Abstract
A transitory pattern of waves associated with an Alberta hailstorm is described. Aerial photographs are compared with radar and sounding data. The waves appear to have been gravity waves in a layer of marked stability overlying the boundary layer.

1. Introduction: Radar history of an Alberta hailstorm

On 11 August 1972, an Alberta storm produced hail over a period exceeding 4 h with some hailstones of diameter exceeding 4 cm. Its continuity was interrupted at the time of development of waves in the lower troposphere, which are the subject of this article. First, a history of the storm is presented using radar data.

The Alberta radar (Humphries, 1974) is an AN/FPS-502 set modified by the Canadian National Research Council. It operates at wavelength 10.4 cm and has a half-power beamwidth of 1.15°. On this occasion it performed a fixed spiral scan (0°–9°), elevating 1° per revolution to complete a scan cycle in 1.5 min. A five-level grey shade Plan Position Indicator (PPI) display of returned power, with thresholds set 10 dB apart, was recorded on 35 mm film.

The storm came within 150 km of the radar at about 1500 MDT (2100 GMT) and passed out of range after 2100 MDT. It appeared to grow in the foothills of the Rocky Mountains northwest of Penhold, the radar site. Its history is presented in Fig. 1, in which PPIs of elevation 1°, at intervals of 30 min, are assembled. A change in the behavior of the storm occurred between 1758 and 1928 MDT, when the motion shifted to the left, and precipitation decreased in intensity. A low-pressure center was moving into the area from the southwest at 8 m s⁻¹, reaching its minimum central pressure of about 100.5 kPa. Frontal structure was not clearly discernible. The position of the low center at 1800 MDT is also shown in Fig. 1.

The tops of growing towers on the right rear of the storm were seeded by a T33 aircraft between 1726 and 1827 MDT in an effort to reduce crop damage by the hail. It seems to the writer that any beneficial effects of this seeding were masked by phenomena discussed in...
this article. Further details of this storm, and case studies of other seeded storms, will be reported separately.

As a function of time, the height of the highest echo top is shown in Fig. 2. Owing to the scan interval of 1° in elevation, there are uncertainties (a function of range), which are indicated by bars straddling the curve at intervals. The curve is based on measurements every 1.5 min and is drawn smoothly by hand. With continuous data, the curve would probably show variability on shorter time scales than those indicated, since the highest tops succeed one another rapidly in storms such as this (Renick, 1971). The storm tops sank to a minimum, below the tropopause, at the time of development of the waves, which are described in the next section.

2. Cloud photographs

About 100 photographs of the storm were taken from a Cessna 320 aircraft flying at about 6 km above ground.
FIG. 4. The storm at 1814 MDT, looking NNE.

FIG. 5. The storm at 1830 MDT, looking NNW.
Fig. 6. The storm at 1837 MDT, looking NNW.

Fig. 7. The storm at 1909 MDT, looking north.
level. Independently, 34 more were taken from the ground at Penhold, at intervals of 2 min, as the storm passed 90 km to the north.

The storm at 1658 MDT is shown in Fig. 3. It was moving away from the camera, from about 266° at 10 m s\(^{-1}\). On the rear, which sloped markedly downwind, growing towers were seen, and anvil clouds extended into the distance. Shallow cumulus clouds bordered the main convective activity on the rear, and a layer of stratocumulus lay behind the storm at a low level.

After 1730 MDT the storm gradually changed to the pattern shown in Fig. 4 at 1814. The main activity was on the left flank. Instead of sloping downwind, the rear of the storm was nearly vertical. The motion had deviated to the left, from 266° toward 238°. A train of waves had formed in the stratocumulus layer, three of them visible in the foreground. The upper surfaces of these waves were lenticular in form; this finding shows that a stable layer was overlying the stratocumulus. The wave adjacent to the storm sloped upward into it, extending higher than those to the rear. On the right rear flank of the storm, a pair of stunted cumuliform rolls was seen, oriented roughly along the direction of motion of the storm. Normal to the wave crests, one discerns a pattern of longitudinal rolls in the stratocumulus cloud. Indicating increased wind shear through this layer, the longitudinal pattern first appeared shortly after 1700 MDT, and the stratocumulus cloud showed both types of waves as it gradually spread southward around the right flank of the storm.

In many of the ground-based photographs taken from Penhold, it was possible to discern the smooth summit ridge of the wave adjacent to the storm. By comparing radar views with the photographs taken from the same ground location, it was possible to assign a scale of elevation to the latter, and using the radar for ranging, to measure the height of the summit ridge of the wave at its merging into the storm. The highest point was 3.0 ± 0.5 km above ground, and the lowest visible point was roughly 2.5 km.

