Gravity Waves and GOES IR Data Study of an Isolated Tornadic Storm on 29 May 1977

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ABSTRACT

Enhanced convection-initiated gravity waves associated with an isolated tornado in the absence of a squall line are investigated. Ray-tracing computations based on data observed on 29 May 1977 indicated that the wave sources were located in north-central Oklahoma. Comparison with a radar echo map during the time period when the waves were excited showed that the waves were generated by an isolated cloud with enhanced convection. GOES infrared digital data during the time period from wave excitation to tornado touchdown were analyzed. Results showed that the cloud where the gravity waves were excited was characterized by both a very low temperature at the cloud top and a very high expansion rate of the cold cloud-top area. The lead time between the excitation of the gravity waves and the tornado touchdown is discussed in conjunction with the growth rate of the clouds associated with the tornado.

1. Introduction

Association of gravity waves with enhanced convection in thunderstorms and fronts has been suggested by Curry and Murty (1974), Gossard and Sweezy (1974), Stull (1976) and others. Einaudi and Lalas (1975) indicated that gravity waves can propagate upward through the atmosphere and stimulate cloud growth. Uccellini (1975) proposed that gravity waves were an important mechanism for triggering severe convective storms.

To detect gravity waves, Gossard and Munk (1954) employed surface-based pressure and wind velocity sensors, Bean *et al.* (1973) used FM-CW radar, while Browning *et al.* (1973) exploited high-power pulsed Doppler radar waves. In the past ten years, CW Doppler soundings of the F-region ionosphere have been used to observe 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). Rice and Sharp (1977) made a study of gravity waves in the Atmospheric Explorer-C (AE-C) satellite by using cold cathode ion gage data and noted that their occurrence patterns were spatially correlated with the locations of strong tropospheric wind shears associated with subtropical jet streams.

In the study of enhanced convection and other mesoscale activity, geosynchronous satellite data provides a potentially powerful tool. Purdom (1976) has noted that intersecting cloud lines observed from GOES imagery can be used in mesoscale forecasting of convection and thunderstorms. Sikdar *et al.* (1970) have used ATS-3 visible data to measure thunderstorm anvil expansion rates. Adler and Fenn (1978) showed examples of cold area expansion rates related to thunderstorm growth using SMS window channel IR data. These measurements were for areas smaller than entire cirrus anvils and provide a technique to monitor individual thunderstorms rather than a group of storms under a large cirrus shield. By using the technique employed by Alder and Fenn (1978), one can compare the growth rate of individual thunderstorms at cirrus anvils with the location of the source of gravity waves detected by the Doppler sounder array.

Recently, gravity waves associated with tornado activity (Hung *et a.*, 1978a; Hung and Smith, 1978) and hurricanes (Hung and Kuo, 1978) have been observed. 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. By using a ray-tracing technique, more than 20 case studies have shown that most of the enhanced convection-initiated gravity waves associated with tornadoes were generated by thunderheads embedded in a squall line (Hung *et al.*, 1979a,b). This is a study of the en-

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hanced convection-initiated gravity waves associated with an isolated tornado without the presence of a squall line. The gravity waves associated with this isolated tornado are compared to those from the tornadoes embedded in squall lines.

In this study, we are particularly interested in the analysis of the change of cloud top temperature with respect to time for the clouds associated with the source of the gravity waves compared to the clouds which were not associated with gravity wave generation. GOES IR digital data during the time period between the excitation of the gravity waves and the touchdown of the tornado were used in this analysis.

2. Gravity wave observations and clouds with intense convection from radar echoes

During time periods with severe weather activity, wavelike disturbances are observed in high-frequency CW Doppler records. The data from the Doppler sounder array are subjected to a power spectral density analysis to obtain wave periods of these Doppler fluctuations while the direction of the propagation 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 the atmosphere are used in determining the locations of the sources of the waves. A detailed description of the observation system, the data processing techniques, wind data and atmospheric models used in ray-tracing computation are given in Hung and Smith (1978) and Hung *et al.* (1978a).

For the gravity wave study, the probable errors in the determination of the azimuthal angle of the wave arrival and the ray-tracing computation have been discussed by Hung *et al.* (1978a), Hung and Smith (1979) and Hung and Kuo (1978). In this case the actual location of the tornado touchdown is within the ±5° accuracy in the determination of the wave propagation vector.

