Evidence of atmospheric gravity waves during the 2008 eruption of Okmok volcano from seismic and remote sensing observations

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[1] Okmok volcano erupted on July 12, 2008, following an 11-year hiatus. Detailed inspection of the syn-eruptive seismograms revealed the presence of an ultra long-period mode at a frequency of 1.7 mHz, which is not a characteristic of the background seismic noise at Okmok. Data collected by the National Oceanic and Atmospheric Administration Geostationary Operational Environmental Satellite (GOES) and National Aeronautical and Space Administration Moderate Resolution Imaging Spectroradiometer (MODIS) sensors displayed the propagation of a vigorous ash-and-steam plume up to about 17 km above sea level. We suggest that the observed ultra long-period signals represent the response of the seismometer to changes in gravity associated with buoyancy oscillations set off in the lower atmosphere above Okmok by the emplacement of the eruption column. Calculations based on simple modeling of these effects allowed estimation of peak atmospheric pressure perturbations associated with the eruption of less than 1 mbar. Citation: De Angelis, S., S. R. McNutt, and P. W. Webley (2011), Evidence of atmospheric gravity waves during the 2008 eruption of Okmok volcano from seismic and remote sensing observations, Geophys. Res. Lett., 38, L10303, doi:10.1029/2011GL047144.

1. Introduction

[2] Atmospheric waves with periods from a few to several minutes from various sources, including volcanic eruptions, have been extensively studied [Press and Harkrider, 1962; Pierce and Posey, 1970; Bath, 1982; Watada and Kanamori, 2010]. These waves can propagate as acoustic and gravity modes. Overlapping acoustic-gravity regimes exist under certain conditions. Propagation of acoustic modes is controlled by the atmospheric wind and temperature profiles and occurs at shorter periods, less than ~250 s, and with phase velocities of about 330 m s\(^{-1}\) or greater. Gravity waves (GW) are generally observed at periods from a few to several minutes and phase velocities of the order of tens of m s\(^{-1}\). GW arise from perturbations to the hydrostatic equilibrium and propagate in fluids, such as the atmosphere, with stable density stratification due to vertical temperature or density gradients: the perturbed fluid oscillates under the effects of the restoring force of gravity.

[3] The thermal energy emitted by eruptions and the mechanical displacement of the atmospheric medium induced by the emplacement of eruptive plumes, are potential sources of atmospheric GW. Distinctive barometric observations of GW at frequencies as low as 0.97 mHz have been reported, for instance, during large Vulcanian explosions at Soufriere Hills Volcano. Ripepe et al. [2010] explain their generation with a mechanism of displacement of the atmospheric medium induced by the propagation of the eruption plume and energy trapping in the lower atmosphere.

[4] Coupling between atmospheric sources and the solid Earth has been discussed in the literature [Harkrider, 1964; Kanamori et al., 1994; Tanimoto and Artru-Lambin, 2007; Lognonné, 2009], although there exist scarce observational evidence of seismic waves generated by these mechanisms at long periods (<3 mHz). Kanamori et al. [1994] showed that explosions associated with the eruption of Mt. Pinatubo, in 1991, excited atmospheric oscillations in the frequency band of seismic Rayleigh surface waves; Watada [1995] further expanded this work showing that coupling between the atmosphere and the solid Earth is possible when their resonant modes overlap. Lognonné [2009] demonstrated that the signals associated with the eruption of Mt. Pinatubo could be explained by a high-altitude atmospheric source such as an eruption-generated shock wave. In general, however, the exchange of energy between the atmosphere and the ground is not efficient. Even in the presence of largely unconsolidated sediments, such as on volcanoes, the sound speed in the atmosphere and the seismic velocity in the upper crust differ by a factor of ~10 (representative values are ~340 m s\(^{-1}\) for sound speed in atmosphere and ~3000–4000 m s\(^{-1}\) for seismic velocity of the upper crust in volcanic regions); if one accounts for the obvious difference in density between atmospheric air and the solid Earth (a factor of ~1000), the overall impedance contrast at the air-ground interface is very large. In these conditions the Earth’s surface tends to behave as a rigid, not deformable, boundary relative to sources in the atmosphere [Watada and Kanamori, 2010].

