CHARACTERIZATION OF PREDICTED INFRASONIC PHASES FOR IS59, HAWAII

Milton Garcés[1] and Colin Potter
Infrasound Laboratory, University of Hawaii, Manoa
[1]Also at the University of Alaska, Fairbanks

Douglas Drob and Michael Picone
Naval Research Laboratory, Upper Atmospheric Physics Branch

Roger Hansen and Kent Lindquist
Geophysical Institute, University of Alaska, Fairbanks

Sponsored by U.S. Department of Energy
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation
National Nuclear Security Administration

Contract No. DE-FC04-98AL79801

ABSTRACT

The atmosphere is a dynamic and complex medium, and infrasonic waves traveling through this medium will be strongly affected by its properties. The wind field, temperature, and composition of the atmosphere up to heights of 150 km will determine how sound waves are propagated between a source and a receiver. We integrate acoustic wave propagation models, the Naval Research Laboratory (NRL) Horizontal Wind Model (HWM93), the NRL Mass Spectrometer and Incoherent Scatter (MSIS90) atmospheric model, and the United Kingdom Meteorological Office (UKMO) Correlative Analyses to investigate the effects of atmospheric variability on the types of infrasonic phases that may be observed at CTBT array IS59 in Hawaii. Array IS59 [*Garcés and Bass*, 2000 (this issue)] started recording and archiving infrasonic data in May 25, 2000, and has recorded a variety of regional and distant events. We use the results of our theoretical and data assimilation work to characterize the response of IS59 so that it possible to associate and locate events using multiple arrays.

Key Words: Hawaii, infrasound, travel times, atmospheric models, phase identification, source location

OBJECTIVE

The objective of this work is to characterize the predicted phases and azimuth deviations of signals that can be observed with the Hawaii CTBT infrasonic array. This objective is fulfilled by integrating detailed atmospheric and acoustic propagation models and comparing the predicted results to recorded array data. This research addresses the need for accurate infrasonic source locations, which are essential to CTBT enforcement.

RESEARCH ACCOMPLISHED

1. Introduction

Infrasonic waves with frequencies between 0.02 and 10 Hz can travel thousands of kilometers before being significantly attenuated by viscosity and thermal conduction. Atmospheric wind, temperature, and composition fields from the ground to 160 km determine how these waves propagate. Between 60 km and 160 km infrasonic waves are strongly affected by solar tides (hourly), geomagnetic storms (daily), and solar EUV radiation (monthly). Below the stratospause (60 km) meteorological waves may eliminate or encourage waveguide propagation, depending on their strength and position. The acoustic propagation medium and therefore the predicted phases, travel time curves and azimuth deviations change significantly throughout the day and the seasons. Our studies (*Garcés et al*., 2000a-b, 1999a-c) show that in order to optimize phase identification and source location accuracy, infrasonic wave propagation models should access reliable atmospheric profiles evaluated within several hours of a suspect event. Ground truth validation of our approach is provided by the analysis of Concorde signals by *LePichon* *et al*. (2000). In this study we use daily numerical weather prediction nowcasts from UKMO (< 50 km) and 6-hour climatological estimates from the NRL-HWM-93 and NRL-MSISE00 empirical atmospheric models (*Hedin*, 1991; *Hedin et al*., 1996; *Drob and Picone*, 2000) to evaluate the climatology over Hawaii for the whole of 1996 and for selected days of 1999. We compute the trajectories for acoustic rays propagating in these backgrounds using the formulation of *Garcés et al*., 1998. The effects of vertical winds, horizontal gradients, and spherical geometry are ignored.

2. Model results

Previous work (*Garcés et al*., 2000a-b, 1999a-c) has shown that the solar tides introduce significant hourly variability in the wind field of the Mesosphere and Lower Thermosphere (MLT). Figure 1 shows the zonal (E-W) and meridional wind (N-S) for 1996. The solar tides have dominant diurnal and semidiurnal periods, and thus each panel is separated by three hours so that we can observe the changes in phase. At this latitude (19^{o} 35.5’ N), the zonal winds are more variable than the meridional winds, and geomagnetic effects not as significant as in the higher latitudes. Planetary waves in the troposphere introduce significant daily variability in the zonal winds. The clearest seasonal change is the reversal of the thermospheric winds and the zonal stratospheric winds. The seasonal thermospheric reversal is affected by the solar tides, which have high amplitudes above 100 km heights. Figure 2 shows the sound speed at Hawaii for 1996. Except in cases of extreme solar activity or near the thin boundary layer near the ground, at the lower latitudes the variability in the sound speed is negligible compared to the variability of the wind.

We now trace rays through the atmospheric models shown in Figures 1-2. Figure 3 illustrates the hourly time-dependence of thermospheric ducting caused by the solar tides in the MLT. Each color corresponds to a different local time separated by 6-hours. It is clear that the turning height of a ray may vary throughout the day, and that this change in path will affect the amplitude and frequency content of a received signal. Figure 4 shows the height in the atmosphere at which rays turn before arriving at the Hawaii array from an azimuth of 0^{o}. Since the stratospheric meridional winds are weak, there are no predicted stratospheric arrivals expected from either the North or the South (180^{o}). Thus, barring anomalously strong storms, all phases arriving in Hawaii from the North or South are thermospheric. Figure 5 shows the azimuth deviation for waves arriving from the North. The azimuth deviation for this arrival angle is determined by the zonal winds, which are strongly affected by meteorological waves in the troposphere. In general, the arrival azimuth needs to be corrected towards the left in Winter and towards the right in Summer. This means that an arrival detected near 16 h Hawaii Time with a slowness of 2.5 s/km arriving from the North in middle of Summer has a true azimuth of ~5^{o} East of North. However, the exact value of the azimuth deviation will depend on the strength and location of storm systems in the Pacific.

