | -9  | 6.5  | 18.0 | 11.0 | 18.0 |
| IW2 | 688  | 0.92 | 3.1  | 44  | 24.5 | 33.5 | 28.0 | 33.5 |
| IW3 | 532  | 0.88 | 3.2  |     |     |     |     |     |
| IW4 | 523  | 0.92 | 3.3  | -102| 31.0 | 35.0 | 31.0 | 34.0 |
| IW5 | 510  | 0.95 | 4.4  | -12 | 28.0 | 40.0 | 32.0 | 40.0 |
| IW6 | 470  | 0.92 | 4.6  |     |     |     |     |     |

and the results are summarized below.
Figure 4.4: Spectrum of sound speed variations in the tilt, spice, and total fields in Section C3 of the TAVEX tow

### 4.4.1 Sound Speed Spectrum

In order to generalize the spice contributions in an environment, and compare them to those of tilt, sound speed spectra can be used. These are computed using the variation in sound speed with range in the spice field (or equivalently, the variation along isopycnals in the total field), and then averaged over depth. Analogs to the spice sound speed spectrum can be computed for the tilt and total fields. These are useful for comparing the effects that tilt and spice have on the overall sound speed. Figure 4.4 is an example of such a spectrum. At long wavelengths, the tilt variations dominate, while at shorter wavelengths, the contribution of the spice structure is much closer in magnitude to or (in some cases, though not the one shown) exceeds that of the tilt. Occasionally, the tilt and spice spectrum levels will exceed those of the total sound speed spectrum due to the uncompensated intrusions described in Section 3.6;

Although the sound speed spectrum is a familiar way of displaying and analyzing how sound speed is affected by spice on different scales, there are many characteristics of spice variation which cannot be shown by a single spectrum. Specifically, the spectrum of spice variations changes as a function of both depth and range. Section 4.4.2 presents a type of analysis which deals well with depth dependence, but does not easily handle scale (wavenumber), and Sections 4.4.3.2-4.4.3.4 show ways of displaying the variation in the spectrum with range and depth, using the variable spice.
4.4.2 Covariance

Following Colosi et al. [23], covariance matrices were used to examine the variation in sound speed due to spice and how it relates to depth. A covariance matrix is a measure of the correlation between the sound speed as a function of range at different depths. Each element of the matrix represents a combination of two depths. The elements can be calculated individually using

\[ q_{jk} = \frac{1}{N-1} \sum_{i=1}^{N} (c_{ij} - \bar{c}_j)(c_{ik} - \bar{c}_k) \]  

(4.2)

where \( j \) and \( k \) represent depths and \( i \) represents range. In matrix form, the equation becomes

\[ Q = \frac{1}{N-1} \sum_{i=1}^{N} (c_i - \bar{c})(c_i - \bar{c})^T \]

(4.3)

The result is a diagonally symmetric \( J \times J \) matrix, where \( J \) is the number of depths sampled. Both the \( x \) and \( y \) axes represent depth. For any combination of two depths, the covariance value will be large and positive if there is a large amount of variation at both depths, and the variation is positively correlated. Similarly, a large negative value will result from depths where the sound speed is negatively correlated. If there is little variation, or the variation is not well correlated, the covariance value will be small. When normalized, the covariance matrix becomes a matrix of linear correlation coefficients. None of the covariance matrices shown in this thesis have been normalized, as normalization would make it impossible to compare the covariance of two different sound speed fields. It is important to note, however, that comparison of the covariance values is only meaningful if the same number of samples in range were used to calculate them.

The covariance calculation can also be performed for the tilt and total fields, and used as a metric to compare the amount of sound speed variation due to tilt and spice. In sections with significant internal wave activity, such as IW1, on the left side of Figure 4.5, covariance of the tilt fields are much greater than the spice covariance. In sections (such as C1, shown on the right side of Figure 4.5) which contain only background internal wave activity, the covariance levels are similar, though tilt is generally still dominant.

Covariance can also be used to compare the depths at which each type of variation occurs. In the case of section IW1, the covariance matrices make it clear that tilt and spice variation dominate at different depths (tilt around 15 and 30 meters and spice around 25 meters) resulting in a total sound speed field which has significant variation over the entire water column down to about 40 meters. The reason for the difference in depths is not known. The tilt matrices also generally show stronger off-diagonal components than the spice matrices, meaning that internal waves cause variations which are more highly correlated between different depths.

Covariance matrices are useful for examining the depth dependence of sound speed variations, and the correlation between depths, but they do not easily show information about range dependence or the scale of the variations. The only way to deal with range dependence is to calculate matrices for consecutive sections of data and compare them. Scale is even more difficult, because
Figure 4.5: Covariance matrices for two sections of the TAVEX tow. The left column is computed from a section which is dominated by a large internal wave event. The right column is a section with only background internal wave activity. Both have typical levels of spice variation. The color scale is essentially meaningless but it is included to show the compression that is used around zero to emphasize small variations without sacrificing the range of the scale. Covariance is a correlation between fluctuations in sound speed at various depths, so all vertical and horizontal axes are depth in meters.

As mentioned above, comparison of covariance magnitudes is only meaningful if the matrices are calculated from the same number of samples. For those reasons, covariance was abandoned in favor of the methods presented below which are able to display both scale and range or depth dependence (or both).
4.4.3 Spice Variable

While comparisons of sound speed variations due to tilt and spice are useful from an acoustic standpoint, a more oceanographically relevant quantity is the variable spice. Spice, represented by \( \tau \), is defined to have isopleths (contour lines) in the temperature-salinity plane which are perpendicular to those of density, so that it captures only dynamically passive variations. It is preferable to using temperature or salinity (or sound speed) because its dimensional consistency with density makes it ideal for comparing tilt and spice variations. The spice variable was first used in an abstract sense (without an explicit formula) by Stommel [48], and formulations for absolute values have been proposed by Veronis [49], Jackett and McDougall [61], and Flament [62]. These formulae are valid for all values of temperature and salinity likely to be found in the ocean, but are quite complicated. Though a universally valid formula is important if one wishes to use spice as a tracer for ocean currents, the use of spice in this thesis is merely to track variations along isopycnals (or constant depths in a spice field). Therefore, the much simpler formulation for relative spice variations suggested by Ferrari and Rudnick [58] is more appropriate. This expression assumes linear variations of density, and therefore spice, over the relatively small variations of temperature and salinity found along an isopycnal. If density fluctuations are defined by

\[
\Delta \rho = -\alpha \Delta T + \beta \Delta S, \quad (4.4)
\]

where \( \alpha \) is the thermal expansion coefficient and \( \beta \) is the haline contraction coefficient, spice fluctuations are

\[
\Delta \tau = +\alpha \Delta T + \beta \Delta S. \quad (4.5)
\]

\( \Delta T \) and \( \Delta S \) are defined relative to the mean values of temperature and salinity on a particular isopycnal. Because \( \alpha \) and \( \beta \) are not constant over the entire T-S plane, and because density is also a function of pressure (depth) they must be calculated independently for each isopycnal. They are found using the following formulae:

\[
\alpha = -\frac{\rho(S, \overline{T} + \delta T, \overline{p}) - \rho(S, \overline{T} - \delta T, \overline{p})}{2\delta T} \quad (4.6)
\]

\[
\beta = \frac{\rho(S + \delta S, \overline{T}, \overline{p}) - \rho(S - \delta S, \overline{T}, \overline{p})}{2\delta S} \quad (4.7)
\]

\( \delta T \) and \( \delta S \) are set at 2 degrees Celsius and 0.5 PSU, which are typical of the range of temperature and salinity values along an isopycnal, and the densities are computed using the UNESCO equation of state [2]. Figure 4.6 is a temperature-salinity diagram with density, sound speed, and spice contours. The axes are scaled approximately proportional to the thermal expansion and haline contraction coefficients so that the density contours are close to 45 degrees, and the spice contours are perpendicular.

An example of spice anomalies in a section of data is shown in Figure 4.7b. A plot of density anomalies is also shown for comparison. It is important to note that the spice plot is taken from a spice field, but the density plot is taken from the total field. This is because in the total field,
Figure 4.6: Temperature-Salinity diagram with sound speed, density, and spice contours. All are calculated using surface pressure, and spice is defined relative to average temperature and average salinity. Spice and density contours are perpendicular and equally spaced.

it would be impossible to determine which variations in spice values are due to intrusions and which are due to vertical displacement of water, while looking at density variations in the spice field would be useless, since the spice field is deliberately constructed to remove these variations. The total and tilt fields can be used interchangeably here, since they have the same density. Also note the differing color scales for the two plots, as the magnitude of the density variations is about triple the magnitude of the spice variations.

The plot of spice anomalies is very similar in appearance to the plots in Figure 3.7 which showed the effects of spice on sound speed by subtracting two types of sound speed fields. Both are ways of examining the same features. Sound speed difference plots present the data in a way that is perhaps more comfortable to acousticians, but spice is a quantity that is more useful from an oceanographic standpoint. Several methods for displaying characteristics of the spice variable are shown in Figures 4.9 and 4.10.

4.4.3.1 RMS Variation

Perhaps the most straightforward way of summarizing the spice variation in a data set is to simply calculate an average density anomaly over the entire field, thus reducing a plot such as Figure 4.7b to a single number. An equivalent calculation can be performed for the density anomaly. Since it is assumed that the spice in the TAVEX data was created by passing internal waves, it is interesting to plot the RMS spice anomaly against RMS density anomaly for several data sections to see if sections with more internal wave activity also have more spice. Figure 4.8
(a) Average sound speed profile, total (true) sound speed field, and spice sound speed field for section IW6 (in m/s)

(b) Spice anomalies in Section IW6

(c) Density anomalies in Section IW6

Figure 4.7: Spice (b) and density (c) anomalies in section IW6. The spice plot was made using the spice field (a, right side), and the density plot was made using the total field (a, left side). Note that the spice and density plots have different color scales. Both spice and density scales are in kg/m$^3$. 
is such a plot. There appears to be very little correlation between density and spice variations. There is also not very much difference between the three types of sections (internal wave, trailing internal wave, and calm) except that, as expected, the internal wave sections have much more density variation. The red dot which is far to the left of the others, closer to most of the trailing and calm sections than to the rest of the internal wave sections, is IW3. The density variation for this section is so low because the internal wave is only present in about one kilometer of the six kilometer field. There is almost no distinction between the trailing and calm sections in density variation.

