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Mechanism of lightning-associated infrasonic pulses from thunderclouds

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[1] It has been pointed by C. T. R. Wilson in 1920 that sudden reduction of the electric field inside a thundercloud immediately following a lightning discharge should produce an infrasound signature. In the present work, a model based on linearized equations of acoustics with classical viscosity and atmospheric gravitational stratification effects is employed to study electrostatic production of 0.1–1-Hz infrasonic waves from thunderclouds, with particular emphasis on the still poorly understood initial compression phase of the observed infrasonic waveforms. It is demonstrated that a growth of charge density in thundercloud prior to lightning discharge on time scales on the order of 2 to 6 s, comparable with typical documented time scales of generation of charge in thunderclouds, leads to formation of a pressure reduction in the thundercloud. This is accompanied by emission of compression waves closely resembling those observed in experiments prior to arrival of a rarefaction pulse generated in accordance with the electrostatic mechanism originally proposed by C. T. R. Wilson and further developed by Dessler in 1973 and Few in 1985. The arguments advanced in the present study agree with the ideas of Bohannon and collaborators formulated in 1977 indicating a rapid intensification of the field prior to the lightning discharge. However, we provide a quantitative demonstration that the intensification does not need to be as fast as 0.5 s proposed by these authors.

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1. Introduction

[2] The infrasonic waves correspond to the region of frequencies of acoustic sound waves 0.02–10 Hz, higher than the acoustic cutoff frequency but lower than the audible frequencies [e.g., *Blanc*, 1985]. The attenuation of infrasonic waves is proportional to the square of frequency and these waves can propagate thousands of kilometers through the tropospheric, stratospheric, mesospheric and lower thermospheric regions, exhibiting global propagation characteristics [e.g., *Drob et al.*, 2003]. There is a wide variety of natural and man-made sources which produce infrasonic waves. Natural sources include earthquakes, volcanic eruptions, auroras, meteorological activity, meteors and several others [e.g., *Blanc*, 1985; *Bedard and Georges*, 2000; *Bedard*, 2005; *ReVelle*, 2008]. There is a strong experimental evidence that thunderstorms represent significant sources of infrasonic wave activity spanning a broad altitude range from the troposphere and up to the thermosphere [e.g., *Blanc*, 1985; *Few*, 1995; *Drob et al.*, 2003]. This evidence includes electrostatic production of 0.1–1-Hz infrasonic waves from thunderclouds [*Few*, 1995] and recent discovery of infrasound correlated with lightning induced transient luminous events in the mesosphere called sprites [*Liszka*, 2004; *Farges et al.*, 2005; *Liszka and Hobara*, 2006]. The infrasonic signals carry important information about these and other sources and correct modeling interpretation of observations represents an important task for better understanding of their dynamical features and energetics. The understanding and classification of different infrasonic waves and their sources is also of great current interest from a Comprehensive Nuclear-Test-Ban Treaty (CTBT) verification perspective [e.g., *Assink et al.*, 2008]. The present paper focuses on electrostatic mechanism of production of infrasonic pulses from thunderstorms predicted by C.T.R. Wilson [*Wilson*, 1920] (see discussion below).

[3] The mechanism of a compression wave created by a hot radially expanding lightning channel is well understood [*Few*, 1995 and references therein]. It is believed that the thermal expansion due to the sudden heating of the air in the lightning channel leads to the shock wave and is responsible for the audible part of the thunder spectrum. It has been pointed many decades ago by *Wilson* [1920] that sudden reduction of the electric field inside a thundercloud immediately following a lightning discharge should produce a low-frequency acoustic (i.e., infrasound) signature. *Wilson* [1920] noted that the pressure within a charged cloud must be less than the pressure outside, similarly to that within a charged soap bubble. In contrast to the sudden expansion of the air along the track of a lightning flash, the sudden contraction of

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a large volume of air must furnish a by no means negligible contribution to the thunder [*Wilson*, 1920]. Many experimental and theoretical contributions followed these predictions by C. T. R. Wilson. These contributions are reviewed below. The processes leading to observed infrasound pulses still have not been fully understood and quantified.

[4] *Holmes et al.* [1971] have analyzed forty thunder events from intracloud (IC) and cloud-to-ground (CG) lightning. It was found that the mechanism of thunder production by a thermally driven expanding channel as suggested by *Few et al.* [1967] and *Few* [1968, 1969] appears to account for the dominant frequencies observed from many CG flashes, but cannot explain the high-energy low-frequency peaks of some CG and most IC discharges. It was suggested that the electrostatic mechanism proposed by C. T. R. Wilson [*Wilson*, 1920] is responsible for the large energy peaks at frequencies <10 Hz. In case of this mechanism a lightning discharge will produce a negative pressure change in contrast to the positive pressure change predicted by the expanding channel mechanism [*Holmes et al.*, 1971].

[5] The electrostatic mechanism suggested by *Wilson* [1920] has been applied to a model of a thundercloud with different geometries by *Dessler* [1973]. It was demonstrated that the mutual repulsion of the charged water droplets causes the atmospheric pressure to be reduced within the charged regions of the cloud, and an acoustic rarefaction pulse is generated following a lightning discharge as atmospheric pressure equilibrium tends to be restored in the region from which charge is removed. The author noted that in case of horizontally extended charge region the signal should be best observed by detectors placed directly below or above the cloud due to a beaming effect. The signal amplitude was estimated to be $0.5-50 \times 10^{-6}$ atm (0.05–0.5 Pa) with the spectral peak in the infrasound range of 0.2–2 Hz, and it was suggested that the beamed infrasound signal can reach the ionosphere with negligible attenuation and lead to a detectable interaction [*Dessler*, 1973].