The turning heights of waves propagating along the E-W direction may vary significantly because of the dependence of the zonal winds on meteorological disturbances and because of the marked reversal in the stratospheric zonal wind. Figure 6 shows that stratospheric phases may be expected to arrive from the East (90^{o} azimuth) during Summer. If a sufficiently strong weather system were to appear in Spring and Fall, it may also be possible to induce stratospheric phases. Due to the relatively mild meridional winds, the azimuth deviation along the E-W direction (Figure 7) is slight and seldom exceeds a few degrees. The azimuth deviations of waves arriving from the South are also determined by the zonal winds. Figure 8 shows that the deviation trends for Southerly arrivals are the reverse of those for Northerly arrivals, as expected. As in Figure 4, all Southerly turning heights are in the thermosphere, and most of the variability is induced by the tides. Figure 9 shows the turning height of Westerly waves, showing the presence of stratospheric phases during Winter. The slowness range corresponding to the stratospheric phases depends on the state of the troposphere and stratosphere during that day, and thus a phase identification scheme based on static slowness ranges would lead to an incorrect ID. It follows that for certain arrival directions phase ID should be performed dynamically by using the most recent atmospheric data. Even if phase ID is not in question (as in N-S propagation), it is important to know at which level a ray turned in order to infer the source amplitude. Thus the daily variability of solar tides must be taken into consideration if precise estimates of the magnitude and location of an event need to be produced.

Our present line of research is moving towards providing meteorological nowcasts that can be ingested into the infrasonic propagation models to analyze specific events. For the July 4, 2000 reentry of the Compton Gamma Ray Observatory (CGRO) we used the atmospheric conditions of June 4, 1999 to estimate the expected propagation characteristics in Hawaii (Figure 10). No clear signals from the CGRO were detected by IS59, possibly due to the distant impact (~4000 km) and highly directional radiation pattern of the hypersonic reentry. However, in addition to various regional infrasonic events (*Garces and Bass*, 2000), continuous microbarom signals are recorded by IS59. Figure 11 shows a microbarom signal recorded on July 8 at IS59. The main coherent energy peak in the 0.1-0.5 Hz band arrives from an azimuth of 292^{o} with an apparent horizontal velocity of 0.348 km/s, or a slowness of 2.87 s/km. This azimuth points towards Typhoon Kirogi, which took 27 lives in the Philippines and two in Japan. Very small azimuth deviations are expected for Westerly arrivals, and the slowness corresponds to a turning height that is near 120 km in the thermosphere. Although acoustic generation near the source will be evidently affected by the powerful typhoon winds, propagation near Hawaii will be unaffected by the distant disturbance and is likely to fall near the predicted values. With the addition of other infrasonic arrays within the Pacific Rim, it would be possible to associate and track pressure disturbances across the Pacific and use this ongoing endeavor to validate atmospheric models and maintain readiness in the monitoring of the CTBT.

CONCLUSIONS AND RECOMMENDATIONS

Only thermospheric arrivals are expected to arrive in Hawaii from the North or South throughout the year. The height in the atmosphere at which these rays turn in the thermosphere will be primarily determined by the solar tides. However, for propagation along the meridian, the azimuth deviation will be strongly affected by meteorological disturbances in the stratosphere and troposphere. Arrivals from the East will consist of thermospheric arrivals in Winter and both thermospheric and stratospheric arrivals in Summer. The slowness and turning height values of these arrivals are strongly influenced by the solar tides and by meteorological disturbances in the lower atmosphere. However, the azimuth deviations along the E-W direction are expected to be only a few degrees. In order to produce unambiguous phase identifications and accurate source locations, it is necessary to have access to recent and reliable atmospheric data. It is recommended that integrated global meteorological nowcasts ranging from sea level to heights of 150 km be developed for ingestion into infrasonic data analysis and interpretation programs.

REFERENCES

Drob, D., and J. Picone (2000). *Statistical performance measures of the HWM-93 and MSISE-90 empirical atmospheric models and the relation to infrasonic CTBT monitoring*. Proceedings of the 22nd Seismic Research Symposium: Planning for Verification of and Compliance with the Comprehensive Nuclear-Test-Ban Treaty (this issue).

Garcés, M., and H. Bass (2000). *Installation and pre-certification of CTBT station IS59, Hawaii*. Proceedings of the 22nd Seismic Research Symposium: Planning for Verification of and Compliance with the Comprehensive Nuclear-Test-Ban Treaty (this issue).

Garces, M, D. Drob, M. Picone, K. Lindquist, and R. Hansen (2000a). *Infrasonic CTBT monitoring and the atmosphere.* EOS, Trans. Am. Geophys. Union, 81, S5.

Garcés, M., D. Drob, and M. Picone (2000b). *A theoretical study of the effect of geomagnetic fluctuations and solar tides on the propagation of infrasonic waves in the atmosphere*. Geophys. J. International (accepted).

