Comparison of Wind Profiler and Aircraft Wind Measurements at Chebogue Point, Nova Scotia

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ABSTRACT

In August 1993, a 915-MHz boundary layer wind-profiling radar was deployed at Chebogue Point, Nova Scotia, to provide wind, turbulence, and boundary layer structure information for the North Atlantic Regional Experiment summer 1993 intensive campaign. The National Research Council Canada Twin Otter atmospheric research aircraft was also part of that campaign. During the campaign, the Twin Otter flew 29 soundings over Chebogue Point. This paper describes a comparison of the wind speed and direction measured by the profiler and the aircraft. In the height range 300–2000 m above sea level, the random difference between the wind speed measurements is 0.9 m s^{-1}, and the random difference between the wind direction measurements is 9°. There is a small systematic difference in the wind speeds (0.14 m s^{-1}) that is probably due to uncertainty in the zenith angles of the radar beams and extremely good agreement (within 0.5°) in the wind direction. The Kalman filter–smoother technique used to remove drifts in the inertial navigation system is shown to be important in achieving these favorable results.

1. Introduction

As part of the North Atlantic Regional Experiment (NARE) summer 1993 intensive campaign, a 915-MHz boundary layer wind-profiling radar was deployed at Chebogue Point (near Yarmouth), Nova Scotia, Canada. The profiler, which ran from 3 August through 1 September, was intended to provide information about the winds, turbulence, and boundary layer structure to help interpret the atmospheric chemistry measurements taken at surface sites and on several aircraft. One of those aircraft, the National Research Council Canada (NRCC) Twin Otter, was based in Yarmouth and flew over Chebogue Point most days of August. A total of 29 soundings were made by the Twin Otter over Chebogue Point. Most of the soundings were flown in a shuttle climb or descent pattern (alternating 1-min straight legs with 180° turns).

In this paper, we present a comprehensive comparison of the winds measured by a wind profiler and an aircraft. We present results for aircraft data both corrected and uncorrected for drifts in the aircraft inertial reference system. Winds measured by profilers have previously been compared with rawinsondes (see, for example, Martner et al. 1993; Strauch et al. 1987; references therein). Measurements from several aircraft have been compared by, for example, MacPherson et al. (1992).

Chebogue Point is the south end of a peninsula running roughly north–south along the west coast of Nova Scotia, about 10 km south of Yarmouth. The peninsula is less than 1 km wide, having the Atlantic Ocean on the west and south, and the tidal flats of the Chebogue River on the east. Wind speeds and directions varied widely during the intensive period, with weather conditions varying from fog and mist to clear skies.

The 915-MHz boundary layer wind profiler was developed at the NOAA Aeronomy Lab (Carter et al. 1994; Ecklund et al. 1988). These transportable systems have been deployed at a large number of meteorological and chemical campaigns, as well as in long-term studies in the Tropics. Table 1 gives some of the parameters of the profiler as used in this experiment. The five beams were in two coplanar pairs and one vertical beam.

2. Data processing

Profiler data often contain contamination from ground clutter, birds, aircraft, and poor signal return. Signal processing techniques known as "data cleaning" must be used to remove the contaminated data. The first step in processing the Chebogue Point profiler data

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TABLE 1. Wind profiler operating parameters.

Frequency	915 MHz
Peak power	500 W
Antenna	Microstrip phased array, 1.9 m × 1.9 m
Beamwidth	9°
Beam positions	5
Minimum height to center of range gate	146 m
Pulse length	60 m
Range-gate spacing	60 m
Number of range gates	48
Beam angle from zenith (oblique beams)	21°
Sample time per beam	30 s

was to apply the statistical cleaning technique developed for the boundary layer by Angevine et al. (1993). In this technique, all the available moments of the profiler data are used, and data falling outside (in this case) $\pm 3\sigma$ in velocity, $\pm 2\sigma$ in spectral width, or $\pm 2\sigma$ in signal-to-noise ratio (SNR), where σ is the standard deviation over the (0.5-h) period, were rejected.

Ground clutter was a particular problem at the Chebogue Point site, which has a number of radio towers as well as the usual power lines to cause ground-clutter contamination. The lowest three range gates (146–326 m) were strongly affected by this clutter. In this system, ground clutter biases the measured velocities toward zero. A five-beam configuration provides redundancy in that there are three estimates available for each horizontal wind component—one from each beam of a pair, and one from the average of the pair. In the Chebogue Point data, the south-facing beam had the worst clutter, therefore it was not used. The east–west wind component was determined from both beams in that plane. The vertical beam was also not used since no rain was present during the periods considered. The wind measurements reported below, then, are from the north, east, and west beams.

