Infrasound generation by tornadic supercell storms

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Abstract

Acoustic wave generation by turbulence in the stratified, moist atmosphere is studied. It is shown that in the saturated moist air turbulence in addition to the Lighthill’s quadrupole and the dipole sources of sound related to stratification and temperature fluctuations, there exist monopole sources related to heat and mass production during the condensation of moisture. We determine acoustic power of these monopole sources. Performed analysis shows that the monopole radiation is dominant for typical parameters of strong convective storms. Obtained results are in good qualitative agreement with the main observed characteristics of infrasound radiation by strong convective storms such as total acoustic power and characteristic frequency.

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I. INTRODUCTION

It is long known that strong convective storms, such as supercell thunderstorms are powerful sources of infrasound \[1, 2\]. Detailed observations of convective storm generated infrasound \[1, 3\] provides that at least two different group of infrasonic signals could be identified. The first group, with characteristic period about 1 s, has been found to be in strong connection with proto-tornadic structures, funnel clouds and tornadoes. Based on coincident radar measurements of tornados, which show strong relationship between funnel diameter and infrasound frequency, it is usually supposed that these infrasound waves are generated by radial vibrations of the vortex core \[4\]. The second group of infrasound signals has the periods from 2 to 60 s. Usually the emission appears about 1 hour before observation of tornado. Although detection of these waves are known to be strongly correlated with formation of tornado \[5\], it is usually supposed that these waves are not related with tornado itself and are caused by convective processes that precede tornado formation. The acoustic power radiated by convective storm system could be as high as \(10^7\) watts \[5\]. Although several reasonable mechanisms have been suggested to explain this acoustic radiation, the physical mechanism of the process remains unexplained \[4, 5, 6\].

Broad and smooth spectrum of the observed infrasound radiation indicates that turbulence is one of the promising sources of the radiation. Lighthill’s acoustic analogy \[7\] represents the basis for understanding of the sound generation by turbulent flows. Validation of this theory has been shown by various experiments and numerical simulations (see, e.g., Refs. \[8, 9, 10, 11\] and references therein). In this approach the flow is assumed to be known and the sound field is calculated as a small by-product of the flow. According to this theory in the case of uniform background thermodynamic parameters interaction of turbulent vortices provides quadrupole source of sound. The acoustic power of the source was estimated by Proudman \[12\]. But usage of this estimation for the infrasound radiation from convective storms usually leads to the underestimation of the acoustic power \[2, 6, 13\]. It requires characteristic velocity of the turbulence to be much greater than it exists in any terrestrial storm system. Recent analysis of a non-supercell tornado storm simulation performed by Nicholls, Pielke and Bedard \[14\] suggests that the occurrence of the high frequency infrasound coincided with the development of considerable small-scale turbulence that may have caused small-scale latent heating fluctuations which appear to be the main
mechanism responsible for generating the infrasound in this simulation.

In the presented paper we study acoustic radiation from turbulent convection taking into account effects of stratification, temperature fluctuations and moisture of the air and using Lighthill’s acoustic analogy. Formulation of the generalized acoustic analogy [15] implies: (i) dividing the flow variables into their mean and fluctuating parts; (ii) subtracting out the equation for the mean flow; (iii) collecting all the linear terms on one side of equations and the nonlinear terms on the other side; (iv) treating the latter terms as the known terms of sound.

We show that in the saturated moist air turbulence in addition to the Lighthill’s quadrupole and known dipole sources of sound related to stratification and temperature fluctuations, there exist monopole sources related to heat and mass production during the condensation of moisture. It appears that infrasound radiation from convective storms should be dominated by acoustic source related to the monopole sources related to the moisture of the air. We show that for the typical parameters of the strong convective storm the acoustic output of this monopole source is two orders of magnitude stronger than Lighthill’s quadrupole source, whereas the dipole radiation related to temperature inhomogeneities is of the same order as radiation of Lighthill’s quadrupole source. The dipole source related to stratification and the dipole and quadrupole sources related to inhomogeneity of background velocity are inefficient sources of sound. The total power of the source related to moisture is of order $10^7$ watts for the typical parameters of the strong convective storms, in qualitative agreement with observations [2, 4, 6].