Although the lack of correlation between density and spice variation fails to confirm that the spice is caused by internal waves, it is not unexpected, and in fact leads to an interesting conclusion. The time required for an intrusion to dissipate (see Section 2.4) is extremely long compared to the frequency of passage of internal waves in the region where the data was collected. Therefore, it is likely that the spice in an area of water is due to many previous waves, rather than just one or two that passed by recently, and one additional wave passing through is unlikely to make a significant contribution. The fact that the range of RMS spice values is much smaller than the range of RMS density values suggests that the extremely frequent passage of internal waves has caused the spice variation to remain in a steady state, where creation and dissipation occur at the same rate.

It would be interesting to examine similar data (if it existed) from other continental shelf areas to see if the same relationship, or lack thereof, between density and spice variation was present. The East China Sea has very frequently occurring internal waves, and it seems likely that a minimum amount of internal wave activity would be required to sustain such a constant level of spice. If internal waves pass by too infrequently, the spice created by one would start to dissipate noticeably before another came by and created more. Knowing (or being able to predict) where steady-state spice exists would be useful from an acoustic standpoint, as predicting the impact of spice on acoustic propagation would be much easier if there is a constant, and known, amount of spice.

**4.4.3.2 Spectrograms**

Computing covariance matrices for subsequent sections of a sound speed field can give an idea of how the fluctuations vary in range, and computing covariance matrices for different length sections can give an idea of how the sound speed field varies at different scales. However, a display which offered improved wavenumber resolution and a more intuitive description of variation in range was desired. Spice spectrograms were chosen to serve that purpose.

Spice spectrograms for the spice field are essentially a description of how the temperature and salinity vary along isopycnals, as a function of wavenumber and range. The calculation is identical to one that would be used for an audio signal (such as in Figure 1.3), except that the data is spatial rather than temporal, and comes from a two-dimensional field of values rather than a single waveform. For each depth, the spice values are broken into smaller sections in range, and a Fourier transform is computed for each section, then converted to a power spectrum, producing
Figure 4.8: RMS spice variation versus RMS density variation for the data sections shown in Figure 4.1

a matrix of magnitude values for each range and wavenumber at that depth. The difference between this spectrogram and that of an audio signal is that a separate matrix is produced for each depth in the field, which must be averaged over either all depths, or a limited range of depths.

An example of a spice spectrogram averaged over all depths is shown in the left side of Figure 4.9c. As expected, it shows some variation in range, particularly at higher wavenumbers (shorter wavelengths). The spectrograms for all 13 tow sections are printed in Appendix A and differ significantly. Although the overall levels of spice activity remain very similar (as is also shown by Figure 4.8), some vary much more in range than IW6 (see, for example, Figure A.3c) and section C3 (Figure A.5c) appears to have a peak at about .01 cycles/meter (10-meter wavelength).

4.4.3.3 Spice Spectrum versus Depth

Spectrograms averaged over different depths can give an idea of how the spice activity varies as a function of depth, but the resolution of this approach is limited, because it is cumbersome to compare a large set of these plots. A more convenient way to examine the depth dependence of spice variations is to drop the range dependence and plot the spice spectrum as a function of depth. The result is a plot similar to a spectrogram, but with the horizontal axis showing wavenumbers. A power spectrum is computed from the spice values at each depth by over the entire section in question, producing a matrix of magnitude values for each depth and wavelength. An example for section IW6 (sound speed shown in the left half of Figure 4.9a) is displayed on the right side of Figure 4.9c. It shows that in section IW6, spice activity appears to be concentrated at two depths, around 15 meters and 25 meters. There is also a third, less pronounced, concentration
around 40 meters. This pattern is also visible in the plot of spice anomalies in the section (right half of Figure 4.9b). The higher wavenumber components of each concentration also drop off more rapidly the lower the concentration is in the water column. The reasons for this behavior are unclear.

These features are consistent through most of the data sections, though they vary slightly. Most of the spice variation is usually concentrated at one to three depths, with the shallowest depths showing the most short-wavelength components. Appendix A contains Spice Spectrum versus Depth plots for all 13 tow sections.

### 4.4.3.4 Spectrum Pixel Plots

Because the spectrograms and the spectra versus depth revealed significant variation with both range and depth, a new plot was developed which makes it possible to examine both at once. Of course, there are not enough axes available to view magnitude as a function of range, depth and frequency on a single plot, so the frequency axis was sacrificed in favor of range and depth. In its place, a series of plots representing various frequency bands was used.

To produce these plots, a series of logarithmically-sized wavenumber bands is defined, then for each band, the spice values at each depth are passed through a 6th order Butterworth filter using the MATLAB command filtfilt (which passes the data through the filter twice, once forwards, and again in reverse, resulting in a doubling of the filter order and zero phase shift). The filtered data is then divided into “pixels,” with a depth of three meters, and a length determined by the longest wavelength in the band. The mean square of all the values in each pixel is computed, and the mean square values are plotted as a function of range and depth. Pixel plots for IW6 (sound speed shown in Figure 4.7a) are shown in Figure 4.10, showing six bands spanning wavelengths between 50 and 1000 meters.

These types of plots show that different spice features are dominated by different scales. For example, in section IW6, the large feature at around 1 kilometer range and 28 meters depth shows up very strongly at scales of 368 meters and longer (the top two plots), and is much weaker at shorter wavelengths. On the other hand, the feature at 4 kilometers range and 40 meters depth is clearest in the 136-224 meter plot and the 50-82 meter plot. Pixel plot sets for all 13 tow sections are printed in Appendix A, and show similar variation.
Figure 4.9: Several figures which illustrate various ways of displaying the spice activity in a section of data.
Figure 4.10: Spectrum Pixel Plots for section IW6 (see Figure 4.7a)
Acoustic Modeling

5.1 Introduction

In order to characterize the effects that tilt and spice have on an acoustic field, parabolic equation modeling and ray tracing were employed to calculate propagation through several sections of the TAVEX tow data, and the tilt, spice, and averaged versions of those fields. The following sections describe the two methods of propagation modeling used and some basic results obtained with each that highlight how spice can affect propagation.

5.2 Ray Tracing

Ray tracing is a method of sound propagation modeling which produces a very intuitive visualization of the physics involved. Ray plots can be very helpful in interpreting transmission loss plots produced by parabolic equation models. The ray tracing technique works by representing acoustic energy as rays which are perpendicular to the wave fronts, and uses Snell’s law of refraction to trace their paths as they are refracted as a result of the varying sound speed in the medium. Snell’s law is

\[ k_1 \cos(\theta_1) = k_2 \cos(\theta_2), \]

which simply states that the horizontal component of the acoustic wavelength must remain constant across a horizontal boundary. Since \( k = \omega/c \), an alternative representation is

\[ \frac{\cos(\theta_1)}{c_1} = \frac{\cos(\theta_2)}{c_2}. \]

Snell’s law can be applied to any number of successive interfaces, or to a continuously varying sound speed field.

Solving the wave equation to find pressure amplitudes and travel times using this technique involves making approximations which limit accuracy to frequencies higher than those used in
TAVEX, but plotting the paths of individual rays is nevertheless a useful technique for conceptually showing the effects that spice can have on acoustic propagation. The ray tracing code used for this work is BELLHOP, developed by Michael Porter [63].

Figure 5.1 uses ray tracing to show examples of the effect that small “patches” of spice can have on propagation. The blue lines are rays propagated through a range-dependent environment defined by the profile plotted on the left axes. The red lines are rays propagated through an environment with the same mean sound speed profile, plus a spice patch shown by the colored area behind the rays, which represents sound speed deviation from the mean profile.

The two spice features shown in these figures are typical of two categories that are quite common in the TAVEX data: strong, relatively localized patches placed between 15 and 25 meters depth, and weaker features lower in the water column (around 40 meters depth), which cover a larger area.

As the rays propagate, their amplitudes are attenuated due to several factors. Because a propagation distance of 6 kilometers is too short for absorption to become significant, and also due to the strongly downward refracting sound speed profile, by far the most prominent source of attenuation is bottom losses, or energy lost into the seabed when rays bounce off the bottom. BELLHOP only plots rays while they still retain a significant portion of their energy, which in this case means that each ray is stopped after a certain number of bottom bounces. This is the reason that many of the steeper rays disappear before the end of the field. This is significant because it determines which spice features will affect a received acoustic signal. The spice in Figure 5.1a is more intense than the spice in Figure 5.1b, but because it is so high in the water column, the rays that pass through it do not travel very far before they are attenuated, and there is therefore very little effect on the rays that actually reach the receiver. In Figure 5.1b, the lower rays which actually reach the receiver are affected by the weaker, but lower placed, spice.

5.3 Parabolic Equation

One of the most convenient methods for modeling underwater acoustic propagation through a range-dependent environment is the Parabolic Equation Method, which is based on solutions to the wave equation in cylindrical coordinates, under the assumption of azimuthal symmetry and negligible backscattering. A detailed derivation of the parabolic equation method is given by Jensen, et al. [64], but some of the key steps are presented here. The starting point is the 3-dimensional Helmholtz equation in cylindrical coordinates:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial p}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 p}{\partial \phi^2} + \frac{\partial^2 p}{\partial z^2} + \frac{\omega^2}{c^2(r, \phi, z)} p = 0, \tag{5.3}
\]

where \( p(r, \phi, z) \) is the complex amplitude of acoustic pressure. Equation 5.3 can be simplified to

\[
\frac{\partial^2 p}{\partial r^2} + \frac{1}{r} \frac{\partial p}{\partial r} + \frac{\partial^2 p}{\partial z^2} + k_0^2 n^2 p = 0 \tag{5.4}
\]
(a) Effect of strong spice feature at 20 meters depth on acoustic ray paths

(b) Effect of weak spice feature at 35 meters depth on acoustic ray paths

Figure 5.1: Plot of ray paths in a range-independent field (blue lines) defined by the profile in the left part of each figure and ray paths that encounter spice (red lines). The range-independent profile is plotted on the left, and the colored field shows spice as deviations from the mean profile.
by neglecting dependence on $\phi$ and defining a reference wavenumber, $k_0 = \omega/c_0$, and the index of refraction, $n(r, z) = c_0/c(r, z)$.

