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Effect of Azimuthal Asymmetry Caused by Upwelling on 3D Ocean Acoustic Propagation

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ABSTRACT

3-D underwater parabolic equation model based on implicit finite difference method has been implemented for South Eastern Arabian Sea (SEAS). The bathymetric and geo-acoustic features have been integrated in the model for a 50 km circular region in SEAS. The model can simulate the effects of azimuthal variation in oceanographic features and compute azimuthally coupled pressure due to an omni-directional source. The azimuthal variation in oceanographic conditions can be observed during an upwelling event. In the first case study, the effect of upwelling event on three-dimensional acoustic propagation has been studied by using sound speed profile data derived from *INS Sagardhwani* observations. The difference in Transmission loss mosaic for upslope and downslope propagation is due to bathymetry as well as upwelling. In the second case study, the effect of upwelling only, is studied by running a model corresponding to range independent sound speed profile field and range dependent bathymetry. It was observed that during this upwelling event, the transmission loss is higher at longer ranges during upslope propagation than downslope propagation. This is due to the increase in the thickness of sonic layer duct as acoustic wave propagates from shallow to deep water. The effect of azimuthal variation in intensity of upwelling is observed in top views of transmission loss mosaics for a given receiver or target depth.

Keywords: 3D acoustic propagation; Upwelling; Arabian Sea

1. INTRODUCTION

Most underwater acoustic propagation models are approximated as two dimensional with no interaction between the azimuthal planes. This is a fair approximation, for a basically three-dimensional problem, due to two reasons. One is that three dimensional effects are negligible at shorter ranges and the other is due to non-availability of input data like Sound speed profile, bottom type, etc. along each azimuth. Also, the implementation of a three-dimensional model is computationally expensive for operational purposes. The two important cases where 3D effects are reported in literature are cross-slope propagation over a sloping bottom and propagation around sea mounts[3]. In this study, the effect of an upwelling event on azimuthal acoustic propagation is modelled. Upwelling is a process in which deep colder water rises to the surface, which leads to lowering of sea surface temperature. The change in sound speed profile structure is gradual along the range during an upwelling process[1]. This gradual change in SSP differs along each azimuth and is an ideal scenario to observe 3D effects of acoustic propagation. A 3D parabolic equation model based on implicit finite difference method is used for this study. This model code has been documented and validated with respect to different benchmark cases mentioned by Lee & Schultz[3].

The parabolic equation model developed by Lee and Schultz[3], can compute acoustic field for three-dimensional propagation scenario. The 3 D Helmholtz equation in cylindrical coordinates is given by,

$$\frac{\partial^2 \varnothing}{\partial r^2}+\frac{1}{r}\frac{\partial \varnothing}{\partial r}+\frac{\partial^2 \varnothing}{\partial z^2}+\frac{1}{r^2}\frac{\partial^2 \varnothing}{\partial \theta^2}+k_0^2\left[n^2(r,\theta,z)-1\right]\varnothing=0$$

where

- θ Azimuth angle.
- $\varnothing$ Spatial portion of the acoustic pressure field
- n Index of refraction; n $(r,\theta, z) = c_0 / c(r, \theta, z)$
- c_0 A reference sound speed
- k_0 $2\pi f/ c_0$, with f being source frequency
- z Receiver depth
- r Receiver range.

separating the variables as under,

$\varnothing(r,\theta, z) = u(r,\theta, z)\, v(r)$

and solving we get v as Hankel function, and

$$u_r+u_{zz}+\frac{1}{r^2}u_{\theta\theta}+k_0^2\left[n^2(r,\theta,z)-1\right]=0$$

Dropping first term in the above equation and rearranging the terms,

$$u_r=\frac{ik_0}{2}\left[n^2(r,\theta,z)-1\right]u+\frac{1}{2k_0}u_{zz}+\frac{i}{2k_0 r^2}u_{\theta\theta}$$

