Tornadoes in Canada: Improving our Understanding

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Cloud Physics and Severe Weather Research Section
Environment Canada, Toronto
Outline

• What is a tornado?
• How do tornadoes form?
• How are tornadoes rated?
• Where / when do tornadoes occur?
• How does EC provide tornado alerts?
• Are tornadoes in Canada increasing in frequency and/or intensity?
What is a tornado?

From the AMS Glossary of Meteorology (2012):

- **Tornado** — A violently rotating column of air, in contact with the ground surface, either pendant from a cumuliform cloud or underneath a cumuliform cloud, and often (but not always) visible as a funnel cloud.
  - *Includes waterspouts*
  - *Excludes dust devils and ‘gustnadoes’*
What is a tornado?

Further details:
- Winds spiral inward at surface then spiral upward
- Wind speeds generally 90 km/h to >= 315 km/h
- Average path ~250 m but can range between 2 m and 2+ km
- Average length ~10 km but can range between 50 m and 100+ km

Photo by Justin Hobson

Elie, Manitoba F5

Video
How do tornadoes form?

Tornadoes can occur with any storm type:

• Supercells – tend to produce the most violent and long-tracked tornadoes due to sustained, intense updraft
• Bow echoes and squall lines – vertical vortices along leading edge are stretched by the updraft and intensified
• ‘Pulse’ storms – brief, weak tornadoes along boundaries
• Even towering Cu over lakes – non-supercell waterspouts
• Key is co-location of enhanced vorticity with strong, localized updraft + precip
Supercell Tornadogenesis

• Most supercells are *not* tornadic

• However, most *significant* tornadoes and nearly all *violent* (F4-F5) tornadoes are supercell tornadoes

• Many supercell tornadogenesis theories have evolved through field and modelling work: area of active research

• In the 1970’s, Doppler radar used to identify a region of large cyclonic gate-to-gate shear (TVS) that descended from mid-levels over 20-30 min

• Led to hope that Doppler radars would rapidly advance tornado prediction
“Cascade” Paradigm

• Conceptual *supercell* diagram Lemon and Doswell (1979)

• ‘Top-down’ tornado-genesis process: MLM-> LLM-> TVS-> tornado

• High-resolution numerical models appeared to support this paradigm

• Was thought that the VORTEX1 study in 1994/95 would confirm this conceptual model…

Forms near back of storm
Instead, it was found that nearly 70% of significant supercell tornadoes occurred near pre-existing boundaries (Markowski et al. 1998).

‘Bottom-up’ tornado-genesis process

‘Boundaries’ include old outflow boundaries, lake breeze fronts, drylines, etc.
VORTEX2 Field Project – 2009-10
18 May 2010
Dumas, TX
tornadic supercell
5 June 2009 Goshen Co. Tornado
5 June 2009 Goshen Co. Tornado

Markowski et al., 2012
‘Bow Echo’ Tornadoes

• ‘Bow echoes’ tornadoes
  – bow echoes are likely prodigious tornado producers
  – unlike supercells, form out *front* of the storm
  – many of the tornadoes likely go undetected (cell phone cameras may help here!)
‘Landspout’ Tornadoes

- So called because the formation process, and appearance, are similar to waterspouts
- Damage rarely greater than F1 and often more brief than supercell tornadoes, though can occasionally last 30 min+
- Commonly appear thin and rope-like
- Occasionally occur with atypical translational motion e.g. NE to SW
- Many events occur in the vicinity of boundaries e.g. lake-breeze fronts
‘Landspout’ Tornadoes

Adapted from Lee and Wilhelmson (1997)
Waterspouts

• Any of the processes mentioned previously can produce a tornado over water – a waterspout!

Rice Lake F0 ‘waterspout’, 2003
How does EC rate tornadoes?

- EC conducts both on-site storm damage surveys and remote surveys
- Goal: identify various parameters related to the event:
  - Was it a tornado?
  - Intensity?
  - When did it occur?
  - Where did it occur?
  - Injuries / fatalities?
  - Property damage?
How does EC rate tornadoes?

