

Effects of Atmospheric Profiles on Short Range Infrasound Propagation

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ABSTRACT

A deep understanding of the impact of the natural environment on short range (< 150 km) infrasound propagation is important to the military, specifically for safe and efficient route planning. Passively sensing the infrasound field provides useful information about the condition of infrastructure or any activity of interest along the selected route. Meteorological profiles strongly influence the propagation of an infrasound signal; therefore, understanding the effects of different profiles is crucial for both determining the source of a signal and estimating how far away that signal may be readily detected. This paper focuses on simplified vertical temperature profiles up to 20 km altitude and their effect on an infrasonic signal emanating from an arbitrary point source. A wide-angle, finite-element PE model that correctly handles discontinuities in wavenumber is used for calculating transmission loss. A large number of simulations were performed to investigate the effect that temperature profiles in different layers of the atmosphere have on surface transmission loss and to assess the sensitivity of varying these profiles. A discussion of the results of these simulations are presented as well as an overview of the PE model and temperature profiles used in this study.

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1. INTRODUCTION

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Traditional acoustic propagation (20 Hz - 20 kHz) occurs primarily in the first kilometer of the atmosphere, commonly referred to as the planetary boundary layer, and propagation ranges are up to 10 km. Long-range infrasound propagation occurs primarily in the stratosphere, although the waves do pass through the boundary layer. Using the assumption that returns occur from an altitude approximately $1/10^{\text{th}}$ of the propagation range, short-range propagation occurs in the boundary layer, the free atmosphere, and in the lower portion of the stratosphere. Because of the high temporal variability in this region, the transmission loss can change dramatically with meteorological conditions, as shown in McKenna et al. (McKenna 2008). Therefore, the atmosphere's characteristics from the ground up to an altitude of approximately 20 km is of great importance for infrasound propagation in this distance regime (up to 150 km). Meteorological profiles strongly influence the propagation of an infrasound signal; therefore, understanding the effects of different profiles is crucial for both determining the source of a signal and estimating how far away that signal may be readily detected.

This study begins a detailed analysis of the impacts of meteorological conditions in the atmosphere up to an altitude of 20 km on infrasound propagation. In the work presented here, a simplified approach is used to begin to frame the bounds of refractive effects and provide insights into the resolution needed to reasonably estimate transmission loss under varying conditions. Here a layered atmosphere approach is used, with linear temperature profiles in each layer. By varying the temperature gradient in each layer in a systematic way, a picture of the sensitivity of transmission loss to these changes emerges.

This paper begins by describing the meteorological representation used in the study. Next, a brief description of the propagation model is presented. This is followed by an overview of the methodology employed. Then results are presented and discussed. Finally, some conclusions and a preview of future work are presented.

2. METEOROLOGY

The real atmosphere can be represented as a complex layered medium. In this study, the maximum altitude considered is 20 km, corresponding to $1/10^{\text{th}}$ of the maximum horizontal range of interest. Within this region, the atmosphere can be divided into three distinct layers: the planetary boundary layer (PBL), the free atmosphere (FA), and the stratosphere. For this study, the PBL extends from the surface up to an altitude of 1 km, the FA extends from 1 km to 11 km, and the stratosphere begins at 11 km. Table 1 provides a quick reference of nomenclature, extent, and dominant temperature gradients for each layer.

Table 1: Layer definitions and abbreviations used in this study for the 3-layer atmospheric model.

Atmospheric Layer	Abbreviation	Altitude Range	Temperature Gradient (+/-)
Planetary Boundary Layer	PBL	Surface - 1 km	Day: - Night: +

Free Atmosphere	FA	1 km - 11 km	-
Stratosphere	Stratosphere	11 km - 47 km	+

Table 2: Layer definitions and abbreviations used in this study for the 4-layer atmospheric model.

Atmospheric Layer	Abbreviation	Altitude Range	Temperature Gradient (+/-)
Planetary Boundary Layer	PBL	Surface - 1 km	Day: - Night: +
Free Atmosphere	FA	1 km - 11 km	-
Stratosphere	Stratosphere	11 km - 47 km	+
Inversion	Cap/Subsidence Inversion	Cap: 1 km - 1.25 km Subsidence: 4 km - 4.25 km	+

The planetary boundary layer (PBL) is the layer of the troposphere that interacts with the Earth's surface and is affected by surface friction. Depth of the PBL can vary from as little as 100 m to as much as 3 km above the surface. Wind shear induced turbulence and vertical mixing play a large role in determining the depth of this layer. Areas that receive strong solar radiation (Southern United States and Great Plains in the summer) see deeper PBLs and stronger temperature gradients (Stull, 1988). Most of the time, temperature gradients in this layer are negative during the day and positive during the nighttime.

The free atmosphere (FA) occupies the layer of the troposphere above the PBL. The FA occupies the rest of the troposphere, which can be as shallow as 8 km in polar regions and as deep as 16 km in the tropics with an average depth around 11 km (Pidwirny 2006). For this study, 11 km was used, as this is a good representative average depth of the troposphere. The air in this layer is free from the influence of Earth's surface, i.e. surface friction (Wallace 2006). Temperature gradients are generally similar to or weaker than in the PBL and almost always negative. Temperatures in the troposphere (PBL and FA) naturally decrease with altitude. Decreasing air density with height and strong solar heating at the surface play large roles in this.

The stratosphere extends from 11 km up to the top of the calculation space at 20 km; in the real atmosphere, this layer extends to an altitude of 47 km. Temperatures in the stratosphere increase with height mainly due to the heating effects of ozone. FA and stratosphere layer depths were obtained from the International Standard Atmosphere (ISO 2533:1975).

This study focuses on the influence of dominant temperature gradients in each of these layers on short-range infrasound propagation. To accomplish this, highly simplified profiles using linear temperature gradients are used. In traditional meteorology, these vertical temperature gradients are defined as lapse rates. A positive lapse rate is used to describe decreasing temperature with height, since temperature normally decreases with height in the troposphere where most of Earth's weather takes place (Andrews

2000). However, for clarity, temperature gradient will be used throughout the remainder of this paper and positive values (e.g. +6 C/km) will be referred to as positive temperature gradients.

A relatively shallow fourth layer is included in a portion of this study to investigate the effects of capping, subsidence, and nocturnal inversions. These are referred to as inversion layers where temperature gradients change from negative to positive (Wallace 2006). They are usually shallow features about 500 meters deep or less. Inversions can result from several different processes. One of the more common types of inversions is known as a capping inversion that sits atop of the PBL and acts as a “cap” for vertical air motions (Petty 2004). This is especially common in the central part of the United States where warmer, and typically drier air from the high plains is advected over the existing PBL in lower elevation regions to the east. Another common type of inversion is a subsidence inversion that can occur above the PBL and capping inversion. These are found frequently in areas of high pressure where air gradually sinks and warms through adiabatic compression (Petty 2004). The most common inversion develops overnight and is most prominent just before sunrise. This is known as a nocturnal inversion. The best local infrasound propagation has been experimentally observed under these circumstances (McKenna 2008). When the sun sets and radiational heating shuts off, Earth’s surface begins to cool fairly rapidly. This cooling grows throughout the nighttime from the surface vertically upward resulting in the inversion layer extending as high as 500 meters above the surface. Clear skies and calm winds at night are ideal conditions for strong nocturnal inversions (Wallace 2006). The four-layer model is summarized in Table 2.

