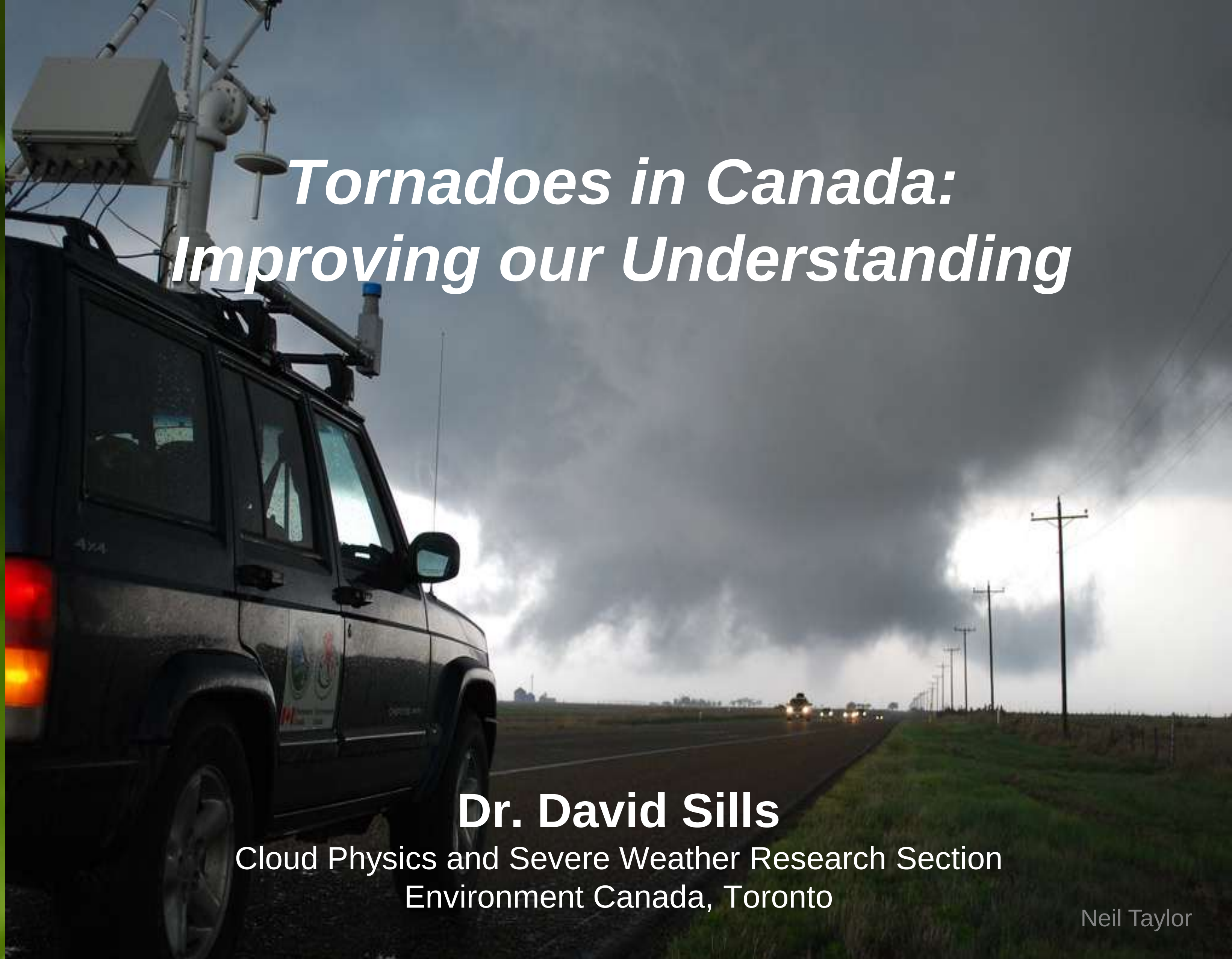
2013

Tornadoes in Canada: Improving our Understanding

David Sills

Tornadoes in Canada: Improving our Understanding



Dr. David Sills

Cloud Physics and Severe Weather Research Section

Environment Canada, Toronto

Neil Taylor

Environment Canada Environnement Canada

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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?

Photo by Justin Hobson

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

How do tornadoes form?



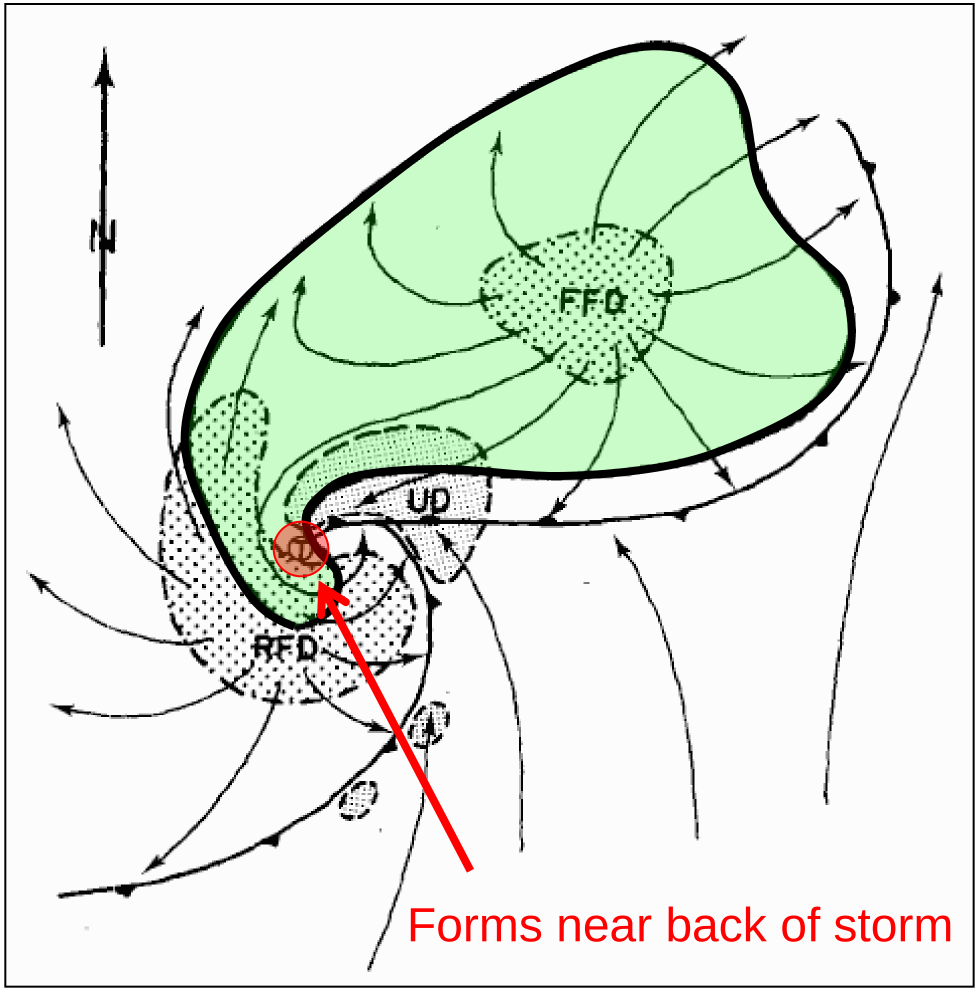

Tornadoes *can* occur with any storm type:

- 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

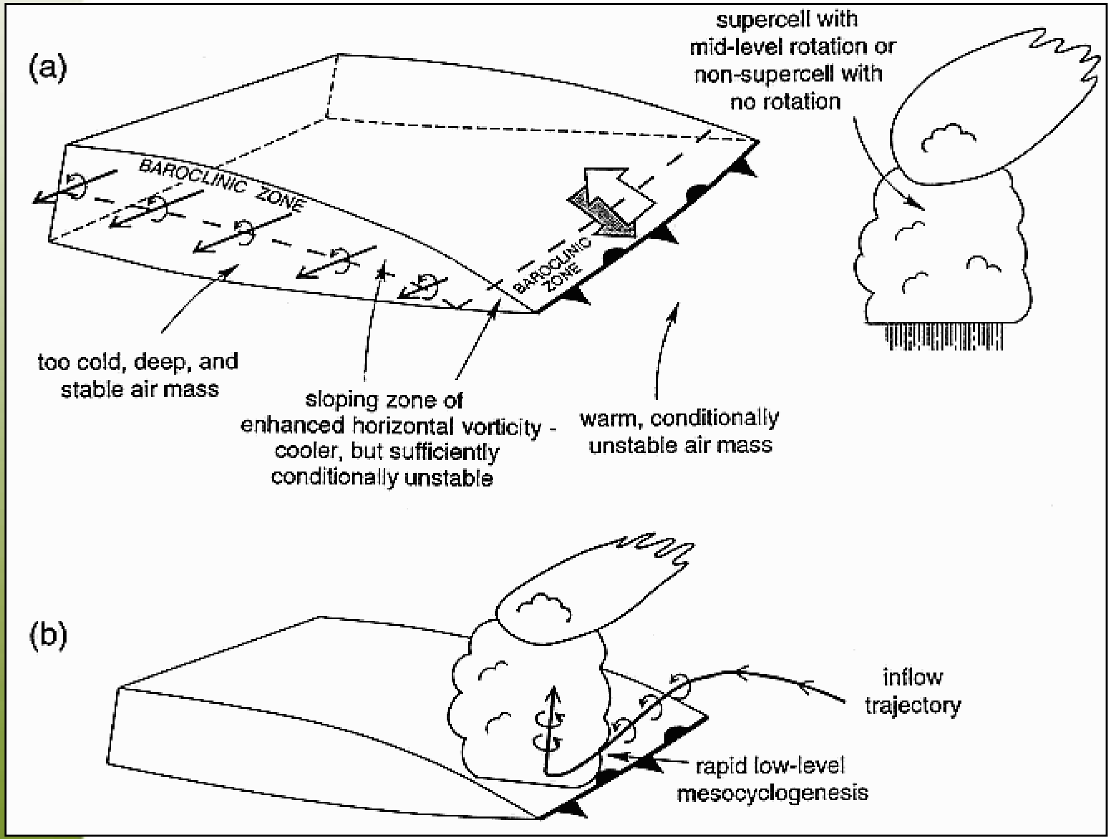
- Most supercells are *not* tornadic
- However, most *significant* tornadoes and nearly all *violent* (F4-F5) tornadoes are supercell tornadoes
- Many supercell tornadogenesis theories have evolved through field and modelling work: area of active research
- In the 1970's, Doppler radar used to identify 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



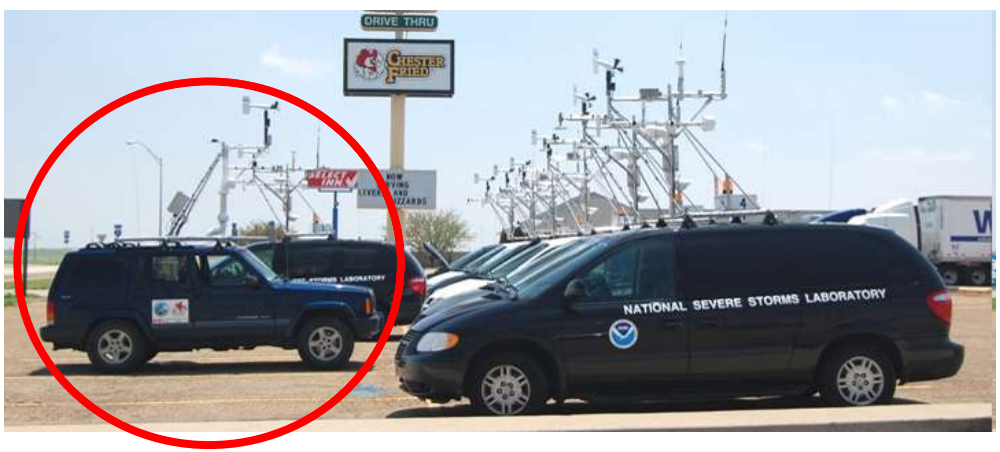
- Conceptual *supercell* diagram Lemon and Doswell (1979)
- ‘Top-down’ tornado-genesis process: MLM-> LLM-> TVS-> tornado
- High-resolution numerical models appeared to support this paradigm
- Was thought that the VORTEX1 study in 1994/95 would confirm this conceptual model…