In order to further reduce the effects of clutter, and to eliminate contamination from the aircraft as well, the profiler data were processed by consensus averaging. The consensus technique operates on a group of data, in this case a 0.5-h sequence, and looks for the largest group of data that fit within a given window. If the largest group contains at least a given threshold fraction of the total number of data, the group is then averaged to produce the result. If no group meets the threshold criterion, no result is produced. For the intercomparison, a window width of 1.2 m s^{-1} and a threshold of 50% (approximately six samples) were used. The consensus technique is useful for removing the effects of intermittent contamination that differs by more than the expected variation in velocity from the true result. It must be used with care, however, since if contaminated data are more common than uncontaminated data, the result will reflect only the contamination. Consensus averaging may also produce the background rather than the true mean result in cases where the true winds are intermittent (have a bimodal or skewed distribution), such as vertical winds in convection.

After cleaning, the nearest half-hour average to each sounding time was chosen for the comparison. Finally, a -12-dB average SNR threshold was used to remove data at heights where poor reflectivity made the data unreliable. All profiler results presented here use the data remaining after all of these processing steps, which we refer to as the "good" data.

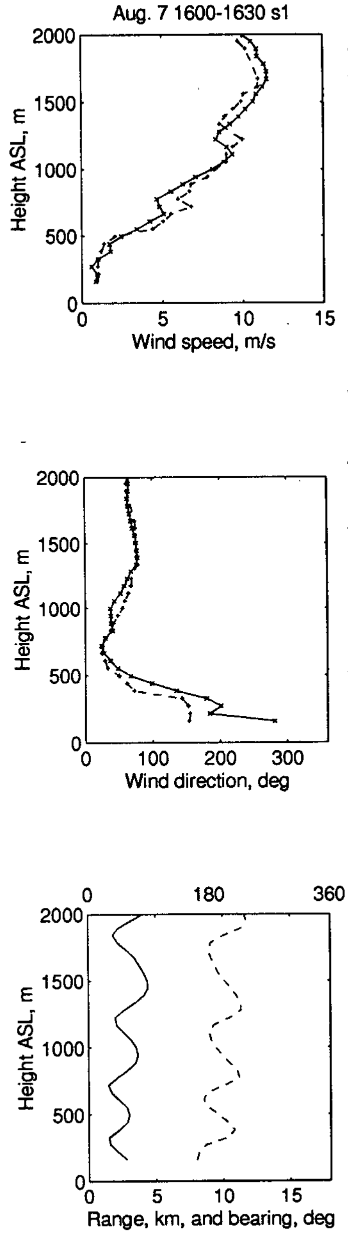

FIG. 1. Wind speed and direction measured by the aircraft (solid with "×") and profiler (dashed with "+"), and aircraft range (solid) and bearing (dashed) from profiler site for the first sounding on 7 August.

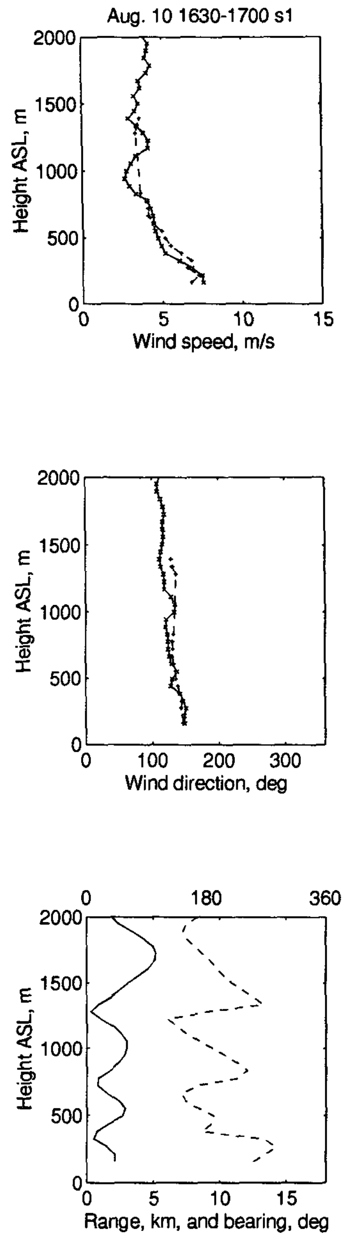

FIG. 2. Same as Fig. 1 but for sounding on 10 August.

