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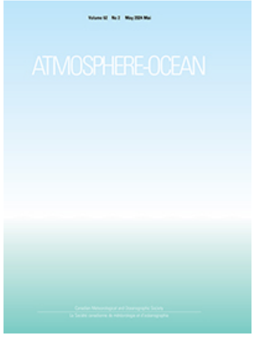

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Assessment of Tornado Alerting Performance for Canada

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ABSTRACT *The Northern Tornadoes Project (NTP) completed a first independent assessment of national tornado warning alerting (watches and warnings) in Canada covering the 2019–2021 period. The NTP undertook this study in the spirit of open data, understanding tornado warning issues unique to this country, and improving tornado warning performance. Utilizing the NTP tornado event database for verification, tornado alerts were reviewed for accuracy and timeliness. For the 250 tornadoes that occurred during the study period – and using a definition of what constitutes a warning 'hit' developed for the study – the standard 2 × 2 contingency table scores were Probability of Detection = 0.23, FAR = 0.78, and CSI = 0.13. Over 70% of tornadoes had no tornado warning, including 35 EF2 tornadoes. The tornado warning results were compared with US National Weather Service tornado warning scores for the US and US states along the southern Canadian border to provide context. NTP also developed a 'report card' aimed at public and media consumption that took into consideration Environment and Climate Change Canada's national performance targets for tornado warning Probability of Detection (POD) and lead time as well as tornado watch issuance. Using weighted scores for these criteria, NTP assigned a total score of 33.3/100, indicating significant room for improvement. A follow-up assessment was conducted for the 2022 tornado season in Canada following the same established procedures. It was found that the number of both tornado watches and tornado warnings had roughly doubled, resulting in a significant increase in the POD for tornado warnings to 0.35. The report card score also improved to a passing grade of 56.6/100. Further exploration of the results showed enhanced performance for tornadoes that occurred within Doppler radar range, when the parent thunderstorm involved supercell processes, and for tornadoes rated EF2 or higher. A number of recommendations are made aimed at further improvements to tornado alerting performance.*

RÉSUMÉ *[Traduit par la redaction] Le Northern Tornadoes Project (NTP) a réalisé une première évaluation indépendante de l'alerte nationale de tornade (veilles et avertissements) au Canada pour la période 2019–2021. Le NTP a entrepris cette étude dans un esprit d'ouverture des données, de compréhension des problèmes d'alerte de tornade propres à ce pays et d'amélioration du rendement des alertes de tornade. En utilisant la base de données des événements de tornade du NTP pour la vérification, les alertes de tornade ont été examinées pour la précision et la rapidité de publication. Pour les 250 tornades qui se sont produites au cours de la période d'étude – et en utilisant une définition de ce qui constitue une alerte « réussie » élaborée pour l'étude – les notes étalonnées du tableau de contingence 2 × 2 étaient Probabilité de détection = 0,23, FAR = 0,78, et CSI = 0,13. Plus de 70% des tornades n'ont pas fait l'objet d'une alerte de tornade, dont 35 tornades de type EF2. Les résultats des alertes de tornade ont été comparés aux résultats des alertes de tornade du NWS pour les États-Unis et les États américains situés le long de la frontière sud du Canada, afin de fournir un contexte. Le NTP a également élaboré une « fiche de rapport » destinée au public et aux médias, qui tient compte des objectifs de rendement nationaux d'Environnement et Changement climatique Canada en matière de probabilité de détection (PDD) et de délai d'alerte de tornade, ainsi que d'émission de veilles de tornades. En utilisant des notes pondérées pour ces critères, le NTP a attribué une note totale de 33,3/100, ce qui indique une marge d'amélioration importante. Une évaluation de suivi a été réalisée pour la saison des tornades 2022 au Canada en suivant les mêmes procédures établies. Il a été constaté que le nombre de veilles et d'avertissements de tornades avait à peu près doublé, ce qui a entraîné une hausse significative de la PDD pour les avertissements de tornade, qui est passé à 0,35. La note de la carte de rapport s'est également améliorée pour atteindre la note de passage de 56,6/100. Un examen plus approfondi des résultats a montré une amélioration du rendement pour les tornades qui se sont produites dans le rayon d'action du radar Doppler, lorsque l'orage parent impliquait des processus supercellulaires, et pour les tornades classées EF2 ou plus. Un certain nombre de recommandations sont formulées en vue d'améliorer encore le rendement des alertes de tornade.*