Garcés, M., R. Hansen, K. Lindquist, D. Drob, and M. Picone (1999a). *Variability of the lower atmosphere and its effect on the propagation of infrasonic waves.* Proceedings of the 21st Annual Research Symposium on Monitoring a Comprehensive Test Ban Treaty.

Garcés, M., D. Drob, and M. Picone (1999b). *Geomagnetic and solar effects on thermospheric phases during Winter*. EOS, Trans. Am. Geophys. Union, 80, S71.

Garcés, M., K. Lindquist, R. Hansen, D. Drob, and M. Picone (1999c). *Temporal variability in the propagation on infrasonic waves over Hawaii and Alaska during Winter*. J. Acous. Soc. Am., 105, 1104.

Garcés, M. A., R. A. Hansen, K. Lindquist (1998). *Travel times for infrasonic waves propagating in a stratified atmosphere*. Geophys. J. International, 135, 255-263.

Hedin, A.E., (1991). *Extension of the MSIS thermosphere model into the middle and lower atmosphere*. J. Geophys. Res. 96, 1159.

Hedin, A.E., M. A. Biondi, R. G. Burnside, G. Hernandez, R. M. Johnson, T. L. Killeen, C. Mazaudier, J. W. Meriwether, J. E. Salah, R. J. Sica, R. W. Smith, N. W. Spencer, V. B. Wickwar and T. S. Virdi, (1996). *Revised global model of upper thermospheric winds using satellite and ground-based observations*. J. Geophys. Res. 96, 7657-7688.

Le Pichon, A. M. Garcés, E. Blanc, M. Barthélémy, D. Drob (2000). *Acoustic propagation and atmosphere characteristics derived from infrasonic waves generated by the Concorde*. J. Acoust. Soc. Am. (submitted).

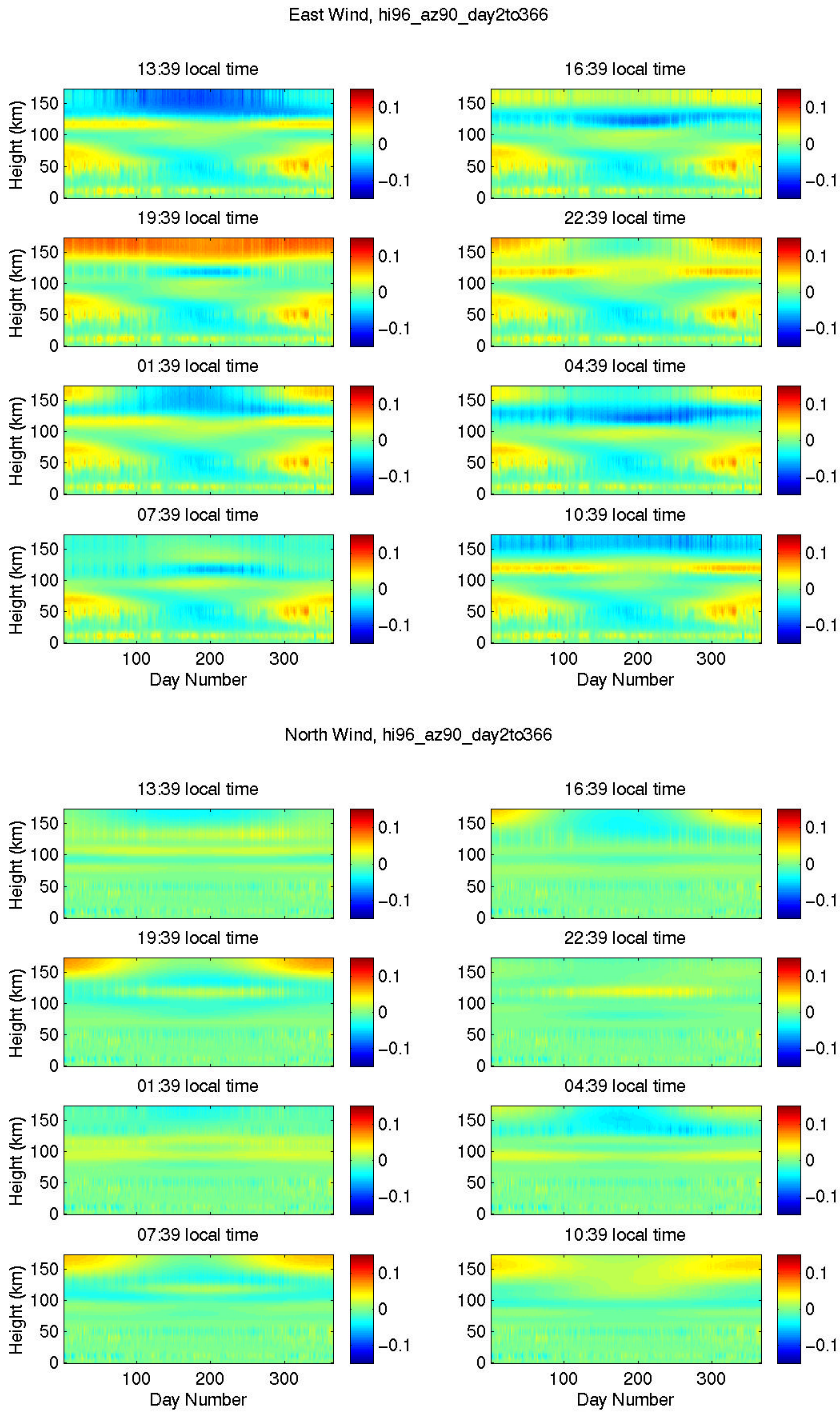

Figure 1. Zonal (upper panel) and Meridional (lower panel) winds (km/s) at Hilo, Hawaii, as a function of height, calendar day number and local time of day. Wind is positive towards the East and the North. Planetary waves produce daily variability up to 50 km, tides dominate diurnal changes in the mesosphere, and geomagnetic storms determine the daily variability of the lower thermosphere. Seasonal changes are visible at all levels in the atmosphere, and are particularly stable in the stratosphere reversal.