Based on the analysis of more than 20 cases of gravity waves associated with tornadic storms, two types of gravity waves have been detected. The first type is the enhanced convection-initiated gravity wave associated with a group of tornadoes (Hung *et al.*, 1978a; Hung and Smith, 1979), and the second is the enhanced convection-initiated gravity wave associated with isolated tornadoes embedded in a squall line (Hung *et al.*, 1978b, 1979a,b). Results of these analyses showed that the wave sources were located where the tornadoes touched down more than an hour after the waves were excited.

During the time period 0200–0245 GMT 29 May 1977, three gravity wave trains were analyzed. The propagation characteristics of these waves are listed in Table 1. The azimuthal angle of the wave propagation for these waves was 93–100° and the horizontal wavelength was in the range 113.0–123.8 km. These waves were apparently associated with one single source.

Fig. 1 shows the ray-tracing results. The computed ray paths of waves observed during different time periods were plotted and labeled as A for observation time 0200–0230 GMT, B for observation time 0200–0245 GMT, and C for observation time 0215–0245 GMT. Since the wave traveling time from the computed probable source to the wave observation point was 138–162 min and the actual touchdown time for this case was 0205 GMT, the signals were again excited more than one hour prior to the touchdown. The characteristics of the gravity waves associated with this isolated tornadic storm in the absence of a squall line are very similar to those from both the group of tornadoes (Hung *et al.*, 1978a; Hung and Smith, 1978), and also those from isolated tornadoes embedded in a squall line (Hung *et al.*, 1979a,b).

The possible error circle of ray-tracing computation, say, for ray path B for the period 0200–0245 GMT is plotted as a dashed line circle with a radius of 50 km.

The analysis of the Doppler sounder record indicated that gravity waves with wave periods of

TABLE 1. Propagation characteristics of the observed gravity waves associated with non-squall line isolated tornadic storms on 29 May 1977

Data sampling time (GMT)	Wave period (min)	Horizontal wavelength (km)	Azimuthal angle of wave arrival (deg)	Wave traveling time from source to array (h, min)	Location of wave source	Tornado touchdown location	Tornado touchdown time (GMT)
0200–0230	15.8	117.8	93	2:42	35.55°N 98.98°W	36.26°N 98.20°W	0205
0200–0245	16.0	123.8	97	2:30	35.91°N 98.20°W		
0215–0245	14.7	113.9	100	2:18	36.10°N 97.15°W		

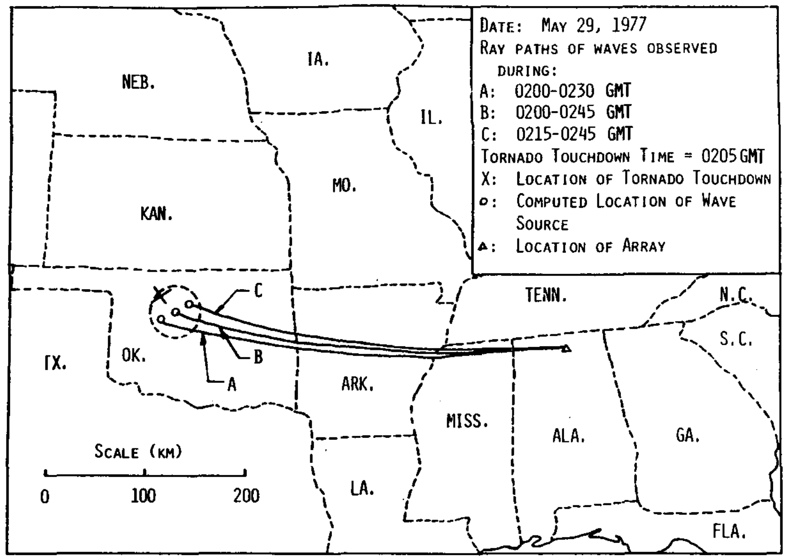

FIG. 1. Computed locations of wave sources and the location of the tornado touchdown. Curves A, B and C express the ray paths at 0200–0230, 0200–0245 and 0215–0245 GMT 29 May 1977. The dashed circle is the error circle for ray path B.

