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By

Nambath K. Balachandran

Final Technical Report
Contract NAS8-33378

Lamont-Doherty Geological Observatory
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1. INTRODUCTION

This report deals with the investigation of gravity waves in the neutral atmosphere and their propagation in the ionosphere and the study of infrasonic signals from thunder. For the ground level monitoring of gravity waves, we have an array of sensitive pressure sensors located in the viscinity of Palisades, New York, about 25 kilometers north of New York city. Travelling ionospheric disturbances (TIDs) which in most cases are manifestations of gravity waves are monitored by determining the Doppler shift of high frequency radio waves reflected from the ionosphere. Doppler shifts of the order of 0.1 Hz are determined and they provide high-resolution measurements of the movements in the ionosphere. By using an array of transmitters with different frequencies and at different locations, we are able to determine the horizontal and vertical propagation vectors of disturbances propagating through the ionosphere.

The mutual repulsion of particles in the charged region in a thunder-cloud gives rise to a pressure deficit in that region. When the lightning stroke discharges the region, a pressure pulse of rarefaction will propagate from the charged region with a speed that of the speed of sound. This signal will have a frequency of the order of 1 Hz and is infrasonic. In principle, by monitoring the infrasound signal, we will be able to infer the properties of the charged region.

2. GRAVITY WAVES IN THE ATMOSPHERE

Gravity waves generated by thunderstorms have been reported by Balachandran (1980). The waves were recorded by an array of sensitive microbarovariographs. The waves were found to travel with the velocity of wind just below the tropopause. On their path, the waves apparantly triggered new thunderstorms. The long-distance propagation of the waves is explained by the presence of a duct associated with the critical level, where the wind velocity becomes equal to the wave velocity. (For details, see the attached paper in Appendix 1).

Statistical properties and the sources of gravity waves at our location were investigated by Gedzelman (1983). In general, large amplitude waves were found to occur during late fall and early winter when upper tropospheric winds directly overhead are fastest and static stability of the lower troposphere is greatest. Mean wave amplitudes correlate highly with the product of the mean maximum wind speed and the mean low level stratification directly aloft. The majority of the waves were generated by shear instability; however, a number of waves were generated by thunderstorms. For details, see the attached paper in Appendix 2.

Gravity waves at ionospheric levels were investigated by means of an ionospheric sounding system in which the Doppler shift of high-frequency radio waves reflected from the ionosphere is evaluated. As the reflection level changes due to the passage of a wave, the path-length of the radio wave also changes resulting in a Doppler shift of the reflected radio waves. Thus the Doppler shift record could represent the gravity wave action at ionospheric levels. The details of the instrumentation for this ionospheric system are given by Davies and Baker (1966).

Transmitters with three different nominal frequencies have been installed at four different locations and all the receivers in the observatory at Palisades, New York. Fig. 1 shows the locations of the transmitters and receivers and the ionospheric reflection points. The array is designed to be ideal for studying the propagation of gravity waves through the F-region of the ionosphere. Since different frequencies reflect from different levels in the ionosphere, and utilizing the horizontal separation of the transmitters, we are able to determine the horizontal and vertical propagation velocities of ionospheric perturbations and thus evaluate their complete propagation vectors. In table 1 is listed the exact frequencies used along with the the locations of the transmitters and the phase-path rate of change associated with a Doppler shift of 0.1 Hz.

A typical record showing TIDs detected by our system is shown in Fig. 2. Time delays in the arrivals of common identifiable phases are clearly evident in the figure. Gravity waves generated by a tropospheric weather system are shown in Fig. 3. These high-amplitude gravity waves at ionospheric levels were detected on January 12, 1982, during the outbreak of severe cold weather over the East Coast. The waves had a period of about 10 min and a speed of about 185 meters/sec arriving from the north-west. The source of the waves was identified as an intense cold upper low centered over south-eastern Canada. At the time of the wave generation, the low was dissipating and the pressure at the ground level as well as temperatures at all levels were changing rapidly. We postulate geostrophic adjustment (Blumen, 1972) as the mechanism for the generation of the waves. This may be the first identified case of wave generation by this mechanism.

3. INFRASOUND SIGNALS FROM THUNDER

Infrasound signals apparently generated by the collapse of the electrostatic field in the thundercloud, along with audible sound and electric field changes have been recorded for a number of cases and reported by Balachandran (1983). The observations seem to confirm earlier theoretical predictions; the infrasound signal is composed of a main rarefaction phase and are beamed vertically. Infrasound may be used to map the charged region in a thundercloud. For details, see the enclosed paper in Appendix 3. In one case in which the lightning channel was reconstructed with the help of audible thunder signals, the infrasound was associated with an intracloud discharge.

4. CONCLUSIONS AND RECOMMENDATIONS.

Gravity waves are generated by severe storms and other tropospheric disturbances. These waves manifest themselves in the lower troposphere as well as in the ionosphere. The source mechanisms for these waves are the oscillations of the top of the thundercloud after it penetrates the tropopause, geostrophic adjustment, wind shear, etc. The ionospheric Doppler technique is an ideal method for investigating the waves at ionospheric levels.

Infrasound generated by the collapse of the charged region in a thunder cloud may be used for remote sensing of the charge distribution and dimensions of the charged region in a thunder cloud. The directionality property of the infrasound may be utilized to map the charged region. The infrasound may reach ionospheric levels and with the Doppler system, may be used as a storm detecting device.

It is recommended that investigations of gravity waves from severe storms be continued so that the relationship of gravity waves to severe storms is fully understood. The Doppler technique may also be utilized for storm detection by utilizing the ionospheric effects of VLF radiation from lightning.

The infrasound is a powerful tool for remote sensing of the charged region in the thundercloud and simultaneous measurements of sound and electric field should be made so that their interrelationship can be fully established.

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Table 1

Location	Frequency	dP/dt for 0.1 Hz
Newton	2.54 MHz	11.81 m/sec
	6.91 MHz	4.34 m/sec
	4.566 MHz	6.57 m.sec
Evans	4.565 MHz	6.57 m/sec
Farmingdale	4.564 MHz	6.57 m/sec
Newburgh	4.563 MHz	6.57 m/sec

Transmitter frequencies of the Lamont-Doherty Doppler Sounder array and the rate of change of phase path necessary to produce a Doppler shift of 0.1 Hz

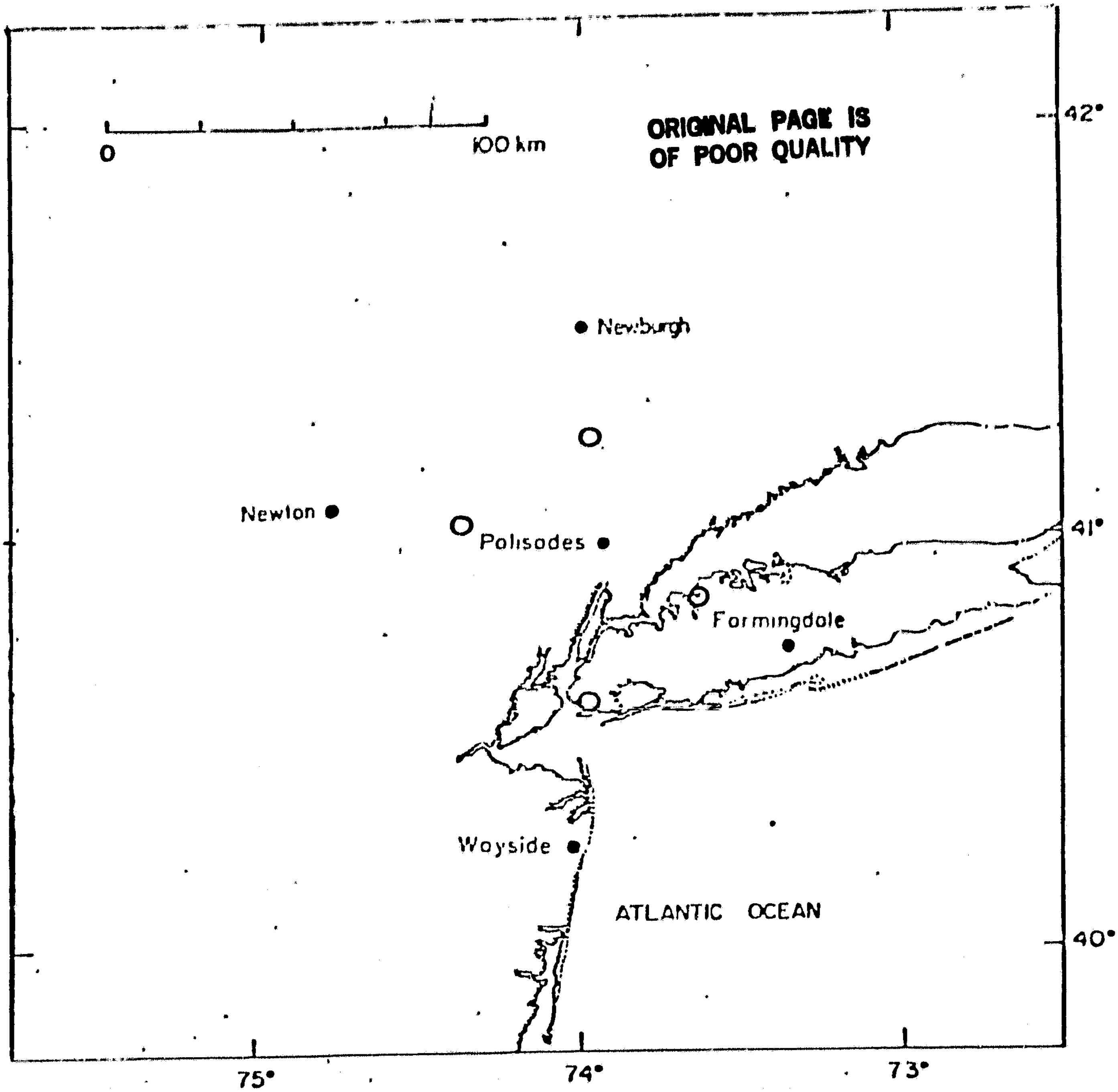
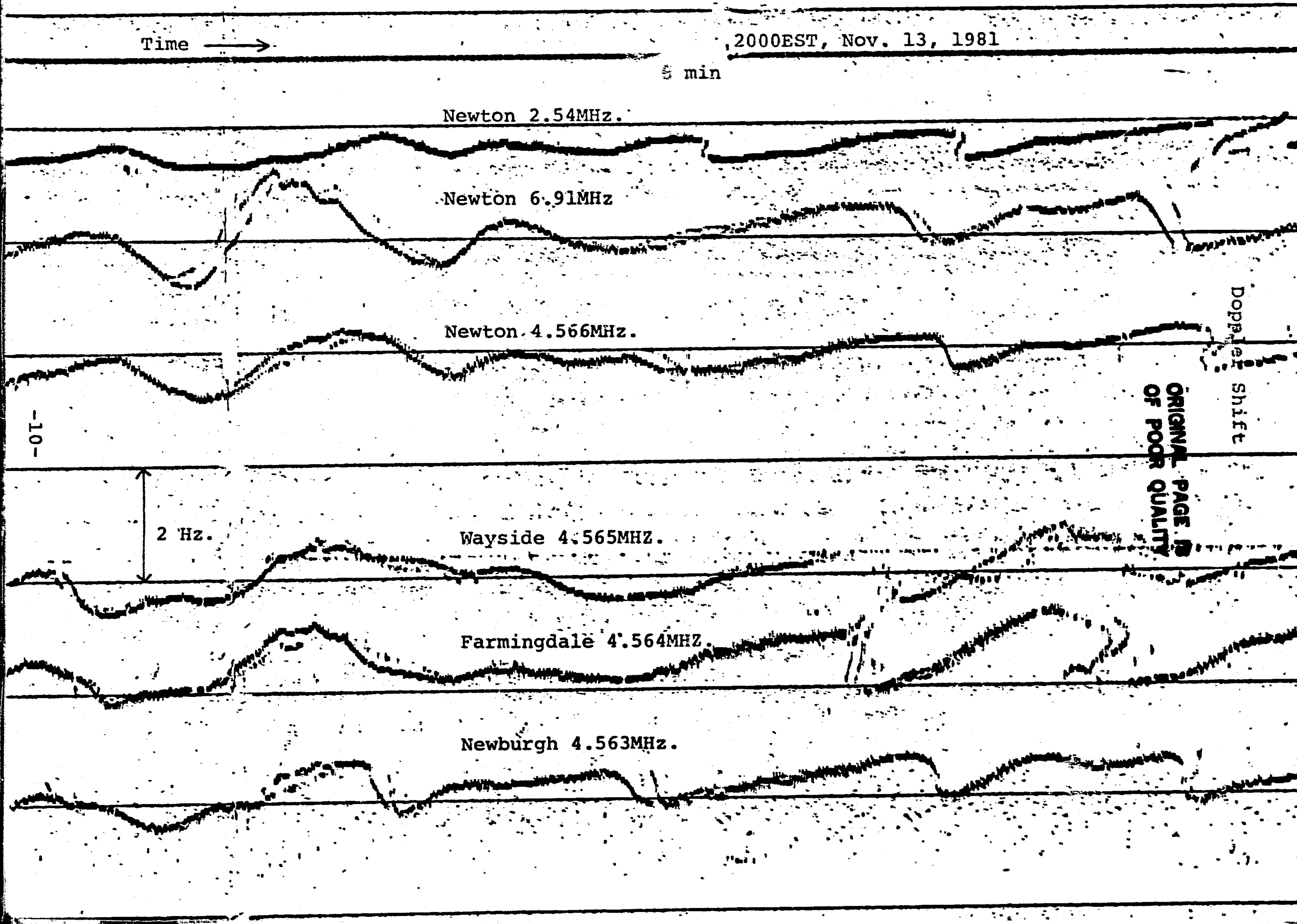


Figure 1. Locations of Doppler-Sounder Transmitting Stations and Receiving Station at Palisades, New York, shown by solid dots. The open circles show the ionospheric reflection points.

