VARIABILITY OF THE LOWER ATMOSPHERE AND ITS EFFECT ON THE PROPAGATION OF INFRASONIC WAVES

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ABSTRACT

Previous work focused on infrasonic wave propagation effects in the Mesosphere and Lower Thermosphere (MLT), which is strongly affected by solar tides, geomagnetic storms, and solar EUV radiation. The present work integrates acoustic wave propagation models, NRL's MSIS90 and HWM93 atmospheric models, and the United Kingdom Met Office (UKMO) Correlative Analyses to investigate in detail the effects of stratospheric variability on the propagation of infrasonic waves over Hawaii and Alaska. Below 55 km heights, the UKMO data, which is based on radiosonde data and NOAA satellite temperature profiles, captures planetary waves with periods of 2, 5, 10, and 16 days. The augmentation of the HWM and MSIS models with the UKMO dataset dramatically alters the acoustic propagation medium and therefore the predicted travel time curves and azimuth deviations of infrasonic waves.

Key Words: Infrasound, Travel Times, Atmospheric Models, Source Location, Alaska, Hawaii

OBJECTIVE

The objective of the project is to improve the source location capabilities of the Alaska and Hawaii CTBT infrasonic arrays. The deliverables of this part of the project are predicted infrasonic wave travel time curves and azimuth corrections at the arrays, based on the best available atmospheric models and data.

Introduction

Infrasonic waves originating near the Earth's surface may be refracted back to the ground by atmospheric conditions in the troposphere, stratosphere, and thermosphere. Wave energy is trapped between the ground and the turning points at each layer, thus creating well-defined ducts. These ducts define distinct infrasonic phases, which may be recorded by pressure sensors and utilized to locate infrasonic sources. According to ray theory, the tropospheric and stratospheric ducts are only generated along the dominant wind directions. However, the thermosphere will frequently have two turning regions, and thus support two distinct phases.

Previous work (Garces et al., 1999a-c) investigated the effects of geomagnetic activity and solar EUV flux variations on the propagation of infrasonic waves in the atmosphere. In that study, we used the Naval Research Laboratory Horizontal Wind Model (HWM) and Mass Spectrometer and Incoherent Scatter (MSIS) models to produce atmospheric data for Fairbanks, Alaska (146.9^{o}W, 64.8^{o}N) and the Big Island, Hawaii (155.3^{o}W, 19.6^{o}N). Atmospheric profiles for the temperature, mean molecular mass, zonal winds, and meridional winds from the ground up to 180 km were computed every three hours for the season of Winter (November 1 to January 31). Waves propagating to heights greater than 180 km were not considered because of the high attenuation encountered by sound waves in these rarefied layers of the ionosphere. Using the atmospheric data, 50 rays were launched along specified directions to compute theoretical travel time curves, azimuth deviations, tau surfaces, and turning heights (Garces et al., 1998). Tropospheric-ducted waves only occur during strong tropospheric winds, which may be irregular. Since the HWM and MSIS models are obtained from 15 year averages, they do not reproduce these irregular weather patterns in the troposphere. The HWM and MSIS models predict Winter stratospheric phases occur only

for waves propagating towards the Eastern quadrant in Hawaii and the Southeastern quadrant in Alaska, along the dominant stratospheric wind direction. These trends reverse in Summer, and the stratospheric phase may completely vanish in parts of Spring and Fall. In contrast, thermospheric phases are present year round. During most of Winter, there were two thermospheric branches, defined by turning points below 120 km and above 150 km. Solar tides created diurnal fluctuations in the azimuth deviations, ray density, and turning points. Furthermore, it was found that strong geomagnetic fluctuations during the solar maximum may induce a wind component that can dominate over the tidal component, and alter the partitioning of energy between the upper and lower thermospheric ducts.

