Plume Convection Over an Urban Area as Observed by Acoustic Echo Sounding

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ABSTRACT

An acoustic echo sounder situated in downtown Toronto has been used to detect convective plumes in the planetary boundary layer and to measure, by means of the Doppler effect, the vertical air motions associated with them. The plumes observed were the order of 390 m in horizontal extent, were detectable to a height of about 400 m, and were characterized by peak upward velocities in excess of 1 m s^{-1}. The sounder measurements are shown to be consistent with surface meteorological parameters, and suggest that free convection over an urban area of considerable surface roughness and non-uniformity is not greatly different from that over uniform land surfaces or water.

1 Introduction

The operation of the acoustic echo sounder (also known as sodar, acdar, and acoustic radar) depends on the scattering of acoustic energy from fluctuations of temperature and wind speed in the atmosphere. The nature of this scattering has been described by Tatarski (1961) and Monin (1962), and observed in the atmosphere by Kallistratova (1961) and in the laboratory by Baerg and Schwarz (1966). It is sufficient to note that the intensity of sound backscattered from clear air is dependent only on the fluctuations of air temperature in the volume insonified, and not on the fluctuations of air velocity. The sound interacts constructively only with a scale of turbulence equal to one half of the wavelength of the incident sound.

If the turbulence in the scattering volume has a mean velocity radial with respect to the antenna, the frequency of sound scattered will differ from that transmitted by an amount given to first order in $|\mathbf{v}|/c$ by

$$\Delta f = -2wf/c$$

where Δf is the difference between the transmitted frequency f and the mean received frequency $(f + \Delta f)$, w is the mean radial velocity of turbulent structure in the scattering volume, $\mathbf{v}$ is the air velocity vector and c is the speed of sound. Various second order corrections to this simple Doppler formula, resulting from wind and temperature variations with height, are discussed by Georges

TABLE 1. Operating Parameters of the Acoustic Echo Sounder

Peak Power	40 W (electrical)
Pulse Width	150 ms
Pulse Repetition Period	4 s
Carrier Frequency	2000 Hz
Antenna Area	1.45 m^2
Beam Direction	Zenithal
Receiver Bandwidth	100 Hz
Number of Periods Timed in a Frequency Measurement	100
Duration of Frequency Measurement	~ 50 ms

and Clifford (1972). However, since wind speeds encountered in the lowest 500 m of the atmosphere are generally less than 0.05 c, first order theory is quite adequate.

Published work by several research groups has demonstrated the value of the backscattered sound amplitude in delineating atmospheric structures, and in complementing observations made with conventional meteorological instruments (Cronenwett *et al.*, 1972; Emmanuel *et al.*, 1972; McAllister *et al.*, 1969). Some observations have been published relating Doppler-derived winds and acoustic backscattering structures (Beran *et al.*, 1971; Mahoney *et al.*, 1973), but the major effort in acoustic Doppler work has been directed towards developing an operational wind and wind shear sensing system (Beran, 1974) where little attention is paid to the structures causing the scattering. The turbulence merely acts as a tracer of atmospheric motion.

2 Equipment

The acoustic echo sounder used for these observations is described in detail by Bennett (1975), while its immediate predecessor is discussed by List *et al.* (1972). Operating parameters are variable, but those used in this work are listed in Table 1. The system is monostatic and the antenna is vertically directed, so that the received sound is scattered by temperature fluctuations alone and any Doppler shift in frequency is a result of vertical air motion. The amplitude of the received signal was recorded as an intensity-modulated trace on a facsimile recorder as a function of the height of the scattering volume and time. The gain of the preceding amplifier was adjusted so that at the height at which echo frequency was being measured, an echo with a signal-to-noise ratio of 10 just exceeded the threshold sensitivity of the recording paper.

Echo frequency was measured at a fixed delay after transmission of the acoustic tone burst using a digital frequency counter. The counter was operated in the period measurement mode to time the duration of a specified number of positive zero crossings of the input waveform. Because the input signal was strongly filtered by several bandfilters in the receiver electronics, high frequency noise did not cause significant triggering errors. However, the scattered sound received at the antenna is the superposition of a large number of randomly-phased sinusoidal components with frequencies determined by the radial motion of the associated scattering centre. The waveform is thus very similar to that of narrowband noise, having a well-defined carrier frequency and an amplitude which varies over a wide range, often falling to near the level of background noise. Because of these amplitude fluctuations, it was necessary to ensure that the frequencies being measured were representative of the signal rather than of the background noise. Accordingly, the signal-to-noise ratio was monitored while the period measurement was being made. A signal-to-noise ratio of greater than ten was determined to be necessary for an accurate period measurement. As explained above, an adjustment of the facsimile recording system enabled a simple test for adequate signal-to-noise ratio to be made.

