ADVANCEMENT OF INFRASOUND PROPAGATION CALCULATION TECHNIQUES USING SYNOPTIC AND MESOSCALE ATMOSPHERIC SPECIFICATIONS

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ABSTRACT

Numerical calculation of infrasound propagation paths 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 (*Infra*sound *M*odeling of *A*tmospheric *P*ropagation) integrates infrasound propagation models and environmental representations, including synoptic updates of the atmospheric specification, 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 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 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 for infrasound monitoring.

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 the following:

- 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 paper 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.

Prior 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 data sets using global spectral methods to specify the details of the entire atmosphere for use in infrasound propagation calculations. The infrasound analysis tool kit InfraMAP (Infrasound Modeling of Atmospheric Propagation) allows 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, 2004). 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

Improving NRL G2S with Mesoscale Atmospheric Specifications

Fine scale atmospheric structures, both resolvable and irresolvable, can be responsible for acoustic wave scattering. Furthermore, the resulting specifics of computational modeling of infrasound from source to receiver are sensitive to the initial and final environmental boundary conditions, as well as conditions at points along the propagation path.

The atmospheric structure responsible for the refraction of infrasonic energy from the surface to the stratosphere and above may change rapidly. Below 55 km these structures are now being resolved on an hourly basis in real-time for civilian and defense applications by powerful operational global and regional scale data assimilation systems that synthesize huge amounts of data from a diverse network of operational satellite-, ground-based, and in-situ sensors. If technologically feasible, use of such atmospheric characterizations is likely to result in higher precision infrasound propagation predictions than are possible using climatology. These observationally based meteorological analysis fields are being produced on a routine basis the by the combined efforts of the National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), Department of Defense (DoD), and the World Meteorological Organization.

The NRL G2S model of Drob et al. (2003) took the first step toward combining the available global operational lower atmospheric specifications from NOAA (Kanamitsu, 1998; Kalnay et al., 1990) and NASA (Bloom et al., 2005) with the NRLMSISE-00/HWM-93 models (Picone et al., 2002, Hedin et al., 1996) of the upper atmosphere for historical and, subsequently, near-real-time infrasound event analysis. A number of realizable technical improvements to the existing G2S environmental prediction system, theoretically shown to be significant to infrasound propagation calculations, are now being implemented. One of these is the incorporation and utilization of operational, high-resolution, mesoscale (regional) atmospheric specifications.

National and DoD weather centers can provide regional atmospheric specifications that have a very high spatiotemporal resolution and accuracy compared to comprehensive global specifications. This is achieved by focusing additional efforts on the meteorological observations and atmospheric physics specific to a given geographic region. To illustrate this increase in information content, Figure 1 shows a comparison of zonal and meridional wind profiles from the HWM-93 empirical wind model, the global NRL G2S system, and the Weather Research and Forecasting (WRF) mesoscale specifications at two locations, I31KZ and Baghdad, Iraq. Improved resolution of the vertical structure can be seen in the 0 to 20 km region.

Utilization of these mesoscale specifications should generally be superior to the utilization of an individual radiosonde profile obtained in the immediate vicinity of a ground-truth event for infrasound propagation calculations for all but very short range (< 25 km) propagation calculations. The operational assimilative analysis serves to remove any instrument calibration biases, as well as reduce statistical measurement errors by corroboration with overlapping and adjacent satellite, radar, and ground-based measurements, as well through known fluid dynamical constraints. In addition, by self-consistently combining all of the available meteorological observations in the immediate vicinity of a ground-truth event into a unified specification, range variations (i.e., horizontal gradients) that are important for infrasound propagation over distance of about 100 km can be resolved and provided. To illustrate this point further, the zonal and meridional wind profiles along a 300 km north-south path at 10 km intervals centered on I31KZ are shown in Figure 2 along with a single G2S profile for comparison. Improvement in the information content of the atmospheric specifications over the lower resolution G2S global specifications is clearly apparent. The significance of topographic variations relative to the vertical scale of the meteorological variations also becomes evident.