The present work extends previous studies by augmenting NRL's MSIS90 and HWM93 atmospheric models with the UK Met Office (UKMO) Correlative Analyses dataset. We use the enhanced atmospheric models to investigate in detail the effects of stratospheric variability on the propagation of infrasonic waves over Hawaii and Alaska during the 89 days of Spring (February 1 to April 30). The UKMO data is based on radiosonde data and NOAA satellite temperature profiles, extends up to 55 km, and captures planetary waves with periods of 2, 5, 10, and 16 days. The UKMO data was used for all heights below 55 km, and was patched with the NRL model outputs using a general weighted and constrained least squares fitting method to non-uniform rational B-splines (NURBS). In contrast to usual interpolation, where a curve is constructed to satisfy the data precisely, in the least squares approximation the constructed curves capture the general shape in a statistical sense (L. Piegl and Tiller, 1997).

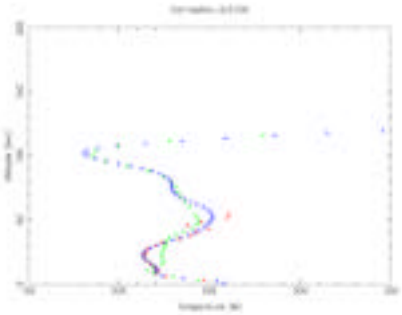


Figure 1. Profiles obtained from NRL models, UKMO data, and the interpolated line. The next number stands for UARS day number 2700, or February 1, 1999. Green points correspond to the MSIS or HWM output, red to UKMO, and blue to the NURB fit (Cammpfire - Combined Atmospheric Measurement and Model Profiles For Infasound Range Estimation.)

The enhancement of the HWM and MSIS models with the UKMO dataset dramatically alters the acoustic propagation medium and therefore the predicted travel time curves and azimuth deviations. In addition to the predictable variability introduced by the tides in the Mesosphere and Lower Thermosphere (MLT), planetary waves and weather disturbances in the lower atmosphere add significant unpredictable variability. Thus, infrasonic wave propagation models would have to access updated atmospheric data for the troposphere and stratosphere in order to produce accurate locations.

Salient Results

We wish to investigate the effect of stratospheric perturbations on the propagation of infrasonic waves. We build on our previous studies of the upper atmosphere, where the HWM and MSIS are robust. The thermosphere is significantly affected by the tides (Forbes, 1995), leading to a diurnal variability in the azimuth deviation and turning points of propagating phases. During periods when the upper thermosphere winds blow counter to the wave propagation, the steep rays are lost to the thermosphere, thus making shallower rays turn at a higher level. This means that shallower rays spend more time in the turning region, leading to extreme azimuth deviations as high as 10 degrees. However, in general, only the thermospheric branches with the highest turning point suffer such high deviations, and stratospheric phases and low thermospheric branches have relatively small deviations, usually less than 3-5 degrees(Garces et al., 1999a-c). This theoretical result is in agreement with historical field observations.

The atmospheric conditions for Alaska during the season of Spring (February 1- April 30, or days 32 to 120) obtained with the MSIS and HWM models are shown in Figures 2.

