Acoustic Transmission Loss through Modelled Oceanography over a Long Time Period Compared to Climatology

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Abstract— Acoustic transmission loss (TL) has been computed using oceanography modeled by the Navy Coastal Ocean Model (NCOM) over an 18 month time period in the Western Pacific Ocean [Jacobs, G. A., J. G. Richman, J. D. Doyle, P. L. Spence, B. P. Bartels, C. N. Barron, R. W. Helber, and F. L. Bub (2014), *Simulating conditional deterministic predictability within ocean frontogenesis, Ocean Modelling*, 78, 1-16]. The predicted acoustic variability over this time period is analyzed at specific locations and acoustic frequencies. Examples of full field TL at a number of snapshots are presented and discussed with respect to environmental acoustic features (e.g. sonic layer and convergence zone). TL thresholds were chosen to calculate ranges that describe the acoustic propagation due to the features and variability was using these metrics is discussed. For example, variability in the width and range of the CZ over time as well as the percentage of time the features persist, is analyzed. Similar analysis is done using the Generalized Digital Environment Model (GDEM) climatology model at the same location and the results are summarized compared. Statistics summarizing the acoustic TL for a number of subsets of the modeled TL and comparisons from climatology are presented and are shown to be non-Gaussian and inconsistent between the two locations.)

Keywords— *acoustic propagation; time series; climatology; ocean model; range dependent acoustic model; statistics;*

I. INTRODUCTION

Acoustic propagation or transmission loss (TL) depends on a number of factors, including frequency and location (geographic and depth) of an acoustic source, water depth along the acoustic path (defined versus range from the source), sound speed versus range and depth, wind speed versus range, and sediment properties (sound speed, density, attenuation) versus range and depth below the bottom. Ocean analysis from Jacobs et al.¹ is used as input for estimates of acoustic transmission loss (TL) for four selected locations in the Western Pacific Ocean over an 18 month time period. For the purposes of examining the variability of the acoustic propagation due to the evolving oceanography, all inputs to the acoustic model are fixed except for the ocean sound speed versus range and depth, which varies with time as predicted by the Navy Coastal Ocean Model (NCOM)².

The Range Dependent Acoustic Model (RAM)² is used to compute acoustic TL for two frequencies (500 and 1000Hz)

along the selected source-to-receiver tracks, using a source depth of 10m. RAM is a fast, research quality, finite element parabolic equation (PE) model that applies a multiple-term Padé approximation to the PE operator³. Bathymetry from the NAVO DBDBV database⁴ is used for the water depth and a geo-acoustic analysis⁵ is used for the sediment description. Water depth and area of interest with the two acoustic track locations are plotted in Fig. 1(a). The shallower site, S1 is approximately 2000m deep and deepens to around 6000m with range and the deeper site, S2, is fairly flat with a depth around 6000m.

An acoustically important phenomenon that occurs in the upper ocean is a sonic layer or surface duct, where energy at certain frequencies, from sources within the duct can be trapped. Mixing and warming near the surface can impact the nature of a duct over various space and time scales¹. The depth of this duct, or the sonic layer depth (SLD) along with parameters such as the acoustic frequency, source location, receiver location, wind speed and sound speed gradients within the waveguide, all define the potential for acoustic ducting. The spatial variability of ducting can be seen in Fig. 1(b), which shows a snapshot of the SLD on Feb 28, 2005. The temporal variability is evident in Fig. 1(c), which shows the standard deviation (*std*) of the SLD over the month of February, 2005.

II. TRANSMISSION LOSS (TL)

RAM TL versus range (km) and depth (m) at 12Z on Feb 28, 2005, due to a 1kHz source (at a depth of 10m), is shown for the two sites, S1 and S2 in Fig. 2(a) and (c), respectively. Fig. 2(b) and (d) show the upper 200m of the waveguide for each of the cases, with the SLD plotted in white. At 1kHz the wavelength (λ) is approximately 1.5m. Near-surface ducting occurs in both cases. S1 has a fairly deep duct that starts at a depth around 130m ($\sim 87\lambda$), deepens to 150m ($\sim 100\lambda$) at 12km, then thins to 70m ($\sim 47\lambda$) at 25km. Beyond 25km it deepens and remains just deeper than 80m ($\sim 53\lambda$) to the maximum range. As is evident by the TL (Fig. 2(b)), the duct weakens beyond the ranges that it thins (12km and 30km), where the energy escapes the duct and either turns back toward the surface due to deeper upward gradients (e.g. ~ 30 km and 70km) or interacts with the bottom (e.g. ~ 40 km). The deeper site has a fairly strong convergence zone (CZ), where lower angle energy from the source does not interact with the bottom, is turned by the pressure gradient near the bottom and converges near the surface around 65km in

range. The duct for S2 is shallower ($\sim 50\text{m}$ or 33λ) and weaker, than at S1, but does not thin significantly with range. The TL in the upper 200m for S2 (Fig. 2(d)) shows weak ducting that persists decreases with range and more detail within the CZ between 60 and 80km. The complexity and variability of the ducted energy within a waveguide is evident in these two cases. Next, the temporal variability over the 18 month ocean analysis period is examined.

