Gravity Waves from Thunderstorms[1]

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ABSTRACT

Gravity waves generated by severe thunderstorms in the eastern Ohio-Pennsylvania area were recorded by an array of microbarovariographs at Palisades, New York and by standard microbarographs across northeastern United States. The waves were associated with the cold mesohigh from the outflow of the thunderstorms. Along their path the waves apparently triggered new thunderstorms. The waves were observed to propagate with the velocity of the wind just below the tropopause. The long-distance propagation of the waves is explained by the presence of a duct associated with the critical level (steering level), in agreement with the derivations given by Lindzen and Tung (1976). The duct was directional and waves were absent to the west of the generating area. In the generating area wave-CISK might have been operating. Sharp vertical temperature gradients associated with the passage of the waves were observed by temperature sensors on a tower.

1. Introduction

Thunderstorms are known to generate secondary disturbances in the atmosphere affecting various levels from the ground up to the ionosphere. Davies and Jones (1971) have reported ionospheric disturbances produced by severe thunderstorms. These disturbances are found to be due to acoustic waves generated by thunderstorms. Rapid mesospheric heating over Wallops Island, Virginia during late summer of 1976 is interpreted by Taylor (1979) as the result of the dissipation of vertically propagating gravity waves generated by severe thunderstorms in the troposphere.

Gravity waves from thunderstorms have been detected at the ground level by a number of workers (e.g., Curry and Murty, 1974). The importance of these waves in the troposphere is that under proper conditions they may intensify existing thunderstorms or excite new ones. This aspect of the gravity waves will be investigated further in this paper.

The exact mechanism of generation of acoustic and gravity waves by thunderstorms is far from clear. Pierce and Coroniti (1966) have proposed buoyancy oscillations of the cloud tops as one possible mechanism. A similar mechanism is suggested by Curry and Murty (1974) who have also presented ground-level observations of thunderstorm-generated gravity waves at London, Ontario. Another possible mechanism is the instability associated with strong wind shear. Also, forced waves may exist due to intense convection and liberation of latent heat (Lindzen, 1974; Lindzen and Tung, 1976).

The advent of meteorological satellites has provided a great boost to thunderstorm study. Visible and infrared cloud pictures provide the opportunity to study the formation, development and dissipation of thunderstorms along with the generation of gravity waves and other secondary phenomena associated with the thunderstorms. Erickson and Whitney (1973) have provided spectacular pictures of wave-cloud formations due to propagating gravity waves initiated by violent convection associated with thunderstorms in the southern Great Plains. Stobie (1975) has presented satellite pictures in which wave clouds are seen radiating from overshooting thunderheads in concentric patterns resembling the wave pattern produced by a pebble dropped into a calm pond. With the help of satellite film loops Thomas *et al.* (1975) have studied gravity waves generated by thunderstorms and wind shear and have evaluated the wave parameters.

During the night of 30 June–1 July 1974 eastern Ohio and Pennsylvania was the scene of severe thunderstorm activity. National Weather Service radar summary maps indicated severe thunderstorms in the area with tops up to 58 000 ft (17.7 km). New York City radar detected rapid formation of new thunderstorms in the area. In this report we present the study of gravity waves generated by these thunderstorms.

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2. Experimental setup and procedure

The Atmospheric Science Group of Lamont-Doherty Geological Observatory operates a four-element array of U-tube manometer-type microbarovariographs at Palisades, New York, about 20 mi (32 km) north of New York City. Details of the instrument are given by Donn *et al.* (1963). The transducer has a flat response for periods in the range of 0.5–15 min and the resolution for pressure measurements is ~5 μb (dyn cm^{-2}). The array geometry is shown in Fig. 1 and each leg is ~4 km. The signals from the pressure transducers are brought to the central location in the observatory by means of leased telephone lines and are recorded on both paper chart and analogue magnetic tape. The paper chart recording (at a speed of 3 mm min^{-1}) is utilized for initial visual monitoring and determining phase differences for those cases for which the paper charts provide enough accuracy. When greater accuracy is needed, the signal recorded on the magnetic tape is utilized. For determining the frequency content of the signal we use the Honeywell SAI-42 analyzer and for determining the time delay between any pair of signals, we use the Honeywell SAI-40 correlator. The delay time corresponding to the maximum correlation is taken as the travel time of the signal between the two transducers. After the time delays are determined wave direction and speed are determined by triangulation. For our four-element array in Fig. 1, wave velocities are computed for the two triangles: Tallman-Tappan-Mellor and Tappan-Mellor-Lamont, respectively. Only those cases in which there is good agreement between the velocities computed across the two separate triangular arrays are considered for further analysis; we have an accuracy of about ±10° for wave direction and ±3 m s^{-1} for wave speed.

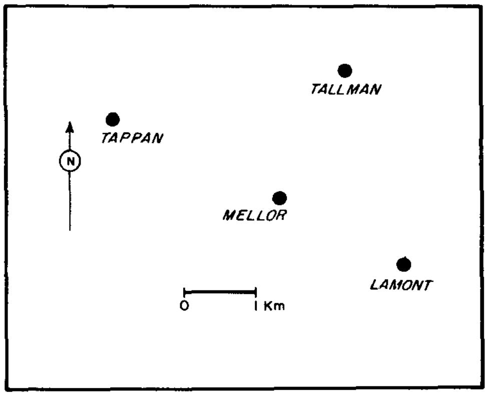

FIG. 1. Multipartite network of Lamont microbarovariographs.

3. Observations

The chart of gravity waves recorded on the Lamont microbarovariograph array during the night of 30 June–1 July 1974 is shown in Fig. 2. The wavetrains follow a sharp increase in pressure at about 2045 EST 30 June. The records indicate an absence of wave activity prior to this time. The waves last for about 9 h and the records become quiet again. The highly coherent nature of the waves becomes obvious from examination of the records in Fig. 2. The standard Weather Service microbarograph at our location recorded a sharp pressure pulse and is shown in Fig. 3a; this pressure pulse started with a pressure jump of ~2 mb in 15 min; such pressure jumps have been described in detail by Tepper (1950). After the pressure jump, the pressure remained at the enhanced level for about 3 h and then dropped to slightly below the background level. A much smaller pressure pulse with amplitude of about 1 mb and duration of about an hour followed the larger pulse. Obviously, the standard microbarograph does not respond properly to detect the high-frequency waves shown in Fig. 2; yet the microbarograph at Lyndon, New Jersey did pick up some waves at the trail end of the main pulse (Fig. 3b).

The larger pressure pulse is found to correspond to the well-known mesohigh resulting from the cold air outflow from the dissipating thunderstorm. The sharp pressure jump at the beginning of the pulse corresponded with the boundary of the cold air at the station. As the pressure jump hit New York City, the surface observation showed a drop of 6°F in temperature and a rise in pressure of 0.06 inches of mercury (~2 mb) in a few minutes and the area experienced a thunderstorm and rain soon after.