14.7–16 min, propagating from north central Oklahoma based on ray-tracing computation, were the only gravity waves detected by the Doppler record with the array system located in Huntsville, Alabama, during the time period 0100–0300 GMT 29 May 1977. Acoustic waves with wave periods of 3–5 and 6–9 min, which were believed to be excited by enhanced convection associated with severe thunderstorms [for a detailed description see Davies and Jones (1972)], were also detected in addition to enhanced convection-initiated gravity waves associated with tornadoes mentioned earlier. *Storm Data*, issued by the National Climate Center, indicated that severe thunderstorms in Kansas, Kentucky, Alabama, Georgia, etc., were observed and only one tornado was detected at north central Oklahoma during this entire time period. Based on more than 20 cases of study for enhanced convection-initiated gravity waves associated with a group of tornadoes (Hung *et al.*, 1978a; Hung and Smith, 1979), and isolated tornadoes embedded in a squall line (Hung *et al.*, 1978b, 1979a,b), wave periods of 10–16 and 25–29 min were observed at ionospheric heights; while the waves in acoustic ranges with wave periods of 3–5 and 6–9 min were detected at F-region ionospheric heights and were believed to be excited by enhanced convection associated with severe thunderstorms (Davies and Jones, 1972). These may explain why gravity waves with sources in north central Oklahoma were the only waves with periods in the range of 14–16 min, detected during this stormy day.

In the present case, the location of the computed probable source of the waves was near the location of the actual tornado touchdown in the north central section of Oklahoma. Figs. 2 and 3 show the radar weather summaries of the south central United States at 0035 and 0135 GMT, respectively, on 29 May 1977, when the observed gravity waves were being generated. These two radar echo maps show an isolated cloud with echo heights of 14.6–17.3 km located in the north-central section of Oklahoma. A comparison of the echo height of this Oklahoma cloud with the clouds all over the United States during this time period indicates that the echo height of the tornado-associated cloud is definitely greater than all the non-tornado-associated clouds; even though severe thunderstorms with enhanced convection spread over Kansas, Iowa, Kentucky, Alabama, Georgia, etc. The report also showed that one tornado touchdown at 0205 GMT was sighted in north central Oklahoma during this time period.

The comparison of the location of the wave sources on Fig. 1 and the radar echo maps (Figs. 2 and 3) indicate that the computed locations of the wave sources were in the isolated cloud associated with the severe storms.

3. Cloud-top temperature and growth rate of cloud from GOES IR digital data

GOES digital IR data from the period 0004–0203 GMT 29 May 1977 were used in this study. The period between observations was 15 min and the temperature resolution of the IR data was 1 K in the range of equivalent blackbody temperature.

In this study, a cumulative histogram is compiled starting from the cold end of the temperature distribution. The number of pixels (picture elements)

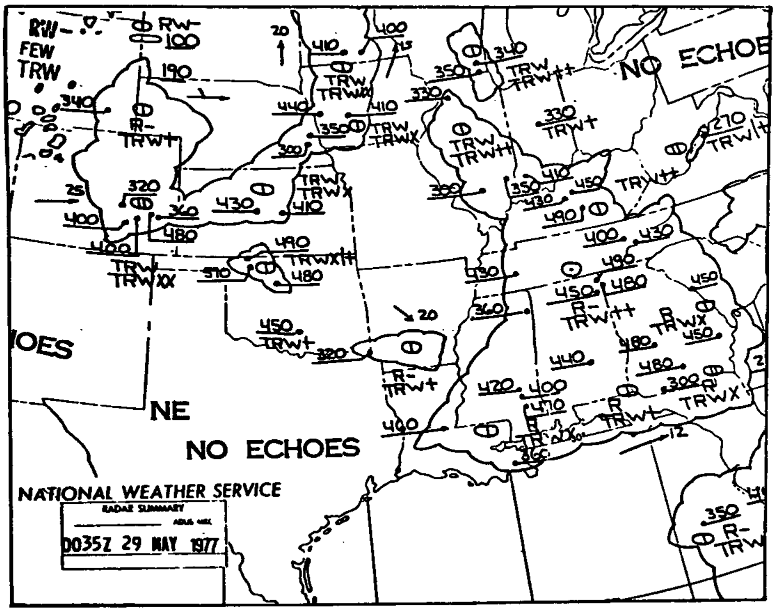

FIG. 2. Radar weather summary of the south central United States, at 0035 GMT 29 May 1977, when the observed gravity waves were being excited.

N_i with blackbody temperature equal and less than temperature T_i is obtained. Physically the number of pixels N_i is proportional to the area of the cold cloud top with temperature $\leqslant T_i$. This also provides data about the horizontal area of cloud penetrating above certain altitudes.

GOES digital IR data for the entire United States were analyzed. It was found that the isolated cloud in north central Oklahoma was the only cloud with a cloud-top temperature $\leqslant$ 204 K during the 0004–0203 GMT 29 May 1977 time period. The cloud-top temperature distribution for this cloud at 0133 GMT is shown in Fig. 4.

