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

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ABSTRACT

Numerical calculation of infrasound propagation paths is necessary to support accurate infrasound event identification, phase association, and source location. 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. Therefore the accuracy of propagation modeling depends in part on the fidelity of the atmospheric characterization. Furthermore, for infrasound propagation at regional and local ranges, characterized by higher frequencies than propagation at global ranges, effects of the boundary conditions of the propagation domain, in particular the terrain elevation, become increasingly important.

The analysis tool kit *Infra*sound *M*odeling of *A*tmospheric *P*ropagation (InfraMAP) integrates infrasound propagation models and environmental representations, including synoptic updates of the atmospheric specification at low and middle altitude, such as the output from numerical weather prediction models that supplement climatological characterization of temperature, wind, and air composition at high altitude. The Naval Research Laboratory (NRL) Ground-to-Space (G2S) semi-empirical spectral model provides a global specification of the atmosphere that can be utilized in InfraMAP. These capabilities for propagation calculation and atmospheric specification allow infrasound researchers to investigate critical propagation phenomena, conduct sensitivity studies, and compare results of numerical modeling with observed signals.

Recent efforts develop techniques for utilizing accurate, high-resolution regional atmospheric specifications and terrain elevation databases with infrasound propagation modeling codes. Mesoscale atmospheric models, which focus on the meteorology of a specific region, can account for and resolve important wind and temperature phenomena relevant to regional and local infrasound propagation. Such models can also provide atmospheric profiles that are consistent with the variable terrain elevation in a region. By investigating realistic atmospheric models and terrain specifications 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. Ground truth events are studied in order to assess performance of techniques for incorporating mesoscale atmospheric models and terrain specifications with propagation models and to evaluate the benefits for infrasound monitoring.

RESEARCH OBJECTIVES

In order to advance the state of the art for high-fidelity infrasound predictions, it is necessary to develop both propagation calculation techniques 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 event identification, phase association and source localization. This is being accomplished by developing and analyzing advanced high-resolution 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 includes sensitivity studies using the NRL G2S specification at various resolutions and studies of 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 includes 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 atmospheric properties 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. Prior work by Drob et al. (2003) has provided a simple framework to account for atmospheric complexity over certain height ranges. The 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, developed by BBN Technologies, makes use of G2S and allows options for specifying the propagation environment by incorporating the output from global numerical weather prediction (NWP) models to supplement the baseline climatological characterization of temperature, wind and air composition (Gibson and Norris, 2003, 2004). These global synoptic specifications are used with infrasound propagation models in order to improve predictions compared to those based on climatology. The global G2S specification has been reasonably well validated and has been applied successfully in many infrasound event studies. However, observed infrasound phases have not been well predicted by state of the art propagation models for several ground-truth events over regional scales (e.g., Bhattacharyya et al., 2003). Therefore, further 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.

There is strong interest in the monitoring community in understanding the physics of regional-scale infrasound propagation. At various infrasound propagation ranges there remain a number of unanswered scientific questions, including: the effect and significance of terrain and internal wave scattering; meteorological reasons for losses of signal coherency; and the frequent infrasonic detection of events in the classical “zone of silence.” For infrasound propagation over regional scales it is clear that regional, or mesoscale, NWP analyses are required to investigate and account for these complex atmospheric effects. For example, mesoscale specifications can enable the resolution of tropospheric and marine inversion layers recently shown to be significant for regional infrasound propagation (e.g., Herrin et al., 2006). A key goal of this research project is therefore to improve the temporal, horizontal, and vertical resolution (i.e., information content) of the existing G2S specifications in the 0 to 35 km region by incorporating output from operational NWP models and thus provide improved regional atmospheric specifications for detailed infrasound propagation calculations. We seek to produce a mesoscale version of the G2S model that can be used with InfraMAP and other propagation calculation codes, and we are improving the capabilities of InfraMAP to support higher-resolution atmospheric specifications and more advanced calculation techniques. 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, particularly at regional and local ranges.

RESEARCH ACCOMPLISHED

Improving NRL G2S with Mesoscale Atmospheric Specifications

The atmospheric structure responsible for the transport of infrasonic energy can change rapidly in both time and space. Below 55 km these structures are being resolved by NWP systems that assimilate vast amounts of data from a diverse network of operational satellite, ground-based, and in situ sensors. National and Department of Defense (DoD) weather centers can provide regional atmospheric specifications that have a very high spatiotemporal resolution and accuracy compared to comprehensive global specifications, including G2S. This improvement is achieved by focusing additional efforts on the meteorological observations and atmospheric physics specific to a given geographic region.

