INFRASOUND PROPAGATION CALCULATION TECHNIQUES USING SYNOPTIC AND MESOSCALE ATMOSPHERIC SPECIFICATIONS

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ABSTRACT

Numerical modeling of infrasound propagation is necessary to support accurate infrasound source location and phase identification. Predicting the details of infrasound propagation relies both on propagation models that capture the fundamental physical processes and on characterization of the propagation medium, namely the global atmosphere from the ground to altitudes above 100 km. The accuracy of propagation modeling depends in part on the fidelity of the atmospheric characterization. The analysis tool kit InfraMAP (Infrasound Modeling of *A*tmospheric *P*ropagation) integrates infrasound propagation models and environmental representations, including near-real-time atmospheric updates, such as the output from numerical weather prediction models that supplement the baseline climatological characterization of temperature, wind and air composition. These capabilities allow infrasound researchers to investigate critical propagation phenomena, conduct sensitivity studies, and compare results of numerical modeling with observed signals. Recent efforts aim to evaluate and quantify the propagation improvements attainable using global and synoptic specifications that characterize the relevant atmospheric physics more fully than climatological models.

Global synoptic models provide specifications that are well-suited for use in long-range propagation predictions. Further investigation of infrasound propagation phenomenology on a regional basis and development of suitable tools for studying regional events are necessary. Thus we investigate combining accurate, high-resolution regional atmospheric specifications with infrasound propagation modeling codes. Mesoscale models, which focus on the meteorology of a specific region, can better account for and resolve important meteorological phenomena relevant to regional and local infrasound propagation. By investigating realistic spatial and temporal atmospheric models at a range of resolutions, we seek insight into the appropriate spatial and temporal scales that are necessary for achieving improved infrasound predictions at the relevant frequencies. Approaches are being developed to assess performance of candidate techniques for incorporating mesoscale atmospheric models and terrain specifications with propagation models and to evaluate the benefits. Evaluation of propagation model performance using synoptic and mesoscale atmospheric specifications utilizes observed infrasound events with known ground truth.

RESEARCH OBJECTIVES

In order to advance the state of the art for high-fidelity infrasound predictions, it is necessary to develop both propagation models and atmospheric characterizations that capture more of the fundamental physics that affect infrasound. The overall objective of this effort is to improve understanding of the effects of atmospheric dynamics on the propagation of infrasound, thus improving infrasonic source localization, phase identification, and discrimination. This will be accomplished by developing and analyzing advanced atmospheric specifications for use with propagation models and applying them in comparison studies using ground truth infrasound events. Specific objectives include:

- Comparing ground truth observations to propagation predictions using existing atmospheric specifications and propagation models. This will include sensitivity studies using the Naval Research Laboratory (NRL) Ground-to-Space (G2S) specification at various resolutions and statistical uncertainty studies to address atmospheric model biases and error budgets.
- Developing a multi-resolution, regional environmental specification capability, based on the NRL-G2S framework, for use in propagation calculations. This will include assimilation of mesoscale atmospheric models that provide high resolution meteorological information on local and regional scales.
- Comparing ground truth observations to propagation predictions using the newly developed regional specifications that incorporate mesoscale atmosphere and terrain elevation.
- Investigating effects of including variable terrain elevation in ray-tracing propagation predictions.
- Developing research products that are useful for improving nuclear explosion monitoring capability.

This work discusses recent progress in providing accurate atmospheric specifications for ground-based nuclear explosion monitoring via infrasound. The propagation properties of infrasound in the atmosphere are driven, in part, by the atmosphere, which has significant spatiotemporal variations. Therefore, in order to accurately relate regional infrasound propagation calculations to microbarograph array observations, the use of adequate atmospheric specifications is required. If the initial conditions for an infrasound propagation calculation (e.g., source altitude and surface conditions) or specifications of the intervening medium are specified inaccurately, then erroneous estimates of ducting heights, travel times, and amplitudes will result. In shifting away from current climatological characterizations, a great deal of complexity is introduced into atmospheric specification. This complexity arises from the natural variability of the atmosphere over all heights. For long-range propagation the time scale of interest ranges from several hours to a month over horizontal scales of roughly 500 km.

Recent work by Drob et al., 2003 has provided a simple framework to account for this complexity over certain height ranges. The NRL Ground to Space (NRL-G2S) semi-empirical spectral model combines numerous sparse datasets using global spectral methods to specify the details of the entire atmosphere for infrasound propagation calculations. The environmental modeling system includes important latitudinal, longitudinal, and hourly variability as given by available historical and near-real-time operational data such the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the National Oceanic and Atmospheric Administration (NOAA)-National Center for Environmental Prediction Global Forecast System (NCEP-GFS) and the NRLMSISE-00 and HWM-93 (Hedin et. al., 1996, Picone et al., 2002) empirical upper atmospheric models, derived from historical databases.