The NRC Twin Otter uses a nose-mounted gust boom and a Litton 90–100 Inertial Reference System (IRS) to measure the three orthogonal components of atmospheric motion and the resultant wind speed and direction over a frequency range of 0–5 Hz (MacPherson 1990). A Kalman filter–smoother integrated navigation algorithm has been developed for postflight analysis to improve the accuracy of the velocity, attitude, and heading data available from the IRS and was used in the wind computations (Leach and MacPherson 1991, 1993). Two additional navaids, a Loran C receiver and a three-axis Doppler radar, provide redundant navigational information that is incorporated by this algorithm. The Twin Otter data for all 29 soundings were processed with this algorithm to remove the drift from the inertial navigation data. The Kalman-filtered data are referred to as "corrected" in this paper. The data for nine soundings were also processed without this correction for comparison and are referred to as "uncorrected" data. In order to compare to the 60-m height resolution of the profiler, the aircraft data were averaged over 60-m height bins. The averages over 60 m contain varying numbers of points, depending on the rate of climb or descent of the aircraft.

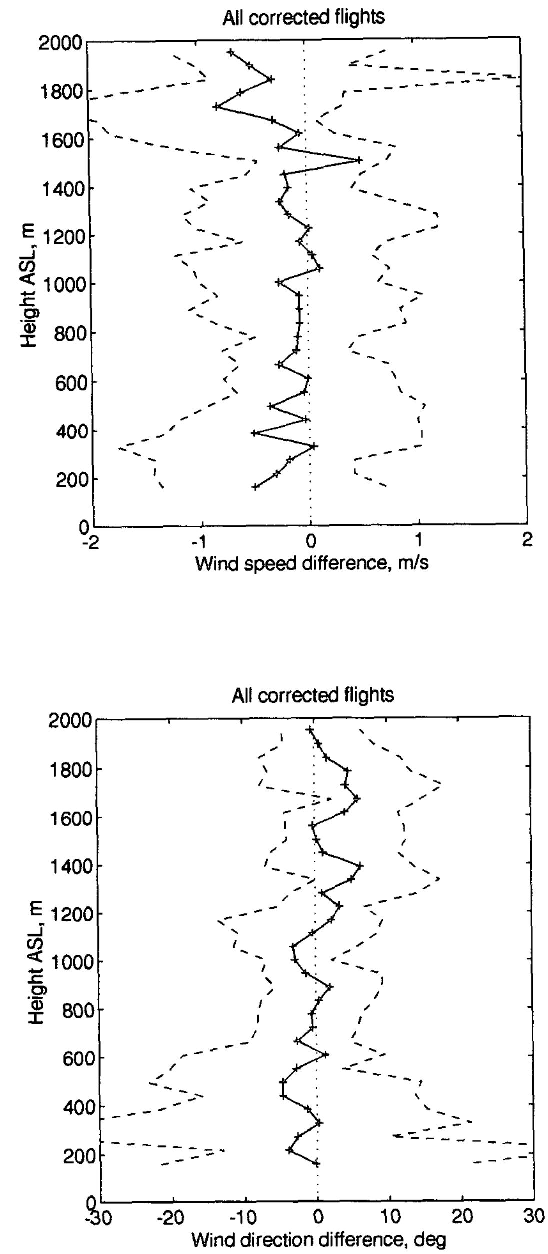

FIG. 3. Wind speed and direction difference median (solid) and 17th and 83d percentiles (dashed) for all 29 corrected flights.

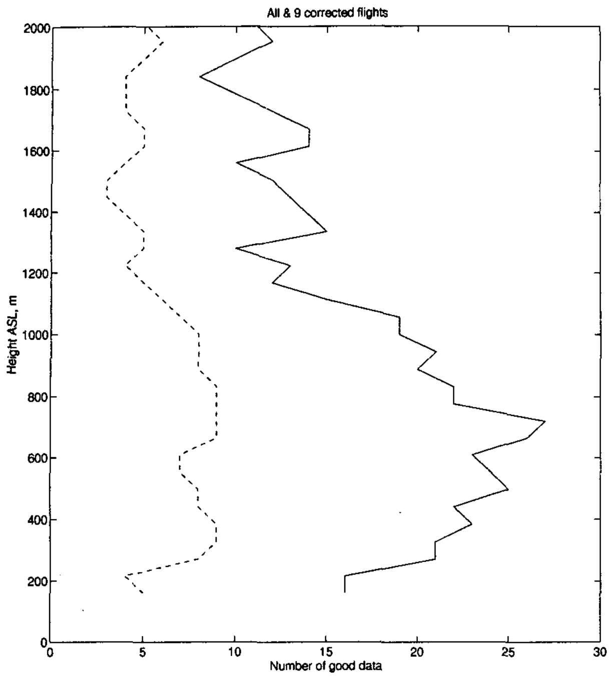

FIG. 4. Number of good profiler data versus height for all 29 flights (solid) and for the nine flights with uncorrected data (dashed).

