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GEOPHYSICS

An Effective Mechanism of Seismic Signal Generation during the Interaction of Tornadoes with the Earth's Surface

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The possibilities of generating of seismic waves of notable intensity related to tornadoes have been considered in several recent publications. In principle, seismic signals can be used for remote registration of tornadoes, and the realization of this idea could widen the possibilities of forecasting these hazardous phenomena. Information about the registration of such events and discussion of possible mechanisms of their generation are given in [1–5]. Preliminary estimates indicate that some of the suggested mechanisms can, in principle, provide a signal intensity powerful enough for their remote recording by modern seismic equipment (however, the issue of discriminating signals from remote tornadoes against the background of noise related, in particular, to signals from atmospheric processes occurring closer to the seismic station is very pressing). It is more difficult to explain soil vibrations that have such an amplitude that they can allegedly be detected at a distance of one or even a few kilometers from a tornado [2, 3]. In our work, we consider the generation mechanism of previously ignored seismic signals, namely, pressure fluctuations in a tornado related to cyclostrophic adjustment of pressure and velocity fields. Estimates indicate that this mechanism can be significantly more effective in a certain range of frequencies than those discussed before.

According to present-day tornado models, the dynamics of these vortices is based on the cyclostrophic balance

$$\frac{V^2}{r} = \frac{1}{\rho_a}\frac{\partial p}{\partial r}. \quad (1)$$

Here, r is the radial coordinate, p is the pressure, V is the absolute value of the tangential velocity, and ρ_a is the mean air density. It follows from (1) that

$$V = \sqrt{\frac{r}{\rho_a}\frac{\partial p}{\partial r}} \sim \sqrt{\frac{\Delta p}{\rho_a}}, \quad (2)$$

where Δp is the pressure deficit in a tornado. The latter (approximate) equation was obtained by substituting the ratio of finite differences for the derivative. Equation (1) assumes axial symmetry (a usual assumption in models), but the latter equation contains an approximate relation between the characteristic horizontal velocity and the pressure deficit, which is likely to be valid even at significant deviations from axial symmetry.

When balance (1) is distorted, the process of mutual adjustment between the pressure field and the velocity field starts, which leads to a new state of cyclostrophic balance. This process can be referred to as cyclostrophic adjustment; in some respects, it resembles a classical geostrophic adjustment, which is characterized by decaying fluctuations in the fields mentioned [6]. In this case, we discuss high wind velocities, and so our main interest is in nonlinear regimes (in recent years, important results in this field have been obtained by Kalashnik and Svirkunov [7, 8]). In the classical theory of geostrophic adjustment, the characteristic time of the process (in particular, the period of fluctuations of the pressure field and the velocity field) is the pendulum day. In our case, planetary rotation does not play any significant role. Double cyclic frequency of tornado rotation is the analog of the Coriolis parameter.

There are grounds to assume that tornado dynamics are typical of strong fluctuations with spatial scales comparable with the size of a tornado. According to official meteorological data, even the class of tornado intensity can frequently change very rapidly. At present, much data is available, with video records of tornado manifestation clearly showing strong fluctuations of these vortices. This can be easily explained. The fluctuations are maintained by strong wind shear, tornado motion over an uneven underlying surface, a non-steady state of the parent cloud, and other external conditions. It is likely that the presence of strong fluctuations means that cyclostrophic balance in the vortex

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Table

Radius of the vortex, m	Wind velocity, m/s	Class of intensity	T, s	f, s^{-1}	λ, km	u, μm	du/dt, μm/s
5	25	F0	1.2	5	2.4	$0.3 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
15	40	F1	2.3	2.5	4.6	$0.5 \cdot 10^{-2}$	10^{-2}
50	60	F2	5	1.2	10	0.1	0.1
150	80	F3	12	0.5	24	2	1
500	100	F4	30	0.2	60	6	1
1500	130	F5	73	0.1	145	100	10

is systematically distorted. Therefore, pressure and velocity fluctuations typical of the cyclostrophic adjustment of these fields constantly occur in tornadoes. If this is all true, the underlying surface over the entire area of contact with the vortex is subject to the influence of pressure fluctuations the amplitude p' of which can possibly be comparable in terms of order of magnitude with the pressure deficit in a tornado Δp, while the cyclic frequency f is on the order of a double cyclic frequency of rotation ω.

