Three dimensional sound propagation in Mien Hua Canyon

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Abstract

In this paper, we report numerical results corresponding to the propagation of sound wave in the Mien Hua Canyon region northeast of Taiwan. The object is to demonstrate the three dimensional (3D) effect of sound wave propagation in canyon region during the Quantifying, Predicting and Exploiting Environmental and Acoustic Fields and Uncertainties(QPE) experiment in 2009. The numerical simulations are carried out using a fully 3-D parabolic equation based model (FOR3D) coupled with a 4D ocean modeling based on primitive equation. The transmission loss (TL) comparisons between Nx2D and 3D calculations are shown to demonstrate the 3D effect due to azimuth coupling, which includes both horizontal refraction and net energy exchange between vertical planes.

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I. INTRODUCTION

Three-dimensional (3-D) propagation effects on underwater sound field still has been regarded as a very difficult and unresolved issue, due to both very limited ocean environmental information and expensive computational cost. Moreover, in most realistic sound propagation scenarios, the 3-D environmental variability is weak enough to allow two-dimensional (2-D) models to correctly predict sound propagation with assumption of there is no energy flux between two adjacent vertical plane. However, with recent emphasis on shallow water and on long range tomography, the significance of three-dimensional (3-D) propagation effects on underwater sound field has attracted more attentions lately, and it is easy to see how 3-D issue may now be essential to address. The 3D effect could be caused by both horizontal refraction and net energy exchange between vertical planes due to complex bathymetry or inhomogeneous of background sound speed. One example of later one is internal wave(nonlinear or linear) scattering of sound in an along-wavefront geometry, which is also known as internal wave ducting sound. It has been studied and observed at sea[Katsnelson, 2000, Lynch, 2006, Badiey, 2005; Lin, 2009]. For across slope propagation the bending of sound rays towards the downslope direction is an established phenomenon too, which is caused by the interaction of the sound waves with a sloping bottom, and it has been studied and observed at sea[Tolstoy, 1996; Sturm, 2009; Heaney, 2009, Chen, 2009]. In this paper, we will address the 3D effect of sound propagation in canyon region, which is seldom investigated before.

This letter is organized as follows. In section 2, the experimental and environmental information will be introduced. Section 3 presents the numerical investigation of 3D effects in Mien Hua Canyon based on 3D sound propagation simulation coupled with 4D ocean modeling output. The concluding remarks are stated in section 4.

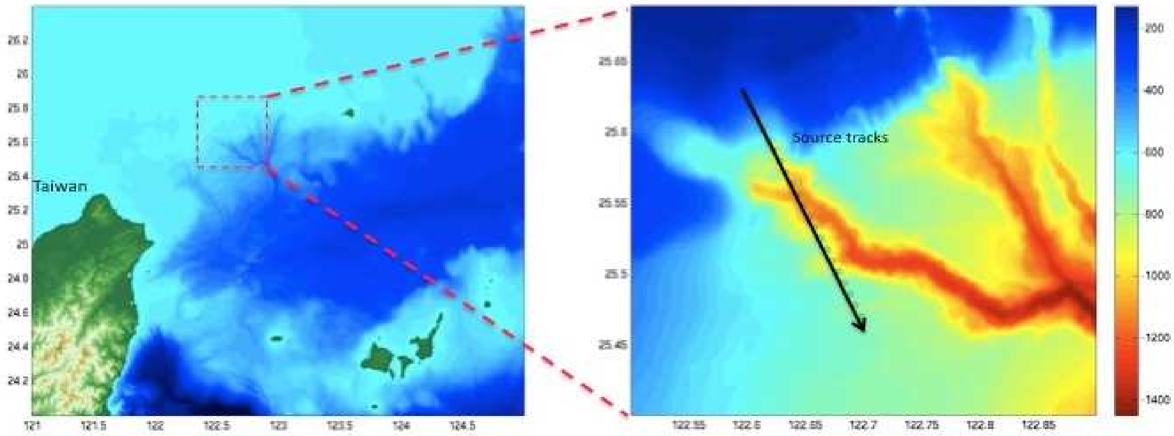


FIG. 1. The QPE experimental region (left panel); Mien Hua Canyon bathymetry and OMAS sound source track.