The paper is organized as follows: In Sec. II equations governing sound generation by turbulence for moist atmosphere are obtained in the framework of Lighthill’s acoustic analogy. Various sources of acoustic radiation are analyzed in Sec. III. Application of the obtained results to infrasound generation in strong convective storms is made in Sec. IV. Conclusions are given in Sec. V.

**II. GENERAL FORMALISM**

The dynamics of convective motion of moist air is governed by continuity, Euler, heat, humidity and ideal gas state equations:

\[
\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{v} = 0, \quad (1)
\]
\[
\frac{D\mathbf{v}}{Dt} + 2\rho \Omega \times \mathbf{v} = -\nabla p - \rho \nabla \Phi, \quad (2)
\]
\[
T \frac{Ds}{Dt} = -L_\nu \frac{Dq}{Dt}, \quad (3)
\]
\[
\rho = \frac{p}{RT} \frac{1}{1 - q + q/\epsilon} = \frac{1}{RT} \frac{1}{1 + aq}, \quad (4)
\]
where \(\mathbf{v}, 2\Omega \times \mathbf{v}, \rho\) and \(p\) are velocity, Coriolis acceleration, density and pressure respectively; \(D/Dt \equiv \partial/\partial t + \mathbf{v} \cdot \nabla\) is Lagrangian time derivative; \(L_\nu\) is the latent heat of condensation and \(q\) is the mass mixing ratio of water vapor (humidity mixing ratio)
\[
q \equiv \frac{\rho_\nu}{\rho}, \quad (5)
\]
where \(\rho_\nu\) is the mass of water vapor in the unit volume; \(\epsilon \equiv m_\nu/m_d \approx 0.622\) is the ratio of molecular masses of water and air; \(a = 0.608\) and \(R\) is the universal gas constant.

In the set of Eqs. (1)-(4) diffusion and viscosity effects are neglected due to the fact that they have minor influence on low frequency acoustic wave generation as well as its propagation.

In the future analysis we also assume \(\Omega = 0\). As it is well known \([16]\), Coriolis effects are negligible for mesoscale convective system dynamics. On the other hand, when the frequency of acoustic waves \(\Omega_a\) satisfy the condition \(\Omega_a \gg \Omega\), Coriolis effects have also negligible influence on acoustic wave dynamics.

The main idea of Lighthill’s acoustic analogy is reformulation of the governing equations in the form suitable for the study of acoustic wave radiation process. To proceed in this direction one have to choose appropriate ”acoustic variable”, that describes acoustic waves in the irrotational regions of the fluid. Generalized Bernoulli’s theorem \([17]\) suggests that the total enthalpy
\[
B \equiv E + \frac{p}{\rho} + \frac{v^2}{2} + \Phi, \quad (6)
\]
where \(\Phi\) is gravitational potential energy per unit mass, \(E\) is internal energy and \(\nabla \Phi \equiv -g\), is one of the possible appropriate choices \([18]\). \(B\) is constant in the steady irrotational flow and at large distances from acoustic sources perturbations of \(B\) represent acoustic waves.

For derivation of acoustic analogy equation in terms of the total enthalpy it is useful to rewrite Euler’s equation in the Crocco’s form
\[
\rho \frac{D\mathbf{v}}{Dt} + \nabla B = -\omega \times \mathbf{v} + T \nabla s, \quad (7)
\]
where \( \omega \) is vorticity, \( T \) is temperature, \( s \) is specific entropy and

\[
Tds = dE + pd\left(\frac{1}{\rho}\right) = dB - \frac{dp}{\rho} - d\Phi - d\left(\frac{v^2}{2}\right). \tag{8}
\]

From the thermodynamic identity

\[
d\rho = \left(\frac{\partial \rho}{\partial p}\right)_{s,q} dp + \left(\frac{\partial \rho}{\partial s}\right)_{p,q} ds + \left(\frac{\partial \rho}{\partial q}\right)_{s,p} dq, \tag{9}
\]

where the subscripts serve as the reminders of the variables held constant, using Eqs. (4) we obtain

\[
d\rho = \frac{1}{c_s^2} dp - \frac{\rho}{c_p} ds + \frac{a \rho}{1 + aq} dq, \tag{10}
\]

where

\[
c_s \equiv \left(\frac{\partial \rho}{\partial p}\right)_{s,q}^{1/2}, \tag{11}
\]

is the sound velocity and

\[
c_p \equiv T \left(\frac{\partial s}{\partial T}\right)_{p,q} \tag{12}
\]

is the specific heat of the air.