3. INFRASOUND PROPAGATION MODEL

Infrasound propagation in the atmosphere is modeled using a finite element representation of the parabolic equation (PE). The formulation handles discontinuities in density and wavenumber by explicitly solving for the physical interface conditions, continuity of pressure and continuity of normal component of particle velocity, at every height in the computation space. This development follows Huang (Huang 1988) and Lee & Seigmann (Lee 1995). A more detailed description of the algorithm used here is in Swearingen, et al., 2016 (Swearingen 2016).

The propagation space is defined as extending from the ground to an altitude of 20 km, and with a horizontal range of 200 km. The ground boundary is acoustically rigid and the highest altitude has a radiation condition. A 10-wavelength absorbing layer using the perfectly matched layer (PML) method (Yevick 2000) is added to the top of the propagation space to ensure no spurious reflections. A 5-Hz point source of infrasound represented with Gaussian spatial dependence is located 2 m above the ground, and receivers are assumed to be on the ground. This source height was selected to represent a source near, but not on, the ground. A 5-Hz frequency was selected to provide a representative signal that potentially propagates to ranges of 200 km while still clearly influenced by refraction. Additional frequencies will be explored in a follow-

on study. Atmospheric absorption is included according to ISO 9613-1; at 5 Hz, the attenuation at 200 km is approximately 6 dB.

4. METHODOLOGY

The parameter of greatest interest for this study is the transmission loss (TL) at the surface. Transmission loss is defined as the loss, in negative decibels, relative to a unit source at the origin. For example, a TL of - 60 dB means that the level is reduced by 60 dB relative to the source. Transmission loss is calculated as

$$TL = 10 \log_{10} \left(\frac{p^2}{p_{ref}^2} \right)$$

where p is sound pressure in N/m^2 at the location of interest and p_{ref} is sound pressure in N/m^2 at the origin (Jensen 2011). Because sound pressure decays with distance, values of TL are always negative.

Using the aforementioned three and four layer models of the atmosphere, a number of simulations were performed to analyze the TL field of an infrasonic signal emanating from an arbitrary point source in an atmosphere consisting of differing temperature profiles. The effects of wind are neglected in this study; this choice was made to further simplify the study and to directly investigate the influence of temperature-driven refraction. A rigid ground surface is assumed and the radiation condition, along with an absorbing layer to ensure no artificial returns, is imposed at the top of the calculation space. The calculation space extends to 200 km in horizontal range and 20 km in altitude. A 5 Hz infrasonic signal is used for all simulations discussed in this paper. Transmission loss at the surface is examined first to explore the relative effects of each atmospheric layer. Finally, contour plots of surface TL are utilized to compare the effects of varying the temperature gradients in two different atmospheric layers and to identify regions where these temperature gradients must be accurately known. These plots are presented in the next section accompanying a discussion of the results found.

5. RESULTS AND DISCUSSION

This section begins by examining short-range infrasound propagation in atmospheres with commonly observed temperature profiles. This provides a base understanding of the general effects of these profiles on TL, as well as a simple check to ensure that the propagation code is operating correctly. Extreme gradients are then examined to estimate minimum and maximum refractive effects. Next, each atmospheric layer (stratosphere, PBL, FA, inversions) is tested for the effects that varying temperature gradients in one layer only have on the surface TL and to estimate how sensitive the surface TL is to each layer. Finally, contour plots are generated to better compare the sensitivity of one layer to another and understand the amount of influence each layer has on surface TL. These plots also provide insight into how finely the temperature gradients must be known to estimate surface TL.

To start, a simulation with an isothermal profile throughout the depth of the calculation space, i.e. temperature gradients of zero in all three atmospheric layers, was performed for reference. Initial tests consisted of idealized atmospheric profiles that are frequently observed in the United States and profiles with the most extreme temperature gradients. These tests verify that the model performed correctly and to provide a rough estimate of the minimum and maximum refraction effects. This initial check is critical, as the effective sound speed profiles have sharp bends present at the layers. These tests were successful in verifying that the codes work properly.

Next, the impacts of varying the temperature gradients were tested one layer at a time. The first layer tested was the stratosphere. Three different stratospheric temperature gradients (+1, +3, +5 C/km) were compared. Each stratospheric temperature gradients were run with the same seven tropospheric profiles (PBL and FA combined) – three upward refracting profiles, three downward refracting, and one isothermal.

