Atmospheric acoustic-gravity waves associated with severe local thunderstorms, tornadoes, and hurricanes can be studied through the coupling between the thermosphere and the troposphere. Reverse group ray tracing computations of acoustic-gravity waves observed by an ionospheric Doppler sounder array, show that the wave sources are in the neighborhood of storm systems and the waves are excited prior to the storms. It is suggested that the overshooting and ensuing collapse of convective turrets may be responsible for generating the acoustic-gravity waves observed. The results of this study also show that the study of wave-wave resonant interactions may be a potential tool for investigating the dynamical behavior of severe storm systems using ionospheric observations of atmospheric acoustic-gravity waves associated with severe storms.

1. Introduction

The ionosphere is capable of sustaining a large number of wave phenomena, waves propagating downward from the magnetosphere, waves propagating upward from the neutral lower atmosphere, etc. The general characteristics of atmospheric waves propagating in the ionosphere have been reviewed by KATO (1976). In this paper, we are particularly interested in the study of ionosphere-troposphere coupling during time periods of severe storms through the analysis of ionospheric observations of atmospheric waves propagating upward from the troposphere. These atmospheric waves are observed on ground-based ionospheric sounding records as perturbations in the electron density.

The correlation between atmospheric acoustic-gravity waves and severe storms has been investigated during the past twenty years. TEPPER (1950, 1954), MATSUMOTO and AKIYAMA (1969), MATSUMOTO and TSUNEOKA (1969), MATSUMOTO et al. (1967a, b), and UCCCELLINI (1975) all proposed that acoustic-gravity waves are an important mechanism for triggering severe convective storms.

Similar results have also been reached from studies of ionosphere observations in which GEORGES (1968, 1973), DAVIES and JONES (1972), SMITH and HUNG (1975), and HUNG and SMITH (1977a, b) showed a correlation between ionospheric wave-
like disturbances and severe weather activity. Recent studies of Hung et al. (1978a, b) indicated a close correlation between atmospheric acoustic-gravity waves and tornado activity. The possibility of using these observations of acoustic-gravity waves as a warning system for severe storms has been discussed by Hung and Smith (1978).

Acoustic-gravity waves at ionospheric heights are observed when severe thunderstorms with tops (radar heights) in excess of about 12 km are within a radius of several hundred kilometers of the ionospheric reflection points (Georges, 1976; Prasad et al., 1975). Malkus (1960) and Saunders (1962) reported that convective regions imbedded in the stratiform anvils of thunderstorms and eye clouds of hurricanes clearly penetrated the tropopause. These observations suggest that the acoustic-gravity waves observed at ionospheric heights are generated by intense convection associated with severe thunderstorms, tornadoes and hurricanes. In such a case, intense updrafts impinge upon and penetrate the tropopause and thereby generate outward and upward propagating acoustic-gravity waves. When the results of Shenk's (1974) analysis of overshooting convective turrets are used in a turbulent flow model of wave excitation proposed by Lighthill (1952, 1954, 1962, 1967), waves with the same period as those apparently associated with severe thunderstorm activity observed in the ionosphere can be generated.

The transformation of the atmospheric acoustic-gravity waves associated with thunderstorms to those associated with tornadoes through wave-wave resonant interactions will be discussed.

2. Analysis of Ionosphere Observations

The ground-based ionosphere observation technique uses radio receivers located at a central site to monitor signals transmitted from three independent remote sites and reflected off the ionosphere approximately half way between the transmitter and receiver sites. When the electron density profile in the ionosphere is perturbed, the total phase path of the radio signal changes resulting in an instantaneous frequency shift in the received radio signal.

The ionospheric Doppler sounder array system employed in this study consists of three sites with nine field transmitters operating at 4.0125, 4.759 and 5.734 MHz. These sites are located in the Tennessee Valley area. A detailed description of the array system has been given by Hung et al. (1978a).

The observed data were subjected to both power spectral density and cross correlation analyses. On some days with severe storm activity, the power spectral density analysis revealed more than one peak. When this occurred, Butter worth's digital filter (Otnes, 1968) was applied to band pass the peaks. After using this digital filter, each peak was found to correspond to a wave from a separate source. Thus, we were able to detect waves from several different sources during the same time period. The horizontal wave vectors and horizontal phase velocities of each of the disturbances were calculated from cross correlograms.
The azimuthal angle of wave propagation was determined to an accuracy of \( \pm 5^\circ \), and the horizontal phase velocity to \( \pm 10\% \).

Ionosphere observations made by Baker and Davies (1969), Davies and Jones (1972), Smith and Hung (1975), Georges and Greene (1975), Georges (1976), Jones and Georges (1976), and Hung and Smith (1977a, b) shows that quasi-sinusoidal oscillations, with two harmonics of wave periods, 3 to 5 min and 6 to 9 min, are observed during time periods with thunderstorm activity.

