ADVANCEMENT OF TECHNIQUES FOR MODELING THE EFFECTS OF ATMOSPHERIC GRAVITY-WAVE-INDUCED INHOMOGENEITIES ON INFRASOUND PROPAGATION

Robert G. Gibson[1], Douglas P. Drob[2], David Broutman[2] and Nathan W. Winslow[1]

BBN Technologies[1] and Naval Research Laboratory[2]

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ABSTRACT

Propagation studies of a growing number of infrasound observations indicate that fine-scale atmospheric inhomogeneities contribute to infrasonic arrivals that are not predicted by standard modeling techniques. In particular, gravity waves, or buoyancy waves, are believed to contribute to the multipath nature of infrasound propagation and to cause penetration of infrasound into the classical shadow zones that are predicted by conventional modeling techniques. Propagation modeling studies using basic parameterizations of gravity wave spectra suggest that gravity waves represent the primary component of fine-scale atmospheric inhomogeneity that affects infrasonic arrivals at regional ranges.

The influence of atmospheric gravity waves on the upper and middle atmosphere provides a significant source of uncertainty in atmospheric specifications. A large fraction of the gravity wave spectrum in operational numerical weather prediction models is either filtered out during the data assimilation process or else not resolved by the models. Prior approaches to modeling infrasound through gravity waves have relied on one-dimensional vertical wavenumber spectral models of gravity waves; this simplified model approach captures the vertical spatial scales in gravity waves as a function of height. Our recent research has developed improved resolution of these wave fields through more sophisticated computational techniques to achieve more complete spectral parameterization.

Atmospheric specification techniques have been developed that incorporate realistic models of gravity waves that are self-consistent with the background flow field and that include effects of altitude, range-dependence, and time-dependence over relevant scales. One shortcoming of prior gravity wave field models recently used with infrasound propagation models is that they ignore the typically strong refraction of the background gravity waves by variations in the mean winds and mean stratification above 15 km. These limitations are addressed in this research by including the refraction effects of the gravity wave field by the background atmosphere as defined by the Naval Research Laboratory-ground-to-space (NRL-G2S) semi-empirical specification. A local atmospheric gravity wave field is represented using the summation of vertical eigenfunctions approximated by a computationally efficient Fourier-space ray-tracing technique. Using this methodology, wave perturbation fields (horizontal wind components, pressure, density, and temperature) are calculated that are self-consistent with the background atmospheric flow.

Broadband, full-wave infrasound predictions computed using the parabolic equation (PE) method are used to model atmospheric infrasound from explosions at ranges of 100s to 1000s of km. Model predictions using the PE method are conducted using range-dependent specifications of the atmospheric wind and temperature from NRL-G2S that are modified by the addition of perturbation terms representing the gravity wave field, in order to characterize the fine-scale atmospheric structure not resolved by numerical weather prediction models. Synthesized infrasound waveforms, obtained using the Fourier-synthesis time-domain PE method, are compared with observed infrasound signals from ground-truth events in order to evaluate the modeling capabilities.

OBJECTIVES

The objective of this research effort is to improve understanding of the effects of gravity waves and other fine-scale atmospheric inhomogeneities on infrasound propagation. The improved understanding of the relevant atmospheric and infrasonic physics will result in enhanced capabilities for modeling infrasound features and waveforms.

It is evident that existing propagation modeling, coupled with state-of-the-art atmospheric characterizations, fails to adequately predict infrasonic arrivals in certain circumstances. In particular, there have been numerous events for which infrasound arrivals are observed by sensors in regions that are predicted by standard modeling techniques to be in zones of silence (e.g., Bhattacharyya et al., 2003; Kulichkov, 2004; Mutschlecner and Whitaker, 2006). This issue is relevant over both local and regional ranges. Recent scientific work in gravity waves, long-range acoustic propagation, and infrasound has indicated that fine-scale atmospheric inhomogeneities contribute to unexpected infrasonic arrivals. We address this issue through systematic evaluation of the relevant atmospheric phenomena, advancement of the state of the art of modeling the interactions between infrasound and fine-scale atmospheric inhomogeneities such as gravity waves, improved atmospheric specification, and model validation.

