# Thunderstorm-Generated Gravity Waves

M. J. CURRY[1] AND R. C. MURTY

*Dept. of Physics, University of Western Ontario, London, Canada*

(Manuscript received 9 August 1973, in revised form 1 March 1974)

## ABSTRACT

Internal gravity waves have been recorded at London, Ontario, using a network of three microbarographs. It has been shown from experimental observations that internal gravity waves are generated by thunderstorms. The spectral behavior of these waves has been found to be essentially monochromatic. A simple model for the generation of these waves is presented and it is shown that the observed properties of the waves are in good agreement with the features of the suggested model.

## 1. Introduction

Observations of microscale fluctuations in atmospheric pressure at the surface of the earth sometimes reveal the occurrence of low-amplitude sinusoidal variations in pressure. The results of various studies have been summarized by Flauraud *et al.* (1954) and by Fullerton (1966). Fullerton observed that nearly all investigators who have studied pressure variations in the middle frequencies have ascribed them to convective activity and internal gravity waves in the lower troposphere. These waves are different from those generated by jet streams (Madden and Claerbout, 1968; Tolstoy and Herron, 1969), nuclear explosions (Yamamoto, 1955, 1968) and volcanic explosions (Pasechnik, 1959). Jet-stream generated waves are usually of several hours duration while those from nuclear explosions are of long period with group velocities of the order of the speed of sound.

Periodic variations in surface pressure and wind were observed from a number of widely scattered stations in southern England in July 1952. Pothecary (1954) suggested that it was possible that the oscillations were set up when the lower airstream was temporarily blocked by the outflow of cold air from an intense outbreak of thunderstorms over the western English Channel.

In 1966, Pierce and Coroniti suggested a mechanism by which thunderstorm activity could generate acoustic gravity waves. Although the downward propagating wave would be strongly attenuated, Pierce and Coroniti concluded that it might retain sufficient amplitude to be detectable by microbarographs at the surface of the earth. Subsequently, Murty and Curry (1969) reported the observation of a strikingly regular microbarometric oscillation and suggested that this trace could have been due to waves generated by an isolated thunderstorm some 120 mi distant. They had only one observing station, however, and were thus unable to measure the speed or direction of propagation of the wave.

Georges (1968) and Baker and Davies (1969) observed some correlation between ionospheric disturbances and severe storms and suggested that acoustic waves could be generated by the storm systems.

Even though thunderstorm systems as possible sources of gravity waves have been suggested, there has been a conspicuous lack of experimental evidence to support such a hypothesis.

In this paper it will be shown that low-amplitude internal gravity waves are generated by strong thunderstorm systems. A simplified model of the generating mechanism is also discussed.

## 2. Experimental arrangement and procedure

The response characteristics of three microbarographs of the type described by Kortschinski *et al.* (1971) were matched to a theoretical response curve having a center period of 10.0 min and half-power points of 3.2 and 32 min. The instruments were separated to form a triangular array having sides of about 4 km. Microbarograms were recorded continuously at all three locations over a period of nearly two years, from 14 November 1969 to 10 November 1971. The charts were manually scanned for the occurrence of wave events, defined as regular oscillations incident upon the entire array. By measuring the differences in times of arrival of a pressure wave at the three stations, the horizontal velocity $v$ and the angle of arrival $\beta$ of the wave were computed. Over the two-year period 145 such observations were made. The mean value of the velocity of the waves was found to be 33.2 m sec$^{-1}$. The observed velocities thus average about one-tenth of the speed of

---

[1] Present affiliation: Atmospheric Environment Service, Downsview, Ontario, Canada.