Eliminating convective derivative of the density from Eq. (11) using Eq. (10) we have

\[
\frac{1}{\rho c_s^2} \frac{Dp}{Dt} + \nabla \cdot \mathbf{v} = \frac{1}{c_p} \frac{Ds}{Dt} + \frac{1}{1 + aq} \frac{Dq}{Dt}. \tag{13}
\]

Subtracting the divergence of Eq. (7) from time derivative of Eq. (13) and using Eq (3) after long but straightforward calculations we obtain

\[
\begin{align*}
B &= S_L + S_T + S_q + S_m + S_\gamma,
\end{align*} \tag{14}
\]

where \( \gamma \equiv c_p/c_v \) is the ratio of specific heats and

\[
\begin{align*}
S_L &\equiv \left(\nabla + \frac{\nabla p}{\rho c_s^2}\right) \cdot (\omega \times \mathbf{v}), \tag{15} \\
S_T &\equiv - \left(\nabla + \frac{\nabla p}{\rho c_s^2}\right) \cdot (T \nabla s), \tag{16} \\
S_q &\equiv \frac{\partial}{\partial t} \left(\frac{\gamma T Ds}{c_s^2} \frac{1}{Dt}\right) + (\mathbf{v} \cdot \nabla) \left(\frac{T Ds}{c_s^2} \frac{1}{Dt}\right), \tag{17} \\
S_m &\equiv \frac{\partial}{\partial t} \left(\frac{a}{1 + aq} \frac{Dq}{Dt}\right), \tag{18}
\end{align*}
\]
\[ S_s \equiv p \frac{\partial \gamma}{\partial q} \left( \frac{\partial q}{\partial t} (\mathbf{v} \nabla) p - \frac{\partial p}{\partial t} (\mathbf{v} \nabla) q \right). \] (19)

Eq. (14) is suitable for identification of different acoustic sources and the study of their acoustic output.

The nonlinear wave operator on the left of Eq. (14) is identical with that governing the propagation of sound in irrotational, homentropic flow. Therefore the terms on the right may be identified as acoustic sources. Propagation of infrasound in the atmosphere was intensively studied by different authors (see, e.g., Ref. [19] and references therein) and will not be considered in this paper.

For simplification of further analysis of the acoustic output of different sources we make several standard assumptions:

(a) Studying acoustic wave generation process for low Mach number flow, all the convective derivatives in Eq. (14) can be replaced by time derivatives \( \partial / \partial t \) [23];

(b) For acoustic waves with the wavelength \( \lambda \) not exceeding the stratification length scale

\[ \lambda \lesssim H \equiv \frac{c^2_s}{g} \approx 10^4 \text{m}, \] (20)

one can also neglect the influence of stratification on the acoustic wave generation process and consider background thermodynamic parameters in Eq. (14) as constants [20].

(c) Neglecting nonlinear effects of acoustic wave propagation and scattering of sound by vorticity and taking into account that \( M \ll 1 \), for the acoustic pressure in the far field we have

\[ p'(\mathbf{x}, t) \approx \rho_0 B(\mathbf{x}, t). \] (21)

(d) Eq. (14) is equivalent to initial set of Eqs. (1)-(4) and therefore it describes not only acoustic waves, but also the instability wave solutions that are usually associated with large scale turbulent structures and continuous spectrum solutions related to "fine-grained" turbulent motions [15, 21]. In the presence of any kind of inhomogeneity, such as stratification or velocity shear, linear coupling between these perturbations is possible, and in principle acoustic waves can be generated by both instability waves and continuous spectrum perturbations. But in the case of low Mach number \( (M \ll 1) \) flows both kind of perturbations are very inefficient sources of sound. The acoustic power is proportional to \( e^{-1/2M^2} \) and \( e^{-\pi \delta / 2M} \) for instability waves and continuous spectrum perturbations respectively [22]. In the last expression \( \delta \) is the ratio of length scales of energy containing vortices and background velocity inhomogeneity \( (V/\partial_z V) \). In the case of supercell thunderstorm \( M \sim 0.1 - 0.15 \) and
\[ \delta \sim 10^{-2}, \] therefore both linear mechanisms have negligible acoustic output and attention should be payed to sources of sound related to nonlinear terms and entropy fluctuations that will be studied below.