Gravity waves shown in Fig. 2 were recorded after the passage of the boundary of cold air. Strikingly regular and almost monochromatic waves were recorded at about 0200 EST 1 July 1974. The waves followed a second sharp increase in pressure at about 0100 EST. The spectrum of the complete gravity wave event is shown in Fig. 4. The most prominent peaks in the spectrum correspond to wave periods of 1280, 492 and 290 s, respectively. The thunderstorm-generated gravity waves thus consist of a range of frequencies or wavelengths corresponding to the different scales of motion associated with the storm itself. Thomas *et al.* (1975) have reported a period of 3 h for the gravity waves radiating from a thunderstorm; the satellite pictures used by them probably cannot resolve higher frequency waves. If we combine the large-amplitude low-frequency wave (pressure pulse) recorded on the standard microbarograph with the higher frequency, lower amplitude oscillations de-

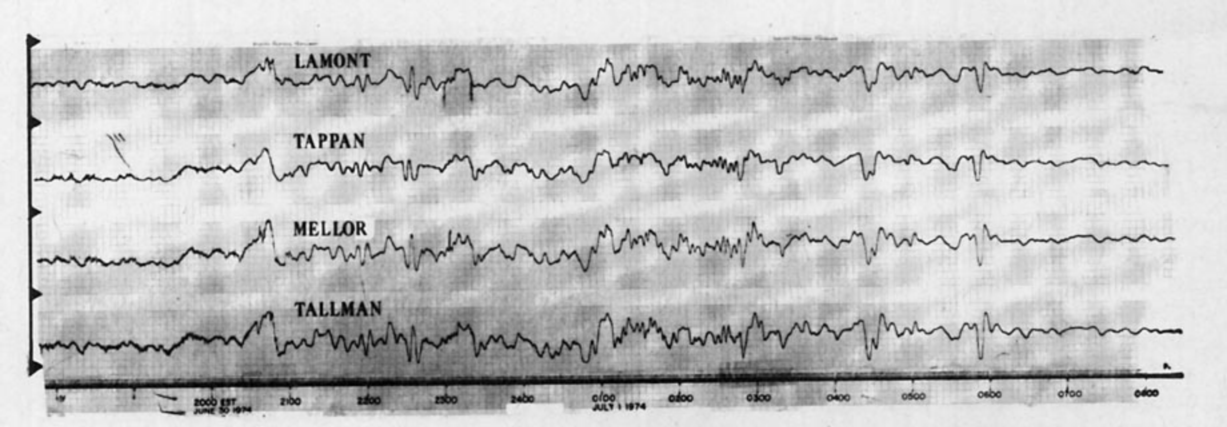

FIG. 2. Gravity waves from thunderstorms recorded by the Lamont network during the night of 30 June–1 July 1974. Maximum amplitude is ~300 μb.

tected by our microbarovariographs, we get the combined picture of the large-amplitude pressure jump trailed by lower amplitude high-frequency waves. The satellite pictures shown by Erickson and Whitney (1973) also present a similar pattern. It may be pointed out that the pressure pulse in Fig. 3b shows remarkable similarity to the pressure signature constructed from altimeter settings corresponding to the mesohigh from an intense thunderstorm as presented by Purdom (1973).

Microbarograph records from stations scattered across the eastern United States were collected in order to determine the general pattern of propagation of the pressure pulse. A profile of the pressure pulse at various stations is shown in Fig. 5. It is found that the pressure pulse traveled from a generally westerly direction with a speed of ~25 m s^{-1}. The remarkable stability in the shape and amplitude of the waveform over a distance of ~1000 km is worthy of notice. The spikes in the pressure pulse at Scranton and Harrisburg (east of Phillipsburg) may be indicative of the proximity of the source; as the pressure pulse travels further eastward these spikes are smoothed out.

The intense thunderstorm activity over Ohio and Pennsylvania began at about 1330 EST 30 June and lasted for about 5 h. As an example, the radar summary map for 1735 EST (2235 GMT) in Fig. 6 shows a line of severe thunderstorms stretched across Ohio and Pennsylvania with individual thunderstorms with tops up to 58 000 ft (17.7 km). It was noticed that thunderstorms with tops above 50 000 ft (15.2 km) were present continuously for a period of at least 5 h. The strong gravity wave activity at our Lamont microbarovariograph array lasted for about 9 h. In our classification of gravity waves we include the long-period pressure pulse (mesohigh) as well as the higher frequency oscillations which follow it. We interpret these gravity waves as having been generated by

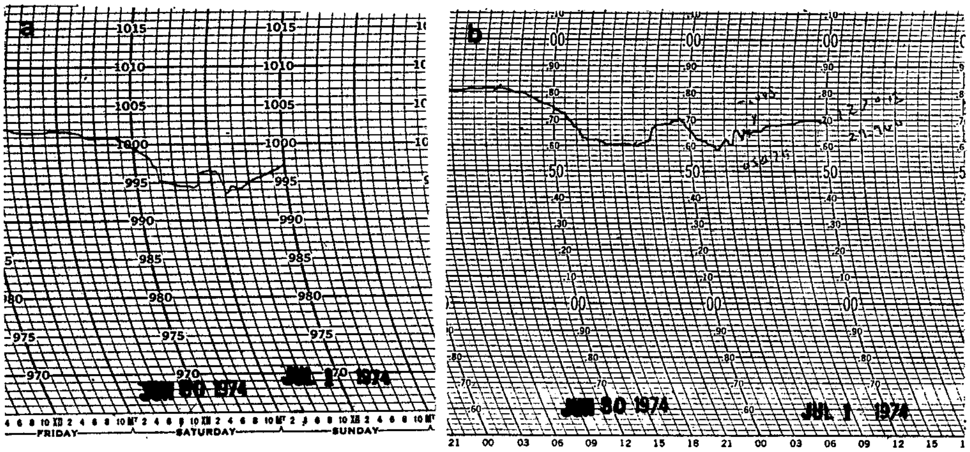

FIG. 3. Microbarograph traces showing the pressure pulses detected by standard National Weather Service type microbarographs at (a) Lamont (pressure in mb) and (b) Newark, (pressure in inches of mercury). Time scales are EST.

the cold outflow from the severe thunderstorms on their dissipation after tropopause penetration. The oscillations of the tops of the severe thunderstorms near the tropopause level may also be thought of as a mechanism for wave generation. Pierce and Coroniti (1966) have proposed such a mechanism, but the cold mesohigh associated with the wave system cannot be explained by this mechanism.

4. The synoptic situation

The severe thunderstorm in the Ohio-Pennsylvania area which generated the gravity waves were associated with the following synoptic situation. On the morning of 30 June 1974, a cold front was extending from a low pressure area in the lower Hudson Bay southward to north Texas. A second cold front was located in the Atlantic Ocean stretching from Nova Scotia down to the Florida Panhandle (Fig. 7). The northeast United States was under the influence of a weak southwesterly flow at the lower levels. The 500 mb chart (Fig. 8) indicated a cold upper air low over the Hudson Bay area with a connected upper air trough over the northeastern United States. The flow at this level was predominantly from the west over the New York area. The surface map for the morning of 1 July showed that first cold front had moved eastward and was located just east of Long Island.

5. Wave velocity

The horizontal trace velocity and direction of arrival of the waves were calculated with the use of data from the multipartite array shown in Fig. 1. The time delays in the arrival of a particular feature of the wave between pairs of transducers are utilized to compute the wave velocity. The waves are observed to be arriving from roughly a westerly direction with a speed of ~ 25 m s^{-1}. This speed and direction are consistent with the arrival times of the pressure pulse at the various standard microbarograph stations shown in Fig. 5.