Further approximations are made which limit accuracy to the far field ($k_0r \gg 1$), and small propagation angles (a wider range of acceptable angles can be obtained at the expense of computation time). Additional terms are dropped by neglecting waves traveling toward the source (assumption of negligible backscattering) and assuming the sound speed has only a weak dependence on range. The result is the one-way wave equation:

$$\frac{\partial \psi}{\partial r} = i k_0 \left( \sqrt{n^2 + \frac{1}{k_0^2} \frac{\partial^2}{\partial z^2}} - 1 \right) \psi,$$

where $\psi$ is the envelope function for the Hankel function solution to the Helmholtz equation, which is assumed to vary slowly in range.

The implementation used in this work is the Range-dependent Acoustic Model (RAM), developed by Michael Collins of the Naval Research Laboratory. RAM uses a Padé series approximation to the square root term in Equation 5.5 and a split-step algorithm for calculating the solution at successive range steps [65]. RAM was run using the Acoustic Toolbox User-interface and Post-processor (AcTUP), developed by Amos Maggi and Alec Duncan of the Centre for Marine Science and Technology at Curtin University of Technology, which provides a common MATLAB interface for RAM and several other acoustic modeling codes [66].

Parabolic equation modeling is an extremely useful tool for examining the effects of sound speed variations such as spice, because it is accurate over a wide range of frequencies, and easily accepts any two-dimensional sound speed field (such as a total, tilt, spice, or averaged field as described in Chapter 3) and produces a full, two-dimensional acoustic pressure (or transmission loss) field, allowing for easy comparisons among propagation through different environments. A sample transmission loss field calculated for a range-independent environment is shown in Figure 5.2. A strongly downward refracting vertical sound speed profile representative of the conditions in TAVEX is used.

The effects of spice on sound propagation were initially examined by propagating a signal through two fields, one with spice and one without, and subtracting the resulting transmission loss fields in decibels. Because the CTD data only covered about 10 to 50 meters in depth, isovelocity layers were added at the top and bottom to complete the field. A constant depth of 75 meters was used, consistent with the TAVEX area. A 300 or 500 Hz source was placed at 64 meters depth, also consistent with the TAVEX setup. The range and direction of propagation were not consistent with TAVEX, however. For the purposes of this thesis, shorter, six-kilometer sections were used, rather than the full 34 or 24 kilometers, and the direction of propagation was along the tow path in each case. No attempt was made to project the measured sound speed fields onto the TAVEX acoustic axis.

The interest in this thesis is in the effects of spice on long-range (far field) propagation, so in order to get a sense of these effects, for each pair of sound speed fields to be compared, the first
Figure 5.2: Transmission loss versus range and depth at 500 Hz for a range-independent environment with a vertical sound speed profile (shown at left) which is representative of the TAVEX environment.

Figure 5.3: Averaged and spice fields used to examine the effects of spice on acoustic propagation. The first 5 kilometers are identical, taken from the averaged field, and the last kilometer is the section that is used for comparison.

(a) Averaged field used for RAM modeling (6 km taken from averaged field)
(b) Spice field used for RAM modeling (5 km taken from averaged field and 1 kilometer from spice field)

To examine the effects of spice on acoustic propagation, comparisons are made between the total and tilt fields, and the spice and averaged fields. As described in Section Comparisons of these two pairs of sound speed fields both show similar features, but at different depths. In
the total field, the spice features are at their original depths, while in the spice field, the same features are still present, but have been moved vertically to straighten the isopycnals. These features can be seen in Figures 5.4a and 5.4b, which show the differences in sound speed between the total and tilt fields, and the spice and averaged fields.

Figure 5.4 shows transmission loss difference (ΔTL) plots for both methods of examining spice impact, using averaged values for temperature and salinity (top row) and with a 1000-m filter (bottom row), along with the corresponding sound speed difference plots. There is a large degree of similarity between both pairs, but also some significant differences. Most of the same features are visible in c that are in d, and similarly with f and g. However, there are some clear differences in shape and magnitude. These differences are not simply the vertical distortion that is present in the corresponding sound speed fields. It is much more complex, the result of spice features interacting with different points in the acoustic field. The similarities serve to validate the process of separating tilt and spice, while the differences emphasize the importance of the position of spice features in the acoustic field. Although there is no way of verifying which method is more accurate, it seems likely that subtracting the tilt acoustic field from the total one is more realistic, as it leaves the sound speed field as close as possible to the measured data while comparing the field with and without spice.

The transmission loss differences that are computed using filtered temperature and spice values are somewhat smaller in magnitude than those that are computed using averaged values, but they are certainly not insignificant, indicating that spice is important over a range of scales. Much of the basic structure of the averaged transmission loss fields is also present in the filtered fields, which suggests that the smaller-scale spice fluctuations could be even more important than the larger ones.

Although this type of analysis does not produce a signal that can be directly compared with experimental acoustic data, it does provide a glimpse of the potential impact of spice on sound propagation which is quick to produce and relatively intuitive to understand. Difference in transmission loss of up to 3 decibels over only 1 kilometer, as shown in Figure 5.4, are significant enough to warrant further study. The next section describes a different technique for modeling which is more realistic as an experimental setup.
Figure 5.4: Comparison of four ways of viewing the effects of spice on the acoustic field. The top two rows are sound speed difference and transmission loss difference using averaged values of temperature and salinity, and the bottom two rows use a 1000-m low-pass filter. All figures are at 500 Hz and the color scales are in dB.
Chapter 6

Correlation Between Spice Activity and Effect on Transmission Loss

6.1 Introduction

The ray tracing and parabolic equation model results of the previous chapter were intended to qualitatively demonstrate the importance of considering spice in acoustic propagation problems. The ultimate goal of this research is to suggest a method to detect the presence of spice using experimental acoustic data. The analysis presented in this chapter provides more quantitative results which serve as a step in that direction.

The experimental premise used for the modeling in this chapter is analogous to the TAVEX setup and environment (flat bottom at 75 meters depth, a single omnidirectional source placed at 64 meters depth, and water properties taken directly from the TAVEX CTD data) in every way except for the receiver configuration. Instead of a horizontal line array on the bottom, this analysis assumes a vertical line array which is towed behind a ship, which is able to capture a field such as the one shown in Figure 5.2. This configuration allows for direct use of the transmission loss fields created by RAM.

It is assumed that the experimenter who would wish to detect spice acoustically has (or will collect) enough information about the water column to create a range-independent average sound speed field and to model internal wave activity. This allows subtracted transmission loss fields created by subtracting the "tilt" transmission loss from the "total" transmission loss to be relevant. The premise here is that variation in a received acoustic signal that is not consistent with what is predicted by an internal wave model may be due to spice.

When creating delta transmission loss plots in Chapter 5, six-kilometer sections were used, with the first five kilometers identical. This scenario was intended to emphasize the fact that, though small differences in the sound speed field close to the source may have very large effects on the resultant acoustic field, spice is still an important factor far from the source. A sound speed
field where spice is present only five kilometers and farther from the source is of course unrealistic, so the approach from the previous chapter is abandoned here. Instead, a straightforward comparison between two six-kilometer fields is used.

6.2 Full Field Average

A simple way of quantifying the effect of spice on propagation is to define a single number to describe the amount of spice variation in a sound speed field and another single number to define the resulting change in predicted transmission loss and look for a correlation between the two. The metrics chosen are RMS spice variation as described in Section 4.4.3.1 and an average of the absolute value of the difference in total and tilt loss. Total minus tilt is chosen because, as mentioned in Section 3.5, it is presumed to be a more accurate representation of the actual impact of spice than spice minus averaged, since the spice features are left at their actual depths, without the vertical movement required to remove internal waves. Examples of the two fields used to calculate these metrics are shown in Figure 6.1. Figure 6.2 shows the resulting scatter plot using the thirteen CTD sections defined in Chapter 4. As expected, there is a distinct positive correlation. The correlation is also very clearly frequency dependent, with higher frequencies more strongly affected by spice.

For the 100 Hz simulations, and all but two of the 300 Hz simulations, the mean effect of spice on the acoustic field was below 1 dB. At the upper end of the frequency range, all spice had at least a 3 dB mean effect on every section at 5000 Hz. These results indicate that higher-frequency sources, perhaps 1000 Hz and above, may be best suited to studying spice using acoustics, while a researcher who wishes to ignore the effects of spice, especially in an environment such as the East China Sea, where spice is extremely prevalent, should use frequencies 300 Hz and below.

6.3 Spatial Filtering and Local Averages

To achieve a more detailed idea of how spice affects acoustic propagation, point by point correlations of the spice and acoustic fields are calculated. Spatial filters of various bandwidths are also applied to both fields in order to compare the correlation at various scales. Because the spice anomaly fields are calculated from data which has had internal waves removed, the sound speed difference between the total and tilt fields is used instead to ensure that the environmental data is spatially matched to the delta transmission loss field, which is also calculated using the total and tilt sound speed fields at 300 Hz.

The effect of spice on a particular point in the acoustic field is of course not related only to the corresponding point in the sound speed field, but to all the points preceding it. For that reason, the correlations are not expected to be particularly strong. The goal of this analysis was to identify a characteristic in the transmission loss field which could be used to recognize the influence of spice in experimental data. It was thought that a spatial scale might be found which best fits the variation in the acoustic field due to spice.
Figure 6.1: Examples of the two types of figures used to examine the connection between the amount of spice in a sound speed field and its effect on transmission loss.

Figure 6.3 shows the filtered sound speed difference and transmission loss difference plots for two different data sections and scales. Visually, the correlation is difficult to define. The correlation can be described mathematically by first plotting a point by point comparison between the two fields, as shown in Figure 6.4. The closeness of the correlation can be quantified by performing a linear regression analysis, as illustrated by the line plotted over the scatter plot.

Two statistics are used to describe the correlations, the correlation coefficient and the p-value. The correlation coefficient, usually represented by R, measures the linear dependence between
Figure 6.2: Scatter plot of spice content versus effect on transmission loss. Spice values (X axis) are the RMS value of all points in a figure such as Figure 6.1a, while delta TL values are the mean of all points in a figure such as Figure 6.1b. The trend lines are added as a visual aid.

two variables. It is calculated using the formula

\[ R = \frac{1}{n-1} \sum_{i=1}^{n} \left( \frac{X_i - \bar{X}}{s_X} \right) \left( \frac{Y_i - \bar{Y}}{s_Y} \right), \]  

(6.1)

where \( n \) is the number of data points, \( X_i \) and \( Y_i \) are individual values of \( X \) and \( Y \), \( \bar{X} \) and \( \bar{Y} \) are the means of \( X \) and \( Y \), and

\[ s_x = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{X})^2}. \]  

(6.2)

A value of \( R = 1 \) indicates a perfect linear correlation with a positive slope, \( R = -1 \) indicates a perfect linear correlation with a negative slope, and \( R = 0 \) means that there is no correlation. Other values of \( R \) are difficult to interpret, but the further from zero \( R \) is, the more strongly correlated the data is.