Several clouds with a cloud top temperature of 206 K were detected during this time period. A cirriform cloud located in southeastern Oklahoma, and a couple of clouds located in Georgia with severe thunderstorm activity shown in Figs. 2 and 3, were found with a cloud-top temperature of 206 K. Fig. 5 shows GOES IR imagery at 0030 GMT.

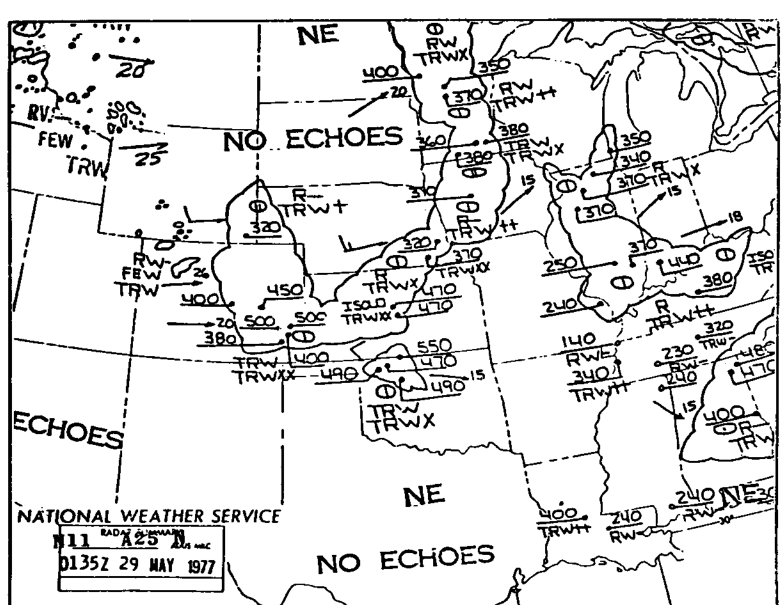

FIG. 3. As in Fig. 2 except at 0135 GMT 29 May 1977.

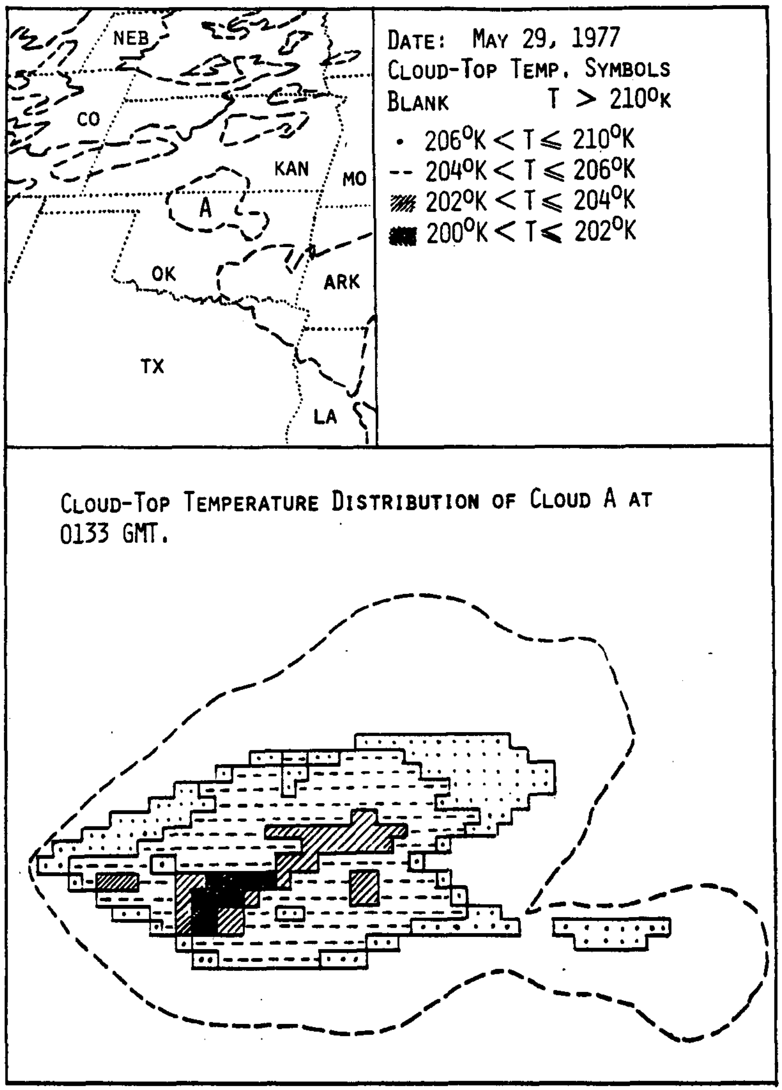

FIG. 4. The cloud-top temperature distribution of Oklahoma cloud which is the source of gravity wave excitation at 0133 GMT 29 May 1977.

