Observations of Infrasound and Subsonic Disturbances Related to Severe Weather

Howard S. Bowman and Alfred J. Bedard

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Summary

During the past 10 years the Geoacoustics Group of NOAA’s Wave Propagation Laboratory studied travelling low-frequency pressure variations related to thunderstorms and severe weather. Two general categories of waves were associated with severe weather conditions: ‘subsonic’ pressure disturbances and infrasonic waves with acoustic velocities. The low-frequency pressure variations were measured at the Earth’s surface using microphone arrays located at times thousands of kilometres from the severe-weather disturbance. The radiated infrasound was related to thunderstorms penetrating the tropopause and spectral analyses were performed on several signals. Possible practical applications to storm warning and classification are discussed for both infrasound and ‘subsonic’ pressure disturbances. Past measurements of these signals are reviewed.

Introduction

A 10-year study of measurements made using infrasonic microphones, by members of the staff of the Geoacoustics Group of NOAA’s Wave Propagation Laboratory revealed two types of travelling pressure fluctuations related to severe weather: ‘subsonic’ pressure variations and ‘infrasonic’ waves with acoustic velocities (the term ‘subsonic’, as used here, refers to disturbances having both frequency and horizontal trace velocity below those of audible sound). Severe thunderstorms were found to be a source of both types of travelling pressure variations.

This paper is organized as described below with the two classes of pressure disturbances discussed in separate sections. Each section is preceded by a short historical summary to place the work presented here in perspective. Experimental results are presented for both subsonic disturbances and infrasound. Particular infrasonic microphone observations are compared with weather radar data and with some detailed studies of weather systems. A summary of the observations and results of studies on infrasonic waves is given in Table 3. More details concerning these measurements appear in the text together with additional new work. Some statistical properties of infrasonic waves are presented for data taken at Washington, D.C., from 1958 to 1967; these are compared with statistics of thunderstorm tropopause penetration. The instrumentation and experimental techniques used in this work are described by Cook & Bedard (1971).

Much of the information contained here has been presented only orally or in internal reports.
Subsonic pressure disturbances

Some past observations

Shaw & Dines (1905) discovered that coherent travelling pressure disturbances occur in the atmosphere and they suggested that at least three sensors should be used to properly trace these disturbances. Johnson (1929) found maxima in the spectral distribution of pressure occurring at periods between 5 and 20 min, and presented several records of pressure fluctuations which he attributed to wave motion on a surface of density discontinuity. Namekawa (1934, 1935) reported extensively on his studies of small pressure fluctuations. Many types of travelling pressure disturbances were reported, including a disturbance moving at a velocity of 60 m s\(^{-1}\) which could not be related to any surface observations. Instances of seiches due to pressure changes in the atmosphere were also presented by Namekawa. Flauraud et al. (1954) reported a possible relation between the observed velocities of travelling pressure waves and the velocities of winds at the 200 mbar level. Gossard (1956) presented experimental data indicating possible propagation of pressure waves from distant areas of convective activity, and he described a method of distinguishing pressure changes due to gravity waves from pressure changes due to convective cells using supplementary wind data.

In the works outlined above, various sources of the pressure fluctuations have been suggested. Many of these generation mechanisms produce local (non-propagating) variations of pressure in the atmosphere which make it difficult to detect travelling pressure waves. The basic problem in the interpretation of observed minor pressure changes in the atmosphere is that of distinguishing which of the various possible causes are involved. The techniques for doing so are described by Cook & Bedard (1971). In the next section results of our measurements of subsonic pressure disturbances are presented, and these are compared with weather radar and other meteorological data.

Experimental results

Using a line of microbarographs with spacings from 25 to over 250 km Bedard (1966) measured long-period, slow-moving pressure disturbances travelling from west of Washington, D.C. These data were compared, using matched passbands, with the data from the local Washington infrasonic station for a two-month period. The Washington, D.C., infrasonic station has four microphones spaced 4–10 km apart in a quadrilateral array. Local weather radar records were also used in this study.

Pressure variations due to squall lines and thunderstorms were recorded, as well as subsonic waves that could not be explained by measured surface weather conditions. Two of the types of disturbances observed are described below.

