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Observations of infrasound from surf in southern California

Stephen J. Arrowsmith and Michael A. H. Hedlin

Laboratory for Atmospheric Acoustics, Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California, San Diego, California, USA

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[1] We observe 10,000's of infrasound signals annually, in the frequency range from 1–5 Hz, at the I57US infrasound array in Southern California. 75% of these signals arrive at I57US at azimuths between 260 and 320 degrees. There is a good correlation between the amplitudes of signals from 260–320° and wave height measurements offshore Southern California, providing firm evidence that the signals from these azimuths are caused by surf action. By modeling the propagation of infrasound for specific time periods (using 3D ray-tracing and up-to-date atmospheric models), we show that amplitudes of signals recorded at I57US are also dependent upon atmospheric winds. The modeled rays that return in the stratosphere fit observations more closely than modeled rays that return in the troposphere, suggesting the signals are from stratospheric returns. Our findings are the first observations of surf infrasound at a long-range from the source region. This suggests that surf signals might serve as a probe of the atmosphere, much like microbarom signals are used to probe the atmosphere at greater range.
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1. Introduction

[2] Infrasound caused by ocean activity is detected at all infrasound arrays in the frequency band 0.1–0.5 Hz, with a peak period of 5 s. Such infrasound signals are called "Microbaroms" and are caused by the non-linear interaction of ocean swells in the open ocean [*Benioff and Gutenberg*, 1939; *Posmentier*, 1967]. Ocean related infrasound at higher frequencies (1–5 Hz) is less commonly observed, and is thought to be related to surf breaking at the shore [*Kerman*, 1988]. The exact cause of surf infrasound is still unknown but it may be due to the compression or expansion of air resulting from breaking waves collapsing, impacting against a cliff or a shallow reef. Surf related infrasound has been observed at the IMS infrasound array I59US in Hawaii, which is located ~7.5 km from the nearest coastline [*Garcés et al.*, 2003; *Le Pichon et al.*, 2004a]. At I59US surf infrasound is characterised by impulsive events with single cycle duration that may be present as groups of pulses for several hours at a time [*Garcés and Hetzer*, 2001]. In this paper we document our observations of surf infrasound at a large range (~200 km) from the coast of Southern California.

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2. Infrasound Dataset

[3] The I57US infrasound array, part of the IMS infrasound network, is located at the Pinon Flat Observatory in Southern California. The 2 km aperture array comprises 8 MB2000 aneroid microbarometers with a passband of 0.01–27 Hz and a sensitivity of 20 mV/Pa. Four microbarometers are fitted with 18 m noise-reduction rosette filters (designed to detect signals between 0.2 and 5 Hz) and the remaining four are fitted with 70 m aperture filters (sensitive to low frequency signals between 0.02 and 3 Hz) [*Hedlin et al.*, 2003]. The site is co-located with an ultrasonic anemometer for wind velocity, air temperature and humidity sensors. The infrasound and meteorological sensors are digitized at 20 and 1 sps respectively, using a 24-bit Reftek 72A-08 data acquisition system.

3. Processing Infrasound Data: The PMCC Algorithm

[4] The Progressive Multi-Channel Correlation (PMCC) algorithm [*Cansi*, 1995] is applied to I57US data, for the full duration of the dataset (September 2001–June 2004), to detect infrasound signals. For a description of the PMCC algorithm the reader is referred to *Cansi* [1995]. For the analysis of surf infrasound we use only the high-frequency sensors (the 4 microbarometers fitted with 18 m rosette filters) and we filter the data using a Chebyshev filter with a passband from 1–5 Hz. This ensures that the resultant detections have frequencies well above the microbarom band.

4. Surf Infrasound Observations

[5] For a period of two years (2002/03), we observe 440,375 detections at the I57US array using the processing scheme detailed above. The detections are associated with three main azimuth ranges: 260–320°, ~340° and 90–110° (Figure 1). 75% of the total number of detections come from the first azimuth range of 260–320° and are the subject of this paper.