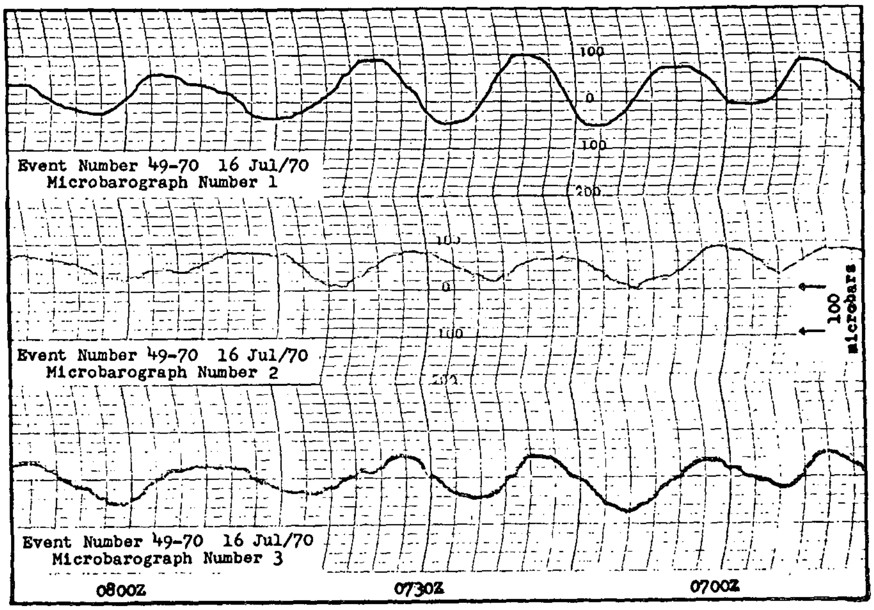

Fig. 1. Microbargrams of event number 49–70, 16 July 1970.

sound and are typical of gravity wave propagation velocities. The mean and median values of the period of the observed waves were about 10 min.

It is not possible to define uniquely a source region for each wave with a single-station, three-microbarograph direction finder. However, one can identify a time-locus of potential source regions which are in the direction $\beta$ at distance $D_s$, given by

$$D_s = v(t_0 - t_s), \qquad (1)$$

where $t_0$ is the time of observation of the wave and $t_s$ the time of its generation. An examination of synoptic data then reveals whether the time history of observed tropospheric phenomena is such that a potential source of energy inhabited any of the possible source regions at an appropriate time.

This method was applied to all 145 wave events. The primary source of synoptic data was the surface charts prepared by the Central Analysis Office of the Canadian Weather Service. These charts are issued for the hours 0000, 0600, 1200 and 1800 GMT daily and are polar stereographic projections drawn to a scale of 1: 20,000,000. They cover the major portion of the North American continent. Also of value were 1:10,000,000 scale surface charts compiled at the Toronto Weather Office for the synoptic situation at 1800 GMT daily. United States Weather Bureau daily maps were also available in some instances.

The charts were carefully scanned for events of meteorological significance in the region defined by $\beta$, $D_s$ and $t_s = t_c$, where $t_c$ is the time for which the chart was prepared. Interpolation between charts was possible in most cases. If one of the possible source regions coincided in time and space with a region in which there

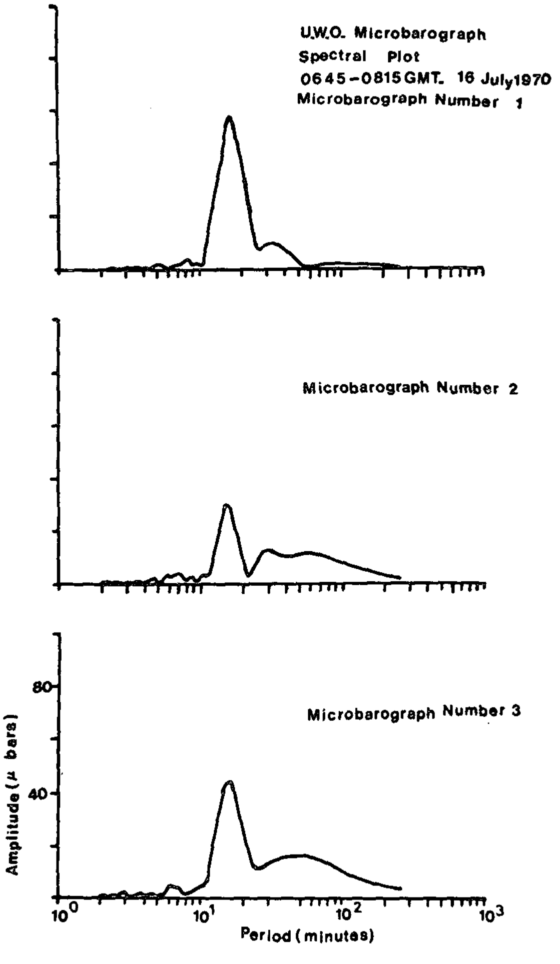

Fig. 2. Amplitude spectra of event number 49–70, 16 July 1970.