[6] Infrasonic pulses with periods of about 0.5 s and amplitudes of about 0.1 N/m^2 (0.1 Pa), which were superposed on the thunder signals had been reported by *Bohannon et al.* [1977]. The pulse waveform was characterized by an initial compression followed by a rarefaction and the authors argued that these pulses were not generated by lightning channel heating. The acoustic source reconstruction placed the origins of these pulses in the cloud within the same volume of space as the horizontal portions of the lightning channels (i.e., presumably in the volume of charge regions through which lightning events propagated). The small delay of the infrasonic event detected by four spatially separated microphones indicated that its origin is in the cloud directly over the array [*Bohannon et al.*, 1977]. We note that appearance of the initial compression in the observed signatures (see Figure 1a for illustration, and further discussion below) is recognized in the existing literature as one of the difficult points in direct application of the C. T. R. Wilson electrostatic mechanism for explanation of observations. These compression pulses have appeared as a feature in many experiments, which followed the work by *Bohannon et al.* [1977]. It was suggested by *Bohannon et al.* [1977] that a rapid (0.5 s) intensification of the thundercloud field prior to the lightning discharge may be responsible for the initial compression part of the observed waveforms.

[7] The infrasonic signals from thunder, which are dominated by sharp rarefaction pulses with periods in the range of 0.4–1.0 s and peak-to-peak amplitude up to 1 Pa were reported by *Balachandran* [1979]. A low-amplitude compressional wave at the beginning of the signal was also observed. The author noted that the signals were highly directional traveling almost vertically downward. Figure 1a provides a model based depiction of a typical morphology of infrasonic pulses observed experimentally. The rarefaction part of the pulses is in agreement with the electrostatic theory advanced by *Wilson* [1920] and *Dessler* [1973] as discussed above. *Balachandran* [1979] provides an important discussion putting the observed pulses in the context of previous observations of infrasound signals from thunderstorms [e.g., *Georges*, 1973 and references therein]. *Balachandran* [1979] emphasizes, in particular, that the signals similar to the one illustrated in Figure 1a have impulsive and intermittent nature, leading to an important conclusion that they have electrical mechanism most likely linked to lightning discharges as the source. *Balachandran* [1979] placed the observed pulses in the same group as was previously reported by *Bowman and Bedard* [1971], and as distinguished by periods of about one second and accompanied by audible thunder. *Georges* [1973] provided extensive discussion of characteristics of infrasound waves produced by convective storms. It was noted that some infrasonic pressure perturbations observed on the ground have remarkable correlation with wavelike fluctuations in ionospheric phase height recorded by ground-based radio sounders. In one observation discussed by *Georges* [1973] the 20 min pulsation was linked to 15–20 min interval between successive emergences of individual cumulus towers in multicellular storms suggesting that the observed pulsations were produced by sequential radiation from individual convective cells within a storm complex. We note that in this case the periods of the waves fall in the gravity wave domain [e.g., *Snively and Pasko*, 2003] and are substantially longer than periods of the pulses discussed by *Balachandran* [1979].

[8] *Balachandran* [1983] further substantiated the arguments advanced by *Balachandran* [1979] by providing data on simultaneous electric field and infrasound measurements. It was shown also that 1-Hz infrasound pulses were associated with the collapse of the electrostatic field in the thundercloud. It was shown that for a distant thunderstorm, when infrasound signals from thunder arrive horizontally to the observation point, no low-frequency signals were present. As the thundercloud apparently moved overhead, low-frequency signals began to appear [*Balachandran*, 1983], consistent with theoretical predictions of *Dessler* [1973] suggesting a highly directional radiation source. The observed pulses had a compressional phase at the beginning followed by the main rarefaction phase [*Balachandran*, 1983]. *Balachandran* [1983] discusses a possible mechanism for the compression phase citing a conference presentation by *Bohannon and Dessler* [1980] (see also *Bohannon and Dessler* [1983]). *Bohannon and Dessler* [1980, 1983] indicated that pressure should increase between the lower positive charge and dominant negative (upper) charge in a thundercloud prior to the lightning discharge. Immediately after the lightning discharge this compression should result in the observed compression wave. We note, however, that

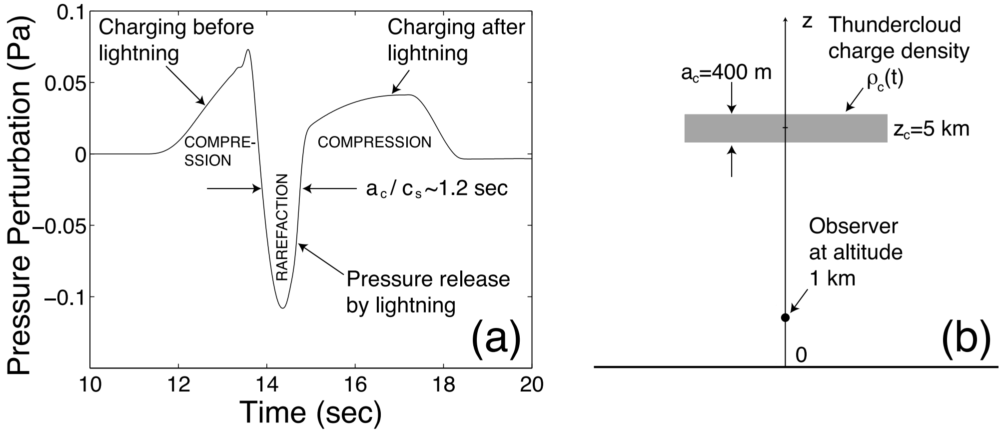

Figure 1. (a) A model depiction of a typical morphology of infrasonic pulses observed experimentally [e.g., *Balachandran*, 1979], including initial compression pulse (i.e., positive pressure perturbation) followed by rarefaction and again compression pulses. (b) One-dimensional system of coordinates used to model infrasonic pulses radiated by time variations of thundercloud charge density $\rho_c(t)$ uniformly distributed in a narrow layer with width a_c = 400 m at altitude z_c = 5 km.

in accordance with the same theory the discharge of the lower positive charge region should always lead to the leading rarefaction pulse, which is not usually observed.