KEYWORDS Tornado; warning; weather; storms; statistical; verification; Canada

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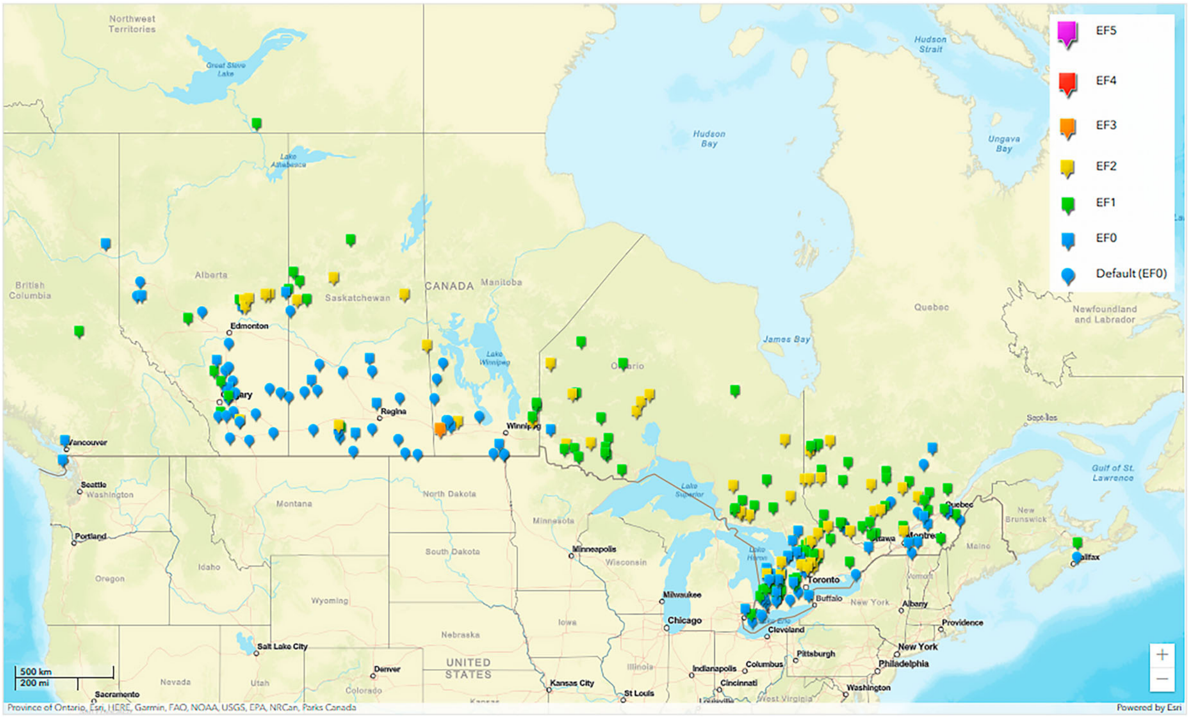

Fig. 1 All 250 tornadoes over land in Canada between 2019 and 2021. Pins colours and shapes indicate EF rating, with legend at upper right.

1 Introduction

Across Canada over the past two decades (2003–2022), severe thunderstorms have caused dozens of injuries and fatalities and were responsible for roughly half of weather-related insured losses (based on data from CatIQ, 2023 and PSC, 2023, the other half was comprised of wildfire, multi-day rain and hurricane events). Environment and Climate Change Canada (ECCC) has the federal mandate for issuing severe weather watches and warnings across the country. To alert Canadians of hazards due to severe convective storms, ECCC issues two sets of alerts: severe thunderstorm watches/warnings (covering winds of 90 kmh^{-1} or higher, hail with diameter of 2 cm or greater, and heavy rain with thresholds that vary by region) and tornado watches/warnings. Though verification statistics for severe thunderstorm warnings have been published by ECCC for certain periods and selected locations (most recently ECCC, 2017), any performance assessments specifically for severe thunderstorm watches, tornado watches and tornado warnings have not been made public.

In the spirit of improving tornado alerting effectiveness for Canadians, the Northern Tornadoes Project (NTP) undertook the first independent assessment of tornado alerting performance in Canada. We used NTP tornado occurrence data and ECCC tornado watches and warnings over the period 2019–2021 to assess tornado watch and warning effectiveness and timeliness. To put the performance assessment results into context, we obtained US National Weather Service (NWS) tornado warning performance data for the states along Canada's southern border. The results, and a summary 'report card' were published in spring of 2022. We then repeated the assessment using NTP tornado and ECCC alert data from the 2022 season to gauge any changes in performance after publication of the initial assessment. Lastly, there are a number of different ways to improve tornado warning performance, and several key recommendations are made.

It should be noted that the tornado warning performance assessment for 2019–2021 was published by the NTP in 2022 and since that time additional tornadoes found from that period have been added to the NTP database. The results presented here are generated using the latest version of the NTP database and are therefore slightly different than the initial results.

2 Data

For tornado occurrence data, we used NTP-confirmed tornadoes over land from 2019 to 2021 (n = 250, Fig. 1). Start times were investigated and obtained for each tornado event. These are the same tornado events that are in ECCC records since NTP confirmations were discussed with ECCC each season to ensure agreement.

For tornado alerts, we used the official ECCC tornado watches (n = 75) and warnings (n = 262) that were the initial tornado watch and/or warning for that region, obtained via NTP partner Instant Weather.

ECCC does issue other warnings and advisories that mention the possibility of a tornado. Severe thunderstorm warnings can contain the phrase, "Remember, severe thunderstorms can produce tornadoes", or list a tornado as a possible hazard. Also, weather advisories for funnel clouds mention the possibility of “a weak landspout tornado”. However, it was found that, in both cases, these ‘tornado tags’ are used far more often than tornadoes actually occur. For example, in 2022, 1660 severe thunderstorm warnings used a tornado tag, which is 43% of all severe thunderstorm warnings issued that year. The number of weather advisories for funnel clouds in 2022 was 15.

3 Methods

To keep the assessment simple, we took a national approach by combining the data from all regions of the country. We then employed the widely used 2×2 contingency table (see Wilks, 2006) to calculate the Probability of Detection (POD), the False Alarm Ratio (FAR) and the Critical Success Index (CSI), as shown in Fig. 2. These parameters tell us the following:

POD – What fraction of tornadoes were correctly tornado-warned? (0 is worst, 1 is best)
FAR – What fraction of tornado-warned events were false alarms? (1 is worst, 0 is best)
CSI – How well did the tornado warnings correspond to confirmed tornadoes? (0 is worst, 1 is best)

We used a somewhat relaxed but realistic definition of a tornado warning success or ‘hit’. This includes tornado warnings issued before the start of the tornado event, the typical definition of a warning hit (no lead time limit was applied). We also included tornado warnings issued at any point during the lifetime of the tornado. Lastly, we included tornado warnings issued within 10 min of the start of the tornado event. This is meant to cover the scenario in which a spotter reports a tornado to ECCC, but the weak, brief tornado has dissipated by the time the warning is broadcast (we considered 10 min to be fair). This extra time allowance should not be a factor for stronger, longer-lived tornadoes that often have a lifetime beyond 10 min.