With these assumptions Eq. (14) simplifies and reduces to

\[ \frac{1}{\rho_0} \left( \frac{1}{c_s^2} \frac{\partial^2}{\partial t^2} - \nabla^2 \right) p' = S_L + S_T + S_\gamma + S_q + S_m, \] (22)

with

\[ S_L \approx \nabla \cdot (\omega \times \mathbf{v}), \] (23)
\[ S_T \approx -\nabla \cdot (T \nabla s), \] (24)
\[ S_\gamma = p \frac{\partial \gamma}{\partial q} \left( \frac{\partial q}{\partial t} (\mathbf{v} \nabla) p - \frac{\partial p}{\partial t} (\mathbf{v} \nabla) q \right), \] (25)
\[ S_m \approx \frac{a}{1 + aq} \frac{\partial^2 q}{\partial t^2}, \] (26)
\[ S_q \approx -\frac{\gamma L_\nu}{c_s^2} \frac{\partial^2 q}{\partial t^2}. \] (27)

First three terms on the right hand side of Eq. (22) represent well known sources of sound: the first term represents Lighthill’s quadrupole source \[7\]; the second term is dipole source related to temperature fluctuations \[23\]; \( S_\gamma \) is monopole source related to variability of adiabatic index, that usually have negligible acoustic output \[18\] and will not be considered in the presented paper; Eq. (22) shows that in the case of saturated moist air turbulence there exist two additional sources of sound. \( S_q \) and \( S_m \) are monopole sources related to nonstationary heat and mass production during the condensation of moisture, respectively.

### III. ANALYSIS OF DIFFERENT SOURCES

For estimation of different acoustic sources we follow the standard \[18, 23\] procedure. Namely, using the wave equation free space Green function

\[ G(t, t', x, x') = \frac{\delta(t - t' - |x - x'|/c_s)}{4\pi c_s^2 |x - x'|}, \] (28)

acoustic pressure fluctuations corresponding to a source \( S_i \) can be written as

\[ p_i'(x, t) = \frac{1}{4\pi c_s^2} \int \frac{[S_i]_{t=t_*}}{|x - x'|^3} \, d^3x', \] (29)

where \( t_* = t - |x - x'|/c_s \).

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7
Calculating acoustic radiation in the far field ($|\mathbf{x}| \gg |\mathbf{x}'|$), we can use following expansions

$$|\mathbf{x} - \mathbf{x}'| \approx |\mathbf{x}| - \frac{\mathbf{x} \cdot \mathbf{x}'}{|\mathbf{x}|},$$

$$S_\alpha(t_s) \approx S_\alpha\left(t - \frac{|\mathbf{x}|}{c_s}\right) + \frac{\mathbf{x} \cdot \mathbf{x}'}{c_s|\mathbf{x}|} \frac{\partial}{\partial t} S_\alpha\left(t - \frac{|\mathbf{x}|}{c_s}\right),$$

and using plane wave approximation for far field derivatives

$$\frac{\partial}{\partial x_i} \approx -\frac{x_i}{c_s|\mathbf{x}|} \frac{\partial}{\partial t},$$

for the Lighthill’s source we obtain

$$p'_L(x, t) = -\rho_0 v_i v_j \frac{\partial^2}{4\pi c_s^2 |\mathbf{x}|^3 \partial t^2} \int v_i v_j d^3 \mathbf{x}',$$

which corresponds to quadrupolar radiation field.