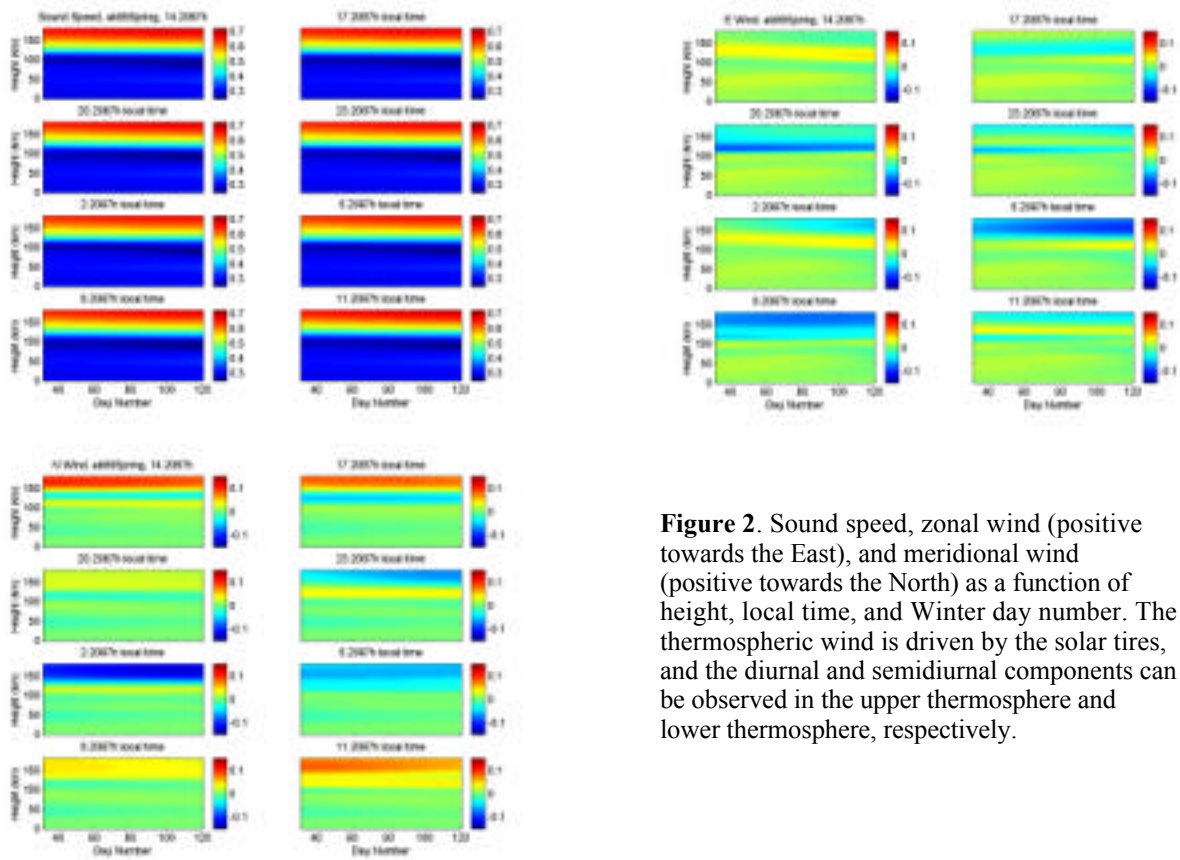
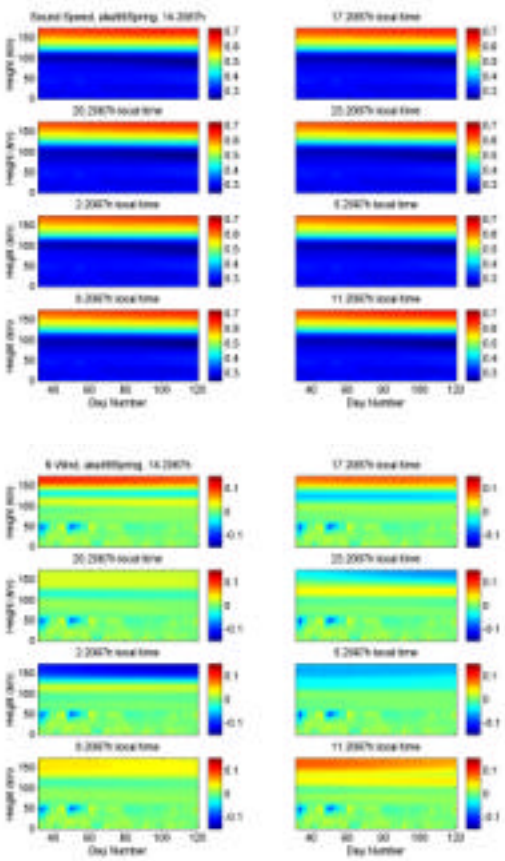


Figure 2. Sound speed, zonal wind (positive towards the East), and meridional wind (positive towards the North) as a function of height, local time, and Winter day number. The thermospheric wind is driven by the solar tires, and the diurnal and semidiurnal components can be observed in the upper thermosphere and lower thermosphere, respectively.