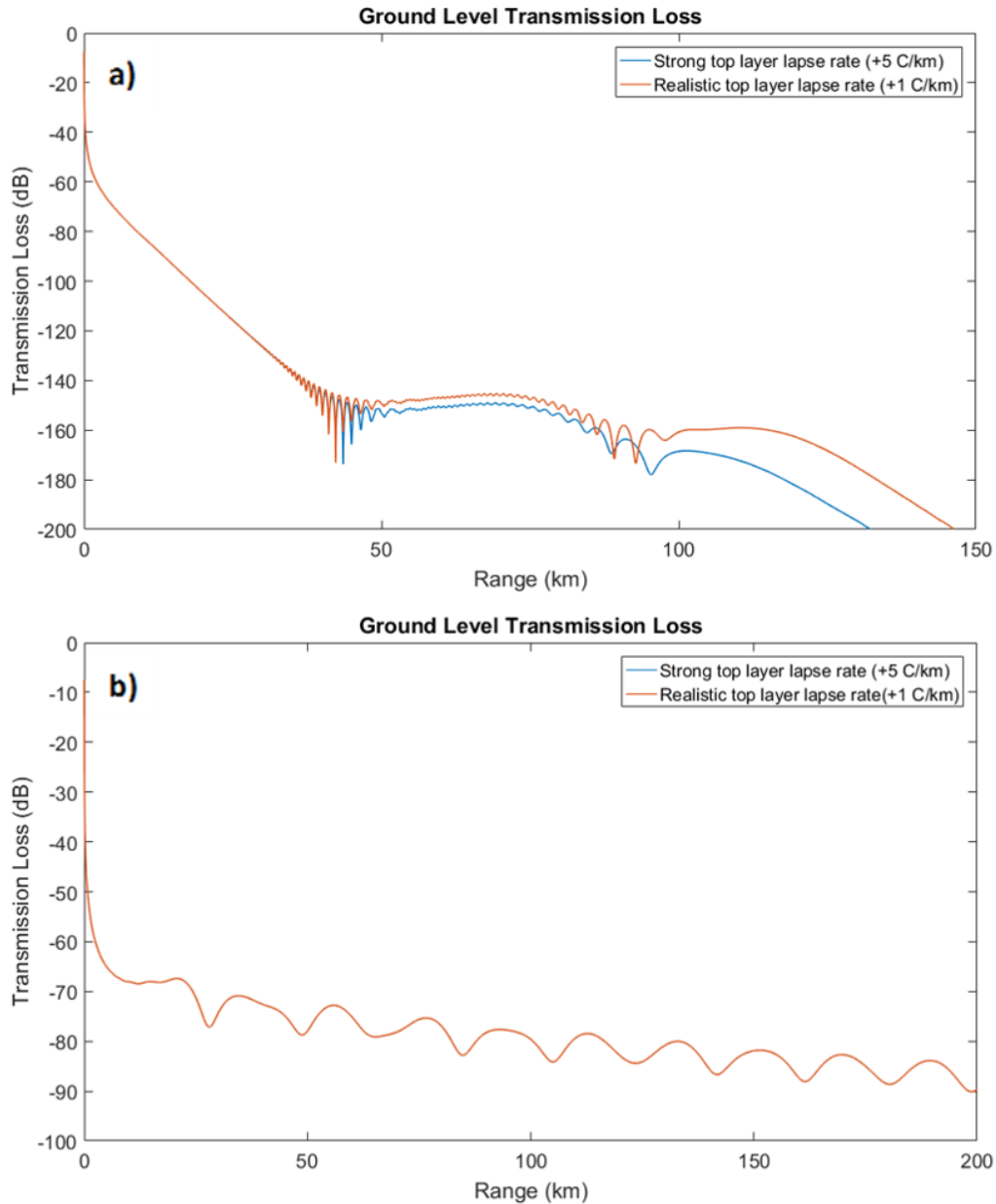


Figure 1. **a)** Surface TL for stratospheric lapse rates of +5 C/km and +1 C/km. PBL: -9.8 C/km; FA: -6.5 C/km. **b)** Surface TL for stratospheric lapse rates of +5 C/km and +1 C/km. PBL: +5 C/km; FA: -6.5 C/km. Curves are completely identical. There is no difference in surface TL between a realistic and strong stratospheric lapse rate above a downward refracting PBL.

In an upward refracting PBL, the surface TL is identical for all stratospheric temperature gradients up until ~40 km. At a horizontal range of 40 km, the surface TL exceeds 145 dB, see Figure 1a. Here the TL curves diverge; however, very few signals would be strong enough initially to be detected after a 145 dB reduction in level, so this divergence is not considered important. It is also important to remember that these calculations are being performed under highly idealized conditions. Additionally, stratospheric temperature gradients of +5 C/km throughout the depths used here are

not found in the real atmosphere, so any differences between the two curves in Figure 1a are an extreme upper limit. In a downward refracting PBL, surface TL is completely identical throughout, indicating stratospheric temperature gradient has no impact at these ranges (Figure 1b). From these results, it can be concluded that stratospheric temperature gradient has a negligible effect on surface TL. Therefore, the stratospheric temperature gradient is fixed at 1 C/km for all later simulations.

Six different PBL temperature gradients (-12, -9.8, -6.5, +2, +5, +10 C/km) were compared in order to examine surface TL sensitivity to temperature gradients in the PBL. For each PBL temperature gradient, a simulation was performed using two distinct paired FA and stratospheric profiles, for a total of 12 simulations.

The negative PBL temperature gradients resulted in upward refraction and the positive PBL temperature gradients resulted in downward refraction. Figure 2 shows surface TL for two different PBL temperature gradients in order to illustrate the difference between a strong and weak nocturnal inversion. For both of these, the FA temperature gradient is set at -6.5 C/km and the stratospheric temperature gradient is set at +1 C/km. There is slightly less TL and more spatial variability for stronger positive temperature gradients. These positive PBL temperature gradients represent nocturnal inversions. In reality, these inversions don't extend the entire depth of the PBL, however, these results suggest that stronger nocturnal inversions generate stronger downward refraction and therefore decreased attenuation at the surface. From this, it can be inferred that surface TL will be lower later in the nighttime as the nocturnal inversion grows and strengthens. This test has shown that the PBL has a significant effect on surface transmission and overall signal propagation, especially for positive temperature gradients.

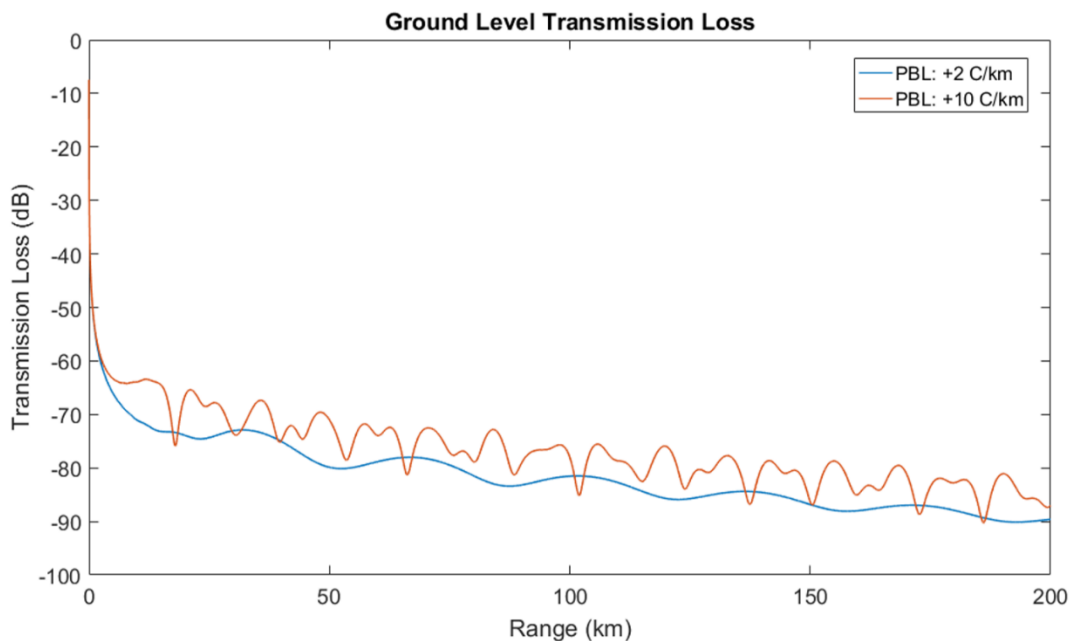


Figure 2. Surface TL for PBL lapse rates of +2 C/km and +10 C/km. FA: -6.5 C/km; Stratosphere: +1 C/km

The FA layer was tested next. Four different FA temperature gradients (-9.8, -6.5, -3, 0 C/km) were compared. Each FA temperature gradient was run with the same three PBL and stratospheric profiles: one upward refracting profile (PBL: -6.5 C/km Stratosphere: +1 C/km) (Figure 3a), one downward refracting profile (PBL: +5 C/km Stratosphere: +1 C/km) (Figure 3b), and one in which both the PBL and stratosphere are completely isothermal (Figure 3c).