Specifically, the objectives are as follows:

- Review recent scientific progress in the understanding of gravity waves, their temporal and spatial variability, and their statistics, in order to develop an improved model of the characteristics of gravity waves that are relevant to infrasound propagation.
- Develop atmospheric specification techniques that incorporate realistic models of gravity waves in a manner that maintains self-consistency with the background flow field and that includes effects of latitude, longitude, and time-evolution over relevant scales.
- Exercise the improved gravity wave models with infrasound propagation models. Examine variability of infrasound predictions over a statistical ensemble of gravity wave realizations. Perform sensitivity studies to establish the effects of key atmospheric model variables on infrasound prediction.
- Perform model validation studies using ground truth datasets, focusing on local and regional ranges.

The effort is anticipated to increase understanding of the regional and local propagation of infrasound through the dynamic atmosphere and also to improve the capability to predict infrasound arrivals and features relevant to phase classification. Research results include spectral-based atmospheric variability specifications; numerical modeling subroutines that enable improved propagation modeling via incorporation of effects of gravity waves and related fine-scale atmospheric structure phenomena; and model/data comparisons.

RESEARCH ACCOMPLISHED

Atmospheric Specification

The atmospheric structure responsible for the propagation of infrasound can change rapidly. Global climatological models have largely been replaced in current infrasound modeling practice by the NRL G2S model of Drob et al. (2003) and Drob (2004), which was developed to provide background atmospheric information for the Nuclear Explosion Monitoring Research and Development program. The G2S data processing system combines operational numerical weather prediction (NWP) specifications with the upper atmospheric empirical models, NRLMSISE-00 and HWM-93 (Picone et al., 2002; Hedin et al., 1996). The near-real-time system incorporates 1°x1° and 1°x1.25° resolution global NWP input fields to the nearest 6-hour interval in the lower atmosphere. The HWM-93 model was recently upgraded to HWM-07 by Drob et al. (2008) via the assimilation of recent upper atmospheric research satellite-based measurements and ground-based measurements.

However, these specifications are unable to resolve all fine-scale stochastic phenomena, e.g., atmospheric irregularities smaller than the model resolution, fine-scale structures above 35 km, and gravity wave fluctuations that cannot be deterministically measured or internally generated by the model. Fine-scale atmospheric structure not characterized by near-real-time atmospheric models such as G2S has been identified as a likely source of refraction, advection and scattering effects that may play a significant role in infrasound propagation. In particular, gravity waves are of interest because their spatial scales are of the same order as infrasonic wavelengths. Gravity waves result from oscillations of air parcels displaced by buoyancy and restored by gravity. The oscillations have time scales ranging from minutes to tens of hours. Vertical length scales of gravity waves are in the range of 0.1 to 15 km, and horizontal scales can span from 10 to 1,000 km. The multi-scale nature of gravity waves presents a challenge to quantification of their properties. Owing to the important influences of gravity waves on the atmosphere's general circulation, vertical structure, and spatiotemporal variability, gravity wave dynamics is a significant atmospheric science research topic area. Recent research progress includes a better understanding of gravity wave source characteristics and evolution with altitude due to changes in wind conditions and atmospheric stability (e.g., Fritts and Alexander, 2003). The development of high-fidelity physically-based gravity wave parameterizations is an active research area.

BBN has previously developed a baseline wind variability model (Norris and Gibson, 2002; Gibson, et al., 2008) for predicting infrasound deviations due to atmospheric effects that are not resolved by the existing atmospheric specifications. The basic variability model uses a power-law wind perturbation spectrum based on the spectral gravity wave model of Gardner (1995, 1993) and generates realizations of horizontal wind perturbation profiles due to gravity waves. A source spectrum is defined near the ground, and as the wave spectrum is propagated up in height, attenuation is modeled by introduction of diffusive damping. Therefore, height-dependent gravity wave dependencies are modeled. Range-dependent effects can be approximated by selecting a dominant horizontal correlation length and combining wind perturbation profiles using Gaussian weighting functions.