Let us make an estimate. The most important characteristics of the tornado are the maximum wind velocity V (or pressure deficit Δp) and effective radius R. If we assume that Δp = 100 mbar [9], it follows from (2) that $V \sim 100$ m/s, which is actually typical of relatively intense tornadoes. We assume that the radius of such a vortex R is ~200 m. Then, the rotation period $T = 2\pi R/V \approx$ 12 s, the fluctuation period during the mutual adjustment of the pressure and velocity fields, is 6 s, and the corresponding cyclic frequency is $f \approx 1\ s^{-1}$. In one of the pieces of evidence given in [2, 3], an approximate soil oscillation frequency in the vicinity of tornadoes is estimated to be 0.1 Hz. This correlates with the above approximation of the pressure field fluctuation frequency in tornadoes.

The amplitude of fluctuations of the force acting on the soil is $F = p'S$, where $S = \pi R^2$ is the area of contact between the vortex and underlying surface. If we assume that $p' \sim \Delta p$, the force in the estimate given above F is 10^9 N. Let us remember for purposes of comparison that a seismic vibrator with an amplitude of a force of 100 t [10], which is a very effective generator of seismic waves, is 1000 times smaller. Seismic waves generated by such a vibrator are reliably recorded at a distance of 50 km. Moreover, acoustic waves from such a source at the same distance of 50 km affect the soil with such an intensity that they generate recordable seismic signals [10].

The amplitude of the seismic waves considered here can be estimated from the solution of the Lamb's problem for half-space [11, 12]. It is also possible to use similar calculations in the case of seismic vibrators (see, for example [13]). In the most interesting limiting cases (near or away from the source), estimates can be obtained without analyzing cumbersome integrals.

Transverse deformation of the surface caused by the influence of the localized stationary force F normal to the surface is expressed by relation [14]

$$u = \frac{(1-\sigma^2)F}{\pi E r}, \qquad (3)$$

where σ is Poisson's coefficient. This relation can be used also in the quasi-stationary case (proximal zone) at horizontal distances much greater than the source size (tornado radius) but many times smaller than the seismic wavelength. In the example considered here, the wavelength is 6 km at wave velocity $c = 10^3$ m/s. Evidence for this is most frequently related to distances not exceeding 1–2 km, i.e., the proximal zone mentioned above. Thus, the analysis of the solution is of significant interest. Let $E = 10^{10}$ Pa; the σ^2 value is usually much less than unity, so we can neglect it in (3). At a distance of r = 1 km, we get from (3) that the amplitude of vertical deformation of the surface is $u \approx 40$ μm in the numerical example considered above. The amplitude of vertical velocity of fluctuations fu is ~40 μm/s. According to [3] and some data in the literature, the velocity of the vibrations necessary for them to be perceived by observers is approximately six times greater (0.25 mm/s). Thus, it is possible that soil vibrations would not be perceived directly in the example considered above. We must keep in mind that this example is not related to the most intense tornado of class F3, according to Fudzita's scale [2, 3]. A transition to class F4 tornadoes (and most of reports are related to such events [3]) changes the parameters (particularly, tornado dimensions) to such an extent that direct perception of fluctuations can basically be possible. It should be kept in mind that the fluctuation amplitude would be even greater if we assume a smaller elasticity of the soil. It is true that the value of parameter E was assumed to be relatively small in the estimate given above. Perception of soil vibration was reported by only a small number of observers, and so their observations may be related to special conditions of some sort, for example, specific properties on the ground.

