Special Research Award: ONR Postdoctoral Fellowship

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LONG-TERM GOALS

The long term goals of this research are to understand the statistics of acoustic fields in deep water ocean environments.

OBJECTIVES

At long ranges, broadband receptions consist of early ray-like arrivals and a finale that is best described in terms of the low order modes. This project mostly deals with experimental observations of the low mode signals. The observations are used to estimate the mode statistics and then compared against reduced physics models. The experimental observations rely on high quality acoustic, and environmental data. For that, this project uses observations from both the Long Range Ocean Acoustic Propagation EXperiment (LOAPEX) and the Philippine Sea EXperiment (PsiEX).

APPROACH

This project consists of two parts. The first part estimates mode statistics from the Long Range Ocean Acoustic Propagation EXperiment (LOAPEX) conducted in 2004. LOAPEX provided a unique opportunity to measure low mode receptions at a series of ranges from 50 km to 3200 km. This project uses the data from LOAPEX to estimate range-dependent statistics such as mode energy, mode time coherence and cross-mode coherence. The second part produces accurate scattering predictions for the modes using the transport theory model. The predictions rely on in-situ estimates of the environmental variability. In order to characterize environmental variability this project uses measurements made during LOAPEX, and PsiEX.

The principal investigator for this project is Dr. Tarun K. Chandrayadula, who is an ONR Postdoctoral Fellow in the Oceanography department at NPS. His adviser is Dr. John A. Colosi who is a tenured Professor in the same department.

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WORK COMPLETED

Mode Transport Theory Coherence: This project validated the transport theory at frequencies of 75 and 250 Hz by performing Monte Carlo simulations with time evolving internal wave sound speed perturbations. The simulations were performed using a deep-water environment typical of the Philippine Sea. Due to the computational burden in computing the time evolving internal waves and the large number of modes at 250 Hz, the calculations were done on the NPS supercomputer Hamming. This work was written up as a journal article, and has been accepted for publication in the Journal of the Acoustical society of America (JASA) [1]. Details concerning the transport theory approach are in the annual report, " Analysis and modeling of ocean acoustic fluctuations and moored observations of Philippine Sea sound-speed structure, award number N00014-11-WR20115."

LOAPEX Observations: This project has completed an analysis of the LOAPEX receptions for estimates of mean mode energy, cross-mode coherence, and mode temporal coherence. The estimates were compared to predictions from transport theory. A manuscript for this topic has been submitted for publication in JASA ([2]).

PsiEX Acoustic and Environmental Observations: Wavefront statistics such as scintillation index and time wander were estimated for the acoustic observations during the PsiEX 2009s pilot study. The estimated statistics were compared with path-integral predictions. This work was presented during the May 2012 Acoustical Society of America workshop held in Hong Kong [3]. The salinity and temperature measurements made during the 2010-2011 leg of PsiEX were used to track isotherms, which were then used to estimate the internal wave displacement spectra for the Philippine Sea environment.

RESULTS

This section discusses the comparisons between LOAPEX observations and transport theory predictions. In addition to that, it reports the most recent work on estimating isotherms displacement spectra from the PsiEX environmental observations.

Transport Theory Coherence vs LOAPEX observations: The work in reference [4] compared transport theory predictions with simulations to show that such reduced physics models could be used to accurately predict mode energy, cross mode coherence, and mean intensity of the pressure field. Until recently, the literature on transport theory did not have predictions for mode time coherence. The transport theory predictions for mode energy, and cross mode coherence were extended to mode time coherence. Extensive Monte Carlo simulations were carried out at 75 and 250 Hz to test the ability of the theory to predict temporal coherence. The agreement between theory, and simulation was good for ranges up to the maximum simulation range of 500-km. Computational constraints made calculations beyond 500-km prohibitive. The theory and simulations showed that the characteristic coherence time (defined as the e-folding time of the coherence function) scales roughly as R-1/2. The coherence behavior can hence be extrapolated out to longer ranges using this scaling relation. This work on time coherence predictions using transport theory has been explained with more detail in reference [1].

With the transport theory approach verified for simulation cases, the next step was to test the predictions for the real ocean. Transport theory predictions were thus set up for the LOAPEX environment. In order to generate accurate predictions using transport theory approach, we used the Garrett-Munk internal wave spectrum ([5, 6]), which is consistent with measurements during LOAPEX [7]. Furthermore, the energy level of the internal waves was also derived from observations, and was roughly at the nominal GM level for the North Pacific. The experimental details of LOAPEX have been summarized in reference [8]. During LOAPEX, a ship-suspended source transmitted to a mode resolving Vertical Line Array (VLA), from stations at ranges of 50 km to 3200 km. At each station the transmissions were performed from two different source depths. One set of transmissions was performed with the source at 800 m, and the rest at 350 m. The two sets of transmissions by virtue of their source depth, differ in their initial mode excitation spectra, and are expected to have different scattering statistics. LOAPEX is hence an opportunity to compare scattering statistics at different ranges, and for different source depths. In accordance with LOAPEX, two sets of transport theory equations were initialized with the two different source depths.