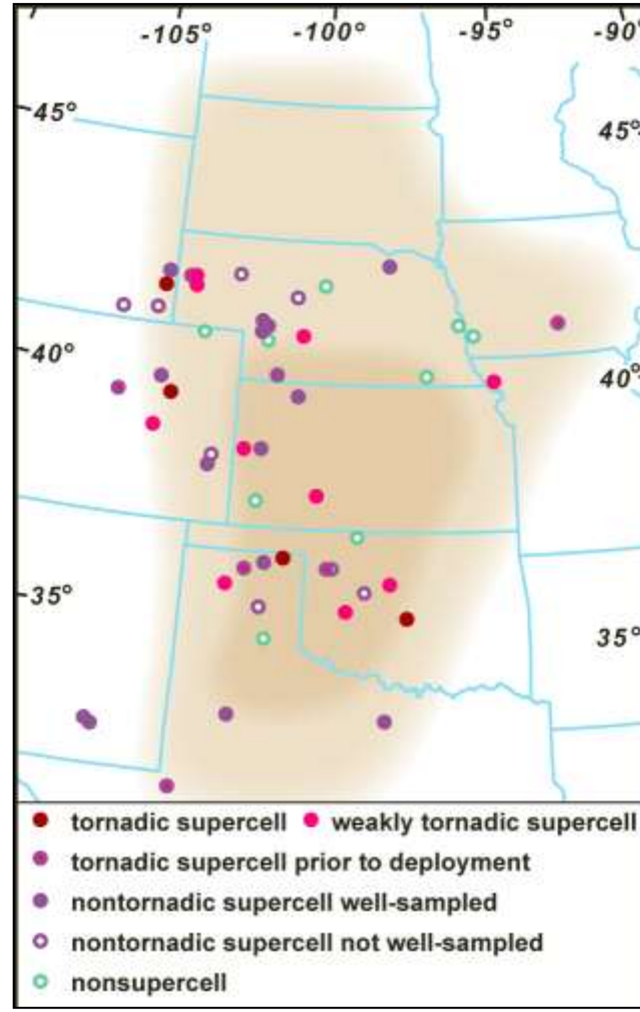
Pre-existing Boundary Paradigm



- 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





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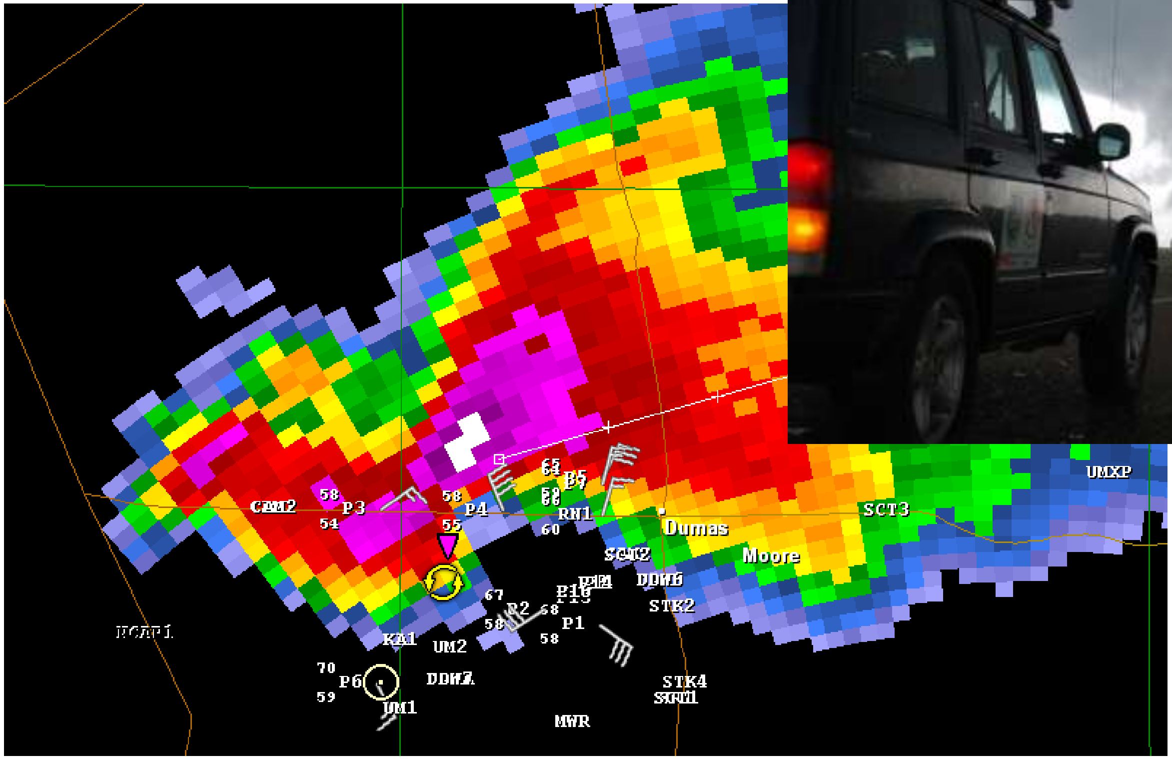
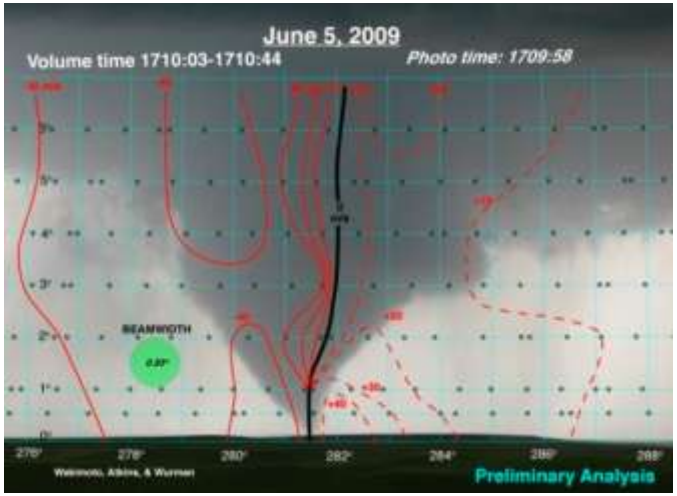
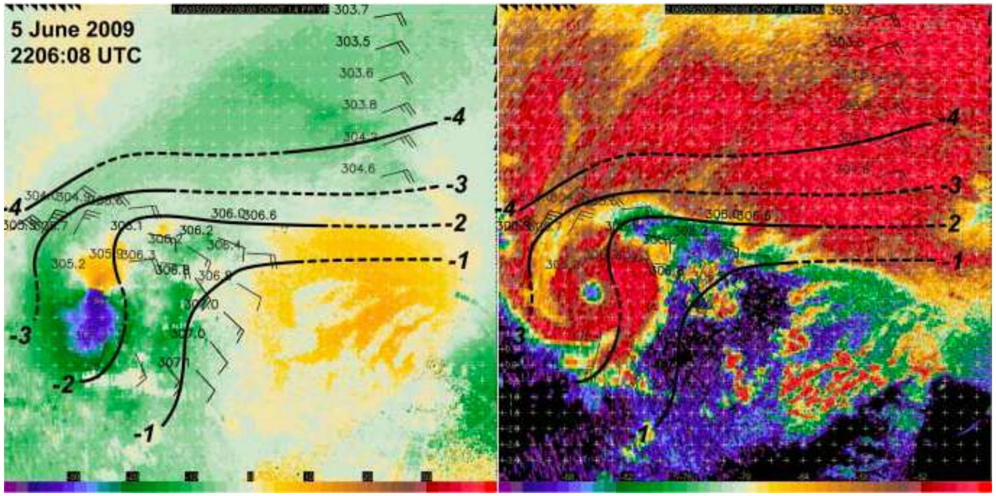
VORTEX2 Field Project – 2009-10

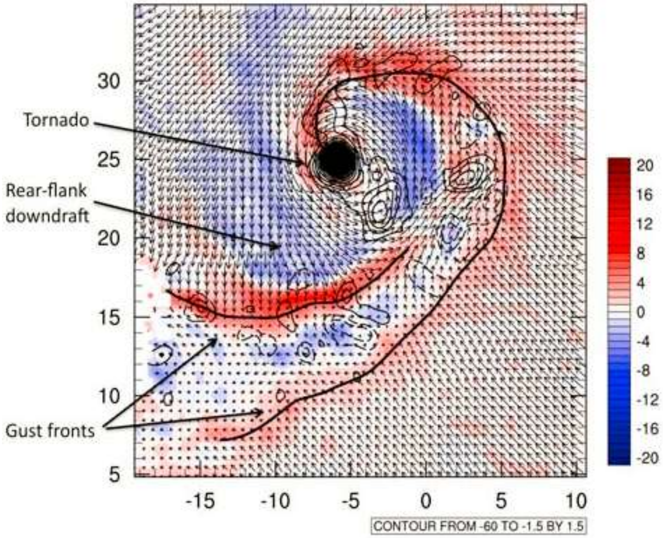
18 May 2010
Dumas, TX
tornadic supercell

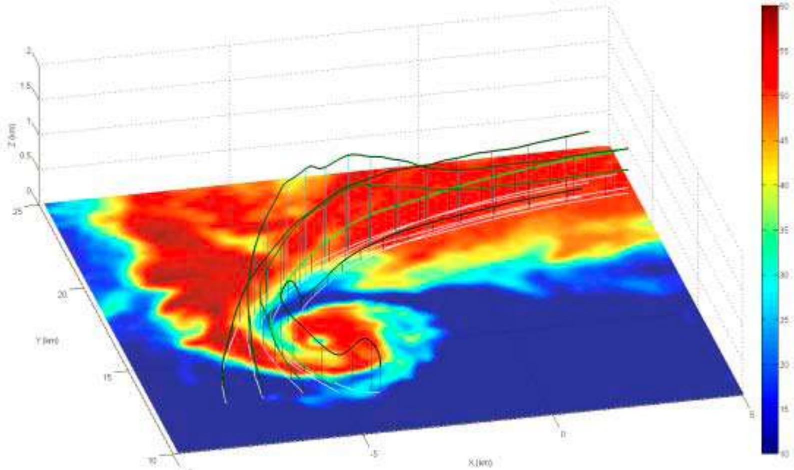


5 June 2009 Goshen Co. Tornado









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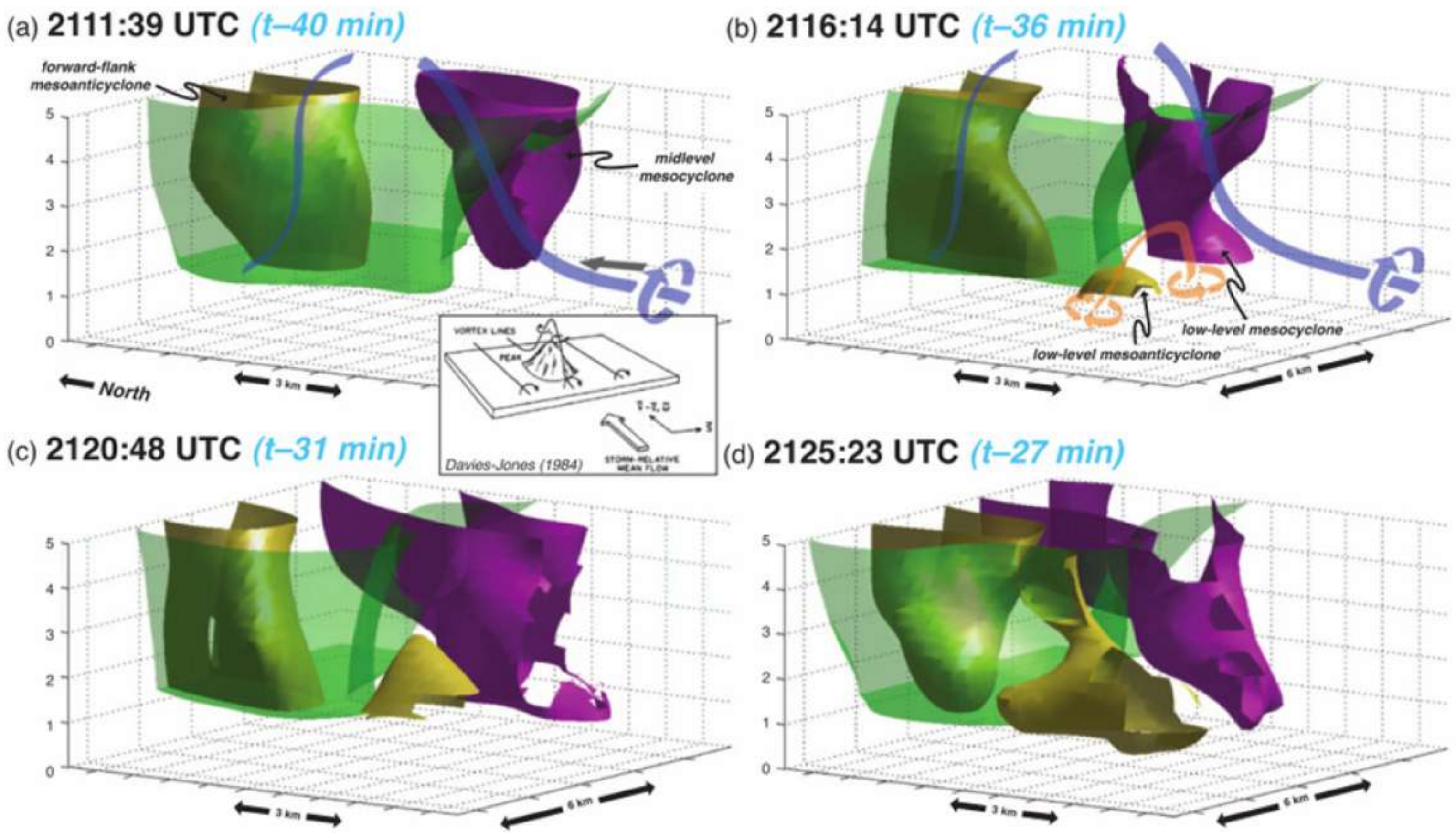
5 June 2009 Goshen Co. Tornado