Model Domains and Initial Implementations

A potential disadvantage of the development and utilization of mesoscale or regional atmospheric specifications is that the available background fields are limited to a specific model domain. These domains generally encompass important regions of interest, but the domains can also be customizable to some extent. By design, the boundary conditions (including the upper level boundary condition) of these mesoscale specifications are provided by the corresponding global atmospheric specifications.

NOAA operates and provides atmospheric specifications at 13 and 20 km horizontal resolution on an hourly basis for the continental US (CONUS) in a reliable and straightforward manner, and the specifications can be used to investigate infrasound propagation from ground-truth events. The NOAA mesoscale system is called the Rapid Update Cycle (RUC). The RUC specifications extend to an altitude of approximately 20 km and are widely used by the commercial aviation and weather forecasting industries. The provision of operational and/or custom mesoscale atmospheric specifications for infrasound propagation calculations is discussed further below.

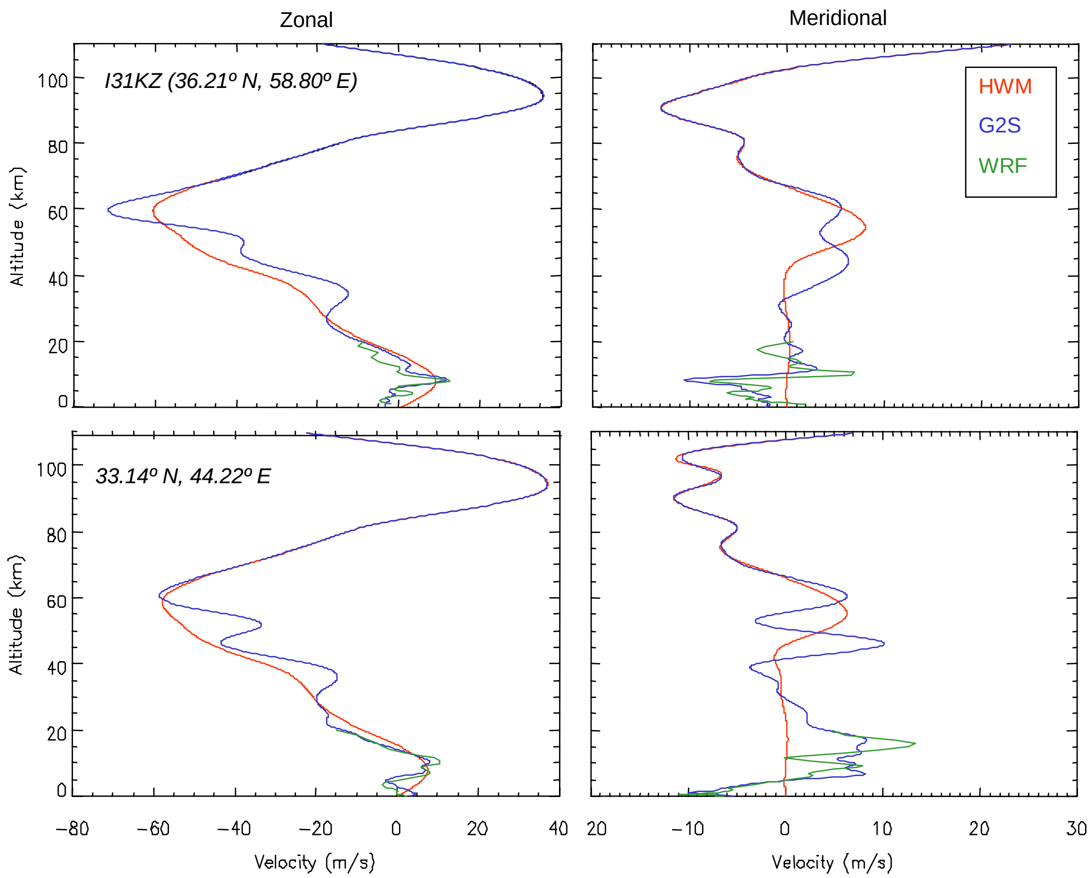

Figure 1. A comparison of zonal and meridional wind profiles from the HWM-93 empirical model (red), NRL Global G2S (blue), and the NRL Mesoscale G2S specifications (under development) that incorporate WRF (green), at two locations, I31KZ (above) and Baghdad, Iraq (below).