Approaches to Improved Gravity Wave Modeling

As discussed above, baseline approaches to modeling infrasound through gravity waves have relied primarily on one-dimensional vertical wavenumber spectral models. This simplified model approach captures the vertical spatial scales in gravity waves as a function of height. During this research effort we have extended this capability by accounting for additional dimensional variability, including horizontal wavenumber. Furthermore, we have extended the capability of the spectral model by allowing input parameters to vary to account for spatial and temporal dependencies. For example, model parameters may be quantified based on latitude and Julian day, whereas the baseline implementation of the Gardner model does not account for the fact that gravity wave fields can vary dramatically with altitude, latitude, and season (e.g., Eckermann, 1995).

The technical approach to the improved gravity wave model has been discussed in Gibson et al. (2009). The modeling technique accounts for the typically strong refraction of gravity waves by variations in the mean winds and the mean stratification above 15 km. The refraction effects of the gravity wave field are calculated using the background atmosphere as defined by the G2S specification. This approach accounts for spatial and temporal variability by defining gravity wave fields based on the background atmospheric temperature and wind profiles. Using this methodology, wave perturbation fields are calculated that are self-consistent with the background atmospheric flow. As described in Gibson et al. (2009), the formulation involves ray tracing in Fourier space, in a way that efficiently approximates the vertical eigenfunctions for a given background. The ray solutions are then Fourier synthesized to give the spatial solution. Since wave phases are also computed, a wide range of problems can be considered, from deterministic mountain waves, to semi-deterministic gravity waves generated by convection, to fully random wave fields. Additional theoretical details of the Fourier gravity wave ray tracing method implemented here are presented in Broutman et al. (2003, 2006, and 2009).

The stochastic gravity wave field is calculated using a realistic gravity wave spectrum based on Warner and McIntyre (2001). Wave fields are typically calculated for altitudes up to 150 km. Integration is typically performed over a range of source frequencies from $2*f$ to $N/\sqrt{5}$, where f is the Coriolis frequency and N is the Brunt-Vaisala frequency. The model includes gravity wave propagation effects of: multiple reflections at turning points; Airy function amplitude approximation at caustics; critical layer filtering; wave field saturation; anelastic amplitude scaling in the dispersion relationship; and dissipation by molecular viscosity in the lower thermosphere. Heuristics have been included to limit horizontal phase velocities to less than 90 m/s as suggested by observation. There are readily tunable free parameters for: source altitude and average source region wave variance; control of the horizontal extent and resolution of the model domain; and arbitrary number of spectral frequencies. We have also begun to systematically examine the numerical parameter space for the source spectrum shape constants, empirical wave amplitude normalization scale factors, and the optimal source spectrum seeding altitude.

An example below (Figure 1) presents and compares two representative sets of atmospheric profiles that include gravity wave perturbation fields computed for regional scenarios. Each gravity wave field is self-consistent with the G2S background atmosphere. Specifically, the figure shows wind profiles, perturbed by gravity wave fields, computed for events with two seasonally different background wind field characteristics. The panel on the left shows the zonal and meridional wind profiles corresponding to the Ghislenghien, Belgium gas pipe explosion event on 30-July-2004. The panel on the right shows the wind profiles in the vicinity of the Gerdec, Albania ammunition explosion event, which occurred on 15-April-2008. These examples highlight the seasonal and latitudinal dependence of the newly developed stochastic gravity wave field fluctuation model as compared to the time- and space-independent gravity wave perturbation model that exists in BBN's current baseline implementation.

