Case Studies of Gravity Waves Associated with Isolated Tornadic Storms on 13 January 1976

R. J. HUNG AND T. PHAN

The University of Alabama in Huntsville, Huntsville, AL 35807

R. E. SMITH

Atmospheric Sciences Division, NASA/Marshall Space Flight Center, Huntsville, AL 35807

(Manuscript received 19 September 1978, in final form 15 December 1978)

ABSTRACT

Penetrative convection, thunderstorms, squall lines, etc., all generate atmospheric gravity waves which can be observed by a ground-based ionospheric Doppler sounder array. Sources of these waves can be determined from reverse ray tracing computations. Case studies of gravity waves associated with isolated tornadic storms on 13 January 1976 were summarized to establish the minimum data sampling time required for correct spectral analysis and ray tracing computations. It was concluded that the data sampling time can be reduced to two to three times the wave period while still obtaining a reasonably good power spectral density. It was also demonstrated that the data sampling time can be reduced to two to three times the time delay of the wave arrival between two station pairs while still obtaining a justifiably good cross-spectral analysis. Computed source locations of the observed gravity waves are compared with conventional and satellite meteorological data.

1. Introduction

The significance of atmospheric gravity waves in atmospheric dynamics and their excitation mechanism have been extensively studied during the past two decades. In laboratory experiments, Townsend (1964), Deardorff *et al.* (1969), Willis and Deardorff (1974) and Adrian (1975) observed that gravity waves were excited when convective elements overshot the top of a mixed layer and penetrated a short distance upward into a stable region. Curry and Murty (1974), Gossard and Sweezy (1974) and Stull (1976), among others, have suggested that thunderstorms or fronts could excite gravity waves in the atmosphere. Einaudi and Lalas (1975) indicated that gravity waves can propagate upward through the atmosphere and stimulate cloud growth. In observations of the equatorial ionosphere Röttger (1977) showed that gravity waves were associated with penetrative cumulus convection. Matsumoto and Akiyama (1969) and Uccellini (1975) have also discussed gravity waves as a mechanism for triggering severe convective storms.

There have been many observations of atmospheric gravity waves. Gossard and Munk (1954) detected gravity waves aloft using surface-based pressure and wind velocity sensors while Bean *et al.* (1973) used FM-CW radar and Browning *et al.* (1973) employed a high power pulsed Doppler radar to observe gravity waves. In recent years, CW Doppler soundings of the F-region ionosphere have been used to detect gravity waves apparently associated with severe weather and thunderstorms (Baker and Davies, 1969; Prasad *et al.*, 1975; Smith and Hung, 1975; Georges, 1973; Georges and Greene, 1975; Hung and Smith, 1977a,b).

Recently, gravity waves associated with tornado activity have been observed (Hung *et al.*, 1978a; Hung and Smith, 1978a). These observations were made with a high-frequency CW Doppler array system in which radio receivers located at a central site, NASA/Marshall Space Flight Center, monitored signals transmitted from three independent remote sites on three sets of frequencies and reflected off the ionosphere approximately half way between the transmitter and receiver sites. When the electron density in the ionosphere is disturbed and fluctuates, the total phase path of the radio signal changes and the instantaneous frequency is also shifted. During time periods with severe weather activity, wavelike disturbances are observed in the Doppler records.

The data from the Doppler sounder array are subjected to a power spectral density analysis to obtain the wave periods of these Doppler fluctuations while the direction of the propagation of the wave vector and the phase velocity of the waves are obtained from a cross-correlation analysis.

Group ray tracing computations using the best available data on the thermodynamic properties of

0021-8952/79/040460-07$05.75

the atmosphere have been employed in determining the locations of the sources of the waves. Detailed description of the observation system and the data processing techniques are given in Hung and Smith (1978a) and Hung *et al.* (1978a).

Analysis of six sets of data from the extreme tornado outbreak of 3 April 1974 showed gravity waves with wave periods of 11–15 min and 26–30 min, horizontal wavelengths in the range 100–220 km and horizontal phase speeds in the range 90–220 m s^{-1} were present in the upper atmosphere (Hung *et al.*, 1978a).

