RESEARCH ARTICLE

Tornado identification and forewarning with very high frequency windprofiler radars

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The ability of very high frequency (VHF) (~50 MHz) windprofilers to measure backscatter, winds and turbulence in the troposphere and the lower stratosphere gives them a unique perspective not available with many other remote sounding radar techniques. This capability has been utilized to study the environment of 31 tornadoes generated in the provinces of Ontario and Quebec in Canada over an 11-year period. Tornadoes were mostly of Enhanced Fujita (EF) types EF0 to EF2, with one being EF3. Focus is on events which produced visible damage. Signals detected show characteristics demonstrating new informative—and potentially predictive—capabilities. A large enhancement in backscattered power immediately above the common volume of the radar and the tornadic supercell, reaching to the tropopause and beyond, when coupled with radar measurements of strong turbulence and wind speeds, provides good radar evidence of tornadic activity.

KEYWORDS
forewarning, humidity, radar, scattering, tornado, tropopause, turbulence, windprofiler

1 | INTRODUCTION

A network of very high frequency (VHF) windprofiler radars (e.g., Hocking, Rötting, Palmer, Sato, & Chilson, 2016), referred to as the O-QNet (Ontario–Quebec Network), was developed in Canada over the period 2004–2016 with the primary intent being to measure winds through the upper atmospheric boundary layer, troposphere and into the lower stratosphere (e.g., Taylor et al., 2016). A map of the radar locations is shown in Figure 1.

Our purpose here is to identify characteristics in the radar signals that correlate with visually observed tornado touchdowns in the radar vicinity.

1.1 | Radars and radar-scattering

Windprofilers cannot probe the tornadoes directly. Rather, they provide details of the environment surrounding tornadic events, from 500 m altitude and up into the stratosphere, especially in conditions of strong turbulence and relatively high humidity. It is this ability to monitor the environment that we will capitalize on.

Our radars use vertical and off-vertical beams to deduce powers, Doppler shifts and spectral variance of scattering targets, which are then used to determine back-scattered powers, wind components and turbulence strengths from 0.5 to ~12–14 km altitude in all weather conditions (including clear-air and severe weather) on a minute-by-minute basis. The tropopause height can also often be measured with the radars (Hocking et al., 2007). All radars use five fixed beams: one vertical and four at typically 10.9° off-vertical in four perpendicular azimuthal directions. The radar configuration cycles between the five beams over a typically 5-min period. Because of the possibility of range-aliased signal being received through sidelobes during a large storm, the radar was also operated in two different modes with pulse...
repetition frequencies (PRFs) of 5500 and 6000 Hz, allowing identification of range-aliased side-lobe contamination, since such range-aliased contamination should cause low elevation scatterers at large range to appear at different ranges in the two modes (Hocking et al., 2016).

With regard to scattering mechanisms, it is important to know that the received power is proportional to the Potential Refractive Index Structure function constant of the atmosphere, denoted $C_n^2$, which is proportional to $\varepsilon^{2/3}M_n^2\omega_B^{-2}$ (Hocking et al., 2016, Equation (7.84)), $\varepsilon$ being the kinetic energy dissipation rate and $\omega_B$ the Brunt–Vaisala frequency. The quantity $M_n$ satisfies (Hocking et al., 2016, Equation (3.288); Tsuda, Miyamoto, & Furumoto, 2001)

$$M_n = -77.6 \times 10^{-6} \frac{p}{T^2} \left[ 1 + 15\frac{500}{T}q_w \right] \left[ \frac{dT}{dz} + \Gamma_a - \frac{7800}{1 + 15\frac{500}{T}q_w} \frac{dq_w}{dz} \right]$$

$p$ being the atmospheric pressure in millibars (hPa), $T$ the absolute temperature (K), and $\Gamma_a$ the adiabatic lapse rate. The specific humidity is given by $q_w = e_w/(1.62p) \approx 0.62e_w/p$, $e_w$ being the water vapour pressure. $|M_n|$ is large when $q_w$ and the humidity gradient term $dq_w/dz$ are large (e.g. Tsuda et al., 2001), so will be dominant in the humid, turbulent air of storms that may produce tornados. Large-scale eddy motions may also alter $dT/dz$ and the existence of hydrometeors may even alter $\Gamma_a$, both potentially further enhancing $M_n$ (also see Appendix S2, Supporting information).