Recent advances in the infrasound analysis tool kit InfraMAP (Infrasound Modeling of Atmospheric Propagation) allow new options for specifying the propagation environment by incorporating the output from numerical weather prediction models to supplement the baseline climatological characterization of temperature, wind and air composition (Gibson and Norris, 2003). InfraMAP modules enable integration of propagation models with near-real-time atmospheric characterizations including NRL-G2S, as described above, and NOGAPS. These synoptic specifications are used with infrasound propagation models in order to improve predictions compared to those based on climatology. However, observed infrasound phases have not been well predicted by state-of-the-art propagation models for several ground truth events (e.g., Bhattacharyya et al., 2003). Therefore, modeling advances that address the fundamental physical processes that affect infrasound are required. Also required, in parallel, are advances in specification of the propagation environment that address fundamental atmospheric physics at appropriate spatial and temporal scales and that can be utilized to improve the performance of advanced propagation models. This paper discusses recent research that will result in improved accuracy and understanding of the underlying physics of infrasound propagation calculations for nuclear explosion monitoring at regional and local ranges.

RESEARCH ACCOMPLISHED

A Regional Scale Atmospheric Model for Infrasound Propagation Calculations

The recent national trend in numerical weather prediction (NWP) is to move away from larger scale global numerical prediction systems such as NOGAPS and NCEP-GFS toward regional or mesoscale weather prediction systems such as the Navy Coupled Ocean and Atmosphere Mesoscale Prediction System (COAMPS^{TM}) and the Weather Research and Forecasting Model (WRF) (e.g., Hodur, 1997; Skamarock, 2004). The idea here is that by focusing only on the meteorology and data from a specific geographic region, these systems can better resolve important meteorological phenomena such as down-slope winds, surface roughness, soil moisture, and cloud physics. In addition these modeling systems include complete three-dimensional data assimilation systems comprised of data quality control, analysis, initialization, and forecast model components. Additional features of these models include globally relocatable grids with user-defined resolutions and dimensions, nested grids, options for idealized or real-time simulations, and source code that allows for portability between a number of different mainframes and workstations.

Physics-based constraints must be employed to assimilate the available meteorological observations (e.g., surface temperature/winds, radiosonde profiles, and satellite temperature sounding) into these systems in order to produce three-dimensional (3d) weather data cubes for weather forecasting. These models solve the time-dependent non-hydrostatic equations for momentum, non-dimensional pressure perturbation, potential temperature, turbulent kinetic energy, and the mixing ratios of water vapor, clouds, rain, ice, and snow. The models contain detailed parameterizations for boundary layer processes, precipitation, and radiation physics. The resulting three-dimensional data grids typically extend from the surface to 35 km and have horizontal resolutions ranging from 10 to 20 km. Examples of some currently available operational model domains from mesoscale models are shown in Figure 1.

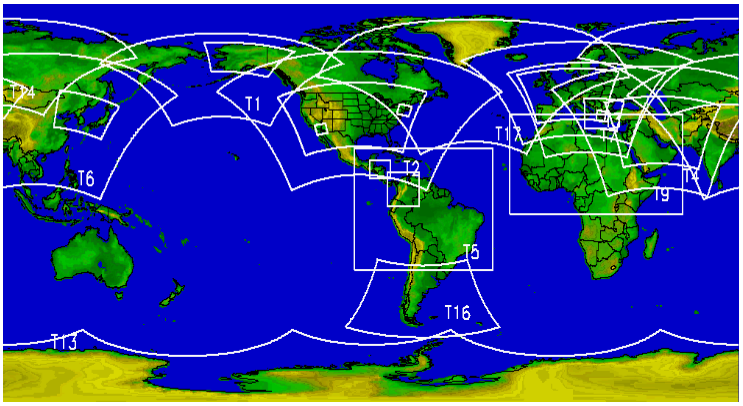


Figure 1. Example model domains for standard operational mesoscale models.

Mesoscale model outputs are typically provided 4 times daily (00/06/12/18Z), but can also be staggered at 00/12Z and 06/18Z, and may include specialized ultra-high resolution nested sub-domains. The Defense Modeling and Simulation Office (DMSO) Master Environmental Library (MEL) maintains online archives of COAMPS data extending back to 1998 for several domains of interest including CONUS, Korea, South West Asia, and Europe. Within the NRL all of the resources needed to generate COAMPS outputs for other regions of interest and times for infrasound research are available. In addition, WRF model initialization fields and source codes are similarly available independently from NOAA, Air Force Weather, and the National Center for Atmospheric Research.

Unfortunately for infrasound propagation calculations, mesoscale models are limited to tropospheric altitudes (< 35 km). Above this altitude the weather systems are dominated by globally coherent planetary waves and vertically propagating tides. These waves and tides become uncoupled from the local influences of tropospheric water vapor, the oceans, and topography, all of which dictate much of the meteorology in the lower atmosphere. Thus the dynamics of the stratosphere and mesosphere cannot be accurately modeled on regional scales. Therefore global NWP models that extend into the stratosphere and beyond are still needed for accurate infrasound propagation calculations. In addition, these models are required to initialize and specify the time dependent mass flux conditions at the boundaries of the mesoscale model domains. Routine development and operation of global stratospheric numerical weather models are well established at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center, which operates the GEOS-4 model, as well as at the European Center for Medium Range Weather Forecasting (ECMWF). Recent NRL research and development efforts geared at operational implementation of a stratospheric and mesospheric numerical weather prediction model, NOGAPS-α (McCormack et al., 2004; Coy et al., 2005), may benefit the ground-based nuclear monitoring research community in the near future.