[9] It should be emphasized that the discussed process of electrostatic generation of infrasound should not be understood as a robust ubiquitous process, but as one that has been observed and we point out that a great variety of waveforms can occur. *Bowman and Bedard* [1971] summarize the results from 10 years of continuous operation of an infrasonic network. The instrumentation used responded to signals below 1 Hz. The severe weather related infrasonic energy detected was typically below 0.1 Hz [e.g., *Bowman and Bedard*, 1971, their Figure 18]. There was a gap in severe weather related signals between 0.1 and 1 Hz. *Beasley et al.* [1976] compared severe weather related infrasound data from this network with lightning activity. They concluded that electrical activity was not the source of the infrasound. It is probable that the release of heat by changes of state within storms is the source of this class of infrasound [e.g., *Nicholls et al.*, 1991; *Nicholls and Pielke*, 1994a, 1994b, 2000; *Pielke et al.*, 1993].

[10] The compression phase followed by the rarefaction phase has been observed as a repeatable and relatively large magnitude feature in several experiments. The infrequency of observed phenomenon may be related to the need of relatively quiet wind conditions [e.g., *Bohannon et al.*, 1977; *Balachandran*, 1979]. In particular, the observations reported by *Bohannon et al.* [1977] occurred during a quiet interval of approximately 20 min, when thunderstorm was passing overhead and when the interference due to the wind noise was negligible. *Balachandran* [1979] indicates detection of only 10 cases of electrostatically produced infrasonic signals over 5 years of observations, emphasizing that signals were detected during calm periods characterized by wind speeds less than 7 m/s. As will be further discussed in the next section, the body force on air responsible for creation of electrostatically produced infrasonic pulses is a strong (quadratic) function of charge density. This aspect also may contribute to detectability of the infrasonic signals, indicating a predominance of relatively low charge densities, producing signatures below the detection threshold.

[11] *Few* [1985] further discusses the apparent discrepancy between observations and the theory of *Wilson* [1920] and *Dessler* [1973], which predicts that the electrostatic acoustic signal is a negative pressure pulse followed (perhaps) by a positive pulse. Contrary to this prediction the reported measurements, including those reviewed above in this paper, begin with a positive pressure pulse followed by a negative pulse, which is itself frequently followed by another positive pulse. *Few* [1985] proposed a solution of this problem by modifying the basic electrostatic theory by including consideration of the diabatic heating of the air in the discharge volume that must occur when positive streamers propagate through the volume. This heating creates a positive pressure change in the same volume of the negative electrostatic pressure. The author further showed that at some distance near the edge of the discharged volume the positive pressure that is produced by the streamer heating must exceed the negative pressure due to electrostatic forces leading to a proper geometric relationship needed to produce an infrasonic wave with a leading positive pressure pulse followed by a larger negative pressure pulse [*Few*, 1985, 1995]. The theory advanced by *Few* assumes that a portion of electrostatic energy comparable to the total electrostatic energy in thundercloud is deposited as heat in a large air volume. The fraction of electrostatic energy deposited as heat is postulated. *Few* [1985] notes that the proposed theory does not provide duration of the positive pulse, and that there is a definite need in development of quantitative computer models providing pressure perturbation solutions that can be compared with measurements. Modeling investigation of related scenarios leading to emission of infrasound pulses documented in the existing literature, with particular emphasis on the initial compression phase, represents a goal of the present paper.

2. Model Formulation

[12] The model employed in the present study utilizes linearized equations of acoustics with classical viscosity and

atmospheric gravitational stratification effects to solve for perturbations in density ρ', pressure p' and velocity $\vec{v}$.

$$\frac{\partial \rho'}{\partial t} + \vec{\nabla}\cdot\rho\vec{v} = 0 \tag{1}$$

$$\frac{\partial \rho\vec{v}}{\partial t} + \vec{\nabla}p' = \vec{F} - \rho'\vec{g} + \mu\left(\nabla^2\vec{v} + \frac{1}{3}\vec{\nabla}\left(\vec{\nabla}\cdot\vec{v}\right)\right) \tag{2}$$

$$\frac{\partial p'}{\partial t} + \vec{\nabla}\cdot c_s^2\rho\vec{v} = -\rho g v_z(\gamma - 1) \tag{3}$$

where $\vec{F}$ in N/m^3 is a model body force acting on a unit volume of air, and all other notations are standard. The linearized versions of the momentum (2) and energy (3) conservation equations, in particular, are obtained by assuming in the original nonlinear equations [e.g., *Hines*, 1960; *Snively and Pasko*, 2008] that the quadratic in velocity perturbation term $\rho\vec{v}\vec{v}$ can be neglected in comparison with the pressure term p, and by introducing the speed of sound $c_s = \sqrt{\gamma p/\rho}$. The assumption of smallness of $\rho\vec{v}\vec{v}$ is always valid for small velocity perturbations, which remain much lower than the speed of sound $v \ll c_s$.

[13] The body force $\vec{F}$ in momentum conservation equation (2) is specified as a given function of time and coordinates. For electrostatic production of infrasonic waves from thunderstorms the force can be represented in the form $\vec{F} = \rho_c\vec{E}$, where ρ_c is thundercloud charge density and $\vec{E}$ is the electric field [e.g., *Few*, 1985]. The physical nature of the force can be best understood in terms of momentum transfer collisions between charged species drifting with velocity $\vec{v}_s$ under influence of applied electric field $\vec{E}$ and neutral air molecules [e.g., *Boeuf et al.*, 2008 and references therein]. If charged species of type s have density n_s and mass m_s, the total force acting on a unit volume of air is

$$\vec{F} = \sum_s n_s m_s \nu_{\rm sm}\vec{v}_s \tag{4}$$

where $\nu_{\rm sm}$ are momentum transfer collision frequencies between charged species of type s and neutral air molecules. We note that $\vec{v}_s = \mu_s\vec{E}$, where the mobilities μ_s are defined as $\mu_s = q_s/(m_s\nu_{\rm sm})$. The charges q_s carry information about sign of charged species of different types (i.e., q_s is positive for positive ions and negative for negative ions and electrons). Having substituted the above expressions for velocity and mobility in equation (4) we obtain $\vec{F} = \rho_c\vec{E}$, where $\rho_c = \sum_s q_s n_s$. The force depends only on the net charge density ρ_c and does not depend on specifics or number of different types of ions creating ρ_c. The physical nature of the force acting on air in the thundercloud situation is the same as in plasma actuators actively investigated in recent years for purposes of aerodynamic flow control [*Boeuf et al.*, 2008].

