Infrared glow above thunderstorms?

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Abstract. Sustained heating of lower ionospheric elec-
trons by thundercloud fields, as recently suggested by Inan
et al. [1996], may lead to the production of enhanced
infrared (IR) emissions, in particular 4.3-μm CO₂ emis-
sion. The excitation rate for N₂(v) via electron colli-
sions is calculated using a new steady-state two-di-
agonal electrostatic heating (ESH) model of the upward coupling of
the thundercloud (1He) electric fields. The vibrational en-
ergy transfer to CO₂ and 4.3-μm radiative transfer are then
computed using a line-by-line non-LTE (non-local thermo-
dynamic equilibrium) radiation model. Linb-viewing radia-
tion profiles at 4.3-μm and typical radiation spectra are
estimated for five different TC charge distributions and au-
enticating ion conductivities. Broadband 4.3-μm emissions
of greater than a factor of two above ambient nighttime
levels are predicted for tangent heights (TH) in the range ~80
to ~130 km for the most perturbed case, with larger en-
hancements in selected narrower spectral regions. The pre-
dicted IR enhancements should be observable to an orbiting
IR sensor.

Introduction

Thundersheds are thought to be the batteries for the
global electric circuit [Hays and Roble, 1979; Roble, 1991].
Intense quasi-electrostatic (QE) TC fields which exist during
brief (~10 ms) periods following lightning discharges are
now believed to heat the free electrons at 50-90 km alti-
itude, leading to the production of new molecular excitation
and optical emissions (spires) [Pasko et al., 1997]. In
addition to the visible and near-IR emission from short-lived
states, notably N₂ first-positive emission [Mende et al., 1995;
Hampton et al., 1996], which are efficiently produced by
the transient QE heating, the possibility also exists to generate
IR roration emissions, such as the 4.3-μm νς hands of
CO₂ or the 5.3-μm fundamental and the 2.7-μm overtone
bands of NO [Whalen et al., 1985]. However, the long life-
times of the IR radiating states (~ 0.1 s) compared to the
duration of the transient QE fields makes QE heating rela-
tively ineffective in producing IR emissions.

On the other hand, it has recently been realized that,
even under the quasi-steady conditions between lightning
discharges, TC fields can maintain the ionospheric electrons
in a heated state [Inan et al., 1995]. Although the quies-
cent fields penetrating to ionospheric altitudes are rela-
tively smaller than the transient fields which produce spires,
they are nevertheless believed to heat electrons significantly
[Pasko et al., 1996]. In this paper, we consider one of the possible consequences of such steady and sustained heating,
命名ly the steady-state excitation of IR emissions.

The coupled heating of transient and quasi-steady
at 70-90 km altitude, it is necessary to model self-consistently the penetration of TC electric fields E to the upper atmosphere.

Previous considerations of this problem [Park and Dejnaka-
stra, 1973, Tsur and Roble, 1985; Roble, 1991; Viteinov and
Timen, 1995] have not accounted for the nonlinear depen-
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N₂ Vibrational Excitation

The ESH model of Pasko et al. [1996] assumes cylindrical
symmetry about the z-axis (altitude) and describes the
steady-state (that is, static) electric field established in
the atmosphere due to a vertical TC dipole charge configura-
tion, consisting of two charges of +Q and −Q separated in
air. Above a perfectly conducting ground at r = 0, the
E field is calculated using the stationary charge continuity
equation, in which TC charges play the role of steady cur-
cent sources, assumed to be maintained against conduction
loss by external means, for example updrafts or other me-
teorological processes. The nonlinear heating effects on δ̇ ε
of the medium above the TC are calculated self-consistently
by solving the nonlinear continuity equation.

Each of the dipole charges ±Q is taken to be distributed
in the form of spherical or disk shaped clouds centered at al-
titude z₀ and of width 2a. The spherical distributions have
positive and negative charge densities α = e^-(r-z₀)^2/σr^2/α^2
where r is the radial cylindrical coordinate, a=3 km, z₀ =5
km, and z_f =15 km. For disk-shaped TC charge distribu-
tions, such as those which exist in a mesoscale convective
system (MCS) [for example, Marshall et al., 1996], the
charge density is α = e^-(r-z₀)^2/σr^2/α^2 (a=9 km) and is uniform in the r direction out to the radius of the disk. Larger E
fields will result everywhere above the cloud if either z_f or
z_f - z₀ is increased.