Five isolated tornadic storms, two on 20 November 1973 and three on 13 January 1976, were also analyzed. Results were similar to those for the data from 3 April 1974. Waves with periods of 10–15 and 25–30 min, horizontal wavelengths in the range 120–290 km and horizontal phase speeds in the range 100–220 m s^{-1} were present in the upper atmosphere (Hung *et al.*, 1978b).

Ray tracing results indicated that, for the case of 3 April 1974, the observed gravity waves were a precursor phenomena due to the integrated effect of a group of tornadic storms which occurred approximately at the same time and place because the waves were excited more than one hour prior to the touchdown of the tornadoes and the wave sources were located in the vicinity of the touchdown points of a group of tornadoes.

Results of the ray tracing computation for the gravity waves associated with isolated tornadoes indicate that the computed wave sources were in the vicinity of the locations where isolated tornadoes touched down more than one hour later.

The applicability of the ionospheric observation of gravity waves as a possible storm warning system is discussed in Hung and Smith (1978a,b).

This paper summarizes case studies of the gravity waves associated with isolated tornadic storms on 13 January 1976. Properly selected data sampling times, long and short, from the Doppler sounder records have been analyzed. It is shown that spectral analysis with data from longer sampling time periods produces a better quality spectrum than that obtained during a shorter sampling time period. This is because the spectrum from the shorter sampling period suffers more distortion from the so-called smoothing effect than the spectrum from the longer sampling period (Båth, 1974). Several examples are given here to illustrate the smoothing effect. Comparisons of computed locations of wave sources with the real touchdown locations of the tornadoes for cases based on spectra from the longer and shorter sampling periods are made. Errors caused by using the spectrum from the shorter sampling period are still within the reasonable range of errors if the data sampling time is on the order of two to three times or longer than that of the wave period which we would like to detect. This provides a guideline for minimizing the data sampling time period.

The results of the present study were also compared with conventional meteorological data and it was found that the excitation of gravity waves was closely related to the movement of a squall line. The computed locations of the wave sources were also compared to satellite photographs.

2. Discussion and results

The present paper discusses how we can minimize the observation time periods or data sampling times required for the detection of gravity waves associated with severe storms. It is known from spectral analysis that a correct spectrum without distortion is impossible to obtain if a limited data window is chosen. If a time window of finite length t is used, we do not get the true spectrum but instead the convolution integral, which represents a certain smoothing of the correct spectrum. The degree of smoothing depends on the window length. The shorter the window length, the stronger the smoothing effect is [see Båth (1974) for details]. The spectrum thus calculated is therefore called the average or weighted spectrum (Blackman and Tukey, 1959). In the spectral calculations of observational data, complete elimination of the window effect is impossible since there is no way to obtain an infinitely long time window. This situation is particularly true for the spectral calculations using the Doppler sounder data with a finite data sampling time. The problem existing here is how short a data sampling time can be used without compromising the results

Fig. 1 shows power spectral densities of the Nickajack Dam, Tennessee to Huntsville, Alabama ionospheric observation data for three time periods on 13 January 1976. Curve A shows results based on a 2 h data sampling period, 1830-2030 GMT. Curves B and C each are based on a 1 h data sampling period, 1830–1930 and 1930–2030 GMT, respectively. It is easy to see that curves B and C have suffered from a much stronger smoothing effect than curve A. Similarity, Fig. 2 shows another set of power spectral analysis of the Ft. McClellan, Alabama to Huntsville, Alabama data for two time periods on the same day. This figure also clearly indicates that the longer data sampling period, curve A in Fig. 2 for 1930–2130 GMT, provides a more accurate power spectrum than the shorter data sampling period, curve B for 2000–2100 GMT. Our immediate problem is how the accuracy of the wave spectrum from the shorter data sampling period affects the determination of the location of the wave source from the ray tracing computation.