[14] The model utilized in the present study is one-dimensional with z axis pointing vertically as illustrated in Figure 1b. The spatially homogeneous charge density ρ_c is confined inside of a layer with vertical dimension a_c = 400 m centered at altitude z_c = 5 km. The chosen vertical extent is consistent with typical values of several hundred meters used in previous publications to explain durations of experimentally observed infrasonic pulses, and these pulses can in principle be used to evaluate extents of charge regions producing them [e.g., *Holmes et al.*, 1971; *Dessler*, 1973; *Few*, 1985]. In model calculations the charge density ρ_c is assumed to be a function of time reflecting different scenarios of charge accumulation and removal in thunderclouds, as depicted in Figures 2 (left) and 3 (left) and further discussed in the next section. The peak value of charge density in Figures 2 and 3 is 20 nC m^{-3}. Depending on particular model scenario only a fraction of this charge density is removed by lightning. We note that representative maximum charge densities reported in literature do not exceed 15 nC m^{-3} [*Colgate and Romero*, 1970] or 6.7 nC m^{-3} [*Marshall and Stolzenburg*, 1998], and that previous studies on the electrostatic production of infrasound employed values 2–5 nC m^{-3} [*Dessler*, 1973; *Few*, 1985]. An important aspect of the electrostatic mechanism is that the magnitude of the produced infrasonic pulses is a quadratic function of charge density. The quantitative results presented in the next section indicate that maximum peak-to-peak magnitude of pressure perturbation produced by the 20 nC m^{-3} density is ~0.8 Pa, while for a factor of two lower values of 10 nC m^{-3} the magnitude drops by a factor of four to ~0.2 Pa. As discussed in the introduction section, the relatively low charge densities typically observed in thunderclouds [e.g., *Marshall and Stolzenburg*, 1998] may be partly responsible for relatively rare detections of electrostatically produced infrasonic pulses. In the chosen model geometry the electric field has only z (i.e., vertical) component and inside of the charge layer can be written as $E_z = \rho_c(z - z_c)/\varepsilon_0$, where ε_0 is the permittivity of free space. We note that with the chosen a_c value and the peak charge density, the peak electric field magnitude is $E_{z\max} = 4.5 \times 10^5$ V/m, which is a factor of 3.8 lower than the conventional breakdown field $E_k = 17 \times 10^5$ V/m at 5 km altitude (this field is assumed to be $E_k = 31 \times 10^5$ V/m at ground level and to scale proportionally to air density at higher altitudes [e.g., *Pasko*, 2006, and references therein]).

[15] We note that in the present work the single layer of time-dependent homogeneous charge density with vertical dimension a_c = 400 m provides modeling representation of the simplest possible geometry for modeling of charge accumulation and removal in thundercloud due to lightning discharge. Depending on type of thunderstorms and a particular region inside of the thunderstorm (i.e., within or outside convective updrafts) four or six charge layers are usually observed [e.g., *Stolzenburg et al.*, 1998; *MacGorman and Rust*, 1998 and references therein]. The model charge layer serves to represent charge removal by a lightning discharge. This charge layer may be associated with either cloud-to-ground (CG) or intracloud (IC) lightning discharge, with modeled infrasonic radiation effects not sensitive to other charge layers, which may be present in the thundercloud during the modeled time interval. The experimentally observed trains of infrasonic pulses have rather complex structure, likely reflecting the multiplicity of charge layers discharged by lightning. However, the compression/rarefaction sequences with very similar morphology have been repeatedly observed in experiments and

