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

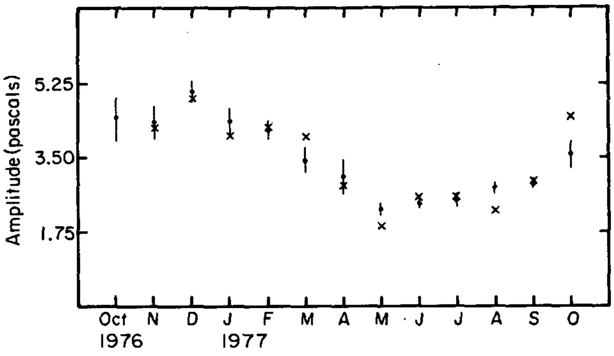

FIG. 1. Monthly mean gravity wave amplitudes. Error bars represent standard deviation of monthly mean based on hourly wave amplitudes within the given month. The crosses represent a term proportional to the product of the mean maximum wind speed and the mean surface to 700 mb stratification.

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

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

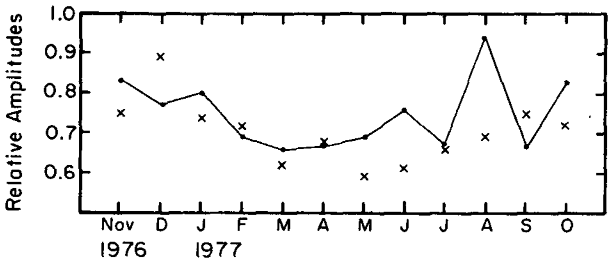

FIG. 2. The ratio of monthly mean wave amplitudes for the 3 h period of early afternoon to the 3 h period just prior to dawn. The crosses represent the equivalent ratios of stratification from the surface to 700 mb.

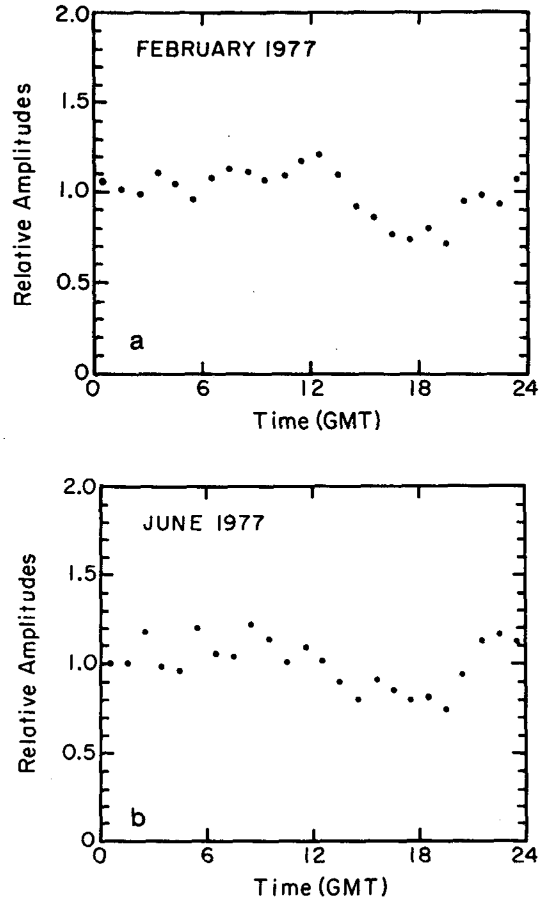

FIG. 3. The hourly mean wave amplitudes during (a) February 1977, and (b) June 1977.

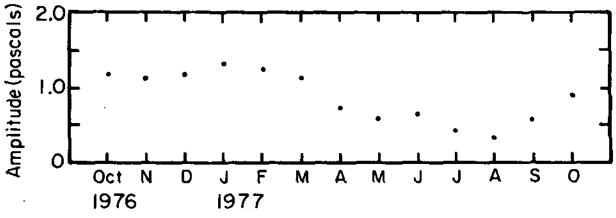

FIG. 4. Monthly mean turbulence amplitudes.