On this particular day, seven waves were detected on the Doppler records. Propagation characteristics of these observed gravity waves and possible wave

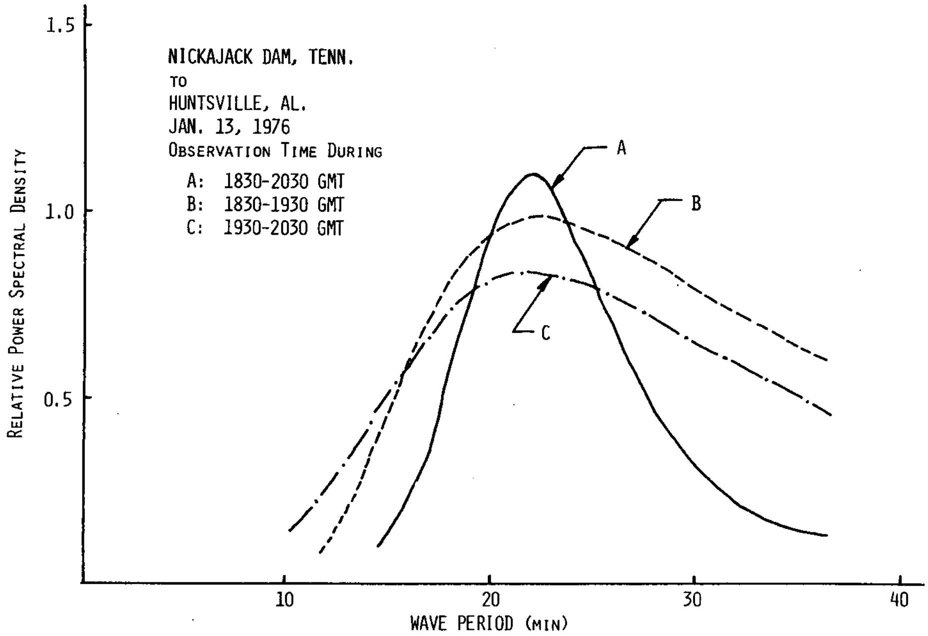

FIG. 1. Comparison of power spectral densities for data sampling time at 1830–2030, 1830–1930 and 1930–2030 GMT 13 January 1976 from Nickajack Dam, Tennessee, to Huntsville, Alabama.

sources based on the group ray tracing computations are listed in Table 1. The wave periods of the observed gravity waves associated with the tornadoes were in the range of 24 to 28 min, and the horizontal phase velocities were in the range of 148 to 200 m s^{-1}.

Fig. 3 illustrates reverse ray tracing results for the gravity waves observed during the 1830–1930, 1930–2030 and 1830–2030 GMT time periods on this day. These three observation periods correspond to the power spectral densities in Fig. 1. Even though the