Fig. 2. Doppler-sounder Record showing TIDs



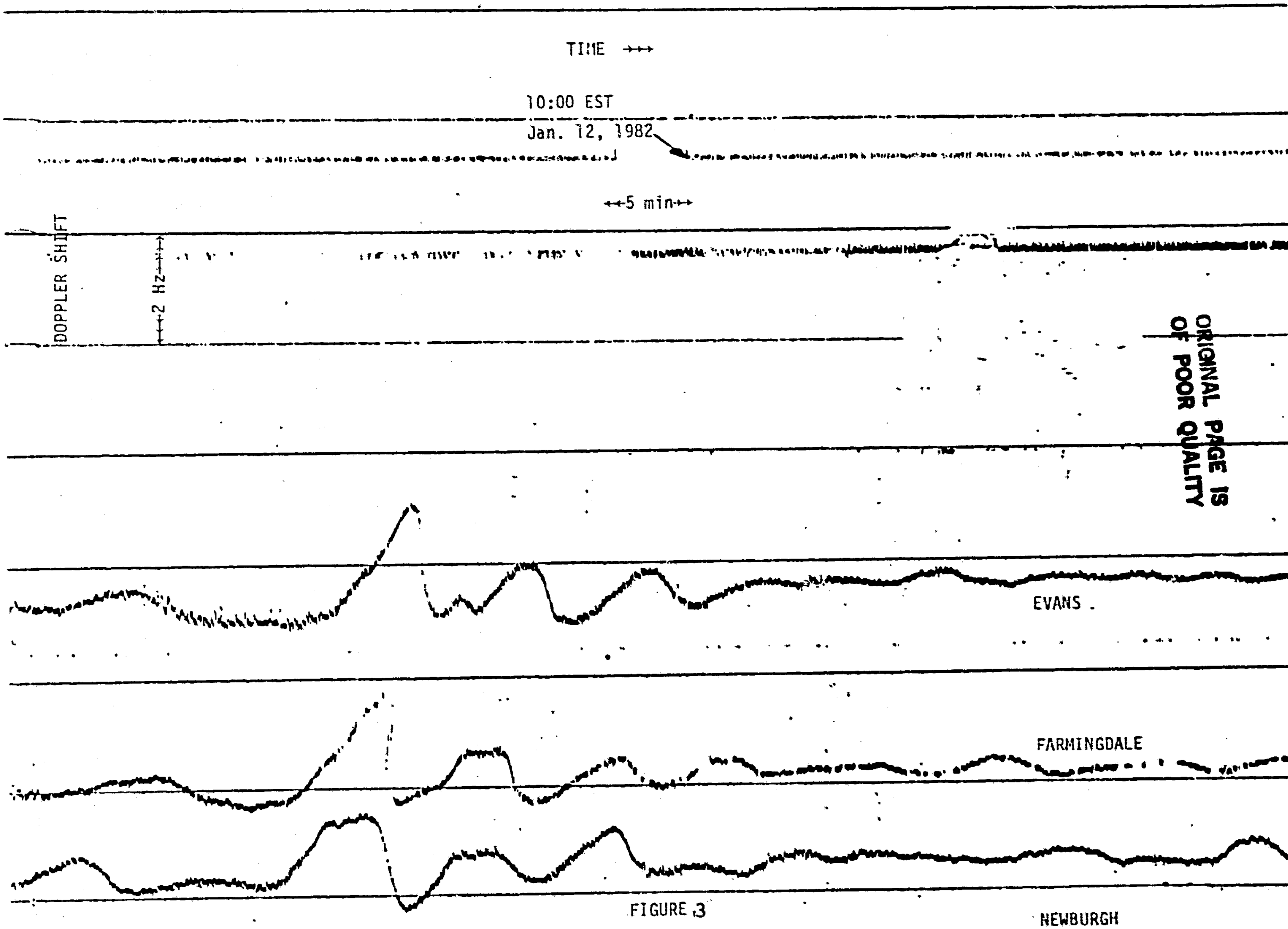


FIGURE 3

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APPENDIX 1

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Gravity Waves from Thunderstorms

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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.

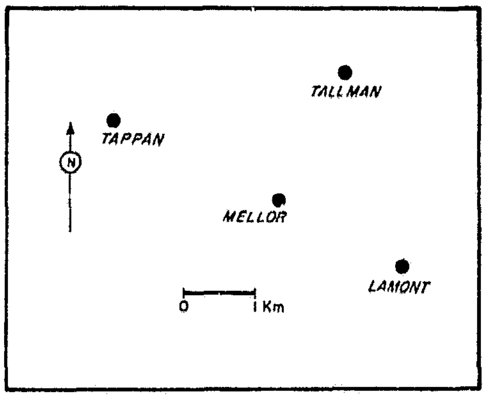

FIG. 1. Multipartite network of Lamont microbarovariographs.

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-

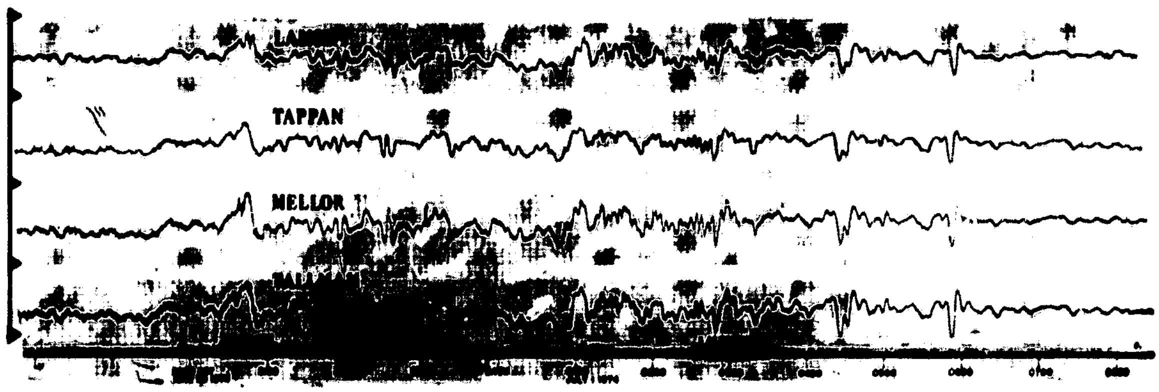

FIG. 2. Gravity waves from thunderstorms recorded by the Lamont network during the night of 30 June–1 July 1974. Maximum amplitude is ~300 μb.

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

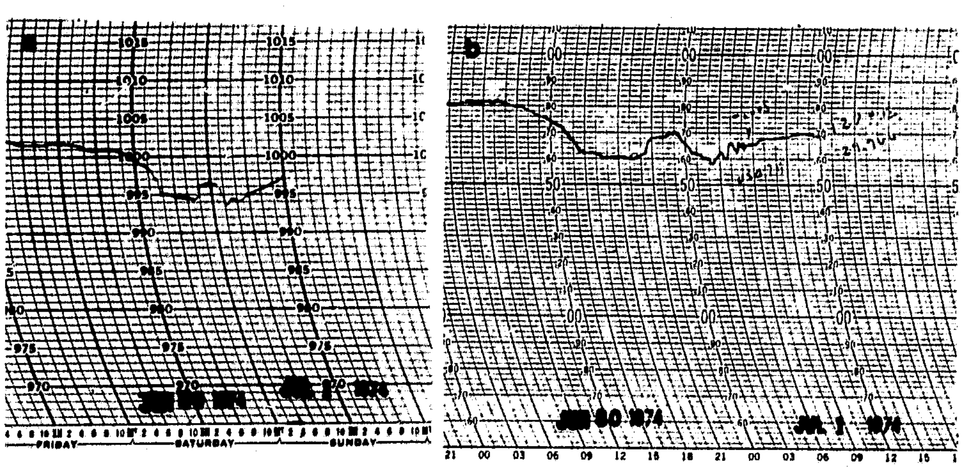

FIG. 3. Microbarograph traces showing the pressure pulses detected by standard National Weather Service type microbarographs at (a) Lamont (pressure in mb) and (b) Newark, (pressure in inches of mercury). Time scales are EST.

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.

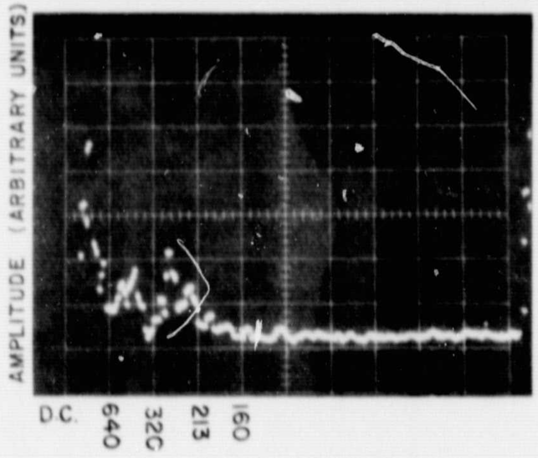

FIG. 4. Amplitude spectrum of gravity waves recorded at Lamont.

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

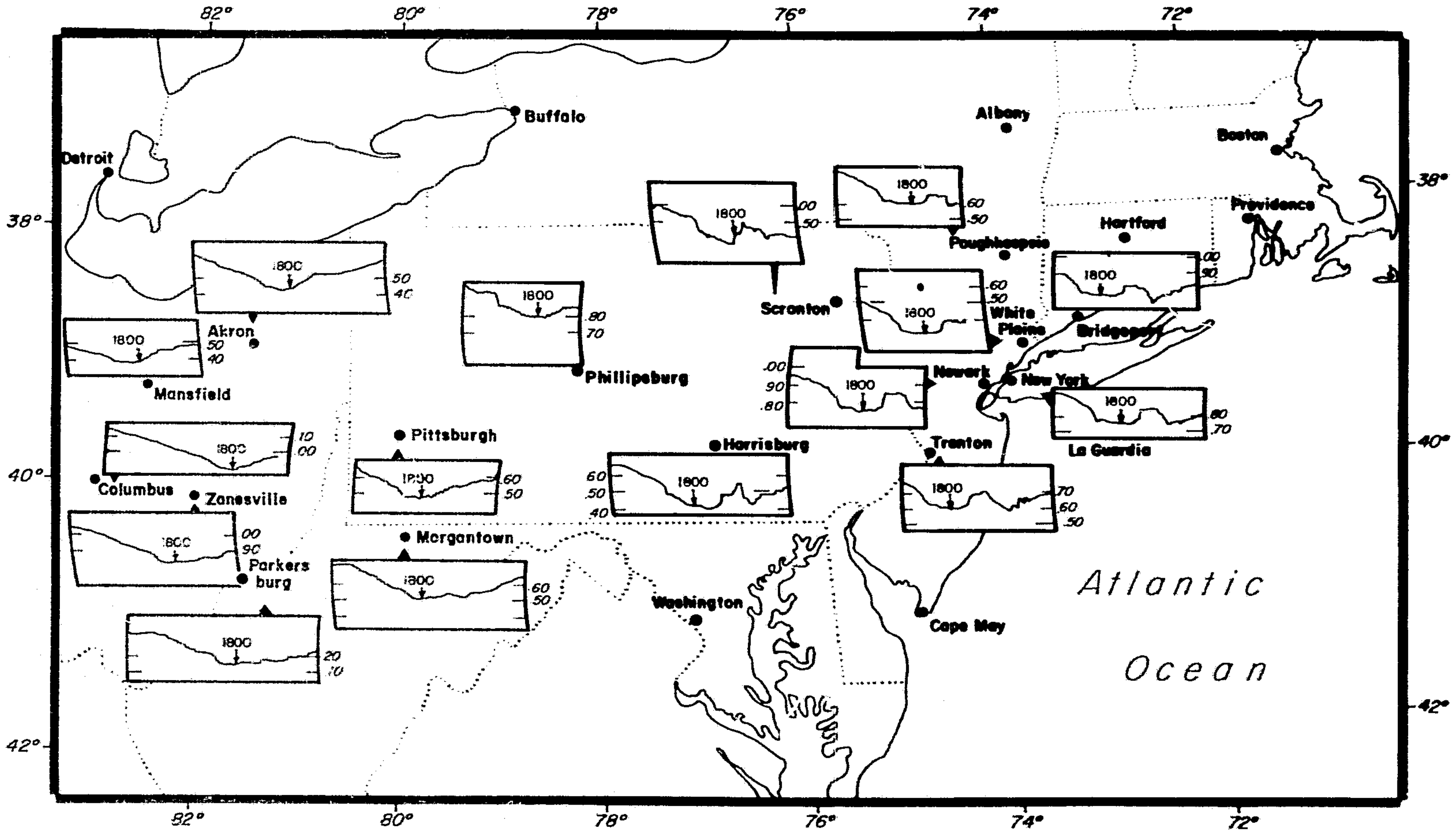

FIG. 5. Map showing the pressure pulses from the thunderstorm at various stations in the northeast. Time reference (arrow) in EST.