Much like the trend in numerical weather prediction modeling, a recent trend in national nuclear monitoring efforts is toward technologies for regional propagation modeling capability in order to improve source detection and classification. There are, therefore, good reasons to develop a regional G2S atmospheric specification capability that takes advantage of and supplements existing operational mesoscale models. First, by staying in step with current trends in operational meteorology, our effort will ensure that future infrasonic monitoring systems will be able to take advantage of the most up-to-date environmental information available. Second, the conformally mapped rectangular grids provided by the mesoscale specification systems will be easier to transform into the spectral domain and merge with similarly gridded and transformed subsets of the Stratospheric NWP data and HWM/MSIS upper atmospheric empirical models.

In the current G2S system (Drob et al., 2003) global vector spherical harmonic transforms are required because of coordinate system singularities at the poles, while conformally mapped regional specifications can be spectrally decomposed, stored, and easily manipulated with simpler 2-D Fourier transforms. This will make client-side reconstruction of the merged atmospheric models for infrasound propagation calculations more straightforward, although some of the same fundamental issues of optimal resolution and interpolation remain. During the ongoing effort, we will develop subroutines that enable improved propagation modeling via incorporation of mesoscale specifications into InfraMAP, and we will investigate the vertical and horizontal resolution required in an atmospheric specification to accurately calculate relevant infrasonic observables. Figure 2 shows how the regional high-resolution G2S framework will be constructed for use in developing an improved understanding of the physics needed to improve national capabilities for infrasound monitoring.

Terrain elevation has been identified as a potentially important issue for infrasound propagation calculation (Drob, et al., 2003). At regional distances the earth is not a locally flat, perfectly reflecting surface for infrasound waves. This is particularly important for propagation modeling over mountainous regions where steep terrain can create shadowing, diffraction, and scattering effects. Many regions of concern contain mountainous areas, which may provide protection against infrasonic detection of clandestine nuclear tests. Furthermore, terrain adds to the complexity of the characterization of winds near the earth's surface. In order to represent complex fluid interaction over variable topography, mesoscale models such as COAMPS and WRF contain detailed terrain models. These systems also contain information on land use, roughness scales, vegetation and soil type that may also be useful for infrasound propagation modeling work. Therefore, another advantage to adapting a regional/mesoscale framework for the G2S model is that inherent to COAMPS and WRF outputs are complete representations of the relevant topographical features that can be simultaneously included along with the environmental specifications for infrasound propagation model calculations. We intend to address issues associated with propagation over variable terrain, so that the atmosphere and the terrain can be evaluated on a consistent spatial scale. Issues to be addressed include: correctly accounting for altitude above mean sea level when evaluating the various atmospheric characterizations; characterizing near-surface winds in the vicinity of rapidly varying terrain such as mountain ranges and islands; consistently modeling ground reflections using physically valid assumptions; and determining spatial length scales that are appropriate for evaluating terrain elevation and slope at infrasonic frequencies of interest. InfraMAP currently incorporates ETOPO 5-minute topography for environmental display purposes but not in propagation calculations. The HARPA ray-tracing model can readily support propagation calculations over variable terrain elevation (Jones et al., 1986). In addition to obtaining the source codes and supplemental data sets needed to run the COAMPS and WRF models locally for infrasonic research and development activities, we have obtained the 30-arc-second (1 km) global Digital Elevation Model (DEM) from the National Geophysical Data Center (Hastings and Dunbar, 1998).