Mesoscale NWP codes typically are nested grid point models that interpolate global $1° \times 1°$ (or $0.5° \times 0.5°$) 6-h meteorological data sets and enhance them through applying additional physical constraints as well as auxiliary input data sets and observations over a particular region. Model output resolutions better than 10x10 km at 1-h time intervals are possible. Some mesoscale NWP codes even include nested grids within nested grids to help resolve significant features and areas of interest. Compared to global NWP models, the mesoscale NWP models include improved specification of atmospheric boundary layer effects, account for non-hydrostatic fluid dynamics, and can resolve large- to medium-scale stationary mountain waves, as well as some types of propagating gravity waves (for example, see Janjic et al., 2001, Janjic, 2003). Output from mesoscale NWP models are merged with global G2S specifications in the process of generating the new mesoscale-G2S specifications (Gibson et al., 2006).

In the prior year's research review, we discussed how prototype mesoscale-G2S specifications can be as accurate or more accurate than individual radiosonde profiles and better for use in infrasound propagation calculations for events of interest. This is because the assimilative NWP analysis products self-consistently combine many different data sets and types of information (e.g., radiosonde profiles, satellite temperature soundings, ground-based meteorological-station observations, and geophysical fluid dynamic constraints) to provide improved accuracy and spatiotemporal information content, while adding range dependence to the atmospheric specifications (Gibson et al., 2006). The primary difference between the existing global G2S specification and the improved mesoscale version is in the available spatiotemporal resolution (i.e., fine-scale structure). Figure 1 shows a comparison of the G2S (red) and mesoscale-G2S (blue) zonal wind profiles (east-west) at the source location during the first launch of the second White Sands Missile Range (WSMR) infrasound calibration experiment (WSMR-II).

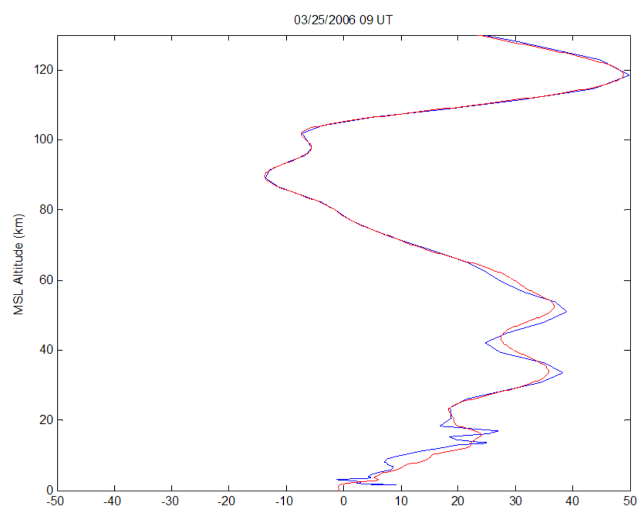

Figure 1. Comparison of G2S (red) and mesoscale-G2S (blue) zonal wind profiles (east-west) for the first launch of the WSMR-II experiment. The vertical coordinate is altitude above mean sea level.

In this example the mesoscale-G2S specifications qualitatively match the existing global G2S specifications. Note, however, the fine-scale wind structures below 20 km given by the mesoscale model, which are typically filtered out in the production of the global G2S specifications. These atmospheric structures (associated with internal gravity waves and related phenomena) can affect infrasound propagation at regional and local ranges and may be responsible for anomalous infrasonic detections in the classical zone of silence. The increased vertical resolution and additional physics inherent in the mesoscale NWP models will enable the new mesoscale-G2S specifications to resolve the vertical temperature (and sound speed) gradients in the first 20 to 500 meters of the atmosphere that result from direct radiative/thermal coupling at the air/land/sea interface. These effects can be significant over major bodies of water or desert regions where day-night surface temperature differences are substantial. The ability to provide this information above an infrasound array (where locally only the 2-m meteorological-station temperatures measurements are available) will be a valuable resource in developing an understanding of infrasound signal coherency loss and related boundary layer coupling phenomena.

Mesoscale NWP specifications for the continental U.S. (CONUS), Alaska, Hawaii, and several U.S. territories are readily available from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction (NCEP). Earlier in this effort we began autonomously downloading and archiving the NOAA Rapid Update Cycle (RUC) time series for the CONUS domain. The RUC system provides mesoscale atmospheric specifications hourly, from 0 to 25 km altitude, at both 20 km and 13 km horizontal resolution. We have assembled a database of 20 × 20 km RUC specifications at 3-h intervals, from 15-Oct-2005 to the present time.

