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Comparisons between multiple in-situ aircraft turbulence measurements and radar in the troposphere

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ABSTRACT

Networks of Windprofiler Radars have the capability to make significant contributions to severe weather forecasting (both on the ground and in the air) through the determination of real-time turbulence strengths, but the potential has still not been fully realized. In order to better understand the accuracy of profilers in determination of turbulence strengths, we have compared radar measurements made at the Harrow radar in Canada (located in Southwestern Ontario as part of the O-QNet radar network) with in-situ measurements made by multiple aircraft. These included measurements made both by commercial aircraft and dedicated research aircraft.

Research aircraft (instrumented with accelerometers and GPS tracking devices) and radar data were analysed using structure function, spectral and spectral-width methods. Data were also recorded on-board commercial aircraft using accelerometer-based studies, and results were recorded for subsequent analyses. Over 92,000 commercial aircraft measurements, 4000 h of radar data, and 15 days of research-aircraft measurements were available for this study, although only a subset of the commercial aircraft data were useable. The radar-based spectral-width method occasionally produced anomalous negative values of the turbulence strength, usually associated with weak turbulence coupled with significant wind variability over scales of tens of kms, but the aircraft data also had limitations. For the commercial aircraft, frequent zeros were common, also associated with weak turbulence. With regard to the research aircraft measurements, it was found through both spectral and structure function analyses that spectral contaminants exist out to scales of many tens of metres (larger than often assumed), but proper allowance for these effects permitted good estimates of turbulence strength. Spatial and temporal variability was large, however, complicating comparisons with the radar.

By comparing the in-situ data to the radar data, it has been possible to place stronger limits on the constants used to determine radar turbulence strengths. Subsequent comparisons with the commercial aircraft data over a six-month period have then been used to show that aircraft and radar probability distributions agree in form, but that the aircraft data are three to five times larger. Corrections for this bias lead to good agreement, both in form and absolute values, for all three data sets.

1. Introduction

Atmospheric turbulence is the major cause of injuries to passengers and crew in flight, and a key participant in the evolution of many small and large scale dynamical events in the atmosphere. However, the stochastic nature of turbulence makes it difficult to predict. Thus high-resolution measurements of turbulence can help in characterizing the structure of turbulence in the atmosphere.

High-resolution estimations of turbulence are possible using in-situ measurements. Instrumented aircraft are one of the main tools for in-situ measurements (Belair et al., 1999; Pavelin et al., 2002). However, in-situ measurements are costly and limited in duration and altitude. On the other hand, radar (Hocking, 1985, 1986; Hocking and Mu, 1997; Nastrom and Eaton, 1997; Narayana Rao et al., 2001) can measure turbulence continuously over a good range of altitudes and during any weather conditions, but provide larger-scale averages.

There have been relatively few studies on the verification of the turbulence measurements by radar. Some attempts have been made to find a correlation between radar and in-situ aircraft measurements (e.g. Shaw and LeMone, 2003; Jacoby-Koaly et al., 2002; Puygrenier et al., 2004). Some of the comparisons involved coordinated simultaneous measurements of turbulence using radar and aircraft (Labitt, 1981; Lee et al., 1988; Meischner et al., 2001). However, even in these types of comparisons, averaging is necessary since radars make measurements over a volume of the

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atmosphere, whereas an aircraft probe makes measurements at localized points in time and space. Other works (e.g. Frisch and Strauch, 1976; Meischner and Baumann, 2001; Shupe et al., 2008, 2012) include the comparisons of retrieved turbulence in the vicinity of convective storms or inside clouds. Furthermore, most of these investigations are limited to the boundary layer of the atmosphere.

In many works which employ radar, the spectral-width method has been used to extract the turbulent energy dissipation rate, ε, from radar observations. Here ε is the rate at which turbulent energy is dissipated to heat by viscosity, and represents the strength of turbulence. While the spectral-width method is powerful, it can sometimes produce negative values of ε due to weak turbulence coupled with (inevitable) errors in mean wind estimates (Dehghan and Hocking, 2011). Although the energy dissipation rate is a positive definite quantity, its determination by radar involves a proxy parameter calculated as the difference of two separate quantities, each with a Gaussian distribution function. These two quantities (measured spectral width and beam-broadened theoretical spectral width) may each independently either over-estimate or under-estimate the true value. If the measured value over-estimates, but the beam-broadened value under-estimates, then the difference (which relates to the strength of turbulence) will be an over-estimate. If, on the other hand, the measured value is under-estimated, but the beam-broadened value is over-estimated, the strength of the turbulence will be under-estimated. Other permutations of the degree of over- and under-estimation can exist. In order to perform proper averages, all types of differences must be considered, including the negative ones. Ignoring negative values (unless small in number or unless geophysical explanations can be found for their existence) biases the means in the positive sense, an undesirable statistical artifact which can have huge implications for interpretation.