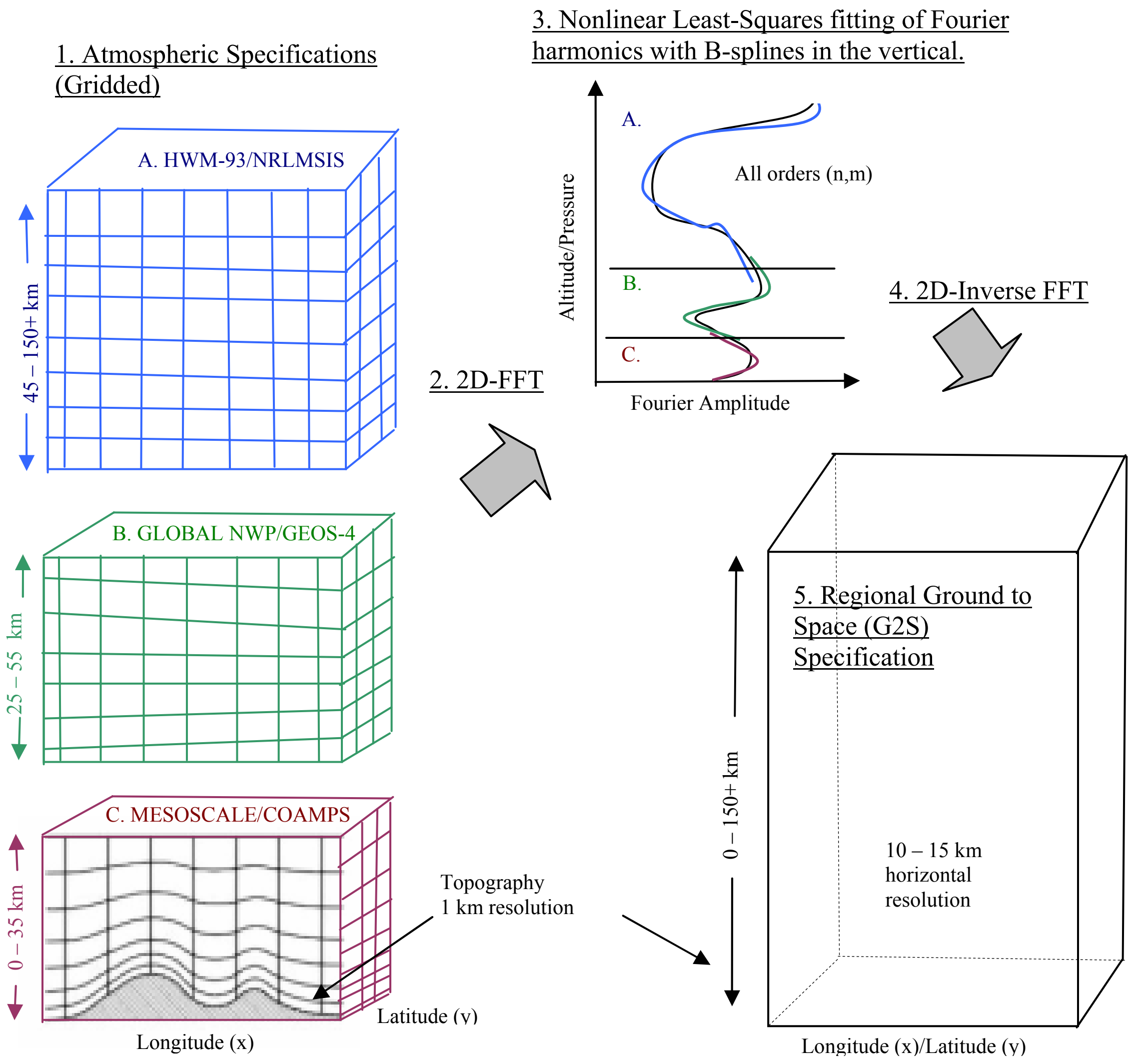


Figure 2. The regional high resolution atmospheric specification framework for infrasound propagation calculations.

At regional distances there are a number of open scientific questions concerning the characterization of infrasonic arrivals at ranges of 50 to 350 km that cannot always be explained by classical ray methods. One specific example is in the observed arrivals at the NVIAR array during the Watusi experiment conducted on September 28, 2002 (Bhattacharyya, 2003). Along with an investigation into the breakdown of classical ray theory, accurate regional specifications of the near field environmental conditions are needed to address the scattering of infrasound off of internal wave structures and topography to explain the observed phenomena. The development of high-resolution regional-scale G2S specification capabilities, begun in the work presented here, will be able to support future calculations and investigations of these aspects of infrasound propagation via advanced propagation models that more fully capture the relevant fundamental physics of a propagating infrasonic wavefront. Recent model developments include a Fourier-synthesis time-domain parabolic equation (TDPE) model [Norris, 2004]. Other researchers are investigating application of 3-d, finite-difference, time-domain techniques (FDTD) to local and regional scale infrasound propagation; initial applications of the FDTD supported by existing low resolution G2S capabilities were recently reported by Collier et al. (2004) and Symons et al. (2004).

A recent ground truth event that demonstrates the value of the G2S atmospheric specification is the 18-Feb-2004 train car explosion in Neyshabur, Iran, which was observed at two International Monitoring System (IMS) infrasound arrays, I31KZ (1579 km to the north) and I34MN (4078 km to the east). Detailed results of analysis and modeling have been recently presented by Gibson and Norris, 2004. At I31KZ, the explosion signal was observed to have travel times ranging from 5200 to 5835 sec. The observed azimuth deviation (from the great circle) was -7.9 deg. Ray-tracing calculations were made using both climatology and G2S. The predicted travel times that are consistent with the observation are shown in bold, with those rows shaded. Significantly higher zonal wind velocities and effective sound speeds are predicted between approximately 30-50 km altitude using G2S. This difference is sufficient to define a stratospheric duct using G2S that is not predicted using climatology. Furthermore, the predicted azimuth deviation using G2S is approximately 95% of the observed value, compared with less than 60% using HWM and MSIS. In this case, near-real-time specifications significantly improve both travel time and azimuth predictions compared to climatology.