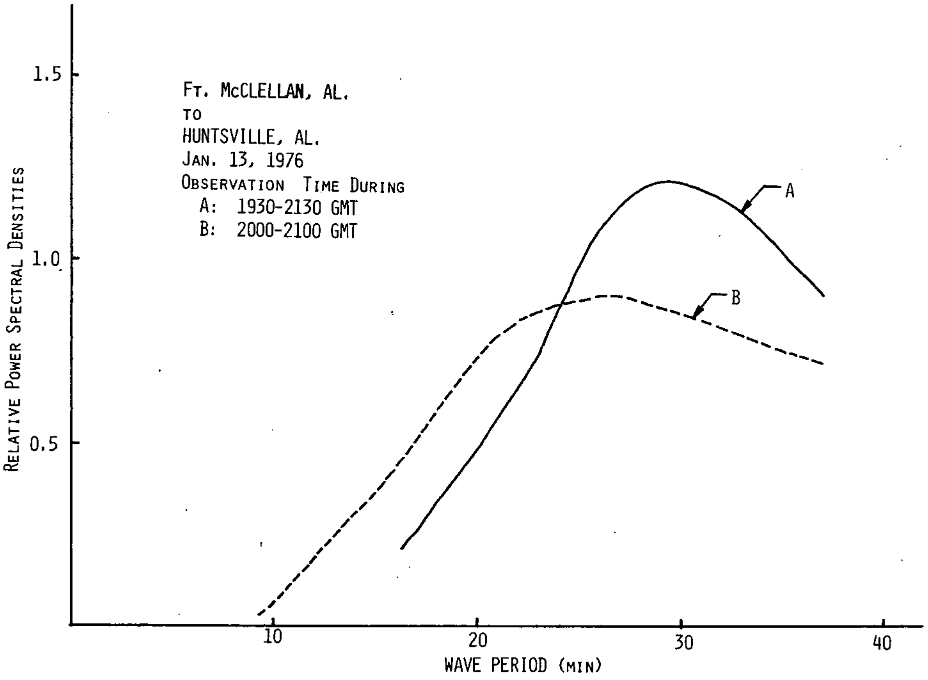

FIG. 2. Comparison of power spectral densities for data sampling time at 1930–2130 and 2000–2100 GMT 13 January 1976 from Ft. McClellan, Alabama, to Huntsville, Alabama.

Table 1. Propagation characteristics of the observed gravity waves associated with isolated tornadic storms on 13 January 1976.

Data sampling time (GMT)	Wave period (min)	Horizontal wavelength (km)	Azimuthal angle of wave arrival (deg)	Horizontal phase speed (m s^{-1})	Possible wave source (touch down time of tornado, GMT)
1830–1930	25.2	200	152	132.2	1915
1930–2030	24.8	312	162	209.6	
1830–2030	25.7	234	165	152	
1930–2130	28.3	287	179.7	169.4	2014
2030–2130	27.9	319.8	181	191	
2000–2200	26.3	234	179.9	148.8	2050
2100–2200	24	213	191	147.9	

data obtained during the shorter observation periods produced power spectra that were distorted by smoothing, Fig. 3 shows that the wave source locations compare reasonably well with the location of the wave source computed from the longer data sampling period. In this particular case, the wave travel time from the computed probable source to the receivers was 55 min and since the actual touchdown time was 1915 GMT, the waves were excited more than one hour prior to the touchdown.

Fig. 4 shows the ray tracing results for the 1930–2130 and 2030–2130 GMT time periods. These two observation periods correspond to the two data sampling times used for the power spectral density analysis in Fig. 2. The results indicate that the locations of the computed wave sources based on both data sampling periods are within the range of the accuracy of the determination of the azimuthal angle of wave propagation. This result endorses the conclusion drawn from Fig. 3. Since the wave travel time from the computed probable source to the receivers was 55 min and the actual touchdown time for this case was 2014 GMT, the signals were again excited more than one hour prior to the touchdown.

Fig. 5 shows the results of the ray tracing computations based on characteristics of waves observed during the 2000–2200 and 2100–2200 GMT time periods. The locations of the computed wave sources based on the wave spectra obtained from both sampling periods for this case are also very close and within the range of the accuracy of the determination of the azimuthal angle of wave propagation. Since the wave traveling time from the computed probable source to the receivers for this case was 57 min and the actual touchdown time was 2050 GMT, the signals were excited more than one hour prior to touchdown. From these results it appears as if we can reduce the observation periods required to insure adequate spectral analysis. The minimum data sampling time depends on the wave period and is generally at least two to

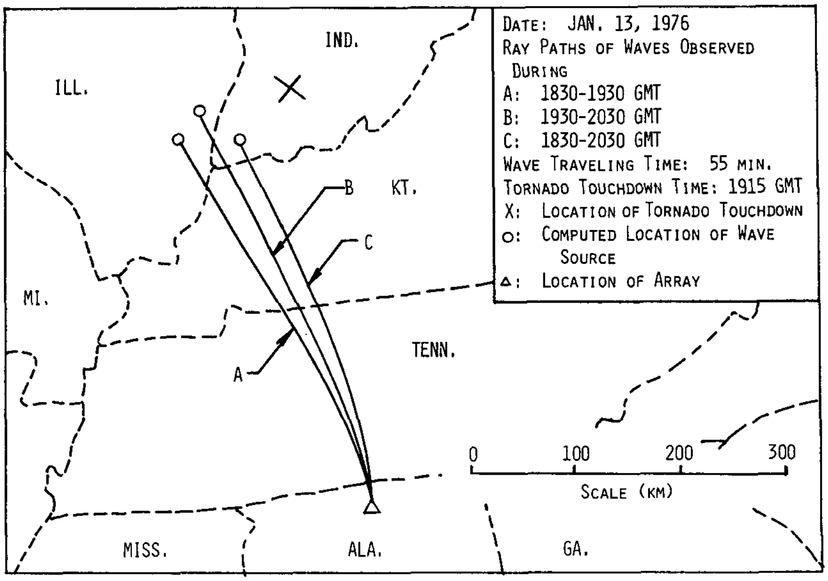

Fig. 3. Computed locations of wave sources for waves observed at 1830–1930, 1930–2030 and 1830–2030 GMT 13 January 1976, and location of tornado touchdown.