To obtain a velocity resolution of ± 15 cm s^{-1} when operating at 2000 Hz, the frequency must be measured accurate to ± 2 Hz. Such an accuracy requires a data sample of the order of 250 ms in duration, or 500 cycles of a 2000 Hz waveform. This amount of data may be accumulated in one measurement, but it is preferable to average shorter data samples from successive pulse interrogations to obtain the required accuracy while retaining useful space resolution in the vertical. In processing the vertical velocity data discussed in this paper, a weighted average of exponential form with an *e*-folding time constant of 60 seconds was used.

The acoustic antenna of the sounder is located at a height of 58 m above ground level, on the balcony of the McLennan Physical Laboratories. It is shielded against background noise by a 3-meter high plywood enclosure lined with acoustic foam.

Wind data for the experiment came from an anemometer mounted at 70 m above ground on the rooftop of the laboratory. Temperature was measured using a thermocouple and a calibrated chart recorder. The probe extended 1 m from the north side of the laboratory, 30 m above ground.

3 Geography of the Toronto Area

The McLennan Laboratory is in downtown Toronto, about 3.5 km north of the Lake Ontario shoreline, which runs from north-east to south-west in the Toronto area. The land slopes gently towards the lake from an area of low hills about 20 km back from the shoreline. A bluff about 35 m high which runs east-west about 2.6 km north of the laboratory is cut by several ravines in the Toronto area. The area surrounding the observing site is heavily built up for at least 17 km in all directions, barring those where the lake is closer. Within the 180° sector centered about south-east and to a distance of 2 km is the business and commercial district, where there are many buildings of over 10 stories. The area for several kilometres in the opposite sector is residential, with buildings of two to three stories, and occasionally a small park or high-rise apartment. Area topography and the extent of urbanization are shown in Fig. 1.

4 Observations and Discussion

While the observations discussed below were being made (November 23, 1973), Toronto was under a ridge of high pressure which extended northwestward from a large high pressure cell centered near Bermuda. Lightly over-

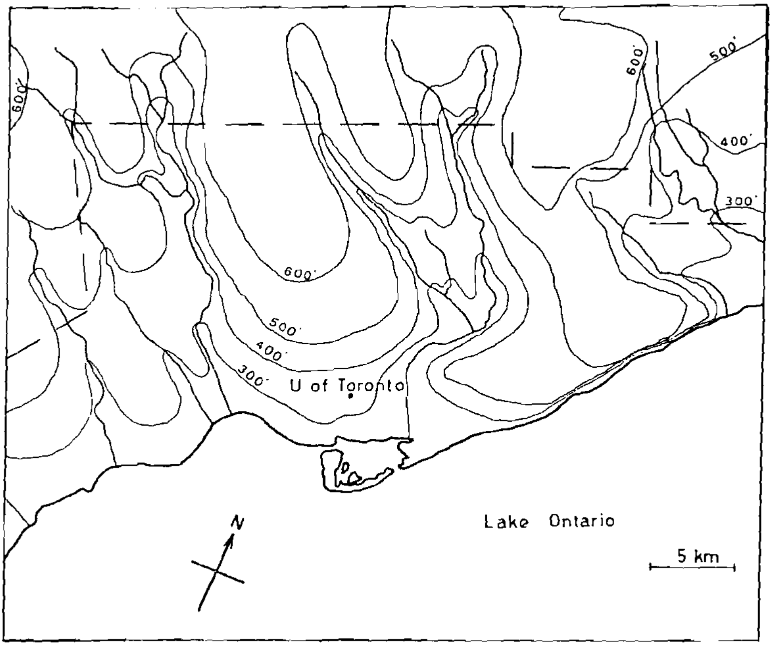

Fig. 1 Topographic map of the Toronto area showing the location of the University of Toronto antenna site and the approximate extent of the built-up area (dashed line).

cast skies present during the morning cleared for several hours in the early afternoon. Winds were from the north at about 2.5 m s^{-1}, and the temperature fluctuated about a mean value of 13°C. Barometric pressure was steady.

