Acoustic ray propagation in the waters off eastern Australia using ocean glider data

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ABSTRACT

The waters off Eastern Australia are very dynamic. The most prominent feature is the East Australian Current (EAC), a strong western boundary current, and eddies it spins off. Along with the EAC and its eddies, upwelling of cold waters, and wind and tide-induced mixing generate an active thermal environment in the coastal waters on the continental shelf. Additionally, internal waves, fronts, and continental shelf waves shifting water masses back and forth across the continental shelf/slope break add further complexity to the oceanographic conditions. Propagation of acoustic rays depends on the temperature field and is affected by these processes which influence the temperature structure. Using temperature and salinity data collected by ocean gliders transiting the waters off Eastern Australia, the dependence of acoustic ray propagation was investigated for several source depths. The formation of surface ducts, sound channels, and convergence were identified and correlated with oceanographic conditions and features. The acoustic rays' propagation depended both on these features and the sound source depth. Rays with high originating angles typically bounced back and forth between the surface and bottom; whereas rays from low originating angles were impacted more by the conditions. This is of key importance to navies for sonar operation.

Keywords: acoustic propagation, east Australian continental shelf, ocean gliders
I-INCE Classification of Subjects Number(s): 54.3

1. INTRODUCTION

The east coast of Australia is strategically significant for a number of different social, scientific and economic reasons. The east coast off New South Wales is both highly populated and home to more than half of the Royal Australian Navy's ships as well important shipping routes. Furthermore, acoustics are used for tracking animals in this region as part of the Integrated Marine Observing System (IMOS). The effect of variability in the area off the East coast of Australia on acoustic performance is therefore vital to many stakeholders. The continental shelf provides challenges to this acoustic performance due to unpredictable acoustic ray characteristics caused by fluxes in salinity, temperature and suspended matter which are synonymous with this region. Dynamical processes associated with the continental shelf can also affect acoustic propagation including wind and tidally induced upwelling, continental shelf waves and eddies. Jones, Zinoviev et al. (1) investigated the effects of eddies and other features on modelled acoustic transmission produced off the east coast of Australia. Using data from the BLUElink ocean modelling system, they noted significant difference in transmission loss when these features were presented, and also noted the dependence of this effect on the source depth.

Here, we wanted to perform a similar study, but focus on acoustic ray paths and use ocean glider observations instead of model data. Ocean gliders, specifically Slocum gliders, provide a robust, accurate and relatively inexpensive method of obtaining information on the oceanographic conditions over the continental shelf. This data can be imputed into ray tracing programs to compute acoustic ray paths, which can be used to identify the impact of changes in the ocean on acoustic ray propagation. This information would be invaluable to SONAR operators conducting ASW (Anti-submarine warfare), as it would provide accurate insight into the limitations of their tools, thus providing a better

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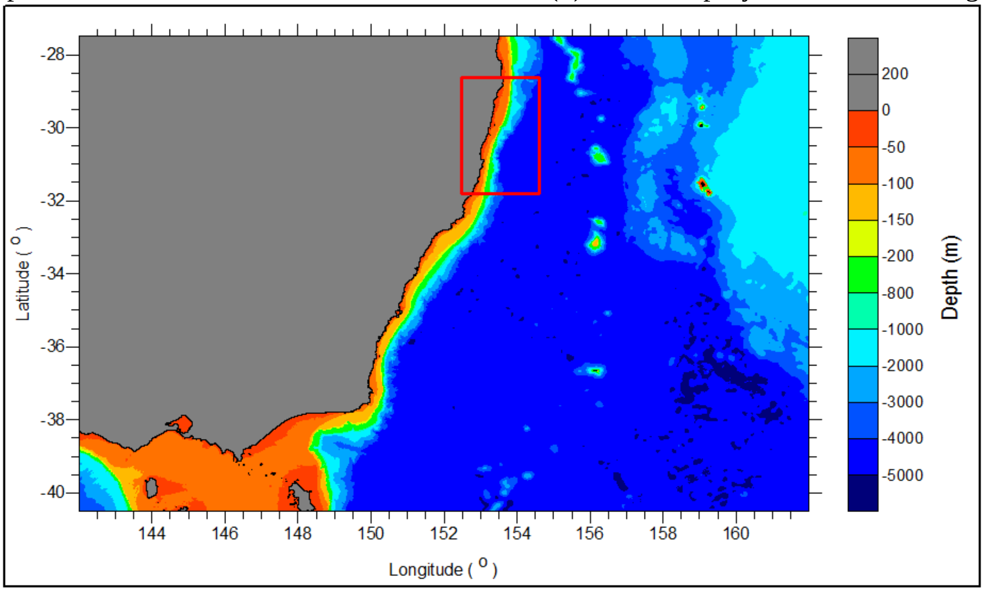
means to overcome these limitations. Our aim therefore, is to examine the temperature variability off the East Coast of Australia associated with certain oceanographic phenomena, using glider data, to examine the effects of these phenomena on acoustic ray propagation. Our path to accomplish this goal is described in section 2. Four different oceanographic conditions were focused on: a well-mixed water water column, a stratified water column, upwelling, and a thermal front. Examples of each are described in section 3. Finally, section 4 provides a summary of this investigation.