During the next 15 min the waves attained their most spectacular development, as shown in Fig. 5 at 1830 MDT. The cumuliform rolls had grown to form a new column at the rear of the storm. The first wave was linked with this column. Ahead of it, a second new wave was found, disappearing under the column. The lenticular forms were seen clearly. To the northeast, ahead of the new wave, there was no suggestion of further waves. Behind the storm, upper left, the wave generation ended abruptly in a cloudless trough. At this time (1825–1843 MDT), the storm velocity was from 238°, at the maximum leftward departure from the mean.

The pattern changed rapidly. By 1837 MDT (Fig. 6) the waves had lagged behind the storm, so that only the second wave remained in contact with it. During this period (1830–1837 MDT) the storm tops sank below the tropopause.

From about 1840 MDT, as the tops rose again, the original column on the left rear of the storm dissipated, leaving only the new column. By 1848 the first and the trailing waves had disappeared. Only the second wave was left, and it appeared to amplify, to the appearance shown in Fig. 7 at 1909 MDT. Longitudinal
rolls began breaking through the smooth lenticular upper surface of this wave at 1846, and it was gradually disintegrating when photography was stopped at about 1920.

3. Structure of the storm at 1830 MDT

Many of the aerial photographs were taken in rapid succession, and there are several informative stereo pairs. Viewing these by the cross-eye method (Fraser, 1968) assisted in relating the waves to the three-dimensional radar and visual aspects of the storm towers, and in estimating their orientation, 115° ± 15°. The structure of the storm at 1830 MDT is shown in Fig. 8.

There was an overhang of echo on the forward right flank of the storm (lower left on each PPI). The photograph in Fig. 5 (with its stereo pair) showed that most of the region under the overhang contained no cloud other than the stratocumulus layer. Convective cloud was closely associated with the echo columns at the rear, which sloped forward. Updrafts emerged around the rear of the storm. The separation of the two waves was 5.8 ± 1.3 km.

4. Sounding data

Radiosondes were released at the following locations and times (see Fig. 1): 1) Penhold at 1540 MDT; 2)
Rocky Mountain House at 1715 MDT; and 3) Edmonton at about 1800 MDT. Very stable layers were found in all three soundings, between pressure levels as follows: 1) 80.5–76.1 kPa; 2) 74.5–72.3 kPa; and 3) 85.3–83.5 kPa. The Edmonton balloon was released 45 km northeast of the high-reflectivity core of the storm, into its low-reflectivity plume, which had recently reached there. Sounding 2, released upwind in clear air, with a second severe storm newly growing 45 km to the northwest, was chosen as the most representative sounding. Wind data from below 2.1 km were missing, and these were filled in on the basis of sounding 1, which did not differ greatly from sounding 3 in this respect. The sounding for the storm area is shown in Figs. 9 and 10. An isothermal layer 1.7 km above ground is clearly apparent in the tephigram, and from the hodograph it is seen that the storm moved to the right of the environmental winds.

5. How did the waves form?

A lack of sounding data around the storm precludes a complete explanation of the waves. However, some suggestions are offered.

In big, mature storms such as this, it appears that air is ingested by the agency of a mesolow, formed together with a warm core by release of latent heat in updrafts. Air of high equivalent potential temperature is drawn from near the ground, with convergence as it approaches the storm. The convergence may be accompanied by some lifting of air in the lowest few kilometers, near the inflow region of the storm. On this occasion, the boundary layer was capped by a stable layer. Lifting of a parcel of air is considered, at the base of the stable layer in the tephigram (Fig. 9). Condensation would have occurred after a lift of about 500 m, at 2.1 km (at LCL in the figure), and instability would have broken out at 2.9 km (at LFC). Alternatively, lifting of the stable layer as a whole through about 700 m would have yielded instability. At the time of most marked development of the waves described in Section 2, it was found that the highest point visible on the wave merging into the storm was about 3 km above ground, rising from roughly 2.5 km. These two numbers correspond well with those obtained from the tephigram. It seems that the lenticular clouds were due to lifting of air originally at or near the base of the stable layer, and the breaking out of instability at LFC in the tephigram is consistent with the cumuliform rolls prominent in Figs. 4 and 7.

Their appearance, and the sounding data, suggest that the waves were internal gravity waves in the stable layer. Why did they form, just temporarily? One refers to the hodograph, Fig. 10. Through the origin on this diagram a line of orientation 115° is drawn, representing the measured orientation of the wave crests. Waves formed and broke away to the rear of the storm, so that the apparent phase speed of the waves, normal to the orientation of wave crests, was less than the speed of the storm in this direction; it was perhaps a few meters per second. The orientation of wave crests, 115°, was similar to the directions of inflow of air near the ground, relative to the moving storm. Near the ground below a wave crest, one visualizes air moving along toward the storm, and rising on approach, with the wave crest above rising too. There appears to have been a connection between the departure of the storm velocity to the left of its mean value, as indicated in Fig. 10, and the formation of the waves at the same time.