Markowski et al., 2012

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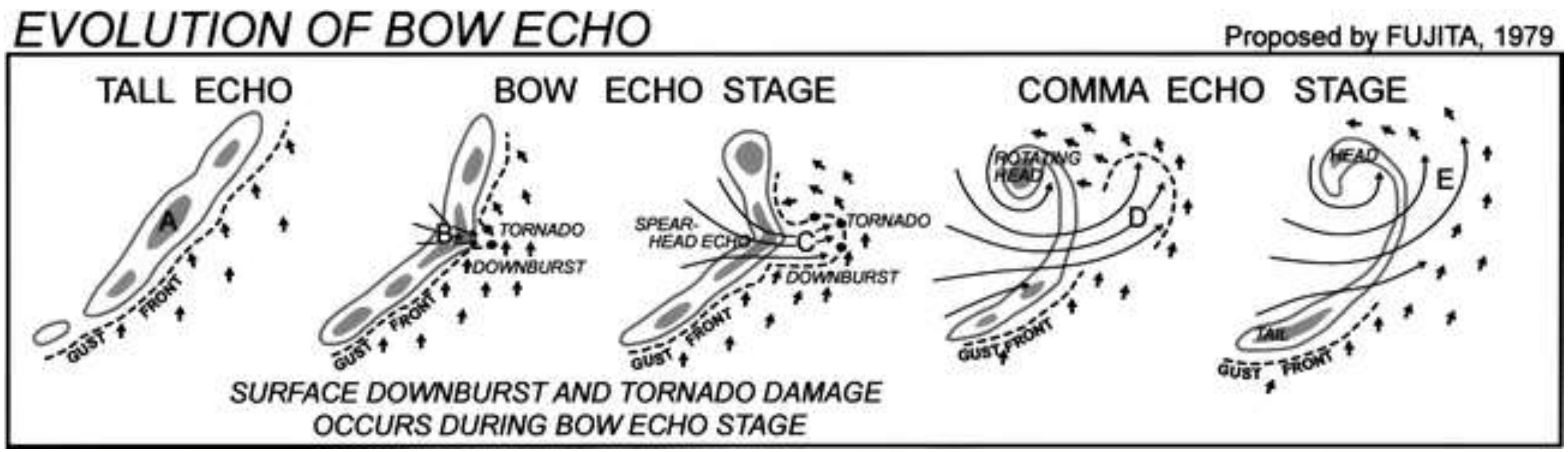
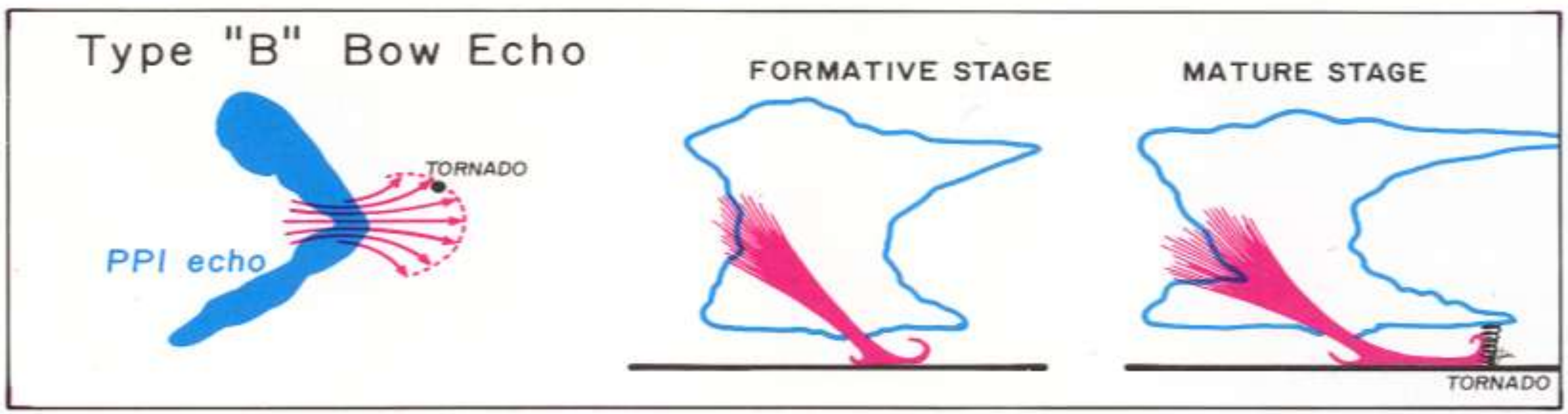
‘Bow Echo’ Tornadoes

- ‘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!)

‘Bow Echo’ Tornadoes





Fujita, T.T. (1985). "The Downburst: microburst and macroburst". SMRP Research Paper 210, 122 pp.

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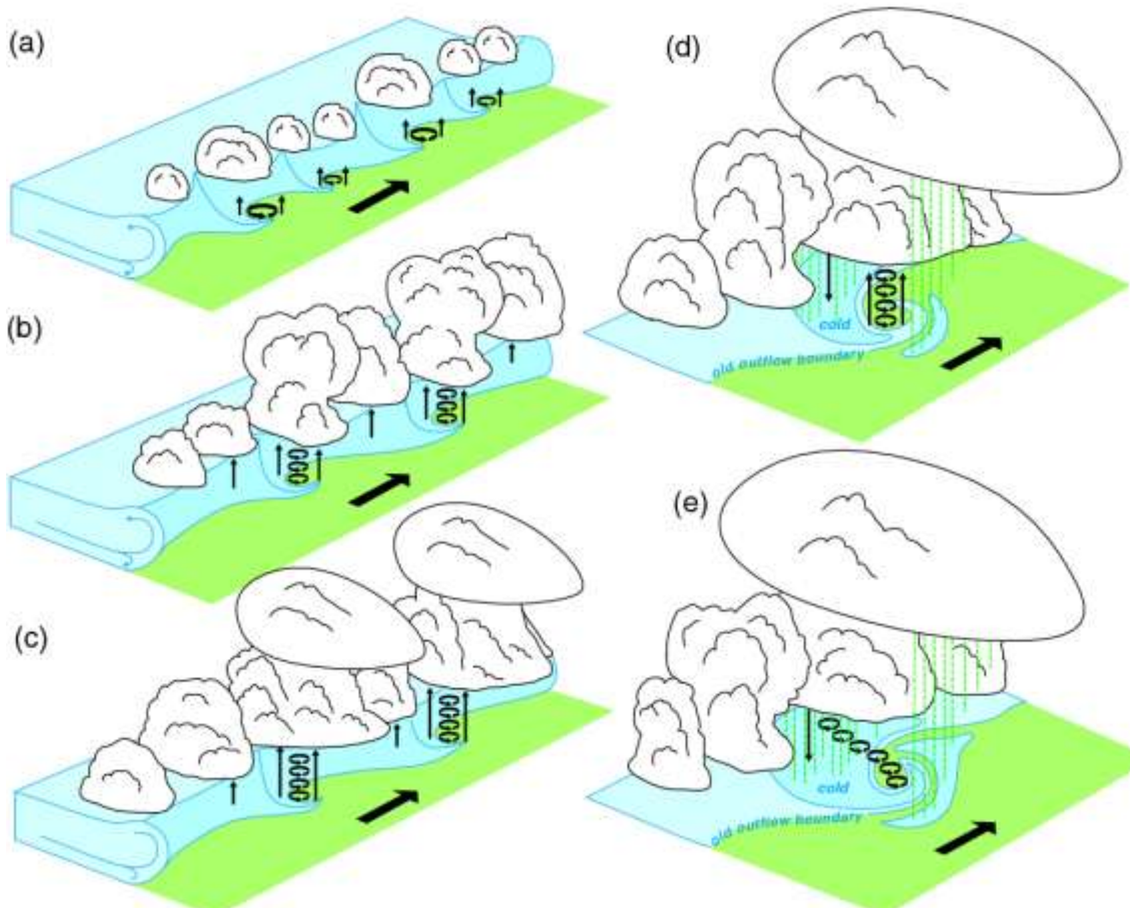
‘Landspout’ Tornadoes

- 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

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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?

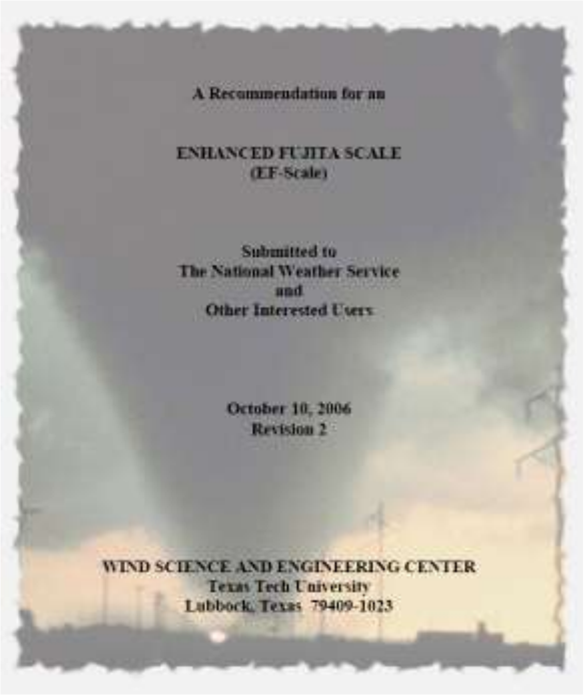
- Fujita Scale
- Developed by Ted Fujita at Univ. of Chicago in the 1960s
- Wind speeds were educated guesses
- Limited number of damage indicators
- Used for tornadic and non-tornadic wind damage
- Implemented in the US and Canada in 1970s

F-scale Category	Estimated Wind Speed Range (mph)	Typical Damage
F0	40 - 72	*Light damage.* Some damage to chimneys; branches broken off trees; shallow-rooted trees pushed over; sign boards damaged.
F1	73 - 112	*Moderate damage.* Peels surface off roofs; mobile homes pushed off foundations or overturned; moving autos blown off roads.
F2	113 - 157	*Considerable damage.* Roofs torn off frame houses; mobile homes demolished; boxcars overturned; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground.
F3	158 - 206	*Severe damage.* Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off the ground and thrown.
F4	207 - 260	*Devastating damage.* Well-constructed houses leveled; structures with weak foundations blown away some distance; cars thrown and large missiles generated.
F5	261 - 318	*Incredible damage.* 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.

From Fujita (1981)

Enhanced Fujita Scale

- 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 for use in the United States in 2007
- 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



A Recommendation for an

ENHANCED FUJITA SCALE
(EF-Scale)

Submitted to
The National Weather Service
and
Other Interested Users

October 10, 2006
Revision 2

WIND SCIENCE AND ENGINEERING CENTER
Texas Tech University
Lubbock, Texas 79409-1023

Damage Indicators (DI)

Number	Damage Indicator (DI)
1	Small Barns or Farm Outbuildings (SBO)
2	One- or Two-Family Residences (FR12)
3	Manufactured Home: Single Wide (MHSW)
4	Manufactured Home: Double Wide (MHDW)
5	Apartments, Condos, Townhouses (ACT)
6	Motel (M)
7	Masonry Apartment or Motel (MAM)
8	Small Retail Building (SRB)
9	Small Professional Building (SPB)
10	Strip Mall (SM)
11	Large Shopping Mall (LSM)
12	Large, Isolated Retail Building (LIRB)
13	Automobile Showroom (ASR)
14	Automobile Service Building (ASB)
15	Elementary School (ES)
16	Junior or Senior High School (JHSH)
17	Low-Rise Building: 1 - 4 Storeys (LRB)
18	Mid-Rise Building: 5 - 20 Storeys (MRB)
19	High-Rise Building: Greater than 20 Storeys (HRB)
20	Institutional Building (IB)
21	Metal Building System (MBS)
22	Service Station Canopy (SSC)
23	Warehouse Building (WHB)
25	Free-Standing Towers (FST)
26	Free-Standing Light Poles, Luminary Poles, Flag Poles (FSP)
C1	Electrical Transmission Lines (ETL)
C2	Trees (T)
C3	Heritage Church (HC)
C4	Solid Masonry House (SMH)
C5	Farm Silos or Grain Bins
C6	Sheds, Fences or Lawn Furniture (SFLF)

Farms / Residences

Commercial / retail structures

Schools

Professional buildings

Metal buildings / canopies

Towers / poles

New Canadian DIs!

Degrees of Damage (DoD)

1. SMALL BARNS OR FARM OUTBUILDINGS (SBO)

Typical Construction:

- Less than 250 m^2
- Wood or metal post and beam construction
- Wood or metal roof trusses
- Wood or metal panel siding
- Metal or wood roof
- Large doors

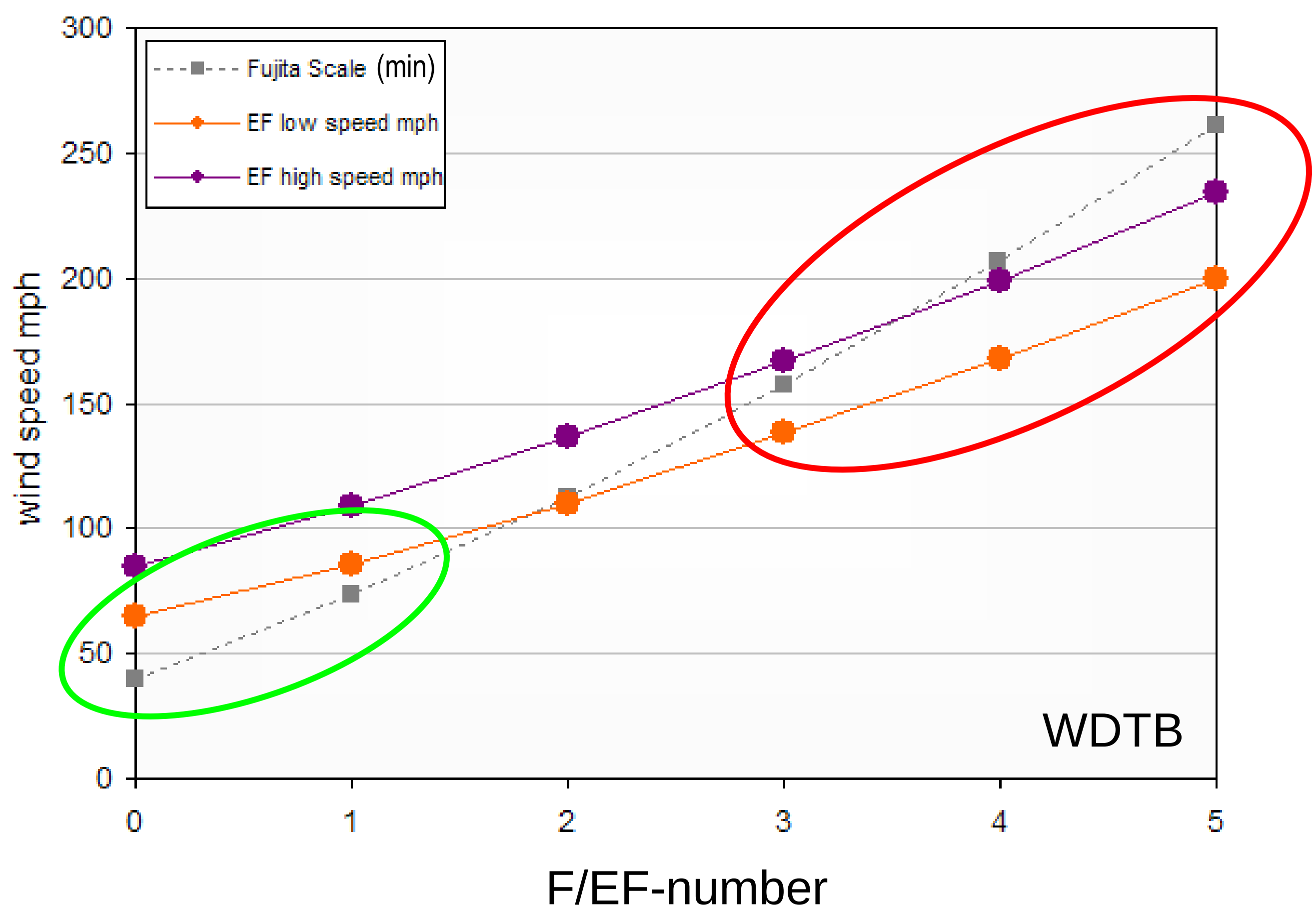
DOD	Damage Description	EXP	LB	UB
1	Threshold of visible damage	100	85	125
2	Loss of wood or metal roof panels (up to 20%)	120	100	145
3	Collapse of doors	135	110	165
4	Major loss of roof panels (more than 20%)	145	125	175
5	Uplift or collapse of roof structure (more than 50%)	150	125	185
6	Collapse of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

DODs wind speeds in km/h

F-scale vs EF-scale

- 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.