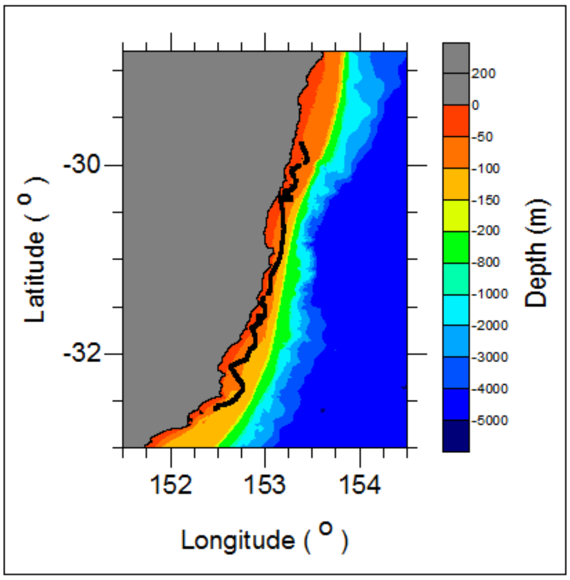
2. METHODS

2.1 Study area

The area where this study is conducted is illustrated in figure 1. The upper panel shows the site on the East Australian coast. The area extends north off of Yamba, roughly south to Forster, covering an area of approximately 315km. The east Australian continental shelf is characterized as narrow, reaching depths of 200m about 25km from the shoreline (3). Of 19 deployments of Slocum gliders in



(a) Geographic overview



(b)

Figure 1 – (a) Region of NSW Slocum glider operations, May 2011- July 2012. (b) Bathymetry for the expanded view of the boxed region indicated in (a) The path of the May 2011 deployment south along coast is indicated by the black line. This path is essentially the target path for deployments 3-19.

NSW waters, 16 have been operated purely on the continental shelf and primarily within 35km of the shore, and zig-zagging on- and off shore. The Slocum glider operates to a depth of 200m, which is optimal for use over the shelf. A typical Slocum glider path off NSW is shown in Figure 1b, which is a magnified view of the red boxed region in Figure 1a.

Although acoustic propagation from all 19 glider operations was determined, this study will utilize data from only four of these glider operations. These four operations occurred during the period of May 2011 to July 2012. The number of days for these four operations differed from 5 to 23 days and only segments of this data are presented here. As seen in Figure 1b for a May 2011 operation, the typical glider path zigzagged across the shelf. Each glider path was portioned into legs with a leg corresponding to one zig or zag across the shelf, or a segment along the shelf. The path from Figure 1b indicates the May 2011 operation (headed south). Other deployments had similar paths through this region.

2.2 Data sources

The IMOS Australian National Facility for Ocean Gliders (ANFOG) has been operating ocean gliders off NSW since 2008. These gliders measure several physical properties including temperature, conductivity (salinity), depth (pressure) and surface currents as well as optical measurements such as absorption, backscatter and chlorophyll (3). The temperature and salinity fields were of primary interest to this study.

The gliders are remotely controlled by ANFOG. They change their buoyancy and use those changes to propel themselves both vertically and horizontally through the ocean. Upon surfacing, they access satellites to communicate with ANFOG, and obtain GPS position for navigation and surface currents determination. Gliders are able to provide relatively economic *in situ* observations of the ocean and serve as a means of maintaining continuous sampling and monitoring over long ranges. Data from Slocum gliders were used in this study, but various other gliders exist.