Fig. 1. Bathymetry (m) from DBDBV (NAVO, 2011) (a), SLD (m) for Feb 28, 2005, 12Z (b) and *std* of SLD (m) over the month of Feb, 2005 (c).

Fig. 3 shows the 1kHz TL at a single (10m) receiver depth, versus range (km) and time, for sites S1 (Fig. 3(a)) and S2 (Fig. 3(b)). The time axis is labeled by month and year and spans the analysis period between Jun 1, 2004 and Dec 21, 2005 at 3 hour increments. Fig. 4 shows the same type TL display for 500Hz. Stronger ducting occurs in the winter months at higher frequencies, as shown by the lower loss (red/orange/yellow,

higher energy) that are continuous in range from the source location (at range=0) to the maximum receiver range (80km). The yellow, green and blue features that persist in time between 0 and 40km at both sites are bottom bounce regions that vary primarily with the sound speed gradients. Persistent red/yellow features between ~ 60 and 70km at Site 2 are CZs and also vary with the sound speed gradients.

Fig. 2. RAM TL versus range (km) and depth (m) at 12Z on Feb 28, 2005, due to a 1kHz source (at a depth of 10m), for S1 (a) and S2 (c). Upper 200m of the waveguide for S1 (b) and S2 (d), with the SLD plotted in white.

Fig. 3. 1kHz TL at a single (10m) receiver depth, versus range (km) and time, for sites S1 (a) and S2 (b) from Jun 2004 to Dec 2005.

Fig. 5(a) contains the same information as Fig. 3(b) for S2, but for a shorter time period, Feb 2005 to mid-Jun 2005. Fig. 5(a)-(i) provides TL snapshots at four times, to give a better understanding of the various phenomenon. The white dashed lines indicate where the snapshots are taken. Fig. 5(b) and (c) give the TL versus range and depth and TL at 10m respectively, at 9Z May 31, 2005. Here we see a summer case where there is no ducting, bottom bounce is evident between 0 and 40km and that the environment is such that the CZ (at $\sim 60\text{km}$) is very weak, that is, it is below 100dB. Fig. 5(a) shows that this type of propagation occurs sporadically from late May to early June. At lower frequencies, as shown in Fig. 4, this weakening of the CZ occurs more frequently, primarily in the summer months. Fig. 5 (d) and (e) showing TL for 21Z Apr 4, 2005, indicate a

typical CZ-type propagation with no ducting, here the CZ is fairly strong at approximately 75dB. Fig. 3(b) and 5(a) indicate that the CZ is almost always present at this location (though can weaken significantly as noted previously), but it can vary in range and extent. Fig. 5 (f) and (g) give an example of a weakly ducted CZ environment for 3Z Mar 24, 2005. Here, the top 800m of the water column (Fig. 5(f)) show a duct that persists only to just beyond 30km and a CZ that is slightly extended in range due to weak ducting at and beyond the CZ range. This type of weakly ducted environment occurs frequently through the non-winter months as indicated in Fig. 3(b) and 5(a) and a lower frequencies, where the wavelengths are longer, as shown in Fig. 4. Finally, Fig. 5 (h) and (i) for 0Z Feb 4, 2005 show fairly strong ducting for the entire range in addition to the CZ. In this case, the CZ is disrupted a little due to interaction with the low angle energy in the duct. This sort of interference is also evident in the strongly ducted events during the winter months in Fig. 3(b) and Fig. 5(a).

Fig. 4. 500Hz TL at a single (10m) receiver depth, versus range (km) and time, for sites S1 (a) and S2 (b) from Jun 2004 to Dec 2005.

III. COMPARISON TO CLIMATOLOGY

It is well understood that climatological averages smooth out many of the interesting phenomenon discussed in the previous section. Climatology may be used in the absence of ocean analysis or predictions, so it is informative to compare model estimates such as those made here with NCOM, to predictions made with climatology. Fig. 6 shows the 1kHz TL computed from GDEM⁶ monthly climatology for the time period of interest (Jun 2004-Dec 2005) for sites S1 (a) and S2 (b) for comparison to Fig. 3. Environmental information from NCOM is provided every 3 hours in time and every ~ 3 km in space whereas the climatology is provided monthly every ~ 9 km in space, which accounts for some of the differences noted. Fig. 7 shows the 500Hz TL computed for GDEM. As expected, for both frequencies at both locations, the climatological estimate is much smoother both in space and time, and significantly underestimates both the strength and occurrence of ducting, while over estimating the strength of the CZ. The climatology does capture the structure and variability on a broad seasonal scale.