Small changes in direction and speed within the wavetrain are observed. Table 1 gives the velocities of waves at various arrival times at the Lamont array. The wave directions vary over the range of 251–288° (measured clockwise from north). The range of arrival angles is plotted in Fig. 6. It is seen that these directions subtend the area of significant radar echoes. An examination of the hour-by-hour radar summary maps showed that the movement of tropopause-penetrating cloud echoes was roughly in agreement with direction changes given in Table 1. We may thus conclude that the change in the direction of arrival of the waves is due to the movement or multiplicity of the source itself.

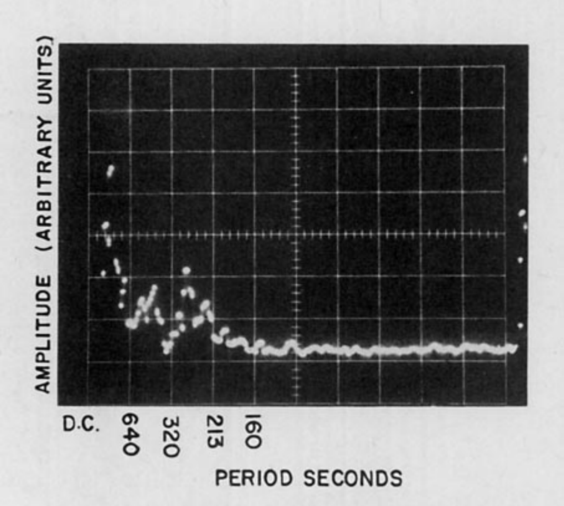

FIG. 4. Amplitude spectrum of gravity waves recorded at Lamont.

The anemometer records along the path of the waves show sudden shifts in wind speed and direction. The gust front or the wind speed changes associated with the gravity waves recorded at the JFK Airport in New York is shown in Fig. 9. Similar anemometer signatures were recorded at the La Guardia Airport in New York and the Newark Airport. It is observed that the maximum wind speed is recorded a few minutes after the passage of the sharpest pressure change associated with the gravity wave. The wind speed changed from an ambient speed of ~ 10 mph (4.5 m s^{-1}) to a maximum of ~ 30 mph (13 m s^{-1}). If the 20 mph wind speed change is taken as the orbital speed due to the wave, then using the maximum value of the pressure increase of 0.08 inches of mercury (2.7 mb) as the perturbation pressure, we calculated the phase velocity for gravity wave using the impedance relation given by Gossard and Hooke (1975), which is $c = P/\rho v$, where c is the phase velocity of the waves, p the perturbation pressure, v the perturbation velocity and ρ the air density. The phase velocity calculated using this formula with the values of perturbation pressure and velocity given above yields a value of 25.2 m s^{-1}. This calculated value for the phase velocity for the gravity waves is in good agreement with the phase velocity measured across our microbarovariograph array. It may be pointed out that the above anemometer data did not provide wind directions.

The anemometer record for the night of 30 June–1 July at the 400 ft (122 m) level of the Shoreham Tower is presented in Fig. 10. The wind was extremely steady with a speed of 20 mph (9 m s^{-1}) from a direction of 210° before the arrival of the waves. At the time of wave incidence (beginning at about 2150 EST) the wind speed increased to 46 mph with the direction changing to 280°. The

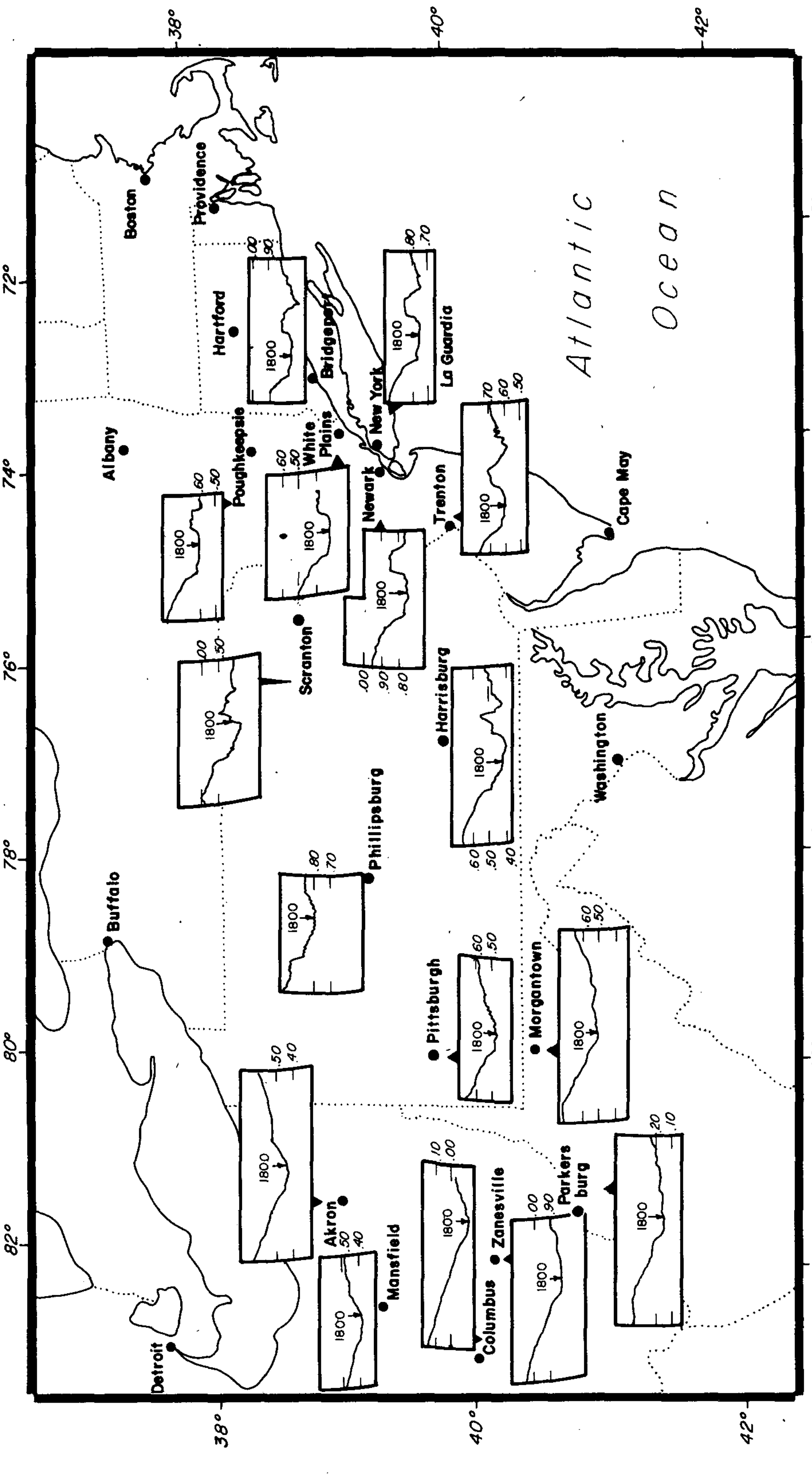

FIG. 5. Map showing the pressure pulses from the thunderstorm at various stations in the northeast. Time reference (arrow) in EST.