Fig. 1 shows records of a subsonic pressure disturbance on 1963 June 7 for the Washington, D.C., infrasonic station and for two of the experimental sites M-X1 and M-X2. On the records labelled Card N9 and Nave N9, system calibrations appear shortly prior to 1800 UT. A disturbance was not found on M-X3. Fig. 3 shows the relative locations of these microphones. The closely-spaced array of the Washington, D.C., station is described by Cook & Bedard (1971). From the times of the initial positive pressure changes, an azimuth of arrival and a propagation speed were determined for the disturbance using the relatively closely spaced sites (4–10 km apart) of the infrasonic station. Using the azimuth and propagation speed so determined, the disturbance arrival times at the more widely-spaced sites (25–250 km apart) were predicted. Fig. 2 shows a radar scope photograph of the weather system; Fig. 3
Observations of infrasound and subsonic disturbances

**FIG. 1. Pressure disturbance of 1963 June 7 (after Bedard 1966)**
Fig. 3. Radar scope sequence for disturbance of 1963 June 7 (after Bedard 1966)

Table 1

Data for disturbance of 1963 June 7

<table>
<thead>
<tr>
<th>Radar</th>
<th>Infrasonic Observatory</th>
<th>Card</th>
<th>M-X1</th>
<th>M-X2</th>
<th>M-X3</th>
<th>M-X4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azimuth</td>
<td>295°</td>
<td>298°</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>15 m s⁻¹</td>
<td>15 m s⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observed arrival time (UT)</td>
<td>1843</td>
<td>1821</td>
<td>1755</td>
<td>Negative</td>
<td>Negative</td>
<td></td>
</tr>
<tr>
<td>Predicted arrival time (UT) Using infrasonic observatory data</td>
<td>1821</td>
<td>1753</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

shows a time sequence of the leading edge of the radar echo from which the disturbance propagation speed and direction were also estimated. Table 1 summarizes the results of these measurements.

Good general agreement was found between the weather system speed and direction as deduced from radar and motions determined from the closely spaced array of infrasonic microphones. The agreement between the predicted and actual arrival times at the M-X sites shows that the velocity can remain constant over paths more than 50 km in length. Four storm systems observed during the two-month test period gave similar results.
Fig. 2. Radar scope photograph of the 1963 June 7 disturbance (after Bedard 1966)
Observations of infrasound and subsonic disturbances

Fig. 4. Pressure disturbance of 1963 May 24 (after Bedard 1966).

Fig. 5. Pressure disturbance of 1963 May 24 (after Bedard 1966).
The observation of 1963 May 24 (Fig. 4 and Fig. 5) represents another class of subsonic pressure disturbance. Although correlation exists after 2300 UT, the dominant feature on these records is the wavelike oscillation occurring between 2200 and 2300 UT. The period is 18 min and the maximum peak to peak amplitude is 327 dyn cm\(^{-2}\). The M-X3 record in Fig. 5 is time-shifted by about 2 hr relative to the other records. Nothing of significance occurred on M-X3 after the time period shown. Table 2 below summarizes the signal data and Fig. 6 is a plot of meteorological data aloft for that time period.

This disturbance remained coherent over a path several wavelengths long. The wavelength computed from the period and horizontal trace velocity was 27 km. The pulse was not observed with the M-X3 equipment, which indicates that the travelling pressure disturbance was generated between sites M-X2 and M-X3. No notable weather features were reported for this time interval at either Washington National Airport or Dulles International Airport. There was close agreement between the predicted and the observed arrival times at site M-X1 and M-X2. Note that the observed azimuth and speed of the pressure disturbance agree with the azimuth and speed of winds near the 450 mbar level (Fig. 6). This is consistent with observations, Flauraud et al. 1954, of an agreement between the motions of some subsonic pressure disturbances and the azimuth and speed of the upper winds.

Without the benefit of supplementary measurements it is difficult to attribute the existence of any particular pressure disturbances to a unique source (e.g. high-altitude winds), and most of the evidence presented (e.g. Flauraud et al. 1954) has been statistical. However, the scale length over which such disturbances can show coherence is an important variable in the design of microphone arrays used to observe such phenomena. This is information provided by the 1963 May 24 measurement described here, which demonstrated that a disturbance could be tracked over a distance several wavelengths long (over 60 km).