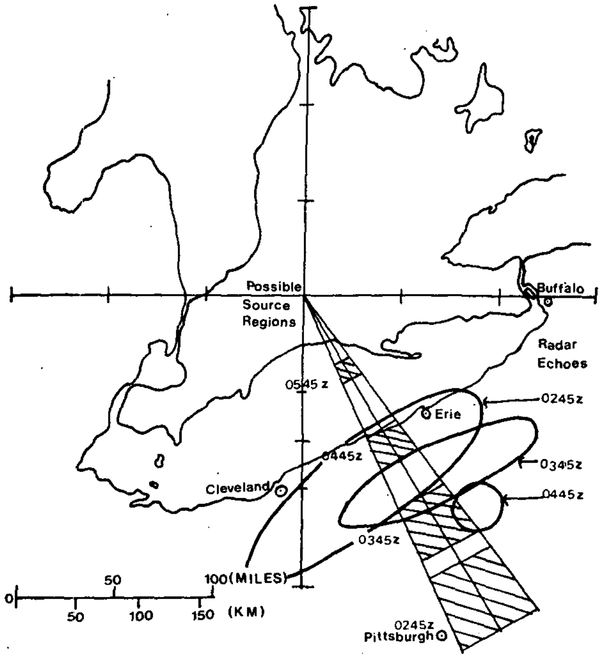

FIG. 3. Source location of event number 49–70, 16 July 1970.

was an appropriate source of energy, that region was identified as the source of that particular wave event. If no such coincidence was found, the wave was identified as having no apparent source.

## 3. Observations

Event number 49–70 (Fig. 1) was recorded at approximately 0645 (all times GMT) 16 July 1970. The waveform is most regular in chart number 1 but maintains a clearly identifiable structure over the extent of the microbarograph array. The maximum cross-correlation coefficients between pairs of records for this event are $\sigma_{32}=0.82$, $\sigma_{31}=0.91$ and $\sigma_{21}=0.76$, where the subscripts of $\sigma$ refer to the microbarograph stations. Analysis-produced values for $v$ and $\beta$ of 21 m sec$^{-1}$ $\pm 12\%$ and $149° \pm 6°$, respectively. The amplitude spectra (Fig. 2) show that the wave consisted essentially of a single component having a period of $\sim$16 min and a mean amplitude of $\sim$45 $\mu$b.

The locus of possible source regions (Fig. 3) leads directly to a storm system to the southeast of Lake Erie. The London Weather Office radar observations for 16 July reported an area of echoes of moderate strength from showers and thunderstorms at 0245 at a mean distance of about 100 mi. By 0345 the echoes had intensified and moved slightly to the east. Strong echoes from thunderstorm activity were observed. By 0445 the area of activity had diminished to a region 20 mi in diameter at a distance of about 140 mi. The track of the storm system and the locus of possible source regions intersect at about 0415. It is therefore concluded that the above event had its origins in a region of strong thunderstorm activity.

Other examples of the generation of gravity waves by thunderstorms were also found, most notably on 17–18 July 1970 and 24 September 1970. The most probable source for the waves recorded at 0345 on 18 July 1970 was found to lie in a region of strong thunderstorm activity ahead of an advancing cold front. The probable time of origin is about 0100 and the distance to the source region about 75 mi. The height of the echo tops was reported as 30,000 ft, indicating strong vertical motions in the region. The waves observed on 24 September 1970 were also attributed to a cold front thunderstorm system. A study of the radar observations suggests two possible sources—an area of thundershower activity at a distance of $\sim$100 mi and a line of strong thunderstorm cells at a range of $\sim$50 mi. The latter is considered to be the more likely source. In either case, it is highly probable that the wave was generated in a region of strong thunderstorm activity.