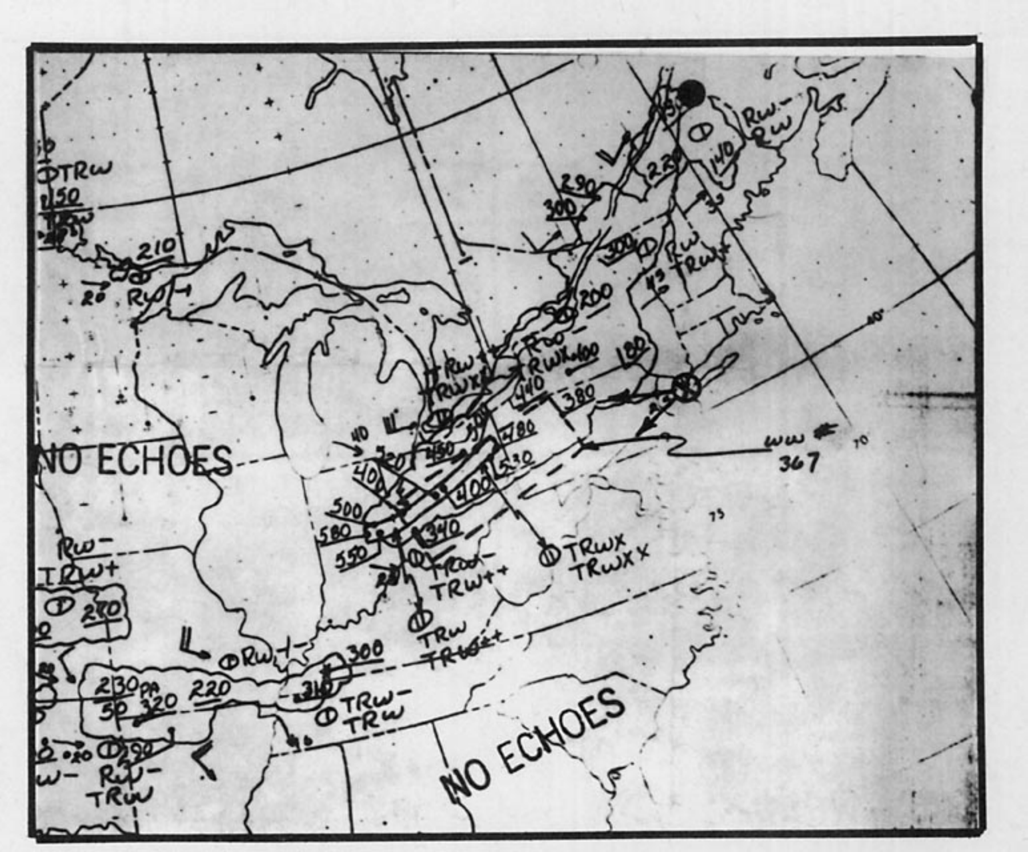

FIG. 6. Radar summary map for 2235z GMT showing the locations of thunderstorms which generated the gravity waves.

maximum speed change associated with the waves is roughly the same as the speed change recorded at Kennedy Airport. The computed direction of the orbital wind is 290° which falls within the range of direction of the gravity waves determined from the Lamont microbarovariograph array. Thus, we can conclude that the waves generated by the thunderstorm obey the impedance relationship for propagating gravity waves.

Both the wind speed and direction traces in Fig. 10 show wavelike undulations. The predominant period is ~10 min.

6. Triggering of new convection by gravity waves

The passage of the gravity wave was accompanied by thunderstorms. We interpret the widespread convective activity as having been triggered by the gravity wave.

It may be argued that the widespread weather phenomena ascribed to gravity waves from thunderstorms also may be generated by a squall-line, cold front or upper air trough. The radar summary map in Fig. 6 shows a line of thunderstorms; earlier and later maps show the line of thunderstorms more or less at the same location (for at least a total period of ~6 h). The radar data show that to the east of this region new thunderstorms developed in an isolated fashion and there is no indication of a traveling squall line. The cold front passed much later after the passage of the pressure pulse and its associated weather. The pressure pulse has the typical shape of the thunderstorm mesohigh associated with the cold outflow (Purdom, 1973). Purdom (1979) has also shown vividly, with the help of satellite pictures, the initiation of new convective activity even at large distances, by the outflow from dissipating thunderstorms. The direction of travel and the arrival times of the pressure pulse also indicate the severe thunderstorms in the Ohio-Pennsylvania region as the source of the gravity wave which initiated new convective activity generally to the east of this region.

The upper air sounding for 1815 EST 30 June for New York City (Fig. 11) showed a conditionally unstable layer below the tropopause. Conditions were thus favorable for instability to develop if this layer is lifted sufficiently by the passing wave. Thus, the gravity wave during its travel was associated with significant convective activity. In New York City with the arrival of the sharp pres-

