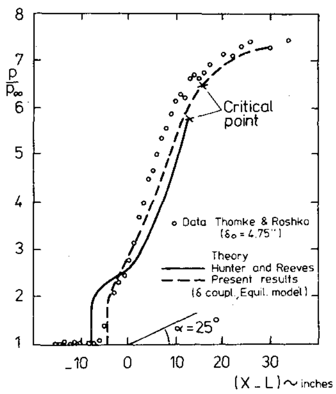

Fig. 1 Comparison of experimental and theoretical pressure distribution (ramp-$M_\infty = 4$).

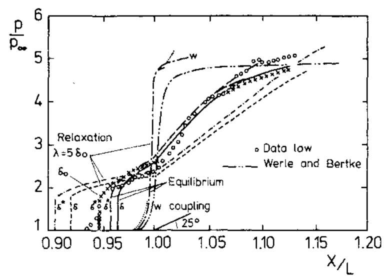

Fig. 2 Effects of coupling and eddy viscosity models (ramp-$M_\infty = 3$).

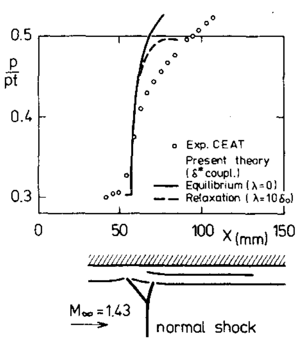

Fig. 3 Application to the transonic interaction ($M_\infty = 1.43$).

and previous Werle and Bertke[9] computations are compared with our theoretical results. The authors use a finite difference technique with δ^* coupling, equilibrium, and frozen viscosity models. A time relaxation procedure on δ^* coupling suppresses the jump. The present method, using a wall coupling, which also avoids the jump, gives similar results. The relaxation or equilibrium viscosity model does not introduce noticeable differences. The same models are used with both δ and δ^* coupling procedures. The last one seems the best, for the two turbulence representations, with an advantage for the relaxation one. Note the large influence of the relaxation length λ for the same δ^* coupling. The principal conclusion is the improved capability of the δ^* coupling/relaxation turbulence integral method to compute an interaction in good agreement with experimental results.

The first attempt to apply this method to the normal shock wave-turbulent boundary-layer interaction is shown in Fig. 3. Experimental results were obtained[10] by a normal-shock blockage ("second throat" type) of a 65×85 mm^2 test section at $M = 1.43$ and for $R_e = 10^5$/m. Static pressure is measured on the tunnel wall. The calculations are conducted only for the supersonic external flow region using a δ^* coupling. The location of the interaction is fixed by adjustment of the pressure after the jump to the experimental value. Compare the results for a large relaxation parameter ($\lambda = 10\delta_0$) with that obtained for equilibrium turbulent viscosity ($\lambda = 0$). The transonic external flow calculations are presently being continued and viscous-inviscid coupling being studied in order to give an assessment of the method for rapid computation in practical transonic cases.

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Ionospheric Doppler Sounder for Detection and Prediction of Severe Storms

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Introduction

THE correlation of atmospheric acoustic-gravity waves and severe storms has been investigated sporadically during the past twenty years. Tepper[1,2] proposed that the

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pressure jump lines effectively lifted the lowest layers of the atmosphere and appeared to initiate squall line development in convectively unstable air. Matsumoto and his colleaques[3-6] contended that atmospheric acoustic-gravity waves were responsible for a pulsating tendency of winter and summer convective storms in western Japan. Uccellini[7] also proposed that atmospheric acoustic-gravity waves were an important mechanism for triggering severe convective storms. He also suggested that the study of atmospheric acoustic-gravity waves could reveal much about the development of thunderstorms.

Experimental observations from cw Doppler soundings of the upper atmosphere have shown that these ionospheric disturbances are apparently associated with severe weather and thunderstorms.[8-15]

During the extreme tornado outbreak of April 3, 1974, Hung et al.[16] detected another two harmonics of wave periods—11-15 min and 26-30 min. On this particular day, 236 tornadoes were recorded in the United States. Among these, 41 tornado touchdowns were identified by the National Severe Storms Forecast Center (NSSFC) within a 800 km radius from Huntsville, Ala., during the time period 1700-2200 UT. These tornadoes were divided into five groups, depending upon the touchdown time and geographical location. A ground ray path computational technique was used to trace the atmospheric gravity waves observed at ionospheric heights in an effort to locate their probable source. Results, based on six ray-tracing computations which covered the 41 tornado touchdowns, showed that the acoustic-gravity waves were excited 1-3 h ahead of the touchdown times.[16]

The analysis of the tornado outbreak of April 3, 1974, seems to indicate that the waves observed are a precursor phenomenon due to the integrated effect of a group of storms rather than a single storm. This paper presents five additional cases of waves associated with isolated tornadic storms. The results are identical in all cases.