More recently, our research has focused on using the Weather Research and Forecasting (WRF) Model, which is at the forefront of the US meteorology enterprise (http://wrf-model.org/index.php). The effort to develop WRF has involved collaboration among the National Center for Atmospheric Research (NCAR), NOAA's NCEP and Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, Oklahoma University, and the Federal Aviation Administration (FAA). WRF allows researchers the ability to conduct simulations reflecting either real data or idealized configurations.

There are currently two main versions of the WRF model—a research version known as Advanced Research WRF Model (WRF-ARW) and the operational version known as the Nonhydrostatic Mesoscale Model (WRF-NMM). The WRF-NMM model is run operationally by NOAA/NCEP and employs a hybrid sigma-pressure vertical coordinate system and rotated latitude-longitude grid. For these reasons this version of WRF is believed to be the best one to provide reliable and accurate mesoscale specification for mesoscale-G2S. Current WRF-NMM model output includes the main atmospheric state variables needed to perform infrasound propagation calculations—pressure, temperature, and the horizontal wind velocity components. Additional atmospheric state variables include specific humidity, vertical wind, and turbulent kinetic energy. Surface level microphysics is also an important aspect of mesoscale NWP models. As a result, auxiliary meteorological quantities included are planetary boundary layer (PBL) height, subgrid scale roughness height, friction velocity, solar zenith angle, surface radiation fluxes, precipitation amounts (including breakdowns of water, snow, and ice), cloud fractions (including low, middle, and high), soil moisture, etc.

Model Domains and Example Implementations

In earlier stages of this effort, the mesoscale-G2S grid used for software integration and testing purposes, systems automation development, and ground-truth validation efforts was limited to the western half of CONUS. More recently, we have utilized the capabilities of the WRF model to generate WRF-NMM specifications for several domains around the world. Representative examples of these domains include the (a) Middle East, (b) Korean Peninsula, (c) southwest United States, and (d) Vanuatu Archipelago; these domains are shown in Figure 2. The Middle East domain can be used to generate specifications for ground-truth events such as the 18-Feb-2004 train car explosion in Iran, and the Korean Peninsula domain can be used to study events such as the reported 9-Oct-2006 underground nuclear weapon test. The southwest U.S. domain supports study of events such as the White Sands Missile Range (WSMR) infrasound calibration experiment, and the Vanuatu Archipelago domain can be used to study events such as infrasound observations from the Lopevi and Yasur volcanoes, e.g., at station I22FR.

Each of these mesoscale specifications is initialized with digital terrain and ground cover databases and the 6-h NOAA operational Global Forecast System (GFS) analysis fields; these same fields are also used by the current global version of G2S. The baseline WRF-NMM specifications produced have a total of 37 vertical levels extending up to approximately 20 km. The number of horizontal grid points provided for each of the domains shown above is 300 × 219, 240 × 161, 280 × 181, and 280 × 181, respectively. The effective horizontal model resolutions are 15 × 15 km, 12.5 × 12.5 km, 10 × 10 km, and 15 × 15 km, respectively.