The weakening of the stratospheric winds occurs quite late in the season. As previously noted, thermospheric variability is driven by the solar tides. The conditions for the same region at the same time, but with the UKMO data enhancement, are shown in Figure 3. The greatest discrepancy between the climatologies occurs during strong jet stream events, which the MSIS and HWM models do not incorporate. A notable example is the drastic increase in zonal wind jet velocities at the beginning of the season, from days 32 to 50. This event may be caused by oscillations in the Arctic Polar Vortex due to large scale planetary waves . This feature is well defined in Antarctica (due to free ocean) but new evidence suggests that it is becoming stronger in the Northern hemisphere due to global warming. The contrast between the raw NRL model output and the enhanced climatologies in Hawaii is still significant, but not as dramatic as in Alaska.



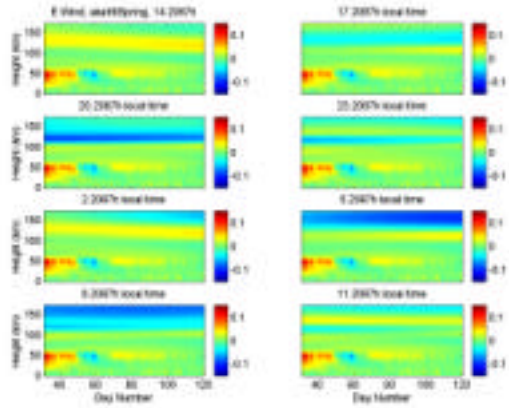


Figure 3. Sound speed, zonal wind (positive towards the East), and meridional wind (positive towards the North) as a function of height, local time, and Winter day number. The UKMO enhancement of the HWM and MSIS models provides atmospheric models which are a step closer to reality.

Figure 4 shows the predicted travel time curves for waves arriving from the West after propagating through the raw MSIS and HWM (AK, Figure 2) and the UKMO augmented (AKA, Figure 3) model atmospheres. The most noticeable difference is the filling in of the shadow zone for the stratospheric phase. Note that Figure 4 shows a superposition of all travel time curves for all selected days, and that there will be a shadow zone when the stratospheric phase is absent. Figure 5 shows the superposition of the azimuth deviations for all selected days, as in Figure 4. The azimuth deviations for model AK can be identified with the phases on Figure 4, in sharp contrast with the scattered deviations corresponding to model AKA. The azimuth deviation and turning height as a function of apparent phase speed, local time, and day number are shown on Figures 6 and 7, respectively. These last two figures are intended to be utilized with array processing algorithms. A detected arrival will possess a specific horizontal phase speed and direction. Figure 6 provides the correction needed to obtain the true azimuth, and Figure 7 provides the height in the atmosphere corresponding to that specific return. Figure 7 is also valuable in identifying specific phases. Turning points below 50 km correspond to stratospheric phases (Is), returns below ~140 km correspond to the thermospheric return with the larger slope on the travel-time curve (Ita) and returns above ~140 km correspond to the thermospheric return with the lower slope (Itb). The results of the AK run shown in Figure 6 are as in the work of Garces et al. (1999a-c), where azimuth deviations are relatively small for the stratospheric and low-turning thermospheric phases, and only the most far-reaching thermospheric returns show deviations as large as 10 degrees.