Further understanding is required of the strengths and weaknesses of existing propagation calculation techniques. Ongoing work will include detailed propagation case studies using G2S and other atmospheric characterizations for a set of ground truth events selected from a body of available data. Comparisons between models and data will be conducted not only using ray-tracing but also using other modeling techniques. By investigating realistic spatial and temporal atmospheric models at a range of resolutions, we desire to gain insight into the appropriate spatial and temporal scales that are necessary for achieving improved infrasound predictions at the relevant frequencies. We intend to assess performance of candidate techniques for incorporating mesoscale (regional) atmospheric models and terrain specifications with propagation models and evaluate the benefits.

A Predicted Annual Time Series of Infrasonic Observables

This research effort includes comparison studies and sensitivity studies to assess the improvements in predicting travel times and back-azimuths (for event location) and phase identification (for localization and association) that are attainable with synoptic and/or mesoscale predictions. A goal of the studies is to test the accuracy and applicability of the infrasound predictions, and to obtain a realistic estimate of the model error budget. Previous efforts at calibrating travel times have focused on stratospheric or thermospheric paths. Typically, these times have been estimated using only a ray-theoretic approach with simple, seasonal atmospheric parameterizations. Ongoing studies in this effort will be focused on developing new understanding of propagation at local and regional ranges.

A number of researchers have suggested and demonstrated that infrasound propagation characteristics vary significantly on a day-to-day basis as the result of natural variability of the lower atmosphere (e.g., Garces et al., 2002; LePichon et al., 2002; Drob et al., 2003). This was recently illustrated with one year of continuous volcanic observations by LePichon et al. (2005). Drob et al., 2003, calculated acoustic ray-turning heights, single skip travel times, ranges, and velocities using a simple ray-tracing code, comparing both the HWM-93/NRLMSISE-00 and G2S models. These initial calculations were limited to only 25 days in January 2003, but clearly illustrated the value added by operational NWP data. These calculations have now been expanded with new ray tracing capabilities to evaluate the impact of time dependent meteorological phenomena on infrasound propagation over an entire year. Travel time, arrival azimuth, and apparent phase velocity of the infrasonic signals from a series of fictitious calibration explosions at White Sands Missile Range (WSMR) are calculated for a number of regionally located infrasound stations. These forward calculations are performed for a total of 1460 (365 x 4) simulated explosions occurring at 6-hour intervals for the entirety of 2004.

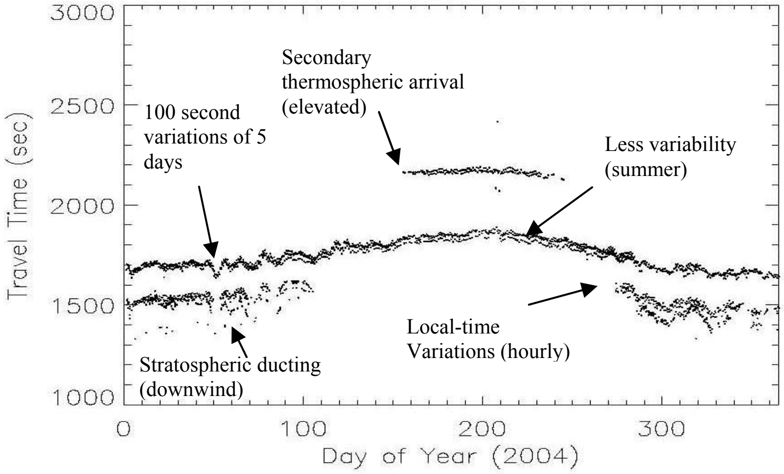
For each of the hypothetical events, a dense quiver of rays that spans elevation angles of ± 50º, and ± 7.5º of true azimuth at .01º intervals was shot toward one of fourteen receivers. In addition, novel pruning techniques based on simple heuristics at intermediate ray turning points are used to terminate integration of rays that have no chance of reaching a detector. Those rays that eventually land within ± 0.75 km of a station are deemed detectable. A check of the numerical stability of the detected eigenrays was then performed by integrating these backwards in time from the receiver to the source. Results shown here are for a series of hypothetical infrasound calibration sources 50 km over WSMR in the spirit of the calibration experiment outlined in Herrin et. al., 2004.

Figure 3 shows the time series of travel time predictions for two of the hypothetical stations, one located 463 km ENE of the source at a bearing of 79º (panel A) and the other located at distance of 405 km WSW of the source at a bearing of 207º (panel B).