The p-value has a much more complicated derivation (which will not be reproduced here), but it is easier to interpret. It indicates the theoretical probability that values that are randomly generated using a Gaussian distribution will be at least as correlated as the data. A common
(a) Band-pass filtered (858-1000 m) and averaged sound speed difference

(b) Band-pass filtered (858-1000 m) and averaged sound speed differences

(c) Band-pass filtered (541-631 m) and averaged sound speed difference

(d) Band-pass filtered (541-631 m) and averaged sound speed differences

Figure 6.3: Pixel plots for sound speed difference and transmission loss difference (total field minus tilt field) which are used for correlation analysis.

Several spatial band-pass filters as described in Section 4.4.3.4 are applied. In this case, 30 bands spanning wavelengths from 10 meters to 1 kilometer are used to allow for a clearer picture of any trends, and because there is no intention to plot all 30 fields as in Figure 4.10. The filtered data is averaged into blocks 3 meters high and 1 kilometer long. Unlike the procedure used to create the pixel plots, the same length blocks are used for all bands, as the number of points in a correlation can affect the value of the correlation coefficient. These filtered and averaged fields are correlated point by point as shown in Figure 6.5 to create a correlation coefficient and a p-value. These two statistics are plotted as functions of wavelength in Figure 6.5.

Both metrics indicate that there is very little spatial correlation between spice and transmission loss. Both statistics vary wildly, with some p-values that approach one, and correlation benchmark is concluding that there is a significant correlation if p is less than 0.05.
coefficients which are often negative. As there is no physical reason for smaller differences in transmission loss to be caused by larger spice magnitudes, these correlations must be attributed to chance, meaning that similar-magnitude positive correlations are most likely also meaningless.

The lack of correlation does not mean that spice is not an important factor in acoustic propagation. As Figure 6.2 clearly shows, spice does have a direct effect on transmission loss. This analysis was an attempt to further define the correlation shown previously in order to find a way to identify the presence of spice acoustically. The results in this section merely show that this was not a useful way to do that. This was not unexpected, because as mentioned previously, the transmission loss at a particular range is influenced by the entire sound speed field between the receiver and that point. Further analysis should be done in which takes this cumulative effect into account.
Figure 6.5: Correlation statistics for sound speed and transmission loss differences as functions of filtering wavelength. Colored lines are individual data sections, and thick black lines are averages. Transmission loss is calculated at 500 Hz.
Chapter 7

Summary and Conclusions

7.1 Conclusions

Internal waves and thermohaline variability both have significant effects on acoustic propagation in the ocean, but the effects of internal waves are much better understood. This work used high-resolution towed CTD data, a process for separating internal wave and spicy variations, and both ray tracing and parabolic equation modeling to advance the understanding of the characteristics and distribution of spice in the shallow ocean and the ways in which it interacts with sound waves.

In the East China Sea, where the data used in this thesis were collected, the spice variation appeared to remain at a relatively constant level over the time and area where the data collection took place, despite the much more variable levels of internal wave activity. Assuming that the supposition that spice is created by internal waves is correct, it appears that the frequency of passage of internal waves and the rate of dissipation of intrusions are balanced to maintain a steady-state level of spice. Further analysis of variation in the spice variable revealed that spice activity is distributed over a large range of scales, from ten meters to kilometers, and it is irregularly distributed in both range and depth. In many (but not all) sections it is concentrated at two depths, generally around 15 and 25 meters.

Subtracting transmission loss fields calculated using the RAM parabolic equation model showed that total minus tilt and spice minus averaged gave very similar results. In other words, in examining the effect of spice on transmission loss using versions of a sound speed field with and without spice, internal waves can either be included in both fields or neither field, without greatly affecting the results. This finding served as validation for the tilt/spice decomposition process.

Further PE modeling showed a direct correlation between the magnitude of spice variation in the water column and the effect on transmission loss, an effect which grows more pronounced with increasing frequency. There is a considerable amount of variability in the transmission loss
data that is not accounted for merely by the amount of spice, indicating that other factors are also important. One possible example (most likely one of many) of such a factor is illustrated by the ray tracing results. These relatively simplistic models showed that in a strongly downward refracting environment such as the one where TAVEX took place, a relatively weak intrusion low in the water column can have a greater effect on the received signal than a stronger intrusion closer to the mixed layer since shallower-angled rays which only interact with the lower intrusion will be stronger when they reach the receiver.

Finally, point-by-point correlations of the effects of spice on sound speed and transmission loss fields were calculated in the hope that they might reveal a spatial scale which might be used to identify the presence of spice using acoustic data. Unfortunately, no such signature was found. Although the more ambitious goals of comparing a propagation model with the TAVEX acoustic data and identifying a metric by which spice could be recognized acoustically were not accomplished, significant progress was made toward these ends. Several methods of characterizing the complexity of spice were suggested, which allow for detailed comparisons between different sections of towed CTD data. It was also shown that the impact of spice on sound propagation is equally complex, and dependent on the magnitude of the spice variation, the depth of dominant spice features, and the acoustic frequency used. Other important influences are likely but have yet to be explored.

7.2 Suggestions for Future Work

Since the effect of spice on sound propagation is a largely unexplored area, there are many opportunities for further work in this area, both using the TAVEX data and by taking additional measurements which could be even better suited to this analysis. Using the TAVEX data, the analysis presented in Chapter 6 should be continued, taking into account the cumulative effect of the sound velocity field on transmission loss to look for an identifiable characteristic of spice in the acoustic field. One approach could be to calculate the correlation coefficient or p-value as a function of range, perhaps using ray tracing analysis to identify the most important ranges to examine.

A further logical step following the work presented here would be to model propagation through thermohaline intrusions in a way that could be readily compared with the acoustic data collected by NRL. This clearly requires modeling over distances of 34 or 20 kilometers, in order to match the conditions of the experiment. It would probably also be necessary to find a way to realistically recreate representative spice content (something that is already relatively common practice for both linear and nonlinear internal waves), since the tow data only includes one data section along each acoustic axis, and sound speed fields which vary over time are necessary to study the resulting variation in an acoustic signal. A further complication is that the longest section is contaminated by uncompensated spice activity that creates problems in the separation process. Even better than creating representative static intrusions would be to model the how the intrusions move and develop over time, but that would most likely require data that showed
the three-dimensional shapes of the intrusions and followed them over time, and the TAVEX
tows only provide an instantaneous (in the sense that each point in space is only measured at
one time), two-dimensional picture of any particular intrusion.

A more theoretical avenue, and one which could improve the results of the analyses presented
in this thesis and those suggested above, would be further development of the tilt and spice
separation process to deal with uncompensated intrusions. In its current form, this process
ignores these intrusions, resulting in their appearance in both tilt and spice sound speed fields,
often creating higher levels of variation in one or both fields than in the original sound speed
data. A comparison of the shapes of adjacent isopycnals might be helpful, since internal waves
generally bend several isopycnals into a similar shape, while uncompensated intrusions cause more
erratic distortions. Another possible method could involve a comparison between temperature
and salinity contours, since internal waves will push both in the same direction, compensated
intrusions will push them in opposite directions (assuming the mean salinity and temperature
gradients are both gravitationally stable), and uncompensated intrusions result in uncorrelated
or partially correlated disturbances.

Additional experimental work that could be useful would be studies similar to TAVEX in
other areas of the world, which could be used collectively to explore the relationship between
internal waves and spice (i.e. how directly is the level of spice variation in a region related to the
amount of internal wave activity?). Since internal waves are much easier to measure, and have
been studied much more extensively in the past, this information could help predict how much
of an effect spice will have on sound transmission in a certain area without the need for detailed
measurements to characterize the spice in that region. Several improvements could be made to
the TAVEX setup to produce data even better suited to studying spice, such as taking CTD
measurements (either moored or towed) at shallower depths to give a more complete picture of
spice in the mixed layer, and towing over the same area multiple times in order to measure the
stability of intrusions over time.

An experiment could also be designed to get an even more complete picture of how intrusions
form and decay. Ideally, such an experiment would take place in an area with a very weak current
and where internal waves occur very rarely, so that the spice created by one can be observed
undisturbed for several months as it develops and decays. Periodic towed CTD measurements
should be used to record detailed water column data similar to the data in TAVEX while using
moored or drifting CTD arrays to track the development of the intrusions. Acoustic measure-
ments should also be made periodically at a variety of frequencies to study the acoustic impact
of the spice as it changes over time.

Spice is a very complicated topic which needs much more research in order to be understood
as well as internal waves, from both acoustic and oceanographic standpoints. The work presented
in this thesis provides a step in that direction.
Appendix A

Spice Distribution in All 13 Tow Sections

A.1 Introduction

Figures 4.9 and 4.10 show several ways of looking at the spice content of a section of CTD data. These plots are all valuable in understanding the ways in which spice varies as a function of range, depth, and scale. To further reinforce the amount of variation that spice displays, and for the sake of completeness, the same plots are presented here for all 13 tow sections.