One of the challenges in utilizing the NOAA CONUS RUC for infrasound propagation calculations is related to the handling of the horizontal coordinate system. The NOAA RUC specifications are provided on a 301 x 225 Lambert equal area projection. This horizontal grid system is problematic because bivariate interpolants that are continuous in the first derivative across the grid cells are computationally expensive to approximate from the unequally spaced grid points as compared to equally spaced grid points. Interpolation of the unequally sampled fields for use by propagation codes would increase computational times significantly. An alternate approach is to interpolate from the RUC coordinates to an equally spaced coordinate system in advance. This requires a significant amount of computational time compared to other aspects of the G2S mesoscale data fusion process.

In the current implementation of the G2S-mesoscale model merging process, the NOAA Global Forecast System (GFS) and NASA GEOS-4 stratospheric specifications, which provide information content in the 25 to 55 km region, and the corresponding global G2S specifications, which provide information content in the 55 km region, are interpolated to the RUC grid points before merging all of the data sets in the vertical direction. Because the NOAA RUC fields are self-consistent with the NOAA GFS specifications, and because the NOAA GFS and NASA GOES-4 are implicitly self-consistent with the corresponding global G2S specification in the 45 to 55 km region, no significant discontinuities arise between various data sets in the overlap region. As a result, merging of the various fields in the vertical can be performed by averaging the last four grid points of the RUC specification with the other overlapping data sets. The resulting unified specification has 96 vertical levels, with the majority of levels in the first 25 km. These specifications are then interpolated to a regularly spaced latitude and longitude grid at 0.125° intervals using a cubic Shepard method for bivariate interpolation of scattered data, as outlined by Renka, 1999.