[6] The detections from 260–320° have a mean frequency of 1.58 Hz, which does not vary seasonally. Their amplitudes are found to fluctuate, with discrete periods of relatively high amplitudes (~0.02 Pa RMS) observed (Figure 2). Such fluctuations in signal amplitudes are not observed for signals from other azimuths. By comparing the signal amplitudes with wave height measurements recorded at ocean buoys offshore Southern California, times of high amplitude are found to correlate with times of high wave height during winter months (Figure 2). Such a correlation is not evident during the summer months. Wave height profiles are very similar at five separate buoys along the

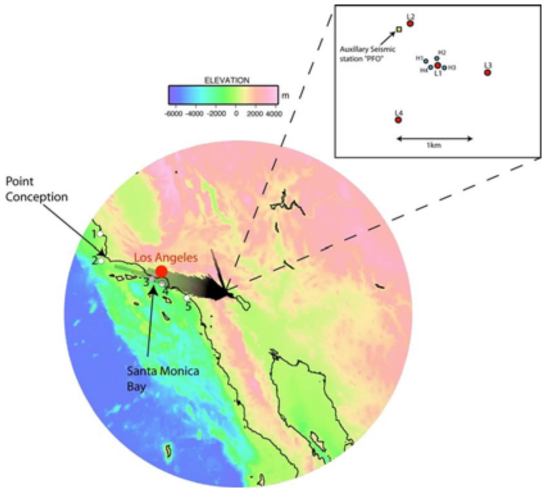

Figure 1. Gnomonic azimuthal projection (centred on I57US) showing a polar histogram of arrival azimuths for the 440,375 detections observed in 2002/03. The background colour scale represents elevation above sea level. White circles represent the locations of 5 different ocean buoys: (1) Diablo Canyon, (2) Harvest, (3) Point Dume, (4) Santa Monica bay and (5) Dana Point. Inset: A schematic figure of the eight element array at Pinon Flat, California. The four long period elements (L1–L4) are shown as red circles. The four high frequency elements (H1–H4) are shown as blue circles. The location of the co-located seismic station (PFO) is also shown.

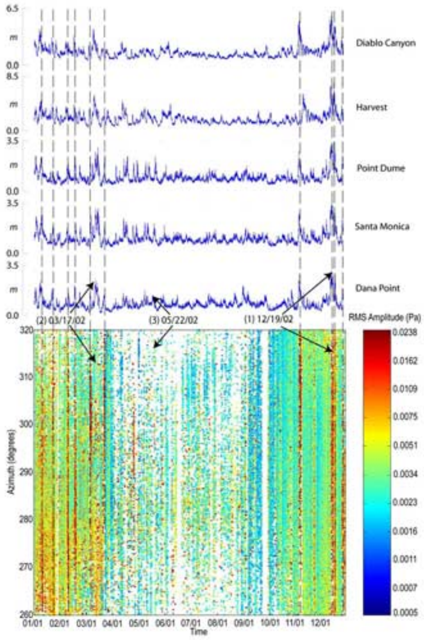

Figure 2. Bottom panel: Graph showing all the 2002 detections plotted as a function of time and azimuth. The logarithmic colour scale represents the mean amplitude associated with each detection. Top panel: Wave height in metres recorded at an ocean buoy located at (33.8544°N, 118.6329°W) in Santa Monica bay. Wave height data were obtained from the Coastal Data Information Program at http://cdip.ucsd.edu.