$p'_L$ can be estimated in terms of characteristic velocity $v$ and length scale $l$ of energy containing turbulent eddies. Fluctuations in $v_i v_j$ in different regions of the turbulent flow separated by distances greater then $l$ tend to be statistically independent, and therefore generation of sound can be considered as by a collection of $F/l^3$ independent eddies, where $F$ is the volume occupied by the turbulence. The dominant frequency of the motion $\sim v/l$, so the wavelength of the radiated sound $\Omega \sim l/M_t$, where $M_t \equiv v/c_s \ll 1$ is turbulent Mach number. Therefore, each eddy is acoustically compact. Acoustic pressure generated by single eddy is $p'_L1 \sim (l/|\mathbf{x}|)\rho_0 v^2 M_t^2$, and acoustic power it radiates $N_{L1} \sim 4\pi |\mathbf{x}|^2 p'_L1/\rho_0 c_s \approx \rho_0 v^3 l^2 M_t^5$, that corresponds to Lighthill’s eighth power law. For total acoustic power this yields Prandtlman’s estimate

$$N_L \sim \frac{\rho v^8}{l c_s^5} F.$$

(34)

Similar arguments can be used for estimation of acoustic power of thermo-acoustical source $S_T$ related to density (and therefore temperature) fluctuations, that produce dipole source $[18]$. The physics of this kind of acoustic radiation is the following: ”hot spots” or ”entropy inhomogeneities” behave as scattering centers at which dynamic pressure fluctuations are converted directly into sound. The acoustic power is

$$N_T \sim \frac{\rho \Delta T^2 v^6}{l T^2 c_s^5} F = \frac{\Delta T^2}{M_t^2 T^2} N_L,$$

(35)

where $\Delta T$ denotes the rms of temperature fluctuations.
Acoustic sources $S_q$ and $S_m$ are related to the moisture of the air. They produce monopole radiation and physically have the following nature: suppose there exist two saturated air parcels of unit mass with different temperatures $T_1$ and $T_2$ and water masses $m_{\nu}(T_1)$ and $m_{\nu}(T_2)$. Mixing of these parcels leads to the condensation of water due to the fact that

$$2m_{\nu}(T_1/2 + T_2/2) < m_{\nu}(T_1) + m_{\nu}(T_2).$$

Condensation of the water leads to two effects, important for sound generation: production of heat and decrease of the gas mass. Both of these effects are known to produce monopole radiation [18, 23]. Consequently, turbulent mixing of saturated air with different temperatures will lead not only to the dipole thermo-acoustical radiation (35), but also to the monopole radiation.

According to Eqs. (5) and (36) for humidity mixing ratio fluctuation $q'_s$ we have

$$q'_s = q_s(T + T') + q_s(T - T') - 2q_s(T).$$

In the limit $T'/T \ll 1$ this yields

$$q'_s \approx \frac{\partial^2 q_s}{\partial T^2} T'^2.$$  

Substituting (17) into (29) and using (38), (30) and (31) we obtain

$$p'_q(x, t) = -\frac{\rho_0 \gamma L_{\nu}}{4\pi c_s^2 |x|} \frac{\partial^2 q_s}{\partial T^2} \frac{\partial^4}{\partial t^4} \int T'(x', t)T'(x'', t) d^3 \mathbf{x'},$$

which corresponds to monopole radiation field.

For total acoustic power radiated by monopole source related to the moisture we have

$$N_q = \frac{4\pi |x|^2}{\rho_0 c_s} \langle p'(x, t)p'(x, t) \rangle \sim \frac{\rho_0 \gamma^2 L_{\nu}^2}{c_s^5} \left(\frac{\partial^2 q_s}{\partial T^2}\right)^2 \frac{\partial^4}{\partial t^4} \int d^3 \mathbf{x'} d^3 \mathbf{x''} (T'(x', t)T'(x', t)T'(x'', t)T'(x'', t))$$

Fluctuations of temperature in different regions of the turbulent flow separated by distances greater than length scale $l$ of energy containing eddies are not correlated and therefore the integral in Eq.(41) can be estimated as $F_1 l^3 \Delta T^4$, where $F_1$ is the volume occupied by saturated moist air turbulence. Taking also into account that the characteristic timescale of the process is turn over time of energy containing turbulent eddies $l/v$ finally obtain

$$N_q \sim \frac{\rho_0 \gamma^2 L_{\nu}^2 \Delta q^2 M_t^4}{l c_s} F_1 = \frac{\gamma^2 L_{\nu}^2 \Delta q^2}{M_t^4 c_s^4} F_1 N_L,$$
where $\Delta q$ is the rms of humidity mixing ratio perturbations. The acoustic power of the source related to the gas mass production we obtain

$$N_m \sim \frac{\rho_0 a^3 c_s^3 \Delta q^2 M_i^4}{l} F_1 = \frac{a^2 \Delta q^2 F_1}{M_i^2} F N_L.$$  (42)

IV. APPLICATION TO INFRASOUND GENERATION BY STRONG CONVECTIVE STORMS

In this section we apply our findings to study infrasound generation by strong convective storms. Taking for typical parameters of supercell storms $v \sim 5$ m/s, $\Delta T \sim 3^\circ$ K [2, 16], $T = 270^\circ$ K and $c_s = 330$ m/s and using Eqs. (34) and (35) we see that the dipole radiation related to temperature inhomogeneities is of the same order as radiation of Lighthill’s quadrupole source.