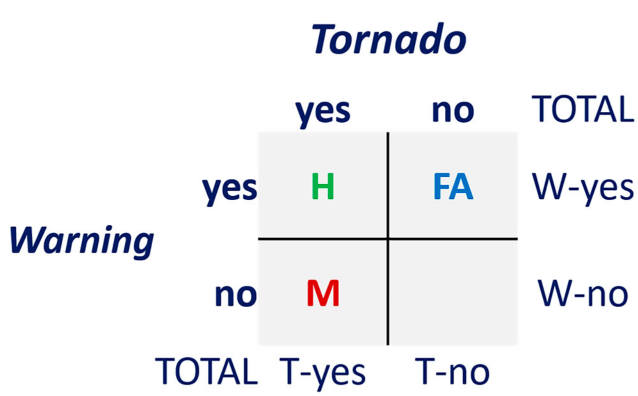

Fig. 2 A contingency table for tornadoes and tornado warnings with the hits (H), misses (M) and false alarms (FA). These are used to calculate several common parameters: POD = H/(H + M), FAR = FA/(H + FA), CSI = H/(H + M + FA).

When dealing with multiple tornadoes occurring closely together in space and time, we considered one tornado warning for a region with three tornadoes in it as three separate hits. Finally, only tornadoes with at least part of their lifetime over land were considered since only those would be covered by tornado warnings (note, however, that ECCC does issue tornado warnings over large bodies of water as part of its marine programme).

A tornado watch is issued when forecasters identify a region where conditions are favourable for the development of severe thunderstorms that may produce tornadoes. Ideally, these are issued well ahead of storm initiation and serve to heighten public awareness of tornado potential should storms develop. For events where a tornado is confirmed, the NTP considers the optimal progression to be: (1) tornado watch issued for area, (2) tornado warning issued for area, and finally (3) tornado occurs in area. For every tornado occurrence, we noted if the tornado developed in an area under an active tornado watch and was successfully warned.

4 Results

The contingency tables and parameter values for each year from 2019 to 2021 are shown in Fig. 3, while Fig. 4 shows the contingency table and parameter values when data from 2019 to 2021 are combined. Table 1 shows when tornado warnings were issued relative to the recorded tornado start times. A reminder here that the first two rows would be considered hits under our assessment rules. The percentage of tornado warnings issued before or during a tornado does not exceed 28%. The best performance was for the year 2020 when 16% of tornado warnings were issued before the tornado occurred. Overall, for 2019–2021, 74% of tornadoes had no tornado warning issued at all.

To put these tornado warning performance values into context, we compare them to NWS tornado warning performance statistics in two ways. First, using US national values compiled by Brooks and Correia (2018), and second, via a more direct comparison – using only data from states in the contiguous US bordering Canada over the same 2019–2021 period.

Before making these comparisons, it should be stated that they are not exactly ‘apples to apples’. There are currently 32 weather radars in the ECCC network, versus 160 in the NWS network. Almost all of those cover only southern Canada, meaning numerous severe storms in more northerly latitudes occur outside of radar range. During the 2019–2022 period, ECCC was in the midst of a programme to replace existing C-band radars with S-band radars having dual-polarimetric scanning technology, an important upgrade in terms of the ability to detect severe weather. The NWS has employed S-band radars with dual-polarimetric scanning since 2013, optimized for tornadic storm detection including the ability to scan more quickly in severe storm situations (every 1–2 min compared to 6 and 10 min for the new and old ECCC radars, respectively). The NWS also has many

2019

		Tornado yes	Tornado no	TOTAL
Warning	yes	15	61	76
	no	55		55
	TOTAL	70	61	131

POD = 0.21
FAR = 0.80
CSI = 0.11

2020

		Tornado yes	Tornado no	TOTAL
Warning	yes	23	82	105
	no	58		58
	TOTAL	81	82	163

POD = 0.28
FAR = 0.78
CSI = 0.14

2021

		Tornado yes	Tornado no	TOTAL
Warning	yes	20	60	80
	no	79		79
	TOTAL	99	60	159

POD = 0.20
FAR = 0.75
CSI = 0.13

Fig. 3 Contingency tables for 2019 (left), 2020 (centre) and 2021 (right) showing hits (green), misses (red), false alarms (blue) and column and row totals. POD, FAR and CSI calculations for each year are also shown. We note some of the extremes here – the CSI was lowest in 2019 (red), the POD highest in 2020 (green) and the FAR lowest in 2021 (blue).

more forecasters watching radars and issuing tornado warnings than ECCC. In fact, NWS forecasters can often focus on just the one radar for which their office is responsible and are, therefore, typically less dependent on automated storm feature detection and ranking algorithms. Lastly, though local NWS offices issue tornado *warnings*, tornado *watches* are issued by a national Storm Prediction Center. This is unlike ECCC offices that have responsibility for both types of alerts (it is unclear if this is an advantage or a disadvantage). Though there are these differences, we can still learn from the extensive US experience with tornado warnings and their verification (Brooks, 2004; Brooks & Correia, 2018).

2019-2021

		Tornado yes	Tornado no	TOTAL
Warning	yes	58	203	261
	no	192		192
	TOTAL	250	203	453

POD = 0.23
FAR = 0.78
CSI = 0.13

Fig. 4 As in Fig. 3 but showing combined results from the 2019 to 2021 period.

One other item that needs to be discussed in order to understand the US–Canada comparison is the 'performance diagram' and what it illustrates. A performance diagram is able to show values of POD, FAR, CSI and bias (ratio of tornado warnings to tornadoes) all in one chart. The key to understanding the diagram is that performance improves towards the top right.