![Fig. 6. Winds and temperatures aloft on 1963 May 25 (after Bedard 1966).](https://academic.oup.com/gji/article-abstract/26/1-4/215/586700)
Table 2

Data for disturbance of 1963 May 24

<table>
<thead>
<tr>
<th>Azimuth Speed</th>
<th>Radar Observatory Card</th>
<th>M-X1</th>
<th>M-X2</th>
<th>M-X3</th>
<th>M-X4</th>
</tr>
</thead>
<tbody>
<tr>
<td>275°</td>
<td>25 m s⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observed arrival time (UT)</td>
<td>2232</td>
<td>2219</td>
<td>2203</td>
<td>Negative</td>
<td>Not operational</td>
</tr>
<tr>
<td>Predicted arrival time (UT) Using infrasonic observatory data</td>
<td>2217</td>
<td>2159</td>
<td>2132</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bowman (1968) reported on a class of subsonic pressure waves observed in the Washington, D.C. area. These waves occurred when various types of severe weather systems were in the area; he observed cases where local thunderstorms, hailstorms, snow storms, or combinations of these appeared to generate subsonic waves which propagated across the infrasonic microphone array. He found that even when the pressure noise due to local wind turbulence was high, the subsonic waves were observable because of their high amplitudes. The subsonic waves of longer period were associated with the storms showing larger hail size. These subsonic waves had horizontal trace velocities between 13 and 70 m s⁻¹ and periods between 4 and 15 min. The pressure amplitudes were usually too low to measure with conventional barographs. Waves which occurred when the jet stream axis in the neighbourhood of the tropopause was over the microphone array, had propagation directions which were in the direction of the winds at the tropopause.

Infrasound

Preliminary considerations

In addition to the data reviewed in detail in this paper, past measurements of low frequency sound associated with thunderstorms and severe weather have been reported at higher infrasonic and low audio frequencies. Frequencies above 1 Hz are above the design passband of NOAA infrasonic microphones. Uman (1969) reviewed measurements of the acoustics of thunder. Various values have appeared in the literature for the spectral energy peak of thunder, but recent measurements (e.g. Few 1969) suggest that the acoustic energy of thunder is broadly distributed from below 10 Hz to 150 Hz, in contrast with older measurements which placed dominant frequencies in the 0-5 Hz to 20 Hz range. Therefore, it is unlikely that the longer-period infrasound processed by the NOAA infrasonic microphones, typically 20-s periods, is directly related to the lightning channel.

Many observations have been made of acoustic energy in the 4- to 6-s period range (microbaroms) associated with ocean waves. This category of infrasound is readily identified and is specifically excluded from consideration here. Benioff & Gutenberg (1939) reported a single observation of 0.5- to 1-s period infrasound recorded at intervals of 20 s, which they believed to be related to ocean waves. Krasilnikov (1960), referring to observations of infrasound made by Shuleikin, points out that the observations may be explained by aerodynamic sound generated by vortex shedding from wave crests, and mentions 6 Hz as a typical observed frequency. He also suggests the possibility of using this infrasound (‘the voice of the sea’) for storm warning purposes. It is clear that the range of infrasonic frequencies from 1 Hz to 10 Hz should be given more attention in the future.
### Table 3

**Summary of past observations of infrasound related to severe weather**

<table>
<thead>
<tr>
<th>Observations</th>
<th>Investigators</th>
<th>Location of observation point</th>
<th>Conclusions/Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>First related observations of infrasound to areas of severe weather containing tornadic storms</td>
<td>Chrzanowski et al. (1960) (unpublished)</td>
<td>Washington, D.C.</td>
<td>Infrasound was related to tornadic storms and could be distinguished from magnetic-activity related signals</td>
</tr>
<tr>
<td>Attempt to measure infrasound in the immediate vicinity of severe storms</td>
<td>Hass, Hoecker &amp; Matheson (1961) (not documented)</td>
<td>Norman, Oklahoma</td>
<td>Experiment was inconclusive</td>
</tr>
<tr>
<td>Reviewed characteristics of infrasonic signals related to severe storms</td>
<td>Cook &amp; Young (1962)</td>
<td>Washington, D.C.</td>
<td>Presented details concerning observations of infrasound attributed to tornadic storms</td>
</tr>
<tr>
<td>Observed that the azimuth from which infrasound arrived shifted direction during an interval of locally severe weather</td>
<td>Goerke &amp; Woodward (1966)</td>
<td>Boulder, Colorado</td>
<td>It is possible to track the motion of a severe storm system by monitoring the radiated infrasound</td>
</tr>
<tr>
<td>Infrasound was related to local severe thunderstorms and compared with radar</td>
<td>Young, Greene &amp; Bowman (1968) (unpublished)</td>
<td>Washington, D.C.</td>
<td>Storm cells with high elevation for radar returns may be the source of radiated infrasonic energy</td>
</tr>
<tr>
<td>Infrasound was related to isolated areas of distant severe weather</td>
<td>Bowman (1969) (unpublished)</td>
<td>Boulder, Colorado, Washington, D.C. (single observatory data)</td>
<td>These isolated storms were severe and were characterized by other investigators as splitting storms with rotation</td>
</tr>
<tr>
<td>Infrasound was measured from the same source area at multiple infrasonic stations</td>
<td>Bowman (1969) (unpublished)</td>
<td>Washington, D.C., Boulder, Colorado, Pullman, Wash.</td>
<td>It is feasible to locate the source area using azimuth crossings from several observations</td>
</tr>
<tr>
<td>A relation was found between the reported hail size and the dominant period of infrasound from the severe storm area</td>
<td>Bowman (1970) (unpublished)</td>
<td>Washington, D.C., Boulder, Colorado, Pullman, Wash., College, Alaska</td>
<td>A plot of hail diameter as a function of predominant period of infrasound suggests a relationship</td>
</tr>
</tbody>
</table>
Observations of infrasound and subsonic disturbances