Analyses of six sets of data from the extreme tornado outbreak of April 3, 1974, showed that gravity waves with wave periods of 11 to 15 min and 26 to 30 min, horizontal wavelengths in the range 100 to 220 km, and horizontal phase speeds in the range 90 to 220 m/sec were closely associated with tornadic storms (Hung et al., 1978a for details).

Five isolated tornadic storms, two on November 20, 1973 and three on January 13, 1976 were also analyzed. Results are similar to those for the data from April 3, 1974 with waves with periods of 10 to 15 min and 25 to 30 min, horizontal wavelengths in the range 120 to 290 km and horizontal phase speeds in the range 100 to 220 m/sec present (Hung et al., 1978b for details).

Analyses of data obtained during two different time periods during the life of Hurricane Eloise on September 23, 1975, showed that gravity waves with wave periods of 20 to 24 min, and wavelengths from 220 to 300 km, and horizontal phase speeds from 150 to 200 m/sec were present (Hung et al., 1978c for details).

3. Reverse Ray Tracing and Wave Sources

Theoretical discussions of group rays of atmospheric acoustic-gravity waves by Bretherton (1966), Jones (1969), Cowling et al. (1971), and Bertin et al. (1975) indicate that the geometrical optics approximation is valid and the wave is assumed to be locally plane so that a local dispersion relation of atmospheric acoustic-gravity waves, proposed by Hines (1960), is satisfied. Ray tracing can then be carried out by following the group velocity in a wind-stratified model atmosphere.

Wave energy in a lossless transparent medium propagates in the direction of the group velocity (e.g., Yeh and Liu, 1972). This direction, which is termed the ray direction, in general, in an anisotropic medium is different from that of the wave vector. In the reverse ray tracing computation the group velocity is integrated with respect to the time domain from the ionospheric reflection point back down to the tropopause using the wave period, wavelength, and azimuthal direction of wave propagation obtained from the observational data, the initial vertical wave vector computed from the dispersion relation, and appropriate atmospheric parameters. The effect of wind is taken into account by considering the time-space transformation given by the Galilean transformations of the displacement vector, time, Doppler shifted wave frequency, and wave vector. The detailed description of the group ray tracing computation is given in Hung et al. (1978a).

In this study, the neutral wind is treated as constant in each slab of the atmo-
sphere considered while the values of atmospheric parameters for each altitude are calculated from the U.S. Standard Atmosphere (UNITED STATES COMMITTEE ON EXTENSION TO THE STANDARD ATMOSPHERE, 1962), and profiles of the neutral winds are established by fairing in winds computed from the KOHL and KING (1967) model above 100 km altitude with meteorological rocketsonde data from Cape Kennedy, Florida below 90 km.

Three examples of the computed group ray path of the waves (one due to the integrated effect of a group of tornadic storms, one due to an isolated tornadic storm, and the other due to a hurricane), and the locations of the wave sources are given in this study. Figure 1 shows the computed reverse group ray path of the waves observed during the 2000–2200 UT, April 3, 1974 time period, and the locations and times of four tornado touchdowns where the actual data were provided by the National Severe Storm Forecast Center. As shown in this figure, the tornado touchdown time for event No. 1 was 2125 UT; event No. 2, 2130 UT; event No. 3, 2130 UT; and event No. 4, 2145 UT, April 3, 1974. The wave traveling time from the computed wave sources to the receivers at Huntsville, Alabama was 1 hr and 52 min. From the comparison of tornado touchdown times (2125–2145 UT) with wave observation time (2000–2200 UT) and wave propagation from source to observation point (112 min), it can be concluded that the signal was excited roughly 2–3 hr ahead of the touchdown of the tornadoes. Figure 2 is a radar summary, provided by the National Weather Service, for the 1935 UT, April 3, 1974 time period, which corresponds to the time when the ionospheric disturbances observed during the 2000–2200 UT time period, at Huntsville, Alabama were excited. It clearly indicates that the tops of thunderstorms are significantly above the tropopause in the Indiana area. This example shows that the observed gravity waves are a precursor phenomena due
to the integrated effect of a group of tornadic storms which occurred approximately at the same time and at the same region.

Figure 3 shows the reverse ray tracing results for the observed gravity waves associated with the isolated tornadic storm during the 2130–2330 UT, January 13,
1976 time period. In this case, since the wave traveling time from the computed probable source to the receivers at Huntsville, Alabama was 55 min and the actual touchdown time was 2245 UT, the signal was excited more than one hour prior to touchdown. The actual tornado touchdown location is well within the \( \pm 5^\circ \) accuracy in the determination of the azimuthal angle of propagation of the wave.