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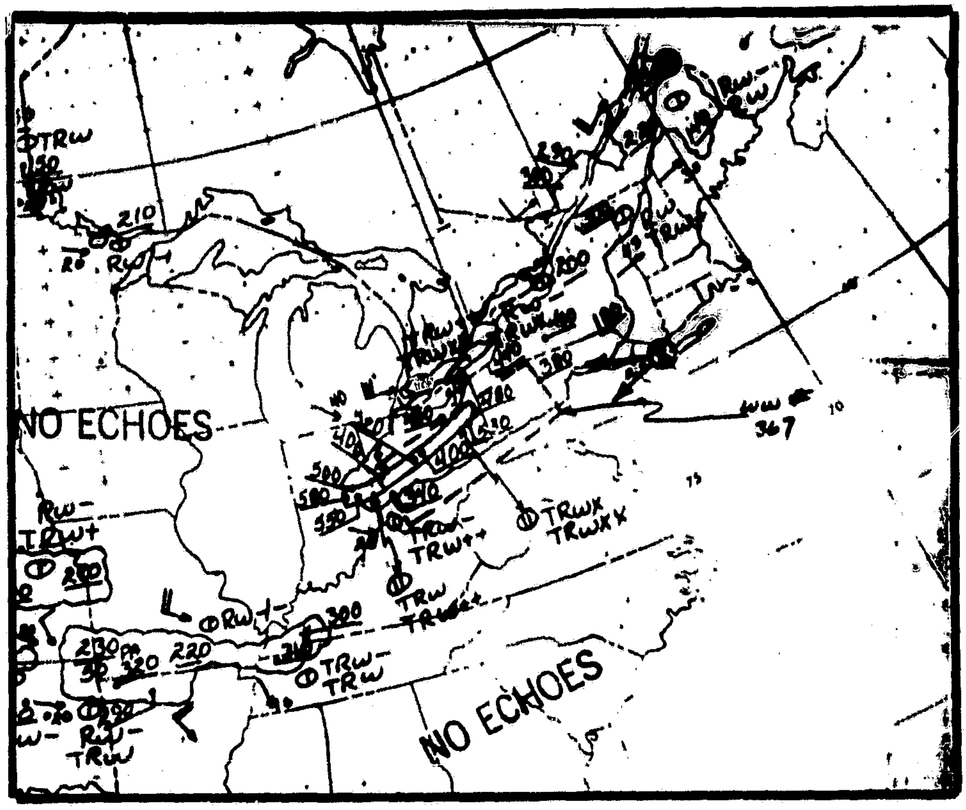

FIG. 6. Radar summary map for 2235Z GMT showing the locations of thunderstorms which generated the gravity waves.

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-

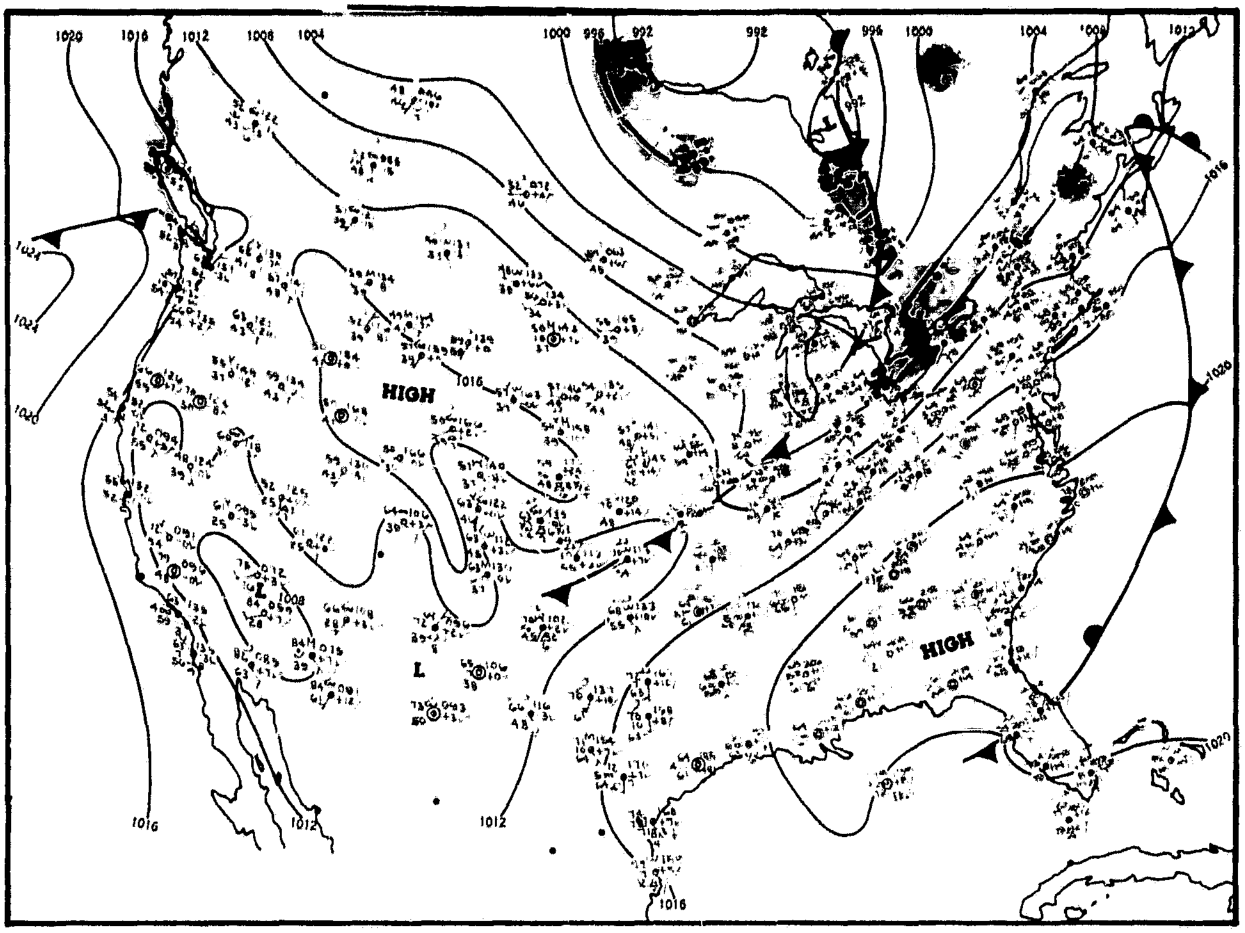

FIG. 7. Surface weather map for 0700, EST, 30 June 1974.

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-

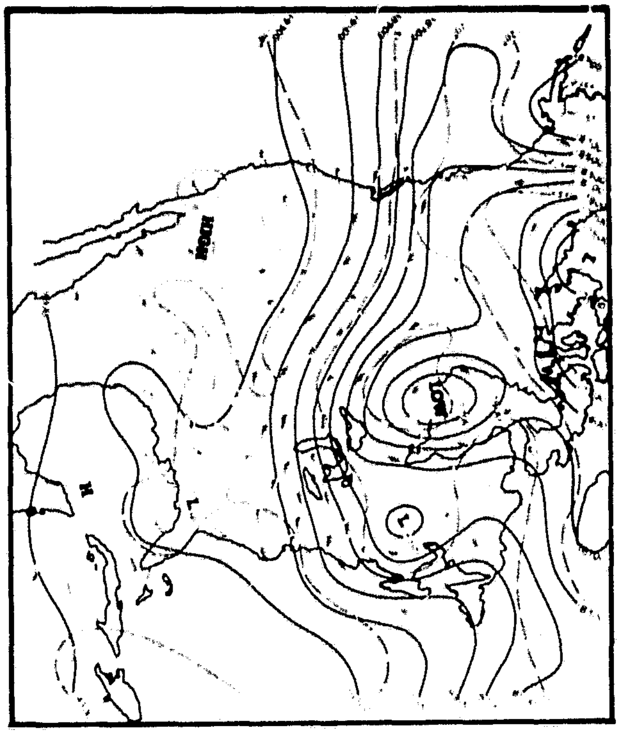

FIG. 8. 500 mb map for 0700, EST, 30 June 1974.

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

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

Shoreham Tower a temperature inversion developed between the levels of 33 and 150 ft with a gradient of +6.2°C km^{-1} and a superadiabatic lapse rate existed between 150 and 400 ft with a temperature gradient of −10.2°C km^{-1}. The background gradient, before the wave incidence, was a stable −4°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°C km^{-1} and the temperature gradient in the layer between 200 and 400 ft was −18.2°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

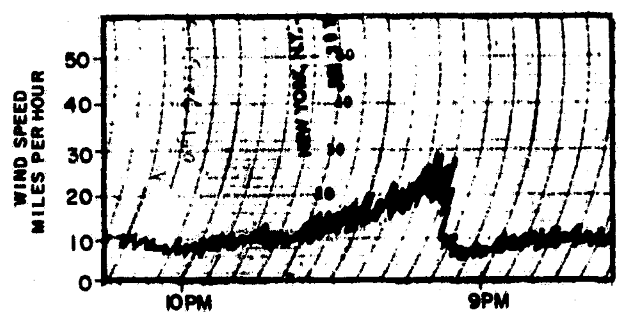

FIG. 9. Anemometer record showing the wind speed shift at the passage of the gravity waves at J.F.K. Airport.

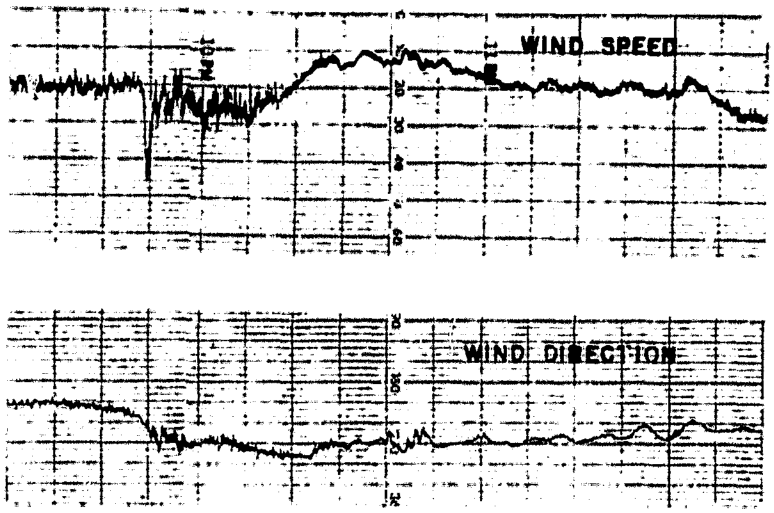

FIG. 10. Wind speed (mph) and direction (deg) for the 400 ft. level at Shoreham on Long Island.

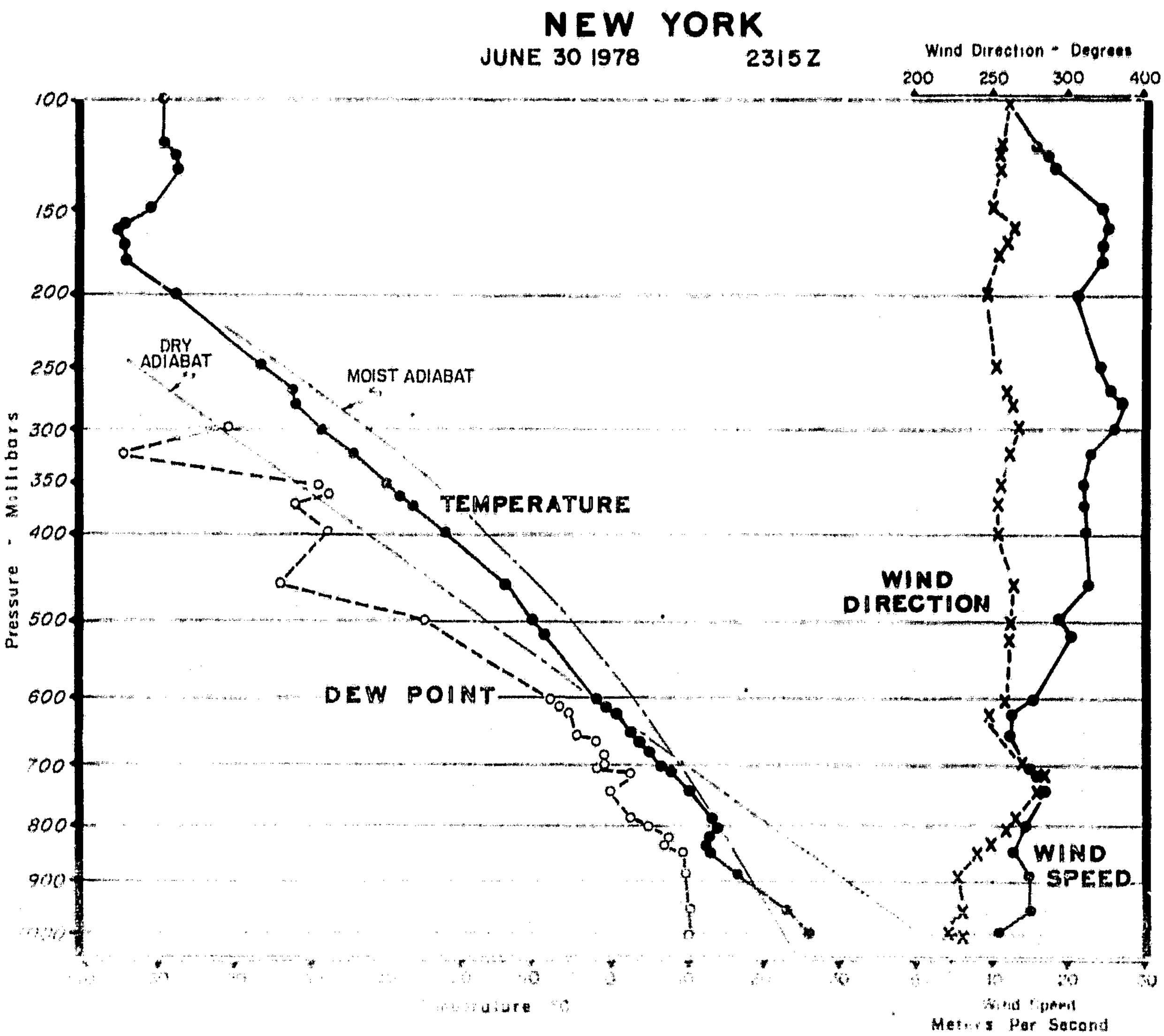

FIG. 11. Upper air [illegible]ature and wind data for New York [illegible] EST, 1 July [illegible].

