On using ocean swells for continuous infrasonic measurements of winds and temperature in the lower, middle, and upper atmosphere

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[1] The arrival azimuths of coherent microbarom signals observed in Hawaii during 2003 are associated with high ocean wave activity in the Pacific Basin, the dominant wind directions in the troposphere, stratosphere, and mesosphere, and the thermal structure of the atmosphere. Some of the seasonal trends in the microbarom observations can be explained by the winds in the stratosphere and lower mesosphere, while some of the daily variability can be explained by the winds in the troposphere and lower stratosphere. However, coherent energy from powerful swells may overcome the wind-carried microbarom signals and arrive to the station through thermospheric ducting. Our observations suggest that either (1) the wind speeds in the troposphere, stratosphere and mesosphere may be underestimated in atmospheric models or (2) elevated leaky infrasonic waveguides are persistent propagation paths that should be investigated in more detail. *INDEX TERMS:* 0350 Atmospheric Composition and Structure: Pressure, density, and temperature; 0394 Atmospheric Composition and Structure: Instruments and techniques; 1610 Global Change: Atmosphere (0315, 0325); 4560 Oceanography: Physical: Surface waves and tides (1255); 4504 Oceanography: Physical: Air/sea interactions (0312). **Citation:** Garcés, M., M. Willis, C. Hetzer, A. Le Pichon, and D. Drob (2004), On using ocean swells for continuous infrasonic measurements of winds and temperature in the lower, middle, and upper atmosphere, *Geophys. Res. Lett.*, *31*, L19304, doi:10.1029/2004GL020696.

1. Introduction

[2] *Willis* [2004] and *Willis et al.* [2004] demonstrate that microbarom observations at IMS infrasound station I59US in Hawaii (19.5915 N, 155.8936 W) match the seasonal distribution of large storms and associated large swells in the Pacific. Like microseisms, microbaroms are believed to be generated by speaker-like ocean displacement induced by the nonlinear (sum frequency) interactions of ocean surface waves traveling in nearly opposite directions with similar frequencies [e.g., *Donn and Naini*, 1973]. However, while microseisms propagate through the ground as a result of vertical excitation through the ocean, microbaroms propagate to infrasonic stations after near horizontal propagation through the atmosphere [*Tebulevich*, 1995]. Thus seismic and infrasonic measurements sample complementary portions of the total radiated source field. However, microbaroms will be primarily affected by the dynamic temperature and wind structure of the atmosphere, whereas microseisms will be propagated through the relatively static geologic structure of the Earth. This paper seeks to explain in more detail the effects of atmospheric temperature and winds on the spatial, temporal, and spectral distribution of coherent and incoherent microbarom energy.

[3] A power spectral density plot for IMS station I59US is shown in Figure 1 on Willis et al. (this issue). During the winter season, when surf is highest, the frequency band above 2 Hz is dominated by sound from breaking ocean waves [*Garcés et al.*, 2003]. The large, broad peak between 0.1 and 1 Hz corresponds to coherent and incoherent microbarom energy arriving from all possible source regions in the Pacific. The microbarom peak usually has a maximum at 0.2 Hz, corresponding to the 10s periods common to open-ocean swells, but may have a secondary peak between $\sim$0.12–0.15 Hz or the peak may appear to broaden to include this frequency band. As discussed by *Willis* [2004], the lower frequency component corresponds to large, long-period swells that can be sufficiently energetic to dominate the coherent infrasound field in the microbarom band. Previous work [*Daniels*, 1952; *Donn and Rind*, 1971; *Rind*, 1978] related microbarom amplitude variability to solar tide fluctuations in the thermosphere during winter and stratospheric wind strength during summer. Their studies concentrated on the results from an infrasound station in the Eastern US that was primarily exposed to microbaroms arriving from the N Atlantic. *Le Pichon et al.* [2003, 2004] suggest a correlation between the prevailing direction of the stratospheric winds and microbarom arrival azimuths observed by Southern hemisphere stations. These austral stations would primarily observe the ocean swells driven by southern hemisphere typhoons and the continuous circumpolar winds. In this study we investigate microbaroms arriving at Hawaii from anywhere in the Pacific Ocean, and we present a relationship between the arrival direction of coherent microbarom energy and the dominant wind