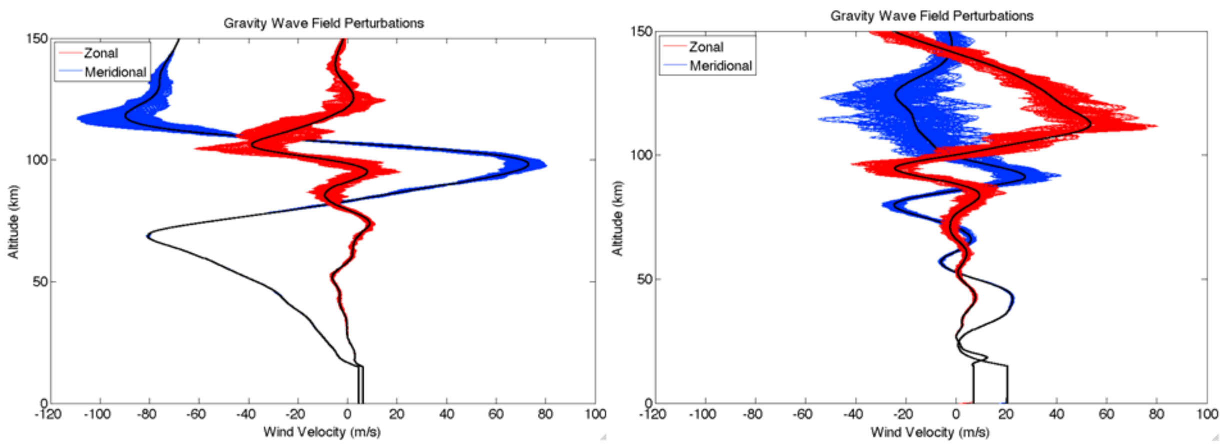

Figure 1. Zonal and meridional wind profiles, including gravity wave perturbations, for two scenarios: the Ghislenghien, Belgium event [50.6566 N, 3.879 E], which occurred on 07/30/2004 at approximately 07:00 UT (left panel); and the Gerdec, Albania event [41.394 N, 19.655 E], which occurred on 04/15/2008 at approximately 11:00 UT (right panel).

Research has included tuning gravity wave model results to published observational datasets. This enables an improved capability to define the recommended range of values for the free model parameters over a range of latitudes and seasons. Examples of seasonal, latitudinal, and altitudinal dependence of the gravity wave perturbations are shown in Figures 2 and 3. Figure 2 shows seasonal variation of the standard deviation of the zonal wind component of the gravity wave perturbation profile at fixed latitude. Figure 3 shows latitudinal variation of the standard deviation of the meridional wind component of the gravity wave perturbation profile for a fixed date.