- **Fujita Scale**
- Developed by Ted Fujita at Univ. of Chicago in the 1960s
- Wind speeds were educated guesses
- Limited number of damage indicators
- Used for tornadic and non-tornadic wind damage
- Implemented in the US and Canada in 1970s

<table>
<thead>
<tr>
<th>F-scale Category</th>
<th>Estimated Wind Speed Range (mph)</th>
<th>Typical Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>40 - 72</td>
<td><em>Light damage.</em> Some damage to chimneys; branches broken off trees; shallow-rooted trees pushed over; sign boards damaged.</td>
</tr>
<tr>
<td>F1</td>
<td>73 - 112</td>
<td><em>Moderate damage.</em> Peels surface off roofs; mobile homes pushed off foundations or overturned; moving autos blown off roads.</td>
</tr>
<tr>
<td>F2</td>
<td>113 - 157</td>
<td><em>Considerable damage.</em> Roofs torn off frame houses; mobile homes demolished; boxcars overturned; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground.</td>
</tr>
<tr>
<td>F3</td>
<td>158 - 206</td>
<td><em>Severe damage.</em> Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off the ground and thrown.</td>
</tr>
<tr>
<td>F4</td>
<td>207 - 260</td>
<td><em>Devastating damage.</em> Well-constructed houses leveled; structures with weak foundations blown away some distance; cars thrown and large missiles generated.</td>
</tr>
<tr>
<td>F5</td>
<td>261 - 318</td>
<td><em>Incredible damage.</em> Strong frame houses leveled off foundations and swept away; automobile-sized missiles fly through the air in excess of 100 meters (109 yds); trees debarked; incredible phenomena will occur.</td>
</tr>
</tbody>
</table>

From Fujita (1981)
The EF-scale was developed at Texas Tech Univ. (McDonald and Mehta, 2006) involving many US interests.

- Has much improved wind speed / wind damage correlation with large number of damage indicators while consistent with existing US database.
- Adopted officially at EC on April 1, 2013.
- First tornado rated using the EF-scale occurred on April 18th, 2013, at Shelburne, ON – rated EF1.
## Damage Indicators (DI)

<table>
<thead>
<tr>
<th>Number</th>
<th>Damage Indicator (DI)</th>
<th>Farms / Residences</th>
<th>Commercial / retail structures</th>
<th>Schools</th>
<th>Professional buildings</th>
<th>Metal buildings / canopies</th>
<th>Towers / poles</th>
<th>New Canadian DIs!</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Small Barns or Farm Outbuildings (SBO)</td>
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<td>2</td>
<td>One- or Two-Family Residences (FR12)</td>
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<td>3</td>
<td>Manufactured Home: Single Wide (MHSW)</td>
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<td>4</td>
<td>Manufactured Home: Double Wide (MHDW)</td>
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<td>5</td>
<td>Apartments, Condos, Townhouses (ACT)</td>
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<td>6</td>
<td>Motel (M)</td>
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<td>7</td>
<td>Masonry Apartment or Motel (MAM)</td>
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<td>8</td>
<td>Small Retail Building (SRB)</td>
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<td>9</td>
<td>Small Professional Building (SPB)</td>
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<td>10</td>
<td>Strip Mall (SM)</td>
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<td>11</td>
<td>Large Shopping Mall (LSM)</td>
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<td>12</td>
<td>Large, Isolated Retail Building (LIRB)</td>
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<td>13</td>
<td>Automobile Showroom (ASR)</td>
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<td>14</td>
<td>Automobile Service Building (ASB)</td>
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<td>15</td>
<td>Elementary School (ES)</td>
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<td>16</td>
<td>Junior or Senior High School (JHSH)</td>
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<td>17</td>
<td>Low-Rise Building: 1 - 4 Storeys (LRB)</td>
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<td>18</td>
<td>Mid-Rise Building: 5 - 20 Storeys (MRB)</td>
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<td>19</td>
<td>High-Rise Building: Greater than 20 Storeys (HRB)</td>
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<td>20</td>
<td>Institutional Building (IB)</td>
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<tr>
<td>21</td>
<td>Metal Building System (MBS)</td>
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<td>22</td>
<td>Service Station Canopy (SSC)</td>
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<td>23</td>
<td>Warehouse Building (WBN)</td>
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<td>24</td>
<td>Free-Standing Towers (FST)</td>
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<td>25</td>
<td>Free-Standing Light Poles, Luminary Poles, Flag Poles (FSP)</td>
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<tr>
<td>26</td>
<td>Electrical Transmission Lines (ETL)</td>
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<tr>
<td>C1</td>
<td>Trees (T)</td>
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<tr>
<td>C2</td>
<td>Heritage Church (HC)</td>
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<tr>
<td>C3</td>
<td>Solid Masonry House (SMH)</td>
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<tr>
<td>C4</td>
<td>Farm Silos or Grain Bins</td>
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<tr>
<td>C5</td>
<td>Sheds, Fences or Lawn Furniture (SFLF)</td>
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</tbody>
</table>
Degrees of Damage (DoD)