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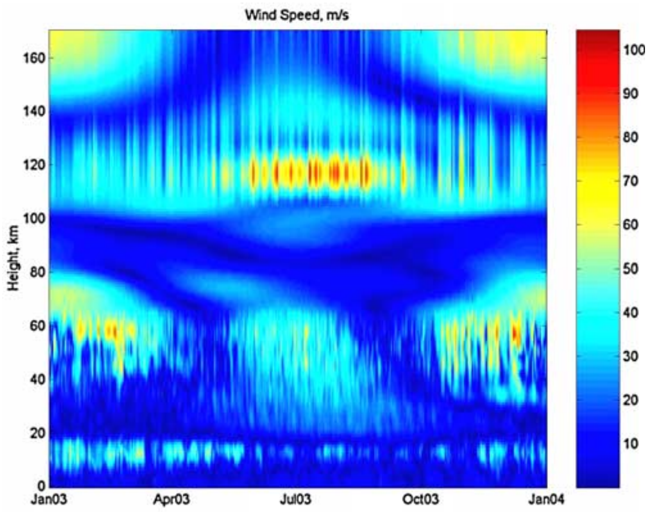

Figure 1. Wind speed provided by the G2S atmospheric specifications over Hawaii for 2003 at 18 GMT.

direction in regions of the troposphere, stratosphere, and lower mesosphere. In addition, we postulate that microbaroms generated by energetic swells may refract in the thermosphere to arrive at a station from any direction.

2. Meteorology Directs Where Sound Will Strike

[4] The temperature and winds in the atmosphere determine where sound waves travel [e.g. *Cox et al.*, 1954]. Infrasound can propagate for long ranges in waveguides defined by the thermal and wind structure of the atmosphere. Along the downwind direction, infrasonic energy may be trapped between the ground and the troposphere and lower stratosphere (tropospheric ducting) and between the ground and the stratosphere and lower mesosphere (stratospheric ducting). However, if the winds are not sufficiently strong, these tropospheric and stratospheric waveguides do not reach the ground. From a ray theory perspective, such elevated waveguides would not be able to transfer energy to ground-based recording stations. But in practice, such waveguides may leak energy to the ground through diffraction and scattering [*Garcés et al.*, 2002b]. Due to the high temperatures at the thermosphere, infrasonic energy is always refracted back to the ground by the thermosphere (thermospheric ducting), although the attenuation is stronger for these paths.

[5] In order to produce atmospheric specifications for infrasonic propagation studies, the Naval Research Laboratory (NRL) Ground to Space (G2S) model [*Drob et al.*, 2003] was run to produce a self-consistent dataset extending from January 1, 2003 to March 29, 2004. Global spectral coefficients of wind, temperature, and density were produced at 6-hour time intervals. These coefficients have a triangularly truncated spectral order of 72 (T-72) resulting in an effective output resolution of approximately 2.25 degrees.

[6] From the Earth's surface to 10 mb (0 to 35 km), we use 1 × 1 degree operational global aviation weather forecasts from then NOAA National Centers for Environmental Predication (NCEP). From 1 to .4 mb (20 to 55 km), we use the 1.0 × 1.5 global assimilative analysis from the NASA Goddard Space Flight Center, Global Modeling and Assimilation Office (GSFC-GMAO). This data set is limited distribution but available for basic scientific research. The upper atmosphere conditions (50 to 170 km) are specified by the HWM/MSIS models, which use the 3-hour and daily geomagnetic activity (Ap) and solar EUV flux (F10.7) indices from the NOAA space environment center (SEC). The trade winds typical of the tropical regions are generally limited to the lower 4 km of the atmosphere, and may be excessively averaged by the 1 km grid of the G2S specifications.