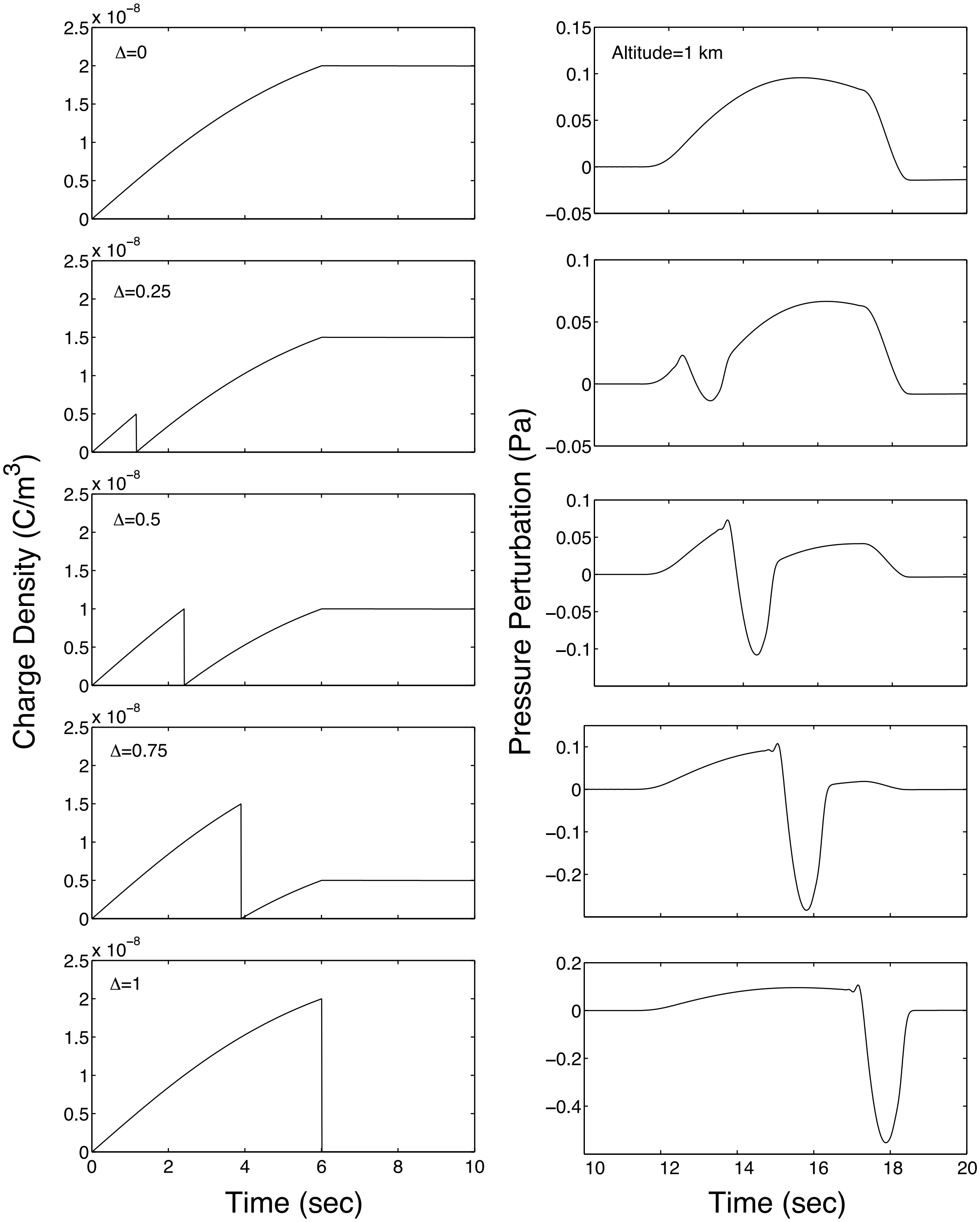

Figure 2. (left) Time dynamics of charge density $\rho_c(t)$ used to model different scenarios of accumulation and removal of thundercloud charge. (right) Corresponding pressure perturbation waveforms detected by a model observer positioned 4 km below the source charge (see Figure 1b).

the goal of the present work is to demonstrate that charge accumulation and removal in the simplest possible one-layer geometry is sufficient for explanation of this morphology.

[16] The simulation domain extends 5 km above and 5 km below the charge center (i.e., has 10 km total extent in altitude, see Figure 4) with boundary conditions supporting outgoing acoustic waves with no reflections. The pressure perturbation is monitored by an observer positioned 4 km below the charge center as depicted in Figure 1b. Results of the present study are not sensitive to a particular position of the observer. We ignore contributions of image charges in the