[5] However, it has long been recognized that perturbations of the atmospheric pressure field leave their footprint on seismic records through other, relatively well understood, mechanisms. At low frequencies (below ~2 mHz), the effects of changing atmospheric pressure include Newtonian attraction of the sensor by atmospheric masses above the station, static ground displacement (both vertical displacement and rotation) due to atmospheric loading of the elastic crust, and the associated free air and inertial effects [Zurn and Widmer-Schnidrig, 2003]. These effects, collectively, produce near-surface changes in gravity sensed by the mass of a seismometer as accelerations. Incidentally, these otherwise not desirable effects were recognized during the 2008 eruption...
2. Background

Okmok Volcano, located in the central Aleutian Arc, Alaska, is a dominantly basaltic complex topped with a 10-km-wide caldera. Okmok erupted several times in the past 100 years, most recently during July and August 2008. Whilst former eruptions in 1945, 1958, and 1997 produced lava flows within the caldera, the 2008 eruption was a large phreatomagmatic event and was the first to be monitored by the Alaska Volcano Observatory (AVO) using ground-based instrumentation [Larsen et al., 2009].

The seismicity at Okmok volcano is monitored in real-time by AVO with a network of eight short-period (Mark Products L4-C, T = 1 sec) and four broadband seismometers (Guralp CMG 40T, T = 30 sec) installed between 2002–2004 (see Figure S1). The 2008 eruption of Okmok was characterized largely by a lack of long-term precursory seismicity. A sequence of scattered small earthquakes began at 14:36 (Universal Coordinated Time, UTC) on July 12, 2008 and increased in size and number at about 18:30 UTC, just one hour before the onset of the eruption. The main phase of the eruption began at 19:43 UTC, and lasted about 10 hours. Intermittent ash-and-steam emissions accompanied by elevated seismicity continued from July 12 to August 19, 2008 when the eruption ended. For a detailed account of the eruption, the reader may refer to Larsen et al. [2009].

3. Data Analysis

Firstly, we inspected the continuous seismic record across the entire network in order to characterize the background noise at Okmok. Figure 1a shows comparative power spectral density plots for three hours of pre-eruption background, early on July 12, 2008 and the initial phase of the eruption as recorded at station OKFG. Comparison with long-term ambient noise probability density functions, calculated using the method of McNamara and Buland [2004] (not shown here, but available from the Incorporated Research Institution for Seismology website, http://www.iris.edu/servlet/quackquery/pdfPlots.do), confirmed that the data of Figure 1a are representative of the seismic background at the OKFG site and, generally, at Okmok. Interesting characteristics of the frequency domain representation of the eruption signal include large spectral amplitudes in the 0.1–10 Hz band and a pronounced peak at 1.7 mHz. The 1.7 mHz peak is visible in all three components of station OKFG (Figure 1b), significantly larger in the vertical direction. This exceptionally monochromatic oscillation corresponds to a time interval of about 1 hour from 22:30 to 23:30 UTC on July 12, 2008 (Figure 2).

We investigated the polarization of this ultra long-period (ULP) signal at station OKFG: the records were corrected for instrument response and the horizontal-component velocimetry seismograms rotated into the radial and tangential directions with respect to the location of the eruptive vent. The seismograms were band-pass filtered (Butterworth, zero-phase, 2-pole filter) between 200–1000 seconds in order to investigate the particle motion signature of the ULP oscillation. The hodogram plots in the horizontal, vertical-radial, and vertical-tangential planes show a quasi-vertical polarization of the signal with very limited particle motion in the horizontal plane. We, additionally, scanned the seismic records of the three other broadband instruments in the network searching for similar ULP signals. Unfortunately, data were severely corrupted due to telemetry dropouts during the most intense phase of the eruption and extensive

**Figure 1.** (a) Power Spectral Density (PSD) of three hours of pre-eruption background (light gray) and three hours of eruption tremor (black) at station OKFG (vertical component). The inset shows the actual seismic data used in the PSD analysis (plotted to their relative scale). (b) Spectral amplitude of eruption signals (July 12, 2008, 21:00:00–24:00:00 UTC) at station OKFG. Note, the obvious peak at 1.7 mHz that is visible on all three components.