Rewriting the above equation in the operator form,

$$\frac{\partial^2}{\partial r^2}+2ik_0\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}+\frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}+k_0^2\left[n^2(r,\theta,z)-1\right]u=0$$

Then, defining the operators,

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$$X = n^2(r,\theta,z) - 1 + \frac{1}{k_0^2}\frac{\partial^2}{\partial z^2}$$

$$Y = \frac{1}{k_0^2 r^2}\frac{\partial^2}{\partial \theta^2}$$

The far field equation can be written as

$$u_r = \frac{ik_0}{2}\left(X - \frac{X^2}{4}Y\right)u$$

The PE model uses finite difference techniques[4] for computation of pressure field. In case of 3D propagation, θ-Coupling term will be included. There is flow of acoustic energy in θ direction. In case of *N* x 2D problem, there are *N* vertical planes and θ Coupling is not accounted for. There is no flow of acoustic energy in θ direction, but θ dependence is present.

In this study, the 3D PE model has been implemented for south-eastern Arabian Sea for studying the effect of an upwelling event. The sound speed profile data required for the 3D model run along all azimuths is used from the *in-situ* data collected by *INS Sagardhwani* during Mission 184. The bathymetry data is derived from etopo database. The ocean bottom parameters are provided from an 'internal' database of NPOL.

2. DESCRIPTION OF THE PE MODEL RUN.

2.1 PE Model: Model Domain

The input data for 3D PE model consists of sound speed profile, depth, density and attenuation in water column and sea bed, along each bearing. The region from 8.8 °N - 9.2 °N and 75.6 °E - 76.0 °E was chosen as the most optimum location for simulating the 3D acoustic propagation (Fig. 1). The lack of data between transects was overcome by re-gridding the data to finer grids by carrying out an optimum interpolation technique known as Barnes[2] averaging to derive a gridded database of temperature and salinity.

2.2 PE Model and *in-situ* Data: Spatio-temporal Domain

The CTD profiles collected during July 2016 (Fig. 3) were utilised to study 3D acoustic propagation (3D Acoustic Model). Upwelling characteristics are well identified from the vertical sections of temperature and salinity at the shallow stations indicated temperature is excess of 25° C at the offshore region decreases to less than 23.5° C near to the coast and the thermocline was observed below 15 m depth. The subsurface cold water (21 °C) observed at the 20 m depth level in the southern transects were reached near to the surface (5 m), whereas towards off shore the high temperatures are observed at the surface. The subsurface upward movement is observed in all transects and a maximum upliftment of cool waters was observed at the southern part. As a result of the vertical movement of the subsurface water the surface water pushed towards the off shore and the sharp isotherms observed are the indication of the thermal front that can be observed in the vertical distribution of sound speed profile (Fig. 4).

2.3 PE Model and *in-situ* Data: Input(s) Domain

The 3D PE model has been implemented for the region as shown in the Fig. 1. In the model run, a 1500 Hz source is placed at a depth of 7 m. The model is run for both upslope (source at 75.6 °E, 8.8 °N with water column depth of 329 m) and downslope (source at 76.0 °E, 9.2 °N with water column depth of 83 m) cases (Fig. 2). The source locations have been chosen such that the azimuthal transects are confined to the study area. The PE model run formalism consists of division of the ninety degree arena in to a large number of sectors. And the model is run concentrically at different range intervals up to 50 km. The Geographical north is placed as 90° and east is 0°. The azimuthal steps required for 1500 Hz source will be one-sixty fourth of a degree. The range and depth steps required will be one-fourth of the source wavelength. The