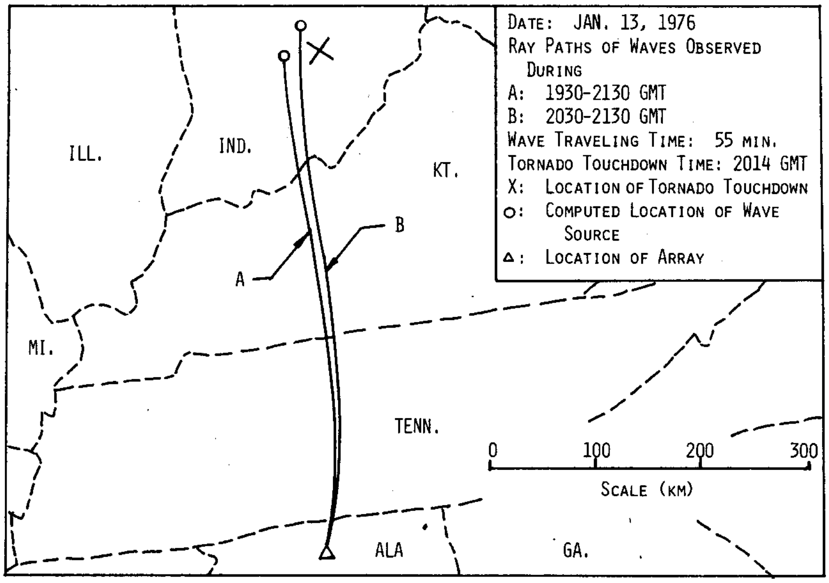

FIG. 4. Computed locations of wave sources for waves observed at 1930–2130 and 2030–2130 GMT 13 January 1976, and the location of tornado touchdown.

three times that of the wave period we would like to detect.

In these cases, the tornado touchdown locations started in the southwest section of Indiana, moved to central Indiana, and finally shifted to central southern Indiana. The movement of these storms was also reflected in the computed locations of the probable sources of the waves during the 1830–2200 GMT time period. Fig. 6 shows the movement of the squall line during the 1735–2035 GMT time period and the computed locations of the wave sources. It clearly shows that the computed locations of the wave sources were right on the squall line as it moved across southern Indiana; and that the computed locations of the wave sources shifted from the southwest section of Indiana, to central Indiana, and finally to central southern Indiana which agreed with the movement of the touchdown locations of the tornadoes.

The probable errors in the determination of the azimuthal angle of the wave arrival, and the ray tracing computation have been discussed in Hung *et al.* (1978a), Hung and Smith (1978a) and Hung and Kuo (1978). In the present case, the computed locations of the wave sources were well within the