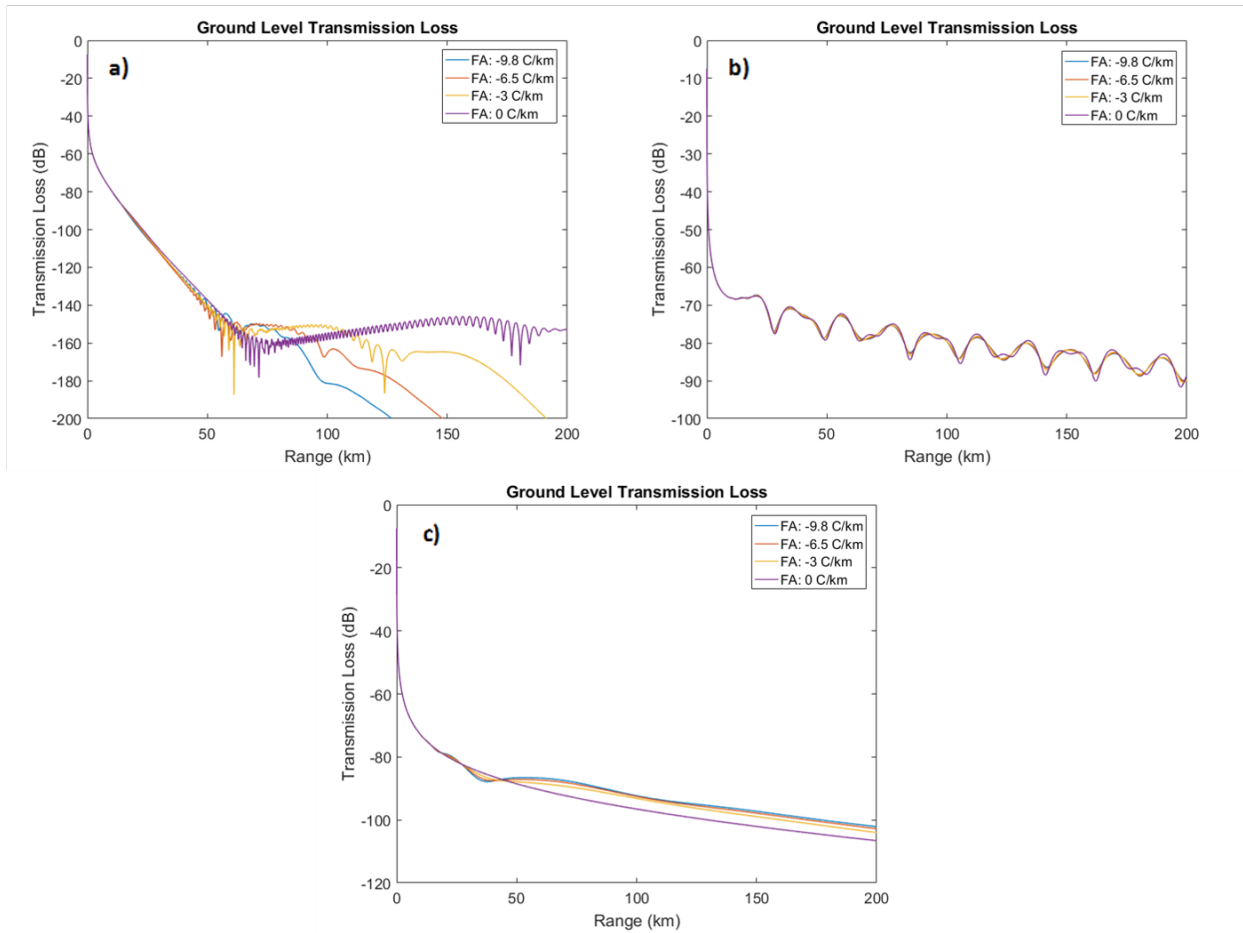


Figure 3. Surface TL for profiles **a)** PBL:-6.5 C/km Stratosphere: +1 C/km. **b)** PBL: +5 C/km FA: Stratosphere: +1 C/km. **c)** Isothermal PBL and Stratosphere.

All FA temperature gradients in Figure 3a match closely up to ~60km, then diverge once the TL values exceed 140 dB, which, as before, is more TL than most signals would overcome. Therefore, it can be concluded that the FA has little to no effect at ranges where signals may be detectable. Figure 3b shows almost identical surface TL for all FA temperature gradients indicating that the FA has no significant effect above a downward refracting PBL. The surface TL curves behave similarly for all FA temperature gradients in Figure 3c except for the completely isothermal case. However, the isothermal case is highly idealized and unrealistic. The results from this test suggest that FA temperature gradient has very little effect on surface TL, especially during nocturnal inversions, but

could have an effect at longer ranges (greater than 100km) for an upward refracting PBL.

After obtaining a general idea of the influence of each layer, a fourth layer was added at 1 km. This layer is 250 meters deep and represents a capping inversion. This layer is added to assess how temperature inversions, which are very common in the atmosphere, effect TL. Since this layer has been added, the FA is now defined above the cap from 1.25 km to 11 km, see Table 2. Two different temperature gradients were compared in this layer, a strong cap (+12 C/km) and a relatively weak cap (+4 C/km). Each cap temperature gradient was run with the same set of profiles to test the effect of the cap in differing upward and downward refracting profiles. An isothermal profile was added for reference.

There was not a significant difference in mean surface TL between the weaker and stronger caps when looking at the isothermal profiles. There was, however, noticeably stronger downward refraction with the stronger cap temperature gradient (Figure 4).

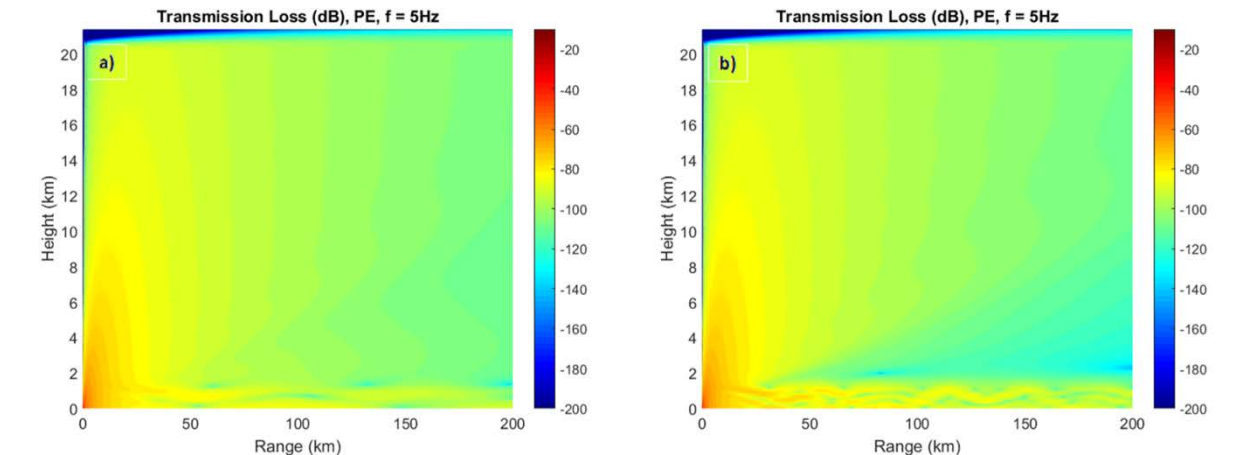


Figure 4. TL for profiles **a)** Isothermal with +4 C/km cap. **b)** Isothermal with +12 C/km cap

Comparing the surface TL between differing PBL temperature gradients in the upward refracting profiles shows increasing TL with decreasing PBL temperature gradient (Figure 5a). This suggests that the effect from capping inversions increases significantly with weaker PBL temperature gradients. Looking at the downward refracting profiles (nocturnal inversion below capping inversion) suggests that varying positive PBL temperature gradients has little effect on surface TL during the presence of a capping inversion (Figure 5b).