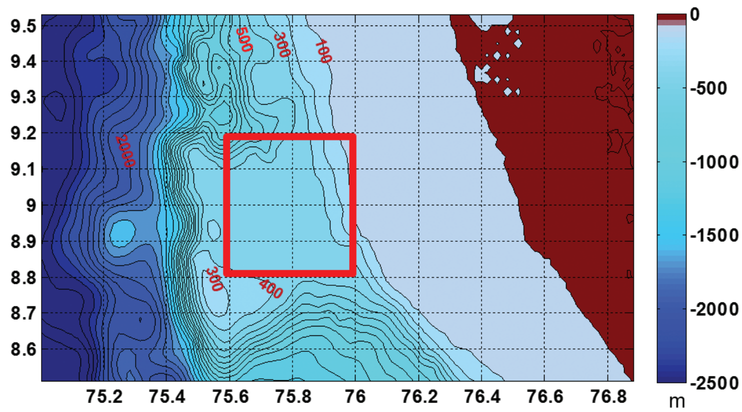

Figure 1. Spatial domain of the PE model run overlaid on etopo bathymetry.

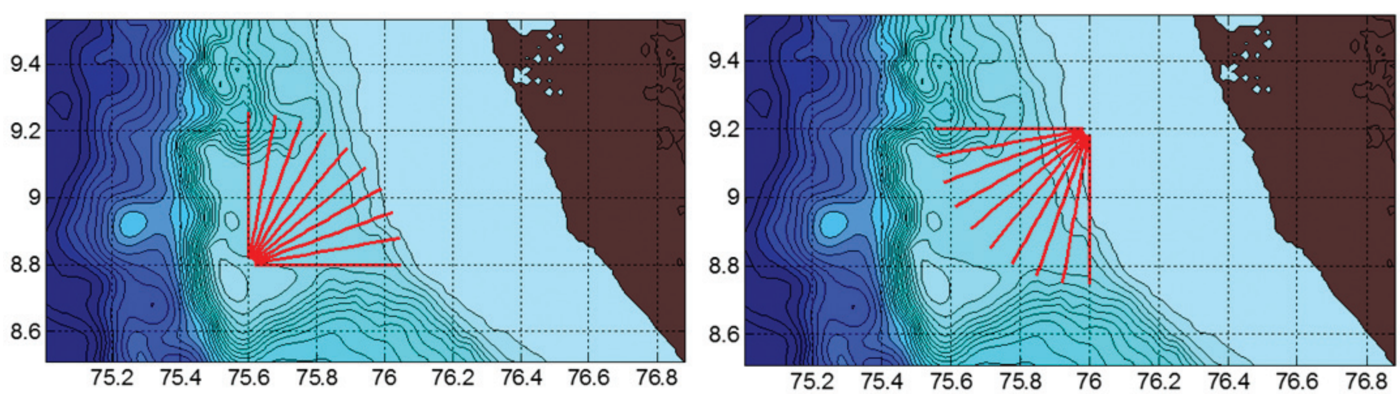

Figure 2. The arena of PE model run.

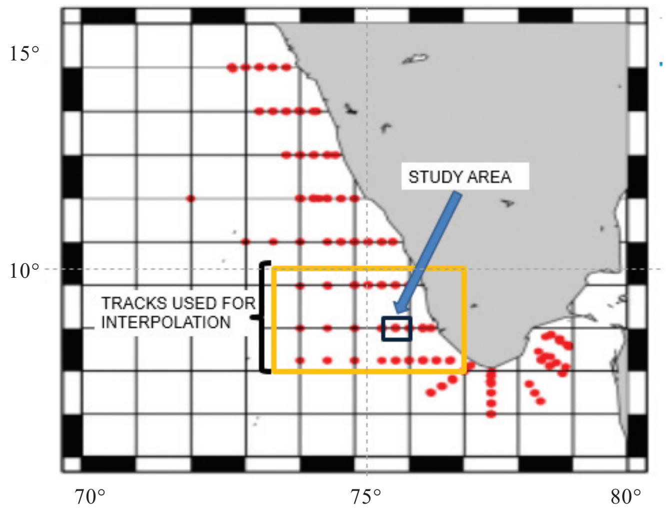

Figure 3. The stations locations for CTD cast.

sound speed profile sections along three azimuths (0°, 45°, 90°), restricted to 100 m and 55 m depth, are as shown in Figs. 5 and 6, respectively for better appreciation of the upwelling feature.