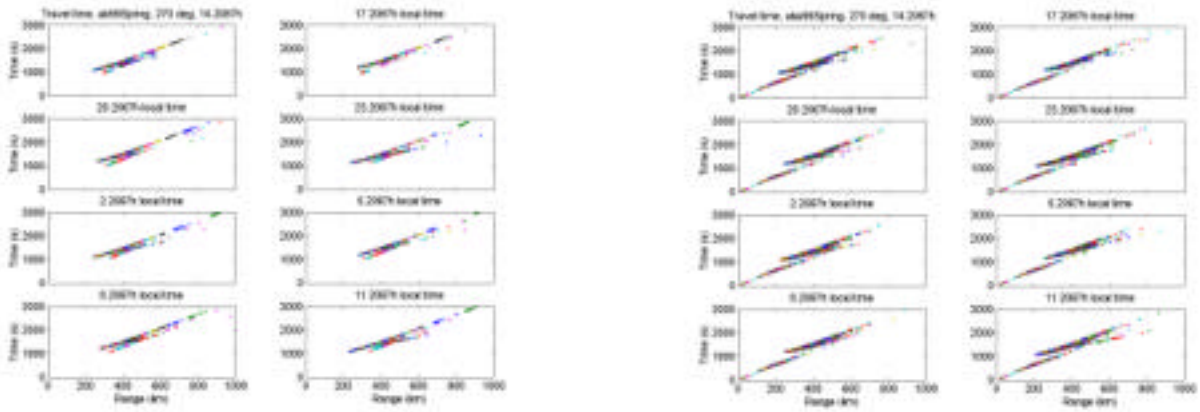


Figure 4. Travel time curves for infrasonic waves arriving from the West for the AK (left) and AKA (right) models. All the travel time curves for the selected time period are superposed. Each line corresponds to a distinct phase and to different reflection levels in the atmosphere. The stratospheric phase in the AKA model is much better defined, and the thermospheric phases are significantly modified.

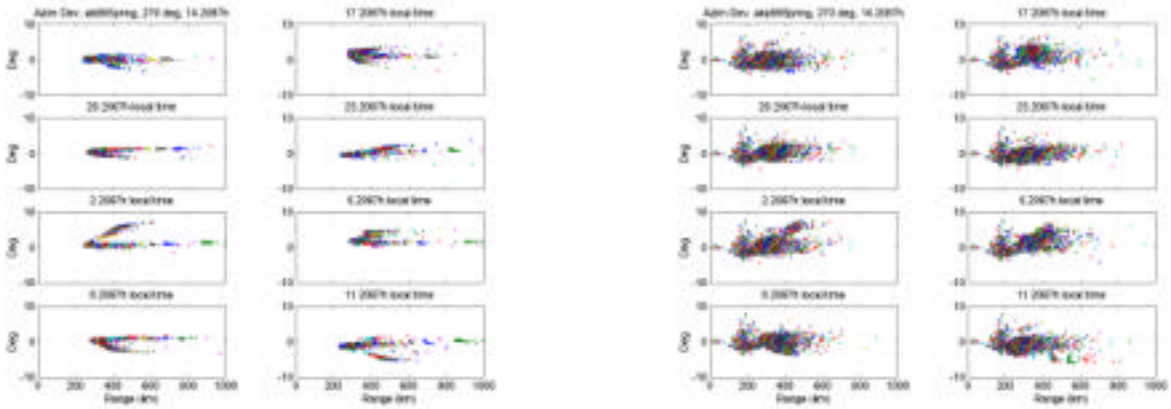


Figure 5. Azimuth deviations for infrasonic waves arriving from the West for the AK (left) and AKA (right) models. All the deviations for the selected time period are superposed. A positive deviation corresponds to a deflection towards the right along the direction of propagation. Seen from the receiving array, a positive deviation corresponds to an angular correction towards the right of the arriving incidence angle.

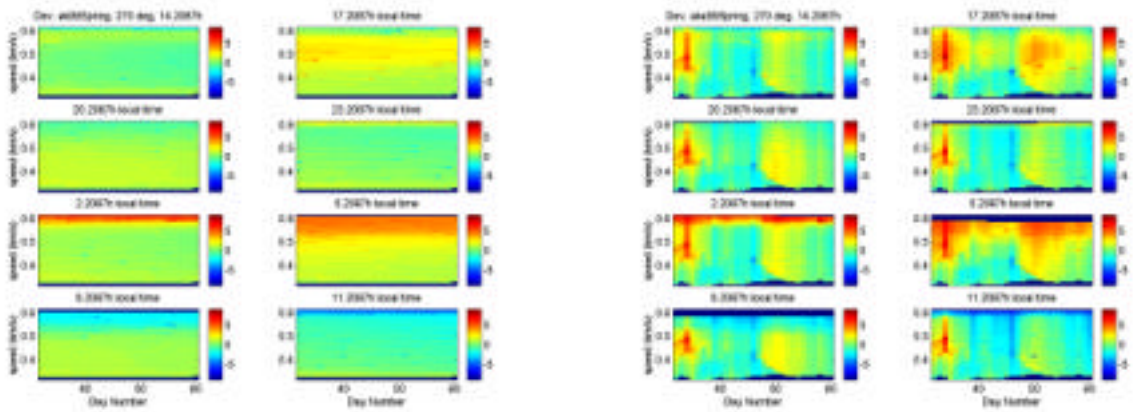


Figure 6. Azimuth deviation as a function of apparent phase speed (trace velocity), local time, and day number. Infrasonic waves are impinging from the West through the AK (left) and AKA (right) atmospheric models. The steepest rays (highest speeds) have the largest deviations, and stratospheric phases have small deviations.