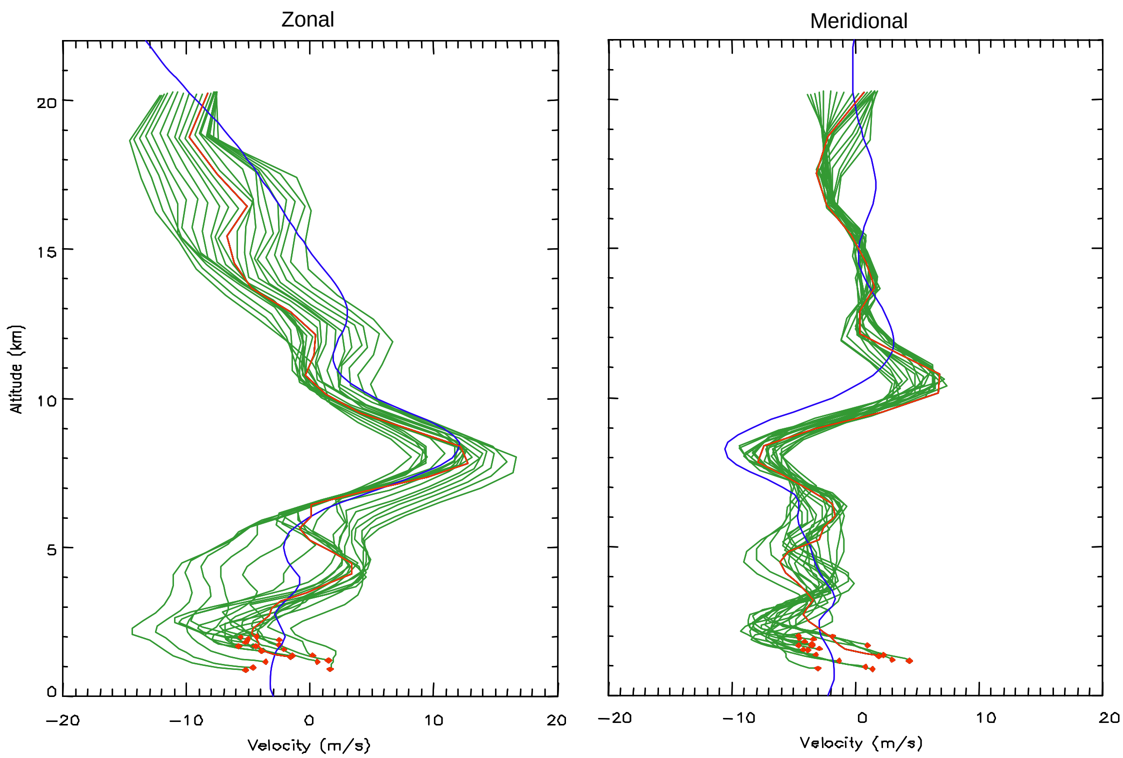

Figure 2. Mesoscale wind profile specifications along a +/- 150 km north/south meridian centered at I31KZ (green). The red profile indicates the profile at I31KZ. The blue profile represents the corresponding G2S global specification. The red dots at the bottom of each profile indicate the surface altitude variation at each location relative to mean sea level.

For practical reasons, the resulting G2S mesoscale grid that has been used for current software integration and testing purposes, systems automation development, and ground-truth validation efforts has been limited to the western half of CONUS. This domain encompasses the regional US infrasound network and includes I57US, I56US, and I10CA, as well as the source regions of White Sands Missile Range (WSMR) and Nevada Test Site (NTS). The domain is shown in Figure 3.

Another aspect of the effort has been to address the issue of the mesoscale vertical coordinate system. Effects ranging from the direct influence of mountain ridges on local wind patterns to the altitude-dependent interaction of humidity with precipitation, soil moisture, and ground cover content are all considered by meteorologists and by the current mesoscale numerical specification and prediction systems. Moderate- to high-resolution terrain models are thus an integral part of mesoscale meteorological specifications that are used to update and initialize operational numerical forecast models. To simplify numerical integration of the dynamical fields, as well as specification of the lower boundary conditions, operational mesoscale atmospheric data fields utilize what is known a sigma vertical coordinate system. This coordinate system is defined relative to the earth's surface and is thus terrain following. This makes direct utilization of existing mesoscale (and global) fields in infrasound propagation calculation difficult because these calculations are almost always performed in altitude coordinates. To illustrate the nature of this coordinate system as it relates to infrasound propagation, a vertical cross section of the first 25 kilometers of the G2S mesoscale atmospheric specification for zonal wind fields at 15 UTC on March 25, 2006, is shown in Figure 4. Each horizontal line represents a data specification level on which the wind and temperature fields are provided.

Note that the vertical resolution of the mesoscale system is on the order of 20 to 50 meters near the surface, increasing to larger, yet variable values with altitude. Being regularly gridded in horizontal directions, these specifications can be interpolated over one dimension in the vertical direction with cubic splines. Efficient vertical interpolation of these fields for infrasound propagation calculations is currently being investigated.