The cut off frequency and sonic layer depth of the sound speed profile at the source for upslope model run is 319 Hz and 36 m respectively. For the downslope model run, cut off frequency and Sonic layer depth at the source location is 1274 Hz and 11 m respectively. The cut off frequency, f_c and sonic layer depth, SLD, at the receiver ranges is also marked in the figures. In Fig. 5, the narrowing of the sonic layer depth near the coast is seen along 45° and 90° azimuth, whereas along 0° (North) the narrowing of sonic layer is absent. Similarly, in Fig. 6, the widening of sonic layer is seen along azimuths away from the coast and the sonic layer is almost constant along the azimuth parallel to the coast.

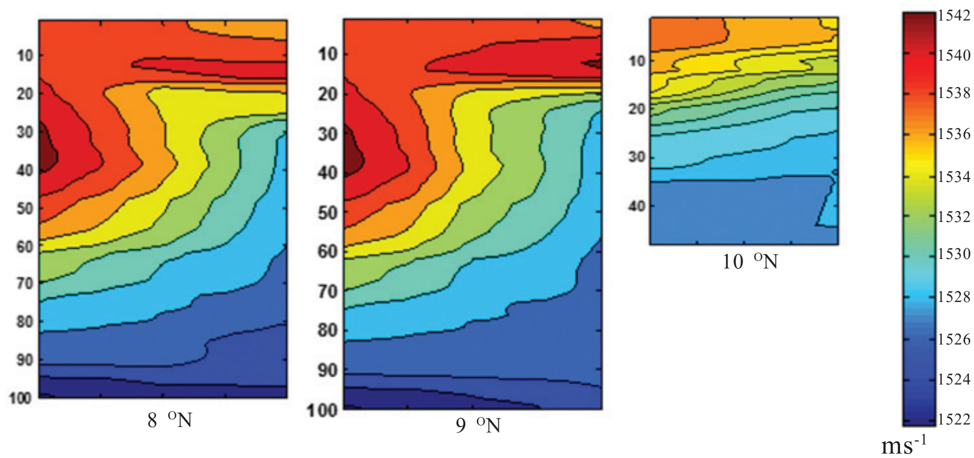

Figure 4. Vertical sections of sound speed in the study area [Mission 184].