The areal expansion of the cloud-top cold elements was studied. Fig. 6 shows the change in the number of areas of cloud tops at different temperature ranges during the period 0004–0203 GMT period for the clouds located in north central Oklahoma. Curve A denotes the time-dependent increase of the number of pixels at cloud top with temperatures $\leq$ 206 K; curve B implies the change of the number of pixels with temperatures $\leq$ 204 K; and curve C indicates the change of the number of pixels with temperatures $\leq$ 202 K. For the cloud area size with temperatures $\leq$ 206 K, the change is very rapid between 0033 and 0103 GMT. During this time period, a great number of gravity waves were being excited. The rate of growth suddenly slowed down after 0103 GMT. At this moment the cloud height increased and the temperature dropped to $\leq$204 K. The growth of the cold area size with temperature $\leq$ 204 K remained very rapid from 0103–0133 GMT; however, it too suddenly slowed down after 0133. At this moment, the cloud height increased once more, and the temperature dropped to $\leq$202 K. After 0148, the area of the cloud top with temperature $\leq$ 204 K started to decrease while the cold area of the cloud with temperature $\leq$ 206 K continued to increase but at a much less rapid rate. The cloud-top cold area with temperature $\leq$ 202 K had its maximum value at 0133 GMT, gradually decreased till 0148, and then sharply decreased. The tornado finally touched down at 0205, apparently as the cloud top was rapidly collapsing. This result is in good agreement with the aircraft observations made by