1.2 | Tornado data base

In regard to tornado records, a data-base of tornado touchdowns provided at https://en.wikipedia.org/wiki/List_of_21st-century_Canadian_tornadoes_and_tornado_outbreaks has been used to determine touchdown times and locations. ECCC (Environment and Climate Change Canada) has confirmed the validity of the observational data and provided information on two additional tornadoes (D. Sills, personal communication). For convenience, a concise table of events is shown in Appendix S3. Times were not always given, but we concentrate on days with only one or two touchdowns in order to make tornado-radar correlations. Some severe events were reported in local newspapers, offering more precise timing information, while weaker ones can be timed to accuracies of ±2 h.

During the time of our study, 148 tornadoes were reported in Ontario and Quebec. Our radars cover about 12% of the area of the two provinces, with the bulk of the radars being in the southern (most heavily populated) areas. Prior to 2007, only two radars were established, resulting in low detection capability in that period. The network was built up progressively and was completed in 2014, gradually enhancing the network detection capability as new radars were commissioned.

2 | POWER SIGNATURES

A variety of signatures measured by the radar will be presented. The first important behaviour is illustrated in Figure 2, which shows a contour-plot of hourly averaged power as a function of height and time recorded by the McGill radar during a confirmed tornado touchdown at Ste. Lazare, QC (20 km from the radar) on July 17, 2010. The key aspect is a region with an ~20 db increase in radar backscattered power evident at 1800 UTC on July 17, above 7 km. Other noticeable events include red blobs at 12 km altitude, which were due in part to bursts of localized turbulence and in some cases aircraft reflections. Our software removes most aircraft signatures, but occasionally some sneak in. Another noteworthy feature is the signal drop-off of 20 dB from 5 to 7 km outside the peak at 1800 UTC; this is normal.

As with all radars, caution is needed in interpretation: noise and sidelobe contamination can be a concern. An increase in power like that at 1800 UTC could be due to lightning interference or man-made radio-bursts, but interference should have no noticeable height structure (since such interference will not be synchronized to the transmitter pulses), and varies typically by less than 5 dB across the height of observations. An example of noise (taken from a radar at Resolute Bay in the arctic, where interference is more common) is shown on the right; the heights are
65–92 km in this case, but the structure of noise is statistically height-independent. The structures in the two figures clearly differ in form, indicating that the data on the left are true radar reflections. The radar software is also coded to remove any rapid spikes in power on time scales of less than 0.02 s, so impulsive noise (including lightning) is removed. Sidelobe echoes are not an issue due to our use of two PRFs as discussed in Section 1.1.

Therefore the peak at 1800 UTC is geophysically real. Studies of other tornadoes show similar structures on nearby radars, an issue we will now pursue. The radar is detecting strong scatter from overhead during the most active phase of the storm in which the tornado is embedded, as discussed regarding Equation (1). The column of enhanced backscattered power extends to about 13 km in height (above the tropopause), with weaker power evident above. We will concentrate on the stronger signal below 13 km.

These events are similar in structure to events termed “overshooting cloud tops” (OT) or “overshoot deep convection” (ODC) which can be detected by satellite and polarimetric radar methods (e.g., Bedka, 2011; also see Appendix S2.2). However we will avoid direct linkage to these processes, and use the term PdO (profiler-detected overshoot) to describe events like Figure 2, where columns of enhanced scatter rise out of the background and reach high into the troposphere and even into the stratosphere. A PdO simply requires that the column exists on all 5 beams, extends to at least 3 km above the level where the signal normally drops rapidly with height in non-PdO conditions (in Figure 2, this is ~6–7 km), and maintains powers within the upper column which are comparable to (to within ~10 dB) power-levels normally seen below 6–7 km.

We discuss the relation of these signals to OT and related phenomena in Appendix S2.2; while a link is expected, no such assumption is made in our subsequent analysis.