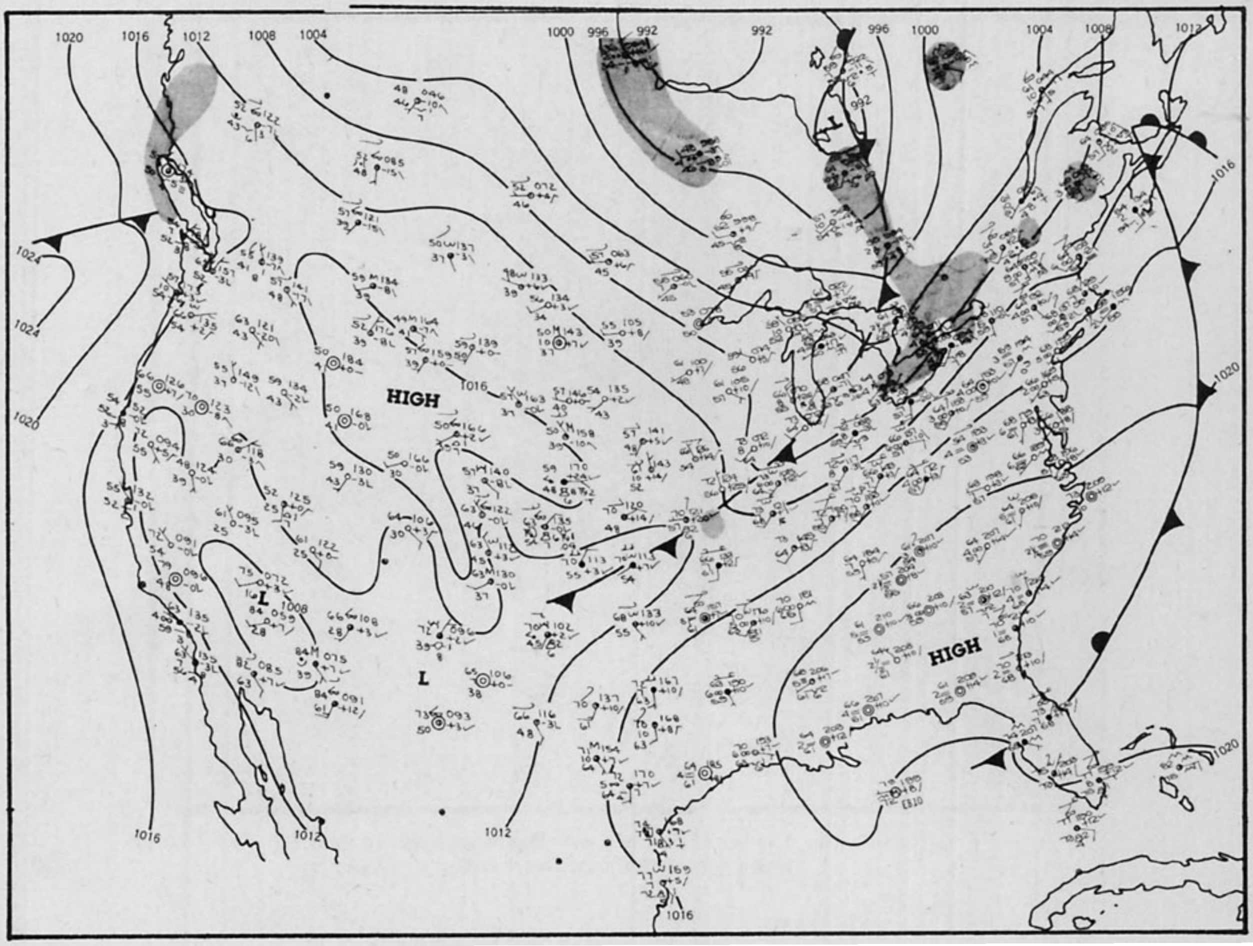

FIG. 7. Surface weather map for 0700, EST, 30 June 1974.

sure rise at about 2030 EST 30 June, temperature dropped by 6°F in less than an hour and thunderstorms developed. Within an hour New York City radar reported very heavy thunderstorms with echo tops up to 30 000 ft. The rain ended at 0145 EST 1 July with a total precipitation of 0.26 inches. After a short interval, rain occurred again during 0415–0445 and 0502–0515 EST. This precipitation seems to be associated with another pressure pulse of ~1 mb which arrived after the main pulse. The second pressure pulse can be seen clearly on both the Lamont and Newark microbarograph records (Fig. 3). This may be an indication of the oscillating nature of the rainfall corresponding to the gravity waves; although the insensitivity of the standard raingauge to such oscillations prevents a more detailed correlation.

The thunderstorm with maximum echo tops, apparently excited by the gravity wave, occurred in the vicinity of Harrisburg, Pennsylvania, as detected by the New York City radar at 2230 EST 30 June (Fig. 12). The sharpest pressure jump arrived at Harrisburg at about 2200. Temperature dropped by 6°F and the microbarograph record showed a pressure rise of ~3 mb in less than 10 min. Thunderstorms developed in the area with New York City radar showing maximum echo top at 37 000 ft., at 2230, roughly 30 min after the arrival of the sharpest pressure rise associated with the gravity waves.

Thunderstorm activity was reported from stations across the Northeast United States and was apparently associated with the gravity wave. At White Plains station the observer has marked thunderstorm activity right on the pressure pulse (on the microbarograph record) itself. Raingage records at a number of stations all indicated varying amounts of precipitation associated with the passage of the gravity waves. It seems obvious that the gravity waves triggered thunderstorms during its travel across the Northeast United States. An atmospheric layer with the proper distribution of temperature and humidity can become unstable by the lift provided by that part of the wave with increasing pressure and such instability can lead to the development of thunderstorms. The upper air sound-

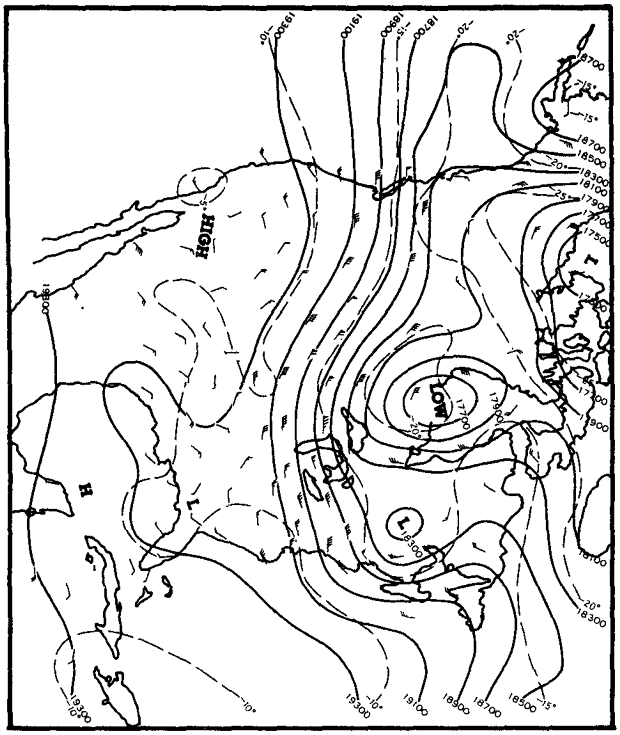

FIG. 8. 500 mb map for 0700, EST, 30 June 1974.

TABLE 1. Azimuth and phase speed of a group of gravity waves each roughly centered at the indicated arrival time during the night of 30 June–1 July 1974.

Arrival time (EST)	Azimuth (deg)	Speed (m s^{-1})
2200	251	24
0200	290	28
0400	260	26
0600	271	25

ings discussed in the next section indicate that such conditions did exist before the arrival of the wave (see Figs. 11 and 13).

Significant changes in temperature and wind associated with the passage of the waves were recorded on two towers on Long Island, one located at Shoreham on the south shore of Long Island (on Long Island Sound) and the other almost due east of Shoreham at Jamesport, a distance of ~27 km. Each tower is instrumented at three different levels.

Temperature data from the three levels on the Shoreham tower are presented in Fig. 14. Temperature data are given for the 33 ft level and for the differences (ΔT) of temperature between this level and those at 150 and 400 ft. Sudden changes in ΔT at both 400 ft (ΔT_1) and 150 ft (ΔT_2) at the time of incidence of the gravity wave are quite prominent in the figure. It may be observed that before the incidence of the wave the traces indicate constant temperature differences. At 2150 EST, when the main pressure pulse hit the tower, the temperature at 400 ft was lower by 1°F, whereas the temperature at 150 ft was higher by 0.4°F, compared to the temperature at 33 ft. These opposing temperature gradients are probably an indication of vertically propagating gravity waves. Computation of the temperature gradients revealed that when the highest amplitude pressure wave hit the Shoreham Tower a temperature inversion developed between the levels of 33 and 150 ft with a gradient of $+6.2°\mathrm{C\ km^{-1}}$ and a superadiabatic lapse rate existed between 150 and 400 ft with a temperature gradient of $-10.2°\mathrm{C\ km^{-1}}$. The background gradient, before the wave incidence, was a stable $-4°\mathrm{C\ km^{-1}}$ for both layers. The Jamesport tower data also gave similar results; at the time of the wave arrival the temperature gradient in the layer between 33 and 200 ft was $+8.7°\mathrm{C\ km^{-1}}$ and the temperature gradient in the layer between 200 and 400 ft was $-18.2°\mathrm{C\ km^{-1}}$. Thus the temperature data from the towers seem to show that gravity waves do generate convectively unstable layers as well as stable inversion layers in the atmosphere as they propagate. In our case we have measurements for only shallow layers; but there is no reason to believe that such conditions do not exist in deeper layers. Fig. 14 also shows strong changes in the temperature gradients later and we may conclude that these are indications of superadiabatic and stable temperature gradients associated with the passage of gravity waves which, according to our microbarovariograph data, lasted for a number of hours.