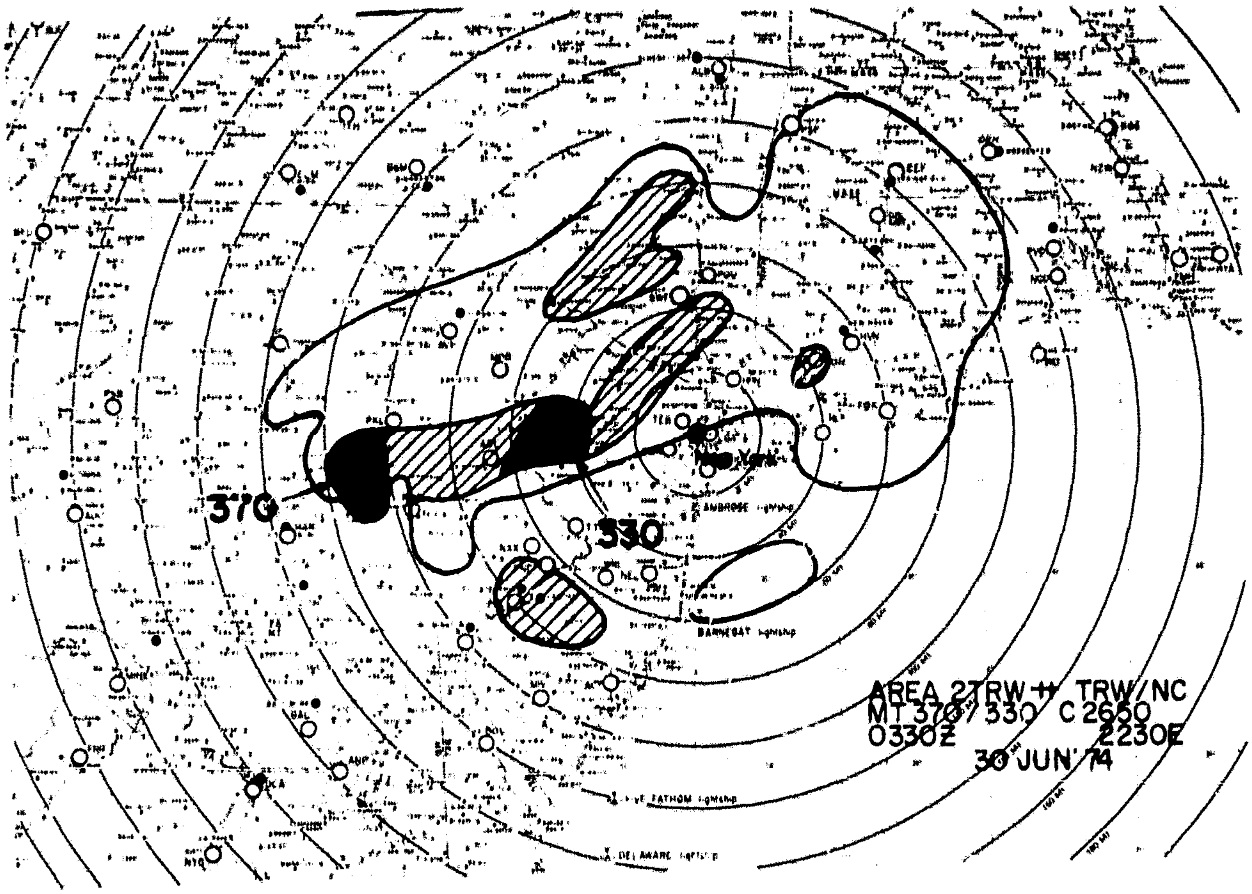

FIG. 12. Radar picture showing echo regions associated with thunderstorms triggered by the gravity wave.

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

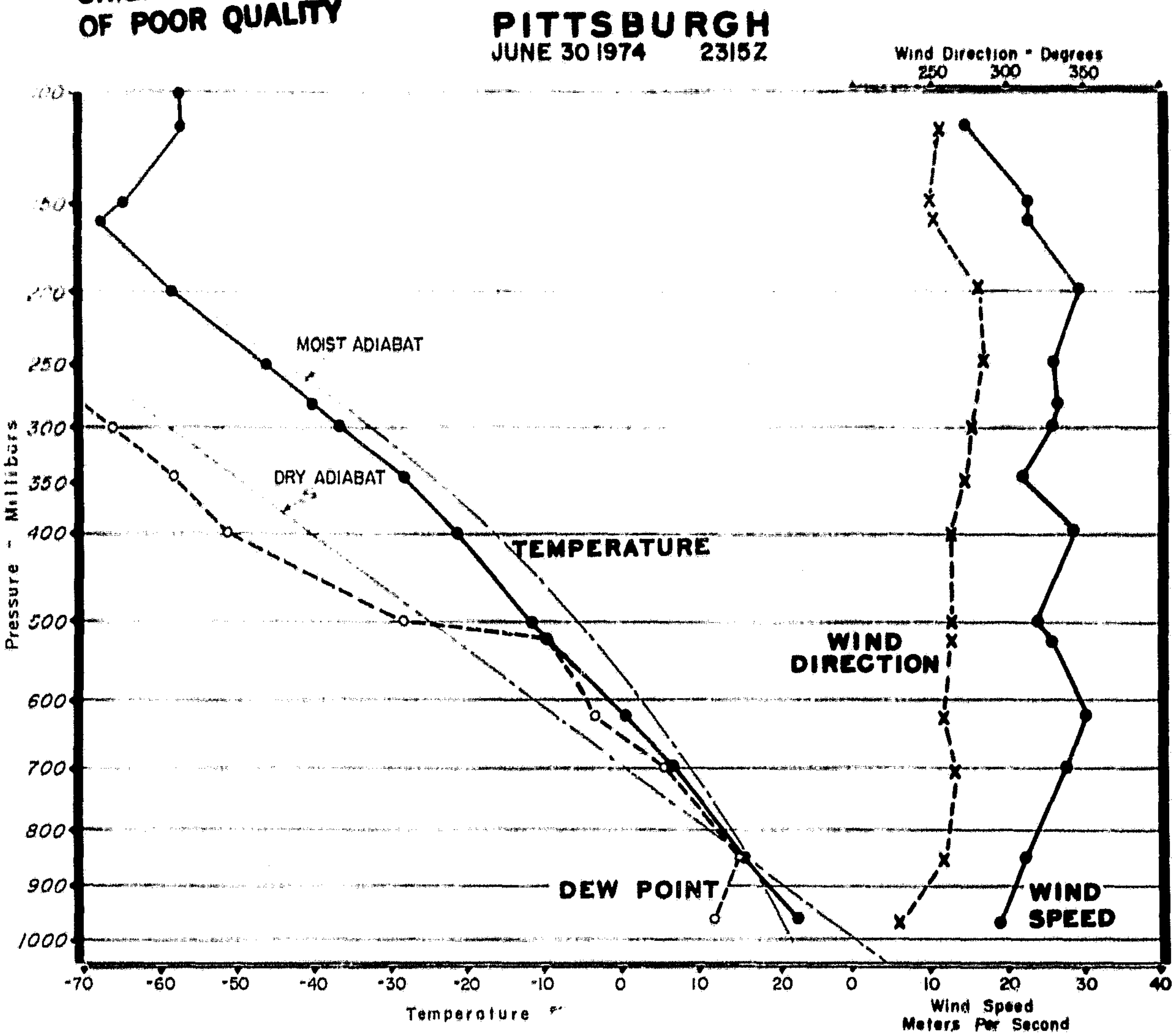

FIG. 13. Upper air data for Pittsburgh for 0000 EST 1 July 1974.

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

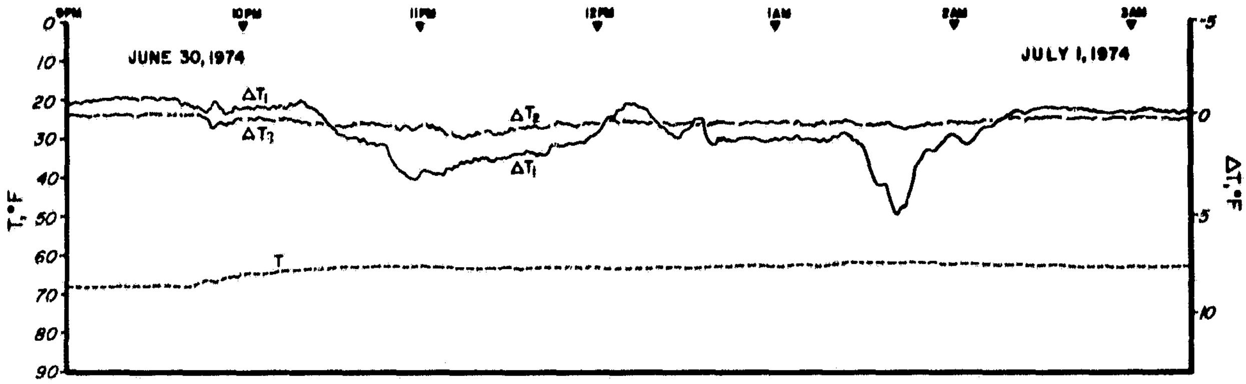

FIG. 14. Temperature changes at the 400 (ΔT_1) and 150 ft levels (ΔT_2) with respect to the temperature at the 33 ft level (T) recorded on the Shoreham tower at the passage of the waves.

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.

Acknowledgments. The author is grateful to Dr. David Rind for reviewing the manuscript and making helpful suggestions and to Mr. George Martin of Long Island Lighting Company for providing the tower data. The work was supported by NASA Contract NAS-8-33378, Army Research Office Grant DAAG 29-77-G-0131 and National Science Foundation Grant ATM 78-06771.

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APPENDIX 2

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Short-Period Atmospheric Gravity Waves: A Study of Their Statistical Properties and Source Mechanisms[1]

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ABSTRACT

Gravity waves for the one year period beginning 19 October 1976 around Palisades, New York, are investigated to determine their statistical properties and sources. The waves have typical periods of 10 min, pressure amplitudes of 3 Pa and velocities of 30 m s^{-1}. In general, the largest amplitude waves occur during late fall and early winter when the upper tropospheric winds directly overhead are fastest and the static stability of the lower troposphere is greatest. Mean wave amplitudes correlate highly with the product of the mean maximum wind speed and the mean low level stratification directly aloft. A distinct diurnal variation of wave amplitudes with the largest waves occurring in the pre-dawn hours is also observed as a result of the increased static stability then.

The majority of waves are generated by shear instability; however, a number of waves are generated by distant sources such as nuclear detonations or large thunderstorms. The waves with distant sources can be distinguished on the basis of their generally much higher coherency across the grid and velocities that depart markedly from the wind velocity at any point in the sounding.

1. Introduction

The purpose of this paper is to present further findings concerning the nature and behavior of short-period atmospheric gravity waves at Palisades, New York. The waves are measured by sensitive microbarographs and have typical periods of 10 min, pressure amplitudes of 3 Pa and phase velocities of 30 m s^{-1}. In previous papers (Gedzelman and Rilling, 1978 hereafter referred to as GR; and Gedzelman and Donn, 1979) attention was focused upon the dynamical aspects and synoptic associations of the waves.

The emphasis of this study is twofold—first to provide a more detailed wave climatology and second, to establish criteria for determining source mechanisms for the waves. In particular, since it has already been established by many researchers (see GR and references contained therein) that most short-period atmospheric gravity waves are shear generated, we shall seek those properties that distinguish the waves produced by other source mechanisms such as distant thunderstorms. The data base for this study is the one year period beginning 19 October 1976.

2. Data sources

The data sources are described at length in GR and Donn *et al.* (1963a,b). Briefly, they consist of an array of four sensitive microbarographs separated by distances between 2 and 5 km and situated in and around Palisades, New York. The instruments contain slow leaks so that the response begins to fall off for oscillations with periods greater than 20 min. For shorter periods the instrument response is nearly flat so that we obtain a reliable picture of the turbulence peak at ~30 s and the "knee" in the gravity wave spectrum at ~10 min (see Herron *et al.*, 1969). The meteorological data come principally from soundings taken at Fort Totten, Queens, which is situated 25 km SSE of Palisades.

The wave climatology is based principally on data from Tappan station because it had the least downtime of all the stations. Unfortunately, beginning about May 1977 the response of Tappan station began to diminish with respect to the other stations. The data have been corrected for this fall-off insofar as possible, but the values presented may still be somewhat small for the last three months.

3. Basic observations

Visual inspection of a sample wave record reveals two distinct phenomena. First, there are very short-period oscillations (≤1 min) that are totally incoherent across the grid and reflect turbulent pressure perturbations associated with wind gusts. We obtained a correlation of 0.85 between the wind speed at Central Park, New York and the turbulence amplitudes at Palisades for the two month period November–

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December 1969. Second, there are oscillations with periods generally greater than 5 min. These can usually be traced across the grid although their coherency is highly variable. These reflect pressure perturbations due to atmospheric gravity waves with an admixture of other small scale phenomena such as frontal passages and downbursts from thunderstorms.

The pressure spectrums obtained by Herron *et al.* (1969) in their study of one year of gravity waves show that there is indeed a distinct minimum of activity at periods between about 1 and 3 min. This enables us to consider higher and lower frequency oscillations separately. Hereafter, we refer to the oscillations with periods less than 1 min as turbulence and to the oscillations with periods greater than 3 min as waves or gravity waves. The various climatological findings of this paper should also be compared to the appropriate ones in Herron *et al.* (1969) for that is the only other investigation covering a comparable period and presenting comparable statistics.

Perhaps the dominant feature exhibited by the gravity wave records is that the wave amplitudes are markedly larger than average when extratropical cyclones are approaching. This synoptic association was shown by GR to result from the concurrence of first, strong winds and low static stability in the mid or upper troposphere directly overhead (resulting in shear instability), and second, large static stability in the lower troposphere (resulting in amplification of the ground-based signals). Although there is appreciable variance, the wave speeds and especially directions match best with the wind velocity at the level of minimum Richardson number. Not often are waves encountered with phase velocities that lie outside the range of wind velocities somewhere in the sounding. The shear generated waves tend to decorrelate quite rapidly in most cases (Herron *et al.*, 1969; Herron and Tolstoy, 1969) and do not travel far from the region of origin (Donn *et al.*, 1973; Hooke and Hardy, 1975; Gedzelman and Donn, 1979). Finally, the shear generated waves are apparently non-dispersive; well defined dispersion relations have been uncovered only for waves emanating from nuclear detonations (Donn *et al.*, 1963a,b; Balachandran, 1968) or other similar causes such as volcanic eruptions.