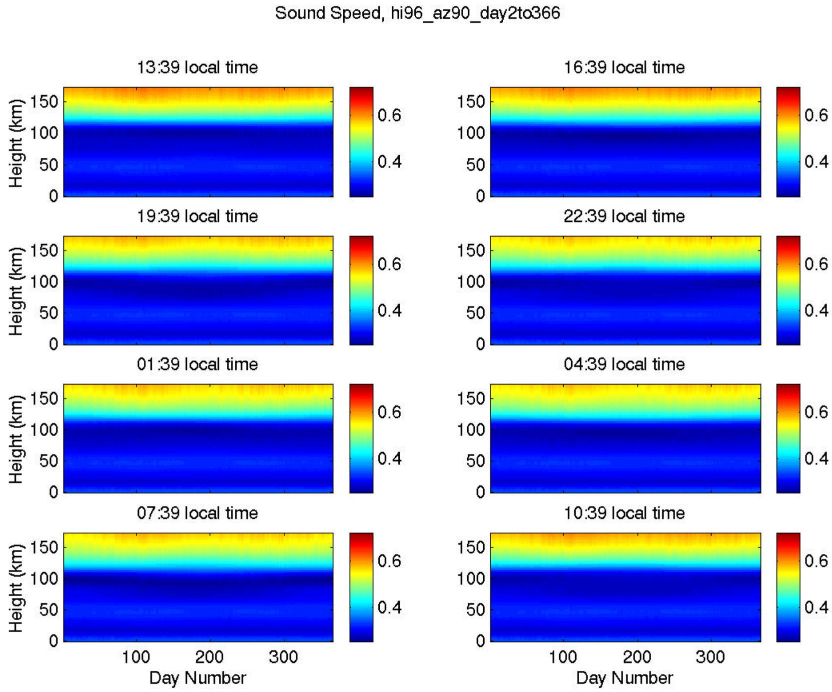

Figure 2. Sound speed (km/s) at Hawaii as a function of height, calendar year and local time of day. The variability is weak compared to that of the wind field. There is a slight increase of the sound speed in the thermosphere due to geomagnetic storms, and Summer cooling in the mesosphere is quite mild.

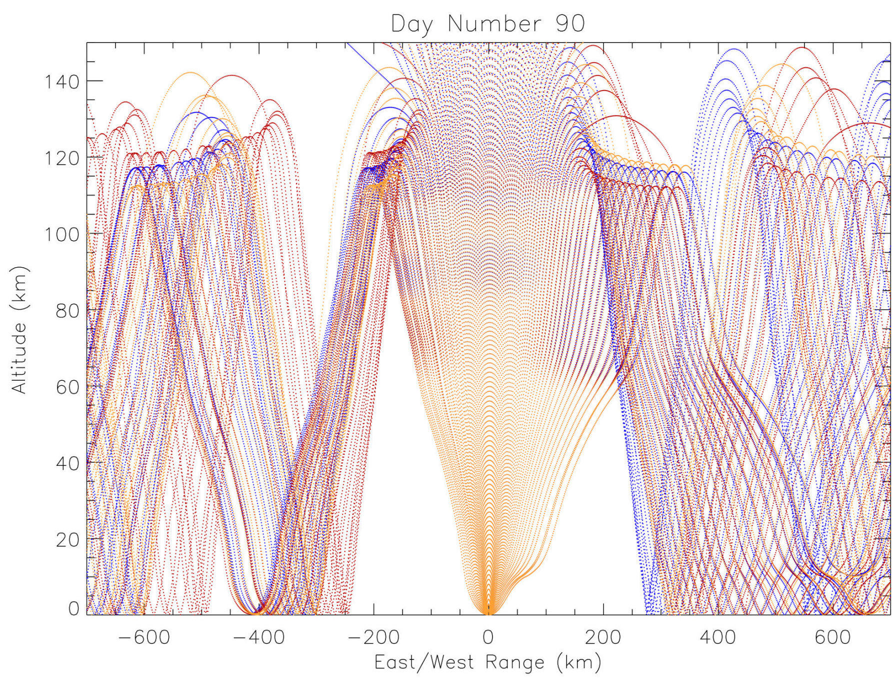

Figure 3. Hourly time-dependence of propagation due to thermosphere ducting over Hawaii. This variability is caused by thermal migrating tides in the middle and upper atmosphere. Each color corresponds to a different local time separated by 6-hours.