2.3 Sound speed determination

The temperature, conductivity, and pressure were measured by sensors on the glider and converted into salinity and density values. The temperature, salinity and pressure were utilized to determine sound speed according to the UNESCO algorithm (4). This algorithm has been found to be one of the more accurate algorithms for calculating sound speed (5).

2.4 Acoustic ray propagation

Sound speed and bathymetry profiles for each of the legs was then run through Dushaw and Colosi’s eigenray trace program in order to determine the set of acoustic rays (2) for the conditions. This program traces acoustic rays along a 2-D sound speed field, which varies both horizontally and vertically. The sound speed fields were constant in time, since the glider sampling interval was much longer than the time for propagation along the leg. In order to examine the propagation characteristics of the acoustic rays, 10 bottom bounces were allowed for each acoustic ray.

3. Results

Analysis of acoustic wave propagation for all of the conditions present on the continental shelf off of eastern Australia is beyond the scope of this paper. Consequently, we will focus and give examples of a few of the typical conditions: a well-mixed water column, a horizontally and vertically stratified water column, upwelling, and a thermal front. Other conditions exist and other processes occur, including eddies, internal waves, continental shelf waves, and encroachment of the EAC, but they will not be examined here. Calculations of transmission loss are not presented here. Also the effects of currents on acoustic propagation are not examined and the focus is on the effects of the sound velocity conditions as set by temperature, salinity, and pressure.

3.1 Well-Mixed Condition

Well-mixed conditions often occur on the continental shelf as a result of wind or tidal induced mixing. The temperature is nearly constant with depth and there is little variation in sound speed (Figure 2d). As a result, a majority of the acoustic rays bounce back and forth between the surface and the bottom forming convergence zones (Figures 2a-c). However, solar heating induces a change in the upper few meters of the water column. This variation in sound speed results in a surface channel in the upper few meters (Figure 2a), for a source depth near the surface (2m). Deeper sources depths do not form this surface duct. However, source depths down to 10m do have acoustic ray paths which are limited to the upper 25m (Figure 2a-b). A lower sound speed occurs within 10-20m of the bottom and causes acoustic rays to become trapped within this low sound speed region. This only occurs when the source depth is 50m or below (Figure 2c).

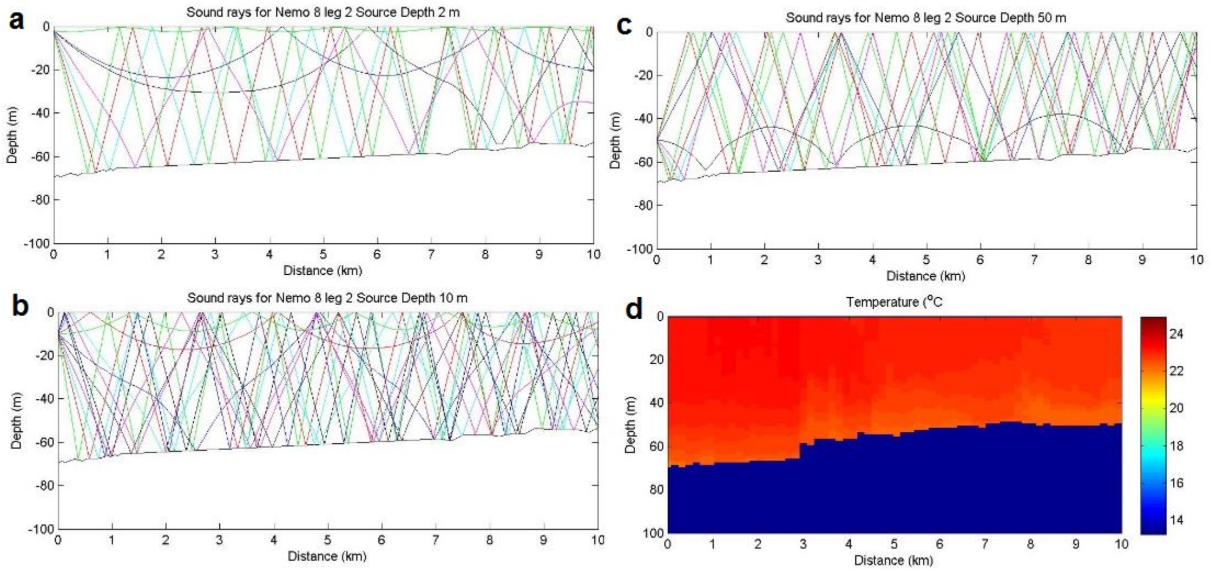


Figure 2 – Acoustic ray propagation paths and temperature profile under well-mixed conditions, taken from leg 2 of Nemo 8, deployed May 2011. Three source depths, a) 2m, b) 10m and c) 50m, were, respectively.