II. DESCRIPTION OF EXPERIMENT

Following the QPE pilot experiment in 2008, QPE Intensive Observation Period 2009 was conducted in the almost same region as pilot cruise, i.e., on the continental shelf and slope of northeast Taiwan, as shown in Figure 1. As suggested by the name- intensive observation period, a large amount effort was carried out to collect ocean environmental data to provide initial condition and assimilation data for ocean forecast modeling through the whole experiment period. The acoustic experiments were also carried out intensively during the second leg of OR1 cruise in both shelf and slope region in the north east of Taiwan. In order to explore 3-D effects of the acoustic propagation in Canyon region, one single day of cruise was devoted to have the OMAS moving source run cross over the Mienhua Canyon. In support this testing, both Nx2D and 3D simulations were carried out during the real time experiment to decide the sound receiver(sonobuoy) deployment locations and source depths. The optimized location were estimated, but due to very limited conditions at sea, the optimized plan could not be carried out. In this letter, we will present the numerical experiments of single frequency sound propagation in the Mien Hua Canyon.

III. NUMERICAL SIMULATIONS

A large number of numerical models have been developed to solve the acoustic propagation problem in the ocean, but most of these models are aimed at providing solutions for two-dimensional (range and depth) problems. Usually this 2D solution provides satisfactory solutions when the three-dimensional effects are weak. However, the nature of the ocean is three-dimensional. For example, the presence of a meso-scale eddy, a sea mount, or a canyon, will introduce an azimuthal dependence. In situations where the three-dimensional effects can not be neglected, the two dimensional models, or Nx2D models, fail to provide accurate solutions. In such case, a numerical model that can give accurate dependence of the field not only on range and depth, but also on azimuth, i.e., a three-dimensional model is needed. Modeling three-dimensional propagation in the real ocean is very difficult because for ocean itself must be modeled by a large number of parameters. In addition, even if a three-dimensional problem is formulated very well by means of mathematical and physical theory, the realistic implementation of such a solution requires huge computational effort. Up to now, only a handful of codes presently in existence can model full 3-D propagation. The code FOR3D by Lee et al (1992) is one of the most sophisticated and widely used program for 3-D PE calculations. It has been extensively revised and extended to incorporate a wide angle capability, be more stable and computationally efficient, and to include many unique capabilities such as the ability to handle density variations, and to handle complicated bathymetry. So in this letter, three-dimensional acoustics effects in the canyon region are studied using FOR3DW, a wide-angle version of the parabolic equation code FOR3D (a finite difference solution, and Ordinary differential equation, and Rational function approximations for solving 3D problems). The TL comparison between Nx2D and 3D calculations are shown to demonstrate the 3D effects.

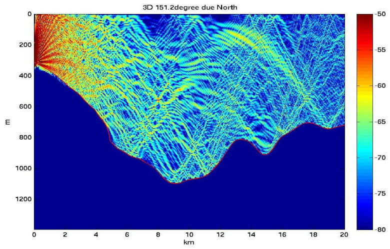
A. Ocean modeling

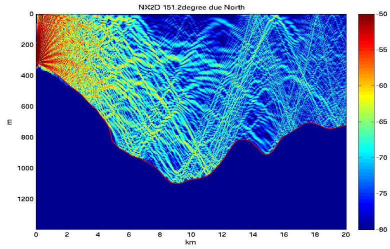
In order to implement the three dimensional simulation of sound wave propagation in the real ocean, one has to provide the three-dimensional ocean environmental data to the acoustic propagation numerical model, which includes both sound speed section in the water column, and three dimensional geo-acoustic model, and bathymetry. It is almost impossible to sample the ocean in 3D in practical due to the rapidly changing of ocean and very limited resources. Therefore, couple ocean-acousic modeling in this case is very necessary. Due to both the limitation of computational resources and ocean modeling, there are a few research result on 3D coupled ocean-acoustic modeling reported before, but those ocean modeling are very rough in both vertical (O(100 m)) and horizontal direction (O(15-20 km))[1]. The ocean modeling simulations utilized the MIT Multidisciplinary Simulation, Estimation and Assimilation SystemS (MSEAS). This system is being used for realistic simulations and real-time forecasts in many regions of the world's ocean. For the ocean dynamics, it employs a new free-surface and two-way nested primitive-equation code[2] (a significant upgrade of the rigid-lid Harvard primitive-equation model[3,4]). The MSEAS system also involves a objective analysis scheme, an Optimal Interpolation scheme for data assimilation. Due to the limited length of this letter, the detailed ocean modeling is reported here, but more information could be found on this website.[5] In general, a 4-D ocean modeling output (3D in space, 1D in time), with 1.5 km resolution in horizontal grid, and 10 meter in vertical grid, is provided as input for acoustic modeling.