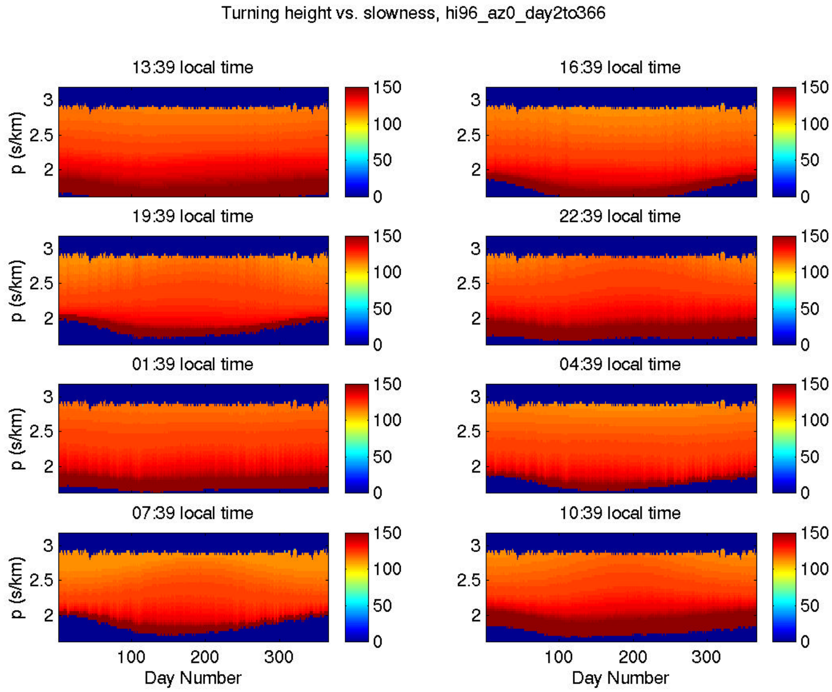

Figure 4. Turning height (km) of rays at Hawaii as a function of slowness (s/km), calendar year and local time of day for an arrival azimuth of 0 degrees. All predicted phases are thermospheric, and their variability is primarily determined by the solar tides and the seasonal changes in the thermosphere.

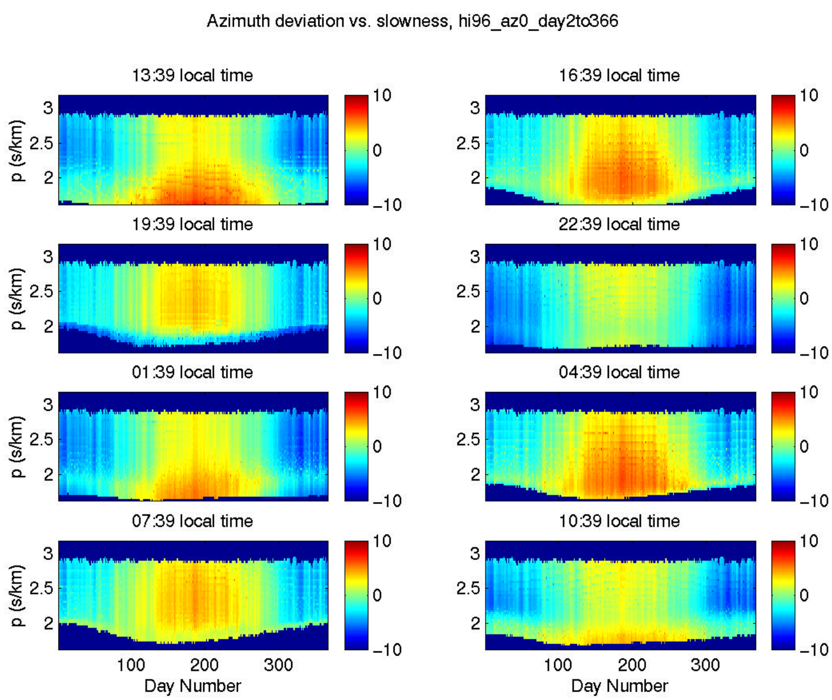

Figure 5. Azimuth deviation (degrees) at Hawaii as a function of slowness (s/km), calendar year and local time of day for an arrival azimuth of 0 degrees. A deviation of +5 degrees means that the arrival azimuth has to be corrected by adding 5 degrees towards the right of the arrival direction. The deviation, which for this azimuth is determined by the zonal wind, is strongly affected by planetary waves in the stratosphere.