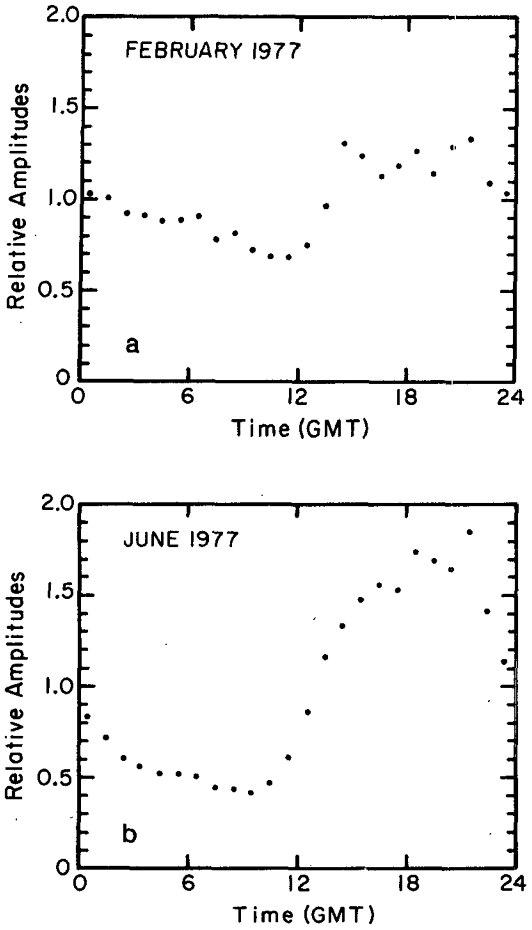

FIG. 5. The hourly mean turbulence amplitudes during (a) February 1977, and (b) June 1977.

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.

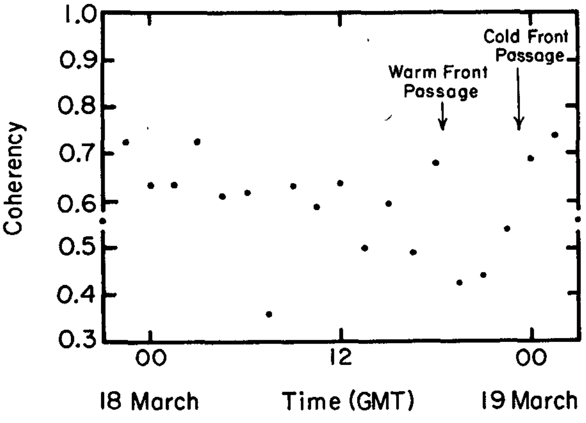

FIG. 6. Average wave coherencies between the grid stations for the storm of 17–19 March 1977. Each value is based on a 90 min sample.

TABLE 2. Properties of wave events.

	Velocity (°/m s^{-1})						Height (km)	
Arrival time	Wave	Maximum wind	Average from source	Coherency	Length (km)	Distance to source (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.

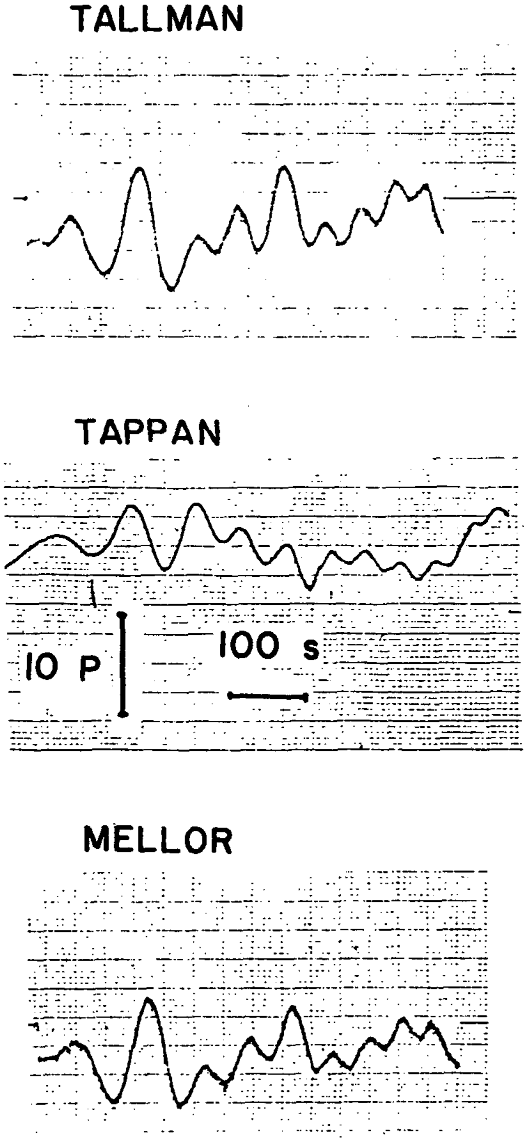

FIG. 7. Gravity wave record from the Chinese nuclear detonation of 17 November 1976. Phase of signal at Tappan is reversed.