Thus, three of the 145 waves were clearly identified as having been generated by strong thunderstorms. Another 35 were found to have been generated in regions where there was thunderstorm activity, although the distances involved and the uncertainties in $v$ and $\beta$ make it impossible to conclude that these waves were generated by individual thunderstorms.

Having established that gravity waves are generated by strong thunderstorm systems, it is of interest to examine a simple model of the generating mechanism.

## 4. Simple model for the generation of gravity waves

### a. *Energy considerations.*

A gravity wave carries energy as it propagates. Therefore, the mechanism which generates a gravity wave must be capable of supplying it with energy. The search for sources for the waves observed in this experiment then amounts to a search for regions where there is energy available for the generation of the waves.

The amount of energy necessary for the generation of acoustic-gravity waves can be estimated in a number of ways. It is well known, for example, that the energy released suddenly by a lightning discharge, about $10^{10}$ J (Vonnegut, 1963), results in the production of acoustic waves. The figures given by Wood (1968) concerning the Great Siberian meteorite of 1908, which was observed to have generated pressure waves (Georges, 1967), imply a kinetic energy before impact of the order of $10^{12}$ J. These numbers are approximately of the same order of magnitude as the estimate of $10^{10}$ J made by Pierce and Coroniti (1966) as the kinetic energy of the oscillations which might generate acoustic-gravity waves at the tops of cumulus clouds. Thus, one is led to expect that energies of perhaps $10^8$ or $10^9$ J are necessary for the generation of tropospheric internal gravity waves. Further, one would expect that a not inconsiderable fraction of this energy should be available for vertical motions.

Fig. 4 shows a simple model for the generation of gravity waves by thunderstorms.

### *b. Thunderstorm as a source of gravity waves.*

The top of the developing thunderstorm cell is assumed to be a hemispherical cap of radius $R$ rising with velocity $U$. The rising cap is assumed to reach a position of stability at or near the tropopause and to create there an oscillation at a characteristic frequency $\omega_s$. The kinetic energy $E_k$ carried into the source region by the cap is then

$$E_k=\frac{\pi}{3}R^3U^2(\rho_a+\rho_w), \tag{2}$$

where $\rho_a$ is the density of the air and $\rho_w$ the mass density of suspended hydrometeors.

The rising cap will also carry thermal energy, since the air within the updraft portion of a thunderstorm cell is everywhere at a higher temperature than air at the corresponding altitude in the ambient atmosphere (Malan, 1963). The amount of excess thermal energy $E_T$ carried into the source region is given by

$$E_T=\frac{2\pi}{3}R^3(\rho_a+\rho_w)C\Delta T, \tag{3}$$

where $C$ is the specific heat and $\Delta T$ the difference in temperature between the cap and its surroundings. It is easily shown that $E_k \gg E_T$ so that the energy available for the generation of waves, while thermodynamic in origin, is kinetic in the source region.

An order-of-magnitude calculation of the value of $E_k$ can be made making use of the values

$\rho_w = 10^{-5}$ kg m$^{-3}$ (Atlas, 1963)
$\rho_a = 0.5$ kg m$^{-3}$ (Berry *et al.*, 1945)
$R = 5\times10^2$ m (Malan, 1963)
$U = 10$ m sec$^{-1}$ (Cunningham, 1958; Marwitz and Auer, 1968).

The computation gives a value of $E_k \approx 5\times10^9$ J, a figure which is comparable to the energy figures discussed earlier and is about two orders of magnitude larger than those suggested by Georges (1973) for the sub-acoustic power emitted by convective storms. The values of $R$ and $U$ used in this calculation are typical of convective cells of moderate strength and could be expected to be larger for severe thunderstorms. It is therefore reasonable to assume that acoustic-gravity wave generation by such a convective system is energetically possible. A brief discussion of the mechanism by which such acoustic-gravity wave generation might occur is given in Section 5.