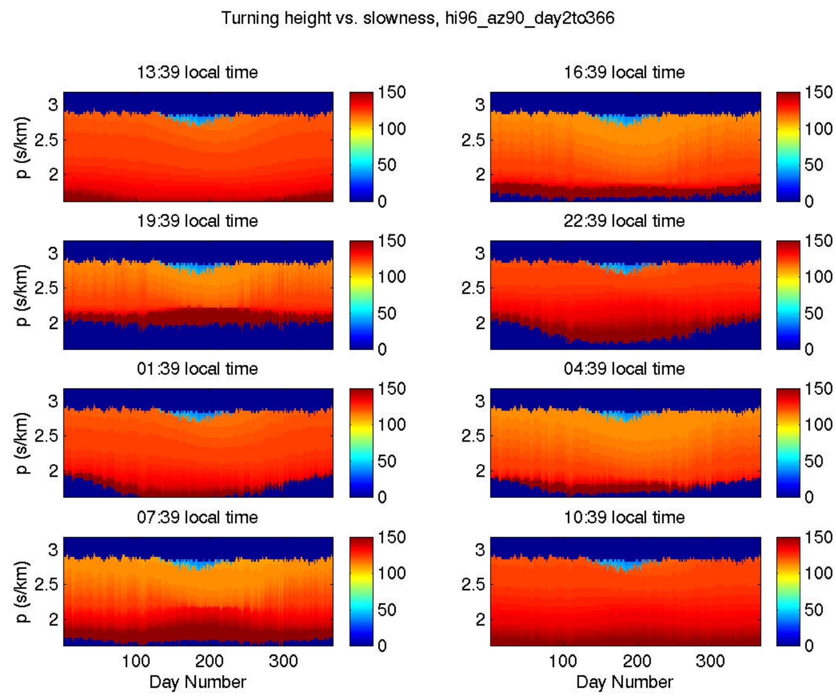

Figure 6. Turning height at Hawaii as a function of slowness, calendar year and local time of day for an arrival azimuth of 90 degrees. Stratospheric phases arrive from the East during Summer. The effects of the tides and the seasonal changes in the thermosphere are clearly seen in the turning heights of the thermospheric phases.

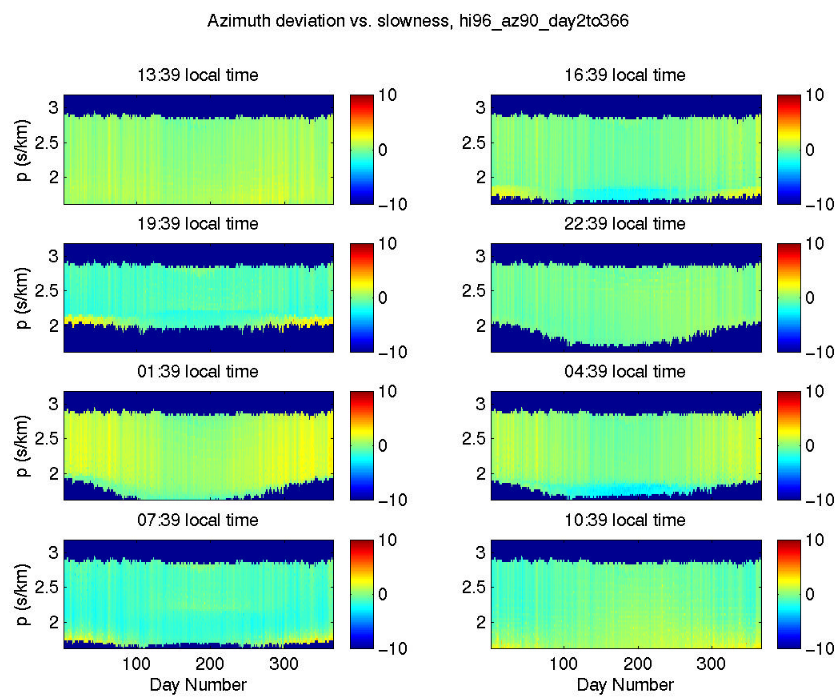

Figure 7. Azimuth deviation at Hawaii as a function of slowness, calendar year and local time of day for an arrival azimuth of 90 degrees. The deviation for this arrival angle is governed by the meridional wind, which is relatively stable and mild. Thus small deviations are expected for arrivals incident from both 90 and 270 degrees azimuth.

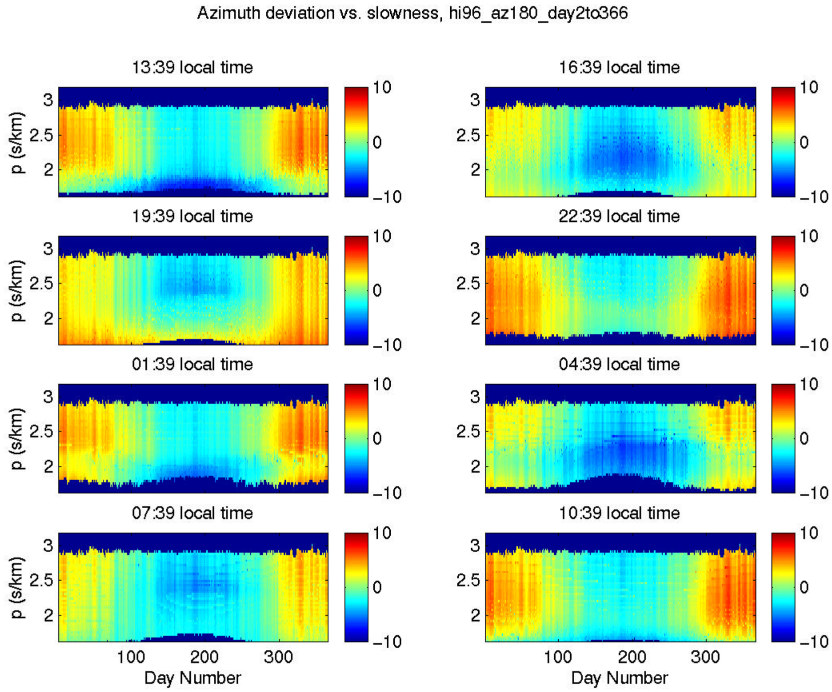

Figure 8. Azimuth deviation at Hawaii as a function of slowness, calendar year and local time of day for an arrival azimuth of 180 degrees. Planetary waves in the zonal wind introduce significant daily variability.