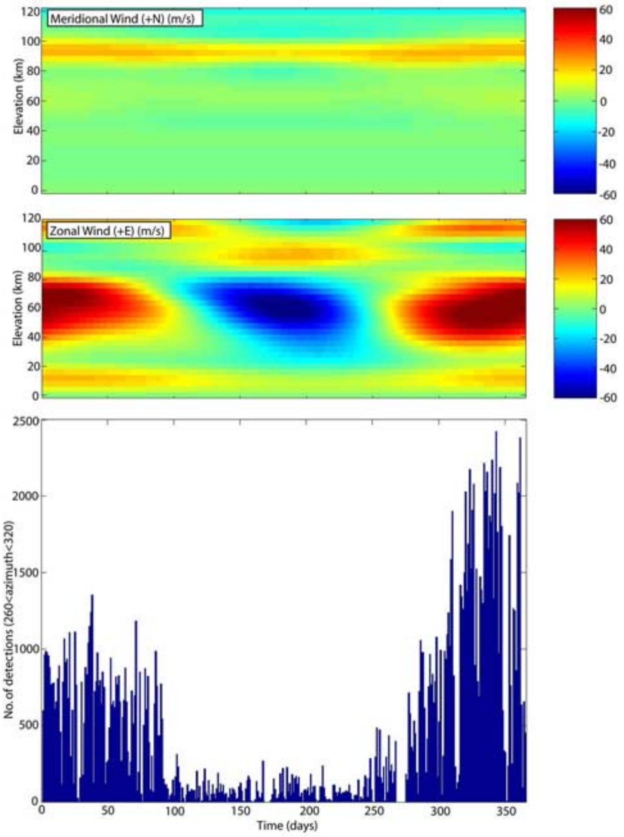

Figure 3. Figure showing the correlation between the seasonal variation of detections from azimuths of 260–320°, and seasonal variations in stratospheric winds, from the HWM model [*Hedin et al.*, 1996]. Top panel: Average Meridional wind along a path between Santa Monica Bay and I57US as a function of day of the year. Middle panel: As top panel for the average Zonal wind. Bottom panel: Number of detections from 260–320° observed each day as a function of day of the year for 2002.

coastline of Southern California: Dana Point (33.4585°N, 117.7675°W) – backazimuth from I57US = 261.5°; Santa Monica (33.8544°N, 118.6329°W) – backazimuth from I57US = 278.4°; Point Dume (33.9792°N, 119.0°W) – backazimuth from I57US = 280.7°; Harvest (34.4547°N, 120.7819°W) – backazimuth from I57US = 284.5°; and Diablo Canyon (35.2083°N, 120.860°N) – backazimuth from I57US = 294.9°. The long-range propagation of the signals discussed in this study indicates that they have been ducted in the troposphere, stratosphere or thermosphere.

[7] In addition to the correlation of signal amplitudes with wave height measurements offshore Southern California, we observe clear seasonal trends in detections from 260–320° (Figure 3). The same seasonal trends in the amplitudes and numbers of detections are observed for each year we have studied. During winter months we observe large numbers of detections (typically 500–2000 per day), while during summer months the detection rate is 83 per day on average (From day 100 to 255) (Figure 3). There is a close correlation between seasonal changes in the numbers of detections and the seasonal reversal of tropospheric, stratospheric and thermospheric winds (Figure 3). This correlation suggests that the ability of I57US for detecting