The performance diagram in Fig. 5 shows NWS tornado warning performance as it evolved from 1986 to 2022, using periods of data from Brooks and Correia (2018) that include warned and partially warned tornado events (updated to 2022). From 1986 to 2007, the NWS increased their national tornado warning performance by sharply increasing the number of warnings while keeping the FAR relatively steady near 0.75. In doing so, the POD increased dramatically from near 0.4 to over 0.75, resulting in an improvement in CSI of nearly 0.05. From 2012 to 2016, there was a successful effort at the NWS to reduce the tornado warning FAR (Brooks & Correia, 2018), resulting in a lower POD but slightly higher CSI that continued to 2022, as shown in Fig. 5. We then add more data to the performance diagram. NWS tornado warning performance data (again including warned and partly warned tornado events) from the US border states for 2019–2021 are shown in Fig. 5 (green). Over that period, there were 167 tornadoes in

TABLE 1. The timing of tornado warnings relative to the start time of tornadoes, for individual years and for the 2019–2021 period.

Relative to tornadoes	2019	2020	2021	2019–2021
Before tornado	7%	16%	10%	11%
During tornado	14%	12%	10%	12%
More than 10 min after tornado	1%	5%	1%	2%
Cancelled before tornado	0%	0%	2%	1%
No warning	77%	67%	77%	74%

The values indicate the percentage of tornadoes out of all recorded tornadoes for each timing category.

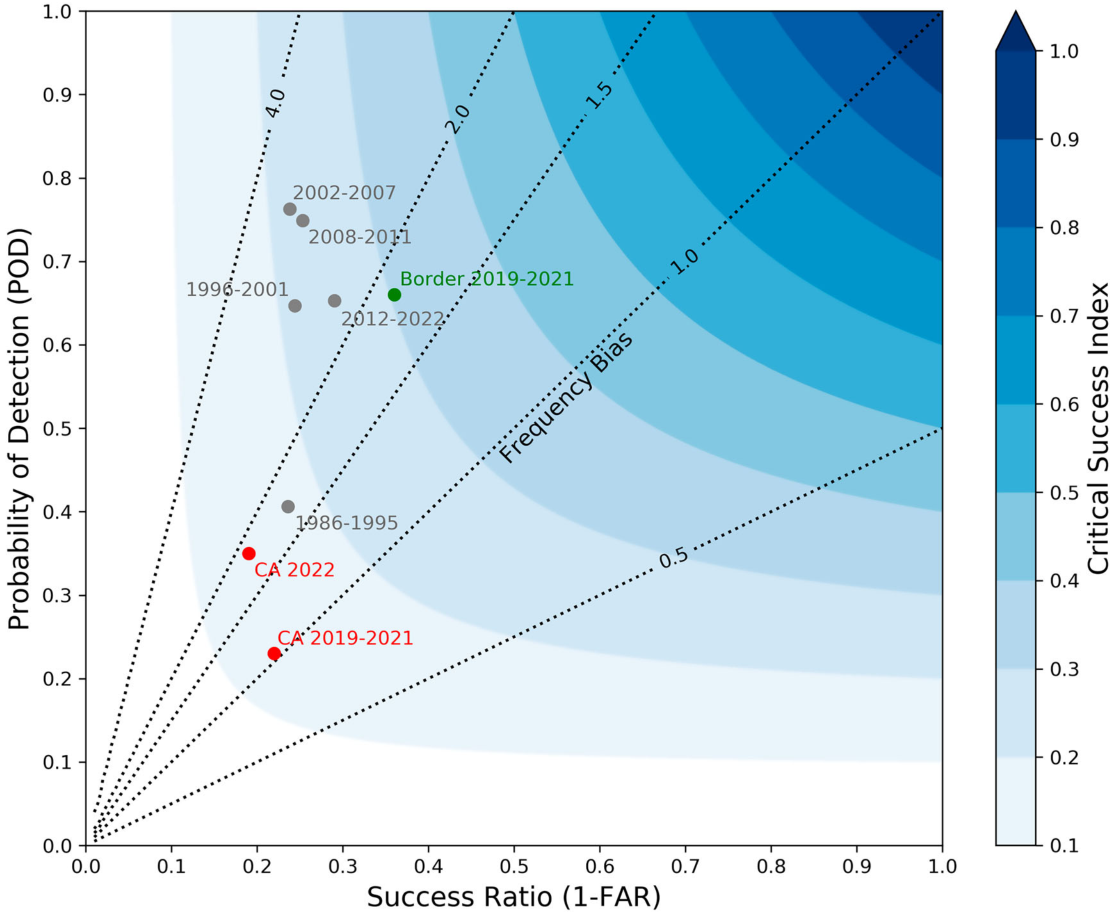

Fig. 5 Performance diagram showing tornado warning performance for NWS national performance over time (grey), NWS border state performance for 2019–2021 (green), and ECCC performance for 2019–2021 and 2022 (red).

those states. It can be seen that the tornado warning performance here is even better than for all of the US in the 2012–2016 period, with CSI reaching 0.3.

Finally, ECCC tornado warning performance data are added in the same fashion. As the NWS definition of a warning 'hit' does not include a 10-minute grace period adopted by NTP for this assessment, short-lived tornadoes that had a warning issued by ECCC less than 10 min after developing are considered unwarned for this comparison, and as such POD and FAR results may be slightly different. The performance over the 2019–2021 period is lower than that of the NWS in the late 1980s and early 1990s. And the overall ECCC CSI for 2019–2021 of 0.13 is considerably lower than the NWS border states CSI of 0.30 over the same period.

5 Report card and recommendations

As part of its ISO 9001 Quality Management System, ECCC's internal national alerting performance targets for severe convective storms are as follows[1]:

- Probability Of Detection for Tornado Warnings equal or better than 0.50,
- Tornado Warnings issued at least 10 min before the event 60% of the time,
- Convective Watches issued at least 6 h before the events 80% of the time, and
- Probability Of Detection for Convective Watches equal or better than 0.65.