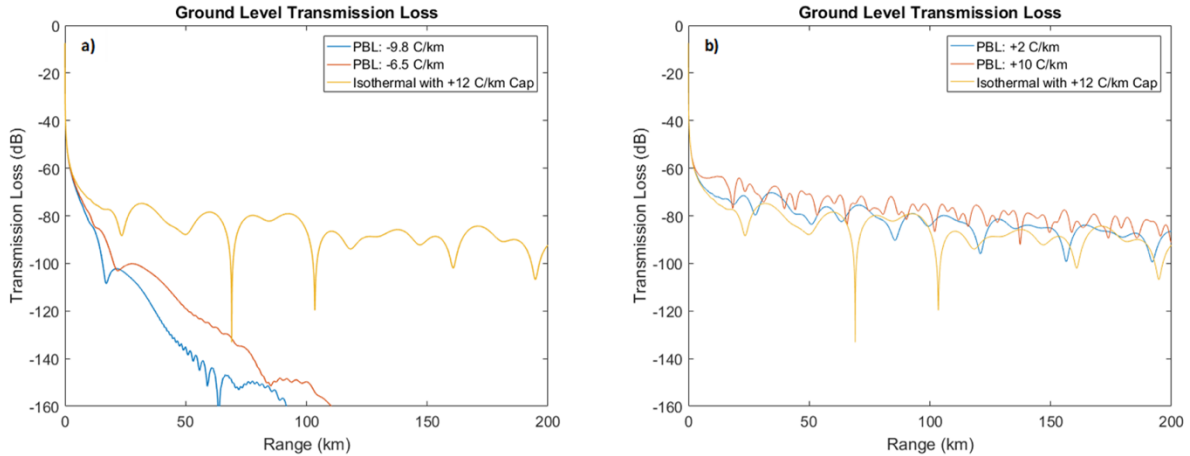


Figure 5. Surface TL for differing PBL lapse rates with +12 C/km Cap (FA: -6.5 C/km Stratosphere: +1 C/km for all profiles). **a)** Upward refracting PBL. **b)** Downward refracting PBL.

Figure 6 shows the same profile (PBL: -9.8 C/km FA: -6.5 C/km Stratosphere: +1 C/km) for three different cases: one with a strong cap (+12 C/km), one with a weak cap (+4 C/km), and one with no cap (Cap = FA temperature gradient). This shows that the existence of a cap does have a noticeable effect on the surface TL, specifically at shorter ranges.

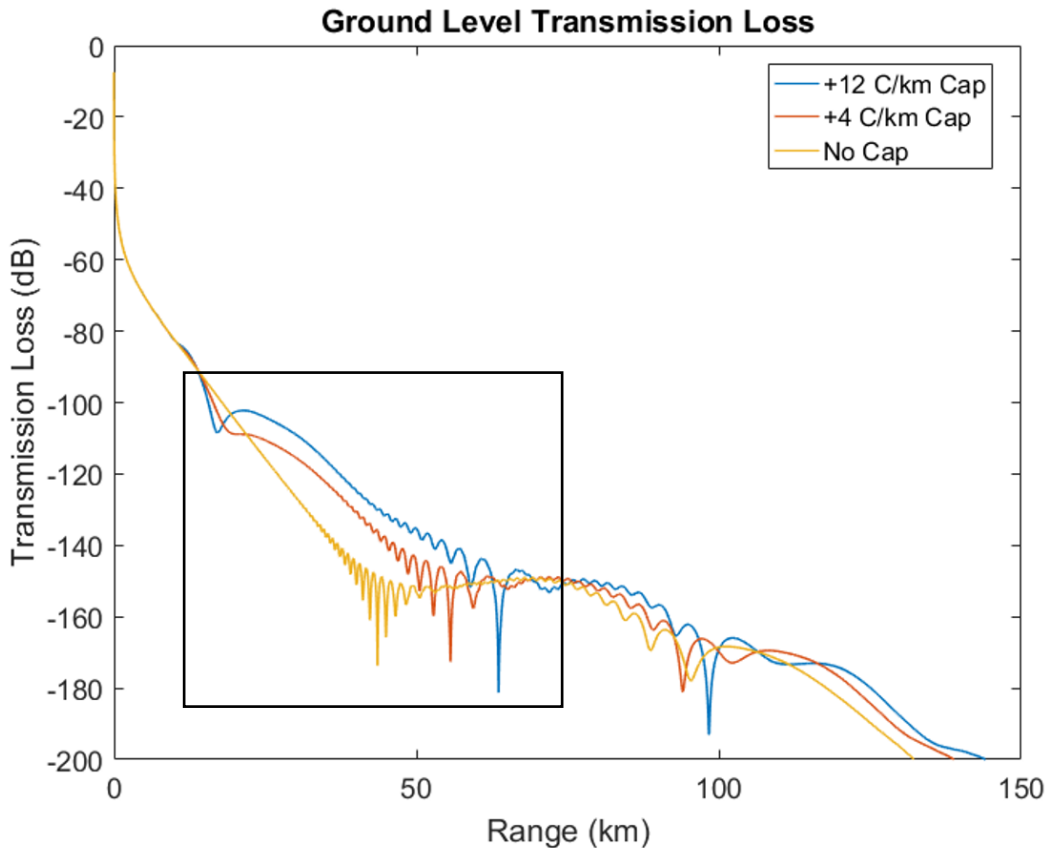


Figure 6. Surface TL for differing cap lapse rates with the same temperature profile (PBL: -9.8 C/km FA: -6.5 C/km Stratosphere: +1 C/km).

The same set of experiments were performed with a 250 meter deep inversion beginning at 4 km to capture the effect of a subsidence inversion typically found in the mid-troposphere. Again, the isothermal cases revealed little difference in mean surface TL. Comparing different PBL temperature gradients in the upward refracting profiles shows similar effects to the capping inversion. The only difference being that varying PBL temperature gradients seems to have a little less of an effect on surface TL for the higher inversion (Figure 7a). In the case where we have a subsidence inversion above a nocturnal inversion we see a little different result. The mean surface TL for the two nocturnal inversions is the same here as they were in the case with a cap (PBL +2: -81.4 dB and PBL +10: -76.7 dB for both subsidence and capping inversion), but the isothermal profile curves differ. The mean surface TL for the isothermal profile increased from -85.1 dB in the cap case to -90.8 dB in the subsidence inversion case. This difference between the capping inversion and a subsidence inversion that sits higher in the free atmosphere is likely due to the differing heights of the inversions.

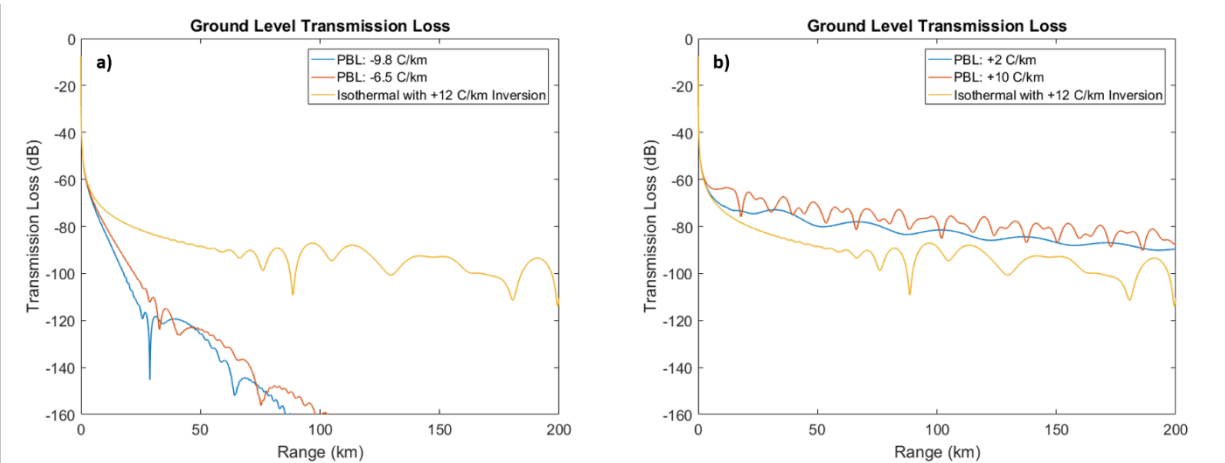


Figure 7. Surface TL for differing PBL lapse rates with a +12 C/km subsidence inversion (FA: -6.5 C/km Stratosphere: +1 C/km for all profiles). **a)** Upward refracting PBL. **b)** Downward refracting PBL.