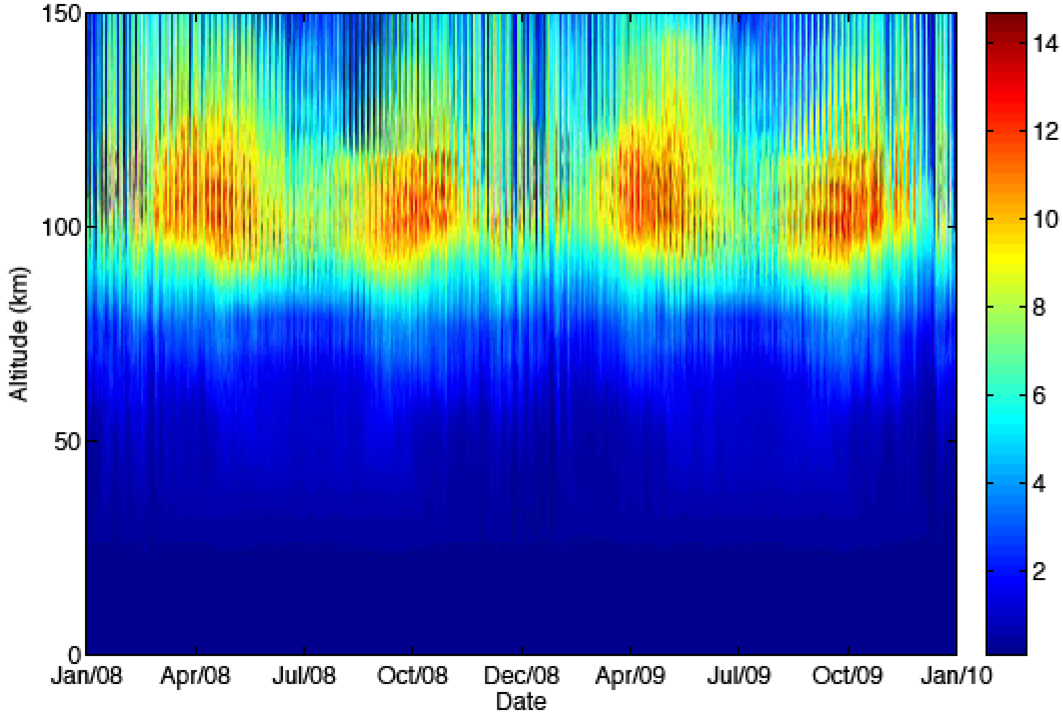

Figure 2. Seasonal variation of standard deviation (in m/s) of the zonal wind component of the gravity wave perturbation $\sigma_{u'}$ at 55° N.

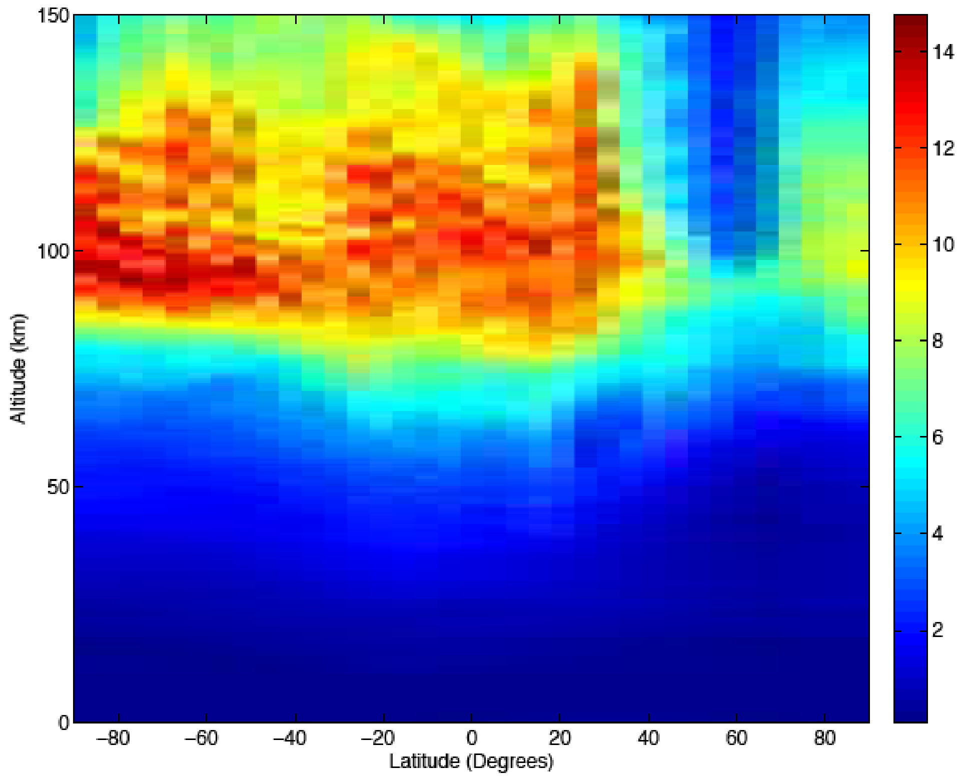

Figure 3. Latitudinal variation of standard deviation (in m/s) of the meridional wind component of the gravity wave perturbation $\sigma_{v'}$ for a fixed date.