3. Results

Figures 1 and 2 show example soundings. In each figure, the wind speed and direction and range and bearing of the Twin Otter from the profiler site are shown. Figure 1 is for 7 August. Good agreement is seen in the wind speeds and directions. The aircraft did not pass as close to Chebogue Point as usual, flying over the ocean south of the site. Figure 2 is for 10 August. The wind speed maximum at low levels (100–200 m MSL) seen here was a recurring feature: 19 of the 29 soundings have a maximum below 500 m. The profiler coverage is limited in this case. No good profiler data are present between 800 and 1300 m MSL because of poor reflectivity due to a stable layer, nor are any good data present above 1400 m MSL. The flight track shown in Fig. 2 is more ideal, staying closer to the profiler site.

Figure 3 shows the median difference in wind speed and direction between the profiler and the Twin Otter for all 29 soundings using corrected data. The sign of the differences is profiler-minus-aircraft. The 17th and 83d percentiles are also shown. The percentiles are chosen to contain the same proportion of the data (67%) as would be contained within plus or minus one standard deviation if the distribution were normal. The median and percentiles are more robust than the mean and standard deviation in the presence of outliers. The median difference is quite small in the middle heights. The profiler speed is biased low in the lowest three heights, probably due to ground clutter, and the random difference (percentile spread) is larger there as well. The random difference increases at the higher heights as the number of good points in the sample

TABLE 2. Median and mean speed and direction differences, percentile spreads [0.5(83d − 17th percentile)], and standard deviations for two height ranges and three groups of soundings.

		All corrected	Nine corrected	Uncorrected
Speed difference (m s^{-1})	Median	−0.14	−0.23	−0.47
heights 4–33	Mean	−0.16	−0.36	−0.68
Speed difference (m s^{-1})	Median	−0.08	−0.16	−0.34
heights 4–25	Mean	−0.08	−0.14	−0.38
Direction difference (°)	Median	0.37	1.6	−2.9
heights 4–33	Mean	0.72	2.0	−2.1
Direction difference (°)	Median	−0.12	1.0	−4.4
heights 4–25	Mean	−0.65	0.56	−3.5
Speed random difference (m s^{-1})	Percentile spread	0.93	0.84	1.0
heights 4–33	Std dev	1.05	0.87	1.2
Speed random difference (m s^{-1})	Percentile spread	0.86	0.88	1.0
heights 4–25	Std dev	0.98	0.86	1.1
Direction random difference (°)	Percentile spread	8.6	9.5	10
heights 4–33	Std dev	16	16	15
Direction random difference (°)	Percentile spread	8.7	9.5	11
heights 4–25	Std dev	17	19	17
Number of points heights 4–33		508	187	187
Number of points heights 4–25		418	150	150