A.2 Figures
Figure A.1: Several ways of displaying the spice in Section C1
Figure A.2: Spectrum Pixel Plots for section C1 (see Figure 4.7a)
Figure A.3: Several ways of displaying the spice in Section C2
Figure A.4: Spectrum Pixel Plots for section C2 (see Figure 4.7a)
Figure A.5: Several ways of displaying the spice in Section C3
Figure A.6: Spectrum Pixel Plots for section C3 (see Figure 4.7a)
(a) Left: Sound speed and average profile. Right: Sound speed with superimposed isopycnals. (Color scales in m/s)

(b) Left: Spice sound speed. Right: Relative spice values. (Color scales in m/s)

(c) Left: Spectrum of spice fluctuations as a function of range. Right: Spectrum of spice fluctuations as a function of depth. (Color scales in dB re: 1(kg/m³)²)

Figure A.7: Several ways of displaying the spice in Section IW1
Figure A.8: Spectrum Pixel Plots for section IW1 (see Figure 4.7a)
(a) Left: Sound speed and average profile. Right: Sound speed with superimposed isopycnals. (Color scales in m/s)

(b) Left: Spice sound speed. Right: Relative spice values. (Color scales in m/s)

(c) Left: Spectrum of spice fluctuations as a function of range. Right: Spectrum of spice fluctuations as a function of depth. (Color scales in dB re: 1(kg/m$^3$)$^2$)

Figure A.9: Several ways of displaying the spice in Section IW3
Figure A.10: Spectrum Pixel Plots for section IW3 (see Figure 4.7a)
(a) Left: Sound speed and average profile. Right: Sound speed with superimposed isopycnals. (Color scales in m/s)

(b) Left: Spice sound speed. Right: Relative spice values. (Color scales in m/s)

(c) Left: Spectrum of spice fluctuations as a function of range. Right: Spectrum of spice fluctuations as a function of depth. (Color scales in dB re: 1(kg/m$^3$)$^2$)

Figure A.11: Several ways of displaying the spice in Section IW5
Figure A.12: Spectrum Pixel Plots for section IW5 (see Figure 4.7a)
Figure A.13: Several ways of displaying the spice in Section IW6

(a) Left: Sound speed and average profile. Right: Sound speed with superimposed isopycnals. (Color scales in m/s)

(b) Left: Spice sound speed. Right: Relative spice values. (Color scales in m/s)

(c) Left: Spectrum of spice fluctuations as a function of range. Right: Spectrum of spice fluctuations as a function of depth. (Color scales in dB re: $1/(kg/m^3)^2$)
Figure A.14: Spectrum Pixel Plots for section IW6 (see Figure 4.7a)
Figure A.15: Several ways of displaying the spice in Section T1a
Figure A.16: Spectrum Pixel Plots for section T1a (see Figure 4.7a)
(a) Left: Sound speed and average profile. Right: Sound speed with superimposed isopycnals. (Color scales in m/s)

(b) Left: Spice sound speed. Right: Relative spice values. (Color scales in m/s)

(c) Left: Spectrum of spice fluctuations as a function of range. Right: Spectrum of spice fluctuations as a function of depth. (Color scales in dB re: 1(kg/m³)²)

Figure A.17: Several ways of displaying the spice in Section T1b
Figure A.18: Spectrum Pixel Plots for section T1b (see Figure 4.7a)
(a) Left: Sound speed and average profile. Right: Sound speed with superimposed isopycnals. (Color scales in m/s)

(b) Left: Spice sound speed. Right: Relative spice values. (Color scales in m/s)

(c) Left: Spectrum of spice fluctuations as a function of range. Right: Spectrum of spice fluctuations as a function of depth. (Color scales in dB re: \(1\,\text{kg/m}^3\)^2)

Figure A.19: Several ways of displaying the spice in Section T1c
Figure A.20: Spectrum Pixel Plots for section T1c (see Figure 4.7a)
(a) Left: Sound speed and average profile. Right: Sound speed with superimposed isopycnals. (Color scales in m/s)

(b) Left: Spice sound speed. Right: Relative spice values. (Color scales in m/s)

(c) Left: Spectrum of spice fluctuations as a function of range. Right: Spectrum of spice fluctuations as a function of depth. (Color scales in dB re: 1/(kg/m³)²)

Figure A.21: Several ways of displaying the spice in Section T2a
Figure A.22: Spectrum Pixel Plots for section T2a (see Figure 4.7a)
Figure A.23: Several ways of displaying the spice in Section T2b
Figure A.24: Spectrum Pixel Plots for section T2b (see Figure 4.7a)
Figure A.25: Several ways of displaying the spice in Section T2c.
Figure A.26: Spectrum Pixel Plots for section T2c (see Figure 4.7a)
Appendix B

MATLAB code

B.1 Introduction

Several MATLAB scripts that were written for this thesis are presented below.

B.2 Tilt/Spice Decomposition

This script decomposes a sound speed field into tilt, spice, and averaged fields, using any length filter for the temperature and salinity values, or an average value.

B.2.1 Description

First, the CTD data is interpolated onto a uniform grid. Next, isopycnals are traced using MATLAB’s contourf function. Isopycnals which do not extend across the entire length of the section or are not in order (density increasing with depth) are removed, as density inversions make it difficult to determine equilibrium depths, and it is impossible to calculate averages of properties over the entire length of the field for isopycnals that are short or not continuous. The data is then interpolated again to create data points whose depths are along the isopycnals but match the ranges of the original grid. To create the tilt, spice, and averaged fields, the temperature, salinity and depth values are replaced with average or filtered values as described in Chapter 3, and the top and bottom portions are filled using other techniques. The filter length can be specified as any value, including zero, which corresponds to using an average instead of a filter. The data points are then interpolated back onto the original uniform grid.