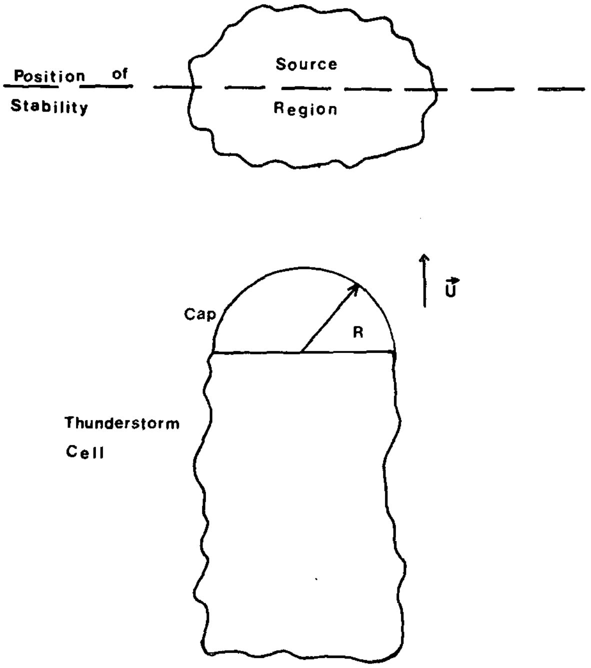

FIG. 4. Simple model for the generation of gravity waves by a developing thunderstorm.

The theory of acoustic wave propagation in the atmosphere has been discussed by Hines (1960), Georges (1967) and others. It will be sufficient to note here that a simple buoyancy oscillation of a parcel of air in a stable atmosphere takes place at the local Brunt-Väisälä frequency and can be expected to give rise to an essentially monochromatic internal gravity wave at a corresponding frequency (Pierce and Coroniti, 1966).

## 5. Case study of wave generation by a thunderstorm

It has been shown in Section 3 that event number 49–70 was generated in a thunderstorm system over Pennsylvania at about 0415 on 16 July 1970. The source region identified for this wave was located approximately 75 mi north of Pittsburgh, 40 mi south of Erie, and 120 mi east of Cleveland. The U. S. Weather Bureau stations at these three cities reported thundershower activity and distant lightning on 15 and 16 July. The station at Erie recorded wind, lightning and flood damage with additional reports of hail and tornado damage. The summary of radar observations for the northeastern United States issued by station MKC in Kansas City for 0045 on 16 July reported a line of severe thundershowers 15 mi wide located 50 mi west of Allentown, Pa., and 40 mi northwest of Baltimore. Clearly, there existed severe storm conditions over the state of Pennsylvania for the whole of 15 July and the early part of 16 July.

Fig. 5 shows a tephigram of data obtained from a radiosonde probe at Pittsburgh at 2315 on 15 July 1970. The lines marked $T$ and $T_D$ are the plots of temperature

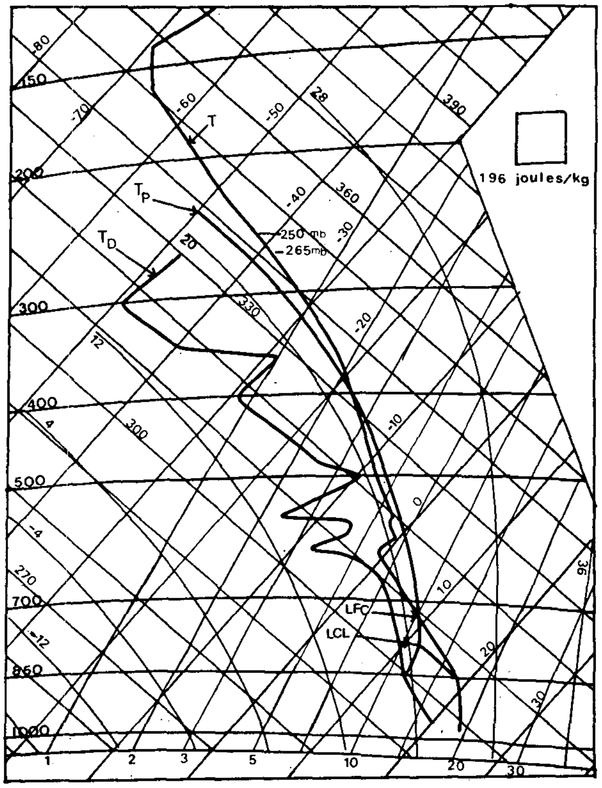

FIG. 5. Tephigram, Pittsburgh, Pa., 2315 GMT 15 July 1970.

and dewpoint, respectively. This sounding is assumed to be typical of the state of the atmosphere over Pennsylvania for several hours before and after 2315.