Several complications with LOAPEX made the experimental analysis difficult. First, the transmissions for a given source depth were made over a relatively short time duration (at most 1 day), and thus the sample sizes in the ensemble averages were low. Second, the source motion was incompletely known, and corrections had to be estimated. Third, for the off axial source, the SNR levels are low. The challenges were tackled as follows. For the relatively short intervals of time within a day, the error-bars were estimated by allowing for the correlation time scales of the internal wave effects. To compensate for the source motion, acoustic tracking with the ray arrivals was used to estimate the source positions, and the phase corrections applied. For the low SNR levels in the off-axial receptions, period averaging was implemented.

Figs. 1 and 2 show comparisons of mean mode energy for the axial, and the off-axial source depth respectively. The mean mode energy estimates are shown in terms of TL estimates for the different ranges. For both the sources, the observations, and theory are in excellent agreement. Note for the off-axial source the lowest modes are very weakly excited, and hence amount of energy these modes acquire depends on the scattering induced mode coupling. The theory and the observations show that by 1600 km, coupling has transferred significant acoustic energy to the lowest normal modes. In propagating to the maximum LOAPEX ranges, the lowest modes have acquired almost 60-70 dB of energy. At 3200 km the mode energy distribution does not show much resemblance to the initial excitations. Figs. 3, and 4 show the mode coherences across mode number and time respectively. For both the figures only modes 1 and 10 are shown. The statistics for the other modes lie in between. The coherences for the on-axis source are relative to mode 1 and for the off axis source they are relative to mode 10. For cross-modal coherence (Fig. 3), the theory consistently underestimates the observations, though the patterns are quite close. The project is presently studying what aspects of the environment could lead to good results on the matter of the mode energies, yet poor results with regard to cross mode coherences. The time coherence estimates in Fig. 4 show the observed and modeled temporal coherence functions for both the on and off axial sources. For the off axial case, fewer time lags are seen; this is because some time averaging was done to boost the SNR. For temporal coherence, the transport theory model shows excellent agreement with the observations both for the on and off axial cases.

This work has been submitted for publication in JASA, and the manuscript is currently under review. Apart from the model-data comparisons, the submitted manuscript gives error estimates due to low SNR, sample size, and the effect of positioning error. These are significant, but often ignored issues in coherence estimation from real experiments. By emphasizing on these issues, this work will guide future efforts at coherence estimation from observations.

PsiEX Environmental Observations: PsiEX contained environmental sensors (microcats, microtemps, and thermistors) that were attached to the source and receiver moorings. Apart from moored sensors, PsiEX also had measurements made using CTDs and XBTs. The observations from the sensors are required to characterize the environmental variability in the much dynamic Philippine Sea. The hydrophones of the array contained thermistors, which measured temperature every 20-30 minutes. The thermistors spanned a total depth of 5000 m, and hence the measurements from the PsiEX array are an opportunity to compare the environmental variability at various depths of the entire water column. Small scale fluctuations due to tides and internal waves were tracked using isotherm displacements. The method for isotherm tracking is similar to the isopycnal tracking used in reference [9], except that this method does not track salinity fluctuations at the different depths, and uses only a mean salinity profile from the CTD casts made during PsiEX. As a first step, the observations during the first 30 days of PsiEX were initially chosen for this analysis. The temperature measurements for the first 30 days made at the different thermistor depths were interpolated onto a common time grid with a sampling rate of 2 samples/hour. The temperature measurements for the chosen time period were used to measure the mean temperatures at each depth. The isotherms were then tracked for the mean temperature surfaces. Fig. 5 shows the tracked isotherms for depths between 250-600 m. The isotherm variability shows significant periodic components, which are potentially due to internal tides. The frequency content of the isotherm displacements were then estimated using a periodogram/spectrum analysis. The spectra calculations used a sample rate of 2 samples/hour, and Hanning windows of lengths 10 days, with 50 % overlap. Fig. 6 shows the isotherm displacement spectra for the temperature surfaces of 16.3 C, 2.7 C, and 1.9 C, which are centered around depths of 315 m, 1400 m, and 2000 m respectively. The displacements are apparently larger with increase in depth. The two most significant spectral peaks that occur at greater than the Coriolis frequency correspond to the diurnal and semidiurnal internal tide frequencies. For frequencies greater than the tide frequencies the spectrum diffuses into smaller peaks. In order to compare the depth structure of the isotherms, the displacements were correlated across depth. The displacement statistics potentially vary as a function of frequency, and thus the isotherms were divided into 1 day blocks and a Short Time Fourier Transform (STFT) performed on each of the segments. Out of the STFT blocks, 6 different frequency bins corresponding to, 0.1, 0.2, 0.5, 0.75, 0.9, and 1.0 cyc/hour were chosen for the correlation analysis. The displacements for the chosen frequencies were cross-correlated for the corresponding frequencies across depth, and normalized with the product of their corresponding standard deviations. Fig. 7 shows the depth correlations for the different frequencies. At the lowest frequency (0.1 cyc/hour), the displacements are significantly correlated across depth, which is potentially due to barotropic internal tides. As the correlation analysis moves to higher frequencies, the displacements quickly decorrelate across depth. The decorrelation across depth for the higher frequencies suggests significant contributions from diffuse internal waves.