B.2.2 Code

```matlab

%%
%% tiltspicedecomp_filtered
```
Decompose towed CTD data into tilt and spice—low pass filter T and S for tilt field, or use average value.

```
clear
cle
close all

sec = 68:70;          % Sections to use
name = 'IW6';        % Name for file
CO = 0;              % [m] Filter cutoff length, 0 = use avg. (no filter)

TX.ymin = 10;        % [m] TAVEX max depth
TXymax = 50;        % [m] TAVEX max depth
TX.xmin = 500;       % min range (m) — avoid extrapolation issues at edge
TX.xmax = 6500;      % TAVEX track 3 km length (m) individual tows % ASA—2013
TX.dx = 3.67;        % TAVEX range sample rate (m) % ASA—2013
TX.dy = 1;           % TAVEX depth sample rate (m)

pathstart = 'E:\CLARE\CTDprocessing\towedCTD_processed\';

% Range and depth vectors to use
r = (TX.xmin:TX.dx:TX.xmax);  
d = (TX.ymin:TX.dy:TX.ymax) ';

% Interpolate from tow data
pathname = 'E:\CLARE\CTDprocessing\towedCTD_processed\filtered\';
[S, rho, pdens, c, T, dgrid, rgrid, wd] = CTDinterpMulti(sec, d, r);
  r = rgrid(1,:);
  d = dgrid(:,1);
  numberofsamples = length(r);

isopyc_vals = mean(pdens,2);              % Use mean density at each depth value to
  % get evenly spaced points
isopyc_vals = isopyc_vals(2:end-1);
mono = [false; isopyc_vals(2:end)<=isopyc_vals(1:end-1)];

while sum(mono)>0
    isopyc_vals(mono) = []; mono = [false; isopyc_vals(2:end)<=isopyc_vals(1:end-1)];
end

nisopycs = length(isopyc_vals);  \% Number of isopycnals for calculations

% Calculate isopycnals
figure
isopycs = contourf(r,d,pdens,isopyc_vals);
close
\% axis ij

% Create matrix of isopycnal depths and corresponding range values--
% intentionally large because required size is unknown
pdensities = nan(nisopycs,1);
isopyc_depths = nan(nisopycs,10000);
isopyc_xvals = nan(nisopycs,10000);
start = 1;

% Define limits for cropping extraneous portions of contour lines
xmin = max(r(:,1)); xmax = min(r(:,end));
zmax = min(d(end,:));
maxpoints = 0;

% Extract locations of isopycnals from contourf output.
for ii = 1:nisopycs
    npoints = isopycs(2,start);  \% Number of points in isopycnal
    if npoints > maxpoints; maxpoints = npoints; end
    pdensities(ii)=isopycs(1,start);  \% Potential density of isopycnal
    next = 1;
    \% Reject points that are outside the defined limits
    for jj = 1:npoints
        x0 = isopycs(1,start+jj);
\[ z_0 = \text{isopycs}(2, \text{start}+jj); \]

\[
\text{if } x_0 > x_{\text{min}} \&\& x_0 < x_{\text{max}} \&\& z_0 < z_{\text{max}} \text{ \\
  isopyc}\_\text{depths}(ii, \text{next}) = z_0; \text{ \\
  isopyc}\_\text{xvals}(ii, \text{next}) = x_0; \text{ \\
  next = next +1; \text{ \\
  end \text{ \\
  end \text{ \\
  start = start + npoints + 1; \text{ \\
  end} \text{|}}} \]

% Delete unused portions of isopycnal depth and range matrices

isopyc\_depths(:, maxpoints+1:end) = []; isopyc\_xvals(:, maxpoints+1:end) = [];

meandepths = nanmean(isopyc\_depths, 2); % Mean depth of each isopycnal

% Get rid of isopycnals that don't exist

nandepths = isnan(meandepths); nancols = isnan(nansum(isopyc\_xvals)); nisopycs = nisopycs - sum(nandepths); pdensities(nandepths) = []; meandepths(nandepths) = []; isopyc\_depths(nandepths,:) = []; isopyc\_xvals(nandepths,:) = [];

% figure

% plot(isopyc\_xvals', isopyc\_depths'); % axis ij

% Get rid of short and noncontinuous isopycnals

% Short is defined as less than 95% of the full range of the field
% short = (max(isopyc\_xvals,[]), 2) - min(isopyc\_xvals,[]), 2)) < 0.95*(max(r) - min(r));

X = isopyc\_xvals;

[x1, x2] = find(~isnan(X));

xend = X(sub2ind(size(X), unique(x1), accumarray(x1, x2, [], @max)));

short = abs(xend - isopyc\_xvals(:, 1)) < 0.95*(max(r) - min(r));

mins = nanmin(isopyc\_depths, [], 2);

maxes = nanmax(isopyc\_depths, [], 2);


% Broken isopycnals run into the top or bottom of the field
broken = mins == TX.ymin | maxes == TX.ymax;

pdensities(short | broken) = []; meandepths(short | broken) = []; isopyc_depths(short | broken,:) = []; isopyc_xvals(short | broken,:) = []; nisopycs = nisopycs-sum(short | broken);

% Make sure the potential density values increase monotonically with depth
% Delete isopycnals that are non monotonic
mono = [false; pdensities(2:end) <= pdensities(1:end-1)];

while sum(mono)>0
    pdensities(mono) = []; meandepths(mono) = []; nisopycs = nisopycs-sum(mono);
    mono = [false; pdensities(2:end) <= pdensities(1:end-1)];
end

figure
plot(isopyc_xvals', isopyc_depths'); axis ij

% Placeholders for filtered temperature, salinity, and sound speed values
S_filt = nan(nisopycs, numberofsamples);
T_filt = nan(nisopycs, numberofsamples);
c_filt = nan(nisopycs, numberofsamples);

% Placeholders for depth, temperature, and salinity values along isopycnals
isoz = nan(nisopycs, numberofsamples);
isoS = nan(nisopycs, numberofsamples);
isoT = nan(nisopycs, numberofsamples);

N = round(CO/TX.dx); % Number of points to use in filter
% Filter coefficients
B = hanning(N);  
B = B/sum(B);  
A = 1;

% Extra points to add to beginning and end for filter
p = ceil(N/2);

for nn = 1:nisopycs
  % Salinity and Temp. values at each point on isopycnal
  Nreal = sum(~isnan(isopyc_xvals(nn,:)));  
  S_temp = interp2(r,d,S,isopyc_xvals(nn,1:Nreal),isopyc_depths(nn,1:Nreal));  
  T_temp = interp2(r,d,T,isopyc_xvals(nn,1:Nreal),isopyc_depths(nn,1:Nreal));

  % Interpolate T, S, and z to match r
  isoz(nn,:) = interp_special(isopyc_xvals(nn,1:Nreal),isopyc_depths(nn,1:Nreal),r,'linear');  
  isoz(nn,isnan(isoz(nn,:))) = interp_special(isopyc_xvals(nn,1:Nreal),isopyc_depths(nn,1:Nreal),r(isnan(isoz(nn,:))),'nearest','extrap');  
  isoS(nn,:) = interp_special(isopyc_xvals(nn,1:Nreal),S_temp,r,'linear');  
  isoS(nn,isnan(isoS(nn,:))) = interp_special(isopyc_xvals(nn,1:Nreal),S_temp,r(isnan(isoS(nn,:))),'linear','extrap');  
  isoT(nn,:) = interp_special(isopyc_xvals(nn,1:Nreal),T_temp,r,'linear');  
  isoT(nn,isnan(isoT(nn,:))) = interp_special(isopyc_xvals(nn,1:Nreal),T_temp,r(isnan(isoT(nn,:))),'nearest','extrap');

if CO == 0
  % Use average values instead of filter
  Sf = mean(isoS(nn,:))*ones(1,length(r));
  Tf = mean(isoT(nn,:))*ones(1,length(r));
else
  % Apply filter
  Sf = filter(B,A,[isoS(nn,1)*ones(1,p) isoS(nn,:) isoS(nn,end)*ones(1,p)]);
end
\[
T_f = \text{filter}(B,A,[\text{isot}(\text{nn},1) \ast \text{ones}(1,p) \\text{isot}(\text{nn},:) \\text{isot}(\text{nn},\text{end}) \ast \text{ones}(1,p)]);
\]

\[
\text{end}
\]

\[
\text{Sfilt}(:,:,\text{end}) = \text{Sfilt}(2p+1:);\
\text{Tfilt}(:,:,\text{end}) = \text{Tfilt}(2p+1:);
\]

% Plot temperature, salinity, and depth for any isopycnals
% if nn == nn
% figure
% subplot(3,1,1)
% plot((ipyeval(:,:,1:Nreal)-r(1))/1000, S_temp)
% hold on
% plot((r-r(1))/1000, Sfilt(:,:,\text{end}), 'c', 'LineWidth', 1.5)
% ylabel('Salinity [PSU]')
% subplot(3,1,2)
% plot((ipyeval(:,:,1:Nreal)-r(1))/1000, T_temp)
% hold on
% plot((r-r(1))/1000, Tfilt(:,:,\text{end}), 'c', 'LineWidth', 1.5)
% ylabel('Temp. [\degree C]')
% subplot(3,1,3)
% plot((ipyeval(:,:,1:Nreal)-r(1))/1000, isopyc_depths(nn ,1:Nreal), (r-r(1))/1000, isoz(nn ,:))
% hold on
% line([0 max(r)-min(r)]/1000,[mean(isoz(nn,:),mean(isoz(nn ,:))], 'Color', 'green', 'LineWidth', 1.5)
% axis ij
% xlabel('Range [m]')
% ylabel('Depth [m]')
% end

% Sfilt = repmat(mean(isoS),1,length(isoS));
% Tfilt = repmat(mean(isoT),1,length(isoT));

% Range matrix to correspond to isopycnal values
isor = ones(nisopycs,1)*r;

% Create grids of temperature and salinity values in range and density to
% fill in top and bottom of tilt field

% Isopycnal values with densities added to cover deleted isopycnals at top
% and bottom of field
rhogrid = [min(pdens(:)):isopyc_vals(2)−isopyc_vals(1):min(isopyc_vals)...
    isopyc_vals(2:end−1)'
    max(isopyc_vals):isopyc_vals(end−1):max(pdens(:))'];

Rtot = r(end) − r(1); % Total length of section
deg = 4; % Degree of polynomial to use

% Use a polynomial fit to create S vs rho and T vs rho profiles. One
% profile for no filter, several (one for each section of length CO)
% for
% filter
if CO == 0

% Polynomial fits
[polyS, ~, muS] = polyfit(pdens(:,S(:,),deg);
[polyT, ~, muT] = polyfit(pdens(:,T(:,),deg);

% Centering and scaling transformation
pdhatS = (rhogrid−muS(1))/muS(2);
pdhatT = (rhogrid−muT(1))/muT(2);

% Evaluate polynomials at density grid points
St = polyval(polyS, pdhatS);
Tt = polyval(polyT, pdhatT);

else

Nsec = round(Rtot/CO); % Sections to divide field into
lsec = floor(numberofsamples/Nsec); % Number of points per section
rsec = zeros(1, Nsec); % Corresponding ranges

St = zeros(length(rhogrid), Nsec+2);
\[ T_t = \text{zeros(length(rhogrid), Nsec+2)}; \]

\begin{verbatim}
for mm = 0:Nsec+1
    if mm == 0
        Ssec = S(:,1:floor(lsec/2));
        Tsec = T(:,1:floor(lsec/2));
        zsec = dgrid(:,1:floor(lsec/2));
        rhosec = pdens(:,1:floor(lsec/2));
    elseif mm == Nsec+1
        Ssec = S(:,end-floor(lsec/2):end);
        Tsec = T(:,end-floor(lsec/2):end);
        zsec = dgrid(:,end-floor(lsec/2):end);
        rhosec = pdens(:,end-floor(lsec/2):end);
    else
        Ssec = S(:,(mm-1)*lsec+1:mm*lsec);
        Tsec = T(:,(mm-1)*lsec+1:mm*lsec);
        zsec = dgrid(:,(mm-1)*lsec+1:mm*lsec);
        rhosec = pdens(:,(mm-1)*lsec+1:mm*lsec);
        rsec(mm) = mean([r((mm-1)*lsec+1) r(mm*lsec)]);
    end

    % Polynomial fits
    [polyS, ~, muS] = polyfit(rhosec(:,), Ssec(:,), deg);
    [polyT, ~, muT] = polyfit(rhosec(:,), Tsec(:,), deg);

    % Centering and scaling
    pdhatS = (rhogrid-muS(1))/muS(2);
    pdhatT = (rhogrid-muT(1))/muT(2);

    % Evaluate polynomials at rhogrid points
    St(:,mm+1) = polyval(polyS, pdhatS);
    Tt(:,mm+1) = polyval(polyT, pdhatT);
end
rsec = [r(1) rsec r(end)]; % Add ranges for half sections
[R, RHO] = meshgrid(rsec, rhogrid); % gridded range and density
end
\end{verbatim}
rhos = mean(pdens,2);  % Average density to use for spice

% Calculate Spice Field
z_spice = mean(izo,2)*ones(1,numberofsamples);

% Interpolate using spice depth (average isopycnal depth)
S_int_s = scatteredInterpolant(isor(:), z_spice(:), isoS(:), 'linear', 'none');
T_int_s = scatteredInterpolant(isor(:), z_spice(:), isoT(:), 'linear', 'none');

S_spice = S_int_s(rgrid, dgrid);
T_spice = T_int_s(rgrid, dgrid);

% Calculate sound speed and density
c_spice = unesco(S_spice, T_spice, dgrid);
rho_spice = waterdens(S_spice, T_spice, dgrid);

% Points outside the average depths of the continuous isopycnals
top = d < min(z_spice(:));
bottom = d > max(z_spice(:));
extrapA = top | bottom;
extrapS = logical(extrapA*ones(1,length(r)));
extrapA = find(extrapA);  % Indices for some points as extrapS

% Calculate second field by using new depth for each point. Use this
% outside the avg. depth of the continuous isopycnals

% Find new depth for each point based on avg. density vs. depth
z2 = interp1(rhos, d, pdens, 'linear', 'extrap');

% Re-interpolate with new depth
S_int_s2 = scatteredInterpolant(rgrid(:), z2(:,), S(:));
T_int_s2 = scatteredInterpolant(rgrid(:), z2(:,), T(:));

S_spice2 = S_int_s2(rgrid, dgrid);
T_spice2 = T_int_s2(rgrid, dgrid);
c_spice2 = unesco(S_spice2, T_spice2, dgrid);
rho_spice2 = waterdens(S_spice2, T_spice2, dgrid);
% Use second field to fill in extrapolated portions of first field

```matlab
c_spice(extrapS) = c_spice2(extrapS);
S_spice(extrapS) = S_spice2(extrapS);
T_spice(extrapS) = T_spice2(extrapS);
rho_spice(extrapS) = rho_spice2(extrapS);
pdens_spice = waterdens(S_spice, T_spice, zeros(size(S_spice)));
```

% Plot spice field
```
figure
contourf(r/1000, d, c_spice, 1490:2:1540)
axis ij
title('Spice Sound Speed')
colorbar
caxis([1490 1540])
```

% Calculate Tilt Field

```matlab
% Interpolate using filtered T and S values
S_int_t = scatteredInterpolant(isor(:), isoz(:), S_filt(:), 'linear', 'none');
T_int_t = scatteredInterpolant(isor(:), isoz(:), T_filt(:), 'linear', 'none');
S_tilt = S_int_t(rgrid, dgrid);
T_tilt = T_int_t(rgrid, dgrid);

% Find extrapolated points
```
```
top = dgrid < ones(length(d),1)*isoz(1,:);
bottom = dgrid > ones(length(d),1)*isoz(end,:);
extrapT = top | bottom;
```
```
% Fill in extrapolated points using polynomial fits
if CO == 0
    S_tilt(extrapT) = interp1(rhogrid, St, pdens(extrapT), 'linear', 'extrap');
    T_tilt(extrapT) = interp1(rhogrid, Tt, pdens(extrapT), 'linear', 'extrap');
else
    S_int_t2 = scatteredInterpolant(R(:), RHO(:), St(:));
    T_int_t2 = scatteredInterpolant(R(:), RHO(:), Tt(:));
```
```
S_tilt(extrapT) = S_int_t2(rgrid(extrapT), pdens(extrapT));
T_tilt(extrapT) = T_int_t2(rgrid(extrapT), pdens(extrapT));
end