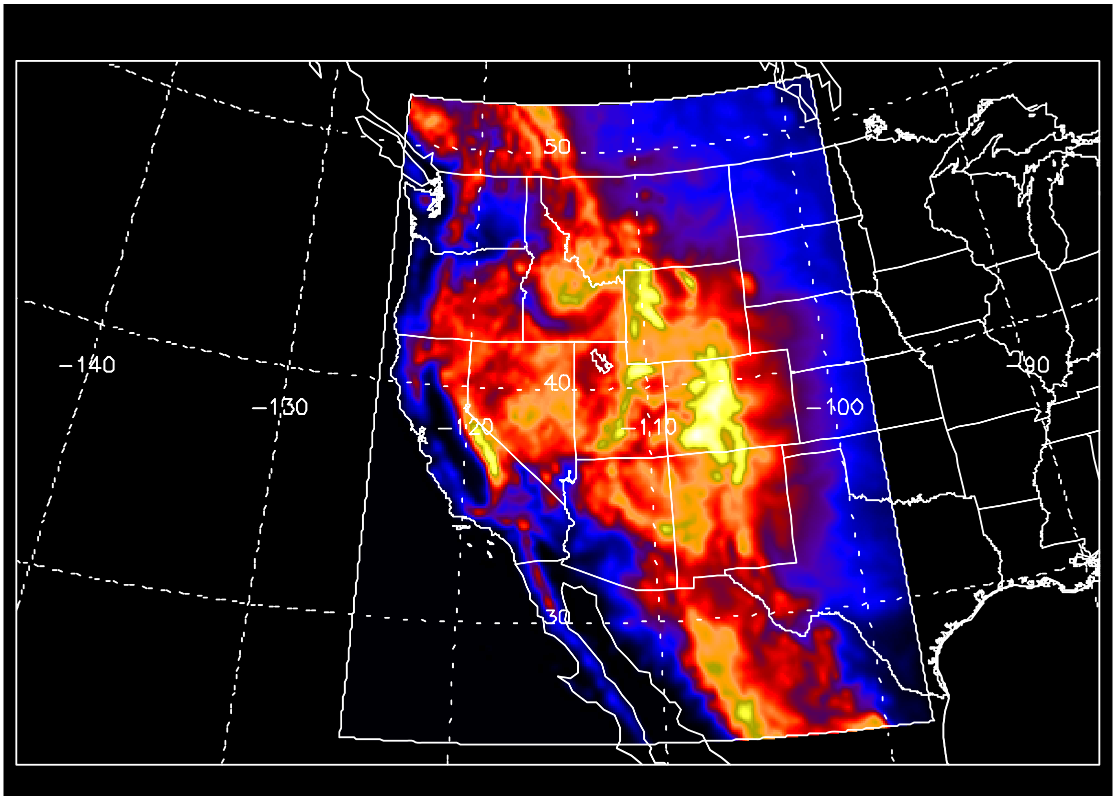

Figure 3. The prototype NRL G2S CONUS-WEST mesoscale specification domain. The image represents the 20 x 20 km terrain elevation model used to specify the lower boundary of the model domain. The color scale ranges from black for mean sea level within the domain, to white in the Colorado Rocky Mountains with an altitude of 3551 meters above sea level.

A static digital terrain elevation model is required to combine mesoscale and recent global atmospheric specification fields with the HWM/thermospheric atmospheric model (MSIS) empirical models in order to translate them into altitude coordinates so that they can be used in infrasound propagation calculations. In addition, detailed range dependent propagation calculations by a number of researchers have clearly demonstrated that terrain scattering effects should not be ignored in mountainous regions. The new G2S mesoscale specifications are being designed to address these issues simultaneously. As a result, in addition to the atmospheric specifications, new capabilities were built into the G2S client software to provide terrain elevation estimates at 30′ resolution (1 km) for any location on the globe to support infrasound propagation models. The NOAA Global Land One-km Base Elevation (GLOBE) digital terrain model provides the underlying data (Hastings and Dunbar, 1998).

Using these mesoscale fields and new tools described above we have now begun to investigate the information content and consequences of G2S-mesoscale specifications for infrasound signal propagation for several ground-truth events. This includes the examination of the fine scale structure of vertical and horizontal gradients in the G2S-mesoscale sound speed and wind fields to assess geophysical significance.