The facsimile record for the period of observation is shown in Fig. 2. A layer echo which may be associated tentatively with a nocturnal inversion (McAllister *et al.*, 1969), began to lift at about 1015 EST (eastern standard time). Direct evidence of weak convection penetrating to the 130 m level appeared about 30 minutes later. This conjecture is based on the familiar acoustic echo pattern associated with convective plumes which has been investigated by several authors (Beran *et al.*, 1971; Kjelaas *et al.*, 1974; McAllister *et al.*, 1969). It has been shown to be an alternation of vertically-oriented regions of strong acoustic scattering with regions of little or no scattering. Individual plumes became more distinct about 1230 EST as the sky cleared. The period of time during which vertical velocity measurements were made extended from 1505 EST to 1545 EST. The height of measurement was centered about 150 m above ground level.

Fig. 3a is an enlarged portion of the facsimile record to be compared with the near-surface air temperature in Fig. 3b, the Doppler-derived vertical velocities in Fig. 3c and the horizontal wind speed in Fig. 3d.

The data show the thermal plumes observed to be very similar to those observed over uniform flat land surfaces (McAllister *et al.*, 1969; Cronenwett *et al.*, 1972) and over water (Ottersten *et al.*, 1974). By contrast, however,

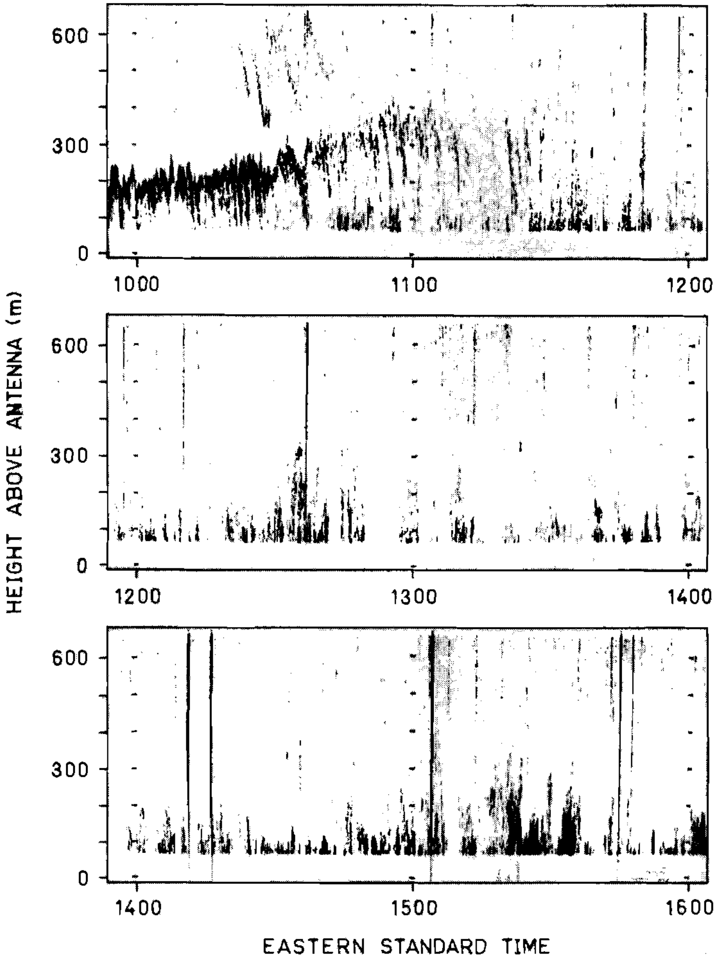

Fig. 2 Facsimile record for November 23, 1973 obtained using a vertically-directed monostatic acoustic sounder. Regions of strong thermal turbulence appear dark. The vertical scale gives the height of the scattering volume above the antenna, itself 58 m above ground level. The slanted structure evident between 1000 and 1115 EST is associated with the lifting nocturnal inversion, while the vertical structures visible throughout most of the record are due to thermal plumes. The period during which vertical velocity measurements were made is between 1505 and 1545 EST. (Dark vertical lines are caused by the noise of passing aircraft.)

