P4.6 AIRCRAFT-CORRELATED TURBULENCE MEASUREMENTS WITH THE DOPPLER ON WHEELS

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1. INTRODUCTION

Aircraft-based *in situ* methods of turbulence detection and quantification are expensive, spatially limited, and precluded by hazardous flying conditions. Remote sensing of atmospheric turbulence offers an attractive alternative but has other problems and limitations. In addition, the methodology necessary to extract turbulence-related information from radar data has not been rigorously established. This paper examines an empirical attempt to correlate aircraft measurements of turbulence with radar-based inferences of turbulence. The analysis uses data collected during development of the Juneau (Alaska) Wind Hazard Alert System (JWHAS) described by Barron and Yates (2004), Morse et al. (2004), and Fowler et al. (2004).

2. DOW RADAR CHARACTERISTICS AND DATA PRODUCTS

The Doppler on Wheels (DOW) is a mobile ground-based scanning Doppler radar originally designed for observations of rapidly migrating small-scale severe weather phenomena (Wurman et al., 1997). The DOW radar operates at a frequency of 9.3 GHz (3 cm wavelength) and has a peak power of 250 kW. With an angular beam width of 0.93° (0.0162 radians), the DOW provides 50-meter resolution at 3 km and 166-meter resolution at 10 km.

Basic DOW data products consist of reflectivity (reflected power), radial velocity, and spectral width. In our analysis, reflectivity is primarily useful as a basis for quantifying data quality. Spectral width and spatial variations in radial velocity are regarded as potential indicators of small and large scales of turbulence, respectively.

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DOW data was collected during the JWHAS development field projects described in Cohn et al. (2004b). Repeated sequences of aircraft-coincident PPI scans were designed to allow the DOW to observe a region through which the aircraft would pass within a six-minute interval. When the aircraft passed through the region of interest, the DOW scanned that area with ±3 minutes.

The DOW radar detects precipitation rather than clear air. Consequently, in the absence of precipitation, the quality of DOW data was extremely poor. When precipitation was present, the quality of the data was largely independent of precipitation type (i.e., rain, sleet, snow). The sole exception was very light drizzle, which was sometimes associated with insufficient scattering and was also spatially intermittent. Rain is often present during southeast flow and mixed flow conditions as described in Cohn et al. (2004a).

DOW data was collected from six observation sites (Figure 1).

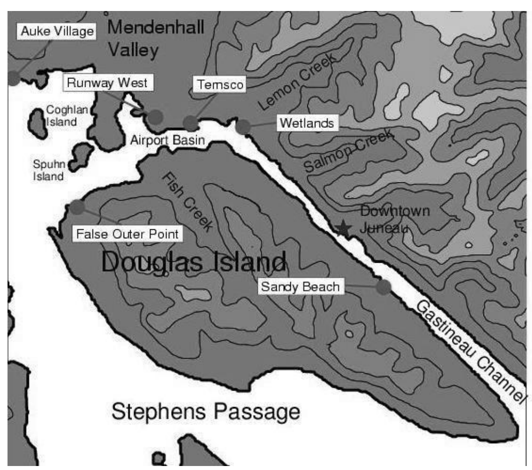

Figure 1: Juneau DOW deployment sites.

3. AIRCRAFT DATA

In situ turbulence measurements were acquired by the University of Wyoming King Air research aircraft. EDR estimates (defined as the cubed root of the eddy dissipation rate) were calculated on the basis of the along-track, cross-track and vertical wind measurements. These estimates will be referred to as the U-, V- and W-components of turbulence, and their calculation is described in Gilbert et al. (2004). Theoretically, in the case of fully developed isotropic turbulence, these components would be expected to have similar values. In reality, large differences are not uncommon.

The final data product is a one-second time series, which also represents a spatial series as the aircraft progresses along the flight track.

On the basis of previous field research, regions called "hazard boxes" were identified that corresponded to areas in which elevated levels of turbulence were likely to be observed. For each crossing of the research aircraft through a hazard box, the median, 75% and 90% EDR values are determined from aircraft time series data within the box. This determination is performed for each of the three directional EDR components. In this manner, aircraft data for each hazard box crossing is reduced to a set of nine numbers. These numbers are compared with turbulence estimates derived on the basis of DOW measurements within the hazard area near the time of aircraft crossing.