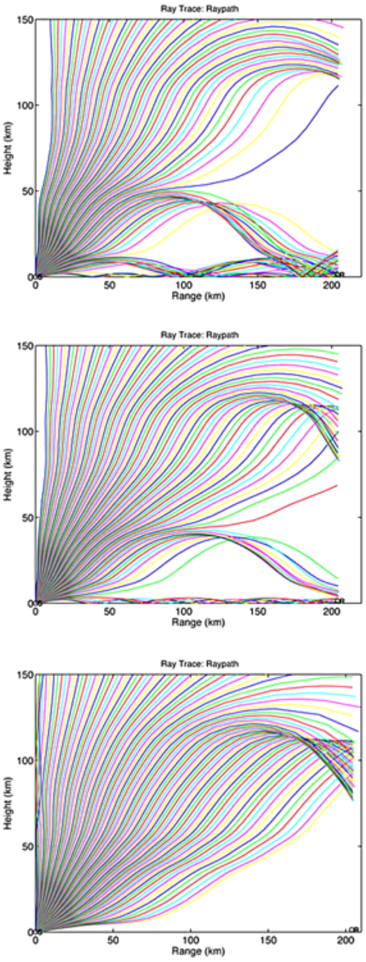

Figure 4. Results of ray-tracing through NRL-G2S models for the following times: (top panel) 12:00 GMT December 19th, 2002, (middle panel) 12:00 GMT February 24th, 2002 and (bottom panel) 12:00 GMT May 22nd, 2002. On each plot "R" labels the receiver location, the source location is chosen as the location of the Santa Monica buoy (33.8544°N, 118.6329°W).

signals from surf is strongly dependent on wind conditions in the troposphere, stratosphere or thermosphere. However, the high values of atmospheric absorption in the thermosphere would mean that surf infrasound would be highly attenuated before reaching I57US [*Sutherland and Bass*, 2004]. This suggests that the signals are from infrasound that has refracted in the troposphere or stratosphere.

[8] In order to determine if the surf signals are from infrasound that has refracted in the troposphere or stratosphere, we have modelled the propagation of infrasound using a 3D ray-tracing routine that provides ray predictions through an inhomogeneous three-dimensional representation of the atmosphere [*Jones et al.*, 1986]. The algorithm accounts for vertical and horizontal refraction as well as horizontal translation of the ray-path due to the moving medium. Horizontal refraction and translation effects are important as they can cause significant biases in the propagation path [*Georges and Beasley*, 1977]. We chose the location of the Santa Monica buoy as the source location (as this is one of the central buoys geographically) and performed the modelling for three separate times: (1) a period of very high amplitude waves and high amplitude detections during the winter (December 19th, 2002), (2) a period of very high amplitude waves but average amplitude detections during the winter (March 17th, 2002) and (3) a period of high amplitude waves and low amplitude detections during the summer (May 22nd, 2002) (Figure 2). For all the modelling computations, the NRL-G2S atmospheric models [*Drob*, 2003] at 00:00 and 12:00 GMT on each day were used. Modelling results are strongly affected by the season but do not vary significantly with the time of day. The NRL-G2S models combine all available observational data from ground-based weather stations with the seasonally averaged Horizontal Wind Model (HWM) [*Hedin et al.*, 1996] and Mass Spectrometer and Incoherent Radar Model (MSIS) [*Picone et al.*, 2002]. The NRL-G2S models are therefore time specific, and are the best currently available models for studying the long-range propagation of infrasound. Rays were traced from the source towards the direction of the receiver at 1° take-off angle intervals from 0–90°. Figure 4 shows the results of the modelling computations for 12:00 GMT on each of the three days. For time (1), when there were very high waves and high amplitude detections, we observe stratospheric and tropospheric returns that reach the ground at the receiver location. Rays are refracted towards the ground due to strong westward winds in the stratosphere and troposphere. At time (2), when there were very high waves and average amplitude detections, the stratospheric returns do not reach the receiver for the specific source location of Santa Monica bay. However, stratospheric returns would reach the receiver for sources further away from Santa Monica bay, in the direction towards Point Conception. Tropospheric returns are fewer and lower in inclination angle. At time (3), when there were high waves and very low amplitude detections observed, there are no stratospheric or tropospheric returns in the ray modelling. There are no thermospheric returns in any of the ray simulations, providing further evidence that the signals are not from infrasound that has refracted in the thermosphere.