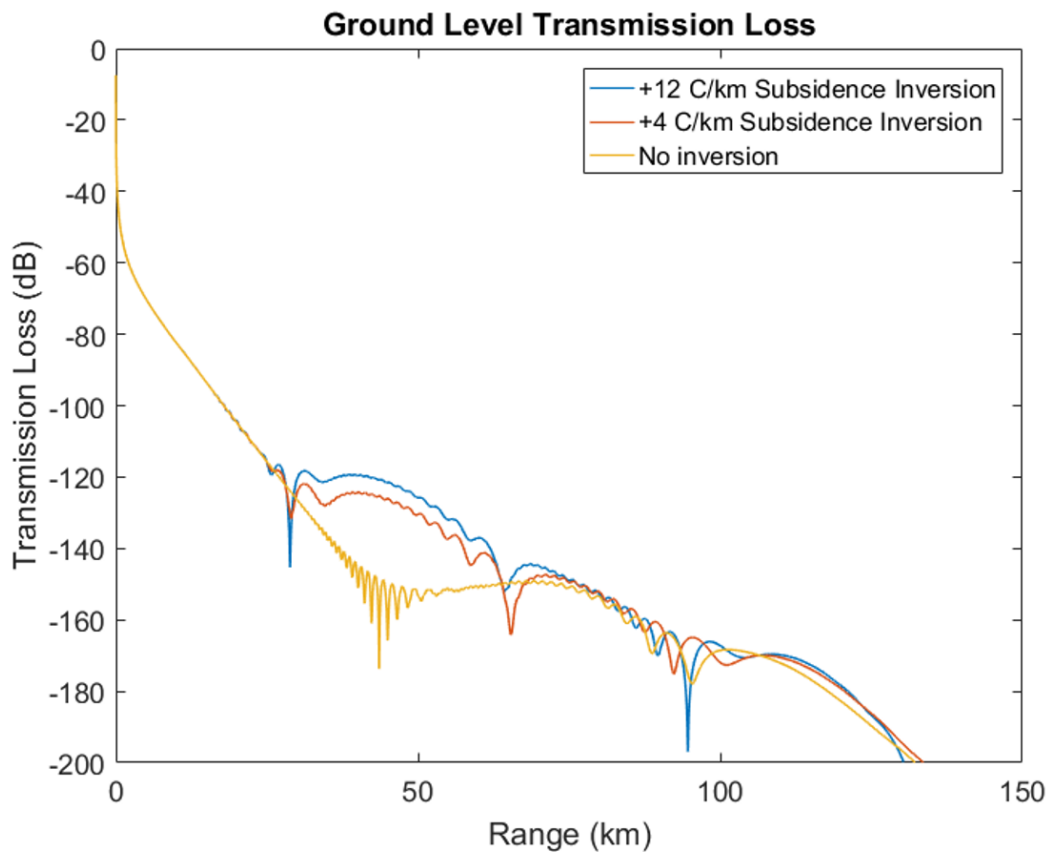


Figure 8. Surface TL for differing subsidence inversion lapse rates with the same temperature profile (PBL: -9.8 C/km FA: -6.5 C/km Stratosphere: +1 C/km).

Figure 8 shows surface TL between a weak, strong, and no subsidence inversion. These results are similar to the same experiment, but with a capping inversion shown in Figure 6. This is further evidence that inversion layers have a noticeable and significant effect on surface TL. This result is similar to that found in studies of the nocturnal boundary layer, c.f. (Waxler 2017). Experimental validation will be sought in the future, and the influence of wind on this effect will be examined in a later study.

A series of contour plots was generated to better compare the relative influence of temperature gradients in two layers. The goal was to identify the sensitivity of TL to changes in temperature gradients. This gives an idea of how well temperature gradients need to be estimated in a certain layer. For each test, five plots were produced to examine surface TL at a range of 10, 50, 100, 150, and 200 km from the source. The 50 km plots will be shown for all experiments; 150 km plots will be shown for selected cases. This is a good representative range as the signal is still strong enough to be relevant in most cases. The values plotted were calculated using a 500 meter average centered on the ranges of interest to capture the average TL rather than an arbitrary point on a curve oscillating about a mean. First, the PBL and FA were compared. The FA temperature gradient varies from -10 C/km to 0 C/km in 1 C increments on the y-axis and the PBL temperature gradient varies from -12 C/km to +12 C/km in 1 C increments on the x-axis. The stratospheric temperature gradient is fixed at +1 C/km for all cases.

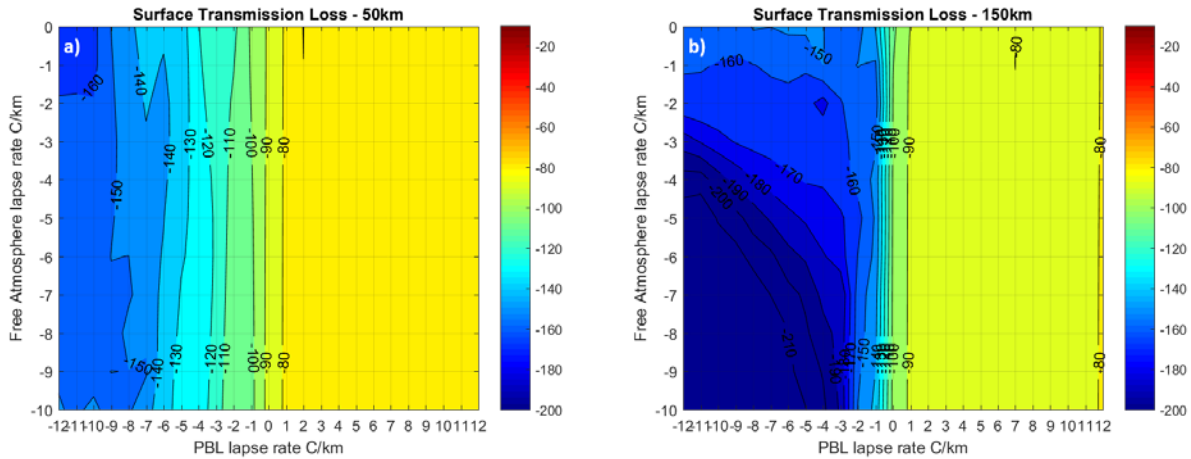


Figure 10. Surface TL at ranges a) 50 km and b) 150 km from the source. PBL lapse rate is on the x-axis and FA lapse rate on the y-axis.