An important parameter that determines the penetration of
the TC fields to high altitudes is the scale height of the
upper-atmospheric conductivity σ. At altitudes below ~60 km,
the atmospheric conductivity is largely determined by
the ion component σ_i, which is not significantly modified by
ESH. Nevertheless, altitude profiles of σ_i are not well
known, especially above an active thunderstorm, and avail-
able in situ data from rockets [for example, Hale et al., 1981]
indicate large variability. Accordingly, we provide results for
different ambient σ_i profiles. At altitudes above ~60 km, the
electron component û is dominant. Although the ambient
profiles of electron density are also not well known, results
are less sensitive to the assumed ambient profiles in this al-
titude range, since the electron conductivity is reduced self-
consistently by ESH. The electrostatic fields penetrating to
higher altitudes are generally of low intensity, so that neither
ionization effects nor excitation of optical emissions need be
considered. Note that the type of coupling considered here
occurs during the entire duration of the thunderstorm, in-
cluding the times between lightning discharges.

With the electrostatic field self-consistently determined as
a function of altitude, the electron distribution function is
readily estimated using a kinetic formulation [Tarakanenko
et al., 1993] by accounting for all electron collisional losses,
**Figure 1.** (a) Three models of ambient electrical conductivity \( \sigma \). (b) Altitude profiles and (c) spatial distributions of \( N_2(v) \) excitation rate due to heated electrons.

including the very important loss due to vibrational excitation of \( N_2 \). The excitation rates for \( N_2(v) \) can then be determined using well-known cross sections [Phelps, 1987]. For numerical calculations, we use parametrized production rates of vibrationally excited \( N_2 \) as a function of \( E/N \) (where \( E \) is the electric field and \( N \) is the neutral number density) [Pasko et al., 1997].

We consider three different nighttime ambient conductivity profiles P1, P2, and P3 (Figure 1a). Profile P1 consists of an ion conductivity profile with a constant scale height of 11 km and an electron conductivity calculated from a typical D-region electron-density profile used in previous work [Inan et al., 1996]. Profile P2 has the same scale height as P1, but has an ionic conductivity ten times larger at each altitude. Profile P3 is probably the most ‘typical’ midlatitude profile and is based on a range of rocket measurements [Hale, 1994, and references therein]. Profiles P1 and P2 bracket the range of variations of \( \sigma \) at altitudes \( \approx 60 \) km.

We combine the three different conductivity profiles with the two different TC charge configurations into five cases which span the range of interest. The five cases are: (i) A1 - spherical, \( Q = \pm 100 \, \text{C} \), \( \sigma \) profile P1, (ii) A2 - same as A1, but with \( \sigma \) profile P2, (iii) A3 - same as A1, but with \( \sigma \) profile P3; (iv) A4 - disk-shaped, \( r = 50 \, \text{km} \), \( Q = \pm 1000 \, \text{C} \), \( \sigma \) profile P3, and (v) A5 - same as A4, but with \( \sigma \) profile P2. TC charges of 100 C are not uncommon [for example, Brook et al., 1992]. Moreover, the effective surface charge density corresponding to 1000 C spread over a disk with radius 50 km is \( \approx 130 \, \text{nC/m}^2 \), several times lower than the values of 400-1200 nC/m² suggested by Marshall et al. [1996] for a MCS. Thus, the TC charge magnitudes used in our calculations are quite conservative.