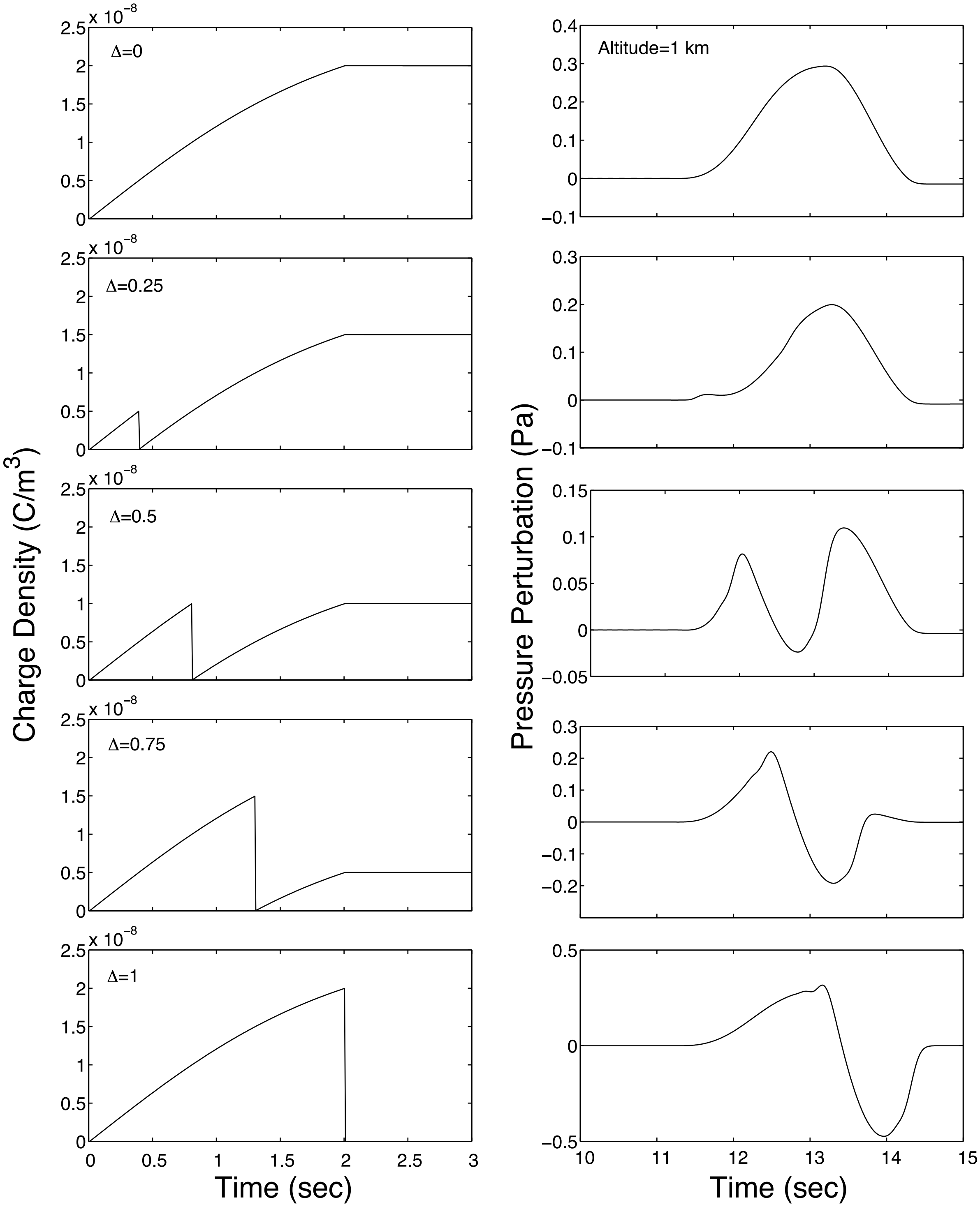

Figure 3. Same as Figure 2 only charge density $\rho_c(t)$ is assumed to grow on a time scale three times shorter than that in Figure 2.

ground and in the ionosphere to electric field inside of the source charge at 5 km altitude. This assumption is valid only if the horizontal extent of the charge layer is small in comparison with its distances to the ground and ionospheric planes. The one-dimensional acoustic wave propagation model does not account for geometric reduction of the infrasonic signal magnitude due to the finite dimension of the source (i.e., as signal propagates to distances exceeding the horizontal source dimension). However, related inaccuracies do not affect the polarity and shapes of the modeled pulses, and therefore do not affect the principal conclusions of the present work. For a relatively narrow altitude range considered in the present study the atmosphere is assumed to be isothermal. In a real atmosphere with a lapse rate of ~6 K/

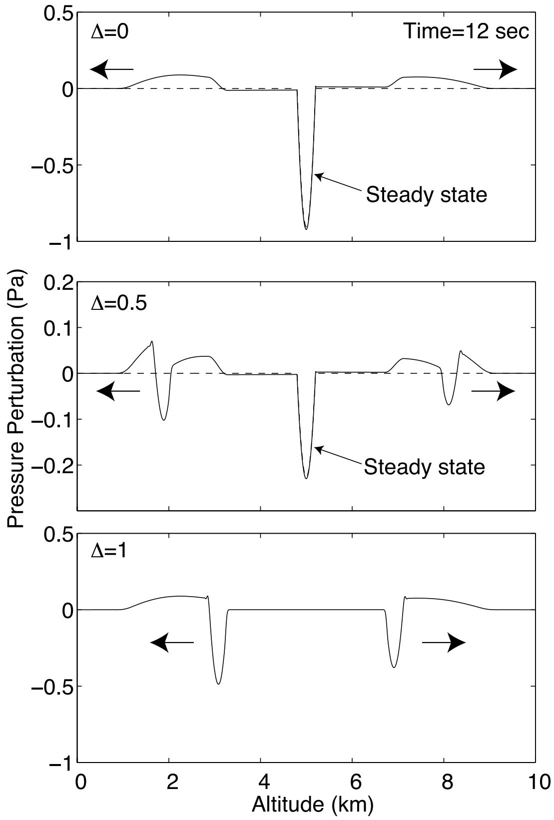

Figure 4. Spatial distribution of pressure perturbation at time instant t = 12 s corresponding to three selected cases (Δ = 0, 0.5, and 1) shown in Figure 2.

km there is a $\sim$2 K temperature difference from top to bottom of the charge layer with width 400 m. In terms of present modeling the isothermal assumption primarily leads to errors in speed of sound propagation on the order of 10% and does not affect principal conclusions of the present work. The vertical temperature profile is critical for quasi-horizontal propagation and ducting of acoustic-gravity waves [e.g., *Snively and Pasko*, 2008]. These effects, however, do not have direct relevance to the present study and are not reproduced by the one-dimensional model.

[17] The ground values of pressure and air mass density are $p_0 = 10^5$ Pa and $\rho_0 = 1.225$ kg m^{-3}. For isothermal atmosphere these values scale exponentially with altitude z as $p(z) = p_0 \exp(-z/H)$ and $\rho(z) = \rho_0 \exp(-z/H)$, where the scale height $H = c_s^2/(g\gamma)$ = 8.3 km, $c_s = \sqrt{\gamma p/\rho}$ = 338 m/s is speed of sound, γ = 1.4 is the ratio of specific heats, and g = 9.8 m s^{-2} is acceleration of gravity. For the specified parameters the acoustic cutoff frequency is $\omega_o = g\gamma/(2c_s)$ = 0.02029 rad s^{-1} and Brunt-Vaisala frequency is $\omega_N = g\sqrt{\gamma - 1}/c_s$ = 0.018334 rad/s. The viscosity μ in equation (2) is assumed to have a value $\mu = 1.8 \times 10^{-5}$ kg m^{-1} s^{-1} [e.g., *Sutherland and Bass*, 2004]. For the frequency (0.1–1 Hz) and altitude (0–10 km) ranges considered in the present work the effects of viscosity are negligible [*Sutherland and Bass*, 2004]. The equations (1)–(3) are solved using a numerical scheme (fourth order in space and second order in time) [*Gottlieb and Turkel*, 1976; *Turkel*, 1980; *Maestrello et al.*, 1981; *Sparrow and Raspet*, 1991]. We note that adopted modeling technique has been originally developed for nonlinear spark pulse problems and is fully adequate for the linear solutions considered in the present work.