3.2 Horizontally and Vertically Stratified Condition

Stratified conditions can occur either vertically or horizontally. Vertically stratified conditions are commonly due to solar radiation heating the upper layers with little wind mixing to transport the heat downward and no upwelling of cold water, which is discussed in section 3.3. Horizontal stratification is often the result of the collision of water masses with different properties. In Figure 3d, both horizontal and vertical stratification are present. The coolest temperature occurs near the bottom at the origin of the transect and the warmest at the surface on the end. There is a strong gradient mid-water column extending to ~7km (Figure 3d). When the source depth is near the surface (2m), the acoustic rays primarily bounce back and forth between the ocean surface and the bottom, although there are deviations for some acoustic rays between 5-7km (Figure 3a). The deviations primarily depend on the originating angle of the acoustic ray. When the source depth is lower in the water column (10m) many acoustic rays with high originating angles again bounce back and forth between the surface and the bottom (Figure 3b). Some acoustic rays, primarily those with low origination angles, have their paths heavily modified by the horizontal stratification (Figure 3b). If the source depth is deeper again (20m), this modification is stronger and some of the acoustics rays with lower originating angles become trapped in the middle of the water column (Figure 3c). High originating acoustic rays are still observed to bounce back and forth between the surface and the bottom with the deeper source depths (Figure 3c).

3.3 Upwelling

Two types of upwelling events are observed on the east coast of Australia: wind driven and current driven. Southerly winds or the southern flow of the EAC transport surface waters offshore. This surface water is replaced by cold, nutrient rich water coming from offshore, transiting inshore along the bottom. Off the coast of NSW, 70% of the upwelling has been observed to be current driven (6). Typical upwelling conditions are seen in figure 4c. Note that the glider is transiting onshore in this section. Cold water underlies warm water and mixing is seen to occur closer inshore. This mixing

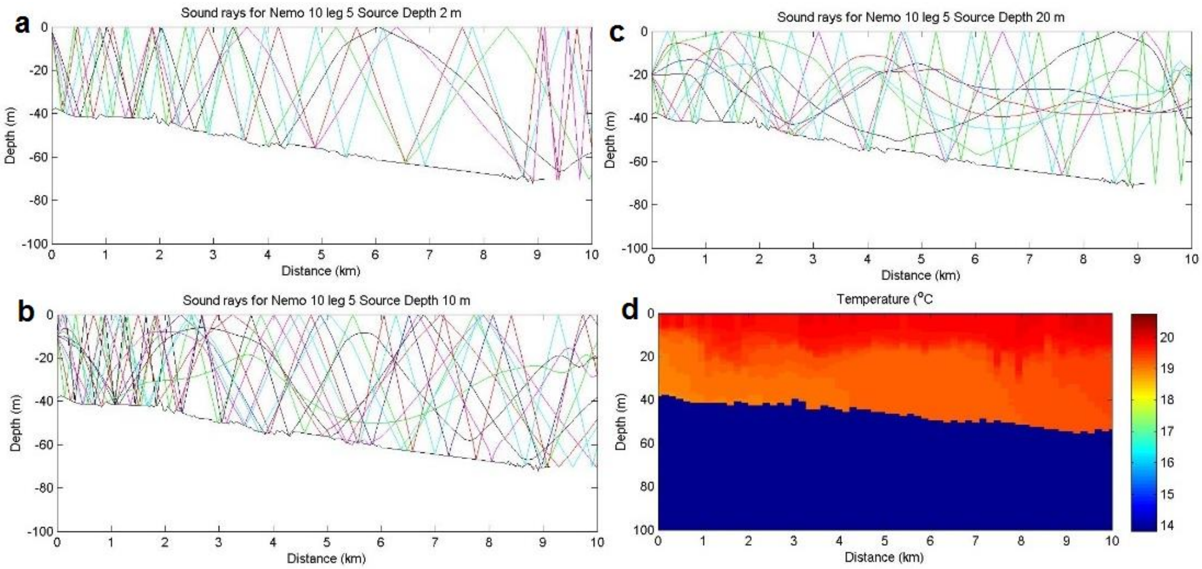


Figure 3 – Acoustic ray propagation paths and temperature profile for leg 5 of Nemo 10, deployed November 2011. Three source depths were studied in a-c and are 2m, 10m and 20m respectively. Both vertical and horizontal stratification are present.