Experimental results

Table 3 summarizes some observations of infrasound related to severe weather.

First observations of infrasound from regions of severe weather. Chrzanowski, Young & Marrett (1960) first described results of experiments relating infrasound to tornadic storms. Predominant periods from 12 to 62 s were observed at pressure amplitudes from 0.2 to 1.5 dyn cm$^{-2}$ peak-to-peak. In one instance acoustic energy was received for over 7 h from within 13° of the same direction of arrival. They found that it was possible to distinguish this class of signal from infrasonic signals due to sources such as magnetic storms and earthquakes. For the one-month period studied intensively, the infrasound from directions of severe storms showed a lower horizontal trace velocity (usually $<400$ m s$^{-1}$) and more high frequency components than the infrasonic signals related to magnetic storms (horizontal trace velocity usually $>400$ m s$^{-1}$). They found agreement between the directions of arrival of infrasonic waves and areas of severe storm activity. However, since they used only a single station the information available at that time did not permit them to locate the radiating storm systems. Assuming an average propagation velocity they found, in some instances, infrasonic arrivals prior to the predicted arrival times from severe weather systems. Similar acoustic signals were also received from directions where there were no reports of tornadoes or funnels, although there were reports of hail in these directions. They noted the desirability of observing these signals using multiple acoustic stations.

The measured properties of these signals were reviewed by Cook & Young (1962), who showed a particular example of an infrasonic signal possibly originating from severe weather in Oklahoma, northern Texas, and Kansas. They observed amplitudes up to about 1 dyn cm$^{-2}$ peak-to-peak, periods between 12 and 50 s, and horizontal trace velocities near the local acoustic velocity in air. At that time much of the work was directed towards relating the infrasound specifically to tornadic storm systems; however, the occurrence of this class of acoustic signal with no reported funnel has been noted.

An early attempt to measure infrasound in the immediate vicinity of severe storms. In May 1961, William Hass and Walter Hoecker of the Air Resources Laboratory of NOAA and Harry Matheson of the Geoacoustics Group made short-term measurements for one month, using a tripartite infrasonic station in the vicinity of Norman, Oklahoma. A paucity of severe storms, severity of local wind noise, and the non-availability of stable infrasonic microphones made the results of this short-term experiment inconclusive. The results of this experiment were never documented.

Observation of changes in azimuth of arrival of infrasound during a local storm. Goerke & Woodward (1966) observed infrasound from the vicinity of a local squall line with an apparent location 20 to 75 km away from the infrasonic station at Boulder, Colorado, for one and one-half hours. The observed azimuth of arrival changed direction by approximately 60° over the measurement time interval. They suggested that the infrasonic source was associated with the leading edge of the 1965 July 25 local storm. However, the possible storm direction shown by the above authors and determined from local weather reports is different from the path of the most severe weather as inferred from hail reports in the Storm Data and Unusual Weather Phenomena Report of ESSA, shown in Fig. 7 of this paper. Fig. 7 is a modification of Fig. 4 in the report of Goerke & Woodward. This alternate storm path in no way modifies the conclusion of Goerke & Woodward that it is possible to track the motion of a severe storm system by monitoring the radiated infrasound. The precise location of the radiating source could not be determined using only one infrasonic station. This storm is of particular interest because the infrasonic station was quiet from the
very onset until the storm passed Stapleton International Airport at Denver, Colorado. It is pertinent to point out that when observing the infrasound from local storms, pressure noise associated with wind turbulence in the storm frequently makes the reception of infrasound difficult, and much interesting information may be lost.