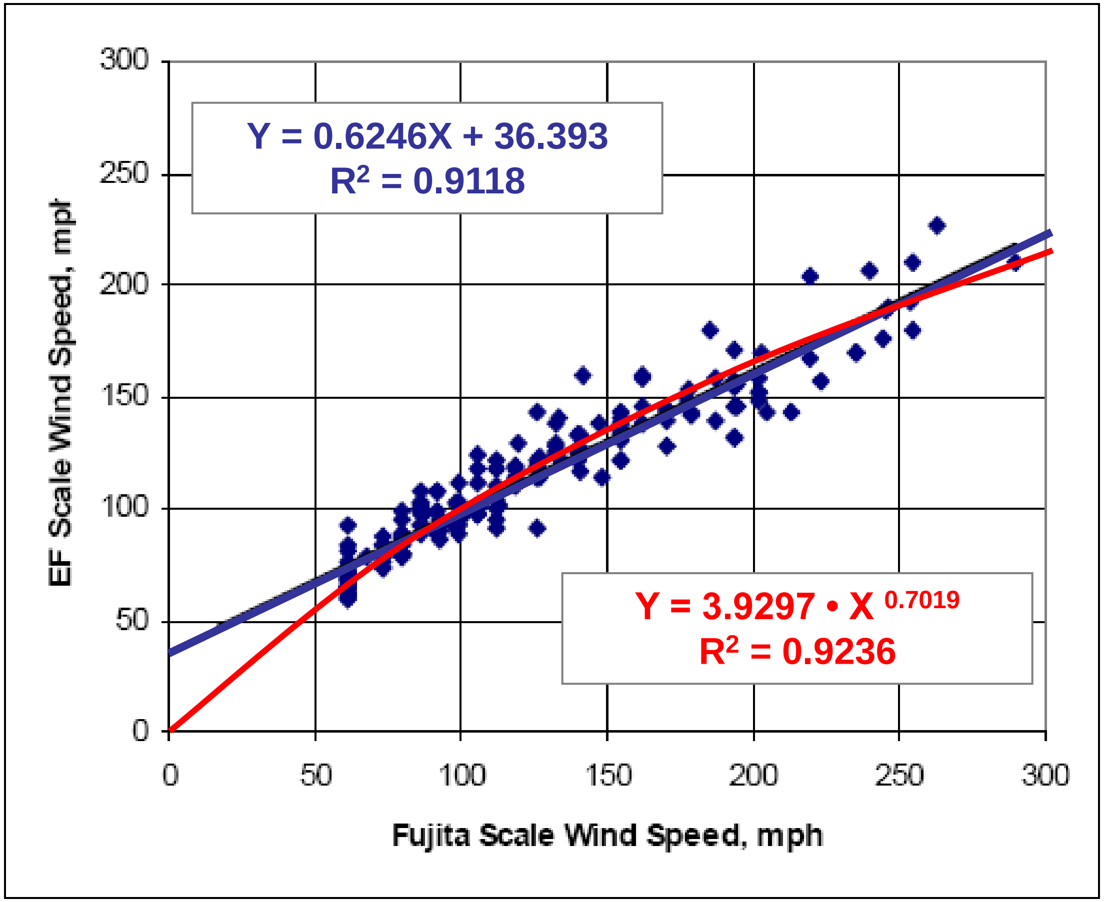
F-scale vs EF-scale



EC Implementation – Power Law

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

F/EF Rating	F-Scale Wind Speed Rounded to 10 km/h	EF-Scale Wind Speed Rounded to 5 km/h
0	60 – 110	90 – 130
1	120 – 170	135 – 175
2	180 – 240	180 – 220
3	250 – 320	225 – 265
4	330 – 410	270 – 310
5	420 – 510	315 or more

EF-Scale Standard

- 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

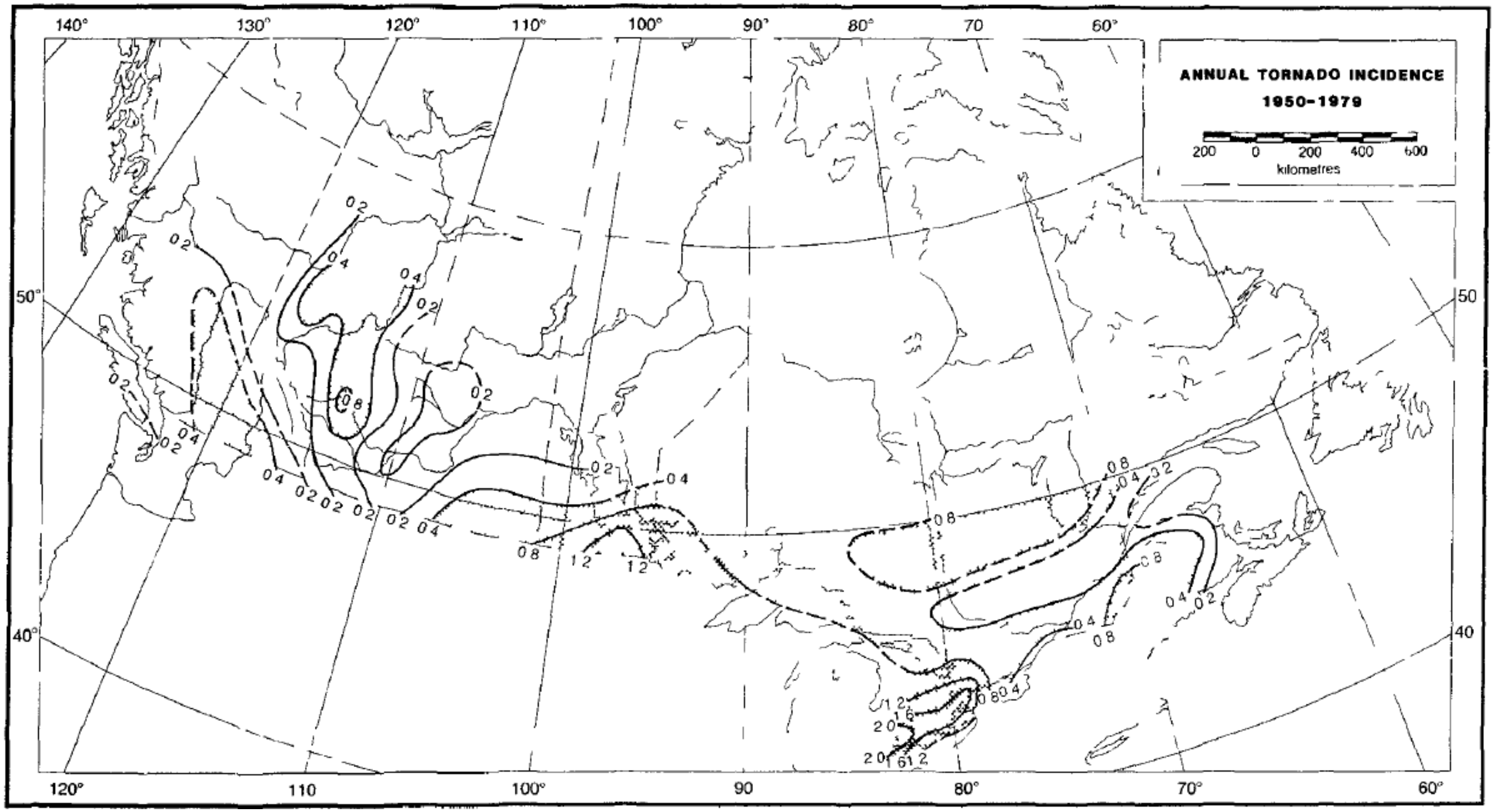
Tornado Damage Studies

Greg Kopp

WindEEE Dome

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)

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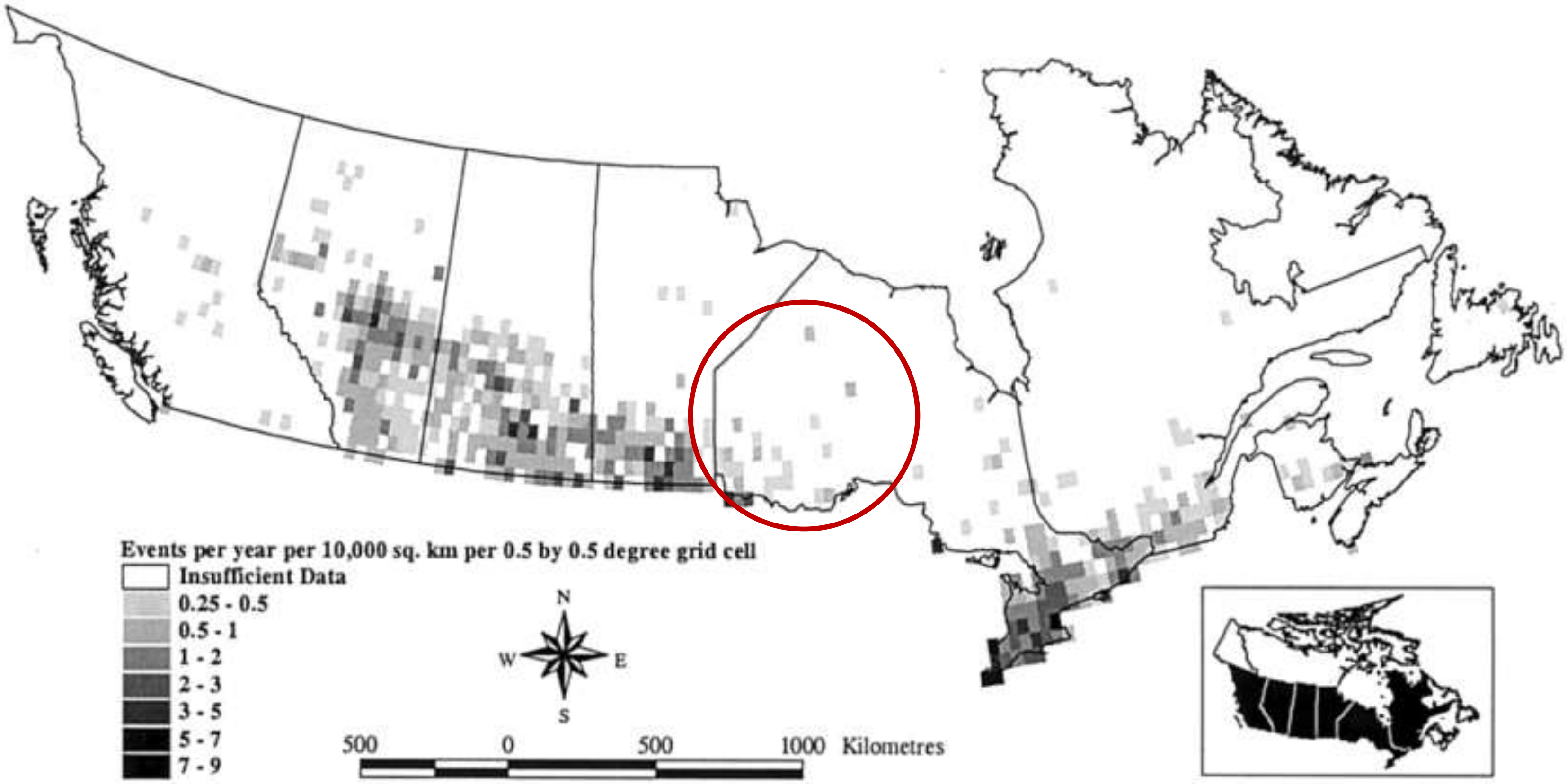
Where / when do tornadoes occur?

Etkin et al. 2001 – max. frequency **7 - 9** tornadoes / 10,000 km^2



Where / when do tornadoes occur?