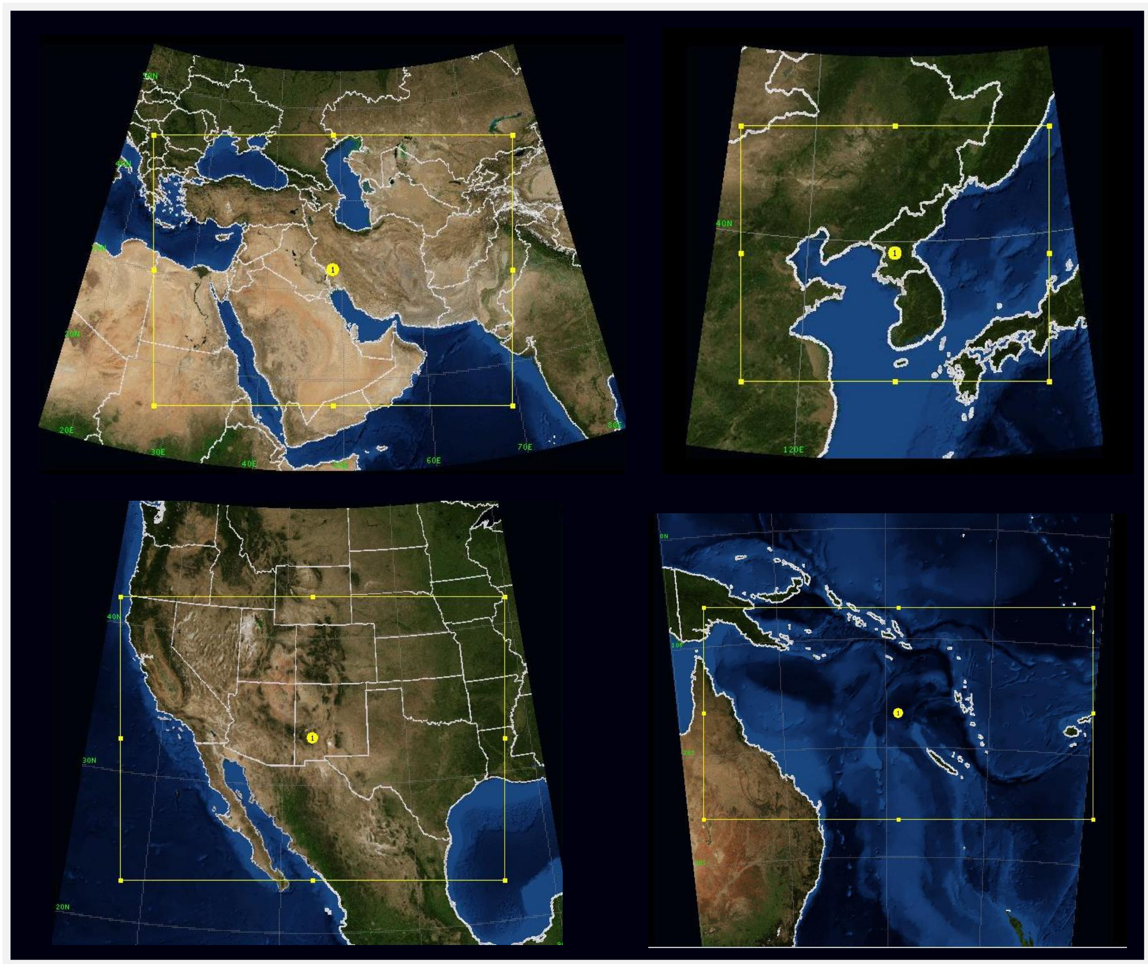

Figure 2. Example of several WRF model domains generated for infrasound event analysis.

A static digital terrain elevation model is required to combine mesoscale and global atmospheric specification fields with the background high-altitude empirical models in order to translate them into altitude coordinates so that they can be used in infrasound propagation calculations. Capabilities have been built into the G2S client software to provide terrain elevation estimates at 30′ resolution (1 km) for any location on the globe. The NOAA Global Land One-km Base Elevation (GLOBE) digital terrain model provides the underlying data (Hastings and Dunbar, 1998).

Recent and ongoing research work is toward development of the capability to generate custom specifications at resolutions similar to these shown above for any arbitrary domain. Effort is required to process the WRF model output fields and combine them with G2S specifications at higher altitudes for use in infrasound propagation calculations. It is reasonably straightforward to augment (or simply replace) the first 20 to 25 km of the existing G2S specifications with WRF specifications since G2S effectively reproduces the NOAA-GFS specifications used by the WRF model at the 20 km upper boundary to within observable accuracies. Additional computational challenges arise due to the staggered grid employed for horizontal output fields in the WRF model. In this system the scalar (mass) and vector (wind) fields are provided at different locations. The staggered gridding scheme simplifies computational aspects of the numerical integration of the WRF model’s prognostic continuity, mass, momentum, and energy equations. The model also employs a projection that rotates Earth’s latitude/longitude grid so that the intersection of the equator and prime meridian is at the center of the model domain. This minimizes the convergence of meridians over the domain, but results in uneven grid spacing. Therefore these grids must be subsequently interpolated to a regular latitude/longitude grid for utilization in the propagation models in InfraMAP.

Selected examples from the mesoscale atmospheric specifications for the Southwest U.S. domain shown in Figure 2 are presented below. Figure 3 shows the static sound velocity at an altitude 10 meters above the ground/sea surface. The date and time, September 09, 2005, 09:00 UT, correspond to the first WSMR infrasound calibration experiment. Note the high sound velocity areas over the deserts of the Southwest United States. Another notable meteorological feature is the warm surface air mass (high sound velocities) over the Gulf of California in contrast to the cold marine surface air layer over the Pacific Ocean.