Only the airport basin hazard boxes (Lemon Creek, North Douglas Island, Outer Point, and Coghlan Island) were used in the final analysis. The Gastineau Channel hazard boxes generally had low levels of turbulence during the wet weather patterns necessary for high-quality DOW data. Moreover, a statistically significant number of coincident data cases (with high-quality DOW data) were acquired only at the Runway West and Temsco Heliport DOW deployment sites.

4. DOW DATA PROCESSING

Many DOW scans were rejected outright on the basis of qualitative visual inspections of the data. Excessive noise, usually a consequence of insufficient precipitation, precludes reliable comparisons with aircraft data. Some scans were also rejected because they were corrupted by mechanical malfunctions. Specifically, many scans were degraded by instabilities in the elevation controller of the radar antenna. This problem was insidious in that it was not promptly detected due to the subtle nature of the errors.

For each radar scan utilized in this analysis, a confidence field was generated using a combination of reflectivity and normalized coherent power. This combination is necessary because reflectivity is an optimal indicator of terrain interference and normalized coherent power is an optimal indicator of insufficient atmospheric scattering associated with patches of very light or no precipitation.

We examined a number of potential DOW-based turbulence parameterizations based on dimensional analysis. One conventional measure of turbulence is the cubed root of the eddy dissipation rate, $\varepsilon^{1/3}$, which has dimensions $m^{2/3}/s$. DOW-based input parameters considered in this study are second moment (m^2/s^2), spatial velocity variance (m^2/s^2), windshear (1/s), and transverse and longitudinal radial velocity structure functions (m^2/s^2). Of these quantities, only second moment is a basic DOW data product (spectral width squared), the remainder are generated via processing of the radial velocity and/or the spectral width.

In some cases, it is necessary to introduce a length scale to satisfy dimensional analysis constraints. Candidates include the turbulence integral scale, radar pulse length, and radar pulse width. An additional length scale parameter is the *f* coefficient derived from the Kolmogorov turbulence energy spectrum, which has dimensions $m^{-1/3}$.

All turbulence calculations begin with a confidence field generated on the basis of reflectivity and normalized coherent power. Radial velocity and second moment are smoothed using a confidence-weighted 3x3 (3 beams by 3 ranges) median filter. A best-fit linear wind field is determined from the confidence-weighted median-filtered radial velocity field by applying a singular value decomposition method to each point and fitting a 13x11 surface of data values. The non-linear residual velocity is determined by subtracting the best-fit linear wind field from the median-filtered radial velocity. Results are not particularly sensitive to the exact smoothing used.

The longitudinal structure function is equivalent to the square of the radial velocity difference between adjacent data points along the same beam. The transverse structure function is equivalent to the square of the velocity difference between adjacent data points along a fixed range. Noise effects on the structure functions are minimized by application of a confidence-weighted median filter to the final product. Finally, windshear values are estimated from a combination of structure function and radial and transverse slopes determined by the best-fit linear windfield.

$$S^2 = W_r^2(r,\varphi) + W_\varphi^2(r,\varphi)/r^2 + D_r(r,\varphi)/(\Delta r)^2 + D_\varphi(r,\varphi)/(r\Delta\varphi)^2 \quad \text{Eq. 1}$$

where S = windshear, W_r = radial slope of best-fit linear windfield, W_φ = transverse slope of best-fit linear windfield, D_r = radial structure function, D_φ = radial structure function, Δr range gate spacing, and Δφ = azimuthal beam spacing.

Quantities derived on the basis of dimensional analysis are assumed to be scaled by an unknown dimensionless quantity (e.g., 2, π, or 10). Six algorithms were derived

1. $\varepsilon^{1/3}(r,\varphi) = f_{KL}(r)\sqrt{M_2(r,\varphi)}$
2. $\varepsilon^{1/3}(r,\varphi) = [M_2(r,\varphi)\,S(r,\varphi)]^{1/3}$
3. $\varepsilon^{1/3}(r,\varphi) = \upsilon_r(r,\varphi)/L^3$
4. $\varepsilon^{1/3}(r,\varphi) = [\upsilon_r^2(r,\varphi)\,S(r,\varphi)]^{1/3}$
5. $\varepsilon^{1/3}(r,\varphi) = D_r(r,\varphi)/(\Delta r)^{1/3}$
6. $\varepsilon^{1/3}(r,\varphi) = D_\varphi(r,\varphi)/(r\Delta\varphi)^{1/3}$

where r = range, φ = azimuth, f_{KL} = Kolmogorov energy spectrum coefficient, M_2 = second moment, L = turbulence integral scale, υ_r = velocity variance, and the remainder are defined above.