Figure 1b shows altitude profiles (at \( r = 0 \)) of the vibrational excitation rate of \( N_2(v) \) corresponding to the different cases. The lateral extent of the regions which are excited are indicated for each case separately in the profiles of figure 1c. Comparison of results for Cases A2 and A1 illustrate that higher conductivity values at lower altitudes (Case A2) allow for better upward penetration of fields and higher field values. However, the most effective coupling is obtained for disk-like TC charge distributions as represented by A4 and A5. The largest perturbations are produced for Case A5, which also provides for the penetration of the electrostatic field to the highest altitude. In Cases A4 and A5 electric fields \( E \approx -1 \) to \(-10 \, \text{V/m} \) are produced near \( z = 80 \, \text{km} \). Such fields are too low to produce significant ionization. In all cases electron densities are near ambient values.

**CO₂ ν3 Vibrational Temperatures**

We determine the populations of the ν3 excited states using a line-by-line non-LTE code [Wintersteiner et al., 1999], in which rate equations for the level populations and the equation of transfer for the radiative flux are solved simultaneously. The extended duration of the TC fields makes it possible to use a steady-state formulation, which ignores transient radiative behavior. We consider the combined effects of electron collisional excitation and the ambient night-time production/loss processes of Nebel et al. [1996] for the \( v_3 \) excited vibrational state populations. The stored \( N_3 \) vibrational excitation is initially transferred, with a time constant of a few seconds at \( 70 \, \text{km} \) to a minute at \( 90 \, \text{km} \), to \( CO₂ ν3 \) vibrational states, which then radiate rapidly at \( 4.3 \, \text{μm} \) (lifetime \( \approx 2.5 \, \text{ms} \)). However, in the mesosphere the effective CO₂ excited-state lifetime and the \( N_3(v) \) relaxation time are both long enough, and considerable by radiation trapping and by the reverse V-V process, whereby the vibrational excitation is passed back to \( N_3 \). Effective \( N_3(v) \) relaxation times are in the range 5-7 min at 70-90 km altitude [Kumer, 1977].

While the vibrational energy is redistributed locally by V-V transfer, it is also being redistributed nonlocally by radiative transport. We allow vertical radiative transfer, horizontal horizontal radiative transfer, and diffusion of the vibrational excitation, since the horizontal scale (lateral extent of the TC charge) is much larger than the vertical scales (neutral-density and enhanced-\( E \)-field scale height). At \( 80 \, \text{km} \) altitude, radiation will only diffuse horizontally a few km in 20 min, negligible compared to the width of the charge distribution. Moreover, one must include in the computation a number of weaker isotopic and hot bands, since they account for most of the radiative recombination over altitude and most of the limb radiance at \( 80 \, \text{km} \), TH, the strongest bands being severely self-absorbed.

In our model calculations, we consider four \( CO₂ \) isotopes and five excited states. We include the most abundant 6626 isotope, along with the minor isotopes 636, 627, and 628, and the excited states 00011, 01111 (which radiates the first hot band), and the states we shall call Group 1 (10011, 10012, and 02211). The notation for the CO₂ states and isotopes is given by Nebel et al. [1994] and by Rothman et al. [1992]. We assume (1) nighttime conditions, (2) a midlatitude model atmosphere similar to the U.S. Standard Atmosphere (1976), (3) non-overlapping spectral lines, and (4) local rotational equilibrium within a band at the kinetic temperature \( T \). We express non-LTE vibrational populations in terms of a vibrational temperature \( T_{vib} \) [Nebel et al., 1994].

The altitude profiles of \( T_{vib} \) were calculated for all bands of interest, and representative profiles are shown in Figures 2a-c for the unheated atmosphere and Cases A4 and A5, respectively. Results for Cases A1-A3 are not shown since enhancements were small. In each case, the \( T \) profile is shown, as well as \( T_{vib} \) profiles for \( N_3(v=1) \) and \( N_3(v=2) \) states. In the ambient case we see that \( T_{vib} > T \) for the strongly non-LTE CO₂ states in the mesopause region, since the production is dominated by radiative excitation. The less abundant isotopes are vibrationally hotter because they are optically thinner and are excited by radiation originating further away near the warm stratopause. On the other hand, on the other hand, \( T_{vib} < T \) for the CO₂ states because radiative loss (cooling \( v \) space) dominates. The \( T_{vib} \) profile for \( N_3 \) is locked to the \( CO₂ 00011 626 \) \( T_{vib} \) in the mesosphere due to the strong V-V transfer. On the other hand, in the thermosphere it is locked to \( T \), because the time constant for V-V transfer becomes very long and the radiative loss is then dominated by collisions.