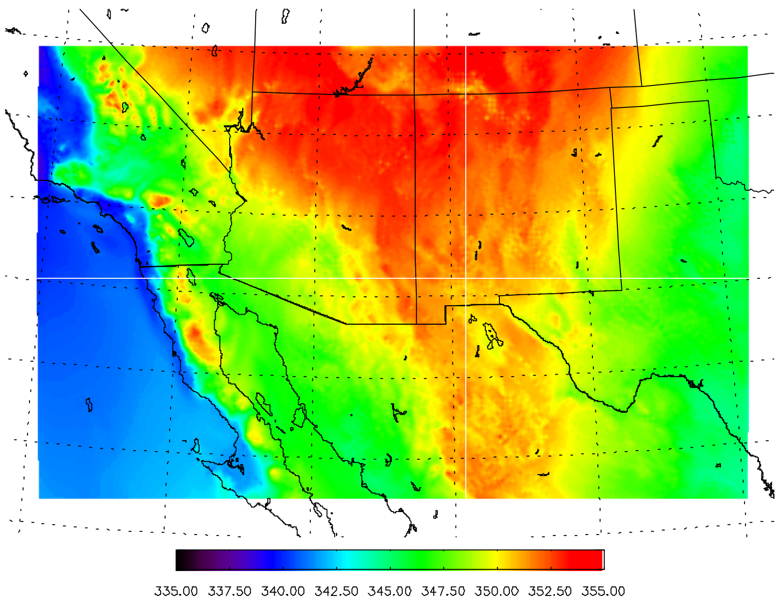

Figure 3. Example output of static sound velocity (m/s) at a height 10 m above the ground/ocean surface (September 09, 2005, 09:00 UT). Lines indicate the locations of vertical slices presented in subsequent figures.

Figure 4 shows an east-west cross section of the meridional (north-south) wind component. These fields are interpolated from the vertical hybrid sigma-pressure grid to an equally spaced vertical grid at 200 m intervals.

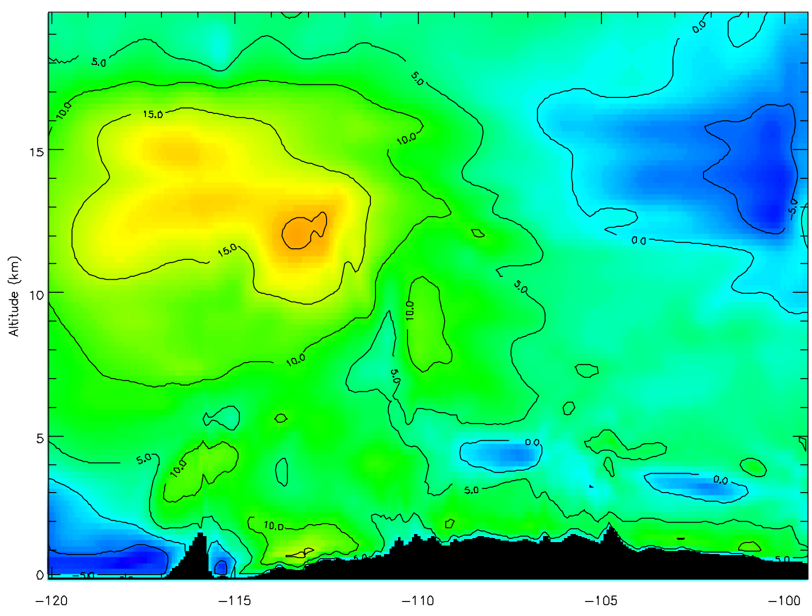

Figure 4. Illustrative east-west vertical slice of the meridional (north-south) wind fields (m/s) for the southwest U.S. mesoscale model domain, as shown above (September 09, 2005, 09:00 UT).

The horizontal and vertical extent of the topography can clearly be seen—for example, at the Baja Peninsula and the Gulf of California. Notable meteorological features include down-slope/drainage winds along the Gulf of California. Decreases in the horizontal winds at the surface, tending toward zero due to friction, are noticeable with the increased vertical resolution of the mesoscale NWP specifications. Figure 5 shows a north-south cross section of the zonal (east-west) wind component. Again the vertical and horizontal extent of the topography relative the vertical and horizontal gradients in the wind fields can be seen.