For shorter ranges (less than 100 km), the FA has very little influence on surface transmission (Figure 10a). The PBL is the dominant factor in affecting surface TL at these ranges. At longer ranges, however, once the PBL temperature gradient becomes negative, FA temperature gradients between -5 C/km and 0 C/km become important. The TL is so strong at this point that the influence from the FA is likely negligible (Figure 10b). The low values of TL in the lower left corner of Figure 10b is most likely a factor of the PBL and FA temperature gradients being strong enough that the stratosphere is not able to refract enough of the signal down to the surface at these ranges. Another feature worth noting is the extremely tight gradient between PBL temperature gradients of -6 C/km and 0 C/km. This suggests that temperature gradients weaker than -6 C/km in the PBL require more accurate estimations to predict surface TL.

Next, the same simulation is run except the PBL temperature gradient varies from -6 C/km to 0 C/km in 0.5 C increments to investigate the previously mentioned gradient (Figure 11).

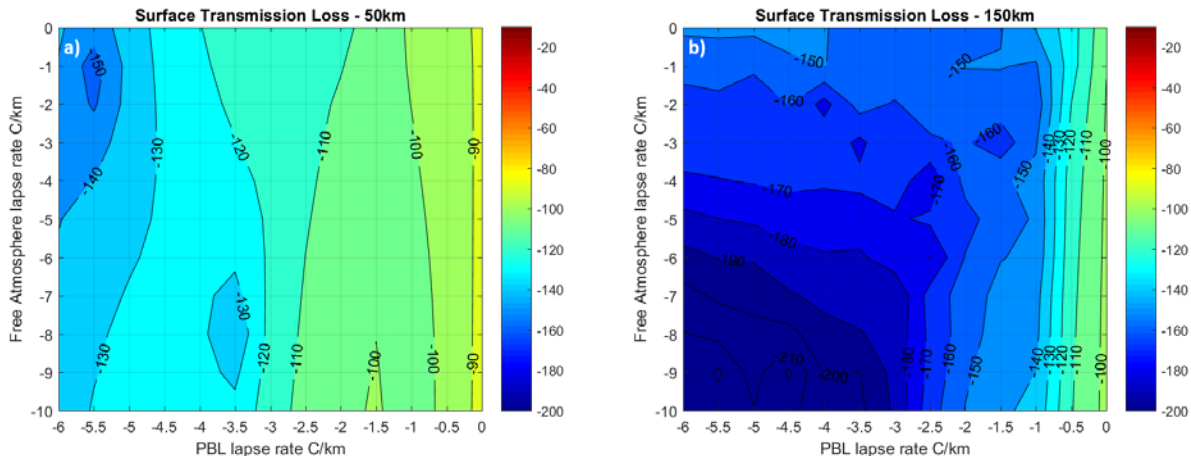


Figure 11. Surface TL at ranges a) 50 km and b) 150 km from the source. PBL lapse rate is on the x-axis and FA lapse rate on the y-axis.

The results are similar here. As the ranges increase, the gradient tightens to the weaker negative temperature gradients and the sensitivity of TL to the PBL increases.

Next, the PBL is compared to a cap. In this simulation the PBL temperature gradient varies from -12 C/km to +12 C/km in 4 C increments on the x-axis and the cap temperature gradient varies from +2 C/km to +12 C/km in 2 C increments on the y-axis (Figure 12). The stratospheric temperature gradient is fixed at +1 C/km. The FA and stratospheric temperature gradients are fixed at -6.5 C/km and +1 C/km respectively.

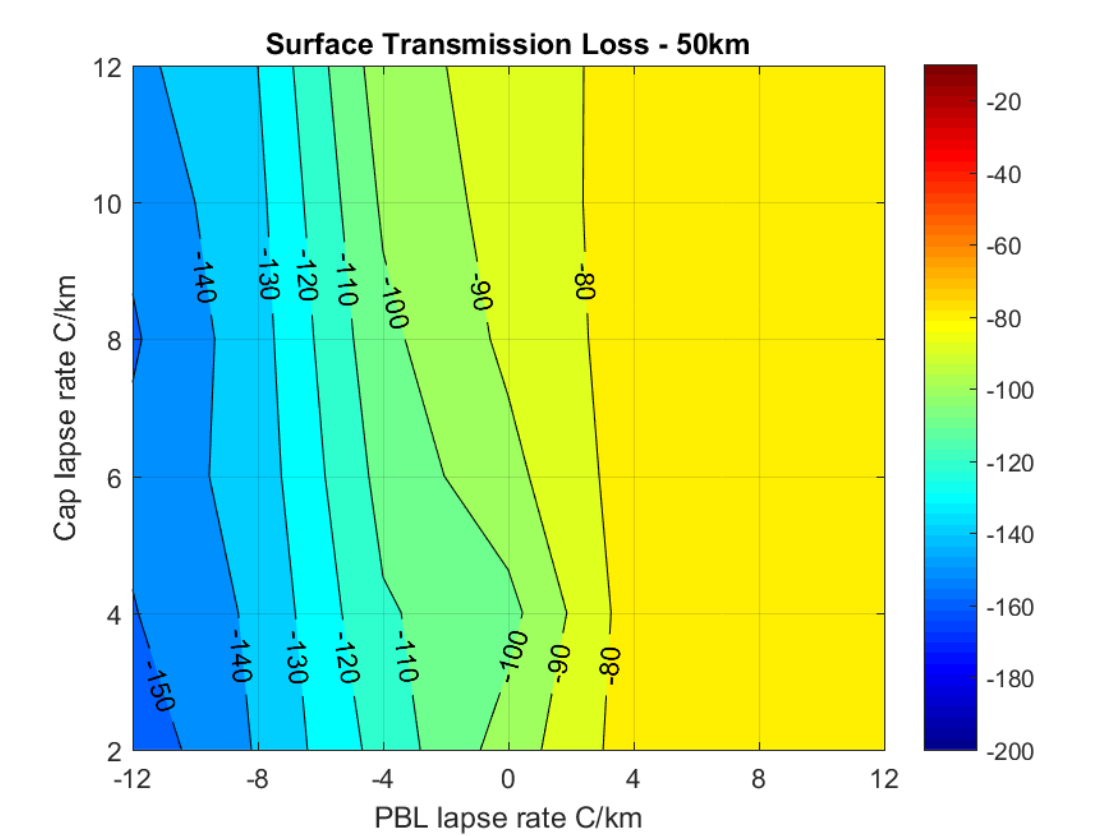


Figure 12. Surface TL 50 km from the source. PBL lapse rate is on the x-axis and cap lapse rate on the y-axis.

These results are similar to the PBL vs. FA simulation in the sense that the cap has little influence compared to the PBL. Once the PBL temperature gradient becomes positive, varying it seems to have little effect on surface TL. This is somewhat surprising considering earlier tests suggested that as positive PBL temperature gradients increased, surface TL would noticeably weaken. This is seen a little in the shorter range (10 and 50 km) plots, however not so much in the mid to longer ranges. From the previous simulations, it is apparent that the PBL is by far the most important factor in determining surface TL and that lower altitudes have the most influence on short range infrasound propagation.

The next tests investigate the importance of the FA above the cap. This is tested with an upward refracting PBL first and then with a downward refracting PBL. In this simulation, the cap temperature gradient varies from +2 C/km to +12 C/km in 2 C increments on the x-axis, and the FA temperature gradient varies from -10 C/km to 0 C/km in 2 C increments on the y-axis (Figure 13). The stratospheric temperature gradient is fixed at +1 C/km.