Infrasound observed during local, severe thunderstorms compared with radar returns. Young, Green & Bowman (1968) reported on infrasound associated with local severe thunderstorms which occurred in the Washington, D.C., area. Records made on 1957 July 31 by the infrasonic microphones in Washington, D.C., showed an ample mixture of pressure variations which transversed the microphone array. The wide spectral range observed was separated into three groups distinguished by period, azimuth of arrival, and horizontal trace velocity. One group contained infrasonic signals with predominant periods of about 10 s. The second group was distinguished by periods of about one second; this group was identified with audible thunder. The third group consisted of subsonic disturbances with characteristics that were associated with tropopause winds. A pressure jump was also recorded and identified from supporting meteorological data. These authors’ observations of infrasound are summarized in the following two paragraphs.

The signals shown in Fig. 8 illustrate the wide and varying frequency range of the storm-generated pressures. The records of 1968 July 02 have periods from 5 to about 60 s, with maximum amplitudes of about 10 dyn cm⁻². During this time a very severe hailstorm was raging over north-western Virginia and was especially severe near the
Fig. 8. Examples of infrasonic signals related to severe storms (after Young et al. 1968).
town of Drainsville, Va., approximately 16 km WNW of the microphone array. The interval between 2255 UT on 1968 August 16 and 0310 UT on 1968 August 17 is an example of radiated infrasound associated with storm cells. At the beginning of this interval sound waves were arriving at the microphone array from 34 degrees east of north. Fig. 9 shows the cloud and precipitation situation determined at 2332, 0033, 0132 and 0230 UT. Acoustic direction and observation time are indicated by the arrows pointing to the centre of the microphone array.

Acoustic radiation appears to originate in one storm cell during the first two time intervals, and from another cell after the first one begins to dissipate. The changing direction of the acoustic waves, consistent with the movement of the storm system, is the strongest indication that the storm cells are the origin of the radiated energy. Table 4 lists acoustic data for the times mentioned above during which both the meteorological data and characteristics of the infrasound are consistent with the possibility that storm cells with high elevations for radar echo returns are the source of the radiated infrasonic energy.
Observations of infrasound and subsonic disturbances

Table 4

<table>
<thead>
<tr>
<th>Date</th>
<th>Time interval (UT)</th>
<th>Time (UT)</th>
<th>Azimuth (deg)</th>
<th>Velocity (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968 July 2</td>
<td>1805-2008</td>
<td>1812</td>
<td>230</td>
<td>335</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1855</td>
<td>269</td>
<td>345</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1920</td>
<td>271</td>
<td>345</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2005</td>
<td>282</td>
<td>410</td>
</tr>
<tr>
<td>1968 August 16-17</td>
<td>2135-2225</td>
<td>2135</td>
<td>341</td>
<td>360</td>
</tr>
<tr>
<td>1968 August 16-17</td>
<td>2135-2225</td>
<td>2135</td>
<td>341</td>
<td>360</td>
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<td></td>
<td></td>
<td>0235</td>
<td>56</td>
<td>340</td>
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</table>

Infrasound observed from well-defined areas of distant severe weather. Bowman (1969) using observations made at Washington, D.C., and Boulder, Colorado, compared infrasonic data with corresponding meteorological data in order to investigate the characteristics of storms evidently radiating infrasound. This section summarizes the major features of this work, which dealt primarily with infrasound detected from distant storms. Under favourable conditions infrasonic energy measured at both the Boulder and Washington stations appeared to be related to the same meteorological source.

The meteorological conditions of several of the severe storms associated with infrasound generation were studied by other investigators (Booker, Cooper & Hart 1967; Barnes 1968; Georges 1968; Booker et al. 1969; Haglund 1969; Prophet 1969). Some of these storms were classed as splitting storms with rotary motion about a quasi-vertical axis; a splitting storm is defined as one in which the high cloud tops penetrate the tropopause and then separate in violent development. Sometimes near the tropopause the sudden development of a new cell adjacent to an original cell typifies a splitting storm. Little is known at this time about the various physical parameters of the splitting storms, and studies are being continued in this area.

Fig. 10 shows the locations and times of several severe storms related to infrasound. The arrows show the great circle paths corresponding to azimuths from which infrasound was measured at Boulder, Colorado, when storms occurred at the locations shown. The storms ranged from severe hail storms to tornadoes, and the direction of arrival of the measured infrasound was within plus or minus five degrees of the indicated great circle path. The infrasonic data and the corresponding storm data given in Table 5 show strong evidence of a causal relationship.