1. SMALL BARNS OR FARM OUTBUILDINGS (SBO)

Typical Construction:
- Less than 250 m²
- Wood or metal post and beam construction
- Wood or metal roof trusses
- Wood or metal panel siding
- Metal or wood roof
- Large doors

<table>
<thead>
<tr>
<th>DOD</th>
<th>Damage Description</th>
<th>EXP</th>
<th>LB</th>
<th>UB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Threshold of visible damage</td>
<td>100</td>
<td>85</td>
<td>125</td>
</tr>
<tr>
<td>2</td>
<td>Loss of wood or metal roof panels (up to 20%)</td>
<td>120</td>
<td>100</td>
<td>145</td>
</tr>
<tr>
<td>3</td>
<td>Collapse of doors</td>
<td>135</td>
<td>110</td>
<td>165</td>
</tr>
<tr>
<td>4</td>
<td>Major loss of roof panels (more than 20%)</td>
<td>145</td>
<td>125</td>
<td>175</td>
</tr>
<tr>
<td>5</td>
<td>Uplift or collapse of roof structure (more than 50%)</td>
<td>150</td>
<td>125</td>
<td>185</td>
</tr>
<tr>
<td>6</td>
<td>Collapse of walls</td>
<td>155</td>
<td>130</td>
<td>190</td>
</tr>
<tr>
<td>7</td>
<td>Overturning or sliding of entire structure</td>
<td>160</td>
<td>135</td>
<td>190</td>
</tr>
<tr>
<td>8</td>
<td>Total destruction of building</td>
<td>180</td>
<td>150</td>
<td>210</td>
</tr>
</tbody>
</table>

DODs wind speeds in km/h
• Though F-scale and EF-scale wind speeds are different, both still have the same damage scales.

• Hence, ratings based on damage will be the same for older events rated with the F-scale and newer events rated with the EF-scale.

• For example, the roof removed from a framed house is F/EF2, and a framed house swept from its foundation is F/EF5.
F-scale vs EF-scale

Graph showing the relationship between wind speed (mph) and the F/EF-number. The graph includes data points for the Fujita Scale (min), EF low speed mph, and EF high speed mph. The graph is labeled with the text "WDTB."
If *power law* regression used instead of *linear*:

- Slightly better fit
- Goes through origin
- Lower bound of EF0 becomes ~90 km/h instead of 105 km/h

After McDonald and Mehta (2006)
## EC Implementation - Scale

<table>
<thead>
<tr>
<th>F/EF Rating</th>
<th>F-Scale Wind Speed Rounded to 10 km/h</th>
<th>EF-Scale Wind Speed Rounded to 5 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>60 – 110</td>
<td>90 – 130</td>
</tr>
<tr>
<td>1</td>
<td>120 – 170</td>
<td>135 – 175</td>
</tr>
<tr>
<td>2</td>
<td>180 – 240</td>
<td>180 – 220</td>
</tr>
<tr>
<td>3</td>
<td>250 – 320</td>
<td>225 – 265</td>
</tr>
<tr>
<td>4</td>
<td>330 – 410</td>
<td>270 – 310</td>
</tr>
<tr>
<td>5</td>
<td>420 – 510</td>
<td>315 or more</td>
</tr>
</tbody>
</table>
Team currently worked on an EF-scale ‘standard’ to be administered by ASCE

• Canadian revisions to be considered for adoption

• Hoping to accept annual proposals for modifications starting in a couple of years
Tornado Damage Studies

Greg Kopp

WindEEE Dome

Canada
Where / when do tornadoes occur?

Newark 1984 – max. frequency just over 2 tornadoes / 10,000 km²

Average annual frequency of tornadoes per 10,000 km² (dashed isopleths have been extrapolated)
Where / when do tornadoes occur?

Etkin et al. 2001 – max. frequency 7 - 9 tornadoes / 10,000 km$^2$
Where / when do tornadoes occur?