A big part of the ongoing work in this project is to fit internal wave modes into the isotherm displacements. Internal tides, which are a major part of the isotherm displacement spectrum (Fig. 6) are phase locked over long periods and have large wavelengths. The internal waves on the other hand are more diffuse in frequency, and wavenumber. Internal tides among other sources are one of the sources of internal wave energy. The PsiEX location is close to internal wave generating sites. The displacement spectra in Fig. 6 show evidence of both internal tides, and waves. Further analyses of the PsiEX observations should throw more light on how internal tides are converted into internal waves.

IMPACT/APPLICATIONS

This research has both scientific and operational applications. This project estimated acoustic coherence which is intrinsically related to processing gain and SNR. The performance of all detection methods depend on SNR. The quality of the comparisons between transport theory, Monte Carlo simulations, and the LOAPEX observations suggest that this model could have value as a Navy acoustic propagation code.

RELATED PROJECTS

This work is closely related to ONR Award N00014-11-WR20115, which is the grant funding Dr. Chandrayadula's post-doc advisor Dr. Colosi. It is also related to the work being done by the North Pacific Acoustic Laboratory group coordinated by principal investigators Peter Worcester (Scripps) and James Mercer (APL - UW). Many other ONR-sponsored researchers work on projects related to NPAL and participate in the NPAL workshops.

PUBLICATIONS

- J. A. Colosi, T. K. Chandrayadula, A. G. Voronovich, and V. E. Ostashev, "Coupled mode theory for sound transmsission through an ocean with random sound speed perturbations: Coherence in deep water environments," *J. Acoust. Soc. Am*, 2012. In-press
- T. K. Chandrayadula, J. A. Colosi, P. F. Worcester, M. A. Dzieciuch, J. A. Mercer, R. K. Andrew, and B. M. Howe, "Observations and transport theory analysis of low frequency, acoustic mode propagation in the Eastern North Pacific Ocean," *J. Acoust. Soc. Am.*, 2012. Under review

AWARDS

None

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[1] J. A. Colosi, T. K. Chandrayadula, A. G. Voronovich, and V. E. Ostashev, “Coupled mode theory for sound transmsission through an ocean with random sound speed perturbations: Coherence in deep water environments,” *J. Acoust. Soc. Am*, 2012. In-press.

[2] T. K. Chandrayadula, J. A. Colosi, P. F. Worcester, M. A. Dzieciuch, J. A. Mercer, R. K. Andrew, and B. M. Howe, “Observations and transport theory analysis of low frequency, acoustic mode propagation in the Eastern North Pacific Ocean,” *J. Acoust. Soc. Am.*, 2012. Under review.

[3] T. K. Chandrayadula, J. A. Colosi, P. F. Worcester, and M. Dzieciuch, “Wavefront statistics from measurements made in the philippine sea and comparisons to path integral theory,” *J. Acoust. Soc. Am.*, vol. 131, pp. 3353–3353, 2012.

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[9] J. A. Colosi, T. F. Duda, Y.-T. Lin, J. F. Lynch, A. E. Newhall, and B. D. Cornuelle, “Observations of sound-speed fluctuations on the new jersey shelf in the summer of 2006,” *J. Acoust. Soc. Am*, vol. 131, no. 2, 2012.