Waves with wave periods of 20-24 min were detected when Hurricane Eloise was in the Gulf of Mexico. The computed location of the source was roughly where the hurricane was located 3 h after the waves were excited. The applicability of the Doppler array to a tornado and hurricane warning system has been discussed by Hung and Smith.[17,18]

Analytical Techniques and Ray-Tracing Computations

The data used in this analysis were obtained from the ionospheric Doppler sounder array discussed in detail in Ref. 16.

The observed data were subjected to both power spectral density (PSD) and cross-correlation analyses. The PSD analysis sometimes revealed more than one peak. When this occurred, Butterworth's digital filter[19] was applied to band-pass the peaks. After using the digital filter, each separated peak corresponds to a wave excited by an individual source. Thus, waves from many different sources in the same time period can be detected, identified, and analyzed. The horizontal wave vector and horizontal phase velocity of each wave are calculated from cross correlograms. The azimuthal angle of wave propagation determined in this manner is accurate to within ±5 deg, and the horizontal phase velocity is accurate to ±10%.

In the six cases of April 3, 1974, gravity waves with two harmonics of wave periods, 11-15 min and 26-30 min, horizontal wavelengths in the range of 100-220 km; and horizontal phase speeds in the range of 90-220 m/s were observed.[16] Gravity waves from the five cases of isolated tornadoes, two on November 20, 1973, and three on January 13, 1976, had wave periods in the range of 10-12 min and 25-29 min, horizontal wavelengths in the range of 120-290 km, the horizontal phase speeds in the range of 140-190 m/s. Two events on September 23, 1975 indicate that gravity waves with wave periods of 20-24 min, wavelengths from 220-300 km, and horizontal phase speeds from 150-200 m/s were present when Hurricane Eloise was in the Gulf of Mexico.

Reverse ray-tracing computations were carried out to compute the sources of the gravity waves observed at ionospheric height. For a detailed discussion of the computation technique, see Ref. 16.

Source of the Waves

The reverse ray tracing, which is started at the altitude of the ionospheric reflection point, continues down to lower limit of the tropopause. The geographic location of the point at which the calculation is terminated is referred to as the probable source. These locations are then checked with the locations and times of tornado touchdowns supplied by NSSFC and the reported track of the hurricane. Results of this comparison for the six cases of April 3, 1974, indicate that the waves are excited near locations where tornadoes are observed to touchdown from 1-3 h later. Results of the same comparison for the five isolated storms are given in Figs. 1-5.

Figure 1 shows the results for the 1900-1945 UT, November 20, 1973, time period. Since the wave traveling time was 66 min and the actual tornado touchdown time was 1935 UT, the signal was excited more than 2 h prior to touchdown. The actual tornado touchdown location is well within the ±5 deg accuracy in the determination of the azimuthal angle of propagation of the wave.

Figure 2 shows the results for the 1945-2045 UT, November 20, 1973, time period. Since the wave traveling time from the

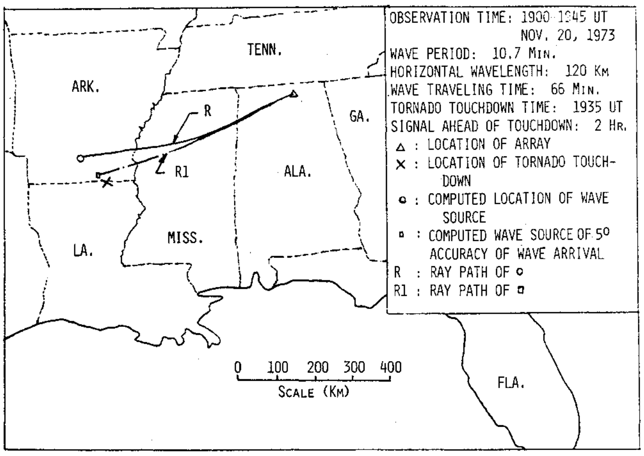

Fig. 1 Geographical map of the computed group ray path of the waves during 1900-1945 UT, November 20, 1973, and the location of actual tornado touchdown.