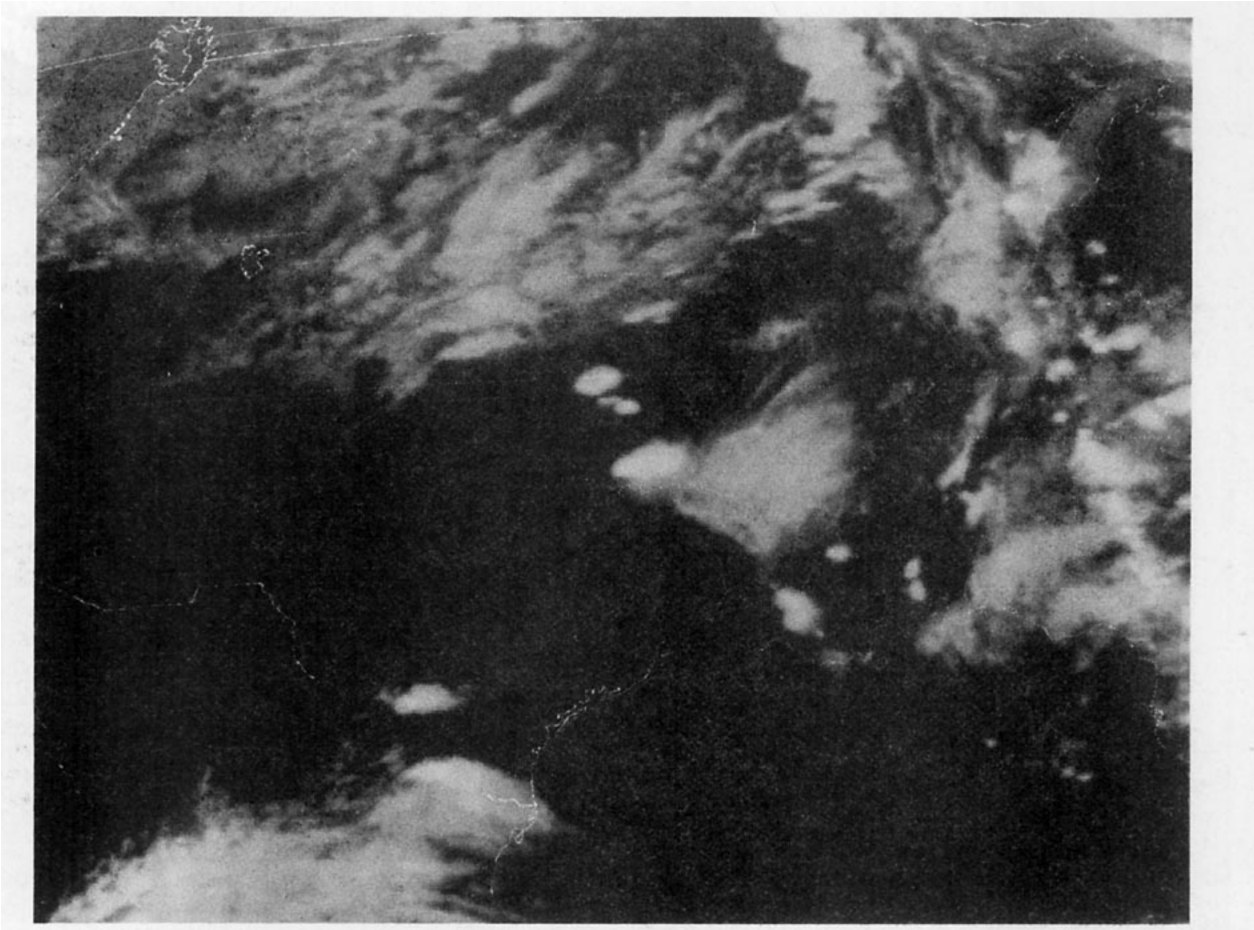

FIG. 5. Infrared image from GOES at 0030 GMT 29 May 1977, showing isolated cloud in north central Oklahoma, responsible for gravity wave generation, and the other non-tornado associated clouds.

Fujita and his associates (Fujita and Caracena, 1977a,b; Fujita and Byers, 1977).

The areal expansion of cloud tops at different temperatures characterize the growth of the height of the cloud top. Fig. 7 shows a schematic expression of the areal expansion and the growth of cloud top heights at different time periods. It clearly illustrates that the cloud grew and expanded rapidly in both vertical and horizontal directions during the time period of gravity wave excitation. The rates of the growth and expansion of cloud tops decreased gradually, and the sudden collapse of the highest portion of the cloud top began ~30 min before the touchdown of the tornado.

The following equation was used to calculate the expansion rate of the cloud:

$$\gamma_i = \frac{dN_i}{dt} \quad \text{[pixels per second]},$$

where γ_i denotes the growth rate of the cloud area with temperature $\leqslant T_i$; N_i, the number of pixels with temperature $\leqslant T_i$; and t the nominal time period between observations. Fig. 8 shows the growth rates of the cold cloud areas with temperatures $\leqslant$ 206, $\leqslant$204 and $\leqslant$202 K identified as curves A, B and C, respectively, during the time period 0004–0203 GMT for isolated clouds located in north central Oklahoma. The collapse rates or negative growth rates of the cold cloud area are shown in parentheses. Two maximum growth rates of 1.2×10^{-1} pixels per second, both for cloud areas with a temperature $\leqslant$ 206 K, occurred during the time period 0048–0103 GMT right before cloud height increased and the temperature dropped to $\leqslant$204 K; an additional peak growth rate occurred during the time period 0118–0133 GMT right before another cloud height increase and the temperature dropped to $\leqslant$202 K. Negative growth rate, which implies collapsing cloud tops, for cloud tops with a temperature $\leqslant$ 202 K appeared right after the second maximum growth rate for cloud tops with a temperature $\leqslant$ 206 K.

Similar analyses of both areal expansion and growth of cloud top height during the same time period for stormy clouds with and without tor-