An indication of the stability of the troposphere at the time of the radiosonde ascent is provided by the Showalter index, obtained graphically by considering a parcel of air at 850 mb to be lifted dry adiabatically to its condensation level and then moist adiabatically to 500 mb. The value of the index is the difference (°C) between the temperature of the ambient air and the temperature of the parcel at the 500-mb level. Petterssen (1956) considers that showers are possible when the index is less than 3, thunderstorms when it is less than 0, and heavy thunderstorms when it is less than −3. The Showalter index for the sounding of Fig. 5 is −1.2.

A parcel at 850 mb in the atmosphere represented by this sounding, if lifted dry adiabatically from 850 mb, reaches its lifting condensation level (LCL) at 782 mb. If lifted further, it follows the moist adiabat labelled $T_p$ and reaches its level of free convection (LFC) at 731 mb. At this point the parcel experiences a net upward force and will spontaneously continue to rise.

The total energy imparted to the parcel by the net upward acceleration is found, by measuring the area enclosed by the curves $T$ and $T_p$ between 731 and 405 mb, to be $\sim$200 J kg$^{-1}$, corresponding to a vertical velocity of about $\sim$20 m sec$^{-1}$ at the 405-mb level. At this level, the parcel experiences neutral buoyancy, while above 405 mb the net acceleration on the parcel is downward. Thus, the parcel will continue to rise above 405 mb but will decelerate until its kinetic energy has been totally changed into hydrostatic potential energy.

The loss of kinetic energy can be determined by measuring the area between the curves $T$ and $T_p$ above 405 mb. Between 405 and 265 mb, the parcel loses $\sim$155 J kg$^{-1}$, while the area enclosed by the $T$ and $T_p$ curves between 405 and 250 mb corresponds to an energy loss of $\sim$215 J kg$^{-1}$. It follows that the parcel will come to rest at some level between 265 and 250 mb.

If the parcel of air which has thus risen from 850 mb to about 260 mb were an isolated bubble, it would then be accelerated downward along $T_p$ and eventually execute damped vertical oscillations about the 405-mb level. However, in the present model the parcel represents the cap of a rising column of air in the thunderstorm updraft system. Therefore, the parcel will not subside but will be trapped at the 265–250 mb layer by the continuing upward flow of air from lower levels. This trapping effect should result in two observable phenomena: 1) an increase in moisture content in the 265-mb region, since the mixing ratio is larger at low

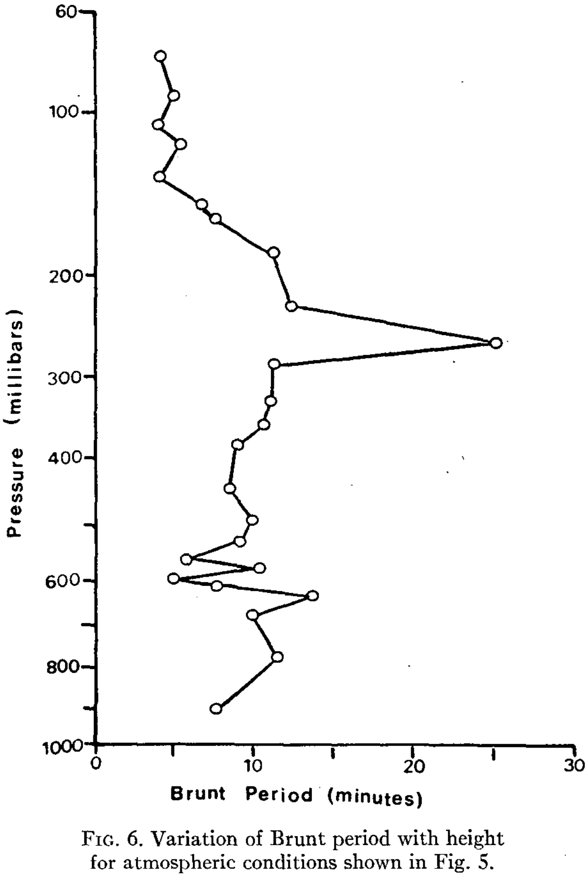

FIG. 6. Variation of Brunt period with height for atmospheric conditions shown in Fig. 5.