Figure 4 shows the horizontal ray path and the geographical location of the probable source of the waves associated with Hurricane Eloise, which were detected during the 0200–0340 UT time period, September 23, 1975. The computed source is right on the storm track at 0600 UT, September 23, 1975. The calculated traveling time of this wave from the probable source to the receivers was 88 min. Thus, in this case, the waves were excited about 4 hr ahead of the storm.

4. Mechanism of Wave Generation and Resonant Interactions of Waves Associated with Storms

Results reported by Georges (1973), Prasad et al. (1975), etc., showed that ionospheric wave-like disturbances were associated with thunderstorms with tops in excess of about 12 km within a radius of several hundred kilometers from the observation points or only when intense updrafts penetrated the tropopause. A similar structure was proposed by Saunders (1962), that the convection regions imbedded in the stratiform anvil of the thunderstorms are clearly the overshooting convective cells which penetrate the tropopause. Observation of the hurricane eyewall by radar echoes made by Malkus (1960) also indicate that the wall cloud penetrates well above the tropopause. By taking photographs from a U-2 airplane flying over the thunderstorms, Vonnegut et al. (1966), also showed that convective overshooting turrets rose above the anvil cloud and penetrated the tropopause.
From a fluid dynamics point of view, Lighthill (1952, 1954, 1962, 1967) indicated that gravity waves could be generated by tongues of turbulence penetrating above the turbulent convection zone. This suggests that the overshooting and collapsing convective turrets may be responsible for the generation of the atmospheric acoustic-gravity waves. The relationship between the dynamics of the penetration of intense convection and waves with wave period $\tau$ based on the turbulent flow model proposed by Lighthill (1952, 1954, 1962, 1967) is given by

$$\tau = \frac{h}{\langle u \rangle}$$

where

$$\langle u \rangle = (\bar{u}^2)^{1/2}.$$  

Here $h$ is the height of the penetration of the turrets above the tropopause, and $\langle u \rangle$ is the turbulent root-mean-square value of the growth (or collapse) rate of the turrets. Recently, Shenk (1974) made extensive observations of strong convective cells from geosynchronous satellite and U-2 airplane photographs. Table 1 shows the results of using the data reported by Shenk (1974) in Eq. (1). The computed possible wave periods, shown in Table 1, are in exact agreement with wave periods of the acoustic-gravity waves observed by Doppler sounder arrays (Baker and Davies, 1969; Davies and Jones, 1972; Smith and Hung, 1975; Georges and Greene, 1975; Jones and Georges, 1976).

It is known that tornadoes are closely associated with severe thunderstorms (Davies-Jones and Kessler, 1974). Our observations of gravity waves associated with tornadoes indicates that waves were observed more than one hour ahead of the touchdown of the tornadoes. These results are apparently similar to the conclusion drawn by Uccellini (1975) for the case of severe convection in which the acoustic-gravity waves are a precursor to the thunderstorms.

The evolution of tornadoes from thunderstorms could result from the wave-wave resonant interaction of two thunderstorm-induced waves. In other words, 3 to 5 min acoustic-gravity waves associated with severe thunderstorms observed in ionospheric heights (Baker and Davies, 1969; Smith and Hung, 1975; Jones and Georges, 1976) can be transformed to 11 to 14 min gravity waves associated with tornadic storms (Hung et al., 1978a; Hung and Smith, 1978), as the severe thunder-
storms developed into tornadic storms, through the wave-wave resonant interaction. If this mechanism is true, the evolution of tornadic storms from severe thunderstorms can be revealed through the study of the transformation of acoustic-gravity waves associated with severe thunderstorms to acoustic-gravity waves associated with tornadoes. To go one step further, assuming that the gravity waves associated with tornadoes are the results of the wave-wave resonant interaction of two waves associated with thunderstorms, the following conditions must be satisfied (SAGDEEV and GALEEV, 1969)

\[ \omega_1(k_1) + \omega_2(k_2) = \omega_3(k_3) \]  

where \( \omega_1, \omega_2, \) and \( \omega_3 \) denote the wave-frequencies of thunderstorm 1, thunderstorm 2, and the waves-associated with tornadoes, respectively; and \( k_1, k_2, \) and \( k_3 \) are the wave-vectors of thunderstorm 1, thunderstorm 2, and the wave-associated with tornadoes, respectively. For the resonant-interaction to be valid, \( |(\omega_1 - \omega_2)/\omega_1| \ll 1 \), and therefore the Taylor expansion is applicable to Eq. (2). This leads to

\[ \omega_i(k_i) = \omega_d(k_d) + \frac{\partial \omega}{\partial k} \cdot \Delta k \]  

where

\[ \Delta k = k_1 - k_2. \]