4. Climatological aspects

The features outlined above provide insight into the climatological behavior of the waves. One could then infer annual and even diurnal cycles for the wave amplitude with the peak activity occurring during the late fall and early winter months when the winds aloft are strongest and when the static stability of the lower troposphere is greatest on average. Waves should also be largest around dawn and smallest during mid-afternoon because of the diurnal variation of stratification.

The annual cycle of wave amplitudes is shown in Fig. 1. The peak activity does indeed come from October through March while there is a distinct lull from May through August. In Herron *et al.* (1969), wave activity remained quite high through May because, during both April and May 1967, winter circulation patterns prevailed throughout the northeast with strong upper tropospheric winds and low surface temperatures.

The previously observed association between the wave amplitudes and the stratification and wind velocity directly aloft receives overwhelming confirmation from the correlation coefficient 0.914 between the monthly mean wave amplitudes and the product of the monthly means of maximum wind speed aloft and static stability (expressed in terms of the potential temperature difference $\Delta\theta$) between 700 mb and the surface (see Table 1). This correlation is significantly higher than either of the partial correlations between wave amplitudes and wind speed aloft (0.64) or stratification (0.73) alone. The correlation of monthly means is also much higher than of instantaneous values (see GR) primarily because at any given instant it is possible for the waves aloft to be at any stage of development.

The diurnal cycle of wave amplitudes is depicted in Figs. 2 and 3. The ratios of the 3 h averages of wave amplitudes during midafternoon to those just before dawn are shown for each month in Fig. 2. These relate quite closely to the ratios of stratification below 700 mb for these same times. Over the entire period the average ratio of the wave amplitudes at these two times was 0.746, while the equivalent ratio of the static stabilities was 0.702. Thus it is clear that the wave amplitudes are on average almost proportional to the low level stratification.

The diurnal cycle of wave amplitudes is shown for two different months (February and June 1977) in Fig. 3. The midafternoon minimum shows up clearly for both months as does the predawn maximum. However, in June there is a secondary maximum

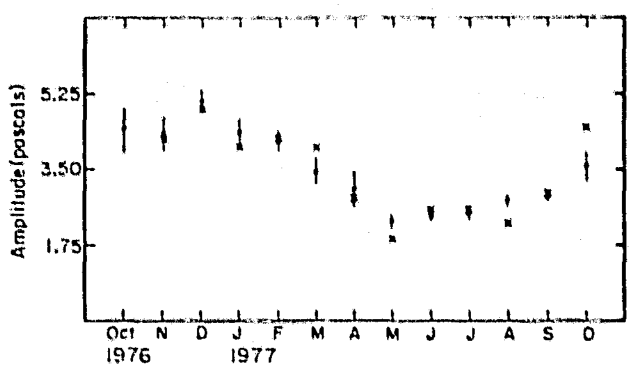

FIG. 1. Monthly mean gravity wave amplitudes. Error bars represent standard deviation of monthly mean based on hourly wave amplitudes within the given month. The X's represent a term proportional to the product of the mean maximum wind speed and the mean surface to 700 mb stratification.

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TABLE 1. Monthly mean values of wave amplitude, maximum wind speed and stratification between 700 mb and the surface.

Month	Stratification ($\Delta\theta$°C)	V_{max} (m s^{-1})	Amplitude (P)
November 1976	14.9	58.5	4.30
December	18.1	56.0	5.06
January 1977	17.5	47.5	4.38
February	16.9	51.8	4.13
March	15.7	52.7	3.45
April	14.5	40.7	3.03
May	13.6	28.5	2.29
June	12.5	42.4	2.43
July	14.5	37.4	2.49
August	13.7	33.9	2.80
September	15.2	39.6	2.88
October	16.6	55.8	3.57

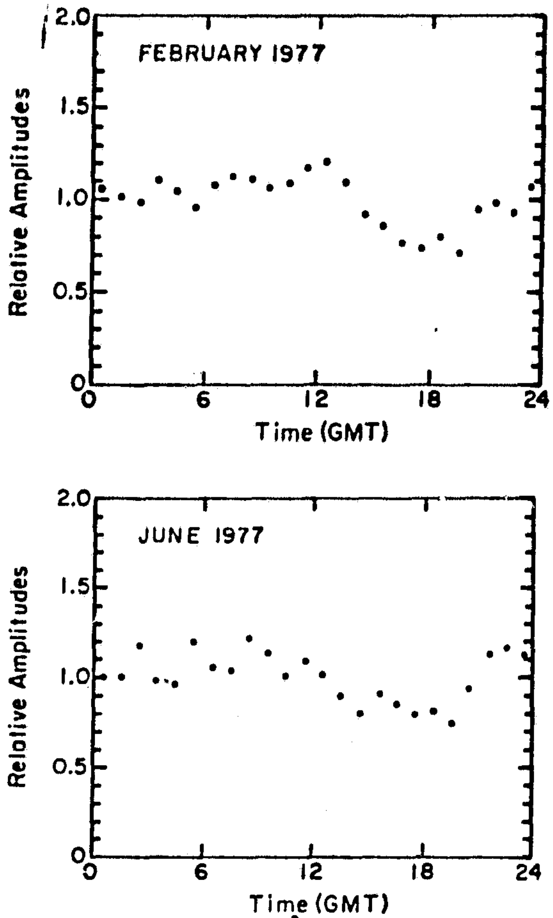

FIG. 3. The hourly mean wave amplitudes during (a) February 1977, and (b) June 1977.

around sunset. This results mainly from the contribution to the pressure variance of nearby thunderstorms.

The turbulent oscillations also exhibit annual and diurnal cycles. The annual cycle is shown in Fig. 4. Our instruments are placed in forested locations so that turbulence amplitudes reflect gustiness levels within the canopy. Thus, as might be expected, turbulent amplitudes increase dramatically after late October when the winds increase and the leaves have fallen. They peak during the winter and begin to decrease rapidly during early spring when the winds decrease and new plant growth begins.

The diurnal cycle of turbulent amplitudes is also quite dramatic as can be seen in Fig. 5. In each month there is a distinct maximum in midafternoon while there is a minimum around dawn. Afternoon amplitudes are more than double the morning values for all months except January through March. Often on clear days the turbulence can be seen to begin an hour or two after dawn, increase until midafternoon and thereafter decrease until it disappears around sunset.

Cross covariances were calculated and used to compute phase velocities and coherencies of the waves. Most of the time the wave amplitudes or coherencies were too small to provide meaningful values. We thus were forced to focus attention on wave "events" such as the times that low pressure areas approach or when thunderstorms are active. We found, as with Herron *et al.* (1969) and Herron and Tolstoy (1969), that the large majority of waves decorrelate within a wavelength. Indeed, coherencies of 0.90 for record sections of 90 min are extremely unusual. For most wave events coherencies vary between 0.4 and 0.7 and, as with ocean waves, tend to be higher in the downstream direction than the cross stream direction. Average coherencies for waves from a typical extratropical cyclone (17–19 March 1977) are shown in Fig. 6. It should be mentioned that for some storms there are packets of highly coherent waves, but these tend to be exceptional. Even so, such waves have velocities that generally match closely

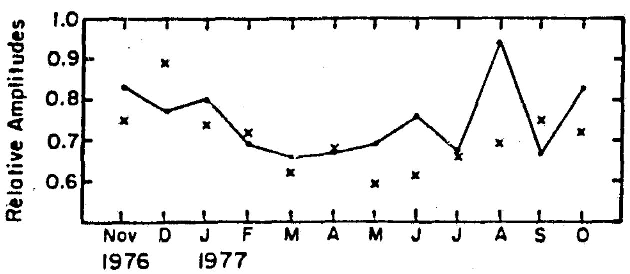

FIG. 2. The ratio of monthly mean wave amplitudes for the 3 h period of early afternoon to the 3 h period just prior to dawn. The X's represent the equivalent ratios of stratification from the surface to 700 mb.

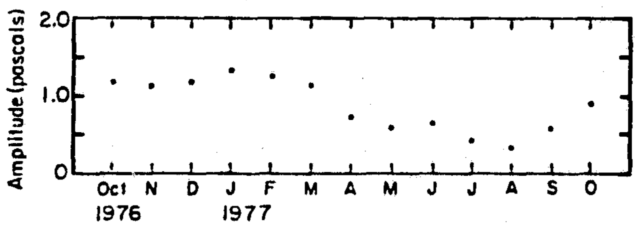

FIG. 4. Monthly mean turbulence amplitudes.

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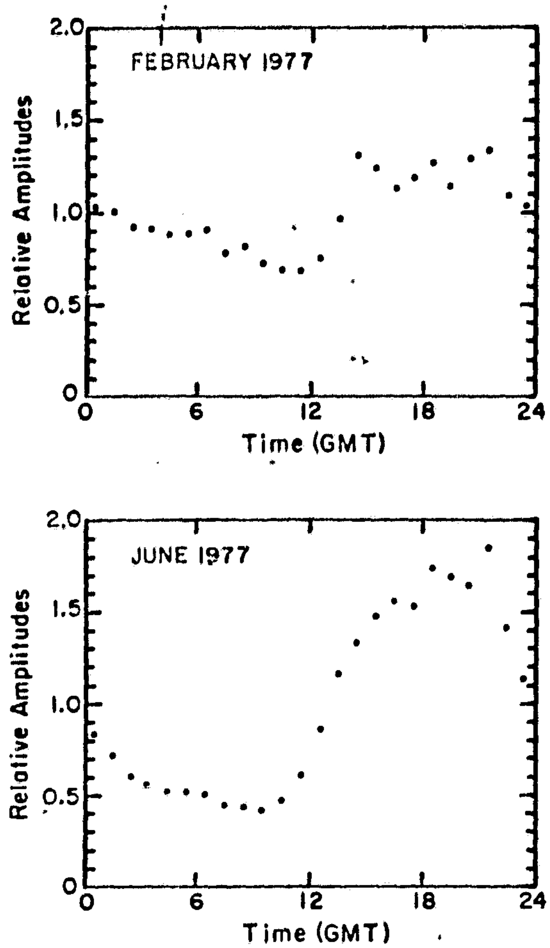

FIG. 5. The hourly mean turbulence amplitudes during (a) February 1977, and (b) June 1977.

with the winds at the level of minimum Richardson number so that shear generation is quite likely.

5. Waves generated by distant source mechanisms

Wave events can be *unambiguously* ascribed to distant source mechanisms if they satisfy the following criteria. The waves must:

1. Come in a distinct and highly coherent packet,
2. Have a velocity that differs (and usually exceeds) the wind velocity at any height directly aloft,
3. Be associated with some (preferably impulsive) meteorological event that occurred at a time and place appropriate to the wave arrival.

The first criterion is a result of the impulsive nature of the source (usually an explosion or a thunderstorm) and the fact that since the source is remote the coherency is apt to be high as with ocean swell. The second criterion is not necessary to waves generated by an impulsive source but is put here to enable one to easily distinguish such waves from those generated by shear instability. When the waves travel with a velocity that matches the wind velocity, detailed meteorological analysis is necessary to demonstrate an impulsive source (*e.g.*, Balachandran, 1980).

The first two criteria are helpful in identifying likely cases of waves generated by distant sources. Once this is done it is necessary to locate the source event itself. We used the following procedure for identifying such cases. All wave packets satisfying criterion 1 were identified during the three month period June–August 1977. This period was chosen because of the high incidence of thunderstorms and the low level of gravity wave activity. The wave velocities (and where possible the coherencies) of the waves were then computed. Finally, the search for an upstream meteorological event was undertaken.

During the three month period only three unambiguous cases satisfying all the criteria were uncovered (see Table 2). This is consistent with the finding of Curry and Murty (1974) that such events occur infrequently. All three cases were generated by thunderstorms that penetrated well into the stratosphere (according to radar echoes), and the arrival of wave packets matched closely with an impulse emanating from the thunderstorm at the time it approached maximum height. A fourth wave event, not from this period, is included because it came from a nuclear explosion and therefore from a known impulsive and distant source.

On 17 November 1976, waves were recorded from a nuclear explosion around Lop Nor, China (see Fig. 7). Although the wave period was only 75 s, the waves had an average coherency of 0.957. The estimates for wave speed and direction are 270 m s^{-1} and 005°, respectively. The estimate for speed is ~10% low but this is not serious in view of the close spacing between the stations and our lack of resolution. The direction, however, corresponds almost exactly with that of the great circle route. In any case, both the unusually high coherency and the fact that the wave velocity differed notably from that of background winds marked this event as one due to a distant event.

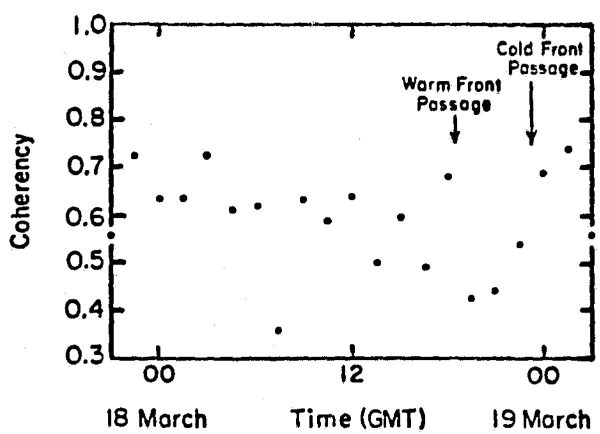

FIG. 6. Average wave coherencies between the grid stations for the storm of 17–19 March 1977. Each value is based on a 90 min sample.

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TABLE 2. Properties of wave events.