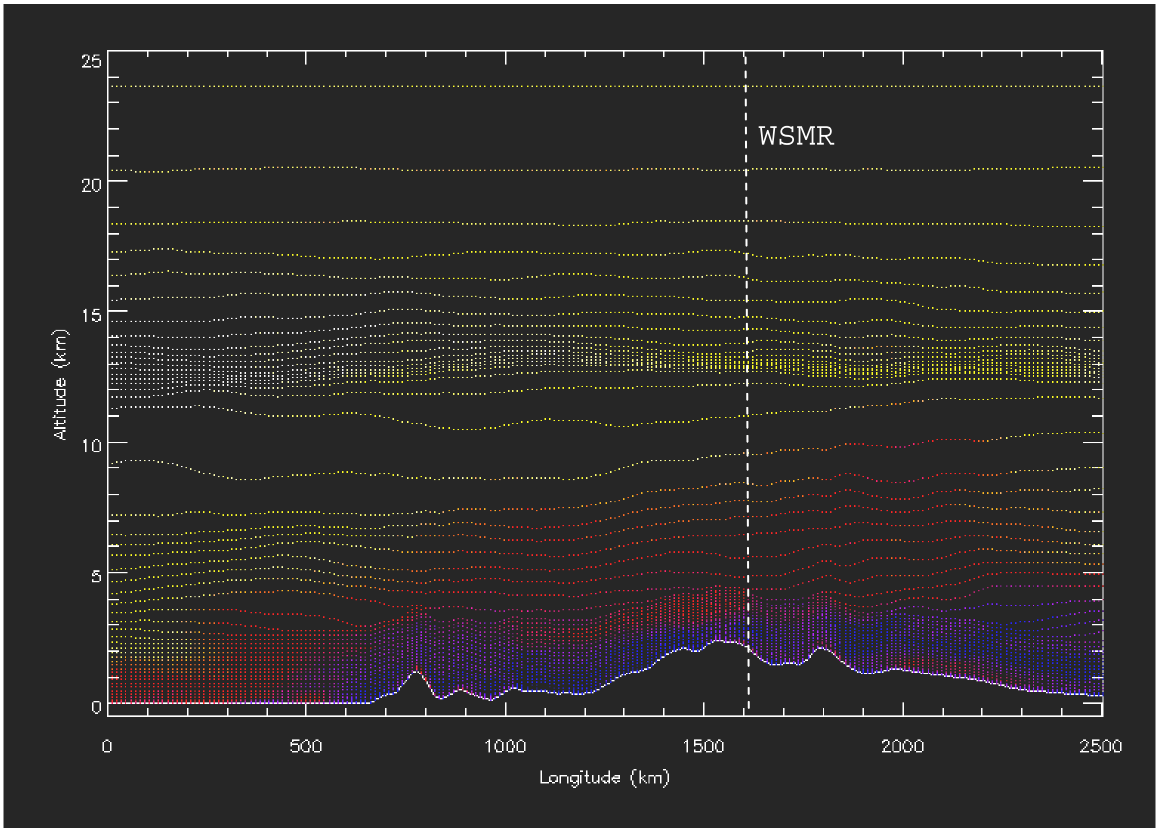

Figure 4. A vertical cross section of the first 25 km of the G2S mesoscale atmospheric specification, zonal wind fields at 15 UTC on March 25, 2006, at a latitude of 33° N. The color scale ranges from 40 m/s eastward (white) to -10 m/s (dark blue). The horizontal axis represents the distance in km from the left edge of the specification domain. The approximate location of WSMR is indicated with a vertical line.

Variable Terrain Elevation and Ray Tracing

Existing ray tracing propagation models for infrasound are limited in how well they characterize the interaction with the earth's surface. In general, a flat surface is assumed and defined using either an equivalent spheroid earth or ellipsoidal earth. As the propagation range decreases, the importance of ray interaction with variable terrain increases. Thus, we are pursuing an effort to integrate variable terrain elevation into ray tracing.

One of the key issues in this effort is identifying the relevant spatial scales over which the variable terrain elevation needs to be resolved for infrasound propagation calculations. To support the evaluation of this issue, we have integrated additional Earth Topographic (ETOPO) databases into the InfraMAP tool kit. Previously, only the ETOPO30 and ETOPO5 databases were available. ETOPO30 provides 30 minute resolution, which translates to approximately 55 km between grid points. ETOPO5 provides 5 minute resolution, or approximately 9 km between grid points. We have integrated the 2 minute ETOPO2 database, with ~4 km grid spacing, and are evaluating the integration of the 30 arc second GLOBE database, which provides very high resolution of order 1 km. Once integrated, each of these databases will be available for use with the ray tracing propagation model. This capability will enable detailed evaluation of the spatial scale issue.