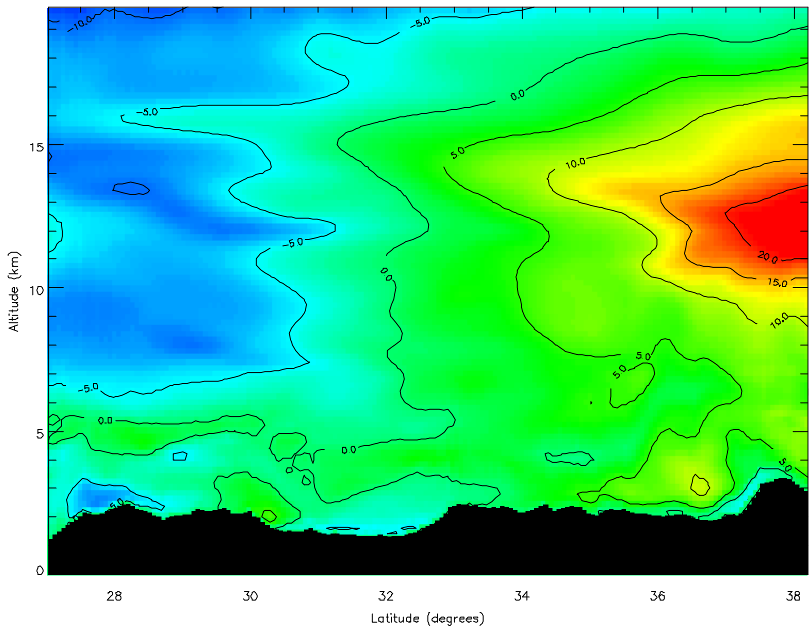

Figure 5. Illustrative north-south vertical slice of the zonal (east-west) wind field (m/s) for the southwest U.S. mesoscale model domain, as shown above (September 09, 2005, 09:00 UT).

Propagation Calculation Techniques Incorporating Mesoscale-G2S and Variable Terrain Elevation

Using the mesoscale fields described above we have begun to investigate the information content and consequences of mesoscale-G2S specifications for infrasound signal propagation for ground-truth events. Comparison studies to date have focused on the ground-truth data sets generated by the 2005/2006 WSMR series of rocket grenade tests. Model-to-measurement and model-to-model comparisons are intended to help identify the relevant physics affecting infrasound propagation and determine the level of confidence in existing and recently developed modeling capabilities. In support of this goal, we have continued development of calculation techniques and software routines for integration of new G2S specifications with propagation models. Environmental characterization fields (e.g., temperature, wind, sound speed) contained in mesoscale data blocks can currently be displayed and manipulated in InfraMAP. Various terrain databases have also been incorporated and can be displayed over both global and mesoscale domains. Propagation modeling techniques using ray-tracing over variable terrain elevation have been developed and integrated in prototype form in InfraMAP. Development of additional modeling capabilities (e.g., parabolic equation) incorporating variable terrain is in progress as a parallel effort.

Additional examples of mesoscale atmospheric fields suitable for use with infrasound propagation calculation techniques in InfraMAP are shown below. Figure 6 displays the height above mean sea level of the first (lowest) layer of a mesoscale-G2S atmospheric specification over the western U.S. Due to the terrain-following nature of the coordinate system, the available specification fields closest to Earth's surface can be seen to follow the major terrain features. At each layer of the specification, all fields necessary for propagation calculations are available. Figure 7 shows an example of one of these fields, horizontal wind velocity, both for the first (lowest) layer and also the 30th layer above the surface. Both zonal and meridional wind components are available; however, for illustration, the figures display the overall magnitude of the horizontal wind.

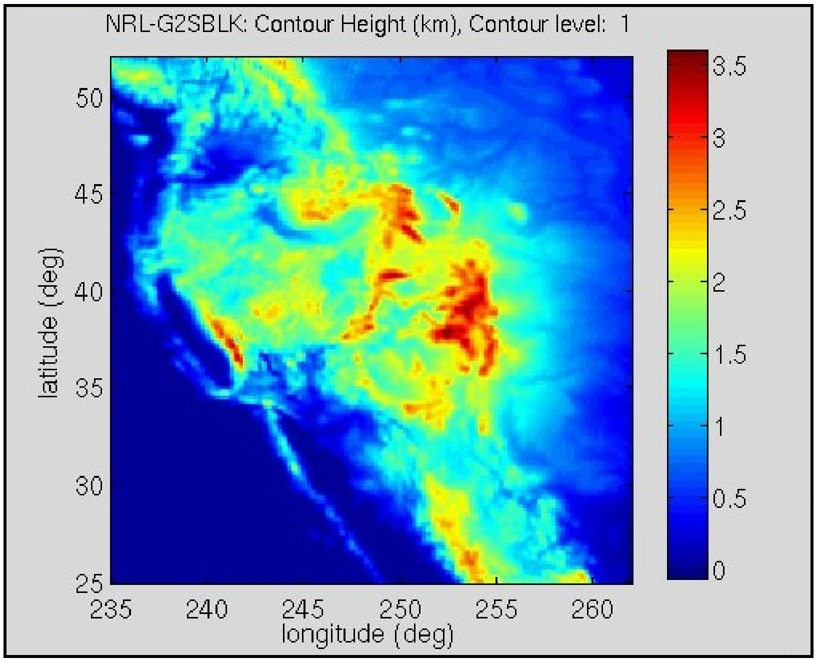

Figure 6. Height (km) above mean sea level of the first (lowest) layer of a mesoscale-G2S atmospheric specification over the western U.S.