Arrival time	Velocity (°/m s⁻¹) Wave	Maximum wind	Average from source	Coherency	Length (km)	Distance to source (km)	Height (km) Tropopause	Cumulonimbus top
1600 17 November	005/270	—	005/?	0.96	19.4	11000	—	—
1530 3 July	300/45.3	340/30.0	295/41.5	≥0.90	28.8	2210	14.2	18.8
0430 5 July	315/47.1	325/40.0	305/50.9	≥0.90	39.0	1490	14.7	19.4
0100 16 July	340/28.5	340/7.5	310/27.8	0.81	21.4	535	15.1	19.8

Thunderstorms have long been known to generate or be triggered by short-period atmospheric gravity waves (Tepper, 1950). On occasion these waves appear to be ducted (Balachandran, 1980) but they may also be freely propagating (Erickson and Whitney, 1973; Curry and Murty, 1974). It is the latter kind we are concerned with here.

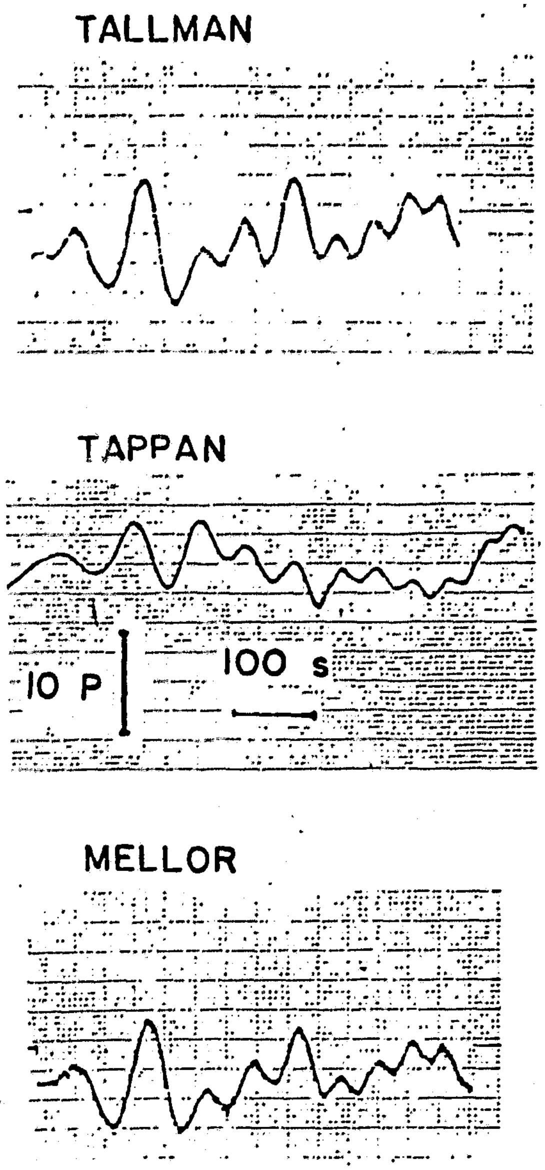

FIG. 7. Gravity wave record from the Chinese nuclear detonation of 17 November 1976. Phase of signal at Tappan is reversed.

At 0100 GMT of 16 July 1977 a highly coherent packet of waves crossed the grid (see Fig. 8). The waves had a speed of 28.5 m s^{-1} from 340°, and the wavelength was approximately 21.4 km. The average coherency during a 90 min period was 0.81, a rather high value and even more impressive when it is considered that the event lasted only an hour.

The principal distinguishing feature of this event was the fact that at the time a large upper air high was situated directly over New York City, and there were virtually no winds through the troposphere. The 850 and 250 mb charts for this time are shown in Figs. 9 and 10 respectively. In addition, no nearby meteorological events that could possibly have triggered gravity waves were observed.

There was severe convective activity taking place along a line extending from Detroit to Montreal as can be seen in the satellite photo for 1935 GMT (Fig. 11). An enormous thunderstorm located near Toronto penetrated the tropopause around 1800 GMT and extended upward to 19.8 km by 1935 GMT. Assuming the waves arriving at Palisades, New York had traveled at constant velocity they were produced by the thunderstorm at the time it reached its greatest height. The wave direction, however, matched more closely with the orientation of the squall line as a whole rather than its largest cell (oriented 310° from Palisades). A satellite film loop provided by NOAA showed no short-period gravity waves approaching Palisades but did show a few cloud bands emerging from the squall line and traveling from 330°. The wave direction can also possibly be accounted for by the fact that the wavefront may well have been turned by the stronger northwest winds located north of the Catskill Mountains.

One interesting question, to which we do not have a complete answer, is why so few cases are observed in view of the large number of thunderstorms that penetrate the tropopause. Nevertheless, the cases share several basic characteristics. All three wave packets came from the northwest quadrant at a time when the winds aloft did also. At such times wave activity is typically quite small so that events would more easily stand out from the background signal. In

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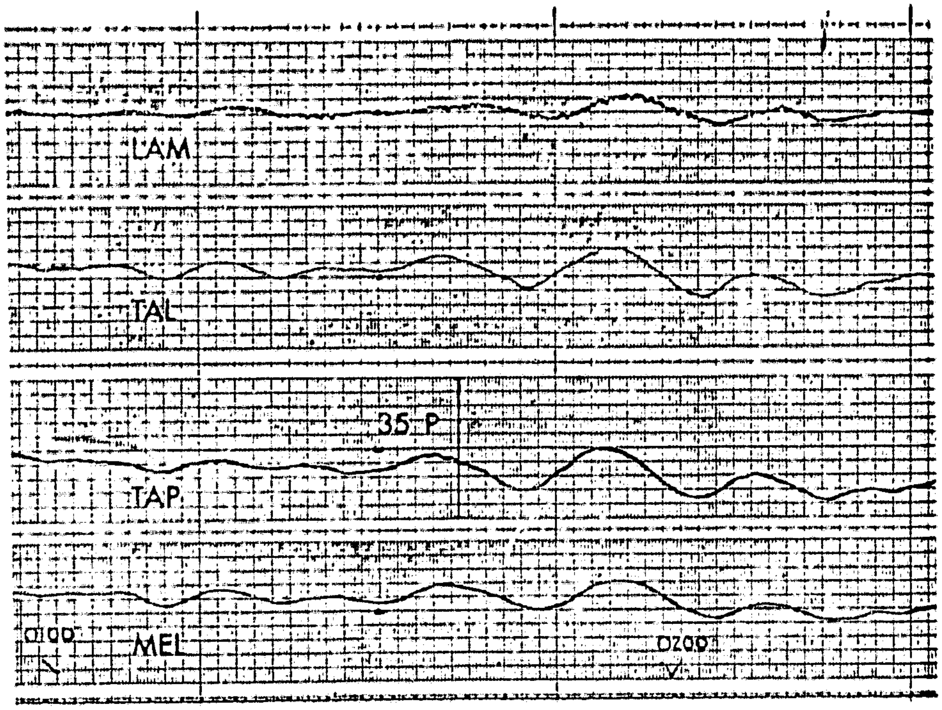

FIG. 8. Gravity wave record of 0100–0300 GMT on 16 July 1977 produced by thunderstorms near Lake Ontario.

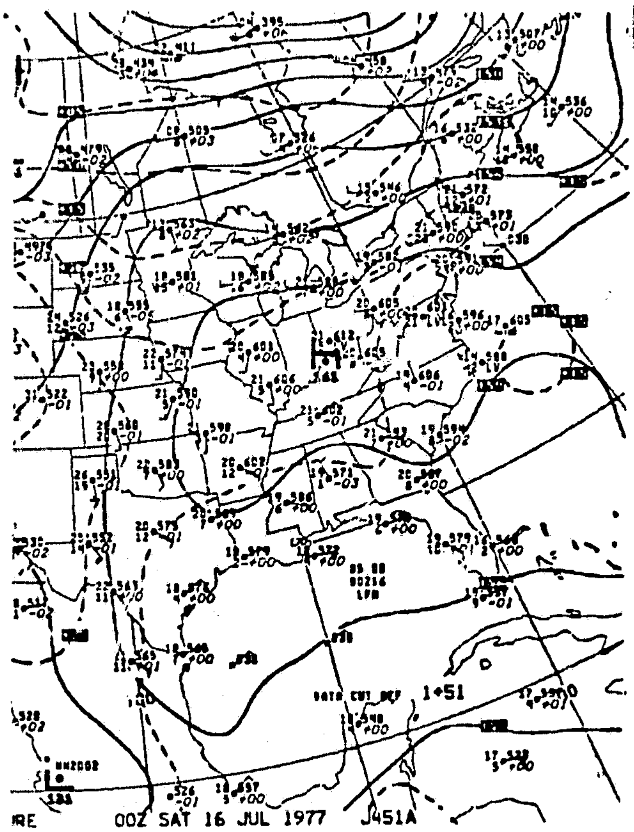

FIG. 9. The 850 mb chart for 0000 GMT 16 July 1977 showing weak winds above Palisades, NY.

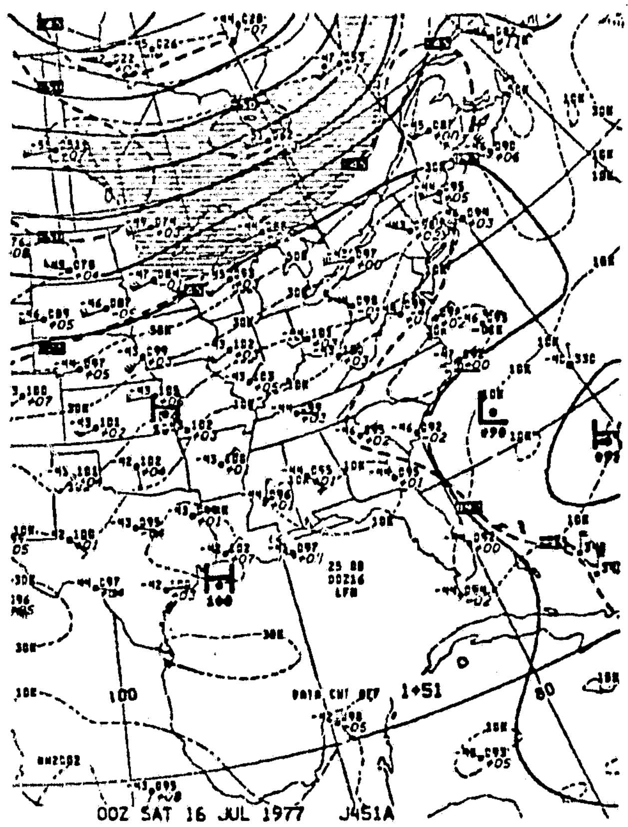

FIG. 10. The 250 mb chart for 0000 GMT 16 July 1977. Winds above Palisades, NY at this level are also quite weak.

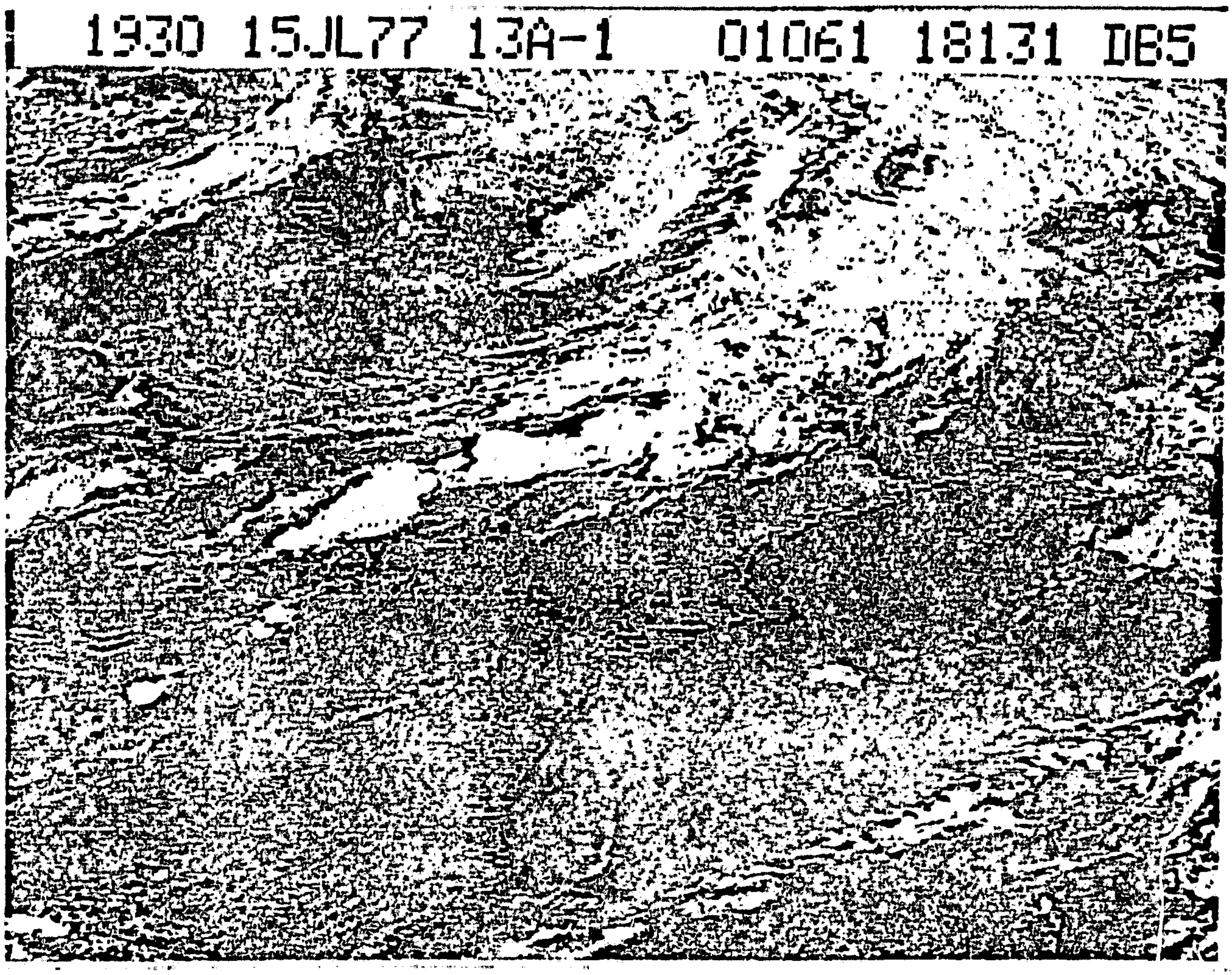

FIG. 11. Satellite photo of 1935 GMT 15 July 1977. Any waves emanating from the squall line would arrive at Palisades from 340°.

all cases the thunderstorms developed quite quickly and rapidly penetrated well into the stratosphere. Indeed, it is not all that often that thunderstorms penetrate the tropopause by almost 5 km.