At this time, the ray tracing model integration with ETOPO5 has been completed. At local interactions between the rays and ground, the ETOPO5 database is used to compute the local terrain height and the local first and second derivatives in latitude and longitude. These data are needed in the ray tracing formulations to resolve the angle of reflection of the ray at the surface.

They are computed using cubic spline interpolation. A 4x4 data grid is loaded surrounding the bounce position. Second derivatives at the grid boundaries are computed using central finite differencing over an expanded 16x16 grid. Then cubic interpolation uses these values to compute the local terrain height and associated derivatives needed for the ray calculations.

As an example of this new ray tracing capability, consider the scenario shown in Figure 5. In the background image (left panel) and profile (right panel), the ETOPO5 topography is displayed. The source-receiver path is defined over a 450 km path, providing ample opportunity for interaction between rays and the complex terrain surface.

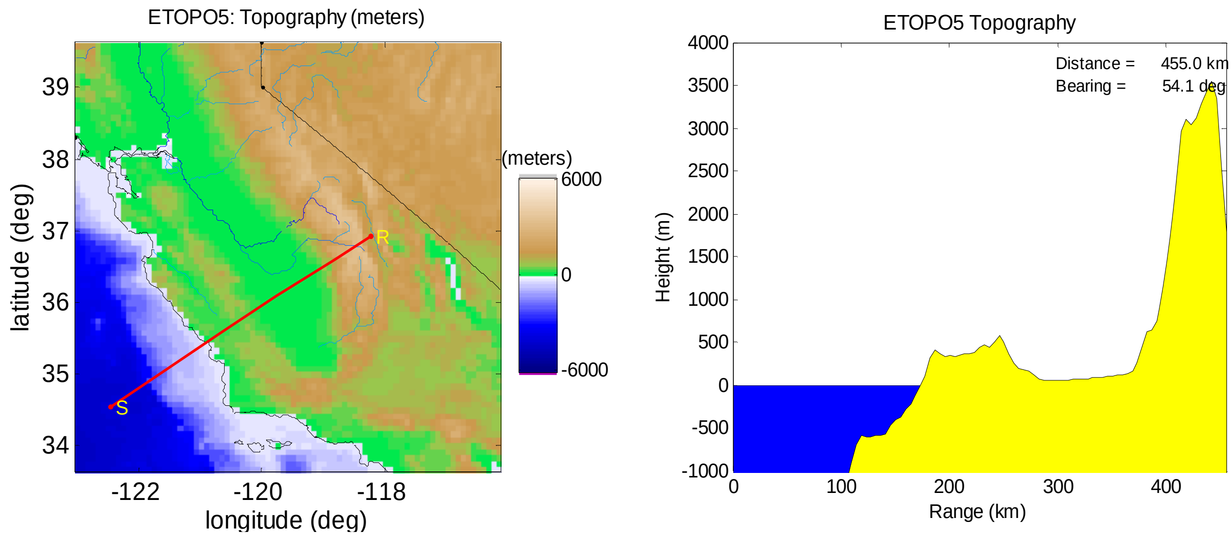

Figure 5. Modeling scenario with source (S) off coast of California and receiver (R) in the Sierra Nevadas. The ETOPO5 database is shown over the region (left) and along the source-receiver great circle path (right).

Figure 6 gives the solution for a ray launched with an initial elevation angle of 15 degrees. There are two bounce points, one at a range of approximately 230 km and the other near the receiver. The first bounce point is shown in more detail in the right panel of the figure. For this resolution and plot scale, the ray appears to reflect specularly, although a more comprehensive comparison with flat earth predictions is needed to fully quantify the effect. In addition to reflection angle, the ray path shape and ray path travel time will vary due to the incorporation of complex terrain.