If we choose the negative sign in Eq. (2), substitution of Eq. (2) into (3) leads to

\[ \frac{\partial \omega}{\partial k} \cdot \Delta k = \omega_d(k_d). \]  

By definition, \( \omega_i = 2\pi/\tau_i \), where \( \tau_i \) is the wave period of species \( i \), and Eq. (2) becomes

\[ \frac{\tau_2 - \tau_1}{\tau_1 \tau_2} = \frac{1}{\tau_3} \]  

which is the relationship which must be satisfied if two thunderstorm associated waves, \( \tau_1 \) and \( \tau_2 \), are to be able to interact resonantly and generate the waves with period \( \tau_3 \) detected at ionospheric heights. For example, thunderstorm-induced waves, with a wave period of 3 min, interacting resonantly with other thunderstorm-induced waves with a wave period of \( \tau_2 \approx 3.896 \text{ min} \) can generate a wave with a period of 13 min. Both waves with wave periods of 3 and 3.896 min are within the range of the wave periods of acoustic-gravity waves associated with thunderstorms detected at ionospheric heights (DAVIES and JONES, 1972; SMITH and HUNG, 1975), and waves with wave periods of 13 min are in the range of wave periods of acoustic-gravity waves associated with tornadic storms (HUNG et al., 1978a; HUNG and SMITH, 1978).

Again by definition \( |k_i| = 2\pi/\lambda_i \), where \( \lambda_i \) is the wavelength of species \( i \), and Eq. (4) becomes

\[ \frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2} = \frac{1}{\tau_3} \left| \left( \frac{\partial \omega}{\partial k} \right) \right|^{-1} \]
which is another relationship between two thunderstorm-induced waves that can result in tornado-associated waves through wave-wave resonant interaction. To give a numerical example, a wave with a wave period of 13 min can be generated through the resonant interaction of a wave with a wavelength of 100 km, with another wave with a wavelength $\lambda_2 \approx 133$ km. In this example, $|\langle \partial \omega / \omega k \rangle| = 500$ m/sec, a typical group velocity from the observational data. The wavelengths of 100 and 133 km are also within the range, 100 to 300 km, of our observations of acoustic-gravity waves associated with thunderstorms and tornadoes (Davies and Jones, 1972; Hung and Smith, 1977a; Hung et al., 1978a). These two examples seem reasonable from our observational data.

The wave-wave interaction condition, Eq. (2), applies to a homogeneous medium. When the medium is inhomogeneous like the atmosphere, additional conditions must be satisfied. If $\omega = \omega(k, t, x)$ for a wave propagating in an inhomogeneous medium, the following conditions must be satisfied (Whitham, 1974)

$$\frac{\partial k_\alpha}{\partial t} + V_{sg} \frac{\partial k_\alpha}{\partial x_\beta} = - \frac{\partial \omega}{\partial x_\alpha}$$

and

$$\frac{\partial k_\alpha}{\partial x_\beta} - \frac{\partial k_\beta}{\partial x_\alpha} = 0$$

where

$$V_{sg} = \frac{\partial \omega}{\partial k_\beta} \frac{dx_\beta}{dt}$$

Here, the subscripts of the Greek alphabet, $\alpha$ and $\beta$, stand for the vector components.

5. Conclusion

Ionospheric Doppler sounder observations during time periods with severe storm activity show a coupling between the troposphere and the thermosphere. Analyses of these observations indicate that acoustic-gravity waves propagating in the ionosphere are closely related to severe storm activity with the waves apparently associated with tornadoes appearing to be excited where tornadoes touchdowned more than one hour later. Results for gravity waves associated with hurricanes show the computed sources of the waves to be located along the track and more than three hours in advance of the location of the storm.

This study demonstrates that ionospheric observations of acoustic-gravity waves can be used as a diagnostic to investigate the dynamical behavior of the severe storms which affect them. A study of wave-wave resonant interactions shows that there is a possibility that tornadoes evolve from severe thunderstorms through this mechanism. This study further indicates that a tornado cannot develop from an isolated overshooting convective turret.

Park and Dejnkarintra (1973) and Dejnkarintra and Park (1974) indicate that thunderstorm effects may be important to some ionospheric processes such as
formation of plasma ducts and the generation of hydro-magnetic waves. Davies and Jones (1972) and Hung et al. (1978a, b) also show that severe storm activity affects the $F$ region ionization. It has been suggested by Webb (1975) that a small fraction of the electrojet current closes through the lower atmosphere via thunderstorm activity to the ground. Further study of atmospheric acoustic-gravity waves associated with severe storm activity may possibly enhance our understanding of the electrical phenomena in the Earth’s upper atmosphere.

Furthermore, it is suggested that ionospheric observations of the coupling between the thermosphere and the troposphere may provide a technique for the early observation and possible short range prediction of severe storm activity.

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