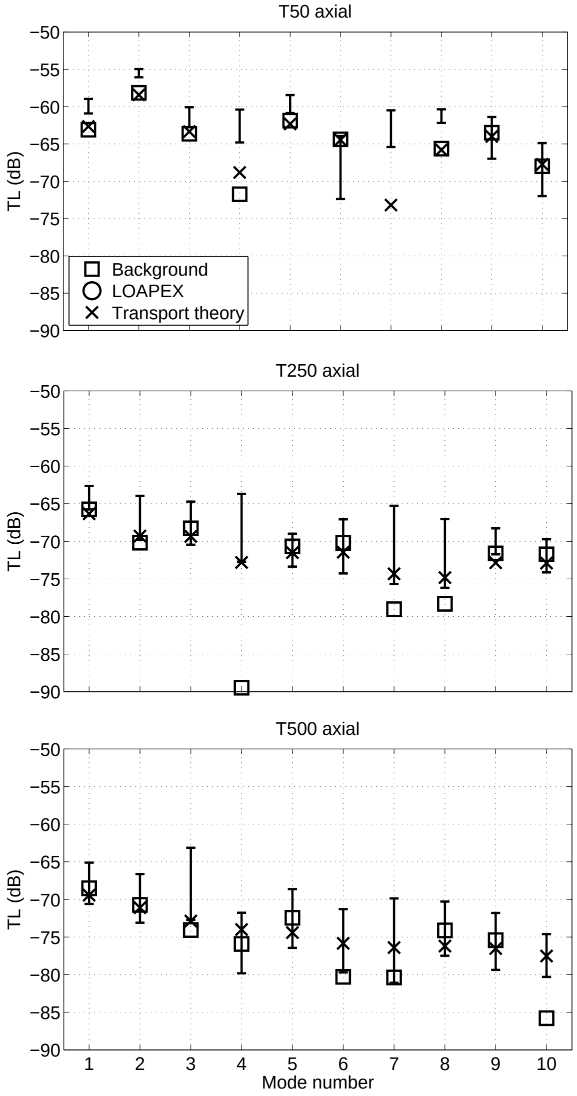


Figure 1: Transmission loss for the LOAPEX axial source (circles) compared with predictions from transport theory (crosses) and predictions for the no internal wave scattering case or the 'background' sound speed profile (squares).