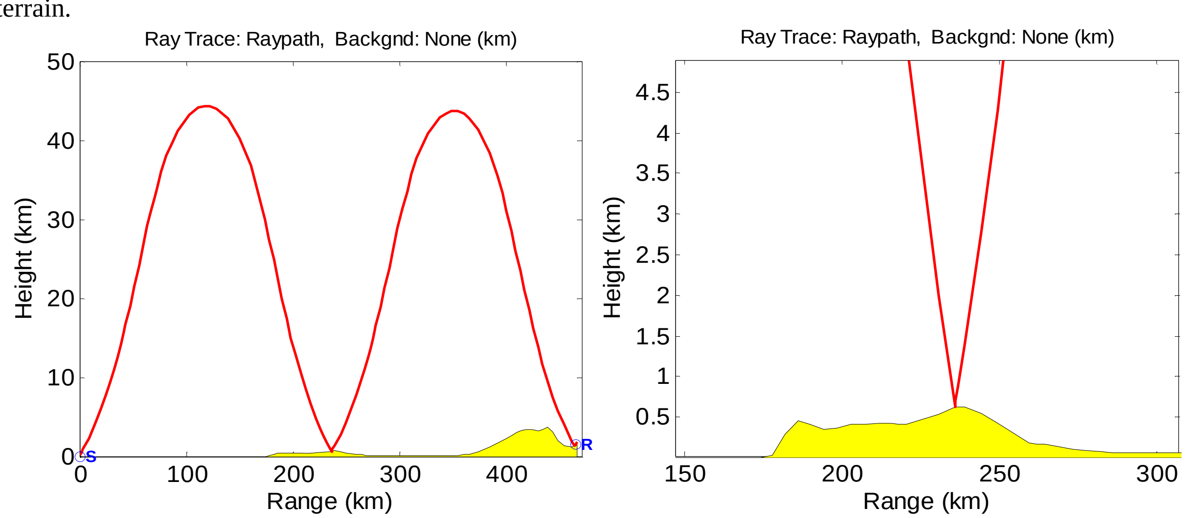

Figure 6. Ray solution for scenario illustrated in Figure 5. The full path of the ray is shown (left) along with the interaction with the complex surface at the first bounce (right).

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.

Research investigations are underway regarding the effects of terrain elevation on infrasound propagation, and the development of calculation techniques for predicting terrain effects will continue.

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*, LA-UR-03-6029, Vol. 2, pp. 587–596.

Bloom, S., A. da Silva, D. Dee, M. Bosilovich, J.-D. Chern, S. Pawson, S. Schubert, M. Sienkiewicz, I. Stajner, W.-W. Tan, M.-L. Wu (2005). Documentation and Validation of the Goddard Earth Observing System (GEOS) Data Assimilation System - Version 4**.** *Technical Report Series on Global Modeling and Data Assimilation*, NASA/TM-2005-104606.

Drob, D. P., J. M. Picone, and M. A. Garcés (2003). The Global Morphology of Infrasound Propagation, *J. Geophys. Res.* 108: doi: 10.1029/2002JD003307.

Gibson, R. and D. Norris (2003), Integration of InfraMAP with near-real-time atmospheric characterizations and applications to infrasound modeling, in *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, BBN Technologies Final Report for Air Force Research Laboratory (AFRL/VSBYE) 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.

Kanamitsu, M. (1989), Description of the NMC global data assimilation and forecast system. *Wea. and Forecasting*, 4, 335-342.

Kalnay, M. Kanamitsu, and W.E. Baker (1990), Global numerical weather prediction at the National Meteorological Center, *Bull. Amer. Meteor. Soc.*, 71, 1410-1428.

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.

Renka, R. J. (1999), Algorithm 790: CSHEP2D: Cubic Shepard Method for Bivariate Interpolation of Scattered Data. *ACM Trans. Math. Softw.*, 25, 1, 70-73.