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

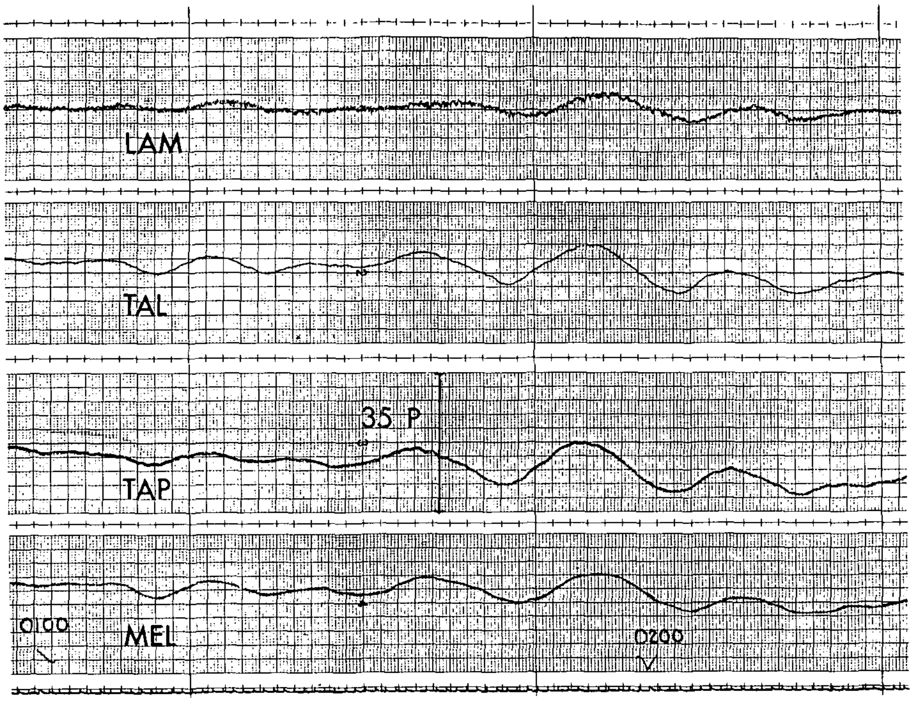

FIG. 8. Gravity wave record of 0100–0300 GMT on 16 July 1977 produced by thunderstorms near Lake Ontario.

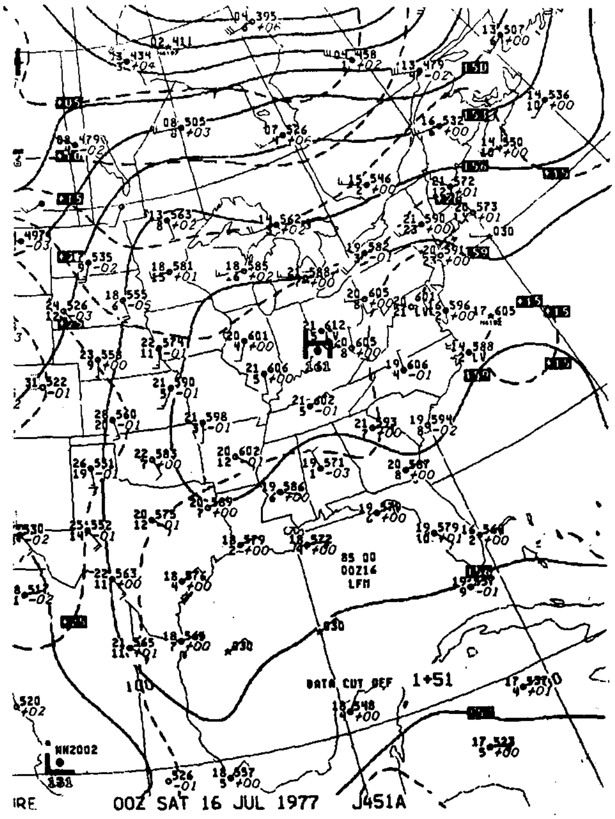

FIG. 9. The 850 mb chart for 0000 GMT 16 July 1977 showing weak winds above Palisades, NY.

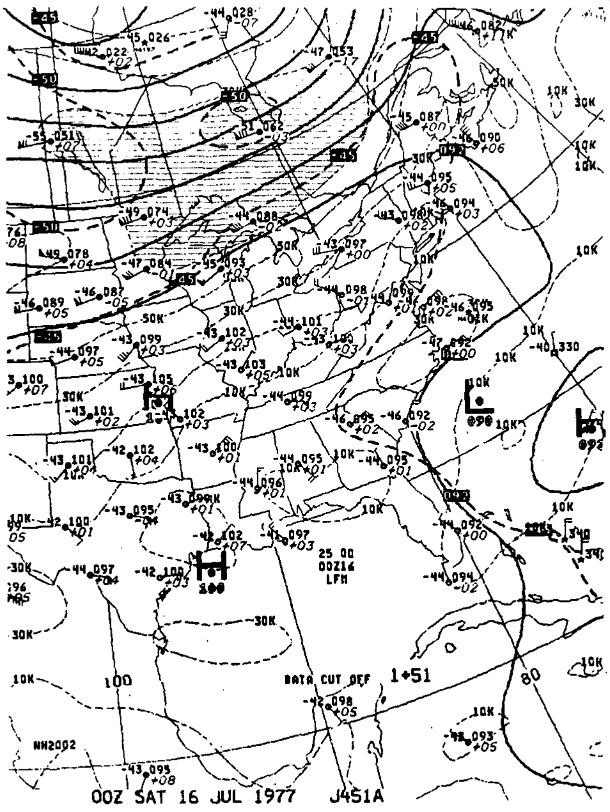

FIG. 10. The 250 mb chart for 0000 GMT 16 July 1977. Winds above Palisades, NY at this level are also quite weak.