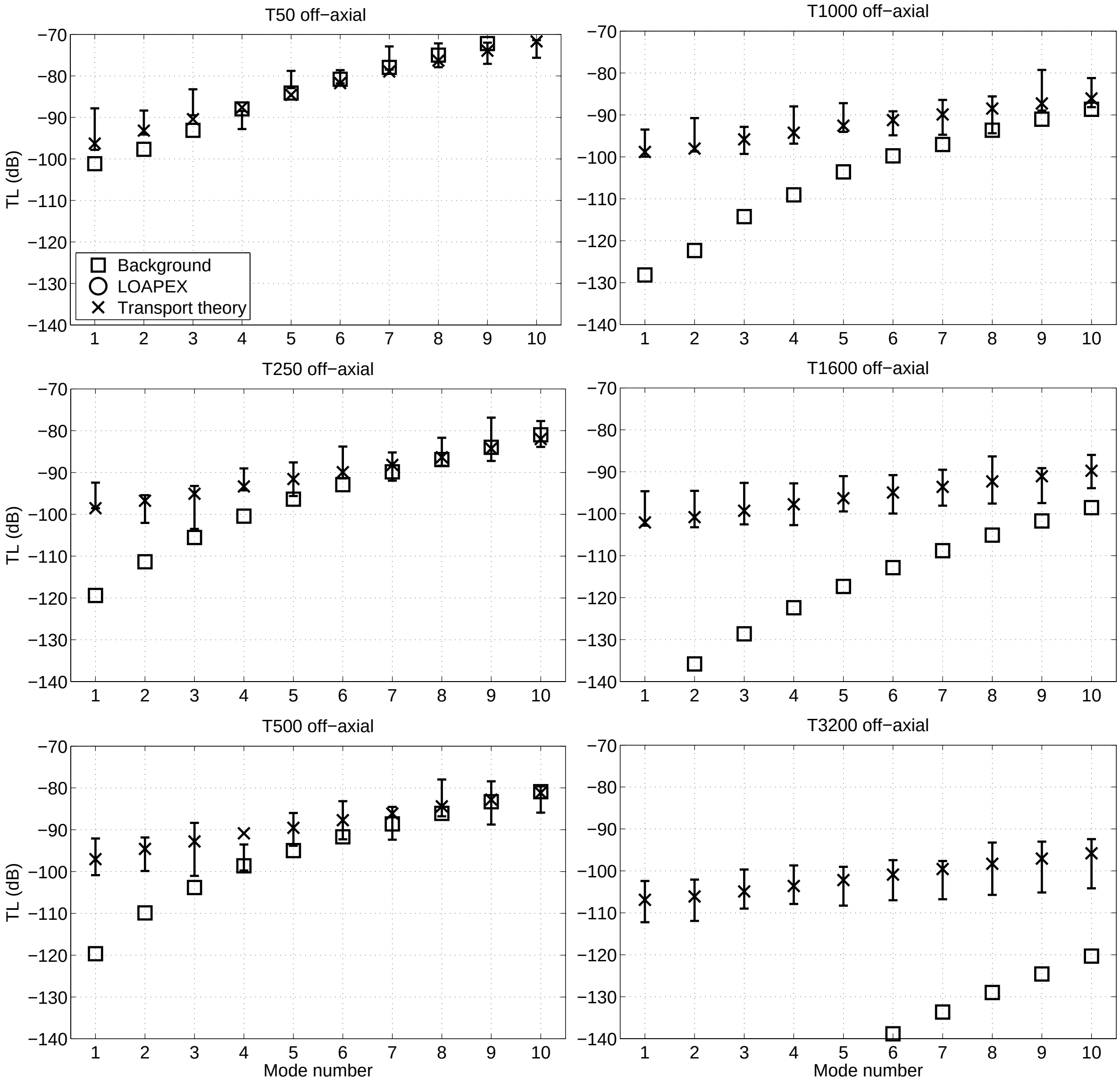


Figure 2: Same as Fig. 1,except for the off-axial source.

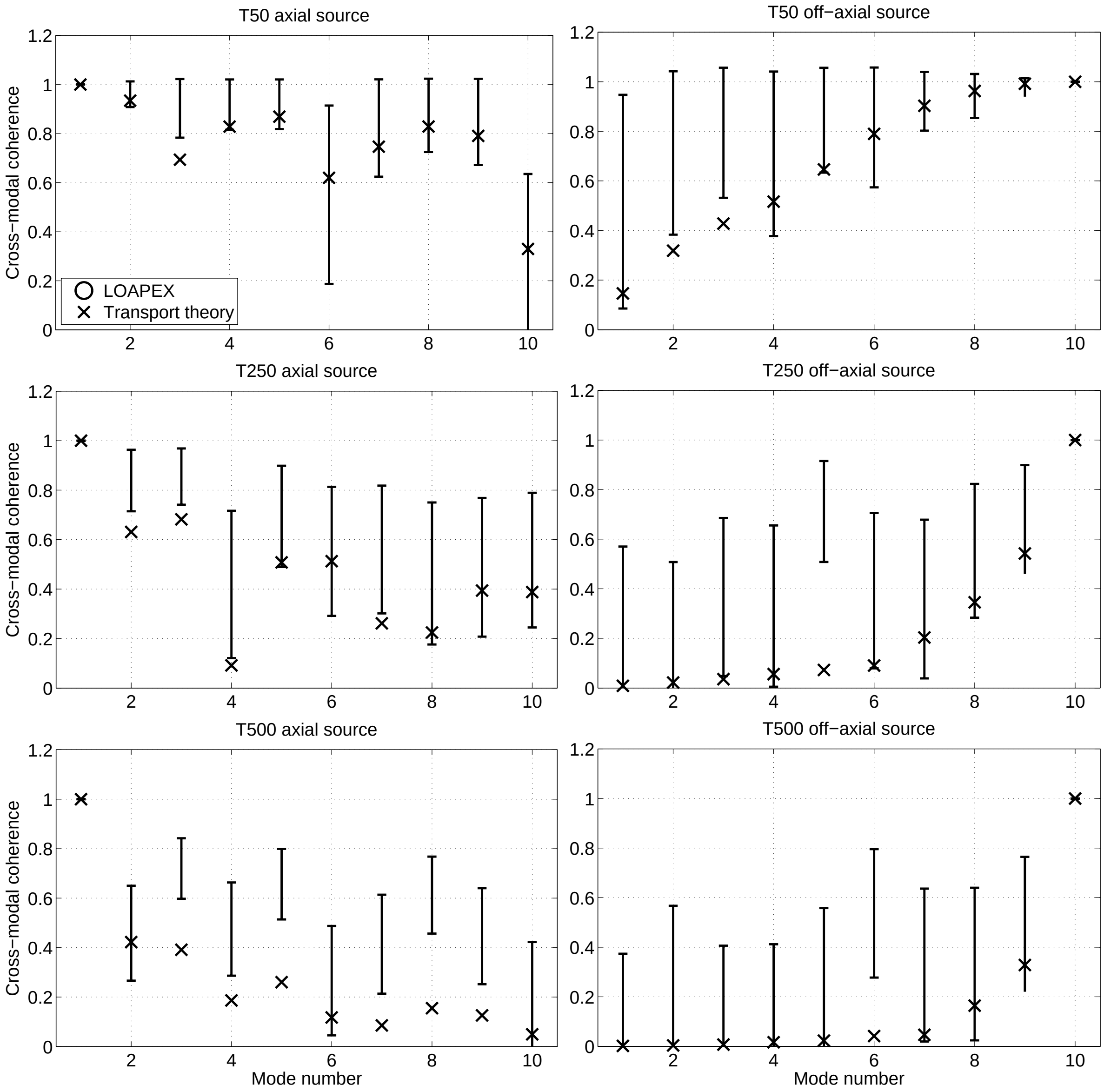


Figure 3: Observed cross modal coherence (circles) with error-bars compared to transport theory (crosses) for stations T50, T250, and T500. Axial source results are plotted on the left while off-axial results are on the right.