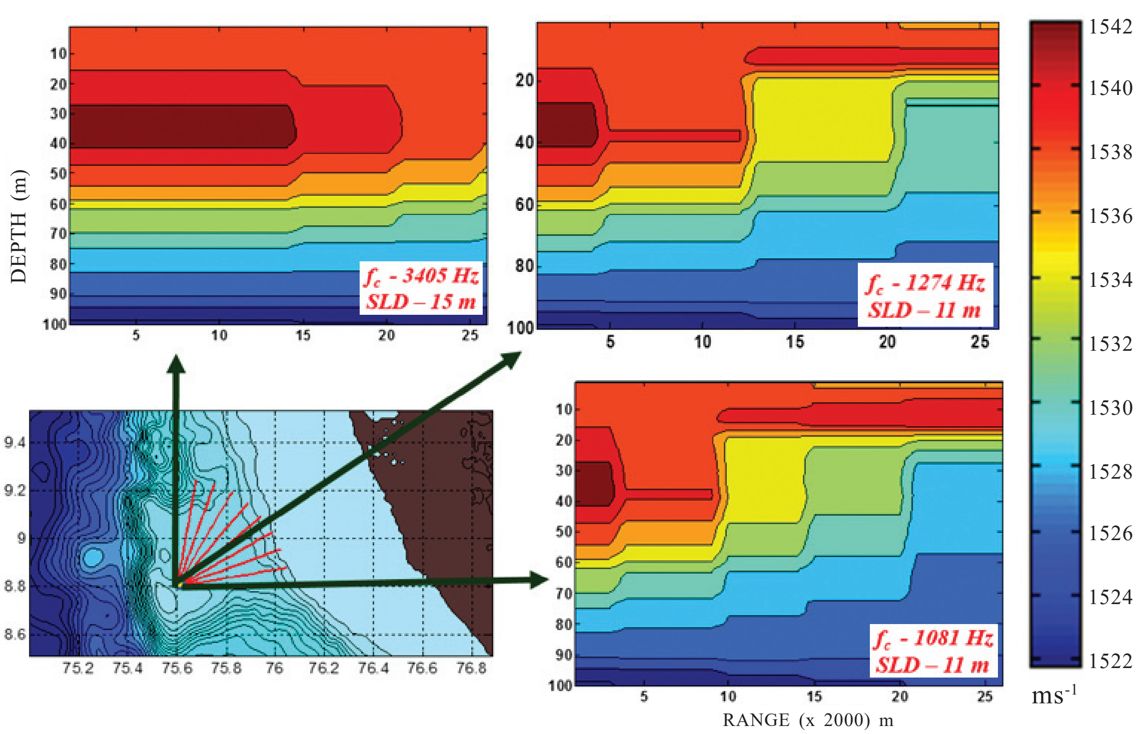

Figure 5. Sound speed along 3 azimuths (Upslope).

3. RESULTS AND DISCUSSIONS

The effect of upwelling on acoustic propagation is studied from upslope (deep to shallow) and downslope (shallow to deep) perspective. The azimuthal transmission loss mosaics (a circular domain of 35 km) corresponding to a receiver depth of 10 m is as shown in Figs. 7 and 8. These mosaics correspond to a source-receiver configuration in the sonic layer. During an upwelling event, the acoustic signals travel longer distance downslope due to widening of sonic layer depth. The acoustic signals travel shorter distance upslope due to narrowing of sonic layer. This is clearly visible in the model results (Figs. 7 and 8). The upslope and downslope model run are repeated with single sound speed profile prevailing at the source location, for simulating a non-upwelling scenario. It is observed that acoustic signal is predicted to travel longer distance upslope than downslope. The shadow zone formed near the coast (Fig. 7) during upslope propagation is similar to the ocean model based acoustic propagation studies reported by Calado[5], *et al*.