Acknowledgments. It is a pleasure to acknowledge the guidance of and many discussions with Dr. N. K. Balachandran of Lamont-Doherty Geological Observatory of Columbia University. This research was supported by NASA Contract NAS8 33378 and NSF Grant ATM 80-15311.

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APPENDIX 3

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Acoustic and Electric Signals From Lightning

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Observations of infrasound apparently generated by the collapse of the electrostatic field in the thundercloud, are presented along with electric field measurements and high-frequency thunder signals. The frequency of the infrasound pulse is about 1 Hz and amplitude a few microbars. The observations seem to confirm some of the theoretical predictions of Wilson (1920) and Dessler (1973). The signal is predominated by a compressional phase and seems to be beamed vertically. Calculation of the parameters of the charged region using the infrasound signal give reasonable values.

INTRODUCTION

Ever since *Wilson* [1920] suggested that low-frequency sound (of frequency of the order of 1 Hz) will be emitted when the charged region in a thundercloud collapses when a lightning occurs, the actual presence of such signals in the acoustic signature of thunder has been the subject of controversy. *Dessler* [1973] made further refinements of Wilson's theory and came to the conclusion that the low-frequency acoustic (infrasonic) signal will begin as a rarefaction pulse followed by compressional pulse before reaching the equilibrium state. *Bohannon et al.* [1977] and *Balachandran* [1979] reported observations of infrasonic pulses from thunder, supporting most of the conclusions of *Dessler* [1973], but introduced new problems, one of them being that the signal, in most cases, initiated as a compression. The work of *Balachandran* [1979] was also criticized because of lack of simultaneous electric field and higher frequency sound measurements. The present paper is an attempt to present such data and confirm the presence of infrasonic signals.

Bohannon et al. [1977] used an array of microphones located on the corners of a square of side 40 m and reported infrasound pulses with a period of 0.5 s. In *Balachandran* [1979] and the present paper we report infrasound pulses with periods up to 6 s from microphones separated by distances of the order of a kilometer. Such large separations are necessary for the unequivocal identification of low-frequency acoustic pulses as well as for demonstrating the nature of vertical propagation of the signal. Here we also report simultaneous measurements of the electric field to positively identify the source of the signal.

One of the criticisms of the findings of *Balachandran* [1979] was that the acoustic measurements were made with the sensors attached to noise-reducing pipes. The noise-reducing pipes were suspected of distorting the highly impulsive thunder signals. For these reasons, for the present experiments, the sensors were taken out of the noise-reducing pipes. In some cases the sensors operated with no electronic filtering. We also installed an electric field mill for electric field measurements in association with acoustic measurements of thunder.

The simple physical explanation for the low-frequency sound pulse is that the mutual repulsion between charged rain drops in the main charged region (negatively charged) leads to a pressure deficit at the middle of the charged region and that when the charged region collapses at the time of the lightning stroke, this pressure deficit propagates as a rarefaction pulse. For reasonable values for the dimensions of the charged region and the field strength, the duration of this pressure pulse turns out to be of the order of a second and amplitude a few microbars (dyes cm^{-2}).

During the summer of 1980, we operated an array of low-frequency condenser microphones (with a flat response in the frequency range of 0.1–300 Hz) along with an electric field mill. Occasionally, signals from selected microphones were subjected to electronic band pass filtering in order to separate the low-frequency component of thunder from the higher amplitude audible part of thunder. This will be explained when the signal is presented.

In Figure 1 is shown the acoustic signal recorded on the 3 microphones of the Lamont array. The top three traces were generated with the use of electronic filters in the pass band of 0.1–10 Hz and the fourth trace is from the third microphone with no electronic filtering (0.1–300 Hz pass band). The strong audible thunder signature is quite discernable from trace 4. The locations of the microphones of the array are shown in Figure 2. It is obvious from the first three traces that the signal arrivals at the three microphones show distinct time differences. After carefully measuring arrival time differences between each pair of signals, we calculated the trace velocity of the acoustic impulses across the array. It is found that the signal is propagating almost horizontally. It may also be noticed that there is no low-frequency (frequency of the order of 1 Hz) signal present in the thunder signature. Thus, the acoustic signals in Figure 1 indicate that in this particular case when the signals arrive almost horizontally, no low-frequency signals are present. This is in agreement with the theoretical deductions of *Dessler* [1973], viz., that the infrasonic signals are highly directional in that the sensor has to be almost directly below the thundercloud to detect them. When the sensors are located away from directly below the thundercloud, the infrasonic component is likely to be absent from the thunder signal.

As the thundercloud apparently moved overhead, low-frequency signals began to appear. The signals shown in Figure 3 clearly show the presence of the low-frequency components. As before, the first three traces are, as in Figure 1, electronically filtered in the pass band of 0.1–10 Hz, and the fourth trace represents the unfiltered signal. The low-frequency component of a frequency of about 1 Hz, especially at the beginning of the signal, is clearly evident on all the traces. The fact that the infrasonic component is picked up by all the microphones with separations of about a kilometer from each other (as shown in Figure 2) shows that it is a real coherent signal and does not represent turbulence due to wind or any such signal of low

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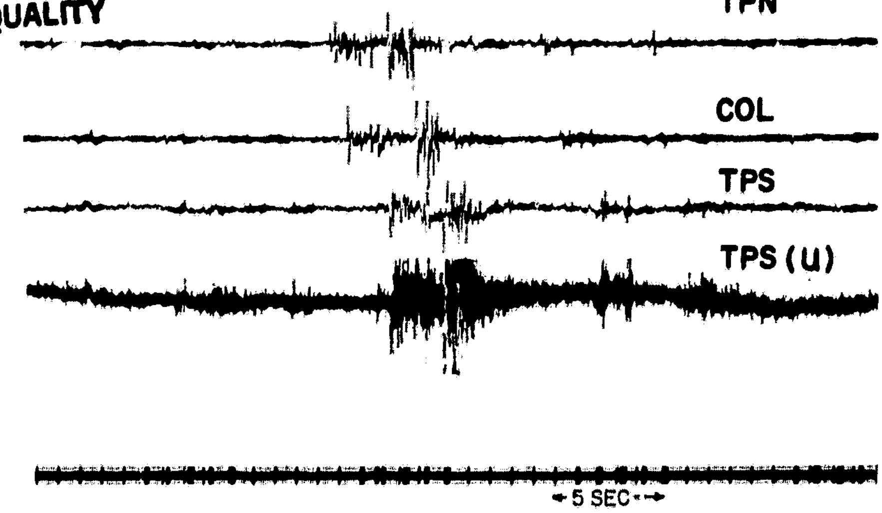

Fig. 1. Thunder signals from the three microphones of the array, recorded during the storm of June 29, 1980. The top three signals have been subjected to electronic filtering in the pass band of 0.1–10 Hz. The fourth trace, TPS(U), is TPS unfiltered. Time increases from left to right. Increase of pressure is upward on the 1st and 2nd traces and downward on the 3rd and 4th.

coherency. There are indications that the low-frequency component is present at other parts of the signal also. It appears, from Figure 3, that the high-frequency audible component of thunder is riding on top of the low-frequency component and that low-frequency component is not the result of a modulation of the amplitude of the high-frequency component. The small time delays between the low-frequency components at the beginning of the signal imply almost vertical propagation indicating an overhead source.

For later measurements we were able to set up an electric

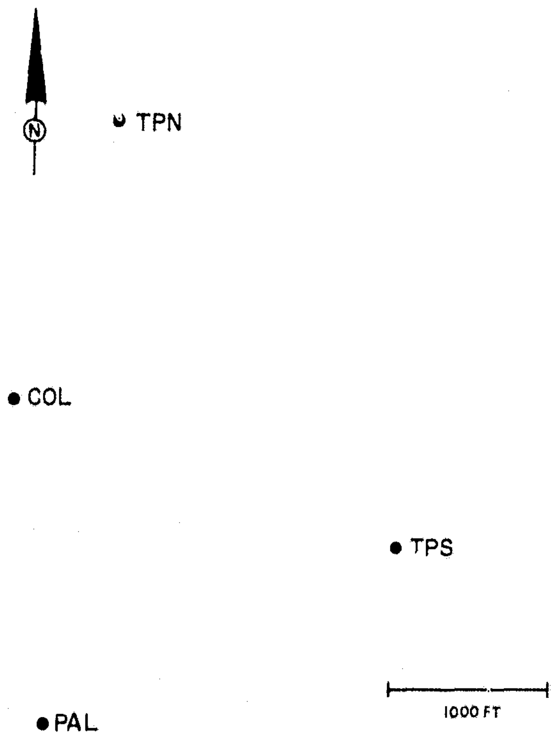

Fig. 2. Lamont-Doherty microphone array.

field mill along with our microphones. The electric field changes associated with the thunderstorm of July 22, 1980, is shown in Figure 4. Long period field changes associated with the movement of the thundercloud as well as sharp field changes related to the lightning strokes are evident in Figure 4. The signals from the four elements of our acoustic array along with the output of the field mill is shown in Figure 5. The acoustic signals have undergone electronic filtering in the pass band of 0.1–10 Hz. It is evident from Figure 5 that coherent infrasonic signals of frequency of about 1 Hz arrive at about 18 s after the sharp field-change due to a lightning stroke. It is also obvious from Figure 5 that the acoustic signals are arriving almost simultaneously at the three sensors located at TPN, COL, and PAL (separated by distances of the order of a kilometer, the exact location being show in Figure 2) and about 0.5 s later at TPS. This indicates that the location of the source may be over the first three stations and that the signal propagates with a small angle to the vertical towards TPS. The signal has the same amplitude at the first three locations, whereas at the fourth (TPS) location the signal amplitude is reduced approximately by a factor of 2. Such amplitude reduction may be an indication that the TPS sensor may be located at the edge of the charged region; *Dessler* [1978] has shown that the infrasound signal will tend to propagate almost vertically down below the cloud and that the signal amplitude will decay significantly beyond the region directly below the cloud. This raises the possibility of using infrasound sensors to map the charged region in a thundercloud. This again confirms the observations presented in Figure 3 as well as provides observational verification for the theory that the infrasound from the electrostatic source is highly directional.

Another example of audible thunder and infrasound along with the field mill record indicating the lightning stroke is shown in Figure 6. In this case the microphones were operated without any electronic filtering. An infrasound pulse of about 0.5-s duration is easily recognizable at the middle of the thunder signal. The infrasound pulse is received approximately 14 s after the lightning stroke.

The spectrum of one of the acoustic signals in Figure 5, along

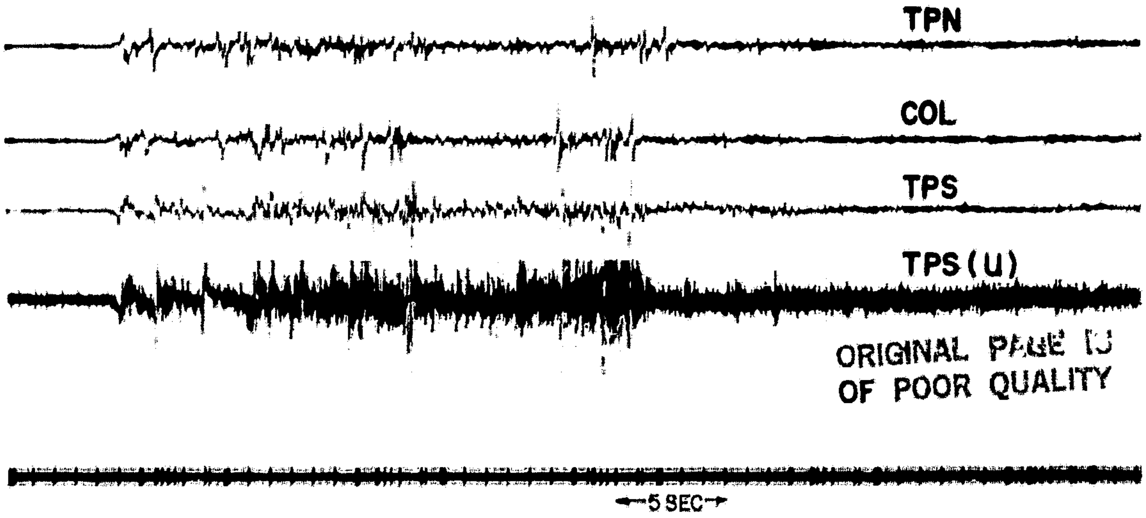

Fig. 3. Thunder signals recorded on June 30, 1980, showing low-frequency components. Other details are as in Figure 1.

with the spectrum of the acoustic background, is presented in Figure 7. The background was very quiet both before and after the arrival of the lightning associated acoustic signal. Within the 0.1–10 Hz pass band of the system, we notice from Figure 7 that the spectrum indicates a peak with maxium amplitude at about 2.5 Hz, with the peak with the lowest frequency at about 1 Hz. The 1-Hz signal is evident in Figure 5 also.

After having established that the low-frequency signals detected by our instruments are indeed associated with lightning discharges in thunderstorms, we will now attempt to study the characteristics of these signals. The infrasound signal from the thunderstorm of July 22, 1980, presented in Figure 5 has a compressional phase in the beginning, followed by the main rarefaction phase. The main rarefaction pulse has a duration of 0.7 s (a frequency of about 1.5 Hz) with a peak to peak amplitude of about 6 microbars. The most interesting aspect of this pulse is that it arrives at the three transducers almost at the same time. This indicates a signal propagating vertically downward over the array. There are other smaller pulses also in the signal; their relationship to the lightning discharge requires further investigation.