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1Auxiliary materials are available in the HTML. doi:10.1029/2011GL047144.
network damage because of the proximity of several sites to the eruptive vent.

The multi-parameter dataset gathered during the Okmok eruption comprised remarkable satellite images including those collected by the National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES) and the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) sensor; these data provided additional, valuable, information about the onset and temporal evolution of the eruption as well as a tool to help interpret its seismic signature. In Figure 3, we show data from the GOES (Band 4, infrared data) and MODIS (Band 31, infrared data) sensors. These are in the thermal infrared portions of the electromagnetic spectrum and are used to retrieve ash cloud temperatures and altitudes at AVO [Dean et al., 2004; Webley et al., 2009]. The GOES images display a radially growing ash-and-steam cloud moving towards the southeast. The MODIS data suggest plume temperatures as low as $-64^\circ C$, approximately 10°C lower than the surrounding atmosphere. Based on these data, maximum plume heights were estimated to be of the order of about 17 km ASL, using the altitude-temperature method of Kienle and Shaw [1979] and Sparks et al. [1997].

4. Discussion

When the atmosphere is disturbed from mechanical equilibrium by a volcanic blast it reacts in an attempt to adjust back to a balanced state; as a result acoustic-gravity waves may be generated. If the vertical size of an eruption plume is of the order of the density scale height of the atmosphere, $H$, the cloud will rapidly rise, overshooting large amounts of denser air to greater heights. On the other hand, if the linear dimension of the plume is smaller than $H$, it will rise because of buoyancy. As the plume rises and penetrates the stratosphere, atmospheric waves are generated. Their propagation is controlled by either the compressibility of the air or gravity, hence, the terminology acoustic-gravity waves [Tahira et al., 1996]. If the bulk modulus of the atmosphere is large enough, acoustic and gravity modes decouple. For large explosions, such as at Okmok, gravity modes are likely to be observed.

We propose that the seismic data presented in this paper, represent ground-based evidence of atmospheric buoyancy-driven oscillations; GW were triggered by the injection of a vigorous plume in the lower atmosphere above Okmok that was clearly identified in the remote sensing data. The GOES and MODIS satellite sensor data (Figure 3) indicate that the eruption plume reached about 17 km asl in elevation. Fee et al. [2010] reported that the low temperatures measured from the MODIS data suggest that undercooling, expansion by decompression of the plume, and its rise past the neutral buoyancy height occurred [Woods and Self, 1992], consistent with the generation of atmospheric GW. Several mechanisms are suitable to explain the generation of GW including the effects of eruption-generated shock waves as proposed by Lognonné [2009] and Dautermann et al. [2009] at Mt. Pinatubo (1991) and Soufrière Hills Volcano (2003), respectively. The temperature pattern measured from the MODIS data (Figure 3) shows that the outer edge of the atmospheric perturbation front at Okmok
was warmer than the local ambient temperature, consistent with a model of GW generated by a shock wave.

[13] Figure 3 confirms that propagation of a large atmospheric perturbation was initiated at about 22:30 UTC on July 12, 2008 strikingly concomitant to the onset of the strong 1.7 mHz mode observed in the seismic records. We suggest, however, that the 1.7 mHz signal does not reflect propagating ground motion (i.e., seismic waves). For the reasons discussed earlier in this manuscript (the reader may refer to the Introduction section) we argue that effective atmosphere-ground coupling is unlikely to have been achieved.

[14] Our preferred explanation is that the ULP signal represents the effect of changing gravity on the instrument as described, for instance, by Zürn and Wielandt [2007]. When a parcel of air changes its density due to a pressure wave, the gravitational field is affected; perturbations in gravitational acceleration are generated near the Earth’s surface and the mass of the seismometer is subject to changes in Newtonian attraction. Müller and Zürn [1983] proposed a simple model of gravity for a homogeneous atmosphere with density \( \rho \) and finite extent \( H \):

\[
g = 2\pi GH \Delta \rho = 2\pi GH \frac{p m}{RT}
\]