The calculations indicate that during the northern hemisphere winter months when the stratospheric winds at mid latitudes blow from west to east, stratospheric ray paths are possible in the eastward downwind direction (A) Figure

3. During the summer months there is a reversal in the stratospheric wind direction from east to west, again resulting in stratospheric ray paths in the westward downwind direction (B) Figure 3. It is well known to the atmospheric science community that stratospheric winds and planetary wave activity in the winter hemisphere are highly variable compared to those in the summer hemisphere. This stratospheric wave variability can result in changes of order 100 sec in travel times over a 5 day period. During the summer months when the stratospheric wind is relatively quiescent, travel times are predicted to remain relatively constant. The calculations also show that the seasonal change in stratospheric winds near the source altitudes (50 km) results in the formation of a second thermospheric ray path which has a reflection height near 130 km. In reality these arrivals will likely not be observed, as classical molecular attenuation was neglected. Finally, the detection time series reveals fine splitting of travel times on the order of 50 seconds over a 24 hour period due to the effects of migrating tides in the mesosphere and lower thermosphere driven by solar heating. When considering the significance of these tidal influences it is important to note that no realistic day-to-day variations of the diurnal and semidiurnal solar migrating tidal amplitudes are included in the G2S (HWM-93) model, only slowly varying seasonal variations. Furthermore, tidal amplitudes may be underestimated by a factor of 2 in amplitude (Drob and Picone, 2000). Because the HWM/MSIS models form the basis for the specification of winds and temperatures for the G2S model above 60 km, any biases or errors above this region will impact calculation of travel times and azimuth deviations for thermospheric phases, regardless of the model selected.

A) Eastward Propagation



B) Westward Propagation

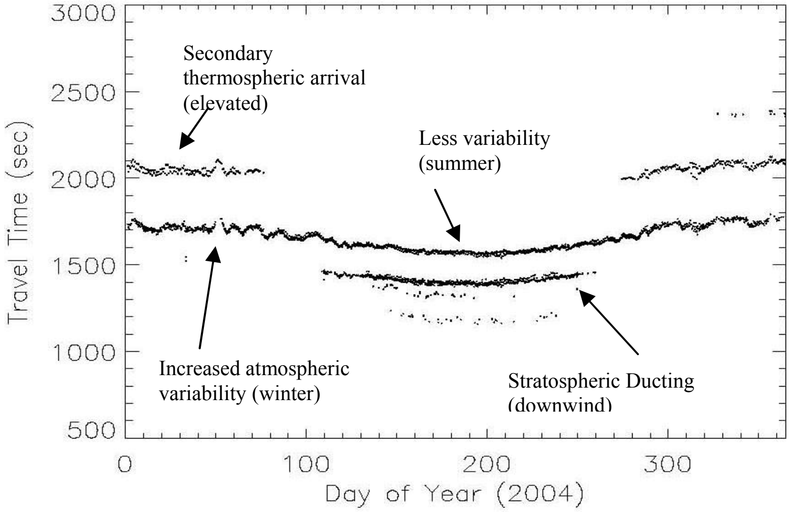
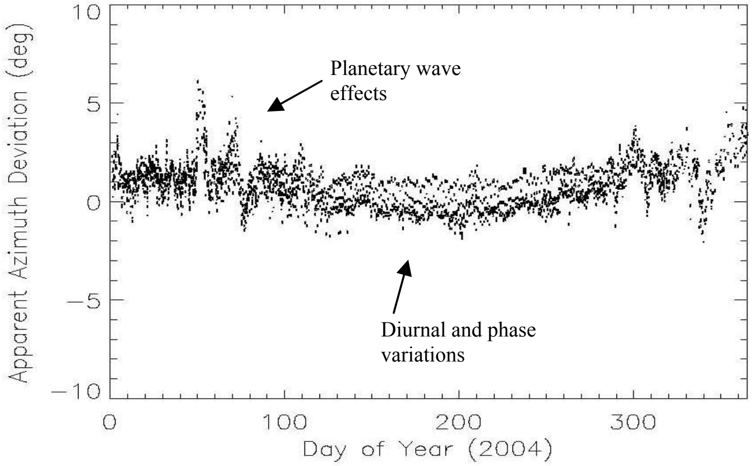


Figure 3. Predicted travel times for two hypothetical stations, one located 463 km ENE of the source at a bearing of 79º (A) and the other located 405 km WSW of the source at a bearing of 207º (B).

Figure 4 shows the predicted azimuth deviations for two stations, one located almost due east of the source at a range of 639 km and bearing of 89º (A), and the other located to the SSE at a distance of 525 km with a bearing of 149º (B). Again large daily variations in the predicted azimuth deviations resulting from the significant tropospheric and stratospheric wintertime synoptic scale wave activity are observed. Apparent azimuth deviations for a typical source-to-receiver configuration may vary by as much as 5.0° over a 5 day period (A, B). In addition the seasonal variation in the apparent azimuth for meridionally oriented source to receiver configurations can range from greater than 7.5° in the winter months to -5.0° in the summer as the result of atmospheric winds (B). The reason for the observed asymmetry is that the stratospheric wind jet is lower and stronger in the winter as compared to the summer, combined with the fact that the tropospheric jet stream is always predominantly eastward. Finally, the predicted hourly variations are on the order of ± 2.5°. Similar variations of volcanic infrasound over a one year period were observed by LePichon et al. (2005). The G2S model showed dramatic improvement over the HWM model in predicting the observations, however significant errors in azimuth deviation of on the order of 3.0° occurred during certain time intervals. Wind corrections of up to 50 m/s in the 65-to-120 km region of the G2S/HWM model were needed to bring the predicted azimuths in line with the observations.