3. Results and Discussion

[18] *Wilson* [1920] emphasizes importance of electric field recovery curves immediately following a lightning discharge for assessment of rates of charge buildup in thunderclouds. Under quasi-steady conditions when a limit of the charge density and corresponding electric field intensity needed for lightning initiation is not reached, the generation of charge is exactly compensated by charge losses (i.e., conduction and through ionization currents). This balance should be violated right before the lightning discharge when rate of charge production is increased. The recovery times reported by *Wilson* [1920] correspond to the times which would have been required to recharge the cloud to the lightning production limit had there been no neutralizing process (i.e., increase in conductivity) due to the action of electric field of the cloud. The measurements reported by *Wilson* [1920] indicate times ranging from 1.5 to 30 s with average 6.9 s for 64 measurements. These charging times are in general agreement with a large amount of data accumulated in the existing literature on ground based [e.g., *Jacobson and Krider*, 1976; *Livingston and Krider*, 1978; *Deaver and Krider*, 1991] and airplane based [e.g., *Blakeslee et al.*, 1989] electric field measurements in the vicinity of thunderstorms. In the present work we demonstrate that a simple growth of charge density in thundercloud prior to lightning discharge on time scales on the order of 2 to 6 s, comparable to typical documented time scales of generation of charge in thunderclouds, is fully sufficient for explanation of the initial compression waves in observed infrasonic pulses generated in accordance with the electrostatic mechanism proposed by *Wilson* [1920] and *Dessler* [1973] and reviewed in the previous section. The arguments advanced below agree with the ideas by *Bohannon et al.* [1977] indicating a rapid intensification of the field prior to the lightning discharge. However, we provide a quantitative demonstration that the intensification does not need to be as fast as 0.5 s proposed by *Bohannon et al.* [1977].

[19] Figures 2 (left) and 3 (left) illustrate different model time dynamics of thundercloud charge density employed in the present study. The difference between Figures 2 and 3 is primarily in the time scale of charge growth (6 s in Figure 2 and 2 s in Figure 3). We introduce the parameter Δ to characterize a fraction of charge removed by lightning. Figures 2 (top) and 3 (top) (marked as Δ = 0) represent a simple episode of charge growth in thundercloud on time scales 6 s (Figure 2) and 2 s (Figure 3), when the growth is not interrupted by a charge removal by lightning. The growth of charge density ρ_c leads to increase in electric field E_z and the resultant body force $F_z = \rho_c^2(z - z_c)/\varepsilon_0$ acting on air. The body force is zero in the middle of the charge layer at $z = z_c$, maximized on the charge layer boundaries, and becomes zero immediately outside the charge layer. The force points upward for $z > z_c$ and downward for $z < z_c$. The application of the force leads to redistribution of pressure inside of the charge layer. Under application of a constant force a steady state solution for pressure is established on a time scale of speed of sound propagation through the physical dimension of the charge

layer, i.e., on time scale $\tau_s = a_c/c_s = 1.2$ s. An analytical expression for steady state solution for pressure perturbation can be obtained if we ignore effects of gravity in equation (2), which in this case can be written as $dp'/dz = F_z$ and easily integrated leading to

$$p'(z) = \frac{\rho_c^2}{2\varepsilon_0}\left[(z - z_c)^2 - \frac{a_c^2}{4}\right] \tag{5}$$

The solution (5) is valid in the region of application of body force $z_c - a_c/2 < z < z_c + a_c/2$. Figure 4 (top) shows spatial distribution of pressure at time $t = 12$ s ($\gg\tau_s$) for the case of charge growth shown in Figure 2 (top left). The steady state solution given by equation (5) is shown in Figure 4 (top) by a dashed line and agrees well with the exact numerical solution. The 6 s time episode of charge growth results in launching of two compression pulses propagating upward and downward from thundercloud with speed c_s as shown in Figure 4. An observer positioned 4 km below the charge layer detects a positive pressure perturbation waveform documented in Figure 2 (top right). The appearance of the compression pulses in this system is virtually unavoidable from the point of view of fundamental conservation of mass and momentum in standard equations of acoustics. However, these compression pulses have not been quantitatively described in previous studies on the subject of electrostatic production of infrasonic waves from thunderclouds [*Few*, 1995 and references therein]. In Figure 3 (top right) the pulse duration is 2 s, reflecting the duration of the charge growth interval in this case (the related spatial distributions are not shown for the sake of brevity). A slight asymmetry between upward and downward propagating pulses in Figure 4 is due to scaling of pressure perturbation with altitude $p' \sim \sqrt{\rho}$ (i.e., due to gravitational stratification effects).

[20] The first scenario discussed above does not include any sudden changes in charge dynamics due to lightning. The remaining scenarios in Figures 2, 3, and 4 illustrate effects of sharp interruption of the charge growth episode due to the removal of different fractions of charge Δ. The $\Delta = 0.25$, for example, corresponds to a case when lightning is triggered after charge density reaches 25% of its maximum value with respect to the unperturbed $\Delta = 0$ case. After the charge removal the system continues to charge with the same rate, but reaches a lower maximum value reflecting charge lost due to lightning (i.e., reaches 0.75×20 nC m^{-3} for the $\Delta = 0.25$ case). The case $\Delta = 1$ corresponds to a situation when cloud fully charges and then all charge is instantaneously removed by lightning at $t = 6$ s in Figure 2 and at $t = 2$ s in Figure 3. The real thundercloud scenarios probably involve some continuation of charging after lightning and fall between $\Delta = 0$ (no lightning) and $\Delta = 1$ (full removal of charge by lightning) cases. The results for sequence $\Delta = 0$, 0.25, 0.5, 0.75 and 1 shown in Figures 2 and 3 illustrate related waveforms as seen by an observer positioned 4 km below the model thundercloud. The sudden removal of charge by lightning leads to reduction (or full removal for case $\Delta = 1$) of the body force acting on air in thundercloud volume and release of two rarefaction pulses traveling in opposite direction and having shapes closely resembling the steady state solution (5) preceding the lightning discharge. These rarefaction pulses represent the essence of the predictions advanced by *Wilson* [1920], as discussed in the introduction section of the present paper. The case $\Delta = 1$ produces pulses with leading compression phase followed by a rarefaction phase and with no trailing compression phase (see Figures 2, 3 and 4). Any continuation of charging after lightning (i.e., for $\Delta = 0.25$, 0.5, 0.75 cases) leads to a trailing compression pulse with magnitude directly related to amount of charge generated after lightning as illustrated in Figures 2, 3 and 4. The physical nature of the trailing compression pulse is the same as that for the leading compression pulse.