Applications to Infrasound Propagation Modeling for Ground-Truth Events

The G2S atmospheric specifications described above, the baseline gravity wave models due to Gardner, and a suite of infrasound propagation models (including 3D ray-tracing, PE, time-domain parabolic equation [TDPE], and normal modes) are currently integrated into the tool kit InfraMAP (Gibson and Norris, 2002; Norris and Gibson, 2004). InfraMAP (*Infrasonic Modeling of Atmospheric Propagation*) has been developed by BBN for use in the study of infrasound propagation and monitoring. InfraMAP can be applied to predict attenuation, travel times, bearings, amplitudes, and waveforms for infrasonic events. The most recent version of InfraMAP includes TDPE waveform prediction capabilities (Tappert et al., 1995) based on either a canonical blast wave (Pierce and Posey, 1970) or any user-defined source waveform. PE and TDPE calculations incorporate effects of horizontal wind components (both mean and perturbations) by utilizing the effective sound speed approximation. Capabilities have also been developed for performing propagation calculations using the new gravity wave model.

Using the baseline gravity wave model, propagation studies have been conducted for various scenarios and ground truth events. These include explosive events at: Nevada Test Site, US (2002); Neyshabur, Iran (2004); Ghislinghien, Belgium (2004); Snohomish, WA bolide, US (2004); Buncefield, UK (2005); Novaky, Slovakia (2007); Gerdec, Albania (2008); Chelopechene, Bulgaria (2008); Sayarim, Israel (2007/2008); and others. Examples from studies that show comparisons of TDPE model output with observed waveforms have been presented by Gibson and Drob (2009) and Gibson (2009).

An example to quantify gravity wave effects on infrasound propagation is the Chelopechene, Bulgaria arms depot explosions (3 July 2008) detected at arrays throughout Europe and northern Africa. Observed infrasound arrivals from this event contain considerably more complexity than simple stratospheric and/or thermospheric phases. Regional observations at both I26DE (Germany) and I48TN (Tunisia) are characterized by multiple discrete arrivals ("pulses") within an extended infrasound signal of duration ~10 minutes (Green et al., 2008). Conventional propagation modeling using G2S predicts a weak stratospheric waveguide and does not predict either the early arrival time or the extended, multi-pulse features. Results of TDPE modeling over a 0-2 Hz bandwidth using a realization of a range-dependent gravity wave field are shown in Figure 4 for the path to I26DE at range of 1017 km and the path to I48TN at a range of 1440 km. A source yield of 100 tons is assumed in the synthetic waveform calculation, based on analyses by Green et al. (2008). The mean atmospheric profiles were defined using range-dependent G2S specifications. The propagation modeling includes effects of atmospheric absorption in the thermosphere (Sutherland and Bass, 2004). The agreement between data and model in arrival time, amplitude, number of pulses, and waveform envelope is striking.