7. Discussion

The propagating pressure pulse from the thunderstorm appears to be confined generally to the east of the generating area. As can be seen from Fig. 5, no pressure pulse was recorded at Pittsburgh and stations to the west of Pittsburgh. It appears that the

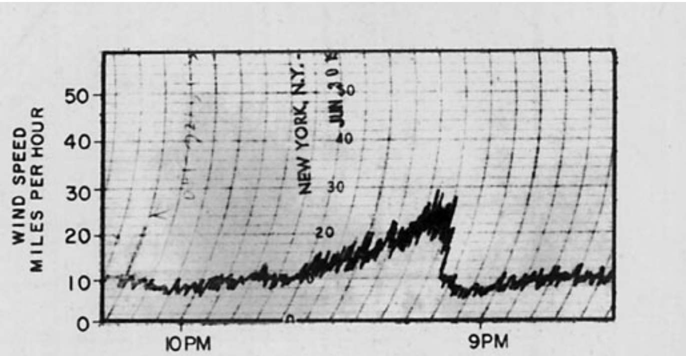

FIG. 9. Anemometer record showing the wind speed shift at the passage of the gravity waves at J.F.K. Airport.

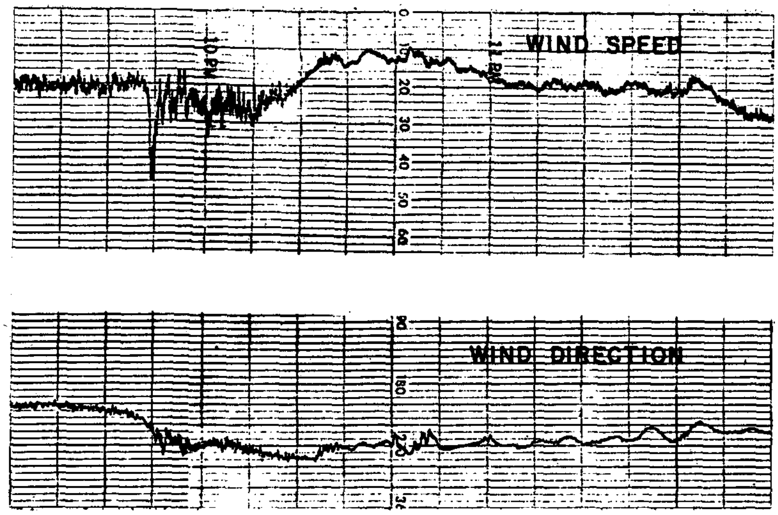

FIG. 10. Wind speed (mph) and direction (deg) for the 400 ft. level at Shoreham on Long Island.

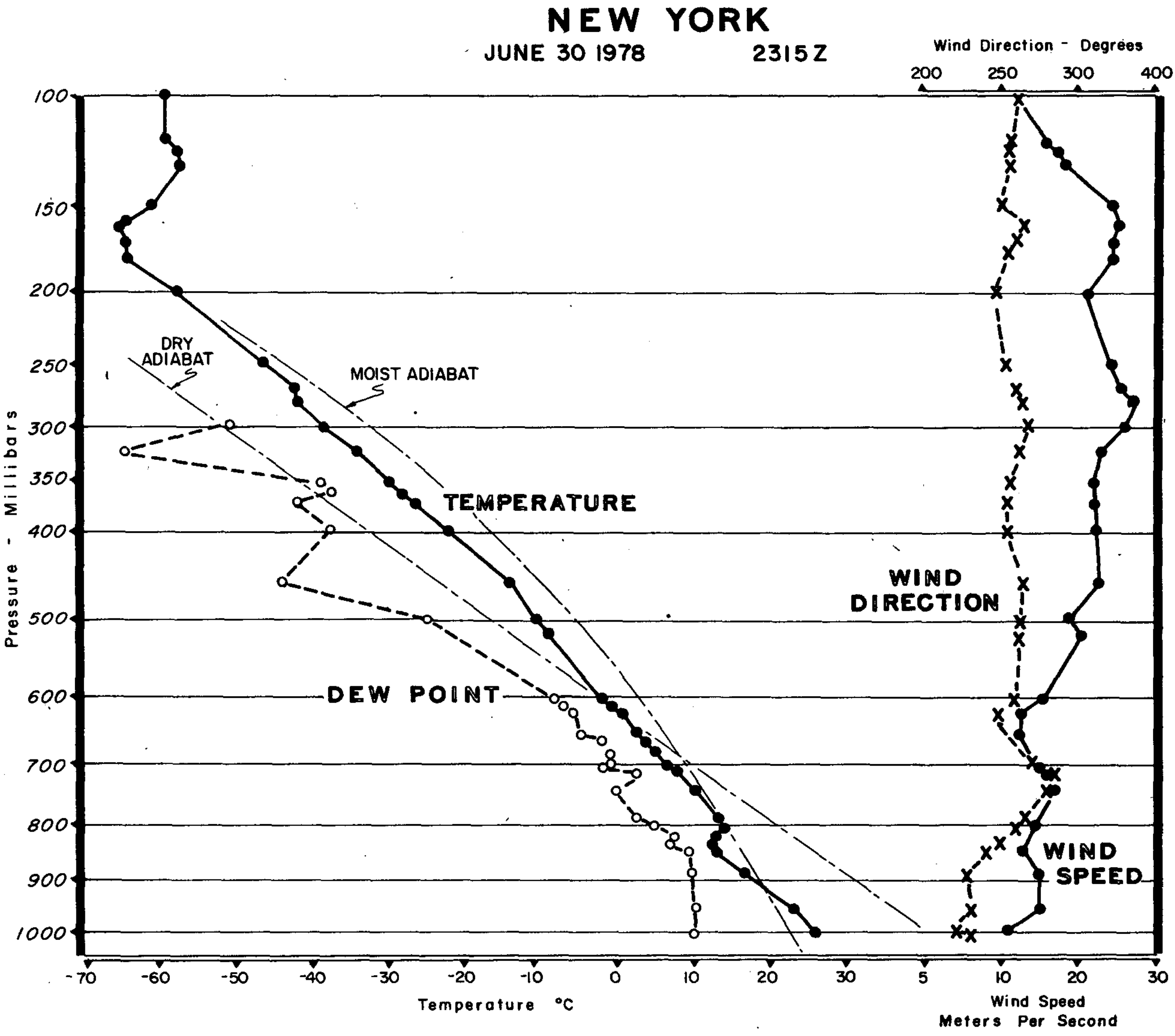

FIG. 11. Upper air temperature and wind data for New York for 0000 EST, 1 July 1974.