Note that convective here means related to thunderstorms – so 'Convective Watches' refers to both severe thunderstorm watches and tornado watches.

The NTP aimed to produce a tornado alert 'report card' that was easily digestible by the media and the Canadian public, making use of ECCC's performance targets. The NTP report card consists of three scored criteria and an overall score. These are discussed below.

a *Probability of Detection Criterion*

The *ideal* score here is 1 or 100% of tornadoes had a tornado warning, but ECCC chose a target of 0.5 or 50%. Based on the

[1]Personal communication, M. Seifert (ECCC Ontario Storm Prediction Centre)

2019–2021 data, the calculated POD for all tornadoes is 0.23 (or 23%). Because the POD deals with the key question of whether a tornado was warned for or not, this criterion was given the highest weighting by the NTP, one that was more than half of the total score but still left room for the other weighted criteria. A weighting of 60% was chosen.

b *Lead Time Criterion*

Ideally, for 100% of tornadoes, tornado warnings should give those affected enough time to take protective action. Here, ECCC chose to set a target of 10 min of warning lead time for 60% of tornadoes. Using the 2019–2021 data, NTP found that this target was met just 8.4% of the time. The NTP has given this criterion a weighting of 30% because while lead time is secondary to whether a warning was issued it is still important that those affected have enough time to take safety precautions.

c *Tornado Watch Criterion*

For events where a tornado is confirmed, the NTP considers the optimal progression to be: (1) tornado watch issued for area, (2) tornado warning issued for area, and finally (3) tornado occurs in area. The ECCC target of a tornado watch being issued six hours prior to the event 80% of the time was relaxed by NTP because the 6-hour threshold was met for only two tornado events over the 2019–2021 period, and having a tornado watch out for even an hour before a tornado warning aids with the public alerting process. Using the 2019–2021 data, NTP found that the relaxed target of having a tornado watch issued before a successful tornado warning was met only 12.1% of the time. Given the focus of our assessment is mainly on tornado warnings, this criterion was assigned only a 10% weighting.

d *Total Score*

Adding up the weighted scores for the three NTP criteria results in a total score out of 100. For the 2019–2021 period in question, the total score was 33.3.

The results of the assessment of ECCC tornado alerting performance covering 2019–2021 suggested there was considerable room for improvement. The following is a summary of NTP's recommended actions to help increase tornado warning performance in Canada (the full recommendations can be found on the NTP website uwo.ca/ntp).

1 INCREASE THE NUMBER OF TORNADO WARNINGS

Significantly increasing the number of tornado warnings, as was done by NWS between 1986 and 2007, should lead to an increased POD, and CSI. The challenge would be to do this in a way that would not significantly increase FAR, though recent research has shown no clear evidence that false alarms – perceived or actual – generate a complacent public (Lim et al., 2019). And, in fact, false alarms and FAR are not mentioned in ECCC's performance targets. While the FAR for the 2019–2021 tornado warnings was 0.78, the FAR for ECCC severe thunderstorm warnings between 2009 and 2016 was even higher at 0.87, with little variation over that period (see ECCC, 2017). Clearly a high FAR is tolerated.

2 INCREASE LEAD TIMES BY FINDING WAYS TO GET TORNADO WARNINGS OUT SOONER

Many times forecasters are waiting for one more scan from the radar, or cues from public reports, to feel confident enough to issue a tornado warning. Confidence is certainly a key issue – and can be increased through highly focused and ongoing training, particularly via simulations since tornadoes are relatively rare events and it is difficult to quickly gain sufficient experience.

3 ENSURE FORECASTERS HAVE CUTTING-EDGE TORNADO DETECTION, NOWCASTING AND FORECASTING TOOLS

Having forecaster-friendly algorithms and applications that use the latest science and technology to highlight the tornado threat – in the next six minutes, the next six hours or the next several days – is key to being prepared to issue a tornado watch and/or warning.

6 Update for 2022

Assessment results from the 2022 season were calculated separately in order to see if there were improvements to tornado alerting performance following the release of the first assessment before the 2022 season began. Again, for tornado occurrence data, we used NTP-confirmed tornadoes over land (n = 106, Fig. 6).

The first thing to note is that the number of tornado watches and warnings increased substantially, and in fact roughly doubled. Over the 2019–2021 period, an average of 25 tornado watches and 87 tornado warnings were issued annually. For 2022, there were 49 tornado watches and 181 tornado warnings. There was a substantial increase in the number of tornado watch and warning *days* as well. For the 2019–2021 period, there was an average of 11.3 tornado watch days and 26 tornado warning days while for 2022 there were 24 tornado watch days and 42 tornado warning days.

As can be seen in Fig. 7, the large increase in tornado warnings and tornado warning days improved the POD considerably – going from 0.23 to 0.35, or a 52% increase. Both the FAR and CSI increased only slightly, with FAR going from 0.78 to 0.81 and CSI increasing from 0.13 to 0.14. A point for the 2022 results was added to the performance diagram in Fig. 5 for comparison.

Table 2 shows when tornado warnings were issued relative to the recorded tornado start times. There was a substantial increase in the number of tornado warnings issued before tornadoes occurred, going from 11% to 24%. However, 65% of tornadoes still had no tornado warning in 2022.

NTP's second annual tornado warning performance report card highlighted the improved scores from the 2022 season.