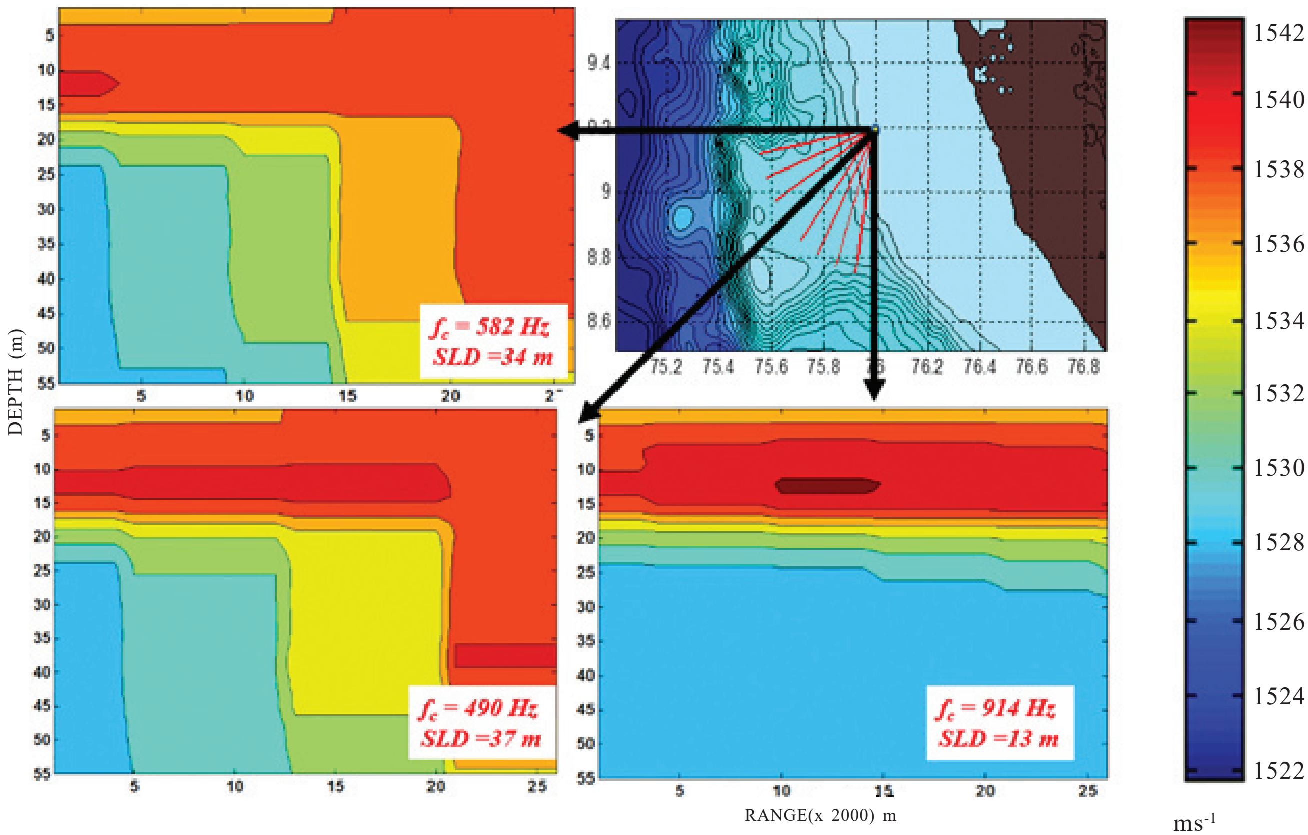

Figure 6. Sound speed along 3 azimuths (Downslope).