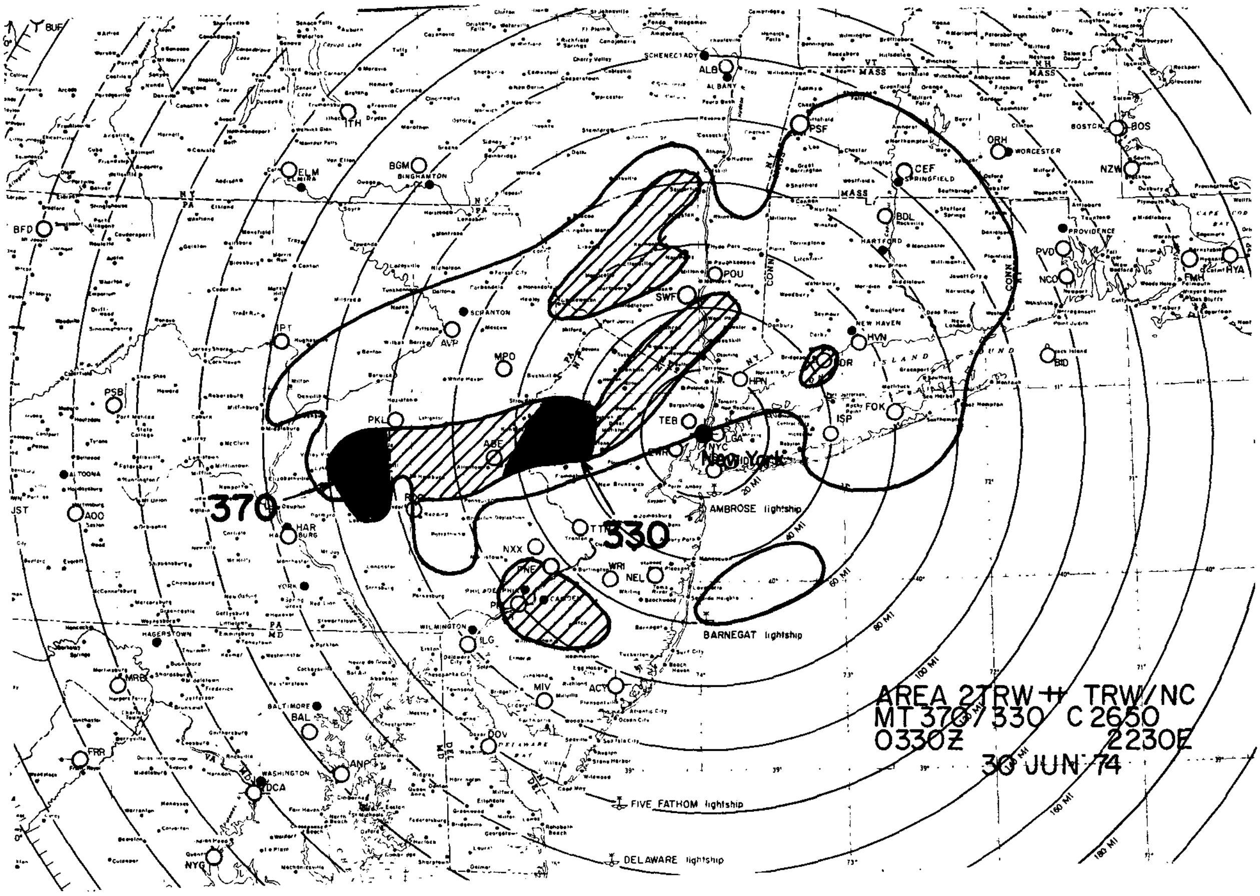

FIG. 12. Radar picture showing echo regions associated with thunderstorms triggered by the gravity wave.

gravity waves from the thunderstorm were confined to a sector roughly from northeast to southeast and propagated to large distances to the east. Such phenomena are also evident in the satellite pictures presented by Stobie (1975) and Erickson and Whitney (1973); the waves do not usually spread out in all directions from the thunderstorm; they are confined to a certain sector, indicating a preferred direction of propagation. In our case this preferred direction seems to be the direction of wind just below the tropopause. This is evident from the upper air data presented below.

The upper air wind and temperature data for 0000 GMT 1 July 1974 is presented for both New York City (Fig. 11) and Pittsburgh (Fig. 13). The temperature and wind structure are remarkably similar for these two stations at a distance of ~560 km. Both soundings indicate that air below the tropopause level, in general, is conditionally unstable at both locations. The most important finding is that the gravity wave propagation velocity agrees with the wind velocity just below the tropopause. Thus the gravity wave has a critical level (where the horizontal component of the phase velocity of the wave is equal to the wind velocity) just below the tropopause level. The tropopause region, in general, is a favored region for the generation of gravity waves because of the strong wind shear below the tropopause; but in our case the wind shear is not very significant.

We mentioned two mechanisms for the generation of gravity waves from thunderstorms, buoyancy oscillation at the tropopause level and shear instability of the thunderstorm outflow. There is difficulty in substantiating buoyancy oscillations as the source mechanism; the critical level below the tropopause will prevent the waves from reaching the ground level. The nondispersive nature of the waves (all the different frequency components of the waves are found to be traveling with the same phase velocity) also favors a wind-shear mechanism as the source. Further, since the waves travel distances of the order of 1000 km without much dissipation, some sort of ducting mechanism must be present. The critical layer mentioned earlier may provide such a mechanism. A shear mechanism is thus a more appropriate source but, as we have seen, the background wind does not have sufficient shear to generate the waves. The only possibility, then, is for strong shears to be present in the thunderstorm outflow. Unfortunately, the available upper air soundings are either too early or too late to show the shear associated with the thunderstorm outflow. We can