[7] In order to investigate the effect of atmospheric winds on microbarom propagation, the wind speed (Figure 1) and wind arrival azimuth (Figure 2) were extracted from the G2S global grids at a vertical profile above the Hawaii infrasound station. We evaluated Figures 1 and 2 at a fixed time (18 h GMT) to eliminate the variability induced in the thermosphere by the solar tides [*Garcés et al.*, 2002a]. Although most of the tropospheric variability appears to be governed by storms, it is possible to observe clear seasonal patterns above 15 km. As will be discussed in the next section, the detection of coherent microbarom energy appears to be primarily dictated by the proximity of the source, the swell extent and size, and the predominant wind direction in specific regions of the atmosphere. Since we do not have the source location for all microbarom sources, we do not address range dependence and focus only on the atmospheric conditions over the Hawaii. The local atmospheric conditions would be reasonably accurate over the last few skips (~3 degrees) to the station. During the discussion of the Hawaii observations, seasonal terms refer specifically to the Central North Pacific.

3. Size Matters, but Consistency Prevails

[8] Modeling the radiation of infrasonic waves from the nonlinear interaction of ocean waves is far from trivial. *Willis* [2004] used the output of the WW3 model to produce a frequency-dependent synoptic plot of the microbarom source regions in the Pacific. His results show that micro-

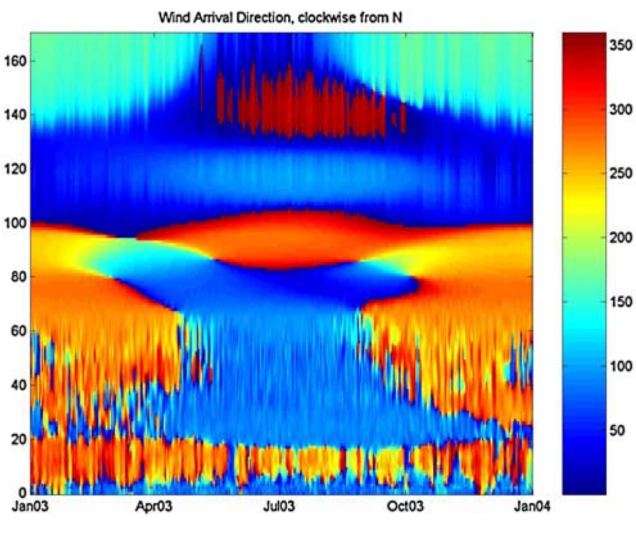

Figure 2. Arrival direction, clockwise from North, of the G2S atmospheric winds over Hawaii for 2003 at 18 GMT.

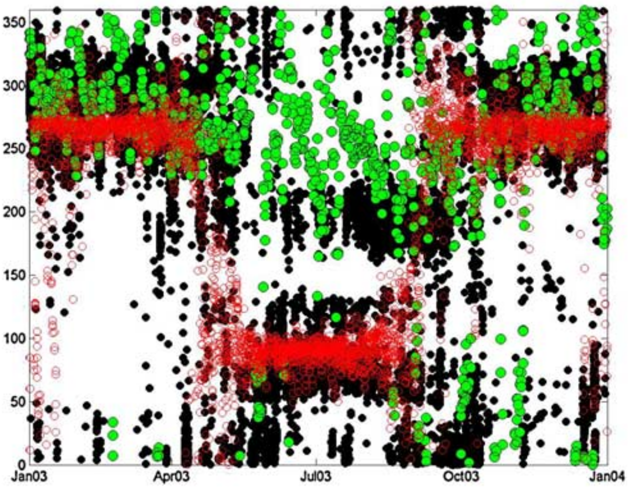

Figure 3. Coherent microbarom (black circles) and wind (green and red) arrival azimuths, clockwise from North, at the Hawaii array for 2003. The transparent circles with the red rim represent the winds between 50–70 km and the green circles represent the winds between 10–20 km. The dominant wind directions match the seasonal variability for some of the arrivals, except for the arrivals from the Southern hemisphere during the Austral winter. These S swells are large, consistent, and powerful, and may overwhelm the 10s period swell energy.