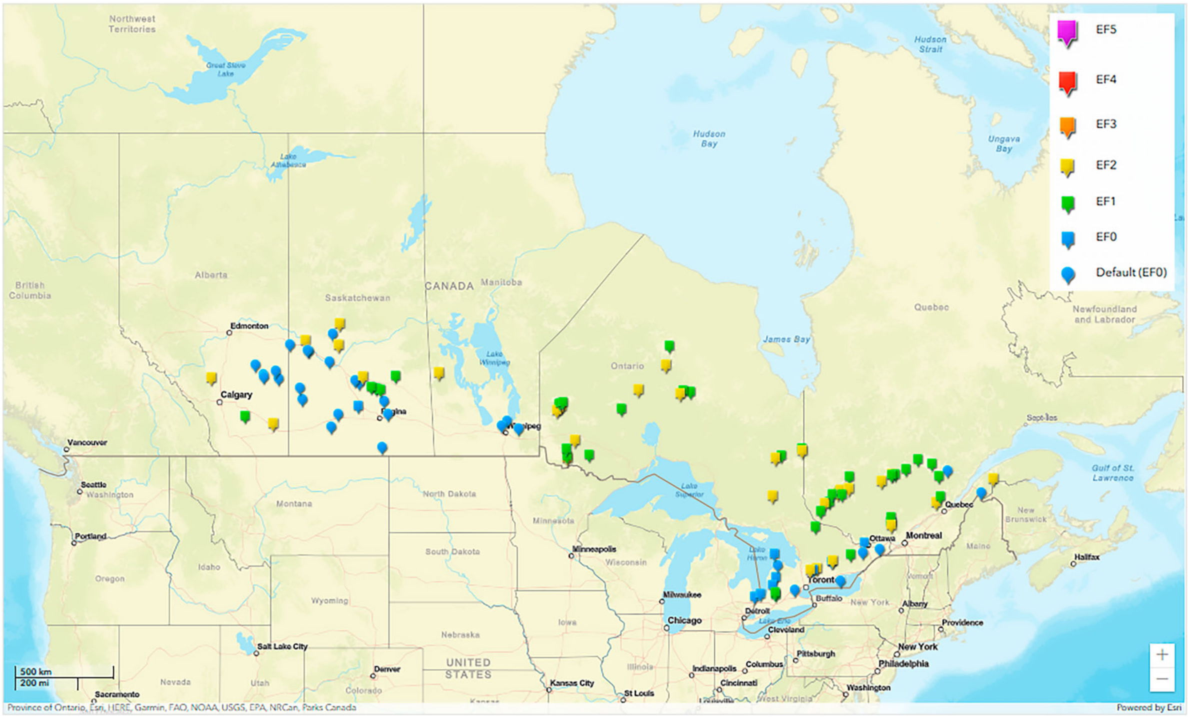

Fig. 6 All 106 tornadoes over land in Canada in 2022. Pins colours and shapes indicate EF-scale rating, with legend at upper right.

As mentioned earlier, the POD went from 0.23 to 0.35. The percentage of warnings with at least a 10-min lead time increased from 8.4% to 19.8%, and the percentage of tornadoes with a tornado watch preceding the tornado warning increased from 12.1% to 37.8%. This gave an overall score of 56.6/100 – a substantial improvement over 33.3/100 and now a ‘passing grade’. The NTP report card for 2022 is shown in Fig. 8.

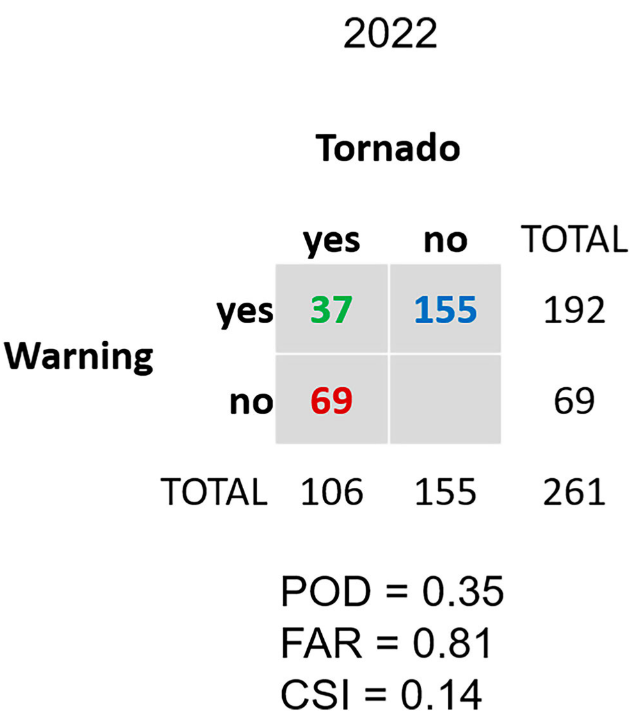

Fig. 7 As in Fig. 3 but showing results from the 2022 period.

7 Further interpretation of the results to date

Tornado alerting performance at a national level was discussed above in general terms. The results are examined in more detail below, considering the influences of Doppler radar and the parent storm type, as well as how POD and lead time are related to the assessed EF-scale rating.

a *Proximity to Doppler Radar*

Here, we examine whether the POD is better when the area of interest is within the Doppler domain of radar coverage, since that is where storm rotation signatures can be detected and also where the radar is able to sample the lower levels of the storms where most severe weather can be detected.

TABLE 2. The timing of tornado warnings relative to the start time of tornadoes, for the 2019–2021 period, 2022, and all four years.

Relative to tornadoes	2019–2021	2022	All Years
Before tornado	11%	24%	15%
During tornado	12%	11%	12%
More than 10 min after tornado	2%	0%	2%
Cancelled before tornado	1%	0%	1%
No warning	74%	65%	71%

The values indicate the percentage of tornadoes out of all recorded tornadoes for each timing category.