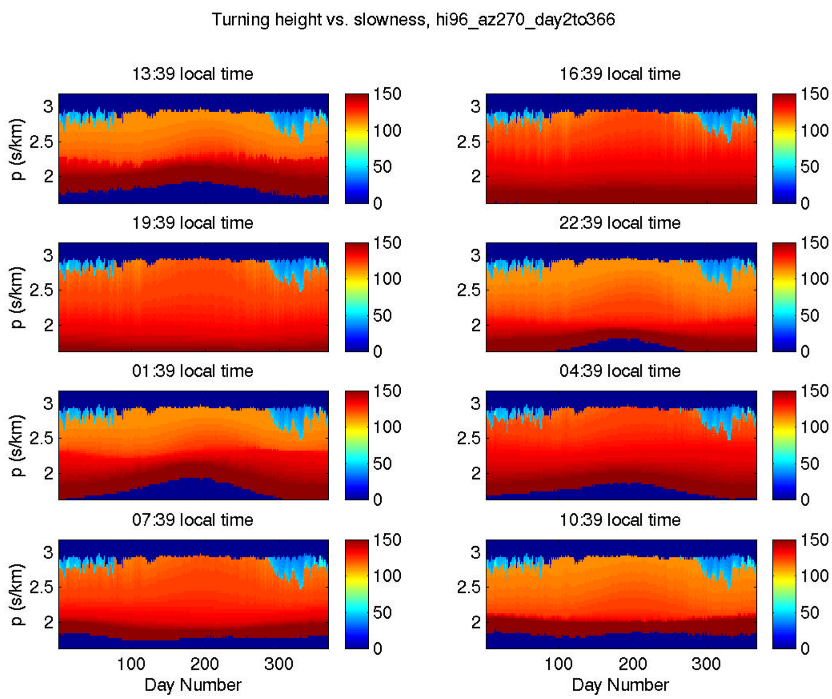

Figure 9. Turning height at Hawaii as a function of slowness, calendar year and local time of day for an arrival azimuth of 270 degrees. Stratospheric phases arrive from the West primarily during Winter.