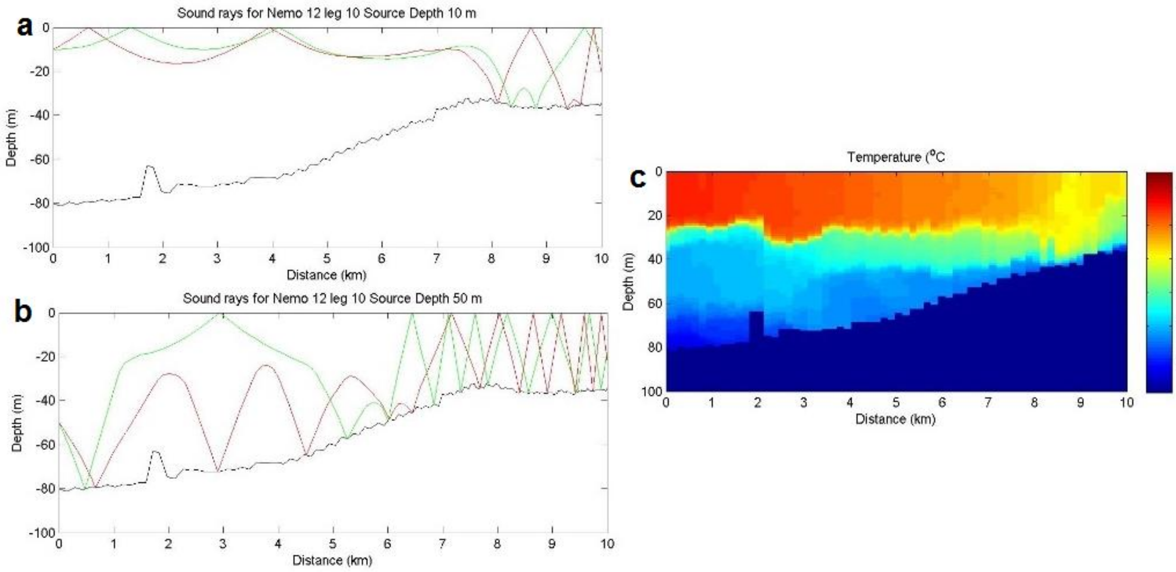


Figure 4 – Acoustic ray propagation paths and temperature profile during an upwelling event, taken from leg 10 of Nemo 12, deployed June 2012. Two source depths were studied in a-b and are 10 and 50m respectively. This upwelling event results in the weakening of stratification toward the shore.

results in weaker stratification (Figure 4c). For a source in the upper layer (10m), the acoustic rays are initially trapped within the warmer upper layer, and only escape once they encounter the weaker stratification closer to the shoreline (Figure 4a). For a source depth below the thermocline, for example 50m, some acoustic rays become trapped within the colder bottom layer and again only escape once they encounter weaker stratification (Figure 4b). Nevertheless, some acoustic rays with higher origination angles have the ability to penetrate this upper layer; however, significant modification does occur (Figure 4c).

3.4 Thermal Front

A number of different processes cause thermal fronts; encroachment of the EAC, upwelling, tidal mixing, outflow from estuaries etc. They are characterized by a strong horizontal temperature change. An example with two thermal fronts is shown in Figure 5d. The first front occurs at ~6.5km and the other at ~9km (Figure 5d). The strongest part of this front is observed at ~9km (Figure 5d). Again, the way that the acoustic rays propagate depends on both source depth and ray origination angle. For all source depths, high origination angle acoustic rays typically bounce back and forth between the bottom and the surface (Figure 5a-c). For source depths within the upper layer (<15m), acoustic rays become trapped in that layer (Figure 5a-b). This does not occur for deeper source depths (Figure 5c). For all source depths, depending on the origination angle, acoustic rays become trapped in the cold bottom layer (Figure 5a-c). However, this effect is amplified when the source depth is closer to the bottom (Figure 5c). Other modifications of the acoustic ray paths occur when encountering the thermal fronts for all source depths (Figure 5a-c).