In order to estimate the intensity of seismic signals in the wave zone, we can use the results from [13] based on an equation for the power of surface waves radiated by a seismic vibrator of radius R,

$$W \approx 0.822\frac{F^2 f^2}{\pi\rho c^3}. \quad (4)$$

Here, ρ is the density of the elastic medium and c is the velocity of the compression wave propagation. This equation is related to the case of a concentrated influence normal to the surface when $\frac{fR}{c} = \frac{2\pi R}{\lambda} \ll 1$. In the case of a tornado, as has been mentioned,

$$f = 2\omega = 2\frac{2\pi}{T} = 4\pi\left(\frac{2\pi R}{V}\right)^{-1} = \frac{2V}{R};$$
$$\frac{fR}{c} = 2\frac{V}{c}, \quad (5)$$

where $\omega = 2\pi/T$. In other words, Eq. (4) is valid under the assumption that wind velocity is much smaller than the seismic wave velocity.

Equation (4) is also valid for other types of waves (compression and shear) with an accuracy of dimensionless factor [13]. This equation can be also expressed by means of the tornado parameters $F = p'S = \pi R^2 p'$, $f = \frac{2V}{R}$. Substituting these last equations into (4), we get

$$W \sim \frac{4\pi p'^2 R^2 V^2}{\rho c^3}. \quad (6)$$

If we assume that the pressure fluctuation amplitude is $p' \sim \Delta p$, then, taking into account (2), we get

$$W \sim \frac{4\pi\rho_a^2 R^2 V^6}{\rho c^3}. \quad (7)$$

The dependence of the power of radiated seismic waves on the tornado intensity appears to be very strong and proportional to the wind velocity to the sixth power and the squared radius of the vortex. If we pass from a typical class F1 tornado to a class F4, Eq. (7) increases by more than five orders of magnitude.

In order to estimate seismic signals in the wave zone, let us use the dependence of the displacement amplitude on the power of the surface wave source [15]:

$$W = 4\pi^3\rho rc^2\exp(\alpha r)\frac{u^2}{(2\pi/f)}, \quad (8)$$

where α is the coefficient of seismic wave absorption. Below, we neglect absorption, because it is significant only at relatively large distances. It follows from (8), (4), and (5)–(7) that

$$u = \frac{1}{\pi c}\sqrt{\frac{W}{2\rho f r}} \sim \frac{F}{\rho}\left(\frac{f}{2\pi^3 rc^5}\right)^{1/2} \sim \frac{\rho_a}{\rho}\left(\frac{R^3V^5}{\pi rc^5}\right)^{1/2},$$

$$\frac{du}{dt} \sim fu \sim \frac{F}{\rho}\left(\frac{f^3}{2\pi^3 rc^5}\right)^{1/2} \sim 2\frac{\rho_a}{\rho}\left(\frac{RV^7}{\pi rc^5}\right)^{1/2}.$$

The amplitude depends most strongly on wind velocity in the tornado and seismic wave velocity. It rapidly increases with increasing tornado intensity. In the numerical example considered here, (V = 100 m/s) at $\rho = 2.5 \cdot 10^3$ kg/m^3 at a distance of r = 20 km from the tornado, we get $u \sim 15$ μm, $\frac{du}{dt} \sim 15$ μm/s. This is a very intense seismic signal. The table shows the Earth's surface deformation amplitudes and rates for tornadoes of different intensities in the case of a harder soil ($c = 2 \cdot 10^3$ m/s) at a distance of 20 km.[1] We note that this distance corresponds to the wave zone for the first two classes of tornado and the proximal zone, where $u \approx \frac{\rho_a V^2 R^2}{Er}$, according to (3) and (2), for classes F4 and F5.

It is likely that creating more effective mechanisms of seismic signal generation related to tornadoes in the frequency range considered here is in essence impossible, since practically all the available potential tornado energy can be used to generate coherent signals by means of this mechanism. For comparison, the main mechanism considered in [2, 3] is *a forteriori* weaker because we considered uncorrelated turbulent pressure fluctuations at lesser spatial scales with amplitudes definitely much smaller than Δp. In order to make more confident conclusions, it is necessary to make further experimental and theoretical studies of large-scale pressure fluctuations in tornadoes.

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