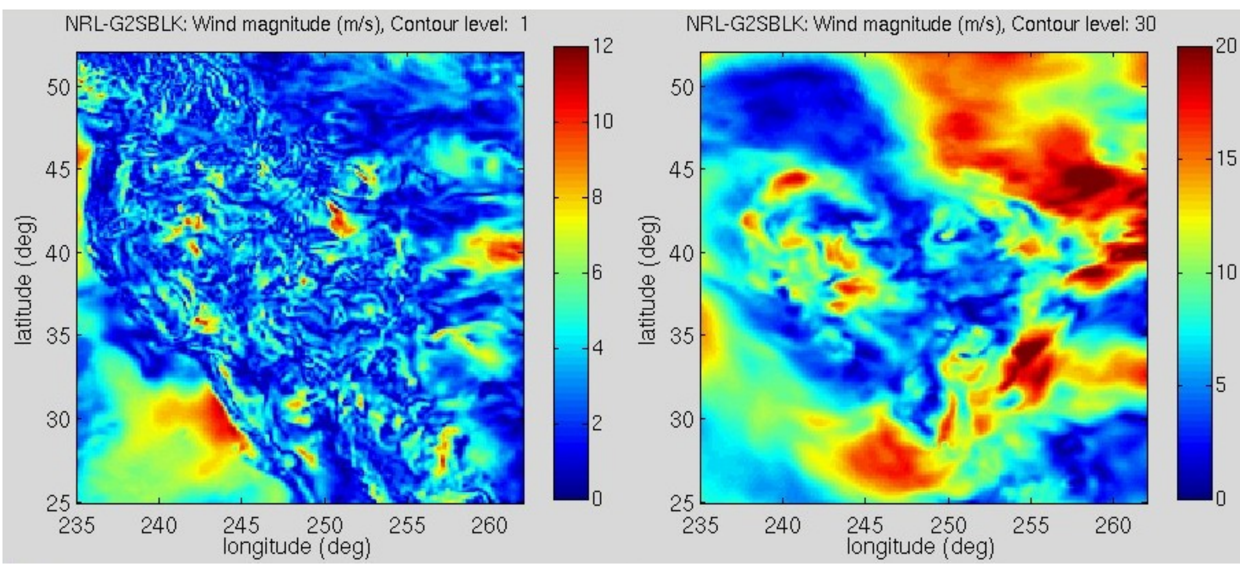

Figure 7. Horizontal wind magnitude (m/s) for the first or lowest layer (left) and for the 30th layer (right) of a mesoscale-G2S atmospheric specification over the western U.S.

The terrain-following nature of the specification layers can also be seen by viewing fields across a slice of the atmosphere. Figure 8 shows horizontal wind magnitude for an east-west vertical slice of the same mesoscale-G2S atmospheric specification shown in Figures 6 and 7. The vertical resolution of the mesoscale system is on the order of 10 to 50 m near the surface, increasing to larger, yet variable values with altitude.