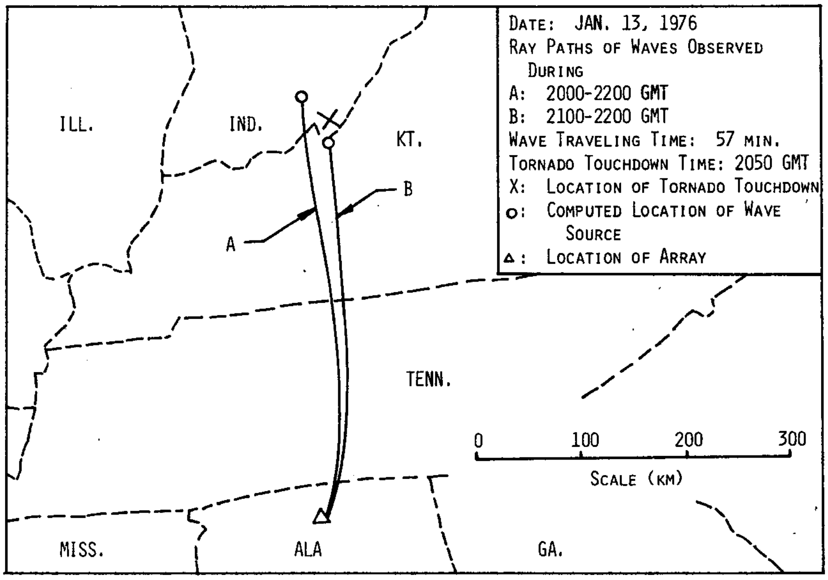

FIG. 5. Computed locations of wave sources for waves observed at 2000–2200 and 2100–2200 GMT 13 January 1976, and the location of tornado touchdown.

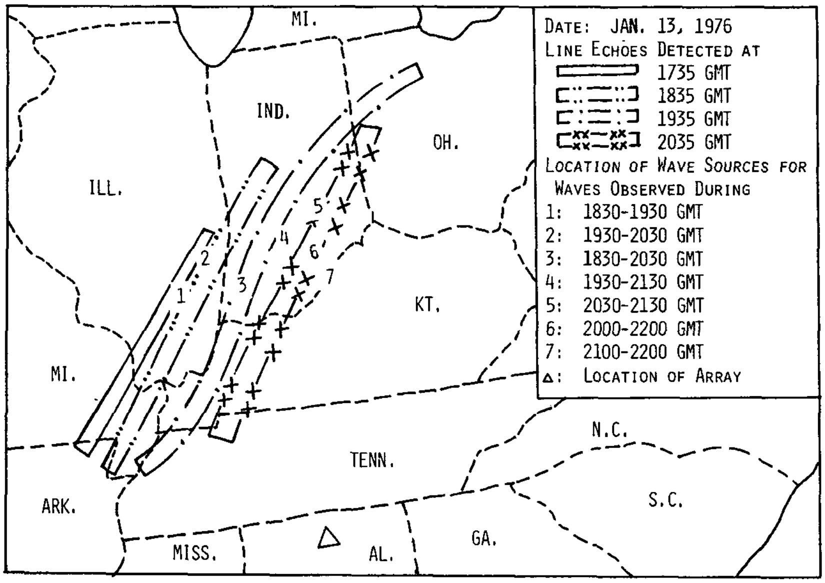

Fig. 6. Comparison of the movement of computed locations of wave sources and the movement of squall line during 1735–2035 GMT 13 January 1976, when the observed gravity waves were excited.

5° accuracy in the determination of the azimuthal angle of wave propagation. The total probable errors for ray tracing are estimated to be within ±15 km per 100 km of horizontal distance.

Studies of the mechanism that excites gravity waves indicate that gravity waves can be generated by penetrative convection (Townsend, 1964; Willis and Deardorff, 1974; Adrian, 1975; etc.). This study shows that gravity waves associated with these tornadoes were excited at the squall line, verifying the suggestions of Gossard and Sweezy (1974) and Stull (1976) that the squall line could excite gravity waves. This study further depicts that the touchdown locations of tornadoes are around the tracks of the movement of the squall line which is responsible for the excitation of gravity waves.

Fig. 7, a photograph from the Synchronous Meteorological Satellite (SMS 1) at 1700 GMT 13 January 1976, reveals, though not very clearly, that overshooting turrets were occurring at the same time the waves described in Fig. 3 were being excited.

3. Conclusions

Analyses of ionospheric Doppler sounder observations together with ray tracing computations show that gravity waves propagating in the ionosphere are clearly related to severe storm activity with the waves apparently associated with tornadoes and appearing to be excited where tornadoes touch down more than 1 h later.