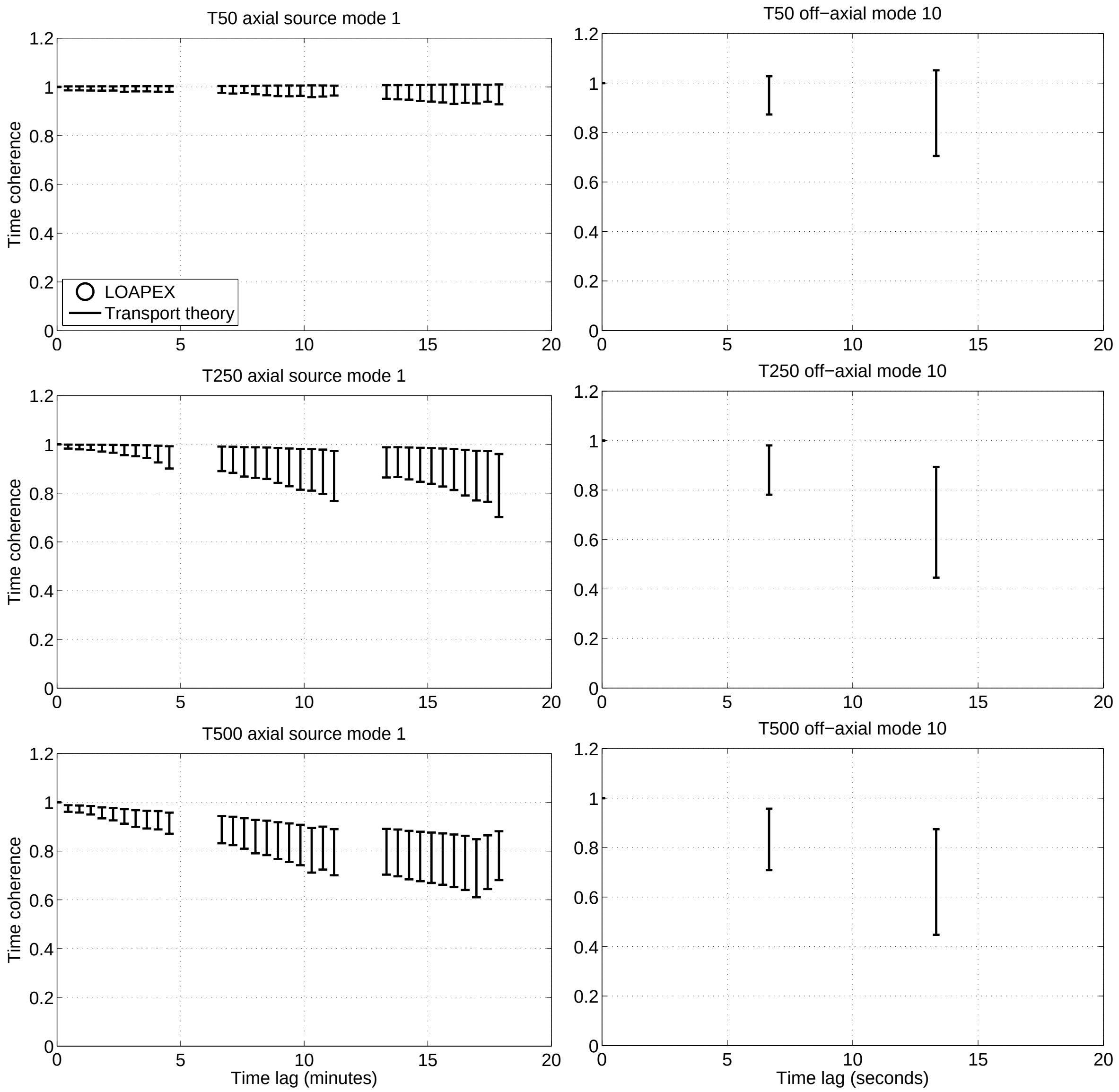


Figure 4: The left panels show observed and transport theory predicted mode 1 time coherence for the axial source at stations T50 (upper), T250 (middle), and T500 (lower). The right panels show observed and transport theory predicted mode 10 time coherence for the off-axial source at stations T50 (upper), T250 (middle), and T500 (lower).