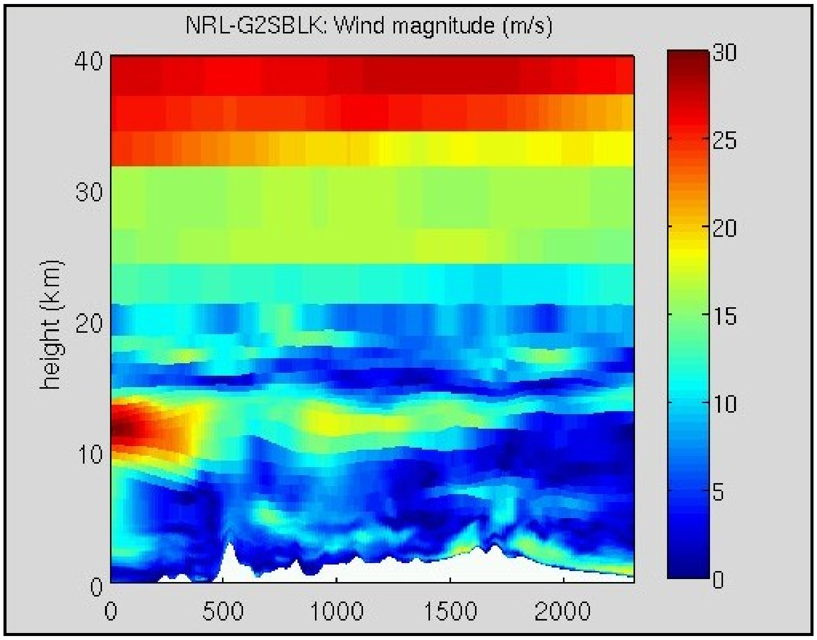

Figure 8. Illustrative east-west vertical slice of the horizontal wind field magnitude (m/s) for the mesoscale-G2S atmospheric specification over the western U.S., as shown in Figures 6 and 7. Horizontal axis is range in km.

In the prior year's research review, progress toward characterizing the interaction of infrasound with Earth's surface was addressed, in particular the effects of variable terrain elevation on propagation. Research in this area has continued, including efforts to identify the relevant spatial scales over which the variable terrain elevation needs to be resolved for infrasound propagation calculations. Figure 9 displays ray paths for propagation from one of the grenade events in the WSMR rocket test series, showing interaction with the high-resolution terrain database.

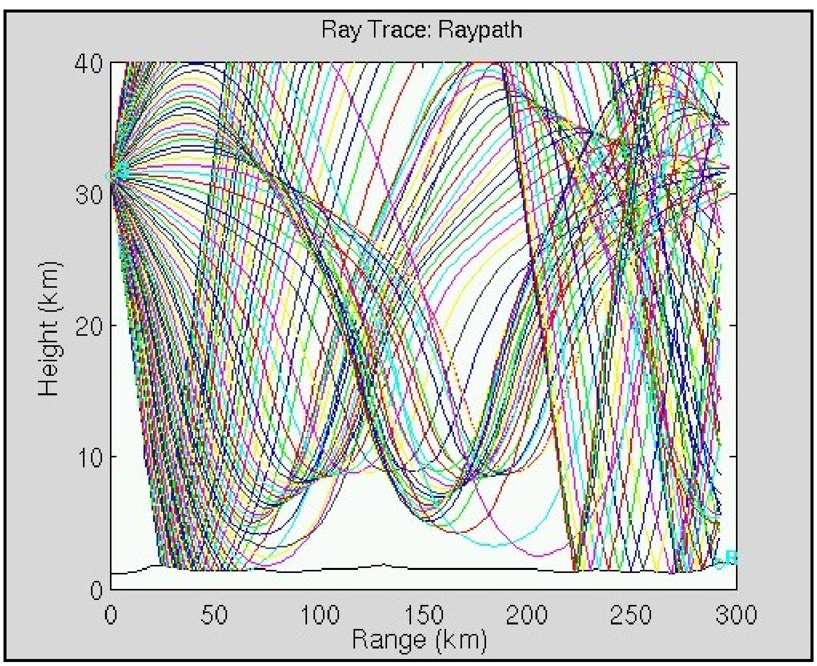

Figure 9. Modeled infrasound ray paths for an elevated explosive source during the WSMR rocket test series. Reflection of rays off complex terrain elevation is shown.

CONCLUSIONS AND RECOMMENDATIONS

Mesoscale atmospheric specifications improve the characterization of the lower regions of the atmosphere and are therefore used with infrasound propagation models in order to improve predictions compared to those based on global specifications. Significant progress has been made toward improved calculation techniques for infrasound propagation, particularly over regional and local ranges. The capability has been developed to supplement existing global G2S specifications with high-resolution mesoscale-G2S specifications for a variety of regional domains and a range of event times in the recent past.

Modeling advances that utilize mesoscale specifications while addressing the fundamental physical processes that affect infrasound are in progress. Also required, in parallel, are continued 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. As mesoscale-G2S models are applied to the analysis of infrasound ground-truth events, research will continue toward tuning the model resolutions in order to provide the most effective specifications for the analysis of infrasound signals. We also intend to explore how to improve accuracy of the WRF-NMM output (and thus mesoscale-G2S specification fields) by direct assimilation of raw measurements and other auxiliary high-resolution data sets (e.g., 5×5 km resolution sea surface temperatures).

Study of ground-truth events at long range will improve understanding of the strengths and weaknesses of both global and regional atmospheric specifications. Study of local and regional events will improve understanding of the importance of mesoscale atmospheric phenomena and terrain elevation effects.

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