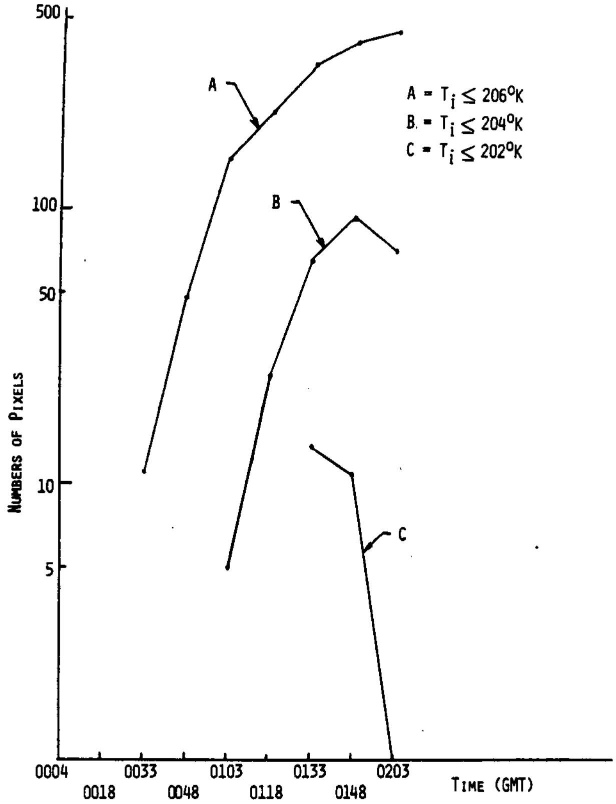

FIG. 6. Cold area expansion and vertical growth of the cloud top in terms of time change of number of pixels with temperatures ≤206 K (shown as curve A), ≤204 K (shown as curve B), and ≤202 K (shown as curve C) during 0004–0203 GMT 29 May 1977, for gravity wave-excited clouds located in north central Oklahoma.

nadoes all over the United States have been accomplished. It is found that only clouds located in Georgia had a comparable growth rate of cloud top at altitude with a temperature of 206 K; however, this Georgia cloud never had a cloud-top temperature of less than 206 K, while the cloud-top temperature of the Oklahoma cloud associated with the tornado was less than 202 K.

This comparison shows that the cloud associated with the tornado had both lower temperature and a higher areal growth rate than the clouds which were not associated with tornadoes.

This study also demonstrates that the collapse of the low-temperature region of the cloud top gives some lead time for predicting the touchdown of a tornado. In this case the lead time was ~30 min; however, this might be due to the sampling time. Further studies are needed with different data rates before definite conclusions can be drawn. The gravity waves were obviously excited during the time period when the low-temperature region of cloud top was growing rapidly. This apparently increases the lead time to more than an hour prior to the touchdown of the tornado; however, once again more cases must be analyzed before definite conclusions can be drawn.

4. Conclusions

In this study, ionospheric Doppler sounder observations of gravity waves associated with an isolated Oklahoma cloud in the absence of a squall line were investigated. Results of the analysis, in-

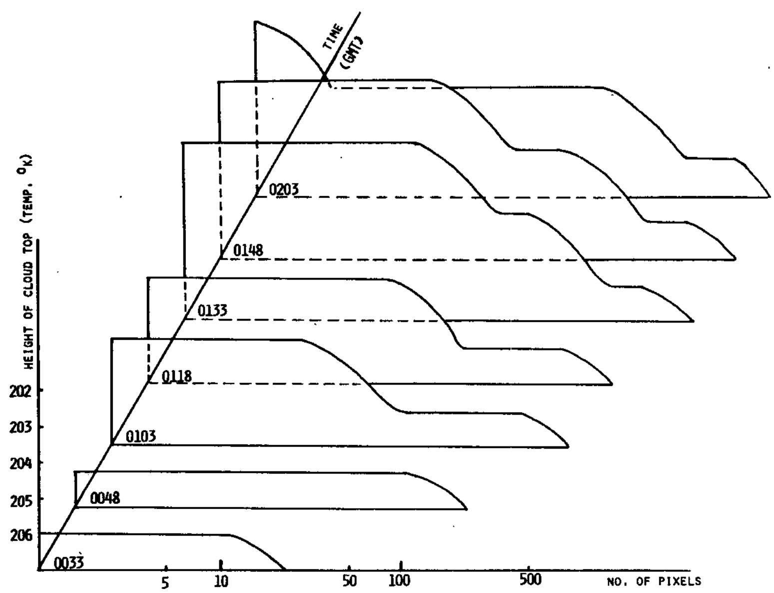

FIG. 7. Schematic expression of areal expansion and growth of cloud-top height during 0004–0203 GMT 29 May 1977 for gravity-wave-excited clouds located in north central Oklahoma.

cluding the wave characteristics, location of wave source and touchdown location of the tornadic storm, and lead time for wave excitation prior to the time of the touchdown of the tornado, were all similar to those from the analyses of enhanced convection-initiated gravity waves associated with a group of tornadoes (Hung *et al.*, 1978a) and enhanced convection-initiated gravity waves associated with isolated tornadoes embedded in a squall line (Hung *et al.*, 1979a,b).