- Measures include anchors in manufactured and permanent structures, masonry ties in permanent structures (schools, hospitals, auditoriums) – relatively inexpensive to implement for new buildings
- BUT implementation required clear definition of ‘tornado-prone’ regions of Canada
- Multi-disciplinary research initiative within EC (Auld, Burrows, Cheng, Elliott, Klaassen, McCarthy, Rousseau, Shephard, Sills, Waller)
Methods

• Needed to build an updated 30-year national database
  – Last database by Newark 1950-1979
  – Period of database for this work **1980-2009**
  – Five regions all with their own databases, needed to be merged and any inconsistencies addressed
  – Used TOP approach (see Sills et al. 2004)

• Needed to develop method to fill known gaps in data
  – Under-reporting in rural / remote areas
Tornado Incidence (verified)

30-yr Average Annual Tornado Incidence (1980-2009)

- National: 61.9
- British Columbia: 0.6
- Alberta: 15.4
- Saskatchewan: 18.0
- Manitoba: 9.6
- Ontario: 12.5
- Quebec: 4.7
- Atlantic: 1.2
Seasonal Variation (all)

Tornadoes By Month / F-scale

N = 1844
Hourly Variation (all)

85% between 1 pm and 8 pm
For 1980-2009 (30-yr) period

Notable tornado events:

- Barrie / Grand Valley ON F4s (1985)
- Edmonton AB F4 (1987)
- Elie MB F5 (2007)
- Southern ON (18 tornadoes F0-F2, 2009)

Average path length = 10450 m
Average path width = 260 m
Average number of fatalities / year = 2
Average number of injuries / year = 29

(biased by large fatality / injury events)
~62 tornadoes/year verified across Canada based on 1980-2009 data
Lightning flash density (flashes/km²/year) on 50 km grid

CLDN 1999-2008
Bayesian Statistical Modelling

• Use CLDN lightning flash density climatology to model tornado incidence, but use a population density mask to adjust for population bias

  • In high population areas, use observed tornado count

  • Otherwise, ‘true’ tornado count is modeled as a Poisson regression with lightning flash density as predictor, and weighted by population density
Canada & U.S. F0-F5 tornado occurrence (1980-2009) on 50-km grid
‘Probability of detection’ weighting mask based on population density (2001 census) on 50 km grid

POD=1 for ≥ 6 persons / km²
Resulting tornado density on 50 km grid

~230 tornadoes/yr modelled across Canada!

Max. frequency 7 - 9 tornadoes / 10,000 km²
Partitioning by F-scale

- Use F2-F4 log-linear slope relationship (*Brooks and Doswell, 2001*) and modelled tornado counts to partition all tornado occurrences by F-scale rating.

**Assumption:** all areas of Canada have the same F2-F4 slope.
‘Tornado-Prone’ Definitions

1. Prone to Significant Tornadoes

Probability of an F2-F5 tornado is estimated to exceed $10^{-5} / \text{km}^2 / \text{year}$. F0-F1 tornadoes will be more frequent.

2. Prone to Tornadoes

Probability of an F0-F1 tornado is estimated to exceed $10^{-5} / \text{km}^2 / \text{year}$.

3. Tornadoes Observed - Rare

Tornadoes observed, but probability of a tornado is between $10^{-5}/\text{km}^2/\text{year}$ and $10^{-6}/\text{km}^2/\text{year}$.

*(threshold of $10^{-5} / \text{km}^2 / \text{year}$ consistent with engineering literature)*
Tornado-prone map published in National Building Code - 2011
All confirmed and probable tornadoes by Fujita (F) scale (historical-2009)
Tornado-prone regions of Canada by Fujita (F) scale (shaded)

- Prone to F2 - F5 tornadoes
- Prone to F0 F1-2 tornadoes
- Tornadoes observed (rare)

- F5
- F4
- F3
- F2
- F1
- F0
Tornado Frequency Analysis (25 km grid)

Cheng et al. (2013, J. Climate)
How does EC provide tornado alerts?

• Examples of recent supercell and nonsupercell tornado events to illustrate EC’s watch / warning process and inherent difficulties…”
Goderich Tornado
21 Aug 2011

Time: 1555 LT (land)
Path length: 20.5 km
Max path width: 1.5 km
Fatalities: 1
Injuries: 37
Estimated Cost: $150M
0.5° Doppler Precipitation Scan
Mesocyclone with 7 km diameter, 70 m s$^{-1}$ delta-V, and shear 0.01 s$^{-1}$
Mesocyclone with 7 km diameter, 70 m s\(^{-1}\) delta-V, and shear 0.01 s\(^{-1}\)
Gate-to-gate shear (TVS) 34 m s\(^{-1}\)
0.5° Doppler Precipitation Scan

1550 LT
Supercell / Pre-existing Boundary
A Very Rare Event

• Occurred well behind cold front
• Supercell / tornado developed over Lake Huron
• Widely used tornado prediction parameters suggested little chance of a significant supercell tornado
• Tornado climatology shows very low frequency in Goderich area and very infrequent F3+ in general
EC Hi-RES NWP Model
EC Alerts