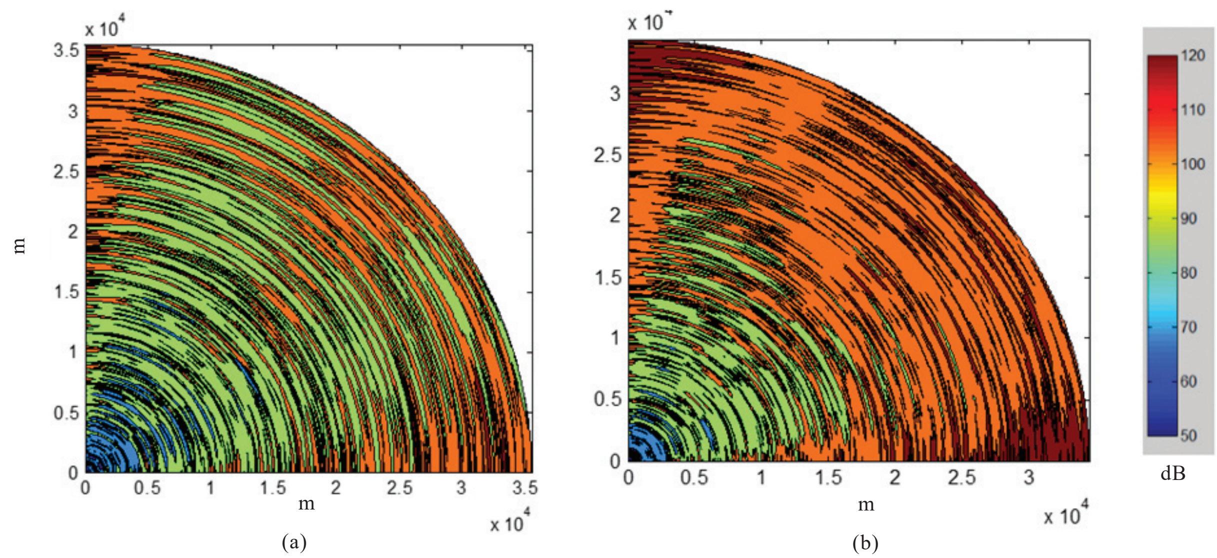

Figure 7. Azimuthal TL plot (receiver at 10 m) – upslope. (a) without upwelling [single ssp] and (b) with upwelling [Azimuthal SSP].

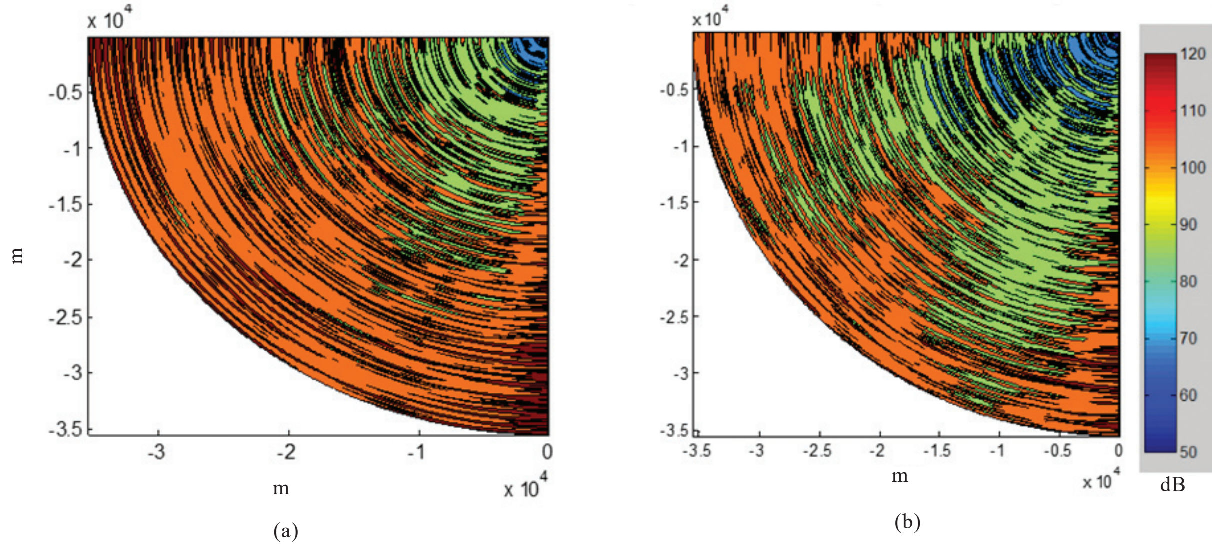

Figure 8. Azimuthal TL plot (receiver at 10 m)- downslope. (a) without upwelling [single ssp] and (b) with upwelling [Azimuthal SSP].

The effect of azimuthal coupling on TL mosaic pattern is due to two factors namely, bathymetry and range-dependent sound speed profiles. This case study shows that 3D effects will be prominent in case of moderately strong range dependence induced by oceanographic phenomenon such as upwelling. The clear difference in Azimuthal TL mosaics in the presence and absence of upwelling points to the need for range dependent modelling for SONAR system analysis.

4. CONCLUSIONS

The 3D PE model has been implemented for SEAS by including the bathymetry, geo-acoustic properties and SSPs in an upwelling scenario. The effect of azimuthal variability in SSP during the event on acoustic propagation is studied and is found to be prominent. Further studies using high resolution *in-situ* data will provide greater insight in to effect of oceanographic features on azimuthal coupling.

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In this study, he played an important role in making the choice of spatio-temporal domain of model run and coordinating the integration of oceanographic data with ocean acoustic propagation model.