where, \( G \) is the gravitational constant, \( H \) the height where the pressure perturbation \( p \) is accommodated, \( m \) is the mean molecular weight of air, \( T \) the temperature in °K, and \( R \) the specific-gas constant. For values of \( H \) between 10–15 km, \( m = 0.02896 \text{ kg/mol}, T = 288.15 \text{ K}, R = 8.314472 \text{ J/mol K}, \) and \( G = 6.673 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}, \) an atmospheric wave of 1 mbar corresponds to a change in \( g \), sensed by the seismometer, of between 5–8 nm/s². Changes in atmospheric pressure also act as a load on the Earth’s surface causing static displacement and tilts. For well-adjusted seismometers tilt is almost exclusively detected on the horizontal components, as its effect is a change in the projection of the vector of gravity onto the axis of sensitivity of the instrument; properly functioning vertical seismometers should not be affected. Because we did not have clear evidence of large apparent horizontal motions in the Okmok data, we considered tilt negligible and proceeded to investigate the effects of vertical ground displacement. Sorrells [1971] calculated an approximate solution for the near-surface displacement response of a homogeneous and isotropic half space to a slowly propagating atmospheric pressure disturbance:

\[
U = \frac{c_0 P_0 (\lambda + 2\mu)}{2\mu (\lambda + \mu)} \frac{1}{|\omega|} e^{i \omega (t - x/c_0)}
\]

where

\[
P_0, c_0, \lambda, \mu, \omega, \text{ and } x
\]

are the amplitude of the pressure disturbance, \( c_0 \) its speed of propagation, \( \omega \) the frequency of oscillation, and \( \lambda \) and \( \mu \) are the Lamé parameters of the material. This displacement field produces, in the vertical direction, gravity signals smaller and of opposite sign to equation (1). The peak change in gravity associated with the displacement \( U \) (equation (2)) is:

\[
|\Delta g_{\text{max}}| = \left| \frac{d^2 U}{dt^2} \right|_{\text{max}} = \frac{c_0 P_0 \omega (\lambda + 2\mu)}{2\mu (\lambda + \mu)}
\]

Figure 3. (a) NASA MODIS and (b) NOAA GOES-11 satellite imagery data gathered during the July 12, 2008 eruption of Okmok volcano. NASA MODIS data are for thermal infrared imagery and NOAA GOES-11 show visible imagery.
The amplitude of these changes depends strongly on the properties of the material. Approximate calculations assuming rock density of 2600 kg m\(^{-3}\), P- and S-wave velocities of 4 km s\(^{-1}\) and 2.6 km s\(^{-1}\), respectively, and values of \(c_0\) typical of atmospheric gravity waves (up to a few tens of m s\(^{-1}\)), suggest that at frequencies of 1–2 mHz the admittance between pressure and gravity is of the order of 0.1–0.5 nm/s\(^2\)/mbar.

These simple models allow us to estimate the pressure changes from the seismic data. If we consider that the seismogram in a narrow band around 1.7 mHz is dominated by a combination of the effects described above, the theoretical admittance coefficients between pressure and local gravity changes can be used to obtain a simple estimate of the magnitude of the atmospheric pressure perturbation. In Figure 4, we plotted the OKFG seismogram corrected for the acceleration response of the instrument. A notable increase in amplitude coincides with the period of inferred propagation of atmospheric perturbations visible in the satellite data (panels 4, 5, 6). Note that corrections for instrument response and filtering were performed on a 2-day seismogram around the time of the eruption in order to avoid undesired signal distortion.

Due to the lack of local barometric measurements we could not obtain an empirical, frequency dependent, transfer function between atmospheric pressure and ground displacement.

5. Conclusions

We have presented seismic and remote sensing data collected during the initial phases of the 2008 eruption of Okmok volcano. These measurements suggest that the injection of a large eruption plume at elevations of up to 17 km asl associated with the vent-opening phase generated atmospheric gravity waves. The seismic data presented in this paper represent original, ground-based, observational evidence of atmospheric gravity waves generated by an explosive volcanic eruption. Simple modeling of the effects that the propagation of atmospheric perturbations have on seismic instruments allowed us to estimate a peak change in pressure associated with the eruption of about 0.8 mbar, consistent with barometric measurements reported at other volcanoes with eruptions of similar size. Gravity oscillations induced by large volcanic explosions have been the focus of several recent investigations and may open new avenues for...
research into assessing the magnitudes of large eruptions and understanding their direct effects on the atmosphere.

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