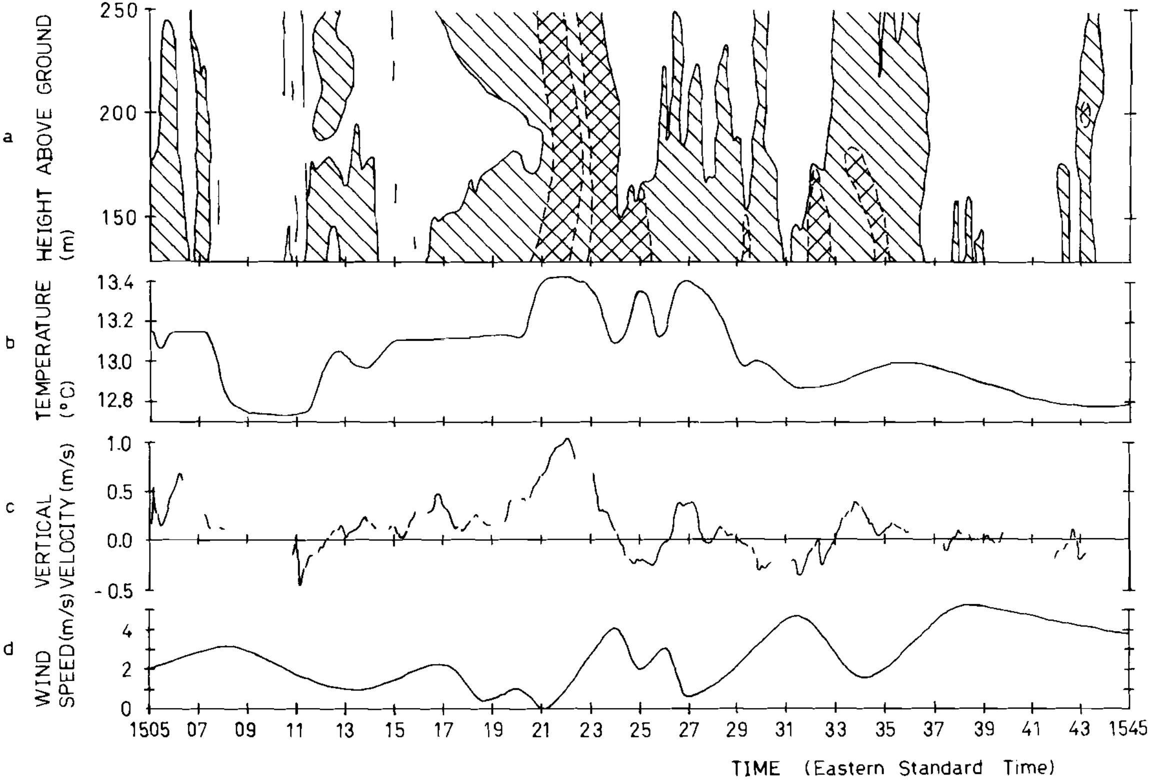

Fig. 3a. (top) Simplified version of the facsimile record in Fig. 1 for the period 1505 to 1545 EST. Plumes are indicated by the hatched areas. The vertical scale gives the height above street level. b. Air temperature measured at 30 m above street level for the period 1505 to 1545 EST. c. Vertical velocity of air at a height of 150 m above street for the period 1505 to 1545 EST, deduced from the Doppler shift experienced by backscattered sound. No velocities were plotted for those periods during which there was insufficient signal-to-noise ratio for echo frequency measurement. d. (bottom) Horizontal wind speed at a height of 70 m above street level for the period 1505 to 1545 EST.

the plumes observed on this and many other occasions at the Toronto site had formed over an extensive fetch of a non-uniform nature, with numerous local sources of heat (roads, buildings) and considerable surface roughness.

The plumes were vertical, having no consistent tendency to slope upwind or downwind. This is in agreement with the observations of Beran *et al.* (1971), who took this fact as an indication of the lack of wind shear at the levels of observation. If it is assumed that there was no wind shear on November 23, 1973, then the mean width at 150 m of the thermally turbulent regions traversing the antenna during the period of observation was 390 m, and the mean width of the thermally quiescent regions was 340 m. This can be compared to scales deduced from aircraft observations of temperature in a convective field by Warner and Telford (1967). They found the temperature pulses (plumes) to average from 200 m to 300 m across, while the quiescent regions averaged 20% larger. Although the agreement is quite good, the sample of sounder-observed plumes is too small for a detailed comparison. Moreover, estimation of the plume dimension from the facsimile record is quite difficult, as the plumes show considerable small scale structure. Blobs of thermally-turbulent air appear to become separated from the main body of the plume, and the plume itself divides into several vertically-oriented scattering regions near the upper limit of detectability.

