THE MEASUREMENT OF TURBULENT SURFACE-LAYER FLUXES BY USE OF BICHROMATIC SCINTILLATION

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Abstract. Scintillation measurements with a HeNe and a CO₂ laser were used to derive turbulent fluxes of heat and momentum in the surface layer. This was achieved by the structure constant or dissipation technique, i.e., by relating the measured structure constants and inner scales of refractive index fluctuations to structure constants of temperature fluctuations and dissipation rates of turbulent kinetic energy, respectively, and then assuming Monin–Obukhov similarity.

The resulting heat fluxes agree well with measurements using the eddy correlation technique but for averaging periods of 10 min. the optical data show a much smoother and physically more plausible behaviour. The optically derived friction velocities are in good agreement with estimates derived from wind velocity and surface roughness. It was also observed that for stationary conditions, 1-min averaged optical measurements already provide good estimates for longer averaged heat and momentum fluxes.

Even though some uncertainty remains about the empirical constants and Monin–Obukhov similarity expressions used, the method clearly proves to be of great value for monitoring surface-layer turbulence.

1. Introduction

1.1. CONVENTIONAL FLUX MEASUREMENT TECHNIQUES

Direct measurements of turbulent fluxes are usually achieved by local eddy-correlation measurements. However the application of this technique is often problematic. The necessary sensors for wind, temperature and humidity must respond very quickly (resolution 10 Hz or better) and at the same time must not show noticeable drift. This makes them delicate, expensive and in many cases difficult to calibrate. However, more serious is the fact that flow distortions by the sensor, mast, etc. as well as horizontal misalignments often cause significant errors (Kaimal and Haugen, 1969; Wyngaard, 1981).

In addition, there are statistical problems due to the fact that temporal cospectra, measured at a fixed local sensor, extend to very low frequencies. To achieve acceptable significance often demands averaging periods of several tens of minutes (Wyngaard, 1973). Such long averaging periods reduce the temporal resolution and conflict with the requirement of atmospheric stationarity within the averaging periods.

Because of these difficulties, alternative indirect flux measurement methods
have been developed. At first glance, the derivation of the fluxes from mean profiles would seem to be very attractive since only slow sensors are required. However, it turned out that the accuracy of the results strongly depends on horizontal homogeneity (e.g., Beljaars, 1982), and the temporal resolution is again very limited. Another approach, the so-called ‘dissipation technique’ (Champagne et al., 1977), infers the fluxes from measurements of (independent) spectra of temperature, humidity and wind velocity. Compared with the eddy correlation method, this technique reduces sensor drift problems and avoids the necessity of an exact horizontal alignment. However, the main disadvantages of local measurements remain: the statistics are relatively weak, and over real terrain, which is never ideally homogeneous, a local measurement can often not be regarded as very representative.

1.2. SCINTILLOMETERS

Recently, optical methods for turbulence measurement have attracted more and more attention among micrometeorologists. The basic optical instrument is the scintillometer. A scintillometer measures the intensity fluctuations of visible or infrared radiation after propagation over some tens or hundreds of meters. The fluctuations are caused by interference after the radiation has been scattered by inhomogeneities in the refractive index of the air, the latter caused by turbulent fluctuations of temperature and humidity. In contrast to local measurements, scintillometers provide path-averaged results.

The optically most active eddies have sizes in the order of the first Fresnel zone radius \( Z_F = \sqrt{\lambda R} \), where \( \lambda \) is the optical wavelength and \( R \) is the path length. Depending on the configuration used, \( Z_F \) is several millimeters to several centimeters. In the turbulence spectrum, this corresponds to eddies in the dissipation range or the high wavenumber end of the inertial range. Accordingly, two turbulence quantities are accessible by scintillometric measurements: the structure function constant (or structure constant) \( C_n^2 \), which describes the spectral amplitude of refractive index fluctuations in the inertial range, and the inner scale \( l_0 \), which denotes the transition eddy size between the inertial and dissipation ranges.

The first scintillometric measurements of \( C_n^2 \) were made quite early (e.g., Tatarskii, 1961). Today, techniques are available also for long optical paths (Ting-I-Wang et al., 1978). Since refractive index fluctuations are usually caused by fluctuations of temperature rather than by those of humidity, \( C_n^2 \) is often interpreted as a measure of the structure constant of temperature fluctuations \( C_T^2 \).

The scintillometric measurement of the inner scale \( l_0 \) only recently reached a stage which allows quantitative applications. This was mainly due to the fact that for the determination of \( l_0 \) from optical measurements, a model for the shape of the spatial refractive index spectrum in the dissipation range has to be assumed and the shape was too uncertain. For a long time, mostly the model of Tatarskii (1971) was used. However there is experimental evidence now (e.g., Thiermann and Azoulay, 1989) that the use of a more exact and complex model for the