Fig. 5. 1kHz TL versus range (km) and time from Feb 2005 to mid-Jun 2005. (a), snapshots of TL versus range and depth (m) for (b) 9Z May 31, 2005, (d) 21Z Apr 4, 2005, (f) 3Z Mar 24, 2005, (h) 0Z Feb 4, 2005 and TL at a 10m receiver versus range for (c) 9Z May 31, 2005, (e) 21Z Apr 4, 2005, (g) 3Z Mar 24, 2005, (i) 0Z Feb 4, 2005.

Fig. 6. 1kHz TL based on climatology, at a single (10m) receiver depth, versus range (km) and time, for sites S1 (a) and S2 (b) from Jun 2004 to Dec 2005.

IV. VARIABILITY OF ACOUSTIC FEATURES

As evident in Fig. 3 and Fig. 4, the acoustic propagation varies significantly with time. In order to characterize this variability, simple thresholds are defined between selected ranges, and ranges are selected from the point at which the TL at a depth of 10m crosses the threshold. The sonic layer (SL) threshold is chosen to be 80 dB between 2.5 and 55km for the purposes of this analysis. The maximum range between 2.5km, to which there is loss lower than the threshold (higher energy) at S2, 1kHz is shown in Fig. 8a. Because of the definition used, at

all locations and frequencies, the SL range varies between the minimum and the maximum. The maximums occur in the winter months when the duct is very strong and extends the full range. During the rest of the year, the SL range varies between the minimum and 10-20km at S1 and between the minimum and 30-40km at S2. At 500Hz at both sites, the duct is weaker and extends to maximum range intermittently in the winter months and at other times of the year generally reaches to only around 10km at S1 and less than 10km at S2.

Fig. 7. 500Hz TL based on climatology, at a single (10m) receiver depth, versus range (km) and time, for sites S1 (a) and S2 (b) from Jun 2004 to Dec 2005.

The convergence zone is a fairly stable feature in deep water, however, there is variability with the range and extent of the CZ. In order to analyze this variability, a method was devised using a threshold crossing to define the CZ. That is, the start range of the CZ is chosen to be where the 10m TL first falls below the threshold (chosen for convenience to be 85dB) after a range of 45km, the CZ width is chosen as the center of the TL below the threshold, and the end range of the CZ is chosen as the threshold crossing beyond this center. Fig. 8b shows the CZ ranges for S1 at 1kHz, for which the minimum range varies between 57 and 68km, the maximum varies between 58.8 and the 80 and the width varies between .5km and 18km. The longer range CZs are due to existence of an SL, which can significantly extend the ranges of the low angle CZ energy. Table 1 and Table 2 summarize the SL and CZ metrics discussed here using predictions from both oceanographic descriptions at S1 and S2, respectively. Table 1 shows SL information for S1, SL maximum range, the percentage of time there is no SL, and percentage of time the SL reaches the maximum range. Table 2 gives SL and CZ information for S2 as in Table 1 along with the minimum and maximum of the start range, end range and width of the CZ (km) and the percentage of time there is no CZ and that the CZ reaches maximum range. The tables also contain information about the occurrence of the features: the percentage of time that the features do not meet the threshold criteria and the percentage of time the threshold is met to the maximum range. For example, at S2, 1kHz, there is no SL 14.6% of the time and the SL reaches maximum range 0.6% of the time. Because S1 is shallow, there is no CZ at that site, thus no CZ metrics.

TABLE I.

S1		SL R (km)	% no SL	% SL=R _{max}
500Hz	NCOM	54.5	6.9	1.2
	GDEM	54.5	52.7	4.8
1kHz	NCOM	54.5	8.7	19.8
	GDEM	12.0	68.8	4.8

TABLE II.