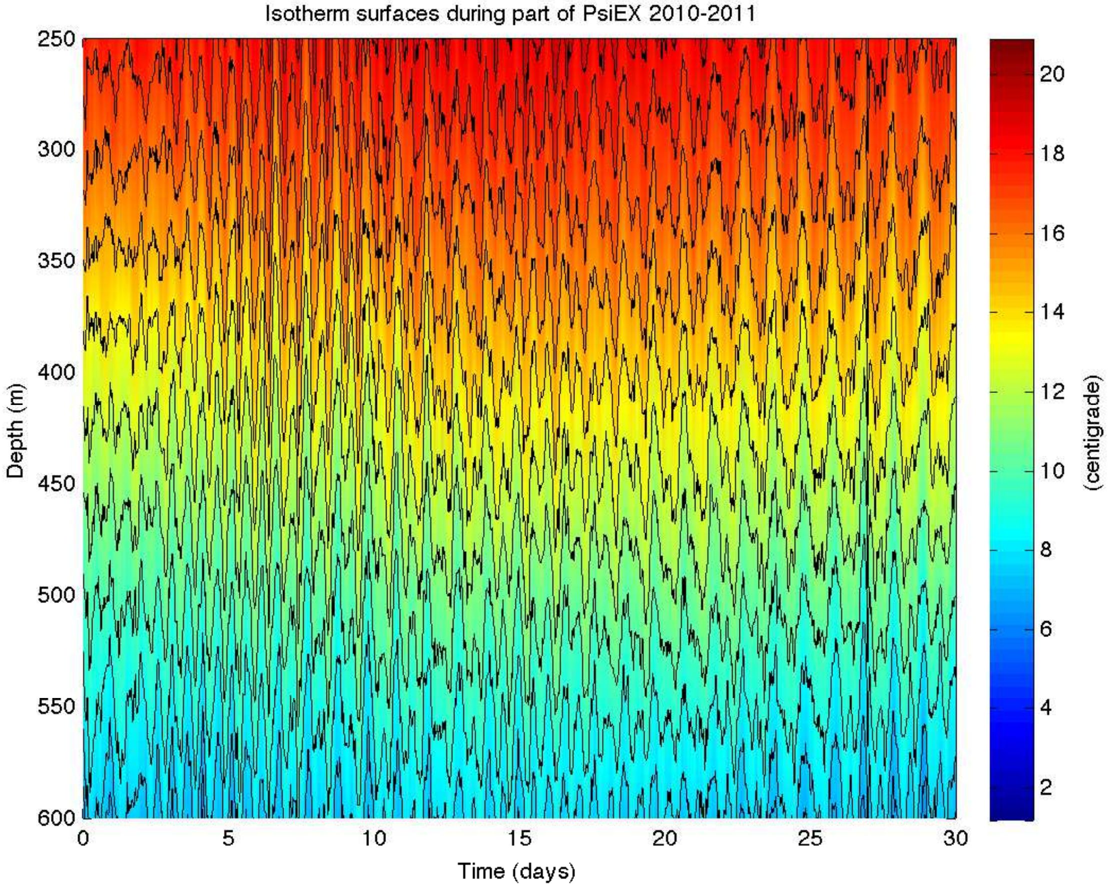


Figure 5: Isotherms (during the first 30 days of PsiEX) around the thermocline. The isotherms were tracked using the temperature measurements made by the thermistors attached to the hydrophones of the PsiEX array. The temperatures at the different times were interpolated onto a common time grid with sampling rate of 2 samples/hour. The temperature surfaces tracked were the mean temperature at each thermistor depth