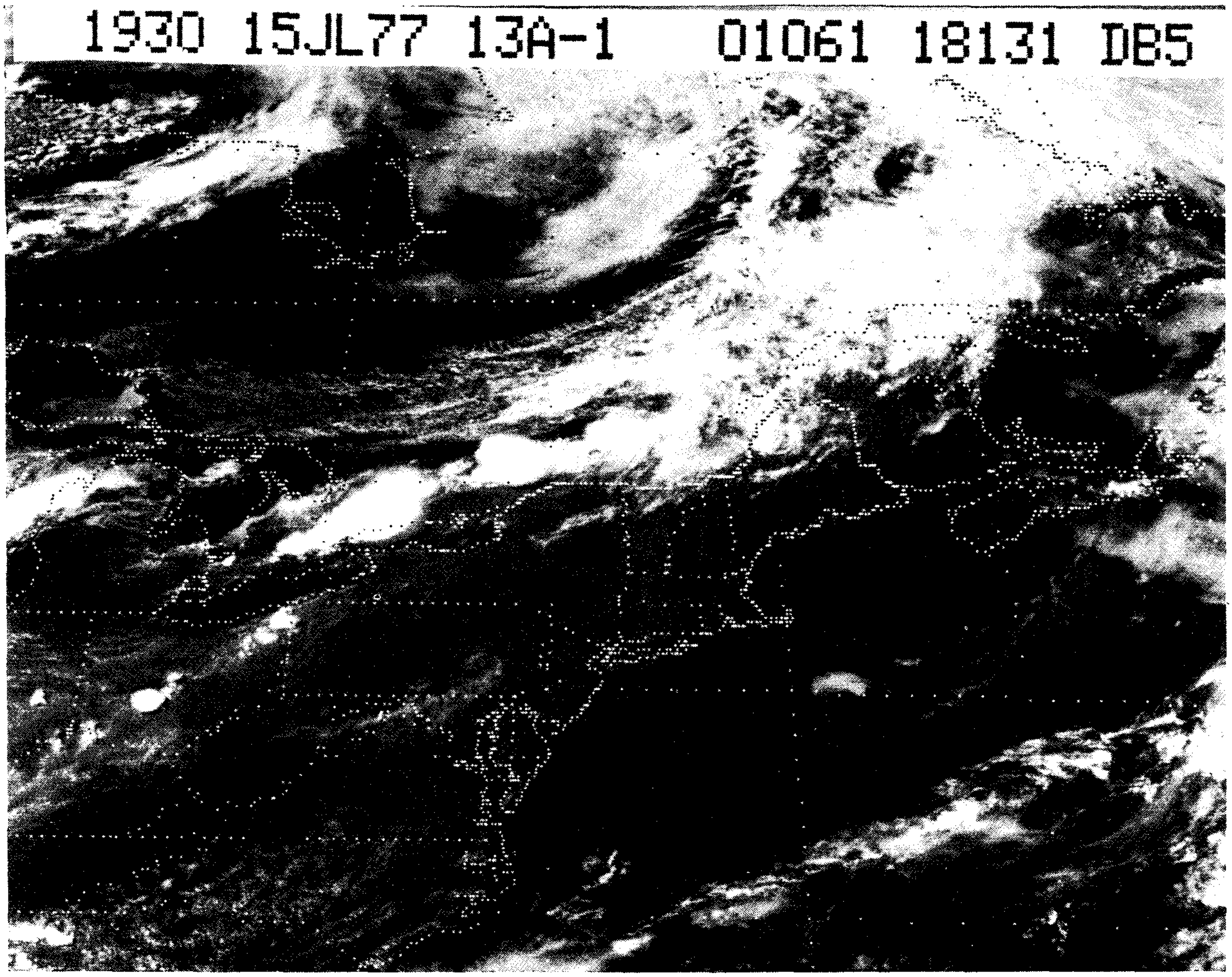

FIG. 11. Satellite photo of 1935 GMT 15 July 1977. Any waves emanating from the squall line would arrive at Palisades from 340°.

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.

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