Measurement of the signature of the infrasound pulse can be used to calculate the electric field and spatial characteristics of the charged region. Applying the derivation of *Dessler* [1973] to the vertically propagating pulse in Figure 5, we get the following results.

The thickness d of the disc-shaped charged region is given by $d = CT$ where T is the period of the infrasound pulse and C is the velocity of sound. In the case of the pulse in Figure 5, $T = 0.7$ s and with $C = 340$ m s^{-1}, $d = 238$ m. The electric field strength E_0 is given by $E_0^2 = (2P/\varepsilon_0)$, where P is the reduction of pressure at the middle of the charged region and ε_0 is the permittivity. For $P = 6$ dynes cm^{-2} (0.6 N m^{-2}), E_0 is 1.1×10^5 V/m, or for the case of infrasonic pulse in Figure 5, the electric field strength just before breakdown was about 10^5 V/m. It may be pointed out that this simple calculation involves the pressure deficit at the center of the charged region and not the pressure due to the radiated acoustic wave. Since we are measuring the pressure change due to the radiated acoustic wave, the actual electric field strength may be larger.

The directionality property of infrasound pulses from thunderstorm was investigated by using the infrasound signals from the storm of August 27, 1976, which provided a large number of infrasound pulses. In Table 1 the azimuth and elevation angles for a series of 12 pulses during the time interval of 0736–0757 EDT on August 27, 1976, are presented. The progression of the source of the signals from the WSW towards almost overhead position and then from the opposite direction can clearly be discerned. The signals have high horizontal trace velocities compared to the speed of sound, indicating vertically propagating signals. The highest angle of incidence of the signal with the vertical (just one case) is 41° indicating the vertically beamed nature of the infrasound signal.

Discussion and Conclusions

The evidence of the presence of infrasonic signals in thunderstorms in association with audible thunder signals and electric field changes presented in this paper seems to indicate the collapse of the electrostatic field as the source of the signal, as suggested by *Wilson* [1920] and *Dessler* [1973]. Our observations agree in some major aspects with the predictions of *Dessler* [1973]. The vast majority of the signals are dominated by rarefaction pulses apparently corresponding to the reduction of pressure inside a charged region; but some deviation from the signature of the pressure pulse for a disc-shaped charge distribution given by Dessler is observed. According to this model, the characteristic signature will begin with a rarefaction followed by a compression. In our case most of the signals begin with a small compression, followed by a large rarefaction and then a compression (Figure 5). The initial compressional phase in Figure 5 last for about 0.25 s. *Bohannon and Dessler* [1981] postulate that this compressional phase is related to the positive shielding layer at the base of the thundercloud. The mutual attraction between this layer and the main negatively charged layer above leads to an increase of pressure that is released as a compressional pulse when lightning occurs. Preliminary calculations using observed parameters of the charged region are roughly in agreement with the observed infrasound parameters.

The theoretical radiation pattern of the electrostatic sound due to the collapse of a disc-shaped and cylindrical charge

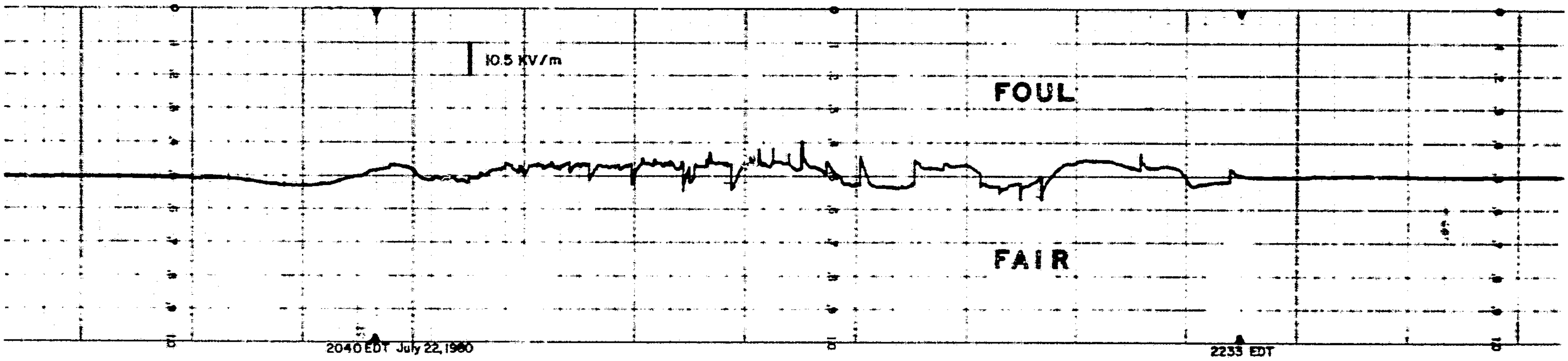

Fig. 4. Recording of the output of the electric field mill showing the electric field changes for the storm of July 22, 1980.

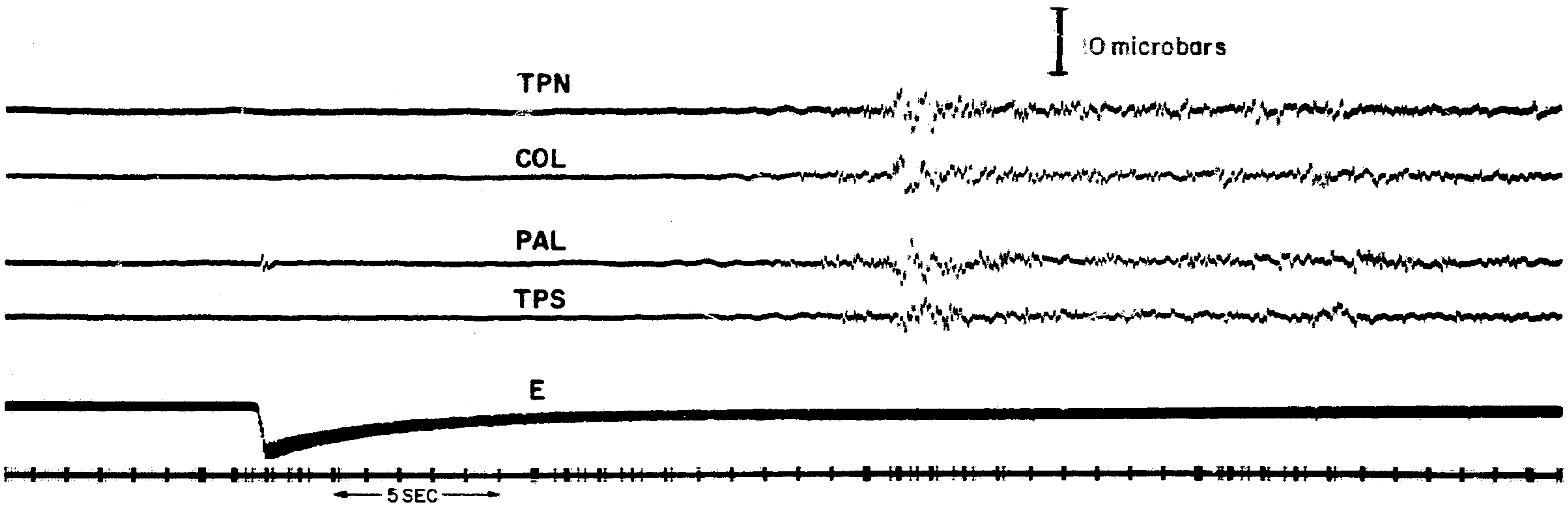

Fig. 5. Infrasound signals (within a pass band of 0.1–10 Hz) from the 4 microphones of our array along with the record of electric field (E) for a lightning event during the storm of July 22, 1980. Pressure increases is upward on the first two traces and downwards on the last two traces. Time increases from left to right.

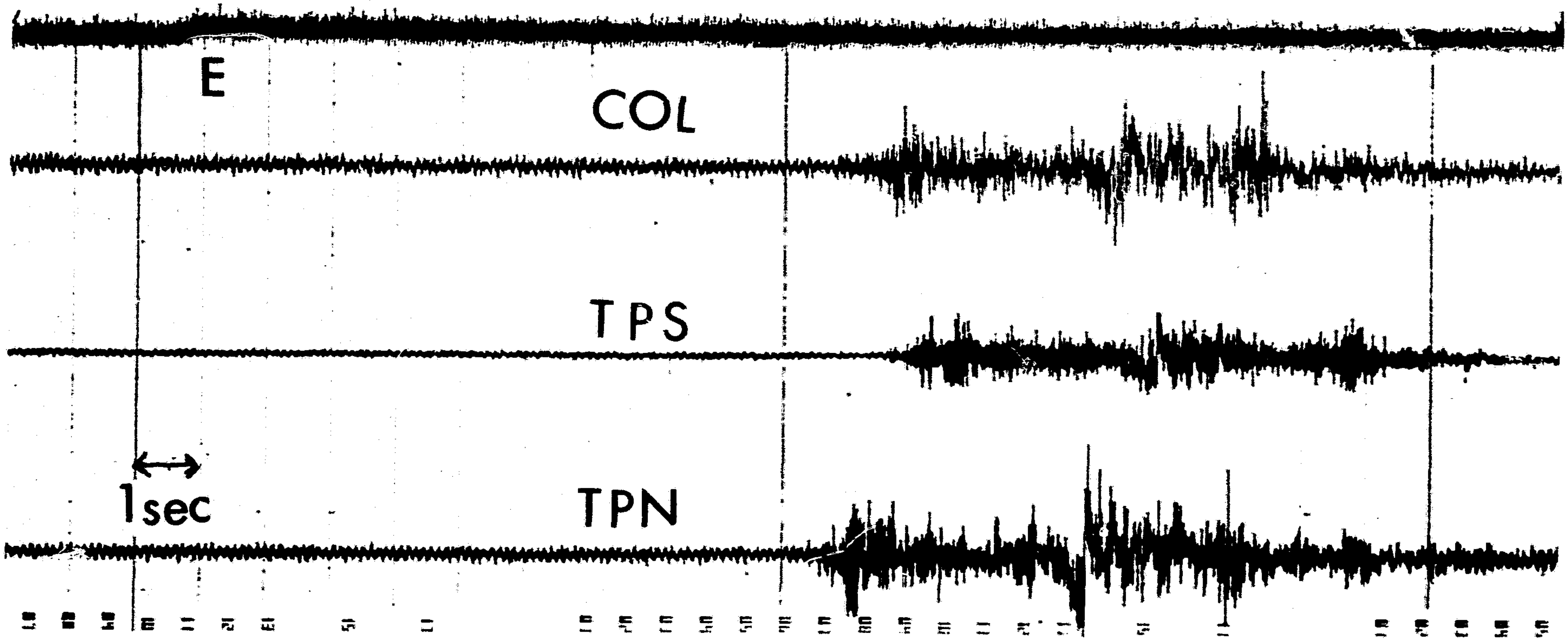

Fig. 6. Electric field (E) and acoustic signals (unfiltered) from a lightning stroke of September 22, 1981. Time increases from left to right.

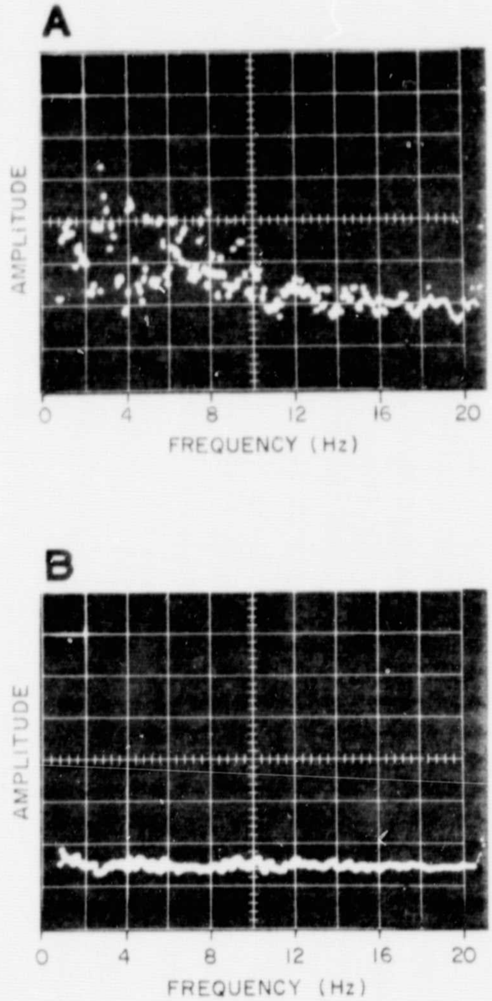

Fig. 7. Amplitude spectrum of one of the acoustic signals in Figure 5.

distribution has been developed by *Dessler* [1973]. His results show a well-collimated beam of infrasound in both cases, and the sensors have to be almost directly beneath the thundercloud to detect the signal. This occurs in spite of the fact that the sound generated is of such low frequency as to cause very little attenuation. The highly directional nature of the signal is due to the source that has a nonspherical volume with a characteristic length longer than the wavelength of the signal radiated.

TABLE 1. Azimuths (Measured Clockwise From North) and Angles of Incidence (Measured From Vertical) of a Series of Infrasonic Pulses From the Thunderstorm of August 27, 1976

Arrival Time, EDT	Azimuth, degrees	Horizontal Trace Velocity, m/s	Angle of Incidence, degrees
073632	249	952	21
074133	252	597	35
074454	252	876	23
074724	245	1351	14
075006	257	3231	6
075142	202	1923	10
075323	008	1861	11
075331	132	525	41
075536	035	1852	11
075710	182	1364	14

Our observations show good agreement with this theoretical prediction. A vast majority of the infrasound signals we received were travelling almost vertically down, and the largest observed angle of propagation is about 45° with the vertical. It may be feasible to use infrasound sensors to map the charged region in a thundercloud.

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