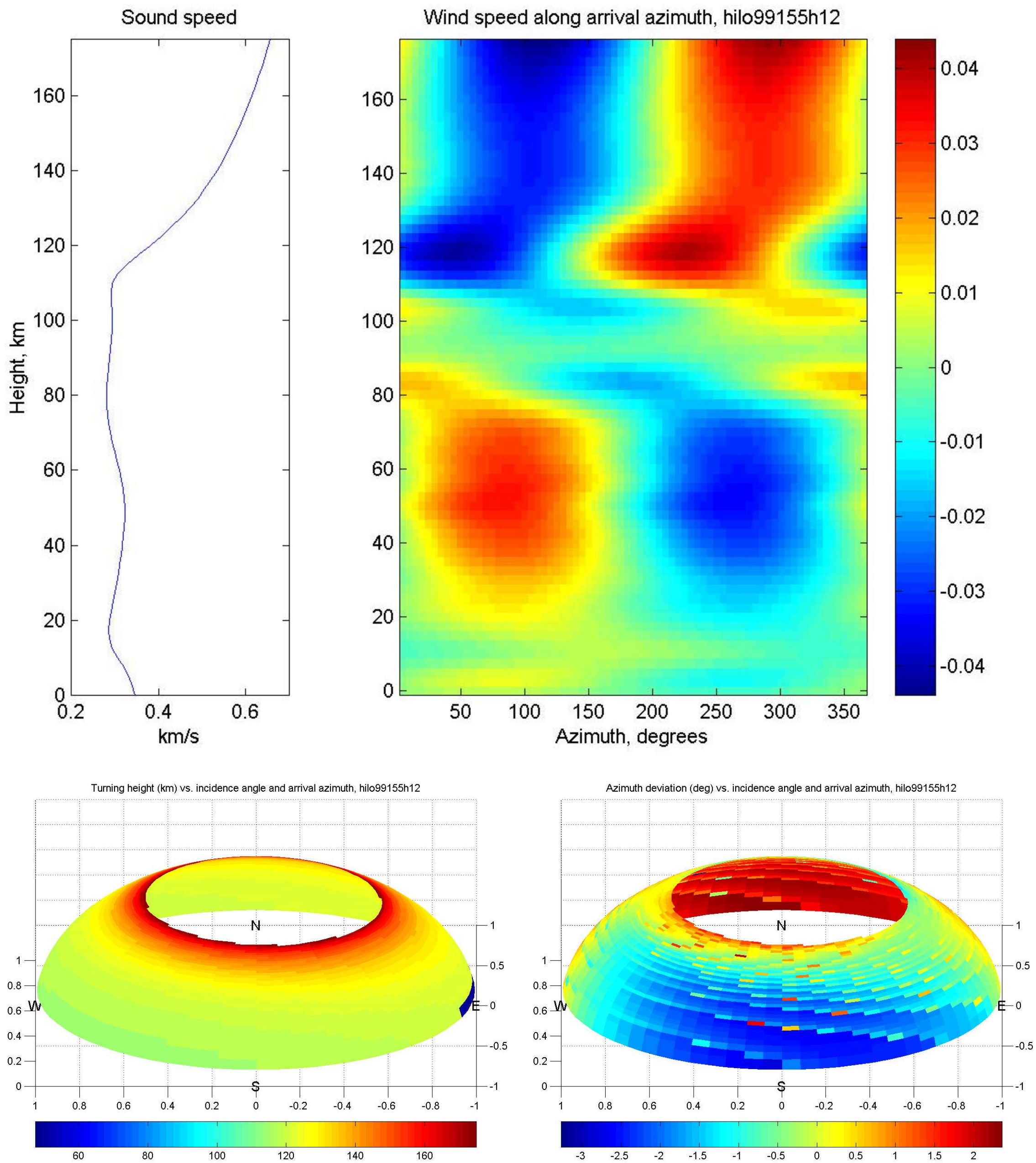

Figure 10. The upper panel show the sound speed and wind speed at Hilo for 12:00 UT on June 4, 1999. The wind speed is plotted as a function of height and arrival azimuth. In this frame a wave launched towards the South would have an arrival azimuth of 0° (N), and a positive wind along this direction would correspond to a Southward, or Northerly wind. The lower panels show the turning height and azimuth deviation of incident rays as a function of arrival azimuth and incidence angle for acoustic energy originating from a source located at the Earth's surface. The truncated hemisphere would be centered at the CTBT array location, and would allow immediate phase recognition. A detected arrival would correspond to a specific azimuth and incidence angle, and the color map on the surface of the sphere would indicate in what height of the atmosphere this ray has turned and its azimuth deviation. The truncated upper part of the hemisphere corresponds to rays which are lost to space.

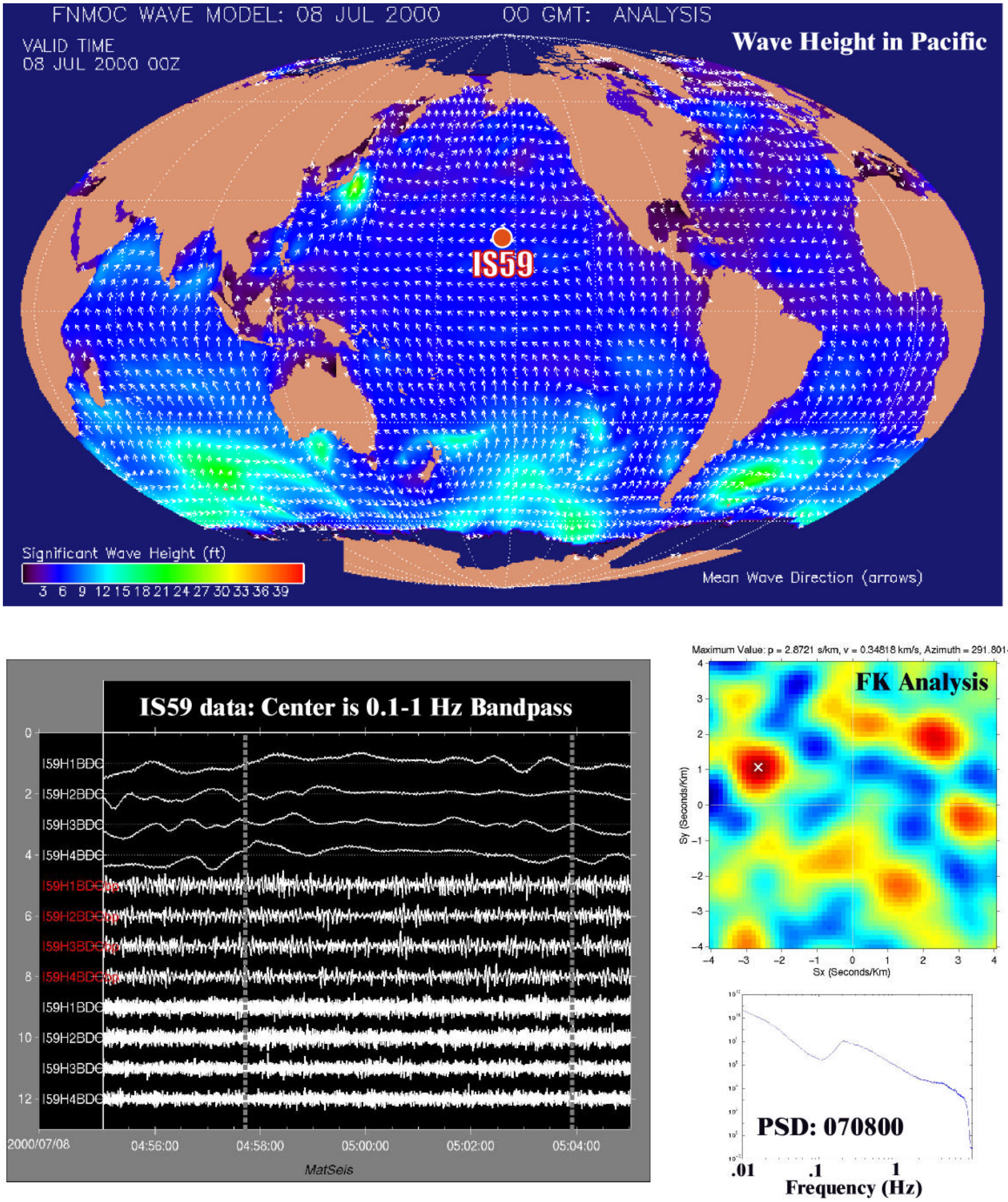

Figure 11. Microbarom signals recorded at IS59 on July 8, 2000. The dominant FK peak may be associated with a region of large significant wave heights generated by Typhoon Kirogi near Japan.