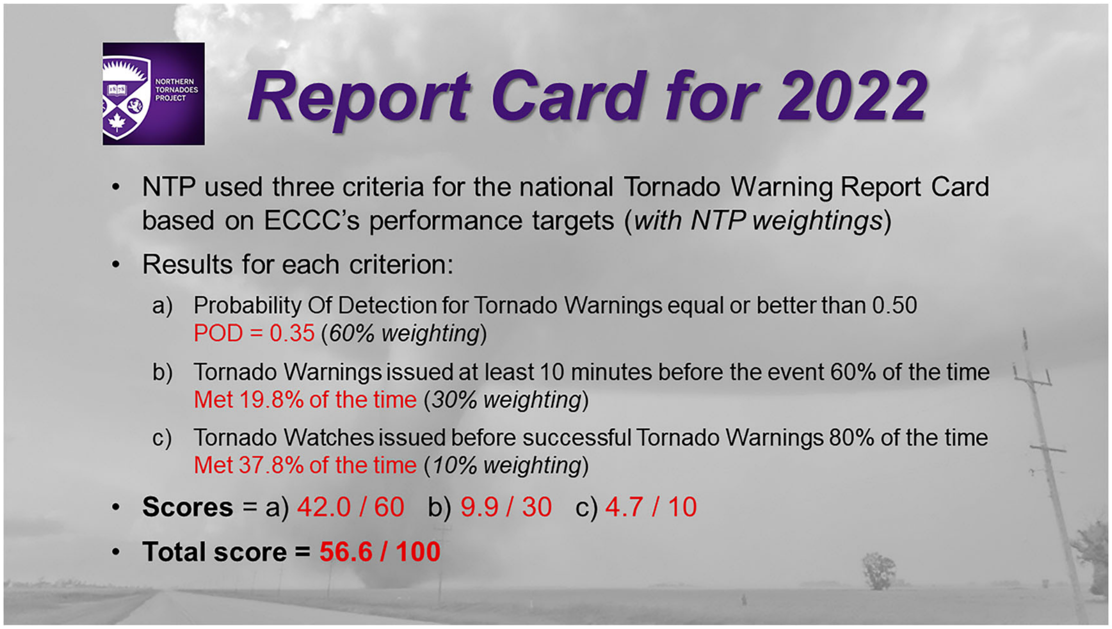

Fig. 8 The NTP tornado warning report card published for the 2022 season.

Over the 2019–2022 period across Canada, new S-band Doppler radars with extended Doppler range (240 km) were replacing older C-band Doppler radars (Doppler range 113 km). And in some cases, near the US border, an NWS NEXRAD radar had the best coverage for the event (Doppler range 300 km). For each tornado, it was carefully determined whether it occurred (fully or partly) within a radar's Doppler range.

For the 2019–2021 period, tornadoes occurring within Doppler range had a tornado warning POD of 0.26 – not much higher than for all tornadoes (0.23). That increased to 0.38 for 2022, a substantial improvement (Table 3).

b *Tornado Type*

We can also compare the tornado warning POD values for different types of tornadoes. The NTP FAQ defines three types of tornadoes: supercell, quasi-linear convective system (QLCS), and landspout. Typically, rotating 'supercell' storms produce the strongest tornadoes, with damage potential up to the top of the EF scale at EF5. So-called 'landspout' tornadoes form with loosely organized storms, often along mesoscale boundaries like gust fronts, and therefore typically produce weak EF0-EF1 damage. QLCS tornadoes occur along the leading edge of a line of storms and are typically stronger and longer-lived than landspout tornadoes. They rarely are able to reach an intensity similar to that of the strongest supercell tornadoes, however.

Landspout tornadoes are also rarely associated with an identifiable signature on radar, and are often brief, making them the hardest to warn for. Other the other hand, supercell thunderstorms often have prominent, long-lived features that modern Doppler radars are designed to detect, and occur in an environment that can sometimes be forecast days in advance. That makes it (generally) easier to anticipate supercell tornadoes. QLCS tornadoes lie in between these two extremes, with focused, low-level rotation often apparent using Doppler velocity products. It is not always so cut-and-dried when it comes to tornado type, however. In some cases, the tornado appears to have developed as a combination of types – what we call 'hybrid' tornadoes.

The tornado type was subjectively determined for each tornado using (as available) radar imagery, lightning data, surface weather analysis maps, storm environment information, and visual characteristics of the parent storm. The supercell tornado type was found to be most common, with 47.5% of all tornadoes associated with supercell thunderstorms over the

TABLE 3. Tornado warning numbers and POD values for various years and periods.

	2019		2020		2021		2019–2021		2022		All Years	
	All events	Doppler range	All events	Doppler range	All events	Doppler range	All events	Doppler range	All events	Doppler range	All events	Doppler range
Events	70	49	81	72	99	85	250	206	106	97	356	303
POD	0.21	0.22	0.28	0.32	0.20	0.24	0.23	0.26	0.35	0.38	0.27	0.30

TABLE 4. Number of tornadoes, percentage of total tornadoes, and tornado warning POD for each tornado type for 2019–2021, 2022 and all years (2019–2022).

	2019–2021			2022			All Years		
	Events	%	POD	Events	%	POD	Events	%	POD
All tornadoes	250	100.0%	0.23	106	100.0%	0.35	356	100.0%	0.27
Supercell	110	44.0%	0.35	59	55.7%	0.39	169	47.5%	0.36
QLCS	76	30.4%	0.13	29	27.4%	0.34	105	29.5%	0.19
Landspout	50	20.0%	0.10	14	13.2%	0.14	64	18.0%	0.11
Hybrid	14	5.6%	0.36	4	3.8%	0.50	18	5.1%	0.39

TABLE 5. Tornado warning POD values versus EF-scale rating for 2019–2021, 2022 and all years (2019–2022).