Wave spectrum analyses of Doppler records from different length observation periods, or data sampling times, indicate that the longer data sampling time periods provide wave spectra with less distortion due to the smoothing effect than the shorter data sampling time periods; however, results from ray tracing computations show that the computed locations of the

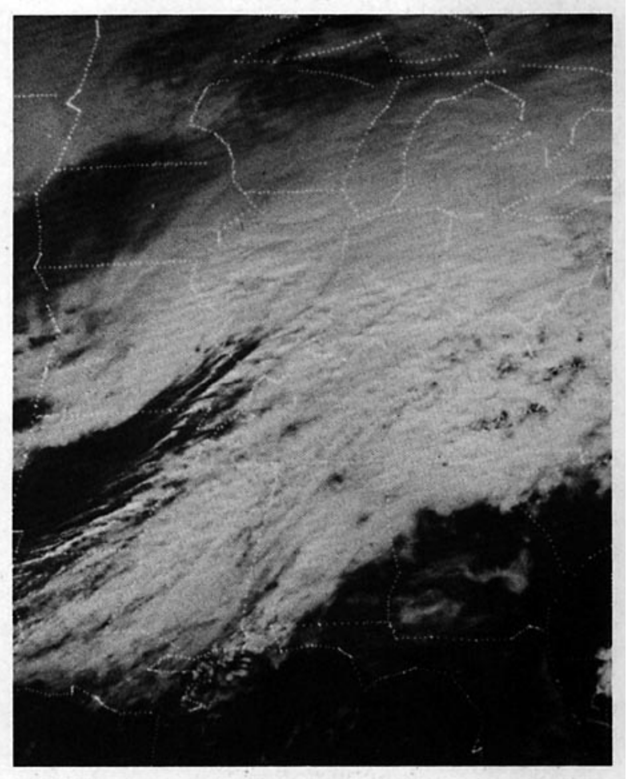

Fig. 7. Photograph from Synchronous Meteorological Satellite (SMS 1) at 1700 GMT 13 January 1976, showing overshooting turrets in southern Illinois and southeastern Missouri that were occurring at the times and locations as the waves in Fig. 3 were being excited.

wave sources based on the spectra obtained from the shorter data sampling periods are very close to those based on the spectra from the longer sampling times as long as the data sampling time is two to three times the wave period. This conclusion suggests that it may be possible to minimize the observation periods required to insure adequate identification of the wave characteristics.

To shed more light on this conclusion, a 30 min data sampling period, which is on the order of the wave period in the present case, was analyzed. It was found that the standard deviation of the power spectral density is on the order of the amplitude of power spectral density. This is because the standard deviation of the spectrum is proportional to the square root of maximum time lag divided by the total number of sampling data (Båth, 1974). This means that the standard deviation of the power spectrum increases significantly when the data sampling period is on the order of the wave period. On the other hand, the result of the cross correlation was reasonably good even though the data sampling period was on the order of the wave period. This is because the time delay of the wave arrival between the two station pairs in the present case was less than half the data sampling time. This also means that the direction of the gravity wave propagation can be determined reasonably well so long as the data sampling time is two to three times the time delay of the wave arrival between two station pairs.

Comparison of the computed locations of the wave sources associated with tornadic storms and conventional meteorological data, in particular the dynamical behavior of the squall line, shows that the wave sources were always located right on the squall line near the touchdown points of the tornadoes. Close examination of the geosynchronous satellite photographs reveals that overshooting turrets were occurring at the same time that the gravity waves were being excited.

The results of the present study suggest that ionospheric observations combined with conventional meteorological data and satellite photographs of convective overshooting turrets, can be used to develop a new remote sensing technique for the detection and prediction of severe storms.

Acknowledgments. Both R. J. Hung and T. Phan appreciate the support of the present research from NASA/Marshall Space Flight Center through Contract NAS8-31171 and the National Science Foundation/U.S. Army Research Office through Grant NSF/ATM75-15706.

REFERENCES

Adrian, R. J., 1975: Turbulent convection in water over ice. *J. Fluid Mech.*, **69**, 753–781.

Baker, D. M., and K. Davies, 1969: F2-region acoustic waves from severe weather. *J. Atmos. Terr. Phys.*, **31**, 1345–1352.

Båth, M., 1974: *Spectral Analysis in Geophysics.* Elsevier, 563 pp.

Bean, B. R., R. E. McGavin and B. D. Warner, 1973: A note on the FM-CW radar as a remote probe of the Pacific trade-wind inversion. *Bound.-Layer Meteor.*, **4**, 201–209.