In many earlier comparisons (referenced above), only positive values of ε have been used and apparent negative values have been neglected. This unfairly biases the mean values.

Only in a few works have negative values of ε been considered in the past. Hocking (1988) suggested that negative values of ε should be used in averaging processes. Nastrom and Eaton (1997) included negative values in the median analysis but not in determining averages, while Dehghan and Hocking (2011) used both negative and positive values in calculating averages. However, this sort of analysis has not yet been used in any major comparisons between radar and in-situ data.

The main objective of this paper is therefore to compare the radar-estimated energy dissipation rate with estimates derived from aircraft data, while properly accounting for the impact of measured "negative" values.

In Section 2, we describe the instrumentation and methods used in this work. Results and analysis of comparisons are given in Section 3. Finally, Sections 4 and 5 present discussion and conclusions respectively.

2. Instrumentation and method

2.1. Radar measurements

The key radar used in this work is a VHF radar located at Harrow (42.039° N; 82.892° W) in Southwestern Ontario, operating at a frequency of 40.68 MHz. The radar is located within 43 km of the Detroit international airport (USA). The large radar antenna-field provides a one-way half-beamwidth of 2.75° (two-way half-beamwidth of $2.75^\circ/\sqrt{2}$). The beam is steered to four off-vertical and one vertical directions in a cyclic manner. One complete cycle takes about 3–5 min (depending on sampling strategies). The radar array comprises 128 antennas which are positioned in groups of four in the form of a square (called a "quartet"), with separations between the antennas in such a quartet of one radar half-wavelength (Hocking et al., 2007). Thirty two quartets are distributed in an area of approximately 11 by 11 wavelengths. The radar parameters of the Harrow radar are given in Table 1.

Table 1
The Harrow radar parameters.

Title	Value
Location	Harrow (42.039°N; 82.892°W)
Operating frequency	40.68 MHz
One way half-power half-beamwidth	2.75 degrees
total area of antenna field	4000 m^2
Mean power	3200 W
Peak power output	40 kW
Gain	25 dB
Wind measurement mode	Doppler
Pulse length	500, 1000, m
Mean power aperture product	1.6×10^7 Wm^2
Duty cycle	5–10%
Height resolution	0.5–1 km
Number of beams	5(Vert.+10.9° off-vert. to N,S,E, W)
Range(off-vertical beam)	0.4–14 km
Range(vertical beam)	0.4–14 km
Digitizer aliasing frequency	> 100 Hz

2.2. Processing the radar data

The radar receives backscatter from turbulent patches in the atmosphere and records in-phase and quadrature components for typically 20–40 s. Spectra are then formed from these time-series. The spectral-width method has then been used to determine energy dissipation rates (e.g., see Hocking, 1997a). The spectral width represents the variance of the radial velocities associated with scatterers in the turbulent patch. However, the spectrum is contaminated by non-turbulent effects such as beam and wind-shear broadening. The beam broadening effect is due to the fact that radar beam has a finite width and this effect always broadens the spectrum. The shear broadening is due to wind shear across the radar beam. This effect could narrow or broaden the spectrum, depending on whether the wind shear is increasing or decreasing with height. In order to find turbulent spectral variance, σ_t^2, first the broadening variance, σ_{nt}^2, must be removed from the measured spectrum variance, σ_e^2, through the following equation (Hocking, 1985):

$$\sigma_t^2=\sigma_e^2-\sigma_{nt}{}^2=(\lambda/2)^2(f_e^2-f_{nt}^2)/(2\ln 2) \tag{1}$$

where f_e^2 and f_{nt}^2 are the measured (experimental) and theoretical non-turbulent broadened two-way half-power squared half-widths of the spectrum respectively, and λ is the radar wavelength.

The beam-shear broadening variance can be estimated either by numerical modeling, or as (Dehghan and Hocking, 2011):

$$\begin{aligned}\sigma_{nt}^2 &\approx \frac{\nu^2}{\kappa}u_\circ^2\cos\alpha - a_\circ\frac{\nu}{\kappa}\sin\alpha\left(u_\circ\frac{\partial u}{\partial z}\zeta\right)\\ &\quad + b_\circ\frac{2\sin^2\alpha}{8\kappa}\left(\frac{\partial u}{\partial z}\zeta\right)^2 + c_\circ(\cos^2\alpha\sin^2\alpha)|u_\circ\xi|\\ &\quad + d_\circ(\cos^2\alpha\sin^2\alpha)\xi^2\end{aligned} \tag{2}$$

where ν is the one-way half-power half-width of the radar beam, u_0 the horizontal wind speed, α the zenith angle, $\partial u/\partial z$ the wind shear, $\kappa=4\ln 2$, and parameters ζ and ξ are defined as $\zeta=2\nu R_\circ\sin\alpha$ and $\xi=(du/dz)\Delta R/\sqrt{12}$, in which $R_\circ$ and ΔR are