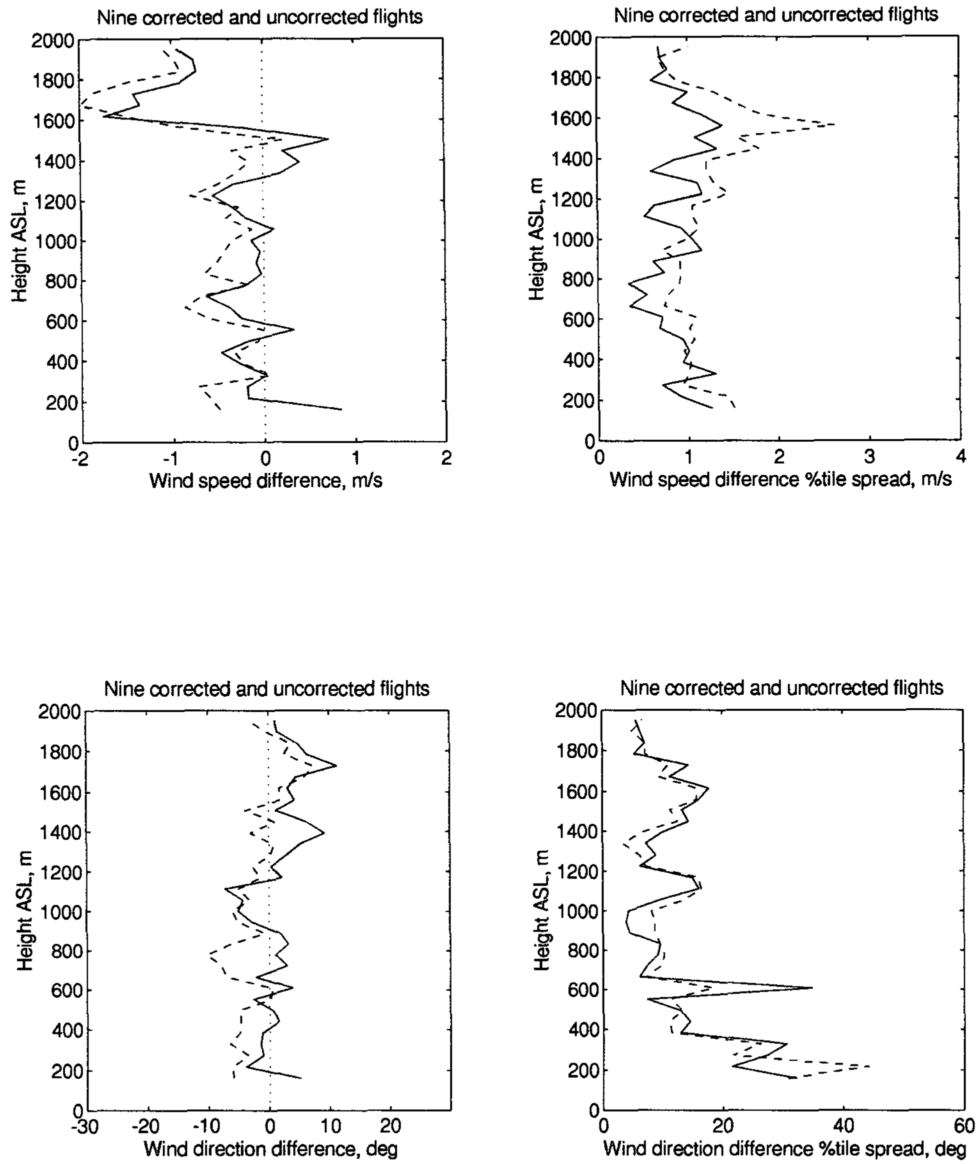

FIG. 5. Comparison of corrected (solid) and uncorrected (dashed) results for nine flights. Wind speed and direction difference median and percentile spread [0.5(83d − 17th percentile)] are shown.

decreases (Fig. 4). The direction difference shows no significant bias and a small random difference except at the lowest heights.

Table 2 gives the median and mean differences, percentile spreads, and standard deviations over two height ranges for three sets of flights: 1) all corrected (Fig. 3), 2) nine corrected flights for which uncorrected data was also produced, and 3) those same nine flights uncorrected. The height ranges exclude the lowest three heights where ground clutter remained a problem despite the data cleaning. The small bias in the speed (about 0.1 m s^{-1}) is quite sensitive to the zenith angle assumed in processing the profiler data. The observed bias is equivalent to less than 0.5° difference in zenith angle, which is itself small compared with the 9° beamwidth. The bias is quite small compared to the random difference, expressed as one-half the difference between the 83d and 17th percentiles of the sample. The random speed difference is about 0.9 m s^{-1}. The direction difference shows effectively no bias (less than 1°) and a random difference of about 9°.

To evaluate the effect of the Kalman filter, we compared corrected and uncorrected data from nine soundings. The differences between the aircraft and profiler winds for these cases are shown in Fig. 5. The median and random speed and direction differences are all worse for the uncorrected cases. The median results over the height ranges are shown in Table 2.

4. Conclusions

This comparison of a large number of soundings has shown very good agreement between the wind profiler and Twin Otter measurements of wind speed and direction. The results are somewhat better than those found in comparisons of profilers to rawinsondes. Martner et al. (1993) found a bias of 0.21–0.99 m s^{-1} and a random difference (standard deviation) of 3 m s^{-1} for each of the horizontal wind components of a 915-MHz profiler. In an attempt to characterize the measurement errors of the profiler itself, Strauch et al. (1987) found a standard deviation of about 1.3 m s^{-1} for a 405-MHz profiler. A comparison of wind measurements from three aircraft (MacPherson et al. 1992) found an accuracy of 1 m s^{-1}.

From the intercomparison results presented here, we conclude that any bias in either the profiler or the Twin Otter wind measurement is less than 0.1 m s^{-1} and that the random error in either system is less than 1 m s^{-1}. These conclusions are only valid for carefully processed profiler data.

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