In order to minimize confusion due to multiple sources, an isolated severe storm was selected for careful comparison with the infrasonic data. This storm, which occurred in Iowa on the evening of 1965 August 26, was studied by Achtemeier (1969) and was characterized as a splitting storm with rotation. The occurrence, direction, and termination of this storm precisely agreed with the occurrence, azimuth, and termination of the infrasound measured at the station at Boulder, Colorado, assuming a reasonable travel speed for the acoustic energy.

Another instance of a distant severe isolated storm is that of the evening of 1969 June 8, which was beyond the range of the Washington, D.C., radar. Fig. 11 shows superimposed radar data taken at the indicated times from the Cincinnati, Ohio, and
FIG. 10. Infrasound from several storms measured at Boulder, Colorado (after Bowman 1969).

Table 5

Summary of infrasonic data measured at Boulder, Colorado, from particular storms

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Date and time</th>
<th>Type of storm</th>
<th>Area of storm</th>
<th>Date and time</th>
<th>Azimuth (Degrees)</th>
<th>Horizontal trace velocity (m s⁻¹)</th>
<th>Period (s)</th>
<th>Zero to peak maximum pressure amplitude (d/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2240-2400</td>
<td>Hail 15 in. cir., 4 in. dia. Tornadoes</td>
<td></td>
<td>0000-0230</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0050-0400</td>
<td></td>
<td></td>
<td>0040-0330</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Haglund (1969)</td>
<td>0000-0800</td>
<td>Hail 1¼ in. dia. Tornado</td>
<td></td>
<td>0430-0830</td>
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<tr>
<td></td>
<td>1950-2245</td>
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<td>2100-2400</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Booker et al. (1967-69)</td>
<td>2000-0300</td>
<td>Funnel aloft</td>
<td></td>
<td>2136-0300</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

* Hail described as pieces flat as the hand and as wide.
the Washington, D.C., airport weather stations. The darkened circles indicate areas of precipitation; the cloud top elevation is given in hundreds of feet. As time passed, some of the highest cloud tops split. Corresponding infrasonic arrivals, denoted by arrows pointing to the Washington, D.C., station appear related to the splitting phenomena. However, a careful investigation suggests that if the infrasound is generated in the area of this storm, the maximum energy is radiated prior to cloud separation. Hail was also produced prior to the separation. This was determined from times and locations of hail reports, radar scope photographs, and with travel times computed for the infrasonic waves. The severe storm in the Cincinnati area, which was associated with the infrasound, produced hail the size of marbles and golf balls in the direction from which the infrasonic arrivals were measured. The cloud deck showed signs of a hook development, signifying rotation.

Frontal patterns in the Washington, D.C., area were similar to fronts through the Cincinnati area. The superimposed radar data show that a local storm moved from west of Washington, D.C., at 2030 to almost south of Washington by 2330 hours UT. Fig. 12 shows the observations at the time of the maximum acoustic energy arrival from the west; at this time the local storm was south of the infrasonic station. The location of the larger size hail was at the same azimuth from which the maximum amplitude infrasound arrived. The displaced trace overlay in Fig. 12 shows the waveform of the correlated plane wave motion traversing the microphone array at the Washington, D.C., site. The multi-channel correlator record at the bottom of this figure shows maximum correlation and maximum amplitude at about 0005 UT, 1969 June 9. Signal was recorded from 1837 on the 8th until 0125 on the 9th, showing horizontal trace velocities from 335 to 395 m s\(^{-1}\) and predominant periods in the range from 10 to 20 s.

Amplitude variations of infrasound from a local storm. Termination of identified infrasound coincident or just prior to a frontal passage could be due to masking by local wind noise. However, on 1968 June 27 the infrasound observed at Washington, D.C., evidently started and stopped twice before the noise level due to local wind turbulence increased, as shown in Fig. 13. Also, infrasound was detected again after the storm passed and after the noise level had decreased. The illustration shows the output of one of the four microphones during times of infrasound reception and the frontal passage through the Washington, D.C., area. According to the weather radar records the storm was directly over Washington, D.C., at 0230 UT, although it was not considered severe. During the intervals when infrasound was received, the signal-to-noise ratio at a single microphone was about 1/2. The horizontal trace velocity measured 345 to 360 m s\(^{-1}\) and the predominant period ranged from 10 to 15 s.