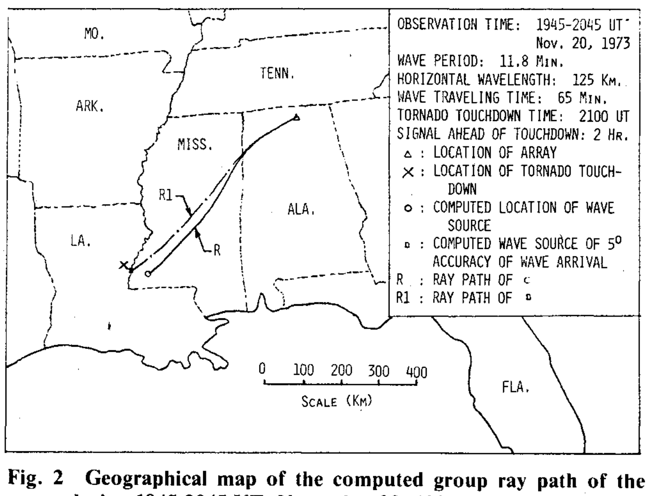

Fig. 2 Geographical map of the computed group ray path of the waves during 1945-2045 UT, November 20, 1973, and the location of actual tornado touchdown.

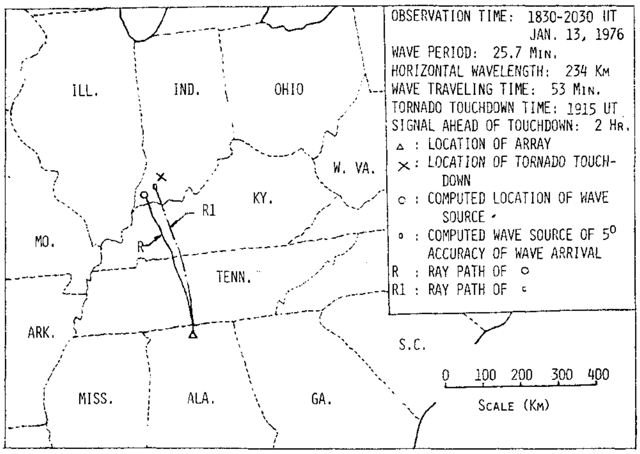

Fig. 3 Georgraphical map of the computed group ray path of the waves during 1830-2030 UT, January 13, 1976, and the location of actual tornado touchdown.

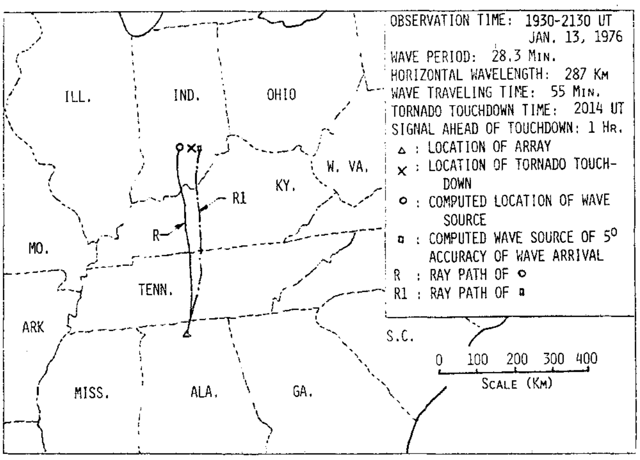

Fig. 4 Geographical map of the computed group ray path of the waves during 1930-2130 UT, January 13, 1976, and the location of the actual torndo touchdown.

computed probable source to the receivers at Huntsville, Ala., was 65 min and the actual touchdown was 2100 UT, the signal was generated roughly 2 h prior to touchdown. Once again, the actual touchdown is within accuracy limitations of the system.

Figure 3 shows the results for the 1830-2030 UT, January 13, 1976, time period. Since the wave traveling time from the computed probable source to the receivers at Huntsville, Ala., was 53 min and the actual touchdown time was 1915 UT, the signals were generated roughly 2 h prior to touchdown.

Figure 4 shows the results for the 1930-2130 UT, January 13, 1976, time period. Since the wave traveling time from the computed probable source to the receivers at Huntsville, Ala., was 55 min and the actual touchdown time was 2014 UT, the signal was excited more than 1 h prior to touchdown.

Figure 5 shows the results for the 2000-2200 UT, January 13, 1976, time period. Since wave traveling time from the computed probable source to the receivers at Huntsville, Ala., was 57 min and the actual touchdown was 2050 UT, the signal was excited more than 1 h prior to touchdown.