levels than at higher altitudes; and 2) a damped vertical oscillation centered approximately about the 260-mb level. This oscillation will be one of the ambient air which has been displaced by the cap of the updraft column, since the air of lower origin cannot rise above this level. In this respect, the 265–250 mb layer can be viewed as a region where the rate of loss by the rising cap of kinetic energy with height is large. The result is an almost impulsive transfer of kinetic energy and momentum from the cap to the ambient air in the source region. It is this air, displaced dry adiabatically from its stable position in the source region, which oscillates about that position of stability. The gravity wave which is generated by this oscillation should then have a frequency equal to the Brunt-Väisälä frequency for the ambient air in the source region.

Values of relative humidity derived from the radiosonde observations were found to be 11% at 300 mb and 38% at 265 mb. This marked increase in moisture content is considered to be due to the trapping effect discussed above.

The characteristic frequency of free vertical oscillations in the atmosphere, the Brunt-Väisälä frequency, is given by (Brunt, 1927)

$$\omega_B=\left[\frac{g}{T}\left(\Gamma_d+\frac{dT}{dz}\right)\right]^{\frac{1}{2}}, \tag{4}$$

where $\Gamma_d$ is the dry adiabatic lapse rate. The corresponding Brunt period is then equal to $2\pi/\omega_B$. The variation of Brunt period with height shown in Fig. 6 is for the atmosphere represented by Fig. 5, where the plotted values represent averages over the layers between the pressure readings. For the 265–250 mb layer, $\Delta z=396$ m, $\Delta T=-3.7$C, $T=232$K, and the Brunt period is 25.0 min. This is somewhat larger than the observed period of the waveform of event number 49–70 (Fig. 2). However, the Brunt period is a strong function of $dT/dz$ when the lapse rate is large, an uncertainty of about 6% in $\Delta T/\Delta z$ being sufficient to account for the difference between the computed Brunt period and the observed wave period in the present example.

It appears certain, then, that the wave observed as event number 49–70 was generated when the updraft region of a strong thunderstorm cell impulsively perturbed stable air at about the 260-mb level, in accordance with the model presented in Section 4. The kinetic energy of the rising cap at the 265-mb level in this model is found to be $\sim 6\times 10^9$ J, which is of the same order of magnitude as the energy estimate made in Section 4.

Other waves which were observed to have been generated in thunderstorm systems, e.g., the waves of 17–18 July 1970 and 24 September 1970, also have spectra which are characterized by the presence of a single dominant component. Waves that have origins in sources other than thunderstorm systems, e.g., in or near frontal systems, have a more complex spectra.

## 6. Conclusions

It has been shown from experimental observations that internal gravity waves are generated by strong thunderstorms. The waves are essentially monochromatic and have been observed to propagate over distances of hundreds of kilometers.

The principal feature of the generation mechanism appears to be the transfer of kinetic energy from a rising column of air within the storm cell to a stable region aloft. It is suggested that a necessary condition for such wave generation is that the rate of generation of kinetic energy from the convective motion to the stable layer be large with respect to the transfer rates elsewhere along the vertical path.

The fact that internal gravity waves are not observed to originate in all thunderstorms suggests that further study of thunderstorm-generated waves could provide information concerning energy exchange processes which may occur near the top of the thunderstorm cell.

*Acknowledgments.* This research is supported by the Atmospheric Environment Service, Department of Environment, Canada, and the National Research Council of Canada. The authors wish to express their appreciation to Mr. Don Scott of the London Weather Office and the U. S. Weather Bureau for providing meteorological data necessary for this work.

