SCATTERING OF SOUND USED TO STUDY THE ATMOSPHERIC BOUNDARY LAYER

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Introduction

We are using the scattering of sound for the remote sensing of thermal turbulence in the atmosphere. Over the past several years an acoustic radar has been developed and operated at the University of Toronto to study the planetary boundary layer. We were one of the first groups to operate successfully in a noisy urban environment. A brief outline of the concept and technique of acoustic echo sounding will be given along with a discussion of some of our observations.

In the past, the study of the planetary boundary layer (50 m — 1 km) of the atmosphere has been limited by the lack of access with direct access being limited to occasional baloon ascents or airplane traverses and in a few cases, to instrumented towers extending beyond 100 m. Recent advances in remote sensing techniques now allow us to remotely monitor parameters of the boundary layer on a continuous real time basis. Acoustic radar, FM-CW radar and lidar (laser radar) are the three techniques being most actively investigated and applied.

Theory

Inhomogeneities in the acoustic refractive index produced by atmospheric turbulence will scatter sound with turbulent fluctuations of both temperature and wind speed contributing to the scattering. The location and intensity of turbulent regions can be determined by transmitting pulses of sound into the atmosphere and monitoring the scattered signal. Repetitive operation generates a cross section of the distribution of turbulence in the portion of the atmosphere advected through the beam of the transmitting system. An understanding of the scattering characteristics of atmospheric turbulence allows the turbulent scattering to be used as a tracer for the study of larger scale structures in the boundary layer.

For the ideal case of homogeneous, isotropic turbulence of sufficient extent to fill the pulse volume, the scattering cross section has been shown to have a linear dependence on the spectral densities of thermal turbulence and turbulent kinetic energy (Monin, 1962). The angular dependence is such that backscattering is due only to thermal turbulence. For backscattering, the scale of turbulence interrogated is equal to 1/2 the acoustic wavelength.

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The operating frequency for an acoustic radar is a compromise primarily between the high noise levels at the low frequencies and the stronger attenuation by the atmosphere at higher frequencies. The University of Toronto acoustic radar normally operates at 2000 Hz and can give reasonable results over the range from 1300 Hz — 3700 Hz.

Quantitative work with acoustic echo sounding is hindered by the uncertainties in the received signal associated with the attenuation of the transmitted and scattered sound. The strong absorption due to the presence of water vapour cannot be accounted for without having knowledge of the real time distribution of moisture in the interrogated volume. For a range of 500 m when operating at 2000 Hz laboratory measurements (Harris, 1966) indicate that for temperatures from -10°C to +30°C and relative humidity from 10% — 90%, the round trip attenuation due to molecular absorption would range from 8 to 50 dB.

Experiment

The University of Toronto acoustic radar is located on the 15th floor balcony of the Physics building on the main campus in the center of the city of Toronto. The system operates in the monostatic mode using the same transducer and antenna for both transmitting and receiving. Monostatic operation means we are looking at backscattered sound and hence detecting scattering only from thermal turbulence. The antenna is a modified microwave antenna with a high power moving coil loud speaker driver as the transducer. The antenna is enclosed in a wooden shield lined with acoustic foam. The transducer is driven by an ordinary audio amplifier. The normal operation involves sending 100 ms pulses at 70 — 90 w electrical power level every 4 s. At that power the sound pressure level 1 m above the antenna aperature is 136 dB while beside the shield it is approximately 70 dB and on the ground it is barely detectable by a trained listener.

The receive section has a gain of 162.5 dB and a very narrow pass band. A variable gain amplifier corrects for the spherical divergence of the scattered sound. The data is recorded on a modified facsimile recorder where each echo train is represented as intensity modulations along a single line. Recording at 90 lines an inch with a 4 s period compresses 1 hour of data into 10 inches of the chart.

Results

Despite the urban background noise, operation of the acoustic radar has been very successful. The unit has been operating on a 24 h basis essentially continuously since March 1973. During this time we have observed structures associated with a wide range of phenomena including:

a) atmospheric gravity waves
b) synoptic scale cold fronts and warm fronts
c) mesoscale cold outflows associated with thunderstorm activity

d) lake breeze circulations
e) layering associated with stable stratification
f) convective fields
g) formation and breakup of nocturnal inversions
h) many periodic structures, Kelvin Helmholtz instabilities and other dynamic instabilities.

The acoustic radar vividly displays the columns of buoyant, thermally turbulent air associated with convective activity. These thermal plumes are observed to occur intermittently with little scattering occurring between them as thermally quiescent air subsides to replace the warm unstable air carried up in the plumes.

The existence of stable layers in the lower troposphere is revealed by the acoustic radar as continuous bands of echoes showing only gradual variation in altitude. Such stable layers are observed in association with nocturnal inversions, synoptic scale subsidence and onshore flow. The decay of the stable layer associated with nocturnal inversions is revealed by the acoustic radar as early morning solar heating generates convective activity. The stable layer is observed to be buffetted and distorted as the thermal plumes impinge upon it. Ultimately the stable layer is lifted and dispersed as the influence of the surface heating extends into the planetary boundary layer.

The acoustic radar has proven to be very effective in monitoring the sequence of events associated with the onset and decay of lake breeze circulations (analogous to the sea breeze). Typically the development of the lake breeze is preceeded by an active period of convection marked by thermal plumes. The passage of the lake breeze front is revealed by the abrupt cessation of convective activity and the development of an intense surface scattering region associated with the internal boundary layer within the inflowing lake-modified air. The continuation of the lake breeze is marked by a regime of stable air in the lower troposphere while the retreat of the lake breeze front often is observed to be followed by the return of convective activity. The acoustic radar is a valuable tool in the study of the dynamic characteristics of lake breeze circulation.

The acoustic radar has also allowed us to monitor and study the passage of both synoptic and mesoscale cold fronts and warm fronts. It also reveals much about the dynamic instabilities prevalent in the boundary layer, particularly with regards to the Kelvin Helmholtz instability.

In addition to the detection of atmospheric structure as revealed by the distribution of thermal turbulence, the acoustic radar has detected scattering from discrete objects. In particular, in the migration seasons, flocks of birds passing through the antenna beam result in a profusion of strong point echoes and during the winter falling snow consisting of large flakes produces a distinct signature on the record.

Our work with the acoustic radar has shown that it can be operated successfully within an urban environment. The technique allows the characteristics and dynamics of many of the features of the planetary boundary layer to be monitored and studied. The acoustic radar offers great promise as an aid to the development of an understanding of the planetary boundary layer.

References

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