When the electrons are heated, enhancements of \( T_{vib} \) occur above \( 70 \, \text{km} \) and are strongest at \( 80 \, \text{km} \) near the peak of \( N_2(v) \) excitation by electrons. The enhancements are quite modest (\( \approx 10 \, \text{K} \)) for Case A2 (not shown), but approach 50
Figure 2. Altitude profiles of $T_{\text{vib}}$ (a) for unheated conditions, (b) for Case A4, and (c) for Case A5. Symbols designate CO$_2$ isotope and states as follows: $\bigcirc$ (626 0001), $\Box$ (636 0001), $\triangle$ (628 0001), $\triangledown$ (627 0001), $\bigdiamond$ (626 0111). Profiles of $T$ (dashed) and $N_2(v=1)$ $T_{\text{vib}}$ (dash/double-dot) are also shown.

K for Case A5. An increase of 10 K (50 K) corresponds to a factor of $\sim$2 ($\sim$17) increase in the upper-state population at $T_{\text{vib}} = 220$ K. A significant feature of the enhancements is that they occur not only in the region of enhanced $N_2(v)$ excitation below 85 km, but extend up into the thermosphere, well above 130 km. The responsible mechanism is IR radiative diffusion of the excitation upward from the region of enhanced production. A similar process is effective in redistributing auroral electron energy deposited in $N_2$ vibration [Winick et al., 1988]. The 626 and 636 0111 states also show significantly enhanced $T_{\text{vib}}$, but the Group I excited-state enhancements (not shown) are negligible.

CO$_2$ 4.3-$\mu$m Limb Radiance

We now calculate the enhanced 4.3 $\mu$m radiance in limb view for LOS with tangent points located at $r=0$. The calculation includes segments on both the near and far side of the tangent point where ambient conditions prevail.

Figure 3a shows the nighttime limb radiance profiles for CO$_2$ A4 and A5 and for ambient conditions, for a sensor with an infinitesimal field-of-view and a wide spectral passband (4.1-4.5 $\mu$m). Cases A1-A3 (not shown) are nearly indistinguishable from the ambient, but enhancements of up to $\sim$20% and $\sim$100% occur for cases A4 and A5, respectively. Near-peak enhancements occur over a broad range of TH from $\sim$76 km to $\sim$120 km, extending well above the region of E-field-enhanced production. Figure 3b shows the enhancement ratio for individual bands as a function of TH for Case A5, demonstrating that the enhancement profile depends strongly on the band. The altitude dependence is much stronger for the 626 00011-00001 (main) band, since its optical thickness prevents radiative diffusion of the enhanced production. On the other hand, the two strongest minor bands, 636 00011-00001 and 626 0111-01101, have broader enhancement profiles, due to the increased radiative diffusion. Near the altitude of peak vibrational excitation ($\sim$80 km), the main-band enhancement dominates, while in the lower thermosphere the two weaker bands have enhancements nearly equal to each other and to the main band. Although the main-band radiance is larger by as much as a factor of six at $\sim$80 km, it only accounts for $5\text{-}10\%$ of the radiance there, since it is severely self-absorbed. This is illustrated in Figure 3c, which shows the fraction of the total limb radiance under ambient conditions originating from the main 626 band, all of the isotopic 00011-00001 bands, the first 626 hot band, and other hot bands (largely first hot bands of minor isotopes and bands arising from Group I states). The main 626 band makes the largest contribution only below 69 km and above 105 km, while the minor-isotope 00011-00001 bands dominate the radiance from 73 to 105 km.