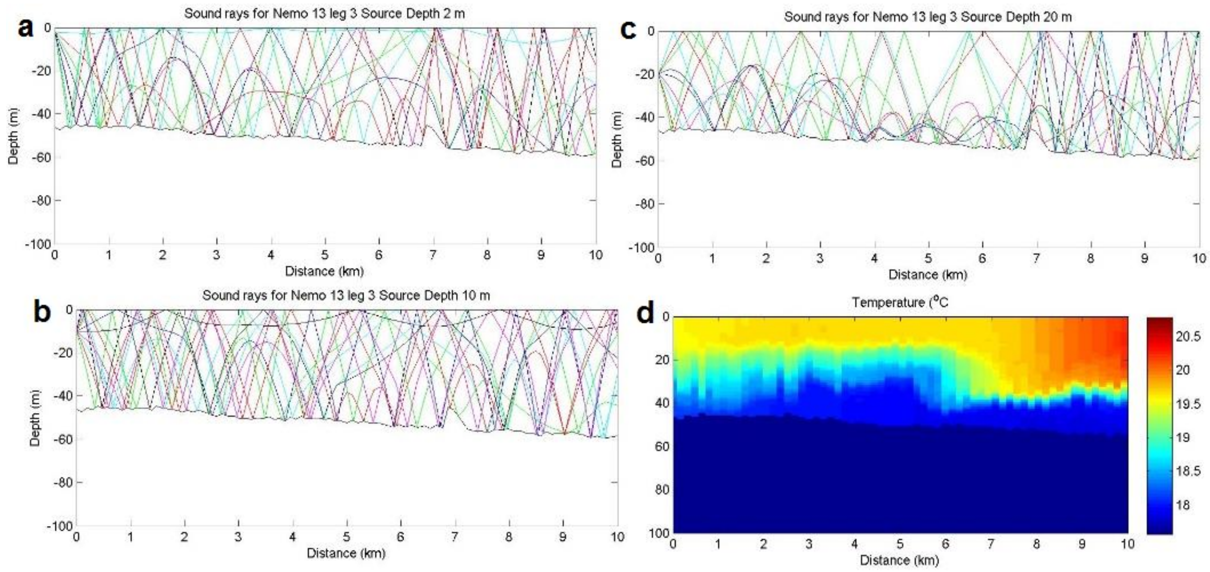


Figure 5 – Acoustic ray propagation paths and temperature profile for a thermal front, from leg 3 of Nemo 13, deployed July 2011. Three source depths were studied in a-c and are 2m, 10m and 20m respectively. Two thermal fronts are observed, one at ~6.5km and one at ~9km.

4. CONCLUSIONS

Acoustic ray propagation depends on the sound speed of the water it is travelling through. Sound speed typically varies both horizontally and vertically depending on the conditions present. On the continental shelf, numerous dynamic oceanographic processes affect acoustic propagation. This study investigated the effects of four different oceanographic conditions on acoustic ray propagation; a well-mixed water column, a stratified water column, upwelling, and a thermal front. The oceanographic conditions were selected from ocean glider data collected off the coast of New South Wales. Additionally, different sound source depths were investigated and found to have an important effect on acoustic ray paths.

From the resultant acoustic ray path determination, several overall patterns were found. For most high origination angle rays, the properties of the water column had little effect, and the acoustic rays bounced back and forth between the surface and the bottom. We expect these results because acoustic rays, which have high origination angles, have high incidence angles and penetrate through the density interfaces, with the result that they are less affected. However, low origination angle acoustic rays were often modified by the thermal characteristic of the water. Surface trapping was mostly observed when the source depth was near the surface and the ray originated at a low angle. Other shallow ducts were also observed, and often appeared even when the source was a bit deeper (10m). Bottom ducts occurred with strong stratification and were more often observed when stratification was combined with low origination angles and a deeper source depth (within 10-20m of the bottom). Convergence zones are observed, especially with high origination angles. Source depth was also seen to be an important factor in acoustic ray propagation. In general, significant modification of acoustic rays was observed in stratified waters.

These acoustic ray profiles do not include any interactions with currents, so their effects are not addressed within this study. However, future work will include the integration of currents into these calculations to investigate their effects. Other future work would also include comparing these results with regional models as well as studying other coastal processes and features of acoustic propagation that are not addressed within this study. A catalog of the features observed within this glider data would be useful for future work.

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