A) Zonal Propagation



B) Meridional Propagation

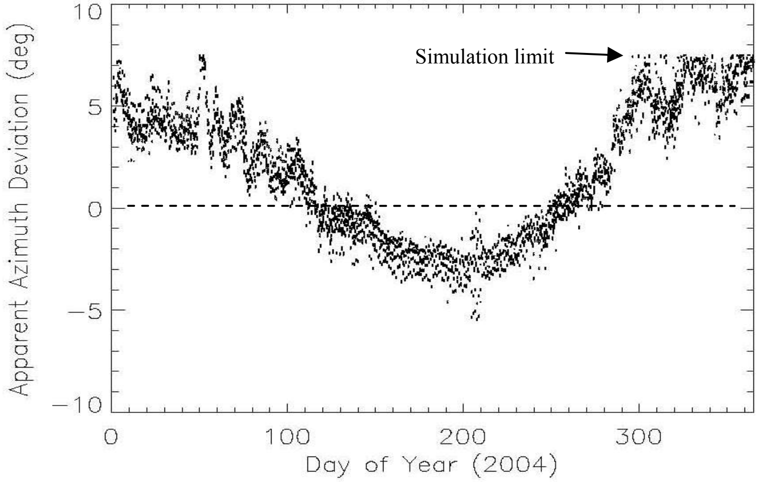


Figure 4. Predicted azimuth deviations for two stations, one located 639 km away at a bearing of 89° from the source (A) and the other located 525 km away at a bearing of 149° from the source (B).

CONCLUSIONS AND RECOMMENDATIONS

Synoptic specifications are used with infrasound propagation models in order to improve predictions compared to those based on climatology. However, observed infrasound phases have not been well predicted by state of the art propagation models for several ground truth events. Therefore, modeling advances that address the fundamental physical processes that affect infrasound are required. Also required, in parallel, are advances in specification of the propagation environment that address fundamental atmospheric physics at appropriate spatial and temporal scales and that can be utilized to improve the performance of advanced propagation models.

Study of long range events will improve understanding of the strengths and weaknesses of global synoptic specifications. Mesoscale atmospheric models and terrain databases, used to improve characterization of the lower regions of the atmosphere, will enable improved understanding of local and regional propagation of infrasound signals. Study of local and regional events will improve understanding of the importance of mesoscale phenomena.

One of the important aspects of the work is to consider the uncertainties introduced by the various physical assumptions and environmental specifications that relate the infrasonic observable back to source characteristics. The significance of these assumptions and uncertainties must be compared to uncertainties in the measurement techniques and statistics of the ground truth event database. Assumptions about the spatiotemporal resolution of environmental specifications can be further quantified deterministically in this line of research. There are a number of known biases and irresolvable atmospheric phenomena that also need to be considered in the evaluation of the performance of infrasonic monitoring systems.

For infrasound applications, G2S is meant to replace the HWM-93/NRLMSISE-00 empirical models as the next generation semi-empirical atmospheric specification tool. Since G2S incorporates HWM/MSIS predictions at high altitudes, the adjustment or updating of the current HWM-93/NRLMSISE-00 internal model coefficients is a high priority, due to known issues regarding tidal predictions in the models.

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REFERENCES

Bhattacharyya, J., H. Bass, D. P. Drob, R. Whitaker, D. Revelle, and T. Sandoval (2003), Description and Analysis of Infrasound and Seismic Signals Recorded from the Watusi Explosive Experiment, on September 28, 2002, in *Proceedings of the 25th Seismic Research Review - Nuclear Explosion Monitoring: Building the Knowledge Base*, Tucson, Arizona, LA-UR-03-6029: Vol. 2, pp. 587-596.

Collier S.L., D.H. Marlin, N. P. Symons, D. F. Aldridge, D. K. Wilson, E. G. Patton, P. P. Sullivan, V. E. Ostashev, and D. P. Drob (2004), Acoustic Wave Propagation in Complex Atmospheric Environments: Third Year Results, in *Proceedings of the Meeting of the Military Sensing Symposia (MSS) Specialty Group on Battlefield Acoustic & Seismic Sensing, Magnetic & Electric Field Sensors*, Laurel, MD.

Coy L, D. E. Siskind, S. D. Eckermann, J. P. McCormack, D. R. Allen, and T.F. Hogan (2005), Modeling the August 2002 Minor Warming Event, *Geophys. Res. Lett.* 32: (7): Art. No. L07808.

Drob, D. P., J.M. Picone, and M. Garces (2003), Global Morphology of Infrasound Propagation, *J. Geophys. Res.* 108: (D21): Art. No. 4680.

Drob, D. P. (2003), Detailed Specifications of the Atmosphere for Infrasound Propagation Modeling, in *Proceedings of the 25th Seismic Research Review - Nuclear Explosion Monitoring: Building the Knowledge Base*, LA-UR-03-6029: Vol. 2, pp. 605-616.

Drob D.P., and J.M. Picone (2000), Statistical Performance Measures of the HWM-93 and MSISE-90 Empirical Atmospheric Models and the Relation to Infrasonic CTBT Monitoring, in *Proceedings of the 22nd Annual DoD/DOE Seismic Research Symposium: Planning for Verification of and Compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT)*, New Orleans, LA, no.07-03, 8 pages.