3 | METHODS AND ANALYSIS

3.1 | Profiler-detected overshoot

Radar data from 2006 to 2016 were initially examined for PdO signatures occurring near-simultaneously with tornadoes listed in the visual database. A PdO on all five beams of a radar was seen on almost all occasions when the radar was less than 100 km from any selected tornado. A tornado more distant than 100 km from any radar registered a PdO on the radar only once, and that was for a tornado 120 km away from the Markstay radar. All subsequent discussions will consider detections less than 120 km from the radar. However, additional criteria needed to be met before a tornado could be assured, as will be discussed shortly.

The process described in the last paragraph identified 31 distinct tornadoes having coincident PdO’s on one or more radars, all of which were subsequently studied further. Another 26 tornadoes went undetected by radar because the nearest radars were not operational at the time, either because they were off for maintenance/repairs or, in several cases, because the tornado damaged power lines, terminating electrical supply.

Events showing storm-caused power outages are nonetheless useful; an example is shown in Figure 3. It shows that the strongest backscattered signals occurred as electrical power to the radar was lost, confirming that the peak power corresponds with the most severe part of the storm, and most likely time for tornado formation. In this case the times of tornado occurrences were known; four tornadoes in the area around Harrow to Leamington were reported (https://en.wikipedia.org/wiki/Tornado_outbreak_of_June_5-6,_2010). All occurred between 0655 and 0715 UTC; the radar signal peaked and then cut out due to power-line damage at 0657 UTC. The radar signal began building up at least 30 min prior to the tornado touchdown(s), and would be evident to an observer 10–20 min before the storm peak, giving predictive capability. The white arrow on the NE beam panel indicates humid air spreading into the tropopause due to the stable stratospheric air above slowing vertical ascent; this is evident on all off-vertical beams. Occurrence of another similar power cut-out is shown in Figure S4.1 of Appendix S4.

This evidence that the humid air is being drawn into the tropopause also serves to further indicate that the radar is truly seeing structures in the main beam of the radar, and not suffering range-aliased sidelobe contamination.

The occurrence of a PdO whenever a tornado is seen locally is of interest, but does every occurrence of PdO produce a tornado?
PdO's are relatively rare (0.07% occurrence), but not all occur in association with tornadoes. Visual observations of power contours over one full summer show that approximately 25% (\(\frac{1}{4}C6\)) of such signatures are associated with tornadoes in summer. They may also occur in winter, generally without tornadoes. As a point of comparison (but without inferring that PdO's are OT's), we note that percentages of OT containing simultaneous tornado detections vary between 14% in Europe up to 63% for the south-central plains of the United States (cf Appendix S2.2).

An example of a 1-month power-height-time plot is shown in Figure 4 as supporting evidence of their relative rarity. In this particular case the only PdO events evident both had associated tornadoes, but (as noted) in other periods such uniqueness was not always evident.

Thus the detection of PdO alone is useful, but insufficient to firmly indicated tornado development. We therefore turn to additional parameters which may help to pinpoint tornado events.

3.2 Winds and turbulence

Our radars measure winds, and are some of the very few instruments worldwide which can reliably measure turbulence strengths, using the most sophisticated available procedures for such determinations (e.g., Dehghan et al., 2014, and references there-in). Representative examples of each are seen in Figure 5.

Figure 5a shows horizontal wind speeds and directions for a typical event. Measurements are shown into the stratosphere (and in this case the polar jet-stream). Winds in excess of 30 m/s in the jet-stream, as here, occurred during all of our tornado events. The wind plots did vary in form from case to case. In some cases, strong winds appeared to descend from the stratosphere toward the ground, and in others strong wave-like oscillations were evident (e.g., Figure S4.4 in Appendix S4). However, wind speeds in the lowest 2 km in excess of 20 m/s were common to all tornado occurrences.