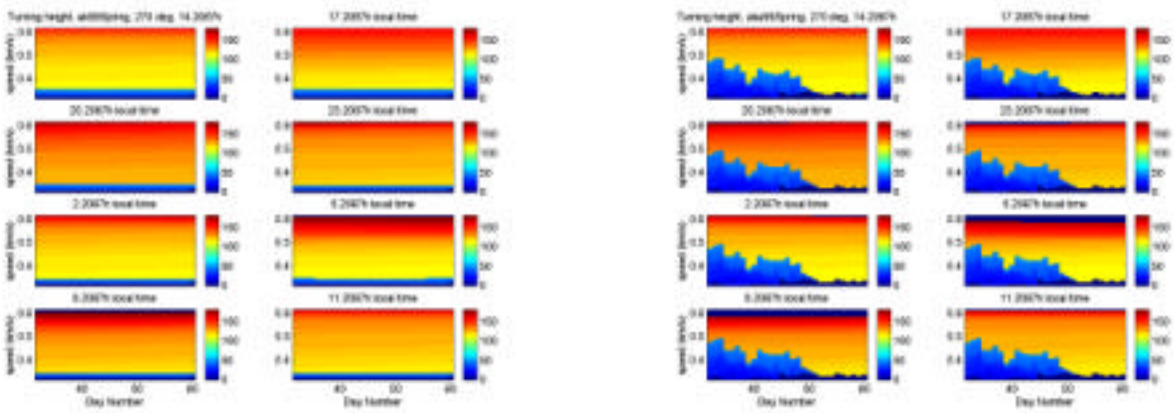


Figure 7. Turning height as a function of apparent phase speed (trace velocity), local time, and day number. Infrasonic waves are impinging from the West through the AK (left) and AKA (right) atmospheric models. The steepest rays (highest speeds) turn at the highest levels.

The runs for model AKA show more varied results. There is more energy going into the stratospheric phase as some of the steeper rays are refracted in the stratosphere by the strong wind speed of the arctic jet (Figure 7). In contrast to the AK run, the AKA model yields azimuth deviations of approximately 5 degrees associated with the stratospheric returns. These returns correspond to rays that turn during periods of strong transverse (Southward, Figure 3) winds, thus producing a significant deflection towards the right of the propagation direction. However, large deviations are still associated with the far-reaching rays refracted in the upper thermosphere during strong tidal winds, although some of these rays are now lost. Another noteworthy difference is that the AK runs predict a stratospheric arrival throughout the month of February (days 32 to 60), whereas the AKA runs predict that this phase may vanish during the zonal wind reversal at the end of the month.

CONCLUSIONS AND RECOMMENDATIONS

Stratospheric disturbances introduce significant variability on the arrival times and azimuth deviations of propagating infrasonic waves. Although the NRL HWM and MSIS models are useful for the study of fundamental principles of infrasonic wave propagation in time-varying atmospheres, these models do not accommodate sufficient variability in the troposphere and stratosphere to provide precise results. More realistic infrasonic propagation models can be obtained from the fusion of the NRL models, whose strength is in the upper atmosphere, with finer-scale lower atmosphere datasets such as the UKMO Correlative Analyses.

The integration of meteorological data with atmospheric models will continue throughout the rest of this project, with the aim of improving the robustness and accuracy of the resulting infrasonic propagation models. After completing a detailed study of the propagation characteristics in Alaska and Hawaii over the yearly cycle, studies should focus on solving the inverse problem for infrasonic source locations using the most realistic propagation models available.

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