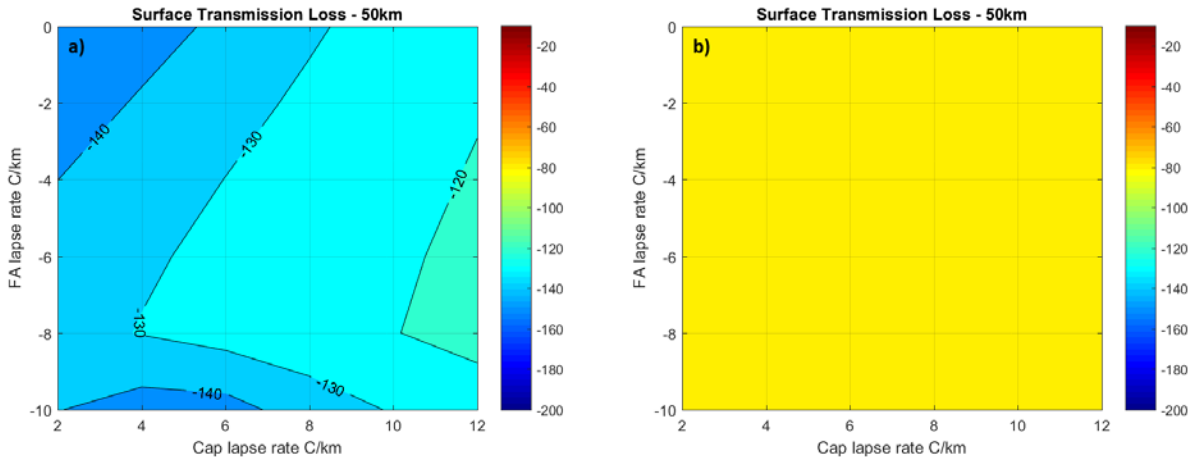


Figure 13. Surface TL 50 km from the source. Cap lapse rate is on the x-axis and FA lapse rate on the y-axis. **a)** PBL: -6.5 C/km (upward refracting) **b)** PBL: $+4$ C/km (downward refracting).

Capping inversions and the FA have no effect on surface transmission in the case of a PBL with positive temperature gradients, as is clearly evident in Figure 13b. In this case, there is no change in TL as the cap and FA temperature gradients vary. This suggests that the temperature gradients in these layers do not need to be accurately estimated during the existence of a nocturnal inversion. What is interesting, however, is that the FA above a capping inversion seems to have some effect in the case of an upward refracting PBL as shown in Figure 13a. However, the TL values are very low.

6. CONCLUSIONS AND FUTURE WORK

When trying to determine the source of an infrasonic signal, knowing the vertical temperature profile of the atmosphere is essential due to how much vertical changes in temperature effect propagation. This paper looked at surface transmission loss and how it responds to varying temperature gradients in different layers of the atmosphere. All simulations were run with a 5 Hz infrasonic signal. This signal was chosen as representative sample within our frequency range of interest.

Starting with systematically testing each layer of the atmosphere provided a good understanding of each layer's importance to the TL measured at the surface. The stratosphere was able to be ruled out for additional testing by determining that it has virtually no effect on surface TL over horizontal ranges up to 200 km. This allowed us to fix the stratospheric temperature gradient at $+1$ C/km and focus in on the other layers. It was then concluded that the PBL significantly affects surface TL, especially for positive temperature gradients. This suggests that surface TL is lower in the late hours of the night due to stronger nocturnal inversions. Lastly, the FA was tested. Temperature gradients in the FA were found to have very little effect on surface TL in atmospheres with a downward refracting PBL. This is true for an upward refracting PBL up to ~ 60 km. After this the FA seemed to have an effect, however, the TL values were so low (less than 140 dB) that the signal from the source would likely be undetectable. Next, a 250 meter deep capping inversion was added just above the PBL at 1 km. It was found that weaker negative PBL Loss temperature gradients allowed capping inversions to affect the

surface TL more significantly and varying positive PBL temperature gradients has little effect during a nocturnal inversion. Ultimately, the presence of a capping inversion was shown to have a noticeable effect on surface TL at shorter ranges (less than 75 km). Results were similar when the inversion layer was moved to an altitude of 4 km to simulate a subsidence inversion. The main difference here was in the isothermal profile curves. The mean surface TL increased by about 5 dB from the cap to the subsidence inversion case. This was attributed to the differing heights of the two inversion layers.

The contour plots provided insight into the importance of one layer compared to another. Comparing the PBL and FA showed that the PBL is the most dominant factor in determining surface TL. FA temperature gradients between -5 C/km and 0 C/km were important at longer ranges (150 km) when the PBL temperature gradient became more negative, though the TL values are extremely low (less than 150 dB) at this point. The PBL was also compared to the capping inversion, which had similar results. In both cases, varying the PBL temperature gradient once it became positive did not change the surface TL. These experiments provided good evidence that lower altitudes have the most influence on short range infrasound propagation.

The authors recognize that only considering temperature is an incomplete representation of the atmosphere. In reality, the coupled effects of wind and temperature are important for accurate estimations of refraction effects on propagation. The effects of wind will be considered in future work. Future work will also include examination of multiple frequencies within the range from 0.1 - 50 Hz. The results of this very simplified study will be compared to experimental data in the future.

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REFERENCES

- Andrews, D.G. (2000). *An Introduction to Atmospheric Physics*. Cambridge University Press, Cambridge.
- Huang, D. (1988). Finite element solution to the parabolic wave equation. *J. Acoust. Soc. Am.* 84(4), 1405-1413.
- International Organization for Standardization (1975) *Standard Atmosphere*. ISO 2533:1975.
- International Organization for Standardization, Geneva, Switzerland, ISO 9613-1: *Attenuation of sound during propagation outdoors--Part 1: Atmospheric absorption* (1995).
- Jensen, F. B., Kuperman, W. A., Porter, M. B., & Schmidt, H. (2011). *Computational ocean acoustics*. Springer Science & Business Media.
- Lee, D. and Siegmann, W. L. (1995). Finite difference treatment of irregular interfaces: an error analysis. *J. Comp. Acoust.* 3(1), 1-14.

- McKenna, M. H., B. W. Stump, and C. Hayward (2008), Effect of time-varying tropospheric models on near-regional and regional infrasound propagation as constrained by observational data, *J. Geophys. Res.*, 113, D11111, doi: 10.1029/2007JD009130.
- Petty, G. W. (2004). *A First Course in Atmospheric Radiation*. Sundog Publishing.
- Pidwirny, M. (2006). "The Layered Atmosphere". *Fundamentals of Physical Geography, 2nd Edition*.
- Stull, R. B.: 1988, *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Publishers, Dordrecht, 666 pp.
- Swearingen, M. E., White, M. J., and McKenna, M. H. (2016). A non-coordinate-transforming method for incorporating topography within the PE. Proceedings of MSS-BAMS, BI-05.
- Wallace, J. M. and Hobbs, P. V. (2006). *Atmospheric Science: An Introductory Survey*. Academic Press, 2nd edition
- Waxler, R., Assink, J., and Velea, D. (2017). Modal expansions for infrasound propagation and their implications for ground-to-ground propagation. *J. Acoust. Soc. Am.* 141(2), 1290-1307.
- Yevick, D. and Thomson, D. (2000). Impedance-matched absorbers for finite-difference parabolic equation algorithms. *J. Acoust. Soc. Am.* 107(3), 1226-1234.