B. 3D simulations with range dependent sound speed profile

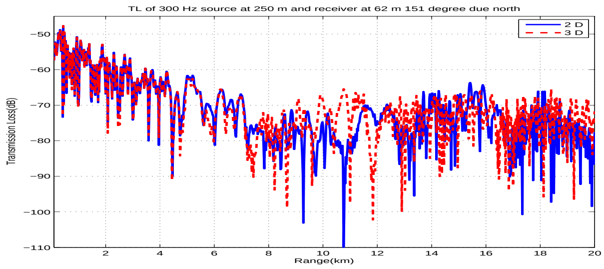
1. Depth intergrated intensity over the water column depth shows dramatic differences between the Nx2D and 3D simulations in the center of domain.

2. It shows the energy focusing and de-focusing along the azimuthal angle directions in





(a) (b)

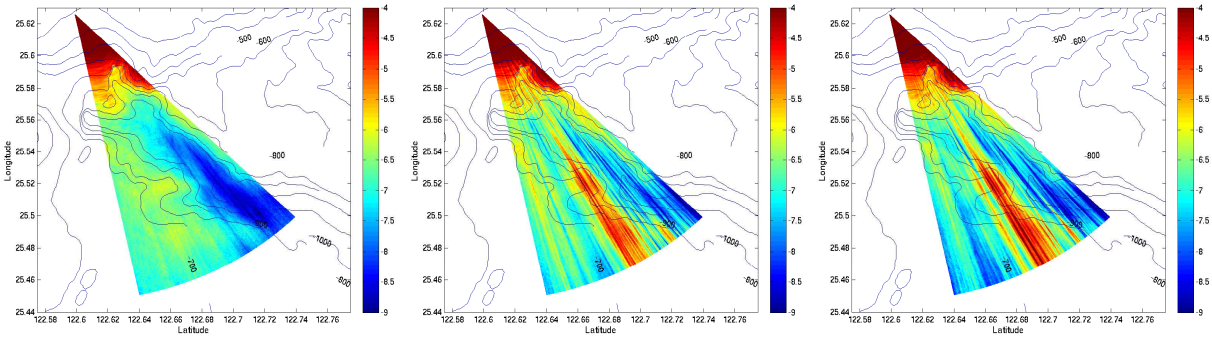


(c)

FIG. 2. 3D and Nx2D sound propagation through Mien Hua Canyon simulations a) 3D simulations : TL as function of range and depth at 151 degree due north; b) Nx2D simulations : TL as function of range and depth at 151 degree due north; c) The comparison of 3D and Nx2D simulations for receiver depth at 62 meter.1.3D and 2D results show the difference in the vertical plane, center of domain. The TL at fixed depth also shows the difference, the difference could be quite big at certain distance. 2. The 3D and 2D difference start to show up apparently after 5 km.

3D simulations.

3. Question is where those differences come from: from horizontal refraction or side wall reflection. (intuitive thinking : echo in a canyon.) In order to understand this: a range independent sound speed background are used to run the 3D test. The comparison between the 3D and Nx2D show the major difference is still there, which mean the bathymetry here play the dominant role. However, the inhomogeneity of water column still caused the horizontal refractions and contribute to 3D effect a little bit too.



(a) (b) (c)

FIG. 3. Depth integrated intensity of 3D and Nx2D simulation coupled with 4D ocean modeling.

C. 3D simulations with range independent sound speed profile

1.

D. Vertical cross section in azimuthal direction

1. Figures 4(a) - 4(o) are used to show the side wall reflection, which is major factor here to cause the 3D effect.
2. Figures 4(a) - 4(c) seems to be not very well to show this.
3. Figures 4(d) - 4(o) seems to be better; one is at about 8 km range, the other one is at about 11 km range, each one has six continuous pictures in it.
4. From the observation of the movie, the 3D effect here are caused by the side wall (bottom reflection as well) reflections at different distance, and then cause the sound wave focusing in the center part of the domain.

IV. SUMMARY AND DISCUSSION OF RESULTS

1. coupled ocean-acoustic modeling in 3D domain.

2. 3D effect in the canyon region

3. 3D effect caused mainly by the sidewall and bottom reflection, 3D modeling show the focusing and de-focusing effect in the azimuthal direction, which Nx2D failed to present.