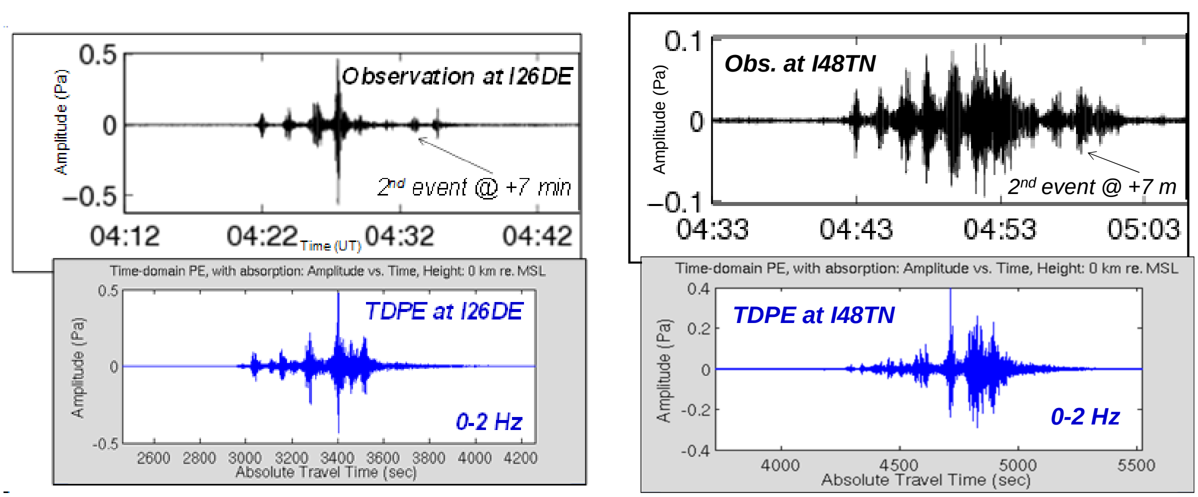

Figure 4. Comparisons between observed infrasound waveforms from the Chelopechene explosion and TDPE synthetic waveforms, including gravity wave perturbation effects. Upper panels (from Green et al., 2008): observations at I26DE (left) and at I48TN (right). Lower panels: synthetic waveforms, computed over a bandwidth of 0-2.0 Hz, and time-aligned with the waveforms in the upper panels.

An additional example is presented for one of the controlled explosions in the test series conducted at Sayarim, Israel, specifically the event of 23-Jul-2007 (Gitterman et al., 2009). This event was a surface explosion of approximately 6 tons yield. It was detected at arrays in Europe and northern Africa. Here we consider the 2460 km path to I48TN (Tunisia). Similar to the Chelopechene event, observations at I48TN are characterized by multiple pulses arriving over a period of several minutes. Analysis of the observed waveform, reproduced from Gitterman et al. (2009), is presented in the upper panel of Figure 5. Figure 5 also shows the TDPE simulation computed over a bandwidth of 0-2 Hz, including the effects of a realization of a range-dependent gravity wave field. The mean atmospheric profiles were defined using range-dependent G2S specifications, and effects of thermospheric absorption are included. Multiple arrivals are predicted in the synthetic waveform, and the arrival times and duration of these pulses are consistent with those in the observation as reported by Gitterman et al. (2009). Amplitudes are underpredicted somewhat, compared to the observation, in this example.