Garces, M., C. Hetzer, K. Lindquist, and D. P. Drob (2002), Source Location Algorithm for Infrasonic Monitoring, *Proceedings of the 24th DTRA/NNSA Seismic Research Review - Nuclear Explosion Monitoring: Innovation and Integration*, LA-UR-02-5048, Vol. 2, pp. 755-765.

Gibson, R. and D. Norris, (2003), Integration of InfraMAP with near-real-time atmospheric characterizations and applications to infrasound modeling, *Proceedings of the 25th Seismic Research Review - Nuclear Explosion Monitoring: Building the Knowledge Base*, LA-UR-03-6029, Vol. 2, pp. 638-645.

Gibson, R. and D. Norris, (2004), Integration of InfraMAP Software with Near-Real-Time Atmospheric Characterizations, Final Report to AFRL under Contract DTRA01-01-C-0084.

Hastings, D.A. and P.K. Dunbar (1998), Development & Assessment of the Global Land One-km Base Elevation Digital Elevation Model (GLOBE), *International Society of Photogrammetry and Remote Sensing | Commission IV | Symposium in September, 1998, ISPRS Archives*, Vol.32, number 4, pp. 218-221.

Hedin, A. E, E. L. Fleming, A. H. Manson, F. J. Schmidlin, S. K. Avery, R. R. Clark, S. J. Franke, G. J. Fraser, T.Tsuda, F. Vial, and R. A. Vincent (1996), Empirical wind model for the upper, middle, and lower atmosphere, *J. Atmos. Terr. Phys*. 58: 1421-1447.

Herrin, E.T., P.W. Golden, P. Negraru, H.E. Bass, G.S. Hunter, W.L. Andre, J.V. Olson, D.L. Osborne, M.A. Garces, M.A. Hedlin , K. Hoffman (2004), Infrasound calibration experiments at White Sands Missile Range: Planning and preparations, in *Proceedings of the 26th Annual Seismic Research Review: Trends in Nuclear Explosion Monitoring*, LA-UR-04-5801, Vol. 2, pp. 645-653.

Hodur, R.M. (1997), The Naval Research Laboratory coupled ocean/atmosphere mesoscale prediction system (COAMPS), *Month. Weather Rev.*, 125 (7): 1414-1430.

Jones, M. J., J. P. Riley, and T. M. Georges, 1986: A Versatile Three-Dimensional Hamiltonian Ray-Tracing Program for Acoustic Waves in the Atmosphere above Irregular Terrain, NOAA Special Report, Wave Propagation Laboratory, Boulder, CO.

Le Pichon, A., M. Garces, E. Blanc, M. Barthelemy, and D. P. Drob (2002), Acoustic Propagation and Atmosphere Characteristics Derived from Infrasonic Waves Generated by the Concorde, *J. Acoust. Soc. of Amer.* 111: (1), 629-641.

Le Pichon, A., E. Blanc, D.P. Drob, S. Lambotte, J.X. Dessa, M. Lardy, P. Bani, S. Vergniolle (2005), Infrasound Monitoring of Volcanoes to Probe High-altitude Winds, *J. Geophys. Res.* 110: No. D13, D13106*,* 10.1029/2004JD005587.

McCormack J.P., S.D Eckermann., L. Coy, D.R. Allen, Y.J. Kim, T. Hogan, B. Lawrence, A. Stephens, E.V. Browell, J. Burris, T. McGee, C.R. Trepte, (2004), NOGAPS-ALPHA modeling simulation of stratospheric ozone during the SOLVE2 campaign, *Atmos. Chem. and Phys.* 4: 2401-2423.

Norris, D., 2004: Time-domain modeling techniques and the study of infrasound propagation, in *Proceedings of the 26th Seismic Research Review*: *Trends in Nuclear Explosion Monitoring*, LA-UR-04-5801Orlando, FL.

Picone, J. M., A. E. Hedin, D. P. Drob, and A. C. Aikin, (2002), NRLMSISE-00 Empirical Model of the Atmosphere: Statistical Comparisons and Scientific Issues, *J. Geophys. Res.* 107: (A12), art. no.-1468.

Gropp W., E. Lusk, N. Doss and A. Skjellum (1996), A high-performance, portable implementation of the {MPI} message passing interface standard, *Parallel Computing* 22: 6, 789-828.

Skamarock W.C. (2004), Evaluating mesoscale NWP models using kinetic energy spectra, *Mon. Weather Rev.* 132 (12): 3019-3032.

Symons N.P., D.F. Aldridge, D.H. Marlin, D.K. Wilson, E.G. Patton, P.P. Sullivan, S.L. Collier, V.E. Ostashev, and D. P. Drob (2004), 3D Staggered Grid Finite-Difference Simulation of Sound Refraction and Scattering in Moving Media, in *Proceedings of the 11th International Symposium on Long Range Sound Propagation*, Fairlee, VT.