Willis and Deardorff (1974) and Adrian (1975) observed that gravity waves can be excited by penetrative convection. The present study supports the suggestions of Gossard and Sweezy (1974), Stull (1976), etc., that isolated clouds with enhanced convection could excite gravity waves.

From the radar summaries and GOES IR digital data, it is shown that the gravity waves were associated with the most intense convection at the time. Based on the analyses from the Doppler sounder records, gravity waves with sources in north central Oklahoma, the only waves with periods in the range of 14–16 min, were observed at ionospheric heights during 0004–0245 GMT. A widespread spectra of waves with periods in the acoustic ranges of 3–5 and 6–9 min were also detected. These acoustic waves were believed to be initiated by intense convection associated with severe thunderstorms. *Storm Data* indicated that one tornado was reported in north central Oklahoma, and severe thunderstorms were observed in Kansas, Iowa, Kentucky, Alabama, Georgia, etc.

Comparison of the computed location of the source of gravity waves with radar echo maps, GOES IR digital data and *Storm Data* indicate that the gravity waves were excited by intense convection associated with tornadic storms located in north central Oklahoma.

A study of the GOES IR data during the time period between the times when the gravity waves were being excited and the touchdown of the tornado indicates that clouds associated with tornado activity are characterized by both a very low temperature at the cloud top which is equivalent to a higher penetration of the cloud top, and a very high growth rate of the cold region of the cloud top, the signature of enhanced convection in the cloud. This conclusion is drawn based on the present case study. Needless to say further studies are required with different data rates before more definite conclusions can be reached.

Comparison between gravity wave observations and GOES IR digital data analysis shows that the gravity waves were excited when the cold region or high-altitude portion of the cloud top was growing rapidly. The data available for this analysis, based on both the Doppler array and the satellite, indicate more than one hour lead time before the touchdown of the tornado. It is also shown in this analysis that the lower temperature region or higher altitude portion, of the cloud elements collapsed before the touchdown of the tornado. This result is in good agreement with the aircraft observations of overshooting tops discussed by Fujita (1973), Shenk (1974), Black (1977), Fujita and Caracena (1977a,b), Fujita and Byers (1977), etc.

It is suggested from the present study that the dynamical behavior of intense convection associated with severe storms can be studied through the investigation of gravity wave generation, together with radar observation and satellite IR digital data.

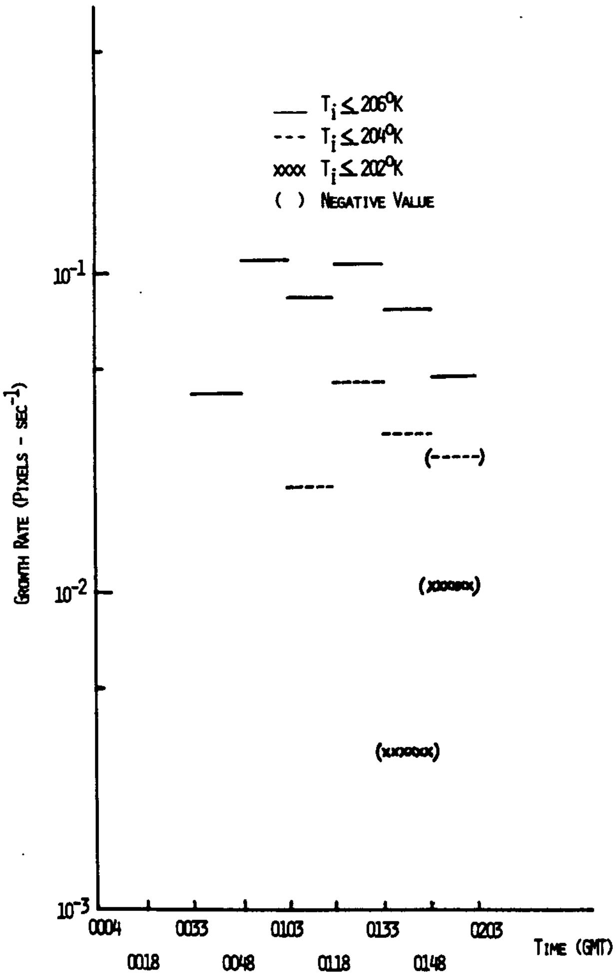

FIG. 8. Growth rate of cold cloud expansion with temperatures ≤206, ≤204 and ≤202 K during the time period 0004–0203 GMT 29 May 1977, for isolated cloud located in north central Oklahoma. The collapse rate or negative growth rate of cold cloud expansion is shown in parentheses.

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