Infrasound observed from the same source area using multiple infrasonic stations. Bowman (1970) studied additional cases showing the feasibility of locating infrasonic sources associated with severe storms using multiple geoacoustic stations. Figs 14 and 15 show data from Pullman, Washington and Boulder, Colorado, for 1969 June 5 and August 9. Fig. 16 shows data from these infrasonic stations together with data from the infrasonic stations at College, Alaska and Washington, D.C., for 1969 August 4.

These figures show that multi-station, long-range acoustic detection of infrasound from severe storm systems is possible. However, at long ranges, propagation effects may obscure important details of the radiated infrasound. For example, wind and temperature gradients can cause azimuth shifts and considerable variations in amplitude. The map in the lower left corner of Fig. 14 shows the precipitation areas for a 24-hr period including the time of the hail events noted. The map shows no measurable precipitation between the events and the infrasonic stations during the times of observation. Figs 14, 15 and 16 are examples of multi-
Fig. 12. Experimental observations for pressure disturbance of 1969 June 8–9 (after Bowman 1969).


FIG. 15. Infrasonic tracking of a severe storm using several stations for the severe storm of 1969 August 9 (after Bowman 1970).
Observations of infrasound and subsonic disturbances

station data. The azimuth crossings and the meteorological events in these areas indicate the source origins of the measured infrasound. These stations were not located for the particular purpose of investigating severe storms; for more strategically located stations it is anticipated that a great number of multi-station observations of the same storm system will be found.

**Hail diameter compared with the predominant period of infrasound.** Bowman (1970) also reported a relation of reported hail diameter to the predominant period of the observed infrasound. This study involved cases where infrasound was measured from areas in which there were hail reports. Fig. 17 shows evidence obtained of the relationship between predominant period and hail diameter.

**Spectral analyses of several infrasonic signatures.** More recently spectral analysis was performed on 10-min data segments from three acoustic signals associated with severe storms. The sections of data showing best signal-to-noise ratio are shown in Fig. 18. These data represent the relative signal levels as a function of frequency, arbitrarily referenced to the wide-band response data of 1968 August 16. Two conclusions may be drawn from Fig. 18: first, there seem to be no sharp peaks in the spectrum of radiated acoustic energy. This suggests a low-Q (broadband) generating mechanism. Second, there is evidence for considerable variability in the acoustic

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**FIG. 16.** Infrasonic tracking of a severe storm using several infrasonic stations for the severe storm of 1969 August 4 (after Bowman 1970).
Fig. 17. Reported hail size as a function of predominant signal period. The arrows indicate measured periods of infrasound from a storm with reported hail as large as 'gallon jugs' (after Bowman 1970).
Fig. 18. Spectral analysis results of three severe storm-related signals.
spectral output from different storms, which suggests that distinguishing characteristics of different storms may be determined from spectral analysis of the radiated infrasound. Note that the low-frequency components evident for the 1969 July 2 data are not present in the 1969 June 9 data or the 1968 August 16 data (Figs 8, 12 and 18).

The statistics of infrasound attributed to severe storms from 1958 to 1967. A computer program was developed for statistical analysis of geoacoustic signals believed to be associated with severe storms tabulated for the years 1958–1967 for the Washington, D.C., station. Figs 19–22 show some of the general properties of this class of infrasonic signal. We have made this analysis using all Washington, D.C. signals having arrival azimuths between 200° and 308° that could not be identified with other source mechanisms. Individual signals in this group have been correlated with isolated severe storms, but it is the general characteristics of the signals that will now be examined. For 89 per cent of the 220 signals analysed, severe weather was reported in the direction from which the infrasound arrived.

Fig. 19 shows measured horizontal trace velocity as a function of day of the year. Note that most signals tend to show trace velocities slightly higher than 344 m s\(^{-1}\), with a few showing trace velocities considerably higher. These very high velocity events may be due to local storms.

Fig. 20 shows the number of measured signals as a function of day of the year. Note that most signals occur in the spring and early summer, with very few of these signals observed in the winter months. Although such statistics are influenced by local noise, the variations in local noise level as a function of time of year at Washington, D.C. are not responsible for the springtime peak in the number of infrasonic signals noted in Fig. 20.
FIG. 20. Number of measured signals at Washington, D.C., as a function of day of the year in calendar days related to severe storms.

FIG. 21. Number of measured signals as a function of the azimuth of arrival.
Fig. 21 shows the number of signals as a function of the azimuth of arrival. Although these data were tabulated at azimuths between 200° and 308°, the infrasound was usually observed at azimuths between 250° and 290°, with 270° being the most frequently observed azimuth.