Blackman, R. B., and J. W. Tukey, 1959: *The Measurement of Power Spectra.* Dover, 190 pp.

Browning, K. A., J. R. Starr and A. J. Whyman, 1973: The structure of an inversion above a convective boundary layer as observed using high powered pulsed Doppler radar. *Bound.-Layer Meteor.*, **4**, 91–111.

Curry, M. J., and R. C. Murty, 1974: Thunderstorm-generated gravity waves. *J. Atmos. Sci.*, **31**, 1402–1408.

Deardorff, J. W., G. W. Willis and D. K. Lilly, 1969: Laboratory investigation of non-steady penetrative convection. *J. Fluid Mech.*, **35**, 7–31.

Einaudi, F., and D. P. Lalas, 1975: Wave-induced instabilities in an atmosphere near saturation. *J. Atmos. Sic.*, **32**, 536–547.

Georges, T. M., 1973: Infrasound from convective storms: Examining the evidence. *Rev. Geophys. Space Phys.*, **11**, 571–594.

——, and G. E. Greene, 1975: Infrasound from convective storms: Part IV. Is it useful for storm warning? *J. Appl. Meteor.*, **14**, 1303–1316.

Gossard, E., and W. Munk, 1954: On gravity waves in the atmosphere. *J. Meteor.*, **11**, 259–269.

——, and W. B. Sweezy, 1974: Dispersion and spectra of gravity waves in the atmosphere. *J. Atmos. Sci.*, **31**, 1540–1548.

Hung, R. J., and J. P. Kuo, 1978: Ionospheric observation of gravity waves associated with Hurricane Eloise. *J. Geophys.*, **45**, 67–80.

——, T. Phan and R. E. Smith, 1978a: Observation of gravity waves during the extreme tornado outbreak of 3 April 1974. *J. Atmos. Terr. Phys.*, **40**, 831–843.

——, —— and ——, 1978b: Ionospheric Doppler sounder for detection and prediction of severe storms. *AIAA J.*, **16**, 763–766.

——, and R. E. Smith, 1977a: Observation of upper atmospheric disturbance caused by hurricanes and tropical storms. *Space Research*, Vol. 17, Pergamon, 205–209.

——, and ——, 1977b: Study of stratospheric-ionospheric coupling during time periods of thunderstorms and tornadic storms. *Space Research*, Vol. 17, Pergamon, 210–216.

——, and ——, 1978a: Ray tracing of gravity waves as a possible warning system for tornadic storms and hurricanes. *J. Appl. Meteor.*, **17**, 3–11.

——, and ——, 1978b: Dynamics of severe storms through the study of thermospheric-tropospheric coupling. *J. Geomag. Geoelectr.*, **30** (in press).

Matsumoto, S., and T. Akiyama, 1969: Some characteristic features of the heavy rainfalls observed over the western Japan on July 9, 1967, Part I: Mesoscale structure and short period pulsation. *J. Meteor. Soc. Japan*, **47**, 255–266.

Prasad, S. S., L. J. Schneck and K. Davies, 1975: Ionospheric disturbances by severe tropospheric weather storms. *J. Atmos. Terr. Phys.*, **37**, 1357–1363.

Röttger, J., 1977: Travelling disturbances in the equatorial ionosphere and their association with penetrative cumulus convection. *J. Atmos. Terr. Phys.*, **39**, 987–998.

Smith, R. E., and R. J. Hung, 1975: Observation of severe weather activities by Doppler sounder array. *J. Appl. Meteor.*, **14**, 1611–1615.

Stull, R. B., 1976: Internal gravity waves generated by penetrative convection. *J. Atmos. Sci.*, **33**, 1279–1286.

Townsend, A. A., 1964: Natural convection in water over an icy surface. *Quart. J. Roy. Meteor. Soc.*, **90**, 248–259.

Uccellini, L. W., 1975: A case study of apparent gravity waves initiation of severe convective storms. *Mon. Wea. Rev.*, **103**, 497–513.

Willis, G. E., and J. W. Deardorff, 1974: A laboratory model of the unstable planetary boundary layer. *J. Atmos. Sci.*, **31**, 1292–1307.