- Tornado began to impact Goderich at **3:55 PM**
- **Severe Thunderstorm Watch** issued for Goderich: **2:02 PM**
  - included the line “A tornado is possible”
  - lead time ~ 2 hours
- **Tornado Warning** issued for Goderich: **3:48 PM**
  - “moving southeast at 75 km/h and will make landfall near Goderich near 4 PM”
  - lead time ~7 minutes
  - Might have been sooner but marine warning issued first
- So despite rare situation, acceptable lead time for many in path
- But who heard the message??
18 Apr 2013 EF1 @ Shelburne

• Occurred at leading edge of small bow echo embedded in squall line – rain-wrapped!

• 10 km track, main damage to barn
EC Hi-RES NWP Model
EC Alerts

- Tornado caused first damage at 5:33 PM
- Severe Thunderstorm Watch issued at 12:11 PM
  - More than 5 hours lead time
  - “Storms could contain large hail and damaging winds”, but no mention of tornadoes
- Severe Thunderstorm Warning issued at 5:37 PM
  - 1 minute lead time for area of worst damage
  - “Most of these storms are not severe, however one or two could produce wind gusts to 90 km/h and large hail”, and no mention of tornado potential
- Snowfall, freezing rain and rainfall warnings also out
- Warnings for ‘bow echo’ tornadoes are very difficult, even worse for ‘landspout’ tornadoes!
‘Next Generation’ Warnings

• interactive Convective Analysis and Storm Tracking (iCAST) prototype – optimizes the human-machine mix

• New approach to severe thunderstorm nowcasting and alerting

• Forecaster manages ‘track’ MetObjects / intensity trends for significant storms

• Alerts then derived from MetObjects

• To be demonstrated (internally) during Pan Am Games in 2015
Human-machine mix:

- *Interactive* ‘Storm Attributes Table’ used to rank storms – *smart filter*
- *Modifiable* 30-min *nowcast* ‘rank weight’ – *warn on nowcast*
- Storm track nowcasts and intensity trends determine if a *first-guess warning area* is generated, modified by forecaster as necessary
TORNADO WARNING FROM ENVIRONMENT CANADA AT 7:10 PM EDT THURSDAY 28 JULY 2012.

TORNADO WARNING FOR:
=NEW= GODERICH – BLUEWATER – SOUTHERN HURON COUNTY

A SEVERE THUNDERSTORM PRODUCING TORNADOES, LARGE HAIL, DAMAGING WINDS AND HEAVY RAIN 10 KM SOUTHEAST OF GODERICH IS MOVING SOUTHEAST AT 40 KM/H. THIS STORM IS EXPECTED TO REACH SEAFORETH AT 8:05 PM EDT.

En français aussi!
TORNADO WARNING FROM ENVIRONMENT CANADA AT 7:10 PM EDT THURSDAY 28 JULY 2012.

TORNADO WARNING FOR:
=NEW= GODERICH – BLUEWATER – SOUTHERN HURON COUNTY

A SEVERE THUNDERSTORM PRODUCING TORNADOES, LARGE HAIL, DAMAGING WINDS AND HEAVY RAIN 10 KM SOUTHEAST OF GODERICH IS MOVING SOUTHEAST AT 40 KM/H. THIS STORM IS EXPECTED TO REACH SEAFORETH AT 8:05 PM EDT.

En français aussi!
Are tornadoes increasing in frequency / intensity?
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We (unfortunately) don’t know, and likely won’t for a long time!
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- Low sample size (rare events)
- Numerous artifacts in data (tornadoes vs. downbursts, EC resources, rise of commercial electronics, storm chasers, etc.)
Are tornadoes increasing in frequency / intensity?

Annual Number of Tornadoes and Tornado Days in Canada
Nombre de tornades et de jours de tornade annuels au Canada
(1970-2009)

Number of Tornadoes/Days (Nombre de tornades/Jours)

1980

N = 1844
Acknowledgements

- Joan Klaassen, Brad Rousseau, Patrick McCarthy, Arnold Ashton, Norbert Driedger, Brian Greaves, Emma Hung, Bob Paterson, Neil Taylor, Bill Burrows, Pat King, Mike Leduc (all EC)
- Vincent Cheng (EC – UofT)
- Greg Kopp (Western University)
- Ed Mahoney / Jim LaDue (NWS Warning Decision Training Branch)
References


References (cont’d)


Questions?

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