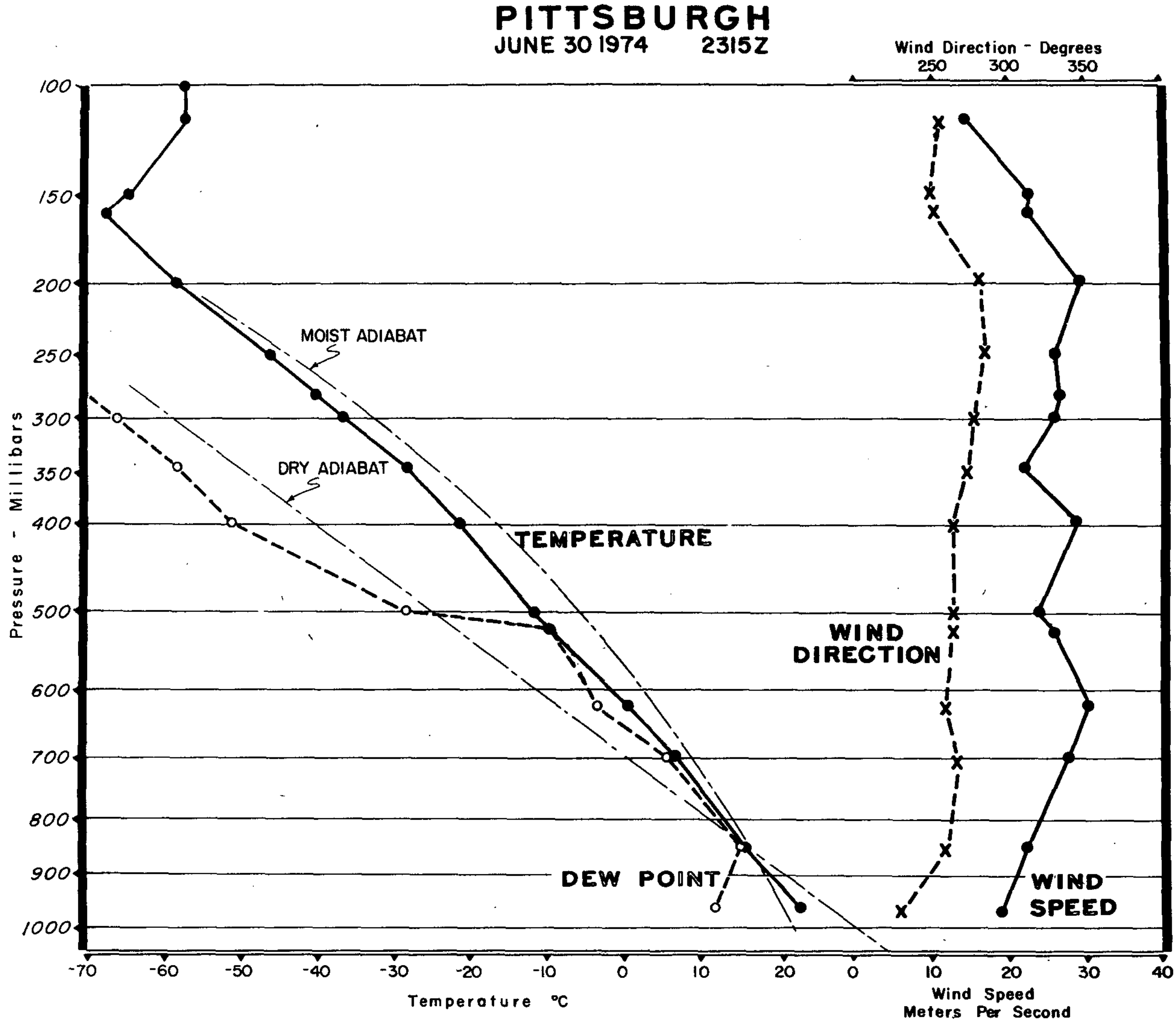

FIG. 13. Upper air data for Pittsburgh for 0000 EST 1 July 1974.

only say that such shear is the most likely mechanism that generated the waves.

Still another mechanism for the generation of gravity waves is wave-CISK, as proposed by Lindzen (1974) and Raymond (1975). Wave forcing takes place as a result of intense convection and the release of latent heat. Raymond (1975) suggested that the storm itself takes the form of a convectively forced internal gravity wave and moves with the appropriate speed of the gravity wave. The soundings for Pittsburgh show convectively unstable layers between 850 and 520 mb. With deep convection and intense precipitation, conditions are ideal for wave-CISK there. Conditions at New York do not seem to be appropriate for wave-CISK. The movement of the gravity waves over large distances, as indicated in Fig. 5, without any significant change in wave amplitude or wave shape, also suggests the presence of a strong duct for the waves. Lindzen and Tung (1976) have discussed the conditions necessary for the ducting of mesoscale gravity waves. The necessary conditions for the ducting require a sufficiently thick stable layer near the ground topped by a layer in which the Richardson's number is less than 0.25 with a critical level (steering level) for the waves also present in this upper layer. As the New York soundings show (Fig. 11) these conditions are satisfied; stable layer exists up to ~450 mb and above this layer a conditionally unstable layer extends all the way up to the tropopause level with a critical layer also present. The sounding shown in Fig. 11 does show fluctuations in the dew-point temperature with height but does not indicate saturation; however, this sounding is a few hours before the arrival of the wave and at the time when

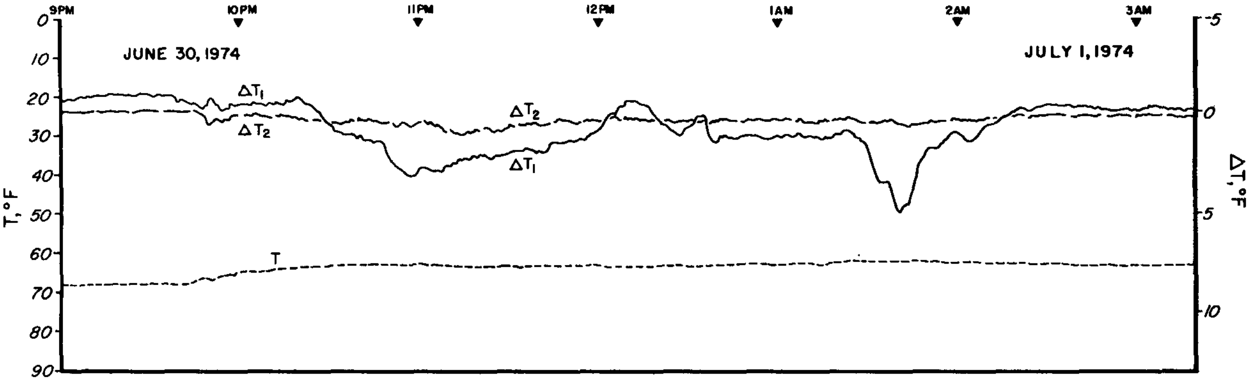

FIG. 14. Temperature changes at the 400 (ΔT_1) and 150 ft levels (ΔT_2) with respect to the temperature at the 33 ft level (T) recorded on the Shoreham tower at the passage of the waves.

the waves arrived the layer probably reached saturation.

Thus, although the conditions were ideal for wave-CISK in the western Ohio-Pennsylvania area during the night of 30 June–1 July 1974, gravity waves and thunderstorms observed to the east of the region were due to the presence of a strong directional duct. That explains why the waves were not observed to the west of this region.

The pressure pulse shown in Fig. 3 may be thought of as an atmospheric solitary wave (Abdullah, 1955), since the pulse travelled long distances without any apparent change of shape or amplitude. Christie *et al.* (1978) have discussed solitary waves on a low-level inversion. In the case of a solitary wave, the amplitude is maintained because of the balancing effects of frequency and amplitude dispersion. In our case we have observed that frequency dispersion is absent. On the other hand, it was pointed out by Abdullah (1955) that a wave of elevation which propagates without change of shape may be thought of as a long wave with vertical accelerations. This idea is in conformity with our observations since vertical accelerations are necessary for initiating convection observed along the path of the wave.

A number of questions have been raised with respect to the initiation of convective activity by gravity waves. After the publication of the idea that convective storms may be triggered by pressure jump lines (Tepper, 1950), it was argued that such effects will be indistinguishable from the pressure changes associated with the convective process itself (e.g., see Lilly, 1978). Since then, Uccellini (1977) has presented evidence of gravity waves initiating convection and also intensifying existing convective activity. It was then argued that if gravity waves initiated convection, then the convective process will dissipate the gravity waves (see, e.g., Einaudi *et al.*, 1979); but Einaudi and Lalas (1975) have shown that rather than dissipating the gravity wave, the latent heat liberated in the convective process will actually intensify the waves. In the present paper we have presented evidence to show that not only do gravity waves initiate convection, but the waves also go through virtually unaltered in shape or amplitude to generate new convective activity in regions with favorable humidity and temperature distributions. In our case the original gravity wave was generated by severe convective activity.

8. Conclusions

Severe thunderstorms generated gravity waves with wavelengths from a few kilometers to hundreds of kilometers. Shear instability of the outflow from the thunderstorm may be the generating mechanism. The waves were ducted below the tropopause level; this duct was effective because of the presence of a critical level and hence the duct was highly directional. The gravity waves appeared to trigger new thunderstorms on their route because the ambient conditions were appropriate for such triggering by the lift provided by the waves. After such triggering the waves propagated further without any apparent change in shape or amplitude indicating that the convective activity initiated by the waves did not lead to their own dissipation.

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