Acoustic scattering is obtained from much greater heights in some plumes than in others. Whereas Warner and Telford (1963) noted that the temperature pulses identifying plumes were not discernible above 500 to 700 m, acoustic scattering from plumes was not detectable above 400 m in our observations. Konrad and Robison (1973) suggest that the height of the minimum intensity of temperature fluctuations is the order of 0.5 Z_{max}, where Z_{max} is the maximum height reached by plume air in overshoot. Thus the height at which the temperature pulses become indiscernible should be scaled by the mixing depth at the time of observation. As this depth was not determined for our data, direct comparison with scaled aircraft data was not possible. It should also be kept in mind that in the case of the aircraft observation, maximum plume height was determined on the basis of the plume being indistinquishable from the background; whereas in the sounder observation, maximum plume height was that at which the sound scattered from the plumes dropped below the sensitivity of the receiver.

The temperature measured at 30 m (Fig. 3b) did not show the very distinct pulse structure discussed by Warner and Telford (1967). This fact suggests that the probe was located at a height at which plumes had not totally disassociated themselves from the forced convection layer. Nonetheless, there is a definite correlation between the appearance of scattering regions at higher levels observed using the sounder and the occurrence of positive temperature fluctuations at 30 m. The magnitude of these fluctuations was from 0.3 °C to 0.6 °C relative to the base level temperature. This range is quite consistent with Warner and Telford.

Vertical velocity data are shown in Fig. 3c. The trace is not shown where there was insufficient signal for reliable frequency measurements. Computed vertical velocities tended to fluctuate quite markedly from one pulse interrogation to the next, so that longer period trends were not easily assessed without data averaging. Thus the observed time series has been smoothed using a digital average of exponential form with a time constant of 60 seconds. Warner and Telford (1967) also noted the masking of average plume vertical velocities by fluctuations of higher frequency.

In our observations there was a definite correlation between the observation of upward vertical motion and the presence of acoustic backscattering at 150 m. Thus the thermally turbulent air with a positive temperature excess was rising. This is consistent with aircraft observations and plume theory. There appears to be a tendency for the themally quiescent air between plumes to have the expected descending motion, but because of the frequent lack of acoustic backscatter from these regions, this deduction cannot be made with certainty.

The horizontal wind speed near the antenna site, and 70 m above ground is shown in Fig. 3d. This data has been smoothed to be comparable with the vertical velocity data. The wind tends to reach a maximum after the passage of an updraft over the antenna, and to fall to a minimum just before. This phase relationship is to be expected, for the updraft must be fed by a horizontal convergence near ground level. This is discussed by Coulman (1970). Coulman noted that at 6 m above ground the maximum in wind speed after plume passage was quite noticeable, while the preceding minimum was often not present.

5 Conclusions

Plumes observed in the urban boundary layer during early winter were characterized by strong thermal turbulence relative to the surrounding air, a temperature excess of the order of 0.5°C at 30 m above ground, upward air motion of the order of 1 m s^{-1} at 150 m above ground, a horizontal extent averaging 390 m at 150 m above ground, a separation averaging 340 m and a vertical extent of greater than 400 m. The passage of a plume over the observing site was preceded by a minimum in horizontal wind speed and followed by a maximum. The fluctuation in wind speed was the order of $\pm$ 1.5 m s^{-1}.

The acoustic backscattering patterns typifying plumes in the urban boundary layer are indistinguishable from those observed over flat uniform surfaces; the plume sizes, separations and maximum heights are comparable and near-surface temperature and wind speed show the expected behaviour during plume passage overhead. This suggests that free convection is not strongly influenced by surface roughness or non-uniformity.

The sounder observations show that individual plumes possess considerable small-scale structure, both in vertical velocity and in the intensity of thermal turbulence.

The accuracy of velocity measurements made with the sounder is estimated to be $\pm$ 15 cm s^{-1}. The corresponding resolutions in height and in time are 30 m and 60 s respectively, though the time resolution can be improved if some deterioration in height resolution can be tolerated.

At present, the only demonstration of the accuracy of the Doppler determinations of air motion made in this laboratory is their consistency with concurrent measurements of related parameters, and with measurements, both remote and in situ, made by other observers (Beran *et al.*, 1971; Mahoney *et al.*, 1973; Warner and Telford, 1967). Work is now progressing towards increasing the reliability of Doppler velocity determinations. A major part of this effort is directed towards the development of instrumentation to sample and record amplitude and frequency data digitally for computer processing.

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