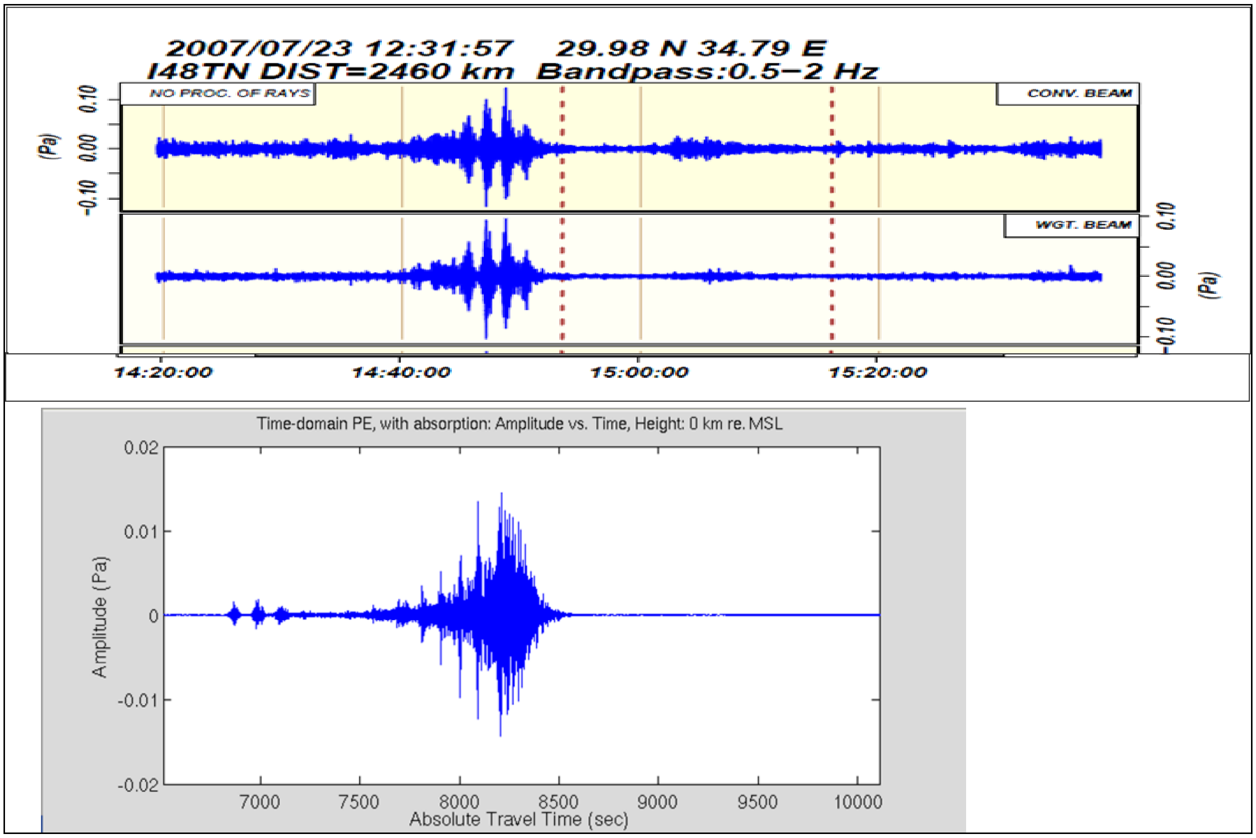

Figure 5. Comparison between observed infrasound waveforms from one of the Sayarim test explosions (23-Jul-2007) and a TDPE synthetic waveform, including gravity wave perturbation effects. Upper panel (from Gitterman et al., 2009): observation at I48TN. Lower panel: synthetic waveform, computed over a bandwidth of 0-2.0 Hz, time-aligned with the waveforms in the upper panel.

Waveform synthetics shown above have been calculated using our baseline gravity wave modeling technique. Modeling of infrasound from ground-truth events has also been conducted using our new stochastic gravity wave field fluctuation model, and comparisons with observations are in progress. Simulations have also been conducted using multiple realizations of gravity wave fields in order to assess consistency and repeatability of predictions and to develop statistical assessments as a part of the model validation activity.

CONCLUSIONS AND RECOMMENDATIONS

Substantial evidence for the importance of specification of atmospheric variability due to fine-scale inhomogeneity has been indicated by TDPE waveform predictions of ground-truth events observed at regional ranges. In several instances, conventional propagation modeling that ignores fine-scale atmospheric structure has failed to predict observed arrivals due to the lack of a stratospheric duct in the baseline atmospheric characterization; these observations exist in so-called “zones of silence.” However, modeled infrasound arrivals that consider energy refracted or scattered from gravity waves agree well in waveform envelope, duration and arrival time with observations. Progress has also been made in the ability to predict infrasound signal amplitude. These results indicate the considerable benefit to regional monitoring that is to be gained by understanding effects of gravity waves on infrasound. Implementation of our existing baseline gravity wave model enables accurate prediction of many observed infrasound features. The model for gravity wave fields has been improved during this research to incorporate additional physical effects. The new gravity wave fields have also been incorporated with existing infrasound propagation models. Testing of the new formulations should continue, including assessment of improvements against baseline models, study of additional infrasound ground truth events of interest, and extensive data/model comparison studies in order to quantify the performance of the techniques and identify research needs.

We recommend continuing extension of the new gravity wave calculation technique to address the latitudinal and seasonal variability of the gravity wave spectrum source function, focusing on effects in the troposphere, and to improve our ability to model it accurately through proper selection of model parameters. Model results should be tuned to the measured seasonal and latitudinal gravity wave characteristics (e.g., wave amplitudes, wavelengths, variances) published in the recent scientific literature. Research should also continue to explore the numerical parameter space for source spectrum shape constants, empirical wave amplitude normalization scale factors, wave-breaking, viscosity characterization, and the optimal source spectrum seeding altitude. By better defining the spatial scales and amplitudes of the relevant gravity wave perturbations, better estimates of the stochastic properties of infrasound propagation will be obtained.

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