	2019–2021	2022	All Years
All tornadoes	0.23	0.35	0.27
Default EF0	0.25	0.57	0.35
EF0	0.26	0.00	0.21
EF1	0.17	0.28	0.20
EF2+	0.30	0.33	0.31

2019–2022 period, followed by QLCS at 29.5% and landspout at 18.0%. Only 5.1% of events were considered hybrid, and many of those involved supercell processes (e.g. supercell-landspout and supercell-QLCS hybrids).

It can be seen from Table 4 that supercell-type tornadoes had better tornado warning PODs, particularly in 2022 where the POD reached 0.39. Over all periods, hybrid events had the highest PODs. As was mentioned previously, many of these events involved supercell processes. But it is likely that the small sample size makes those scores less reliable than the others. As expected, the tornado warning POD for landspout-type tornadoes is relatively low, with the highest POD in 2022 at 0.14.

c *POD by EF-Scale Rating*

Table 5 shows the tornado warning POD values by EF-scale ranking. The POD does not change much between tornadoes rated EF0, EF1 or having a default EF0 ranking (i.e. no damage was found). But for EF2+ tornadoes, the POD does increase considerably for all periods, topping out in 2022 with a value of 0.33. The EF2+ sample size for 2022 is small, however, at only 30 tornadoes. Many EF2+ tornadoes are generated by supercell thunderstorms (that often have a rotation signature on radar), while very few if any are landspout-type tornadoes (where the parent thunderstorm has no rotation apparent on radar).

d *Lead Time by EF-Scale Rating*

Lastly, we examine the lead time aspect of tornado warnings by EF scale rating. As seen in Table 6, there is not a strong relationship between warning lead time and the EF-scale rating. But the number of EF2+ tornadoes that had no tornado warning is important. Over the 2019–2021 period, 15 EF2+ tornadoes had tornado warnings issued before or during the event, while 35 had no tornado warning. This improved somewhat for 2022, though there were still twice as many EF2+ tornadoes without a tornado warning (20) than with one (10).

8 Discussion and further recommendations

The tornado warning performance assessment results from 2022 show that the number of tornado warnings issued across Canada did increase substantially, from an annual average of 87 between 2019 and 2021 to 181 in 2022 (the number of tornado watches issued also roughly doubled). The number of tornado watch and warnings days also increased substantially. This led to an increase in tornado warning POD from 0.23 to 0.35 (though CSI changed only slightly). The percentage of tornado warnings having a lead time of 10 min or better also improved, from 8.4% between 2019 and 2021 to 19.8% in 2022.

It is important to note here that nearly all violent (EF4–EF5) tornadoes are supercell tornadoes, and nearly all tornado-related fatalities are caused by tornadoes rated EF2 or higher. But even for EF2+ and supercell tornadoes, tornado warning POD fell well short of the target POD of 0.5.

So how can tornado warning scores be further improved? Given that 65% of tornadoes – including many EF2 tornadoes – still had no tornado warning in 2022, and the POD remains well below the target, there clearly needs to be even more tornado warnings issued. Even if this effort were to be focused on only supercell tornadoes, it would hopefully improve scores

TABLE 6. Tornado warning status versus EF-scale ratings for the 2019–2021 period and for 2022.

	2019–2021					2022				
Relative to tornadoes	All	Default EF0	EF0	EF1	EF2+	All	Default EF0	EF0	EF1	EF2+
Before tornado	28	6	6	8	8	25	10	0	8	7
During tornado	30	10	6	7	7	12	7	0	2	3
More than 10 min after tornado	6	2	1	3	0	0	0	0	0	0
Cancelled before tornado	2	0	0	2	0	0	0	0	0	0
No warning	184	45	34	70	35	69	13	10	26	20

for tornadoes that are the most capable of causing fatalities, injuries, and catastrophic damage. This may be challenging for forecasters since tornado warnings are some of the only severe weather warnings in Canada that are 'broadcast intrusive' (i.e. will interrupt media broadcasts, and are also sent to cell phones) and are therefore highly visible.

The key to keeping false alarms down while issuing more tornado warnings, and further increasing warning lead times, is enhancing the skill and confidence of forecasters. Expert forecasters are able to quickly attain – and maintain – situational awareness, even when reality begins to deviate from the anticipated scenario. That means they are ready to act when the conditions warrant a warning. They are also able to discriminate between key indicators of tornado potential (e.g. strong Doppler velocity couplet) and look-alikes not associated with tornadoes (e.g. radar sidelobe contamination due to hail).

Finally, while ECCC forecasters have access to a new network of state-of-the-art radars (with Doppler and dual-polarimetric capabilities at S-band), they also need tools that make the most of the data from these radars and other monitoring platforms, including recently upgraded satellite imaging systems (Goodman et al., 2019) and lightning networks (Kochtubajda & Burrows, 2020), for reliable storm tracking, sophisticated severe weather feature detection, and storm intensity nowcasting. Tackling these issues requires a sustained research and development effort, perhaps in coordination with industry and/or academia.

9 Conclusions

NTP completed the first independent assessment of tornado warning performance in Canada, covering the period from 2019 to 2021. A second assessment was undertaken for the 2022 tornado season, and results were compared. The main results are:

- The Probability of Detection for ECCC's tornado warnings is much less than their target of 0.5 (0.23 for 2019–2021 and 0.35 for 2022).
- Only 8.4% of tornadoes for 2019–2021 were preceded by a tornado warning with at least 10 min of lead time – this improved in 2022 to 19.8% but remains far below the ECCC target of 60%.
- While only 12.1% of tornado warning 'hits' were preceded by a tornado watch over the 2019–2021 period, that percentage increased to 37.8% for the 2022 season.
- Though tornado warning POD and lead time values were found to increase for supercell and EF2+ tornadoes, the results were still less than ECCC targets.

It is hoped that the improvements seen in 2022 will continue into the future and be shown in the results of future NTP performance assessments and report cards.

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