% Calculate sound speed and density
ctilt = unesco(S_tilt, T_tilt, dgrid);
rho_tilt = waterdens(S_tilt, T_tilt, dgrid);

% Plot tilt field
figure
contourf(r/1000,d,ctilt,1490:2:1540)
axis ij
title('Tilt Sound Speed')
colorbar
caxis([1490 1540])

% Calculate Averaged Field

% Interpolate using average isopyncal depths and filtered T and S
S_int_a = scatteredInterpolant(isor(~isnan(z_spice)), z_spice(~isnan(z_spice)), S_filt(~isnan(z_spice)), 'linear', 'none');
T_int_a = scatteredInterpolant(isor(~isnan(z_spice)), z_spice(~isnan(z_spice)), T_filt(~isnan(z_spice)), 'linear', 'none');

S_avg = S_int_a(rgrid, dgrid);
T_avg = T_int_a(rgrid, dgrid);

% Fill in top and bottom by averaging or filtering the spice field
for kk = extrapA'
  if CO == 0
    S_avg(kk,:) = mean(S_spice(kk,:))*ones(1,length(S_spice));
    T_avg(kk,:) = mean(T_spice(kk,:))*ones(1,length(S_spice));
  else
    SfiltA = filter(B,A,[S_spice(kk,1)*ones(1,p) S_spice(kk,:)]);
    TfiltA = filter(B,A,[T_spice(kk,1)*ones(1,p) T_spice(kk,:)]);
    S_avg(kk,:) = SfiltA(2*p+1:end);
    T_avg(kk,:) = TfiltA(2*p+1:end);
  end
end
end

end

% Calculate sound speed and density
c_avg = unesco(S_avg, T_avg, dgrid);
rho_avg = waterdens(S_avg, T_avg, dgrid);

% Plot averaged field
figure
contourf(r/1000,d,c_avg,1490:2:1540)
axis ij
title('Averaged Sound Speed')
colorbar
caxis([1490 1540])

% Plot total field
figure
contourf(r/1000,d,c,1490:2:1540);
axis ij
title('Total Sound Speed')
colorbar
caxis([1490 1540])

c = flipr(c);
c_tilt = flipr(c_tilt);
c_spice = flipr(c_spice);
c_avg = flipr(c_avg);
rho = flipr(rho);
rho_tilt = flipr(rho_tilt);
rho_spice = flipr(rho_spice);
rho_avg = flipr(rho_avg);
S = flipr(S);
S_tilt = flipr(S_tilt);
S_spice = flipr(S_spice);
S_avg = flipr(S_avg);
T = flipr(T);
T_tilt = flipr(T_tilt);
T_spice = flipr(T_spice);
T_avg = flipr(T_avg);
% Save new sound speed fields
save(pathname name ' . mat' , ' c' , ' c_tilt' , ' c_spice' , ' c_avg' ,... 
   'rho' , ' rho_tilt' , ' rho_spice' , ' rho_avg' ,... 
   'S' , ' S_tilt' , ' S_spice' , ' S_avg' ,... 
   'T' , ' T_tilt' , ' T_spice' , ' T_avg' , ' r' , ' d');

% clearvars -except pathname name
load( [ pathname name ' . mat' ] );

B.3 RAM Run Definition

This script uses profiles of sound speed, density, depth, and range to produce a run definition that can be used by RAM as run using AcTUP.

B.3.1 Description

The script first reads a file created by tiltspicedecomp_filtered, which contains sound speed, density, range and depth data for a tilt, spice, total, and averaged field. Values for the isovelocity layers above and below the data are calculated using averages from the total field (so that comparisons between the results are not affected by differing sound speeds outside the range of the data). For each range, an array of layer objects (defined in the AcTUP source code) is created containing sound speed and density data for the water column and seabed. The layer objects are combined to create an environment object, and environment objects from each range are combined to create an environment array object. The environment array object is saved as a .mat file.

Because AcTUP can only accept up to 100 bathymetry points, a bathymetry file must also be created. This is simply a text file which lists ranges and water depths. Since all environments used in this thesis were defined to have a flat bottom at 75 meters depth, this file is very small.

B.3.2 Code

% % RAMfield.m % % Clare Nadig % 11/11/2014 % % Create a run definition for RAM using a tilt, spice, total, or averaged % field
clear all
clc
close all

% File(s) to use
[fn, pn] = uigetfile ('E:\CLARE\CTDprocessing\towedCTD_processed\newspice\*.mat',... 'MultiSelect','on');
type = inputdlg('Field\Type');
type = type{1};
savepath = 'E:\CLARE\CMST_Software\AcTUP_v2.2L\AcTUP\RunDef\newspice\';
freq = [1000 5000];

% Add AcTup functions to path
addpath ('E:\CLARE\CMST_Software\AcTUP_v2.2L\AcTUP\Source ')

res = 0.1; % Range resolution desired
dmin = 14; % [m] Minimum depth of CTD data to use
dmax = 49; % [m] Maximum depth of CTD data to use

% Loop through desired environments
for jj = 1:length(fn);

% Delete file extension
k = strfind(fn{jj}, '.mat');
sec = fn{jj}{1:k-1};
secname = [sec type '1000'];
load ([pn sec]);

% Get rid of data outside of 14-49 meters depth
[~,dd1] = min(abs(d-dmin));
[~,dd2] = min(abs(d-dmax));

final_ranges = (r-r(1))/1000;
final_depths = d(dd1:dd2);
n = length(final_ranges);
Use correct sound speed and density

switch type
  case 'Total'
    final_ss = c(dd1:dd2,:);
    final_rh = rho(dd1:dd2,:);
  case 'Tilt'
    final_ss = c_tilt(dd1:dd2,:);
    final_rh = rho_tilt(dd1:dd2,:);
  case 'Spice'
    final_ss = c_spice(dd1:dd2,:);
    final_rh = rho_spice(dd1:dd2,:);
  case 'Avg'
    final_ss = c_avg(dd1:dd2,:);
    final_rh = rho_avg(dd1:dd2,:);
  otherwise
    error('Invalid_Field_Type')
end

Flat bottom
waterdepth = 75;
final_waterdepth = waterdepth*ones(size(final_ranges));

Name and location to save the file
pathname = 'E:\CLARE\CMST_Software\AcTUP_v2.2L\AcTUP\RunDef\newspice\';
savefilename = [pathname secname];

Sound speed and density of isovelocity mixed layer: take from total
field so they match in all versions
mixed_ss = (mean(c(1,:))+std(c(1,:)))*[1;1];
mixed_rh = (mean(rho(1,:))-std(rho(1,:)))*[1;1];

Create bathymetry file—only 2 points needed for flat bottom
range = [final_ranges(1), final_ranges(end)]*1000;
depth = [final_waterdepth(1), final_waterdepth(end)];
bath = [range; depth];
fileID = fopen('E:\CLARE\CMST_Software\AcTUP_v2.2L\AcTUP\')
Bathymetry, secname '.bty', 'wt');
fprintf(fileID, '%u\n', length(range));
fprintf(fileID, '%6.4g\n', bath);
fclose(fileID);

% Create layers, environment, and environment array

% Sediment layers: outside loop because they are range-independent
% First sediment layer
Sed1Data.Name = 'Sediment_1';
Sed1Data.IsHalfSpace = 0;
Sed1Data.RMSRough = 0;
Sed1Data.Z = [0, 2.5];
Sed1Data.Cp = [1500, 1500];
Sed1Data.Cs = [];
Sed1Data.Rho = [1450, 1450];
Sed1Data.Ap = [0.2, 0.2];
Sed1Data.As = [];
sediment1 = AcLayer(Sed1Data);

% Second sediment layer
Sed2Data.Name = 'Sediment_2';
Sed2Data.IsHalfSpace = 0;
Sed2Data.RMSRough = 0;
Sed2Data.Z = [0, 9.5];
Sed2Data.Cp = [1580, 1580];
Sed2Data.Cs = [];
Sed2Data.Rho = [1850, 1850];
Sed2Data.Ap = [0.2, 0.2];
Sed2Data.As = [];
sediment2 = AcLayer(Sed2Data);

% Third sediment layer
Sed3Data.Name = 'Sediment_3';
Sed3Data.IsHalfSpace = 0;
Sed3Data.RMSRough = 0;
Sed3Data.Z = [0, 8];
Sed3Data.Cp = [1615, 1615];
Sed3Data.Cs = [];
Sed3Data.Rho = [1950, 1950];
Sed3Data.Ap = [0.2, 0.2];
Sed3Data.As = [];
sediment3 = AcLayer(Sed3Data);

% Fourth sediment (halfspace) layer
Sed4Data.Name = 'Sediment_3';
Sed4Data.IsHalfSpace = 1;
Sed4Data.RMSRough = 0;
Sed4Data.Z = 0;
Sed4Data.Cp = 1800;
Sed4Data.Cs = [];
Sed4Data.Rho = 2200;
Sed4Data.Ap = 0.2;
Sed4Data.As = [];
sediment4 = AcLayer(Sed4Data);

DirInfo = pathname; % Does not change

EnvArr = cell(1, length(final_ranges)); % Array of environments

% Loop through each range to create environment array
for ii = 1:length(final_ranges) % Top water layer (CTD data)
    Water1Data.Name = 'Water_Column';
    Water1Data.IsHalfSpace = 0;
    Water1Data.RMSRough = 0.92; % Average for whole experiment
    Water1Data.Z = [0; final_depths(1) - 2; final_depths; final_waterdepth(ii)];
    Water1Data.Cp = [mixed_ss; final_ss(:,ii); final_ss(end,ii)];
    Water1Data.Cs = [];
    Water1Data.Rho = [mixed_rho; final_rho(:,ii); final_rho(end, ii)];
    Water1Data.Ap = [];

    DirInfo = [DirInfo; water1Info];
    EnvArr{ii} = cell(1, length(Water1Data.Rho));
    for jj = 1:length(Water1Data.Rho)
        EnvArr{ii}(jj) = [Water1Data.Z(jj); Water1Data.Cp(jj); Water1Data.Cs(jj);
                        Water1Data.Rho(jj); Water1Data.Ap(jj)];
    end