Fig. 22 shows the number of signals as a function of the time of day (UT) at one-hour intervals. The times plotted are those of the maximum amplitude of each signal. Note that the maximum number of observations were at about 0000 UT, which is in the early evening at Washington, D.C. Any statistical study of infrasonic signals on a diurnal or yearly basis must give consideration to the statistical properties of the noise as well. Local noise pressure is usually larger during the daytime hours, becoming smaller in the evening. However, because there is little average variation in the local noise after 0000 UT, and because the infrasonic signal times used were for the maximum amplitude section and not the start of the signal, we infer that the local noise has had little influence upon the form of the statistics of the processed signals. The observed peak in the early evening hours in the spring for this class of infrasonic signal is thus believed to be a function of the source and/or propagation characteristics.

Long (1966) studied the statistics of severe storm tropopause penetration data as a function of time of day for Kansas City, Mo. Long's data have been adjusted to account for the acoustic travel time to Washington, D.C. The direction from Kansas City to Washington, D.C. (274°) is close to the azimuth most frequently observed (270°) for the Washington, D.C., infrasonic signals in the azimuth range 200°–308°.

The diurnal variation in the number of tropopause penetrations observed at Kansas City is similar to the variation in the number of infrasonic signals detected as a function of time of day and both are shown in Fig. 22. The heavy lines are the

![Fig. 22. The number of severe storm-related signals as a function of the time of day (UT) compared with Kansas City tropopause penetration data.](https://academic.oup.com/gji/article-abstract/26/1-4/215/586700)
times of maximum amplitude of the infrasound observed at Washington, D.C. and the thin line bars are the times of tropopause penetration adjusted for the acoustic travel time from Kansas City to Washington, D.C. These data, in conjunction with those showing infrasonic radiation from individual storms penetrating the tropopause, are evidence that storms penetrating to high altitudes provide the necessary conditions for generating infrasound.

Fig. 23 is a histogram of the number of tropopause penetrations observed at Kansas City as a function of day of the year. It shows a spring peak for tropopause penetrations observed at Kansas City, in agreement with the peak in the yearly variation of the infrasonic signals observed at Washington, D.C. (shown in Fig. 20).

Possible practical applications

The infrasonic data associated with severe storms suggest several practical applications. Bedard (1966) suggested that a closely-spaced array of infrasonic microphones be placed at a distance from a point of interest in the direction from which pressure disturbances tend to approach. The data could be telemetered back to an analysis centre and be used to provide storm warnings. Travelling subsonic pressure disturbances may trigger latent convection as they pass through a zone of instability (Donn et al. 1954). In following squall lines, it may be advisable to follow the pressure jump lines and not the line of convective activity which may result from the passage of a wave on an inversion (Tepper 1950).

The infrasound radiated by some severe storms may have other practical uses. We have shown evidence that certain severe storms do radiate infrasound. Closely spaced infrasonic stations (approximately 100 km) could enable local infrasound generation points to be detected, tracked, and the source positions more definitely located.
Spectral analysis of infrasonic signals may provide a tool for classification of different types of storms.

If turbulence is a source mechanism for infrasound, an array of infrasonic microphones could permit regions of extreme high-level turbulence to be identified and tracked. The generation mechanism has not been identified, however, and there are other mechanisms that could also produce infrasound. Colgate & McKee (1969) have postulated that electrostatic forces may be involved in the generation of low frequency sounds. The energy released by condensation is another possibility. To identify the source mechanism or mechanisms, more localized measurements of infrasound are needed, particularly for cases of severe weather which are well documented and studied using other techniques, e.g. Doppler radar.

Infrasonic microphones have the desirable feature that they are passive detectors, and measurements can be made on severe weather without having to penetrate the storm system physically.

The use of infrasonic equipment in conjunction with radar and other sensing techniques appears desirable for additional reasons. Data from various types of sensing systems will provide the analyst with additional evidence badly needed to assess any given situation. Also, any redundancy of measurement increases confidence in one's conclusions.

Possible practical applications including storm warning, tracking, and remote probing for research and classification have been discussed. It is speculated that in particular instances the infrasonic station could be a valuable tool for the meteorologist and act as an adjunct to the weather radar.

Much work remains to be accomplished. Detailed multi-station comparisons for well-defined storm systems should continue. The mechanism or mechanisms of generation of low-frequency sound still remain to be identified. Hopefully, the observational information presented here will help theorists devise wave generation models which, in turn, future observations can be expected to test.

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National Oceanic and Atmospheric Administration,
Wave Propagation Laboratory,
Geoacoustics Group,
Rockville, Maryland 20852.

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