Two events were selected for analysis from the Hurricane Eloise records—the time periods 0200-0340 UT and 0500-0730 UT, September 23, 1975. Comparison of the computed probable sources of the observed waves with the actual storm track indicates that they were excited at the position on the track where Eloise would be located more than 3 h later.[17,20,21] Results in this instance are more debatable however, since the angle between the track of the hurricane and the direction of

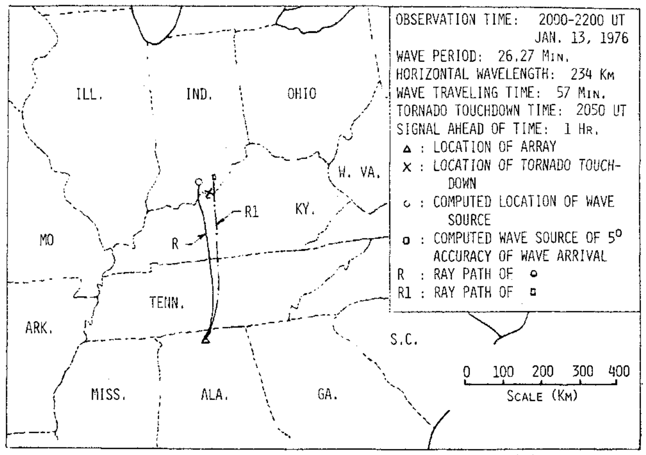

Fig. 5 Geographical map of the computed group ray path of the waves during 2000-2200 UT, January 13, 1976, and the location of actual tornado touchdown.

propagation of the waves is so small that a small error in the propagation direction causes a large error in where the signal was generated along the track and hence the delay between the time of excitation and the arrival of the storm at the location.

Discussion and Conclusions

Observation of atmospheric acoustic-gravity waves at ionospheric height and group ray-tracing computations to determine the sources of waves have been accomplished. For the gravity waves associated with tornadic storms, a comparison of the results of the computations with the locations and times of tornado touchdowns indicates that the wave sources are located in the vicinity where tornadoes touchdown more than 1 h later. For the case of gravity waves associated with hurricanes, the results indicated that the sources of the waves were located more than 3 h in advance of the location of the storm.

Results reported by Georges,[22] Prasad et al.,[10] etc., showed that ionospheric wavelike disturbances were associated with thunderstorms with tops in excess of about 12 km within a radius of several hundred kilometers from the observation point or only when intense updrafts penetrated the tropopause. A similar idea was also proposed by Malkus[23] and Saunders,[24] that the convective regions imbedded in the stratiform anvil of the thunderstorms are the overshooting convective cells which penetrate the tropopause. Using photographs from a U-2 airplane flying over thunderstorms, Vonnegut et al.[25] showed that convective overshooting turrets rose above the anvil cloud and penetrated the tropopause.[25]

From a fluid dynamics point of view, Lighthill[26-29] indicates that gravity waves can be generated by tongues of turbulence penetrating above the turbulent convection zone. This suggests that the overshooting and ensuing collapse of the convective turrets may be responsible for the generation of the atmospheric acoustic-gravity waves.[23-25] Recently, Shenk[30] has made extensive observations of strong convective cells using geosynchronous satellite data and U-2 photographs. When the result of Shenk's[30] analysis are used in the model proposed by Lighthill,[26-29] waves with the same periods as those observed by the Doppler array are excited.

This study suggests that the analysis of ionospheric Doppler sounder observations of atmospheric acoustic-gravity waves can enhance our basic understanding of the life cycle of severe storms. The more than 1 h lead time between the excitation of the waves and the actual touchdown of the tornadoes may be used in the development of a real-time detection and prediction technique.

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Gas Breakdown Thresholds in Flame Induced by Ruby Laser

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Introduction

OPTICAL diagnostic techniques such as spontaneous Raman scattering, fluorescence, and coherent anti-Stokes Raman scattering (CARS) are being developed for applications in combustion media on the strength of their potential for making nondisturbing, real-time point measurements.[1,2] These techniques require the focusing of one or more high-power laser beams into a small sample volume of a medium, in order to generate a desired optical signal in the measurement process. The intensity of the signal generated in the preceding diagnostic processes depends upon the intensity of the incident laser beam(s) in the sample volume. There is, however, a practical limit beyond which an increase in incident intensity will not result in a greater signal. One limiting process is laser-induced gas breakdown. Since gas breakdown severely disturbs the optical and physical properties of the medium through which the beams propagate, its occurrence cannot be tolerated in any optical measurement processes.

This Note reports the results of breakdown threshold measurements in flames. The experiments were performed in

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