    % Add water layers
endif
Water1Data.As = []; 

water1 = AcLayer(Water1Data);

%% Create environment object using the layers 
EnvData.Name = [secname, '_Environment', num2str(ii)]; 
EnvData.LayerArr = {water1, sediment1, sediment2,... sediment3, sediment4};

EnvObj = AcEnvironment(EnvData, DirInfo);

EnvArr{ii} = EnvObj;

end

%% Create Environment Array Object

EnvArrData.Name = secname;
EnvArrData.EnvArr = EnvArr;
EnvArrData.RangeVec = final.ranges*1000; % Convert ranges to meters
EnvArrData.dRInterp = 0;

Def.EnvArr = AcEnvArr(EnvArrData, DirInfo);
Def.Environment = EnvArr{1};
Def.RunID = {'RAMGeo'};
Def.Title = secname;
Def.Freq = freq;
Def.Zs = 64;
Def.Zr = 5:5:100;
Def.RMin = 10;
Def.RMax = max(final.ranges*1000);
Def.NRange = length(final.ranges)+1;
Def.dR = (Def.RMax-Def.RMin)/(Def.NRange-1);
Def.SubDir = 'newspice\';
Def.FPrefix = secname;
Def.ManualEnvEdit = 0;
Def.UseBathFile = 1;
Def.BathFName = ['E:\CLARE\CMST\Software\AcTUP\v2.2L\AcTUP\Bathymetry\' secname '.bty'];
Def. UseSurfFile = 0;
Def. SurfFName = "";
Def. LastFilename = savefilename;

Def. Help.Name = secname;
Def. Help.Range = [min(final_ranges) max(final_ranges)];

Def.RAM. Species = 'RAMGeo';
Def.RAM. zr = 5;
Def.RAM. dz_lambda = 0.05; /* lambda */
Def.RAM. dzgridmin = 0.2; /* Min OP grid depth */
Def.RAM. drgridmin = res;
Def.RAM. dr_dz = 2; /* Relative range resolution */
Def.RAM. zmplt = waterdepth + 5; /* Max depth for TL grid output [m] (-1 means used max environment depth) */
Def.RAM. c0 = 1500; /* Reference phase velocity */
Def.RAM. np = 6; /* Number of Pade Terms (max 10) */
Def.RAM. ns = 1; /* Number of stability constraints */
Def.RAM. rs = 0; /* Max range of stability constraints [m] (0 means full range) */
Def.RAM. irot = 0; /* ?? used for RAMSGeo */
Def.RAM. theta = 0; /* ?? used for RAMSGeo */
Def.RAM. LastLayerDz_Lambda = 10; /* Thickness of bottom layer, since RAM doesn’t support halfspaces */
Def.RAM. AttenLayerDz_Lambda = 10; /* Attenuation layer thickness */
Def.RAM. AttenLayerAttenPMax = 10; /* Attenuation layer max p-wave attenuation [db/lambda] */
Def.RAM. AttenLayerAttenSMax = 10; /* Attenuation layer max s-wave attenuation [db/lambda] */
Def.RAM. CsMin = 10; /* Min shear velocity in substrate [m/s] */

% Default values for Bellhop, Fields and Kraken — not used but AcTUP
% requires these fields to be present
Def.Bellhop.RunType = 'CB';
Def.Bellhop.NBeams = 161;
Def.Bellhop.StartAngle = -80;
Def.Bellhop.EndAngle = 80;
Def.Bellhop.StepSize = 0;
Def.Bellhop.UseBathyFile = Def.UseBathFile;
Def.Bellhop.BathyFName = Def.BathFName;

Def.Fields.GrnPathname = 'E:\CLARE\CMST.Software\AcTUP_v2.2L\AcTUP\Output\Default\Scooter&Fields';
Def.Fields.GrnFilename = secname;
Def.Fields.GrnBaseName = [Def.Fields.GrnPathname secname];
Def.Fields.rmin = 5;
Def.Fields.rmax = Def.RMax;
Def.Fields.nr = Def.NRange;

Def.Kraken.ExhaustiveSearch = true;

% Save file
save(savefilename, 'Def');
end

B.4 RAM loop

Although the AcTUP interface is very convenient for creating simple environments and for running RAM for individual run definitions, it can become quite tedious to run RAM many times for different run definitions through the interface. This script was created to circumvent the interface and run RAM directly, and to loop through any number of run definitions.

B.4.1 Description

The script starts by allowing the user to select any number of files to run, and then uses code taken from the AcTUP source code to run RAM for these definitions.

B.4.2 Code

% % RAMloop.m
%
% Clare Nadig
clear all
clc
close all

% Run RAM propagation code by looping through a batch of run definitions
% (circumvents AcTUP menu/UI)

\% Add AcTUP functions to path
addpath('E:\CLARE\CMST_Software\AcTUP\v2.2\AcTUP\Source')

\% Select files to run
[filenames, pathname] = uigetfile('E:\CLARE\CMST_Software\AcTUP\v2.2\AcTUP\RunDef\*.mat', ...
'MultiSelect', 'on');

Nf = length(filenames);

FALSE = 0;
TRUE = 1;

\% Run RAM: taken from AcToolboxFrontEnd in AcTUP source code
for jj = 1:Nf
tic
clearvars DirInfo ReleaseSpec file GroupName NFiles BaseName
    Status ErrStr
clear RunPropgnCode

\% Get directory info
DirInfo = GetAcDirectoryInfo;
ReleaseSpec = LoadReleaseSpec();
Def.EnvArr = AddSourcePaths(DirInfo);

\% Load next run definition file
\% file = ['partfile num2str(jj, '','%03u') ' .mat'];
[Def, FileOK] = LoadRunDefinition(DirInfo, [pathname filenames{jj}]);
%filenames\{jj\}\);

% Prepare to run RAM
FromFile = false;
APPENDFILE = false;
%Def.RAM.Species = Def.RunID\{1\};
%Def.Environment = SetDirInfo(Def.EnvArr, DirInfo);
Def.EnvArr = SetDirInfo(Def.EnvArr, DirInfo);
GroupName = BuildAndTestOutputDir(Def, DirInfo, ~FromFile);
NFiles = length(Def.Freq);

tic
for ii = 1:NFiles
    switch Def.RunID\{1\}
    case 'Fields'
        f = 0; % dummy
        % remove .grn extension ... this is automatically
        % added later (via AcEnvironment->RunPropgnCode)
        BaseName = StripExtension([Def.Fields.GrPathname,
                                   GrnFnames(ii).name], 'p');
    otherwise
        f = Def.Freq(ii);
        BaseName = Params2Filename(GroupName, '', f);
    end

    %Run the propagation model
    [Status, ErrStr] = RunPropgnCode(Def.EnvArr, Def, f,
                                    GroupName, BaseName, APPENDFILE, Def.RunID\{1\});
    toc
    if ~Status
        switch FromFile
        case false
            disp('ERROR: AcTUP_Run->');
            disp(ErrStr)
        case true
            uiwait(warndlg(ErrStr, 'ERROR: AcTUP_Run->', '
                           modal'), 1);
        end
    end
end
B.5 Calculation of Relative Spice Values

This function accepts a matrix of temperature and salinity values and a corresponding depth vector, and calculates the spice and density anomaly for each point.

B.5.1 Description

Values for dS and dT are defined, and will be used to calculate partial derivatives of density. The values should be typical of deviations of temperature and salinity from the mean along an isopycnal. Next, the average temperature and salinity values for each depth are calculated. The loop calculates the local thermal expansion and haline contraction coefficients for each depth using Equations 4.6 and 4.7. Equations 4.4 and 4.5 are used to compute the density and spice anomaly for each point.

It is important to note that, while spice anomaly is most useful if computed from a spice field, the density anomaly of a spice field is trivial, since by definition the density is constant in range. The density anomaly can also be computed much more simply by subtracting the mean density value from the actual value. The calculation of density anomaly in this function is included for the sake of consistency with the method for calculating spice anomaly, and because comparison between the two methods of calculating density anomaly is a useful way to check that alpha and beta are being calculated correctly, and that the range of temperature and salinity values in the field is small enough that the linearized equation of state used in this function is appropriate.

B.5.2 Code

```matlab
% r elsp ice .m
% Clare Nadig
% 7/21/2014
% Function to calculate relative spice or density values. S_spice and T_spice should be used to calculate spice values, and S and T, or S_tilt
% should be used to calculate density values.
```
% Inputs: salinity, temperature, and depth
% Outputs: spice or density anomalies
%

function [ sp, dens ] = relspice( S, T, z )
%relspice Calculate relative spice values
% Detailed explanation goes here

Ds = size(S,1);        % Number of depth points
%
% rho = waterdens(S, T, z*ones(1, size(S,2)));
% z = [z, z, z];

Tavg = mean(T,2);      % Average values of T and S (reference values)
Savg = mean(S,2);

alpha = ones(Ds,1);    % Thermal expansion coefficients
beta = ones(Ds,1);     % Saline contraction coefficients

dT = 2;                % Temperature and salinity increments used to
dS = 0.5;              % calculate alpha and beta

for ii = 1:Ds

    % Calculate density for values of T and S surrounding average values
    Tloc = [(Tavg(ii)-dT) Tavg(ii) (Tavg(ii)+dT)];
    Sloc = [(Savg(ii)-dS) Savg(ii) (Savg(ii)+dS)];

    rhoT = waterdens([Savg(ii) Savg(ii) Savg(ii)], Tloc, z(ii,:));
    rhoS = waterdens(Sloc, [Tavg(ii) Tavg(ii) Tavg(ii)], z(ii,:));

    % Calculate local values of alpha and beta
    alpha(ii) = -(rhoT(3)-rhoT(1))/(2*dT);
    beta(ii) = (rhoS(3)-rhoS(1))/(2*dS);

end

% Expand alpha and beta to match size of field
alpha = alpha*ones(1, size(S,2));
beta = beta.*ones(1,size(S,2));

% Subtract mean values from T and S
deltaT = T - Tavg.*ones(1,size(S,2));
deltaS = S - Savg.*ones(1,size(S,2));

% Effect of T and S on density
spT = alpha.*deltaT;
spS = beta.*deltaS;

% Relative spice values
sp = spT + spS;

% Relative density values
dens = spS - spT;

end
Bibliography