In non-storm conditions, the median for the energy dissipation rate (\(\varepsilon\)) is around \(2 \times 10^{-4}\) W/kg (Dehghan & Hocking, 2011); a sample plot during a week of non-storm conditions is shown in Figure S4.3 of Appendix S4. “Normal” values are represented by purple and dark blue colours in Figures 5b and S4.3, so conditions in that storm exceed standard turbulence strengths by \(\sim 5-10\times\). It should also be emphasized that these values are direct measurements of turbulence strengths, whereas the power measurements in Figures 2 and 3 were measurements of refractivity variability due to turbulence, which depends on both the strength of turbulence and \(M_n\) (Equation (1)). \(\varepsilon^{2/3}\) increases about 3–5\(\times\), so according to Equation (1) and the associated discussion, the backscattered power due to enhanced turbulence alone should only increase by \(\sim 3-5\times\). This confirms the need for simultaneous and significant increases in \(M_n\) of \(\sim 20-30\times\) in order to account for the almost 20 dB increase in radar signals. Often the zones of turbulence descend from above, and providing PdO has been detected and winds exceed 20 m/s, tornadoes will be seen when turbulence with dissipation rates exceeding \(\varepsilon = 2 \times 10^{-3}\) W/kg reaches the ground.
CRITERIA FOR TORNADO SELECTION

Based on the previous discussions, we have determined that the following criteria are necessary (and largely sufficient) for tornado verification: (a) existence on all five beams of a PdO, as defined earlier (Section 2, paragraph 4), (b) hourly averaged wind speeds in the lower 2 km of the atmosphere of >20 m/s and (c) turbulence strengths in the lower 2 km of the atmosphere in excess of $2 \times 10^{-3}$ W/kg (also see Appendix S2.3).

In Figure 1, locations of all the tornadoes reported by ECCC which were also detected by the radars using the above criteria are shown. A circle with a radius of 100 km is drawn around each site. Circles are colour coded differently for each radar, and tornadoes reported by ECCC are plotted as bullets on the figure, colour coded to indicate the radar on which they registered. Some events were observed by two radars, especially the closely spaced Negro Creek/Egbert pair. These are indicated in Figure 1 by green filled circles with red dots embedded inside. Two bullets with black dots in the middle are evident for the Egbert radar—these indicate that the Negro Creek radar (which might have also been expected to detect these tornadoes) was not operating on the days that these occurred. Tornadoes roughly between the two radars were registered by both, whereas tornadoes close to one or other of the radars were generally detected only by the nearest neighbouring radar.

DISCUSSION

Our radars delineate the storm which produces the tornadoes, and especially the storm ceiling. In all cases studied, the height of the ceiling of the storm can be seen rising as it moves over the radar, and upon reaching the tropopause, humidity from the storm-region may expand into the tropopause layer (e.g., Figure 3) or even punch through it (Figure 2). Of the 31 tornadoes documented, 6 were identified by two radars (37 total detections). Three tornadoes were reported by ECCC but were not detected on the nearest radar, despite being less than 100 km away. This sets limits on the detectability; we can say that 90% of available tornadoes were detected given the operating schedule of the radars. It is conceivable in those three cases that the lateral boundary of the overshooting air surrounding the tornadoes simply did not reach as far as the nearest radar. The likelihood of the radar signatures occurring with no associated tornado is less than 15%, this limit being set by our inability to associate any public report of tornadoes with 5 radar-detected events in our 11 years of data (although this limit is an upper one, restricted by the fact that some tornadoes may have gone publicly unreported, especially in remote areas).

Therefore based on the criteria in Section 4, we now have a capability for tornado detection with 90% success, and <15% likelihood of a false detection.

The importance of the general need of the overshoot to enter the tropopause region is of interest. It may simply be a measure of the vigour required for a storm to produce tornadoes. But while some theories assume that the tornadoes are purely generated at ground level, the potential role of the cold tropopause and strongly vortical stratosphere in assisting tornado development, deserves further future study. Further discussion can be found in Appendix S5.

CONCLUSIONS

Windprofiler radar signals show distinct characteristics when a tornado (EF0–EF3) occurs within about 100 km of the radar.
The criteria outlined in Section 4 are associated with tornadoes within 100 km of the radar with better than 90% reliability. The probability of a false radar tornado-prediction is less than 15%. The enhanced powers last for about 1–2 hr, giving the possibility of some forewarning by the radar of ~10–20 min.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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