- Tornado resilience measures written into National Building Code of Canada in 1995 based on forensic studies of Barrie / Grand Valley F4 tornadoes of 1985
- 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)


Barrie F4 1985

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 adressed
  - Used TOP approach (see Sills et al. 2004)
- Needed to develop method to fill known gaps in data
  - Under-reporting in rural / remote areas

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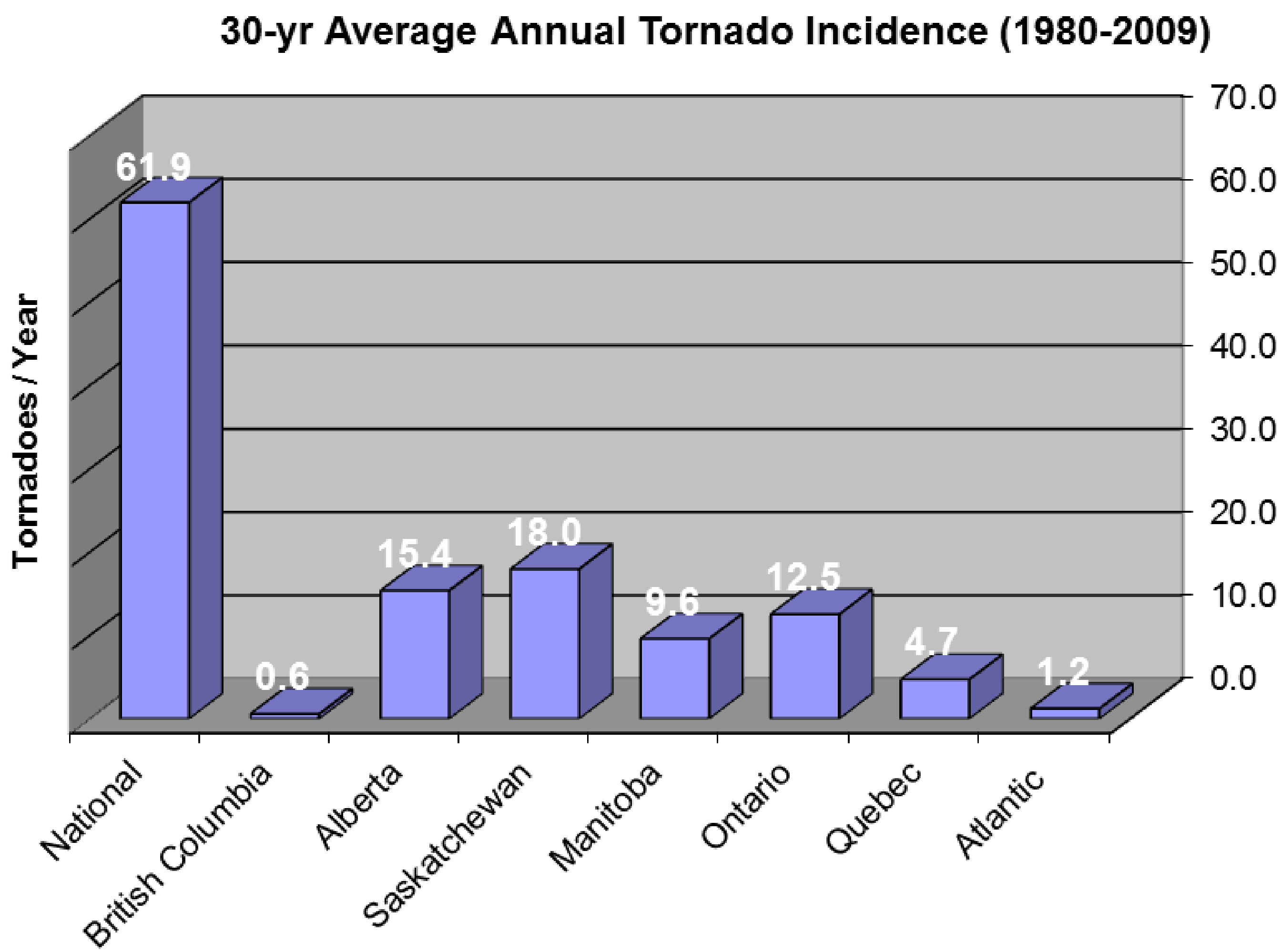
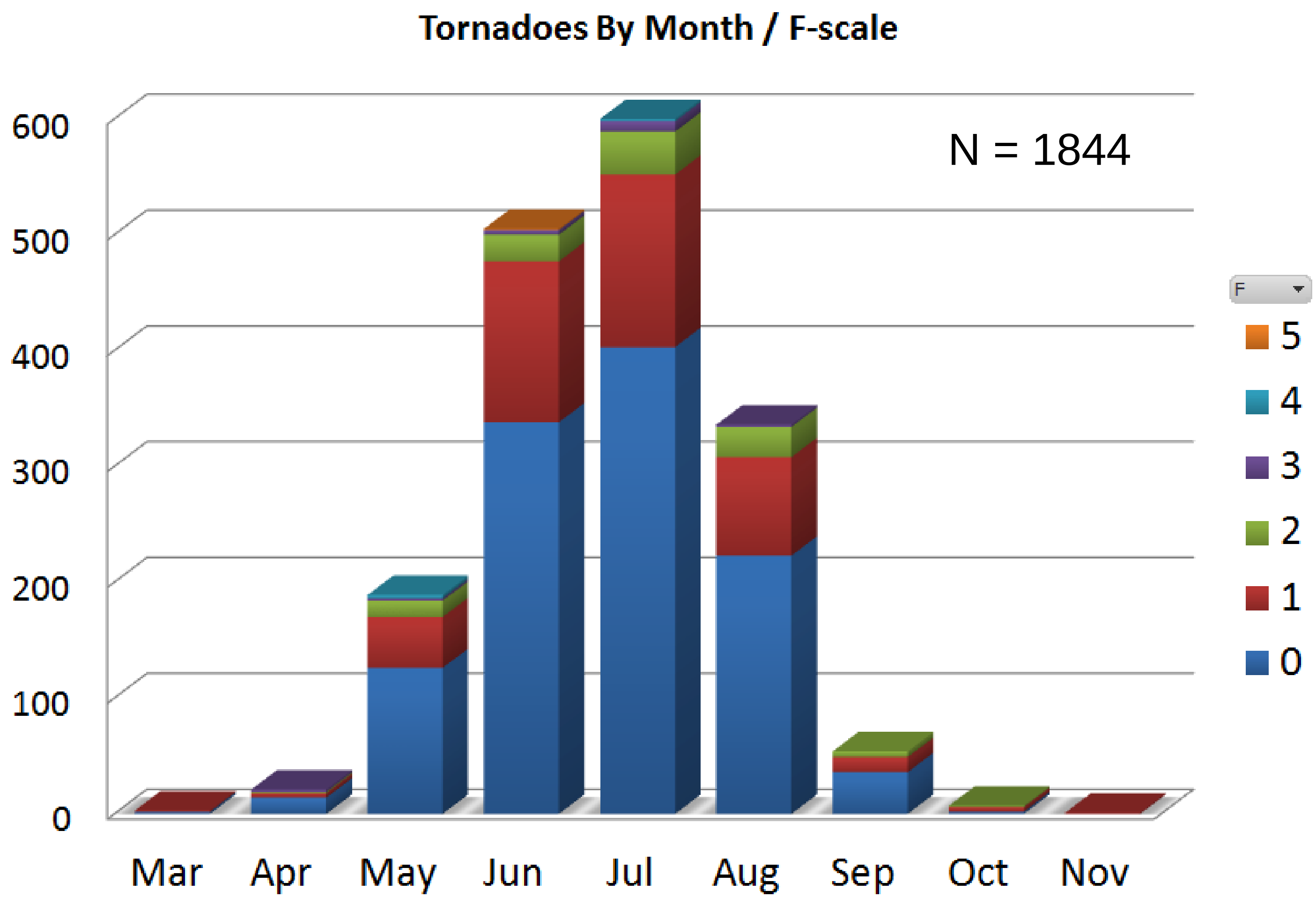
Tornado Incidence (verified)



Seasonal Variation (all)



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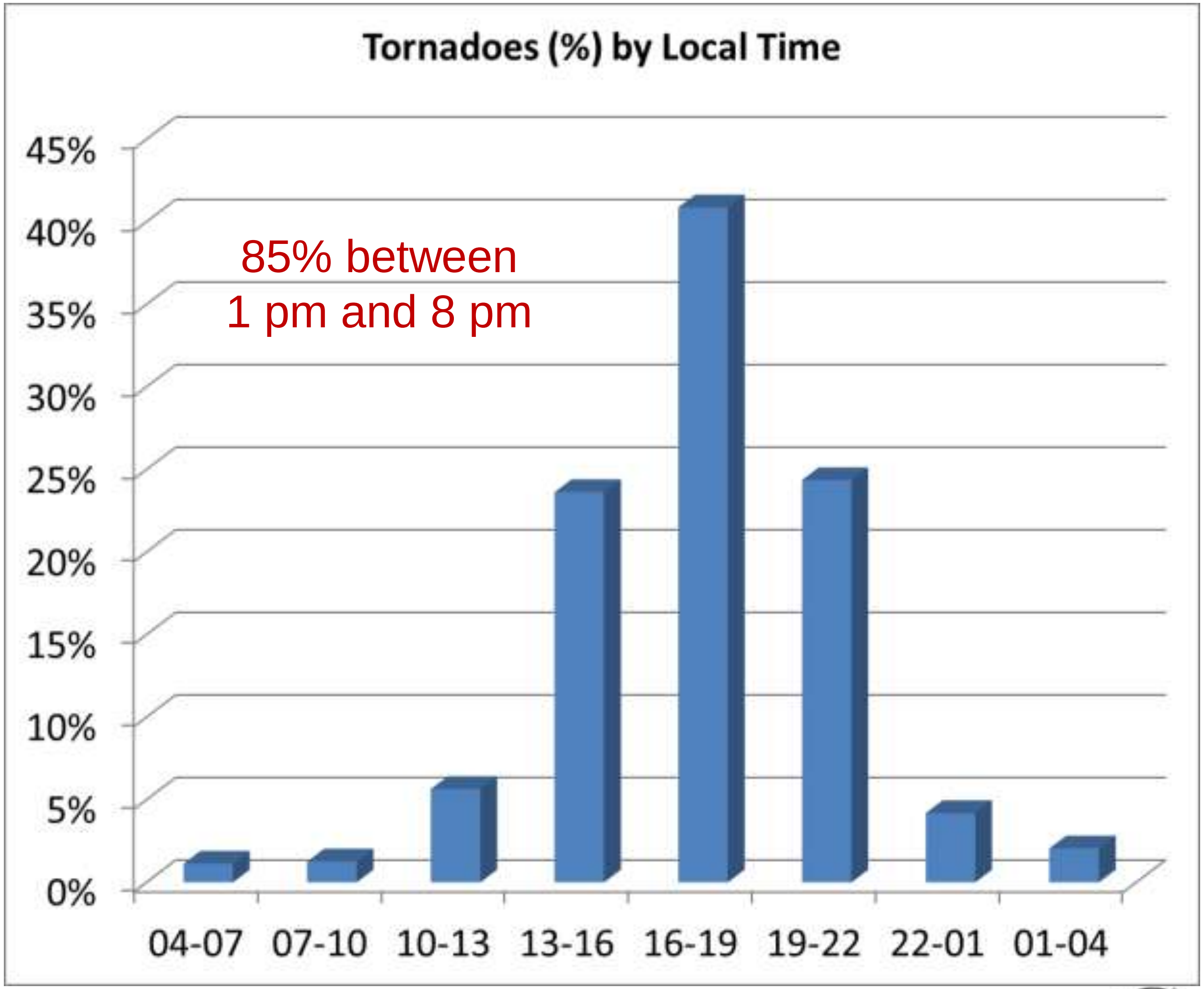
Hourly Variation (all)



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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