[21] In modeling of charge removal by lightning we ignore the fact that charge is usually removed by multiple strokes [*Rakov and Uman*, 2003, p. 112]. In practical calculations we assumed that the removal event is fully completed in a very short time interval of 1 ms. The results of the acoustic model calculations are not sensitive to particular dynamics (i.e., multistroke structure) of the charge removal as soon as it proceeds on time scales substantially less than the speed of sound propagation time through the layer $a_c/c_s = 1.2$ s.

[22] Comparison of cases $\Delta = 0$ and 1 in Figures 2 and 3 indicates that the three times increase in rate of charging leads to an equal increase in magnitude of compression pulse. However, the rarefaction pulse magnitude is defined by the steady state conditions before lightning and remains identical for both rise times in cases when steady state solutions before commencement of lightning are fully established. In this respect the cases $\Delta = 0.25$ and 0.5 in Figure 3 illustrate a very important limiting regime when charging time before lightning is less than the speed of sound travel time through region with physical dimension a_c, $\tau_s = a_c/c_s = 1.2$ s needed for establishment of steady state solution for pressure. This leads to reduction in magnitude of the resulting rarefaction pulse as observed in the corresponding scenarios of Figure 3.

[23] The steady state solution for pressure shown in Figure 4 for the case $\Delta = 0.5$ is also well described by analytical solution (5). The steady state magnitude in this case is reduced by a factor of four in comparison with $\Delta = 0$ case, reflecting a factor of two reduction in charge density and a quadratic dependence of pressure given by (5) on charge density.

[24] Given the fact that charging in storms may be as short as 0.2 s [*Mazur*, 1982] or as long as 1 minute, as reported in winter thunderstorms in Japan [*Kitagawa and Michimoto*, 1994], Figure 5 illustrates model calculations for the $\Delta = 1$ case for charging times 0.2, 2, 6 and 12 s. For the case of 0.2 s ($<a_c/c_s$) charging the steady state solution is not established leading to significant reduction in magnitude of the observed pulse (see Figure 5b). An impulsive application of body force in this case leads to generation of a symmetric *N*-shaped pulse with relatively low magnitude. Figure 5b illustrates that for charging times $>a_c/c_s$ the steady state solution is fully established and the rarefaction part of the model waveform becomes essentially independent on the charging time. We note that this part of the waveform directly carries information about spatial extent of the charge region. Figure 5b further demonstrates that the leading compressional phase of the waveforms is a strong function of the charging time, with longer charging times radiating lower pressure levels. This part of the waveform therefore

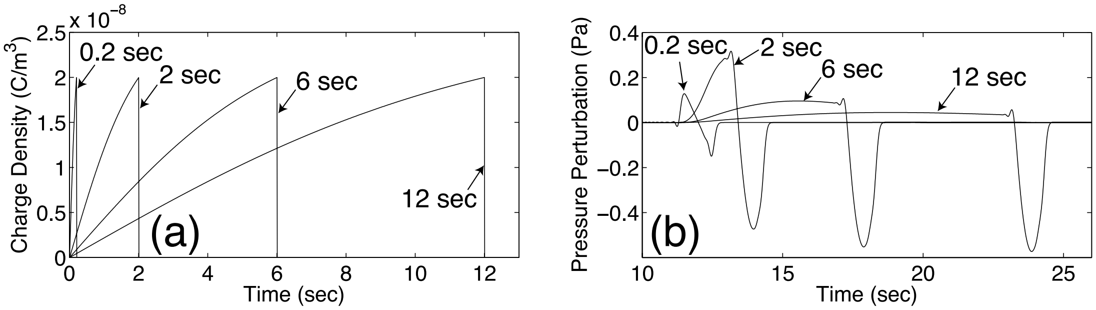

Figure 5. Dependence of the magnitude of the initial compression pulses on a time scale of thundercloud charging for the case $\Delta = 1$. (a) Model time dynamics of thundercloud charge density $\rho_c(t)$ for different time scales of accumulation of thundercloud charge. (b) The corresponding pressure perturbation waveforms observed at 4 km altitude.

can potentially be used for remote sensing of charging times in thunderstorms prior to lightning discharges.

[25] The model pulse corresponding to $\Delta = 0.5$ in Figures 2 and 4 is reproduced in Figure 1a and is used to summarize factors leading to formation of different features of the infrasonic waveform. A reasonable assumption that a lightning discharge should be preceded by an intensification of charge in thundercloud leads to the formation of the initial compression pulse. The removal of charge from thundercloud leads to the rarefaction pulse with duration a_c/c_s defined mostly by the width a_c of the charge layer discharged by lightning. The continuation of thundercloud charging after lightning leads to the trailing compression pulse. We note that the model waveform shown in Figure 1a closely resembles morphology of many infrasonic pulses observed experimentally [e.g., *Balachandran*, 1979].

4. Conclusions

[26] The principal results and contributions, which follow from studies presented in this paper, can be summarized as follows:

[27] 1. Development of a model based on linearized equations of acoustics with classical viscosity and atmospheric gravitational stratification effects allowing quantitative first principles studies of electrostatic production of 0.1–1-Hz infrasonic waves from thunderclouds.

[28] 2. Modeling confirmation of rarefaction pulses generated in accordance with the electrostatic mechanism originally proposed by *Wilson* [1920] and further developed by *Dessler* [1973] and *Few* [1985].

[29] 3. Identification of the growth of charge density in thundercloud prior to lightning discharge on time scales on the order of 2 to 6 s as a simple mechanism leading to emission of compression waves closely resembling those observed in experiments prior to arrival of relatively well understood rarefaction pulses.

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