Processed DOW EDR fields within a hazard box are reduced to a single indicator of turbulence. This is similar to the manner in which each research aircraft pass through a hazard box is reduced to a single indicator of turbulence. For each aircraft hazard box crossing, a DOW PPI radar scan was selected on the basis of proximity in time and an elevation angle that corresponded to the average location of the aircraft passing through the hazard box when viewed from the DOW observation site. From this scan, data corresponding to the hazard box region is extracted and processed as described above.

Each extracted and processed data set was reduced to a confidence-weighted median, 75% and 90% value for each of the six EDR algorithms described above. This resulted in 18 representations of DOW-based EDR estimates for each aircraft hazard box crossing.

5. STATISTICAL ANAYLSYS

For each crossing of a hazard box by the research aircraft, 18 DOW-based representations of turbulence were derived (3 percentile filters for each of 6 algorithms) and 9 aircraft-based representations of turbulence were obtained (3 percentile filters for each of 3 directional components). This produced 162 combinations of DOW and aircraft data.

For each potential combination of DOW-aircraft data, a simple linear regression with two degrees of freedom, allowing both slope and intercept to vary, was performed.

Sixty-five aircraft hazard box passes were associated with DOW data of high quality. Results based on this entire set were unremarkable. The greatest correlation coefficient for any of the 162 potential data combinations was 0.40, corresponding to an R^2 of 0.16. This result corresponded to the combination of 90% DOW EDR algorithm 1 (based on second moment) and the 50% aircraft U-component of turbulence.

One interpretation of this result is that terrain-induced turbulence is anisotropic. Sites at which the DOW scanned directly into the predominant wind direction may have produced different results from sites at which the DOW scanned more or less perpendicular to the predominant wind direction. Also, it may be necessary to segregate the analysis on the basis of aircraft observations from different hazard boxes. In some regions, turbulence may be characterized by smaller scale disturbances and would be more susceptible to detection by algorithms that emphasize second moment. In other regions, turbulence might be characterized by large scale disruptions and would be more discernable on the basis of velocity variance. Also, a directional bias may be exaggerated in DOW turbulence algorithms that incorporate estimates of wind shear. For these, reasons it is useful to consider an independent correlation for each DOW site-hazard box pair.

The most promising results were for a site-box pair that yielded a correlation coefficient of 0.88, corresponding to an R^2 of 0.78. In this case, the

DOW deployment site was at the western end of the airport runway and the hazard box included the northernmost portion of Douglas Island (Fig. 1).

This optimal result was for the combination of 75% DOW EDR algorithm 3 (based on velocity variance) and the 50% aircraft W-component of turbulence. When this same DOW data set is compared to the aircraft median values for the U- and V-components of turbulence, the corresponding R^2 values are 0.72 and 0.61, respectively. In addition, two other DOW-aircraft data combinations had R^2 values in excess of 0.70 for this site-box pair.

An R^2 of 0.78 is quite remarkable for a comparison of this nature. In comparisons of atmospheric measurements made by two distinct instruments, such as aircraft and radar measurements of wind speed, a correlation of this magnitude would be accepted as confirmation that both sensors are operating properly.

Two additional DOW deployment site-aircraft hazard box combinations yielded relatively high R^2 values for DOW-aircraft correlations.

6. CONCLUSIONS AND FUTURE WORK

DOW radar observations of atmospheric turbulence demonstrate potential as aircraft supplements or surrogates for "truth" regressions of wind-related aviation hazards. The manifestation of this potential into a practical application, however, requires more analysis. Significant differences were observed in the regression analyses as a function of DOW site-aircraft hazard box pairs. It is necessary to understand the nature of these differences if the parameterizations between aircraft and radar data are to be applied in generalized and reliable manner.

A radar capable of greater sensitivity in conditions of minimal precipitation and more rapid scanning would greatly improve future efforts to investigate this problem.

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