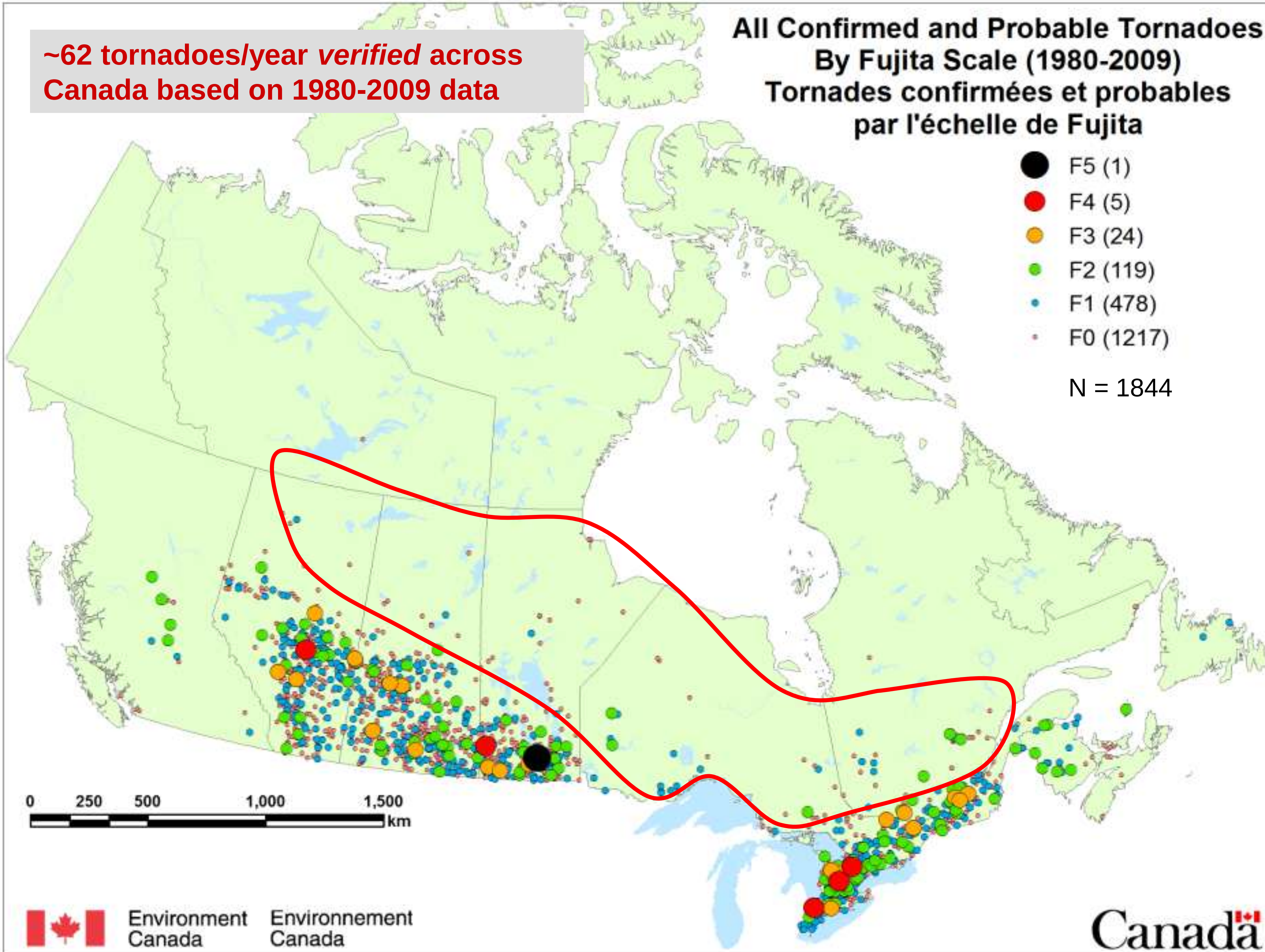
Average path width = 260 m

Average number of fatalities / year = 2

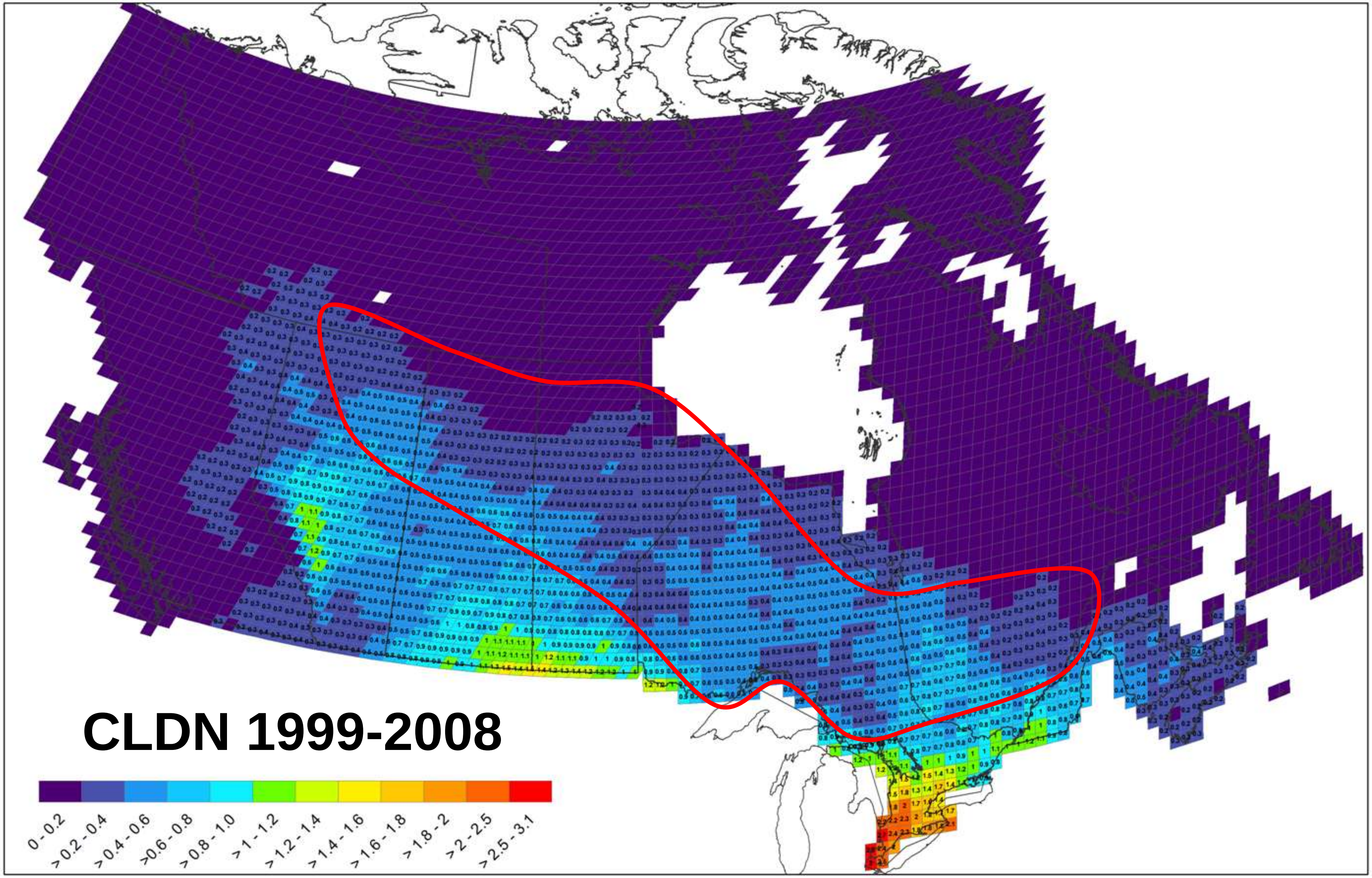
Average number of injuries / year = 29

(biased by large fatality / injury events)

~62 tornadoes/year *verified* across Canada based on 1980-2009 data



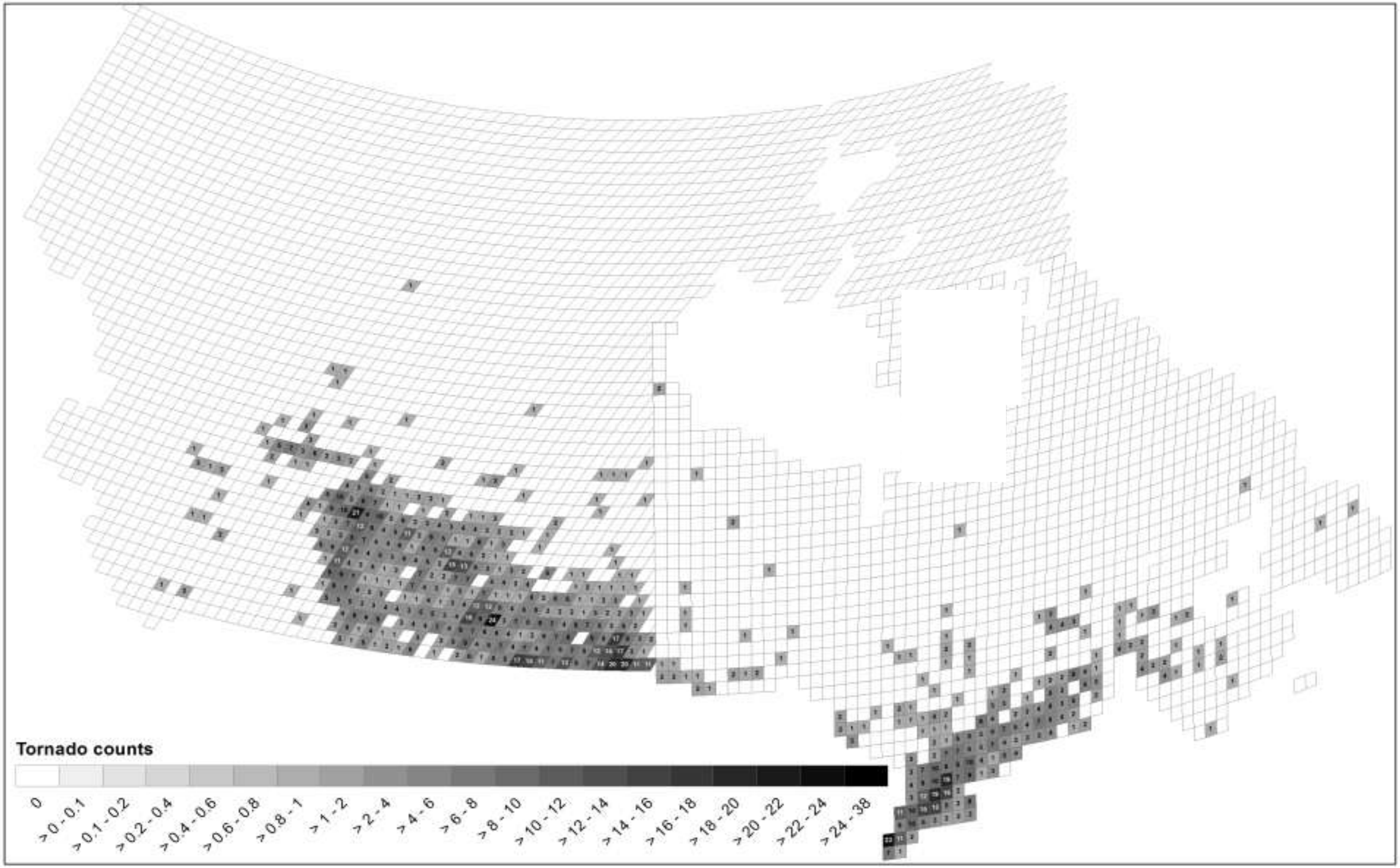
Lightning flash density (flashes/km²/year) on 50 km grid



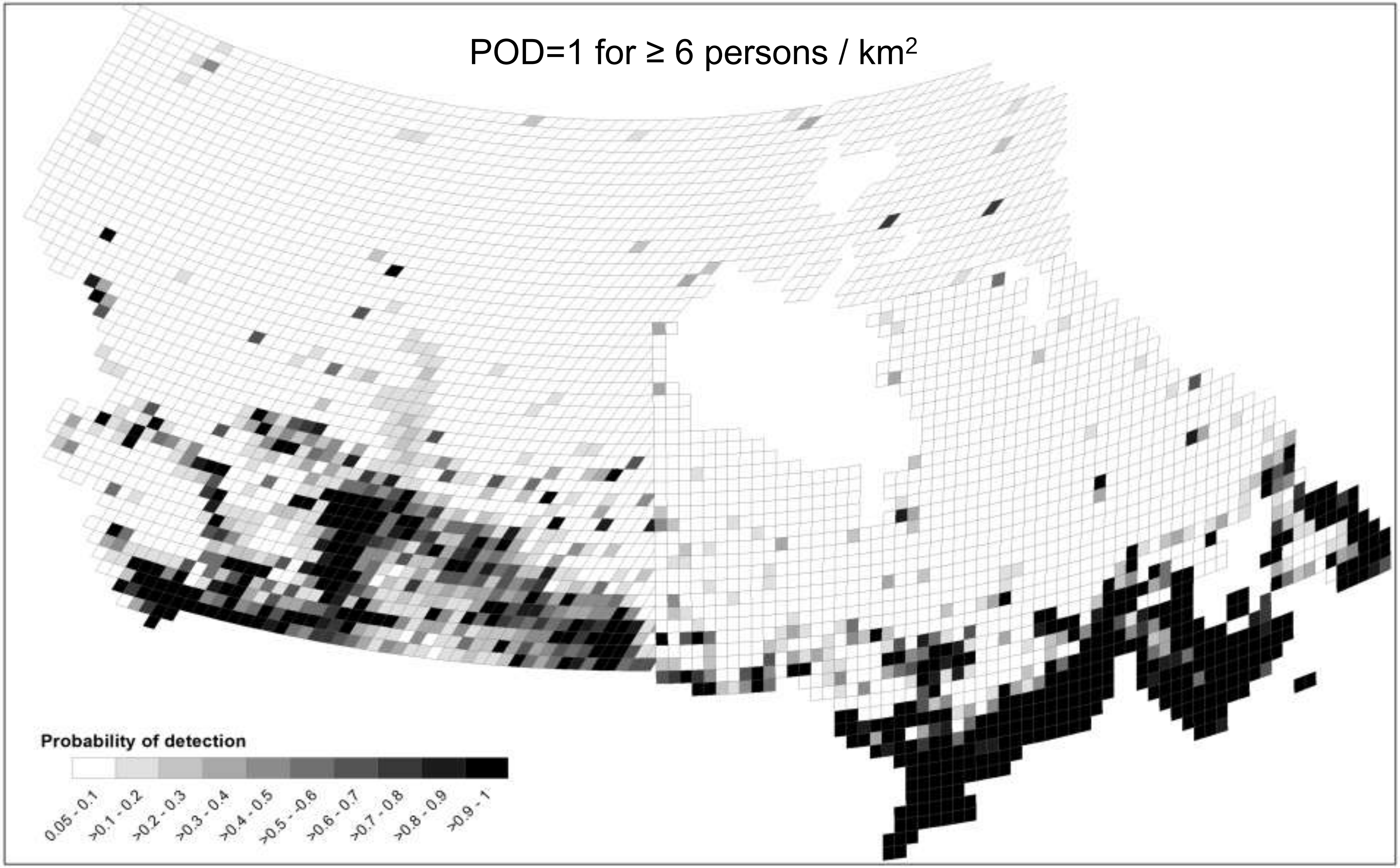
Bayesian Statistical Modelling

- 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

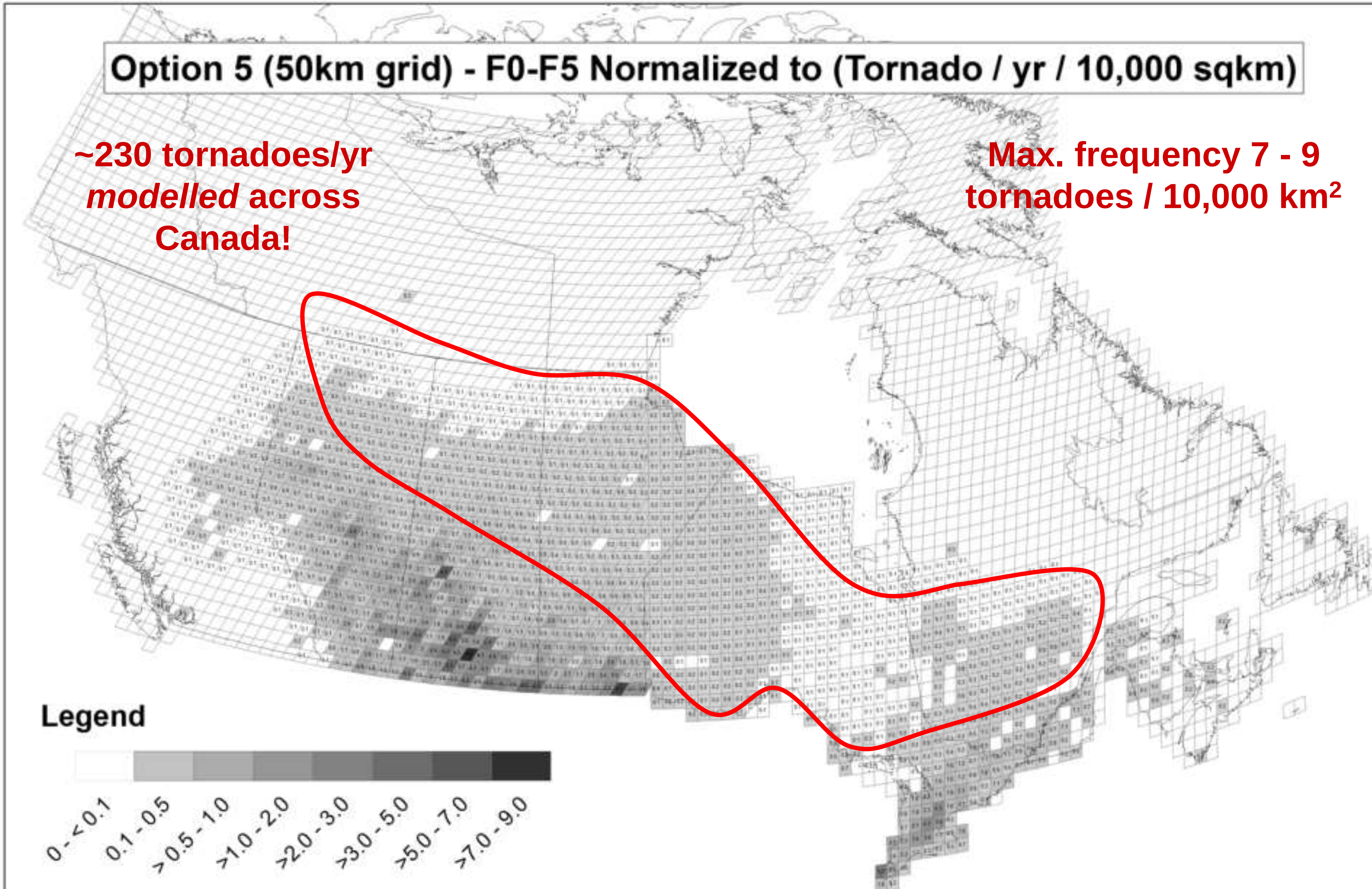
Canada & U.S. F0-F5 tornado occurrence (1980-2009) on 50-km grid