4. horizontal refraction caused by the inhomogeneity of water column also contribute to the 3D effect, but the simulations here show limited effects. These perhaps are due to the limited ocean information, or lower resolution of ocean modeling output.

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List of Figures

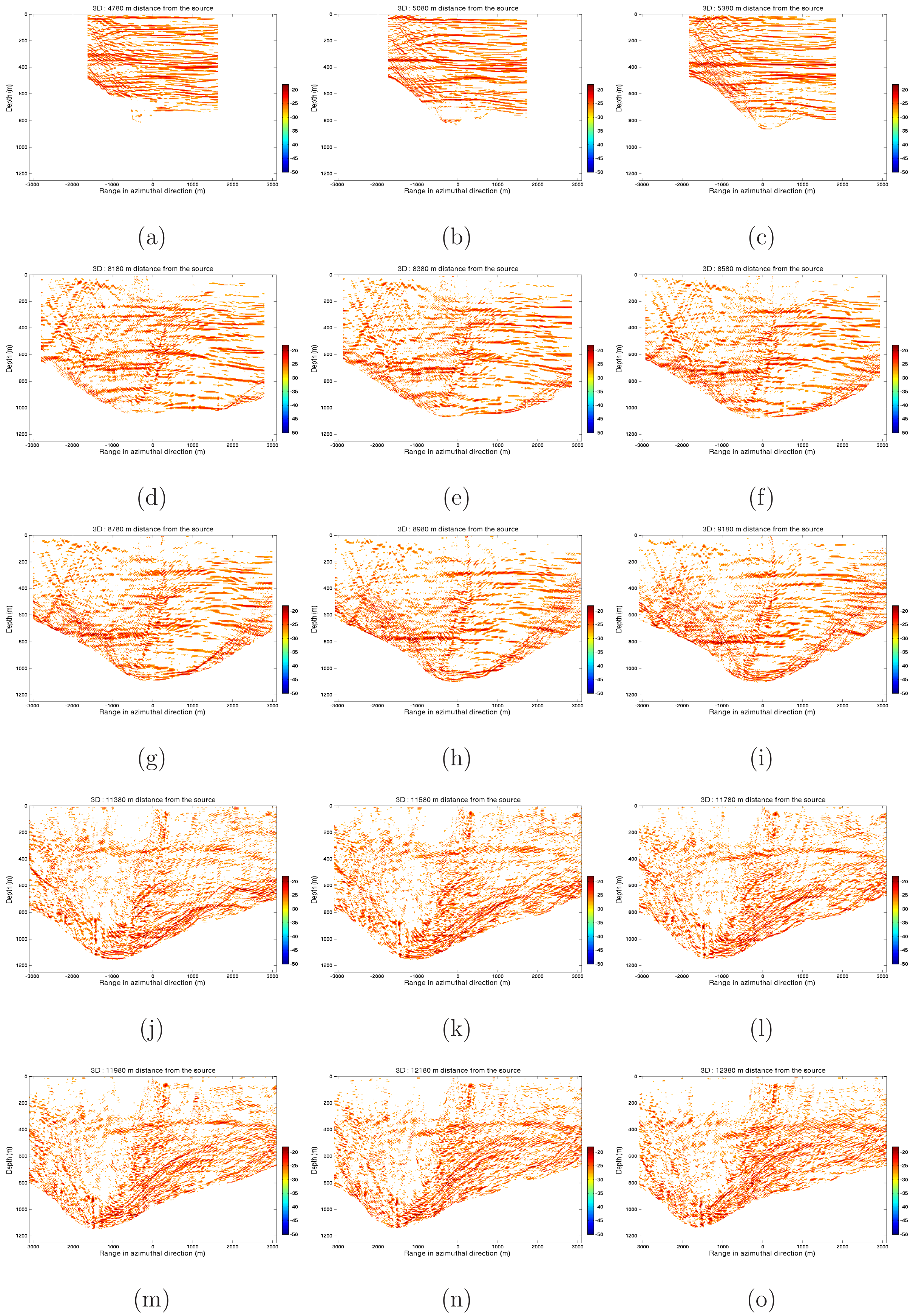

FIG. 4. Cross section of intensity in the azimuthal direction at different distance from sound source. The distance from sound source from a) to i) are from 10.68 to 12.28 km with interval of 100 m between each.