## REFERENCES

Atlas, D., 1963: Radar analysis of severe storms. *Meteor. Monogr.*, **5**, No. 27, 177–220.

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

Berry, F. A., Jr., E. Bollay and N. R. Beers, 1945: *Handbook of Meteorology*. New York, McGraw-Hill, 116–117.

Brunt, D., 1927: The period of simple vertical oscillations in the atmosphere. *Quart. J. Roy. Meteor. Soc.*, **53**, 30–32.

Cunningham, R. M., 1958: Cumulus circulation. *Recent Advances in Atmospheric Electricity*, L. G. Smith, Ed., New York, Pergamon Press, 361–367.

Flauraud, E. A., A. H. Mears, F. A. Crowley, Jr., and A. P. Crary, 1954: Investigations of microbarometric oscillations in eastern Massachusetts. Geophys. Res. Paper No. 27, Air Force Cambridge Research Center.

Fullerton, C. M., 1966: An analytical investigation of sinusoidal microbarometric oscillations. Ph.D. thesis, New Mexico Institute of Mining and Technology.

Georges, T. M., 1967: Ionospheric effects of atmospheric waves. ESSA Tech. Rept. IER 57-ITSA 54, Institute for Environmental Research, 341 pp.

——, 1968: Short-period ionospheric oscillations associated with severe weather. *Proc. Symp. Acoustic-Gravity Waves in the Atmosphere*. Govt. Printing Office, Washington, D. C., 171–178.

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

Hines, C. O., 1960: Internal atmospheric gravity waves at ionospheric heights. *Can. J. Phys.*, **38**, 1441–1481.

Kortschinski, J., R. C. Murty and M. J. Curry, 1971: Microbarograph for meteorological studies: Design, theory, and analysis. *J. Sci. Instr.*, 4, 307–310.

Madden, T. R., and J. F. Claerbout, 1968: Jet stream associated gravity waves and implications concerning jet stream stability. *Proc. Symp. Acoustic-Gravity Waves in the Atmosphere.* Govt. Printing Office, Washington, D. C., 121–134.

Malan, D. J., 1963: *Physics of Lightning.* London, The English Universities Press, 176 pp.

Marwitz, J. D., and A. H. Auer, Jr., 1968: Cloud nuclei spectra and updrafts beneath convective cloud bases in the high plains. *J. Appl. Meteor.*, **7**, 449–451.

Murty, R. C., and M. J. Curry, 1969: Microbaragraphic observation of acoustic gravity waves. *Nature*, **224**, 169–170.

Pasechnik, I. P., 1959: Long-period atmospheric waves preceding thunderstorms. *Izv. Akad. Nauk SSSR, Ser. Geofiz.*, No. 3, 471–475.

Petterssen, S., 1956: *Weather Analysis and Forecasting*, 2nd ed., Vol. 2. New York, McGraw-Hill.

Pierce, A. D., and S. C. Coroniti, 1966: A mechanism for the generation of acoustic-gravity waves during thunderstorm formation. *Nature*, **210**, 1209–1210.

Pothecary, I. J. W., 1954: Short-period variations in surface pressure and wind. *Quart. J. Roy. Meteor. Soc.*, **80**, 395–401.

Tolstoy, I., and T. J. Herron, 1969: A model for atmospheric pressure fluctuations in the mesoscale range. *J. Atmos. Sci.*, **26**, 270–273.

Vonnegut, B., 1963: Some facts and speculations concerning the origins and role of thunderstorms electricity. *Meteor. Monogr.*, **5**, No. 27, 224–241.

Wood, J. A., 1968: *Meteorites and the Origin of Planets.* New York, McGraw-Hill, 117 pp.

Yamamoto, R., 1955: The microbarographic oscillations produced by the explosions of hydrogen bombs in the Marshall Islands. *Weather*, **10**, 321–325.

——, 1968: Propagation velocity of acoustic gravity wave due to large nuclear explosion. *Proc. Symp. Acoustic-Gravity Waves in the Atmosphere*, Govt. Printing Office, Washington, D. C., 69–78.