‘Probability of detection’ weighting mask based on population density (2001 census) on 50 km grid

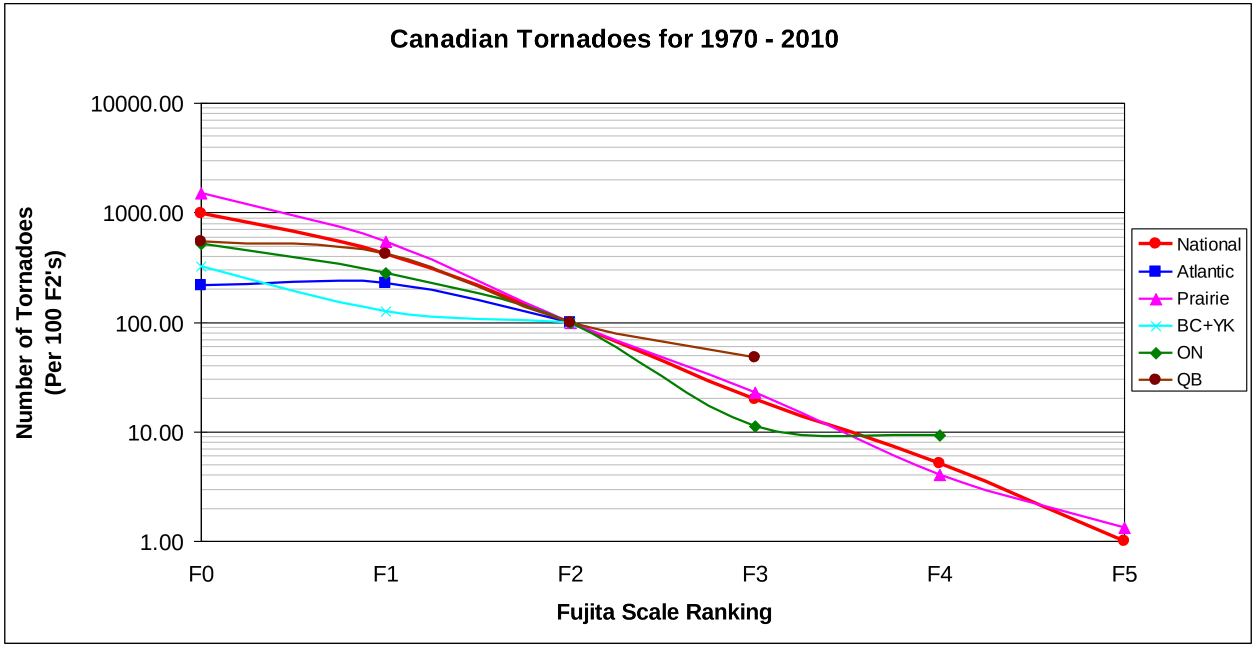


Resulting tornado density on 50 km grid



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

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‘Tornado-Prone’ Definitions

1. Prone to Significant Tornadoes

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

2. Prone to Tornadoes

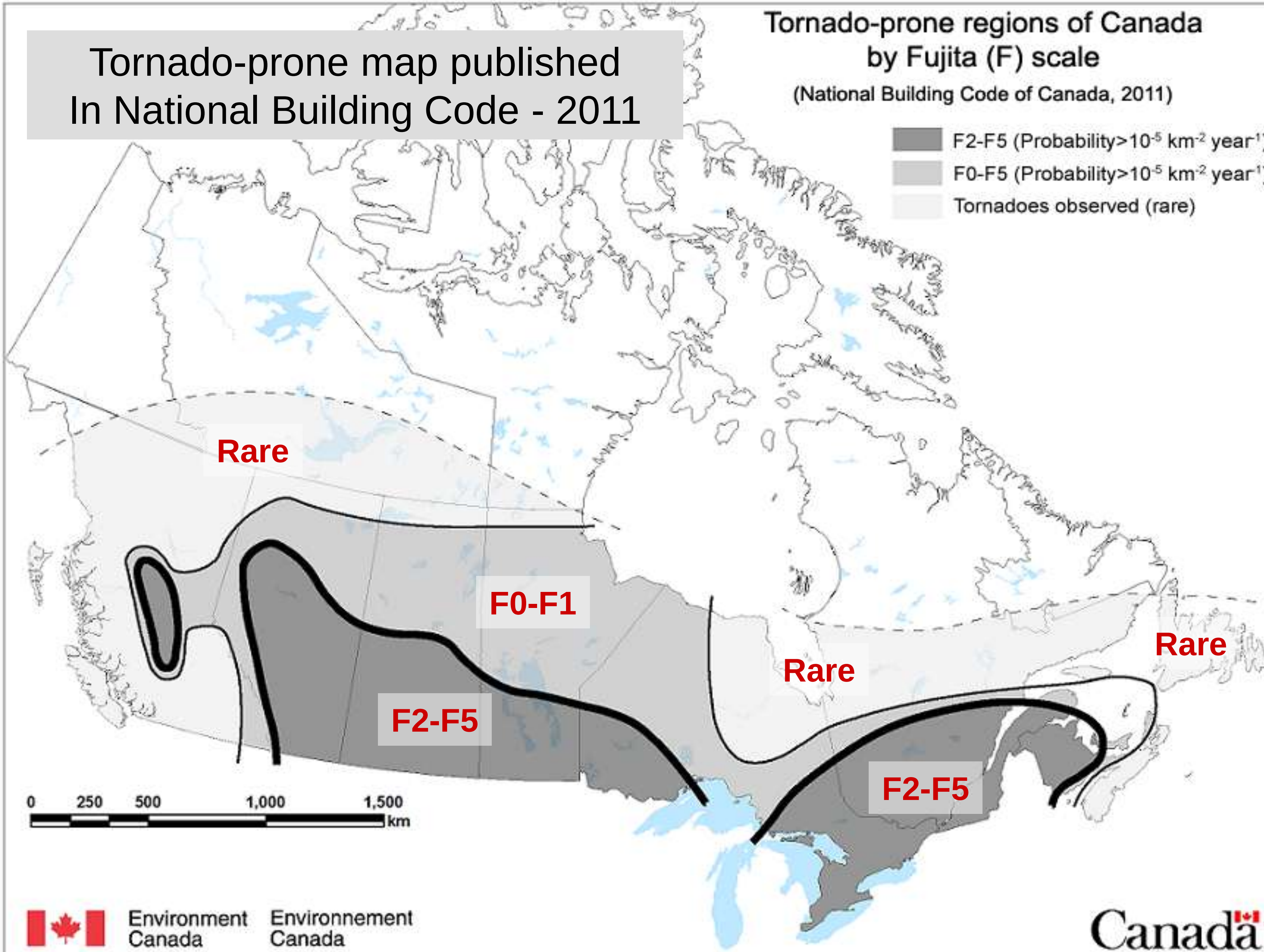
Probability of an F0-F1 tornado is estimated to exceed 10^{-5} / km^2 / year.

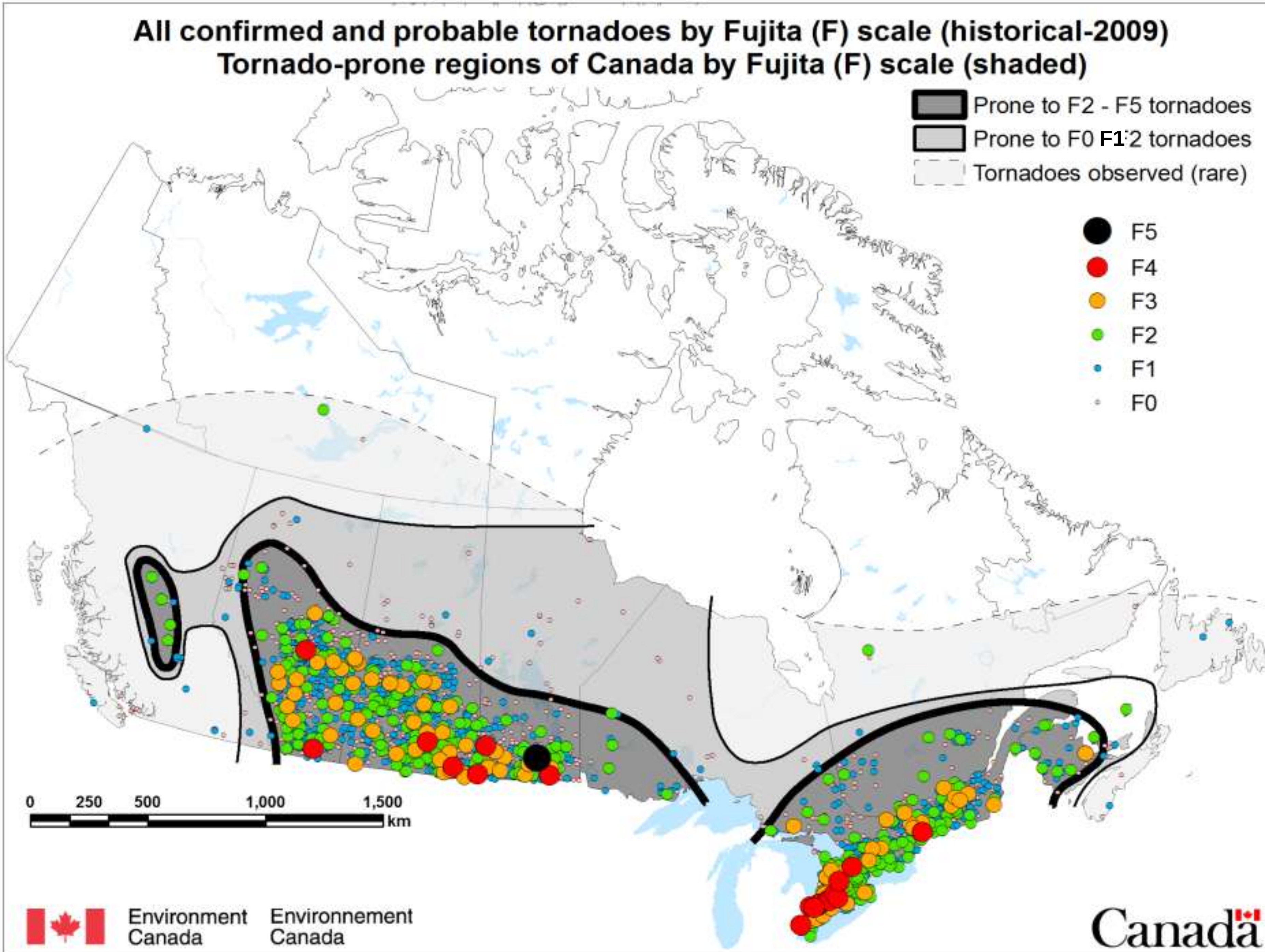
3. Tornadoes Observed - Rare

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

(*threshold of 10^{-5} / km^2 / 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
0 250 500 1,000 1,500
km
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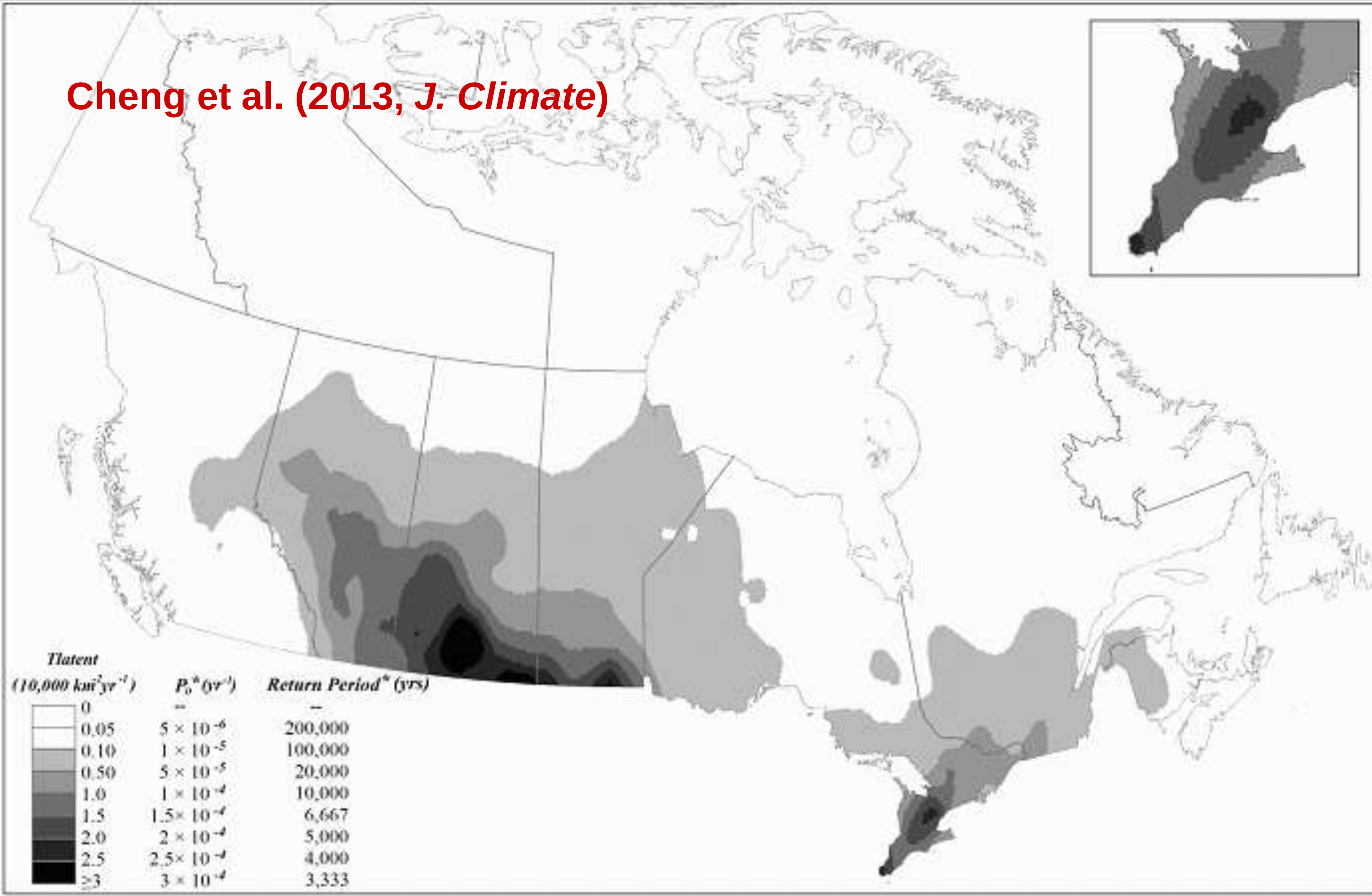
Tornado Frequency Analysis (25 km grid)