The variation in optical thickness of the bands and the dependence of the enhancement ratios on TH lead to interesting spectral behavior, which may be detectable with a limb-looking narrowband multichannel radiometer or with an IR spectrometer. In Figure 4 we show typical spectra for the ambient atmosphere and for Case A5 at 80 km TH. The spectrum is plotted for an instrumental resolution of 2 cm$^{-1}$ and shows considerable structure, including band origins, sharp Q-branches, and broader P- and R-branches. It is clear that spectral-radiance enhancements are dependent on wavenumber and that diverse spectral features are enhanced differently. While the integrated radiance more than doubles, the increase within limited spectral regions, such as the ‘blue spike’ region near 2350 cm$^{-1}$, can be con

Figure 3. (a) Total limb radiance profiles for ambient nighttime and Cases A4 and A5. (b) Heating enhancement ratios for limb radiance in a number of bands versus TH for Case A5. Symbols for upper states of bands same as in Figure 2, except that curve is added (hexagons) for hot bands originating in states other than 626 0111. (c) Profiles of fractional limb radiance in certain band groups for ambient nighttime. Upper (radiating) level designations are: $\bigcirc$ (00011 626), $\bigcirc$ (00011 minor isotopes), $\bigtriangleup$ (626 0111 hot band), $\bigtriangledown$ (statee radiating other hot bands).
Figure 4. 4.3-μm limb spectra for TH = 80 km. Ambient night (thin), Case A5 (thick)

siderably larger. Larger effects are also possible when the heated region is on the side of the tangent point nearer the sensor.

Summary and Discussion

Our results indicate that sustained heating of lower ionospheric electrons by TC fields, as suggested by Inan et al. [1996], may lead to the production of detectable enhancements of 4.3-μm CO₂ emission. Model calculations for five different cases indicate that the strongest effects are expected for laterally extensive TC charge distributions, such as those associated with a MCS, and in cases where the atmospheric conductivity allows penetration of the electrostatic field to relatively high altitudes. Enhancements of CO₂ \( T_{1u} \), start near 70 km, with maximum enhancement of up to 50 K near 80 km altitude. As a result of IR-mediated radiative diffusion, the enhancements extend up into the thermosphere, well above 130 km, despite the fact that significant heating occurs only below 90 km. Limb-view broadband 4.3-μm enhancements of up to a factor of two above ambient nighttime levels are predicted for TH between 77 km and 120 km, with larger enhancements in selected narrower spectral regions. Somewhat larger enhancements would be expected if electron excitation of other molecular vibrational states were allowed, including direct excitation of CO₂ \( v_2 \) and perhaps excitation of O₂(v), which is coupled to CO₂ \( v_2 \) and N₂(v).

The fact that significant IR enhancements are only predicted to occur for Cases A4 and A5 underscores the dependence of the upward penetration of TC field on the profile of \( \sigma \). Simple considerations of the E-field variation in an inhomogeneous medium indicate that effective penetration to ionospheric altitudes is maximized when the fastest e-foldings of \( \sigma \) occur between TC and ionosphere. Our results indicate that significant IR enhancements should occur when the \( \sigma \) profile lies in the range between P2 and P3. In view of the scarcity of in situ data, it is difficult to assess the geophysical conditions under which the conductivity profile would be similar to that described by profiles P2 or P3. However, rocket measurements [Hale, 1994] do indicate profile P3 to be a typical mid-latitude nighttime profile. Thus we can reasonably expect that conditions leading to effective coupling and IR enhancements should occur at least some of the time.

The importance of having a spatially extensive MCS with area \( \sim 10^4 \) km² for obtaining \( E \) fields sufficient to excite N₂(v) is borne out by the rocket measurements of Kelley et al. [1985], showing \( E \) fields of only tens of nV/m above relatively small storm cells with horizontal extents \( \sim 10^{-20} \) km, in contrast to the 1-10 V/m resulting from our calculations for charge distributions similar to those observed by Marshall et al. [1996]. The difference in \( E \) fields between relatively small cells and a MCS is demonstrated by U-2 aircraft measurements near \( \sigma = 20 \) km over a large active storm [Blakeslee et al., 1989]. These measurements reported \( E = 1-7 \) kV/m, in agreement with our calculations for Cases A4 and A5, but greater than the balloon-borne measurements associated with the rocket campaign of Kelley et al. [1980] at 21 km by a factor of \( 10^3 - 10^4 \).

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