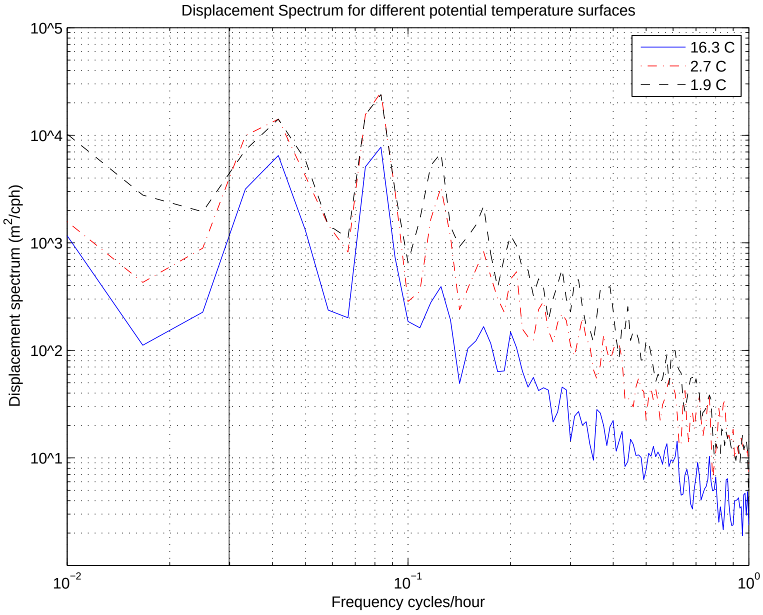
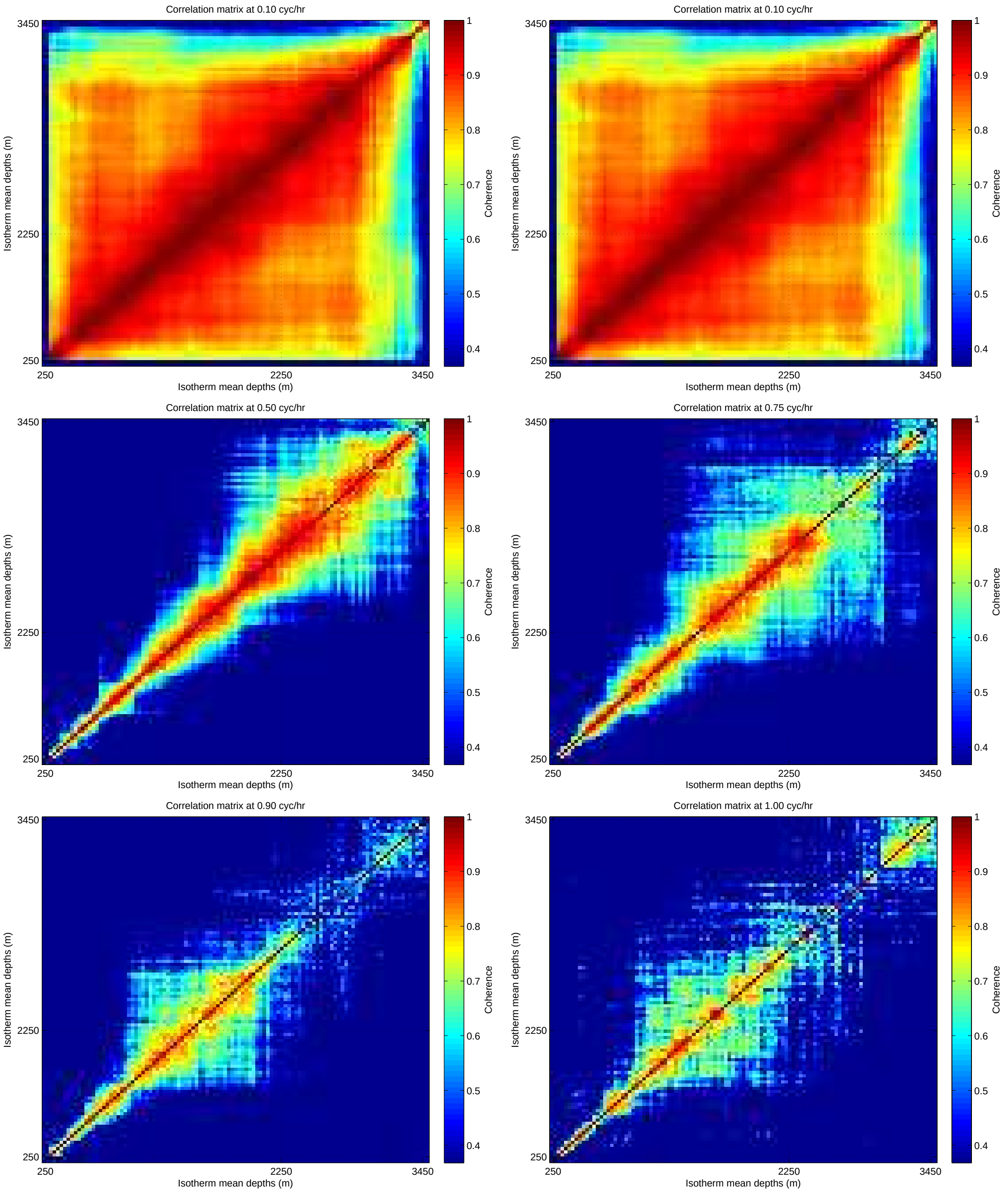


Figure 6: Isotherm spectra for different potential temperature surfaces (depths). The solid black line indicates the Coriolis frequency.



Correlation matrix at 0.10 cyc/hr

Correlation matrix at 0.10 cyc/hr

Correlation matrix at 0.50 cyc/hr

Correlation matrix at 0.75 cyc/hr

Correlation matrix at 0.90 cyc/hr

Correlation matrix at 1.00 cyc/hr

Figure 7: Isotherm correlation matrix for different internal wave frequencies. The correlation matrices shown here were estimated using the first 30 days of the Philippine 2010-2011 observations.