The extension of a train of waves southwestward behind the storm, rather than ahead of it, is attributed to the greater strength, relative to the storm, of the easterlies below the stable layer, compared to the southwesterlies above it. At the rear of the storm near the ground, to the west of the high-reflectivity cores shown in Fig. 8, one expects a downdraft outflow relative to the storm. It is not surprising to find that lifting in the updraft and wave generation were cut off abruptly around the rear.

6. A tentative reconstruction of events

The formation of waves was accompanied by lowering of storm tops below the tropopause. From the tephigram it is seen that tops to 13 km imply inflow of air of very high equivalent potential temperature—of air from very close to the ground. The subsiding of the tops below the tropopause implies that such air was no longer available and that the updrafts were composed of air of much lower equivalent potential temperature. One postulates a temporary coolness of air in the boundary layer and moistening.

This leads to the following tentative reconstruction of events: At 1700 MDT the storm is ingesting warm air from near the surface. The main updrafts are flanked

Fig. 10. Wind hodograph of the environment of the storm at 1715 MDT. Heights are in kilometers above ground. Interval shown is of the isothermal layer in Fig. 9. The two circles show the mean velocity of the storm between 1600 and 1730 and between 1825 and 1843. A line drawn through the origin shows the measured orientation of the wave crests.
by cumulus clouds, which provide a sheath, within which the warm air ascends nearly undiluted. At about 1800 the surface inflow becomes cooler and moister. The flanking cumulus activity diminishes, storm tops descend, and the main updrafts on the rear of the storm become nearly vertical. Generation of new towers on the right flank is interrupted, the storm motion deviates to the left (toward the direction of upper level winds), and waves form in the stable layer. Renewed growth on the right flank leads to the appearance of two columns of updrafts on the rear of the storm instead of one. At about 1830 MDT warmer air near the ground again is encountered and towers of the new column become dominant.

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References


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GATE visiting scientist program

The success of an international experiment like GATE requires not only the exchange of data, but also an exchange of ideas, theories, and the practical details of instrument design and calibration. After the initial analyses of national data, there is great benefit to nations to arrange the exchange of scientists involved in GATE. Therefore, the Tropical Experiment Board (TEB) at its VIIIth session (Geneva, 4–6 May 1976) endorsed and adopted the "GATE Visiting Scientist Program."

The program is an opportunity for scientists who are working on GATE-related problems (e.g., theory, numerical modeling, or data analysis) to continue their work at an institution in another country. Although the program is oriented toward one of five subprogram Data Centers, the opportunities are not limited only to those institutions.

Scientists who are interested in this opportunity may contact their national GATE "focal points" and the institution which they desire to visit. They should also write to the GARP Activities Office (World Meteorological Organization, CH-1211, Geneva 20, Switzerland) and include a curriculum vitae or professional resume, a summary of the proposed work or research project, the name of the desired institution and a proposal for the length of visit. The role of the GAO will be to bring the credentials of the individual to the attention of the institution quickly and to coordinate subsequent arrangements.

At the present time there are opportunities at the following institutions: Canada—Department of Physics, University of Toronto, Toronto; France—The Oceanographic Sub-program Data Center, Brest; F.R.G.—The Max-Planck Institute for Meteorology and the Meteorological Institute of Hamburg University, Hamburg; U.K.—Meteorological Office, Bracknell; U.S.A.—many U.S. government research laboratories, universities, and research centers; and U.S.S.R.—Hydrometeorological Research Center, Moscow, Main Geophysical Observatory, Leningrad, and State Oceanographic Institute, Moscow.

Financial support for these visits and exchanges (including travel and per diem payments) must be worked out on an individual basis. The selection of the individual will depend on the needs and interests of the host institution; the decision rests with the host alone.

First global heat flow map

A map showing the amount of heat flowing outward from the earth's interior—the first map of its kind ever produced—has been issued by the Environmental Data Service. The map is a product of the World Data Center A for Solid Earth Geophysics, operated by the National Geophysical and Solar-Terrestrial Data Center in Boulder, Colo. The map indicates where heat flow measurements have been taken and the approximate flow value at each of about 5500 measurement sites. It also shows a general correlation between high flow and locations where geothermal energy is being produced, or is likely to be produced. Copies of the map may be ordered, either rolled or folded, from the Distribution Division (Code C44), National Ocean Survey, Riverdale, Md. 20810, at a cost of $2.50 each.

The data are also available in digital form on magnetic tape or punched cards. For further information contact: World Data Center A for Solid Earth Geophysics, Environmental Data Service/NOAA, Boulder, Colo. 80302.

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