barom sources with a frequency of 0.2 Hz form predominantly between two storms or in the lee of a storm, and are abundant in the Pacific. Thus a listening post in the midst of the ocean will be continuously bombarded by microbarom signals originating from multiple azimuths and ranges. When these signals arrive at an infrasonic array and are processed to find the most coherent arrivals, a competition ensues. Figure 3 shows as black dots all the coherent arrivals observed in Hawaii for 2003. These arrivals have an apparent horizontal phase velocity that is close to that of the sound speed at the ground, suggesting that the source energy was radiated very close to the horizontal. As discussed by *Garcés et al.* [2002a], when sound arrives near the horizontal the apparent horizontal phase velocity, or trace velocity, does not provide an unambiguous determination of the arrival's propagation path. Depending on the wind aloft, an arrival with a low trace velocity may be refracted anywhere between the troposphere and the thermosphere. Small measurement errors in the trace velocity may imply very large differences in the predicted propagation path of an arrival.

[9] There is an obvious seasonal trend in the observations, with microbaroms arriving predominantly from the NW in winter and S and NE in summer. The prevailing wind directions between 50–70 km are shown as red dots, and the winds between 10–20 km are shown as green dots in Figure 2. We can see that the seasonal pattern roughly coincides not only with the most energetic swell source regions but also with the prevailing wind directions in the selected layers. Microbaroms arriving from the south during summer, which would reach at the Hawaii array through multiple bounces between the thermosphere and the ground, would be affected by the solar tides in the upper atmosphere. As shown by *Willis et al.* [2004], the summer arrivals appear to have a lower amplitude. During the shoulder periods of Spring and Fall, arrivals are more evenly distributed along the compass [*Willis et al.*, 2004], corresponding to the change in the wind patterns and a more equitable partition of swell energy between the N and S hemispheres. By using the G2S models to compute the wind-corrected effective sound speeds over Hawaii, the upper boundaries of the stratospheric ducts are predicted to reach as high as 70 km during winter, and as low as 60 km during summer. However, from April to May and September to October, stratospheric winds are light and stratospheric waveguides are predicted to be elevated above the ground. Likewise, tropospheric winds at ~10 km are only sufficiently strong in January and February to consistently maintain a ground-reaching tropospheric waveguides. Figure 4 shows a close up of Figure 3 for the months of January and February of 2003. These are often the most active swell months for the Hawaiian Islands. Some of the microbarom arrival azimuths in January and February track the tropospheric winds fairly well, corresponding to energy that would be refracted back to the ground between the 10–20 km height in the atmosphere, where there is very little attenuation. Likewise, energy ducted between the lower mesosphere and the ground would suffer very little attenuation and thereby retain a relatively large amplitude. However, some microbarom azimuths do not match the prevailing winds, as in the case of January 4–7, 2003. This case study corresponds to the largest swell event of 2003 [*Garcés et al.*, 2003], is considered in detail by *Willis* [2004], and will be the subject of a separate paper. The marine storm responsible for this event produced high open ocean wave heights over a wide spectrum of frequencies between 0.05 and 0.1 Hz, and thus produced high microbarom source amplitudes between 0.1 and 0.2 Hz. High source amplitudes, coupled with lower attenuation and a larger correlation length at lower frequencies, would permit long-range propagation of this energy over large distances and preferential detection by an array.