Combining Eqs. (41)-(42), using $L_\nu \approx 2.5 \times 10^6$ m$^2$/s$^2$ and $\gamma \approx 1.4$ we obtain

$$\frac{N_q}{N_m} \approx \left(\frac{\gamma L_\nu}{c_s^2}\right)^2 \approx 10^3,$$  (43)

therefore acoustic power of the source related to the gas mass production is negligible compared to the radiation related to the heat production.

Estimation of $\Delta q$ is a bit more difficult. For saturation specific humidity we use Bolton’s formula [24]

$$q_s \approx 3.8 \frac{p_0}{T_c} \exp \left(\frac{17.67 T_c}{T_c + 243.5}\right),$$  (44)

where $T_c = T - 273.15$ is the temperature in degree Celsius and $p_0$ is atmospheric pressure in mb. Taking into account (38) and using $p_0 \approx 800$ mb, we obtain

$$\Delta q \approx \frac{6.8 \cdot 10^4}{(243.5 + T_c)^4} \exp \left(\frac{17.67 T_c}{T_c + 243.5}\right) \Delta T^2 \equiv f(T_c) \frac{\Delta T^2}{T^2}.$$  (45)

Note, that due to the numerator in the exponent $f(T_c)$ strongly depends on temperature, e.g., $f(T_C = 10^5)/f(T_C = 0^\circ) \approx 2$.

Using Eqs. (34) and (41) we obtain

$$\frac{N_q}{N_L} \approx \left[\frac{\gamma L_\nu}{c_s^2}\right]^2 \left(\frac{\Delta T}{M_i T}\right)^4 \left[\frac{F_1}{F}\right]^2 f^2(T_c).$$  (46)

For our analysis we assume $T_c = 0^\circ$C, $(f(0) \approx 1.66)$ and $F \approx 125$ km$^3$ [6]. For estimation of $F_1$ we note that that for atmospheric convection saturation level is usually at the height
\( \approx 1 - 1.5 \text{ km} \). Taking also into account that \( f(T_c) \) rapidly drops with the decrease of \( T_c \), one can expect that main acoustic radiation will be produced at the heights \((1.5 - 4) \text{ km}\), and consequently we assume \( F_1 \approx 0.5F \). Then Eq. (46) yields

\[
\frac{N_q}{N_L} \approx 2 \times 10^2.
\]

Therefore, we conclude that infrasound radiation of supercell storm should be dominated by the monopole source related to the heat production during water condensation. Assuming additionally constant of proportionality in Eq. (34) equal to 100 \([6, 23]\) and \( l \approx 10 \text{ m} \) for total power of the radiation we obtain

\[
N_q \approx 2.4 \times 10^7 \text{ watts},
\]

in qualitative agreement with observations \([2, 4, 6]\).

As it was mentioned above, the characteristic frequency of the emitted acoustic waves \( \Omega \sim v/l \), and using the characteristic values of the velocity and length scale we obtain for the period \( \tau \sim 10 \text{ s} \).

V. CONCLUSIONS

In the presented paper we have considered acoustic radiation from turbulent convection in the framework of generalized acoustic analogy taking into account effects of stratification, temperature fluctuations and moisture of the air. Analysis shows existence of monopole sources related to heat and mass production during the condensation of moisture in the saturated moist air turbulence, in addition to the Lighthill’s quadrupole and known dipole sources of sound related to stratification and temperature fluctuations. It has been shown that for the typical parameters of the strong convective storms infrasound radiation should be dominated by monopole source related to the moisture of the air. The total power of the source related to moisture is of order \( 10^7 \) watts, in qualitative agreement with observations of strong convective storms \([2, 4, 6]\).

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