[9] In order to determine if the arrivals are from stratospheric or tropospheric returns, the observed phase velocities are compared with those predicted from ray-tracing. The use of phase velocities as a classification tool in infrasound is the subject of some debate. *Ceplecha et al.* [1998] provide a classification scheme of infrasound arrivals based on phase velocity, however *Garcés et al.* [2002] show that the classification of arrivals based on phase velocity may be ambiguous. In this letter we show that the phase velocities are suggestive of stratospheric returns. For time (1), for the time interval from 12:00–13:00 GMT on December 19th, 2002, the mean phase velocity of the arrivals observed at I57US is 376 ± 29 m/s. The steepest arriving tropospheric arrival has an angle of inclination of 18.5° from the horizontal. The temperature at 12:00 GMT was recorded at $-3°$C by an air temperature sensor at I57US. Taking the standard formula for the speed of sound in air,

$$v = 331.4 + 0.6T_c(\mathrm{m/s}),$$

we obtain a speed of sound equal to 329.6 m/s. Therefore the horizontal phase velocity of the steepest arriving tropospheric arrival is 347 m/s. This is equal to the minimum possible phase velocity observed (within the error bounds). Since this phase velocity is for the steepest arriving tropospheric return, and because most tropospheric returns arrive at lower angles (especially on 24th February 2002 when we still observe signals), the observed phase velocities do not match those predicted by the modelling in general. The phase velocity predicted from the closest matching stratospheric return in the ray-tracing modelling is 365.2 m/s. This matches the observed phase velocities much more closely (to well within the specified error bounds). Sources of error in comparing the modelled and observed phase velocities include measurement error (including effects due to the array configuration, and detection algorithm), errors in the atmospheric models used (in particular the ray paths are very sensitive to finer scale spatial and temporal structure and terrain effects that are not modeled with NRL-G2S model) and errors in the propagation model (in this study we use a ray-shooting algorithm). However, the phase velocities suggest that the signals are from infrasound that has refracted in the stratosphere. Such an observation is consistent with previous studies that have cited the dominance of the stratosphere [e.g., *Donn and Rind*, 1971]. A study of regional meteorological data from sites near the propagation path could provide further information on winds in the troposphere, and therefore on the expected ray-paths and phase velocities. However, such a study is beyond the scope of this letter.

5. Discussion and Conclusion

[10] The observations presented in this paper suggest that the 10,000's of high frequency signals observed annually at I57US are dependent upon two main factors: the amplitudes of waves offshore Southern California and the variability of winds in the stratosphere. It has been shown that there is a good correlation between the amplitudes of acoustic signals observed and wave height recorded at ocean buoys. Furthermore, in a couple of specific case studies where there is a poor correlation with wave height, we have shown that this is due to the fact that winds in the stratosphere are inhibiting the refraction of rays at those times. This clear correlation with wave height strongly suggests that the signals are caused by infrasound that has been generated by surf activity. Since the back-azimuths of the signals observed parallels the Southern California coastline from Los Angeles to Point Conception, it is difficult to isolate a specific source location. The signals may come from a specific sea-cliff or bay, or may come from the whole stretch of coastline from Los Angeles to Point Conception. *Garcés et al.* [2003] also observed a correlation between wave height and the amplitudes of large numbers of detections at the I59US IMS array in Hawaii. The primary difference in this study is that the source region (i.e. the coastline at azimuths of 260–320°) is located at a long range from the receiver.

[11] Our findings show that surf infrasound may be detected above the noise level at a large range ($\sim$200 km) from the source. The observation of a repeating signal that generates 10,000's of detections annually and exhibits clear seasonal variations, suggests that surf signals might serve as a probe of the atmosphere in the same way microbarom signals are used to probe the atmosphere at greater range [*Garcés et al.*, 2004]. Surf infrasound signals may be used as the input of an inversion procedure to evaluate more precisely the vertical structure of the wind up to an elevation of $\sim$60 km. A similar type of study was performed using volcano infrasound by *Le Pichon et al.* [2004b]. The results of such a study would allow us to refine the most up-to-date models of the atmosphere. With the addition of close-in measurements, surf infrasound could also provide an excellent dataset for studies of the attenuation of infrasound signals.

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S. J. Arrowsmith and M. A. H. Hedlin, Laboratory for Atmospheric Acoustics, Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California, San Diego, CA 92093-0225, USA. (sarrowsmith@gmail.com; hedlin@epicenter.ucsd.edu)