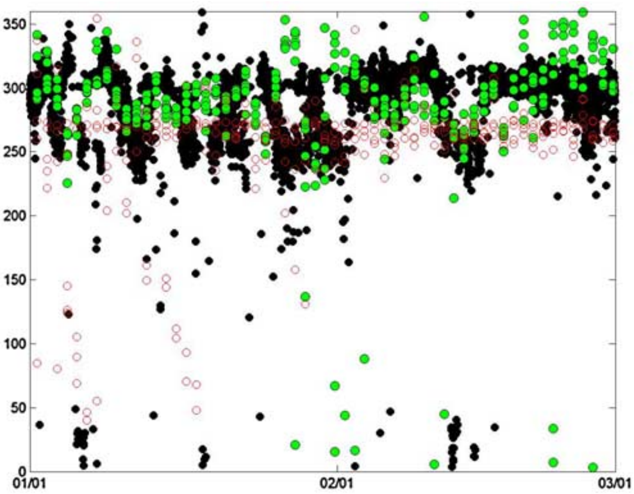

Figure 4. Same as Figure 4 but only for January and February, and showing a match between the tropospheric wind direction and a number of the microbarom arrival azimuths.

[10] Thus it is possible to explain the structure of ocean-related infrasound spectra observed in Hawaii by attributing (1) a broad 2–5 Hz energy peak to breaking ocean waves (surf) in the littoral zone, (2) 0.2 Hz energy to the predominant 10 s swell energy and (3) 0.1–0.2 Hz energy to 12–20 s period swells associated with powerful storms. The surf peak depends on the swell energy arriving near the array site, and in Hawaii surf sound appears to be propagated in the boundary layer and the troposphere. The coherent component of the main microbarom peak at 0.2 Hz depends on the prevailing winds and the amount of swell energy in the ocean. However, the energy of the main microbarom peak is the sum of coherent and incoherent components, and the amplitude of this peak may be related to the diurnal tides in the upper atmosphere [*Rind*, 1978]. If atmospheric winds do not support tropospheric or stratospheric waveguides, a low trace velocity could correspond to refraction in the mesosphere and lower thermosphere. Coherent microbaroms in the ~0.12–0.2 frequency range may arrive from any direction where energetic long-period swells are interacting, and under certain circumstances may also be used to study the mesosphere and lower thermosphere [*Garcés et al.*, 2002a]. Returns from the upper atmosphere would explain southerly arrivals associated with the powerful southern hemisphere swells during the boreal summer.

4. Concluding Remarks

[11] Infrasound generated by the ocean waves can be used to continuously study the temperature and wind structure of the atmospheric boundary layer, troposphere, stratosphere, mesosphere, and lower thermosphere. Ocean surface winds generate swells, which may interact nonlinearly to generate infrasound, which in turn may propagate for thousands of kilometers along the lower, middle, and upper atmosphere. Once these ocean swells reach a coastline, waves break and generate infrasound that may propagate along the boundary layer and lower atmosphere.

[12] Our studies suggest that a large portion of coherent microbarom arrivals observed in Hawaii are strongly affected by advection from the atmospheric winds in the 10–20 and 50–70 km height ranges. However, energetic swells can generate strong microbarom signals that may arrive from any direction, and may be refracted back to the ground at the thermosphere.

[13] By comparing the predicted atmospheric waveguide boundaries with the observed microbarom arrivals, we conclude that either (1) the wind speeds in the troposphere, stratosphere and mesosphere may be underestimated in atmospheric models or (2) elevated leaky infrasonic waveguides are persistent propagation paths that should be investigated in more detail. In particular, it would be valuable to study diffraction and scattering of infrasonic energy into and out of these postulated elevated waveguides.

[14] If an infrasound array were to be optimally designed for the reception of microbaroms, it may be possible to individually remove coherent arrivals associated with open-ocean sources to yield signals refracted from different layers of the atmosphere and source regions. This may permit the identification of interesting transient reflection and refraction layers in the atmosphere as well as facilitate the recognition of microbarom signals produced by reflections from coastlines. Microbarom amplitude studies may yield further information on the variability of the atmospheric wind structure.

[15] Although ocean swells have been previously used as a natural source for continuous measurements of atmospheric winds over long horizontal ranges, recent advances in measurement and modeling techniques can provide new insight on this complex but tractable method for continuous, passive acoustic tomography of the atmosphere.

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