S2		SL R, km	% no SL	% SL=R _{max}	CZ Start	CZ End	CZ Width	% no CZ	% CZ=R _{max}
500 Hz	NCOM	29.0	55.6	0.02	57.0 - 65.5	59.5 - 79.5	0.5-13.5	30.1	.06
	GDEM	29.0	21.0	10.7	61.5 - 63.0	64.0 - 72.5	2.0-5.5	16.0	5.3
1 kHz	NCOM	54.5	14.6	0.6	57.0 - 68.0	58.5 - 79.5	0.5-18.0	32.9	3.9
	GDEM	3.0	68.8	26.4	61.5 - 62.5	63.5 - 66.0	1.5-4.5	0.02	5.3

V. STATISTICS

Statistics over various subsets of the data are computed using 1dB TL bins for each frequency at each of the sites. The range of the statistical variability is such that it is difficult to easily summarize or draw conclusions based on the statistics, but examples of the statistics at the deep site, S2 for 1kHz are discussed. None of the distributions analyzed were Gaussian, many are bimodal and a number are multi-modal. Fig. 9a shows the PDF of all the 1kHz information over the entire 18 months from S2, using NCOM (black) and GDEM (green). The GDEM distributions tend to be spikier because they are populated with less data (1 field per month rather than 1 field every 3 hours). The NCOM data has the peak at 102 dB and has a distribution that is wider above the peak and trends a little toward bimodal. The GDEM distribution has a peak at 109 dB and is wider below the peak. Fig. 8b considers a subset of this information taken around a depth of 10m, so energy near the surface from all phenomenon is captured (e.g. ducted, CZ and bottom bounce). Here both distributions show multi-modal behavior, which can be loosely attributed to ducted energy (peaks with lower TL) and CZ energy (peaks with higher TL). Future efforts will attempt some angular analysis to more robustly separate the phenomenon. Fig. 9c and 9d show the distributions for the 60m and 150m receiver depths, respectively. Next, the TL was subset into 20km range bins. It is expected that ducted, bottom bounce and CZ energy will populate the ranges below ~60km and the CZ and ducted energy will populate the higher range bins, but as shown in the previous section, there is no clear division of acoustic phenomenon by range or depth. Fig. 10 shows the distributions for all depths for each of the 4 20km bins. The distributions for the lower two bins (0-20km in Fig. 10a, and 20-40km in Fig. 9b) are similar for both NCOM and GDEM, but differ significantly at the higher ranges (40-60km in Fig. 10c and 60-80km in Fig. 10d). Fig. 11 shows the distributions divided

into both range (from left to right) and depth (top to bottom). Here the subset for which the NCOM and GDEM show best agreement is 150m deep between 20 and 40km (Fig. 11j). Comparisons were also made (but are not shown) to the shallow S1, little similarity was found between the two sites due to the different waveguide shapes and propagation types.

Fig. 8. Range (km) for acoustics features at S2, 1kHz, sonic layer (a) and convergence zone (b).

VI. CONCLUSIONS

This study presents TL versus range, depth and time, computed by a research grade acoustic propagation model (RAM) at two locations and two frequencies over a long (18 month) time period. Oceanographic descriptions from both a high fidelity ocean analysis, and from climatology were provided to the acoustic model for this analysis. The NCOM analysis provided snapshots every 3 hours (resulting in 4640 snapshots) and the climatology was provided monthly (18 snapshots, only 12 unique). Examples of full field TL at a number of snapshots are presented and discussed with respect to environmental acoustic features (e.g. sonic layer and convergence zone). TL thresholds were chosen to calculate ranges that describe the acoustic propagation due to the features and variability was described using these metrics. For example, at the deep site, S2, the 1kHz CZ range was found to vary between 57 and 68km and the width of the CZ varied between .5 and 18km, and 32% of the time, the energy in the CZ did not meet the threshold (85dB). At S1, the shallower site, the 1kHz

SL contained energy that met the threshold (80dB) was present more than 92% of the time, and varied significantly in range.

This study provides an interesting analysis of the temporal variability of TL over a long time period and a strong basis for further study using larger and more varied datasets. This and expanded datasets can be used to understand the nature of TL and its dependence on the varying waveguide.

Fig. 9. Distribution of TL for S2, 1kHz for NCOM (black) and GDEM (green), using all ranges and depths (a), all ranges, 10m depth (b), all ranges, 60m depth (c) and all ranges, 150m depth (d).

Fig. 10. Distribution of TL for S2, 1kHz for NCOM (black) and GDEM (green), using all depths between 0 and 20km (a), 20 and 40km (b), 40 and 60km (c) and 60 and 80km (d).

Fig. 11. Distribution of TL for S2, 1kHz for NCOM (black) and GDEM (green), using the depths and ranges of interest. (a) 10m depth, 0 to 20km, (b) 10m, 20-40km, (c) 10m, 40-60km, (d) 10m, 60-80km, (e) 60m depth, 0 to 20km, (f) 60m, 20-40km, (g) 60m, 40-60km, (h) 60m, 60-80km, (i) 150m depth, 0 to 20km, (j) 150m, 20-40km, (k) 150m, 40-60km, and (l) 150m, 60-80km.

ACKNOWLEDGMENT

The author thanks Richard Keiffer and Robert Zingarelli for many helpful discussions.

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