Cheng et al. (2013, *J. Climate*)

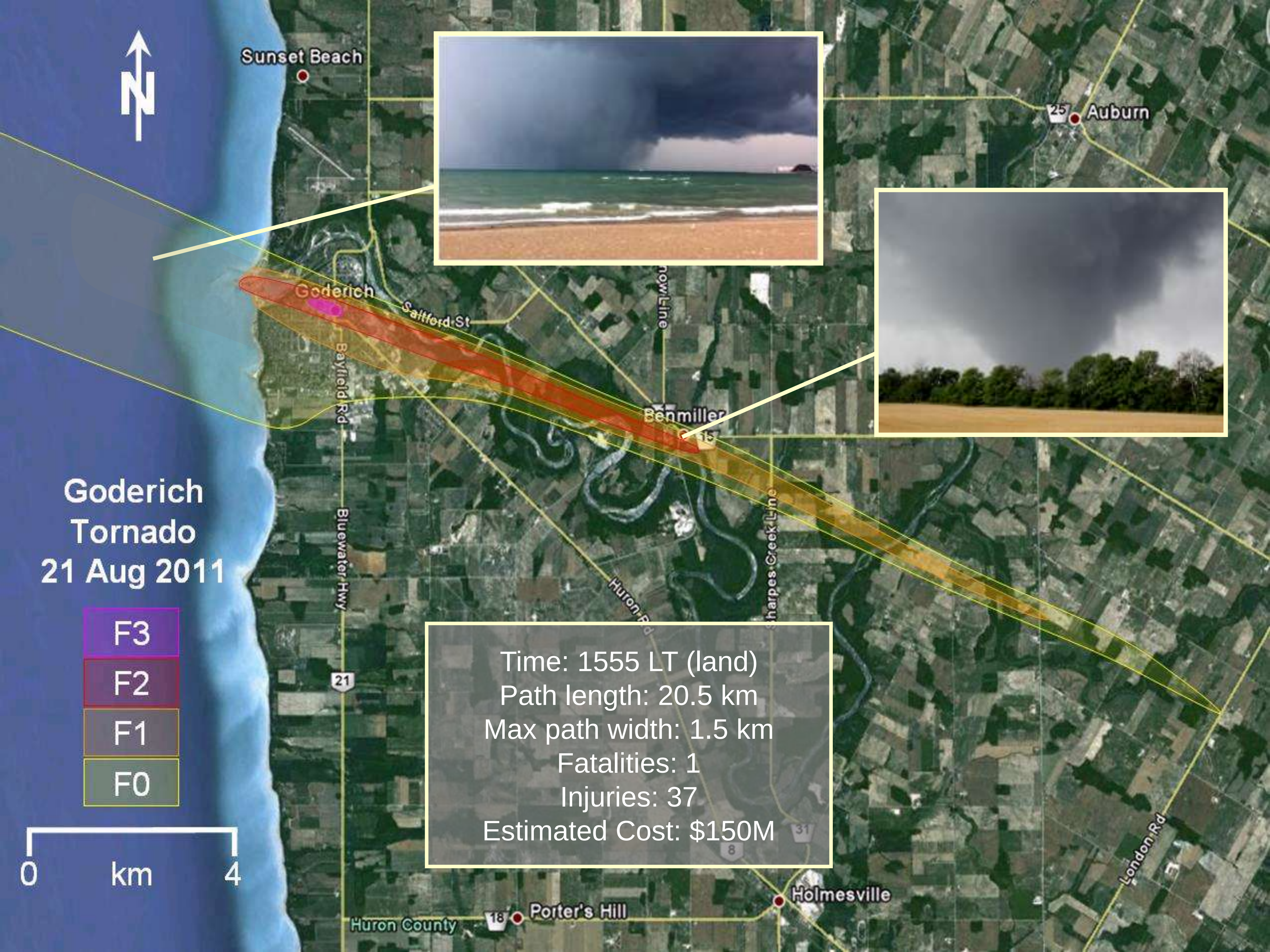


How does EC provide tornado alerts?

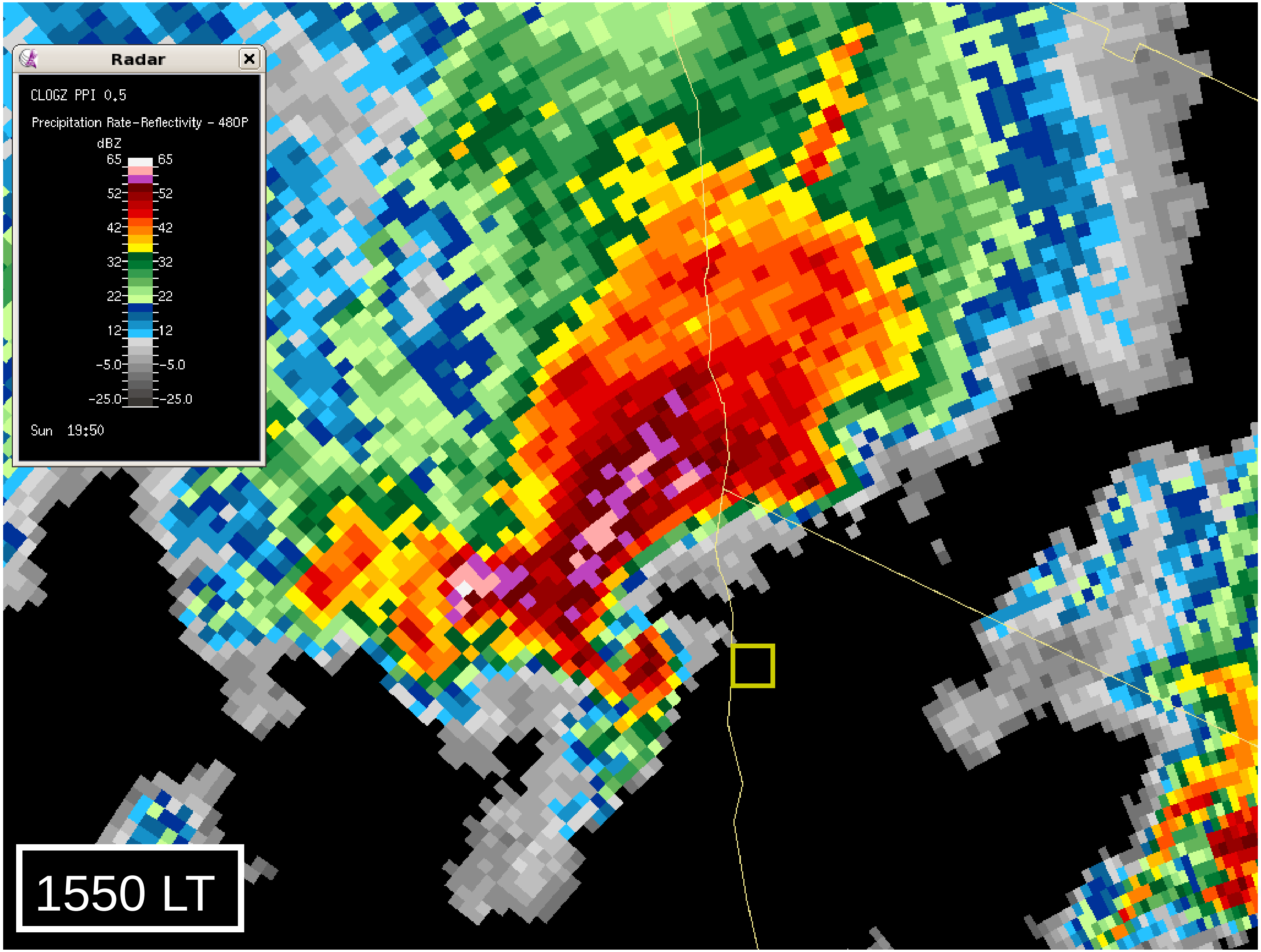
- Examples of recent supercell and nonsupercell tornado events to illustrate EC's watch / warning process and inherent difficulties…

GODERICH

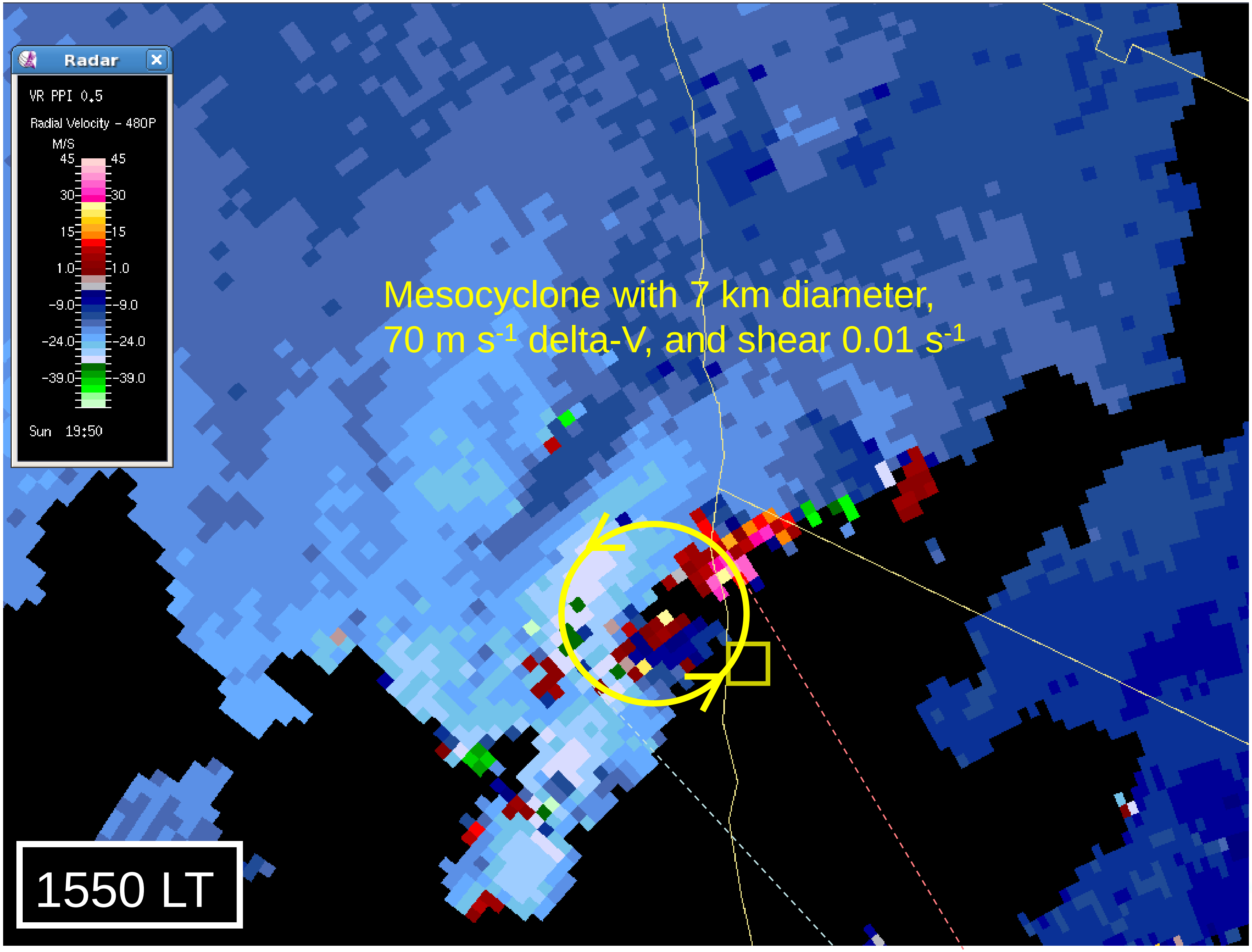
Canada's prettiest town


N
Goderich
Tornado
21 Aug 2011
F3
F2
F1
F0
0
km
4
Sunset Beach
Auburn
25
Goderich
Saltford St
Bayfield Rd
Benmiller
Bluewater Hwy
Huron Rd
Sharpes Creek Line
21
London Rd
31
8
Holmesville
18
Porter's Hill
Huron County
Time: 1555 LT (land)
Path length: 20.5 km
Max path width: 1.5 km
Fatalities: 1
Injuries: 37
Estimated Cost: $150M

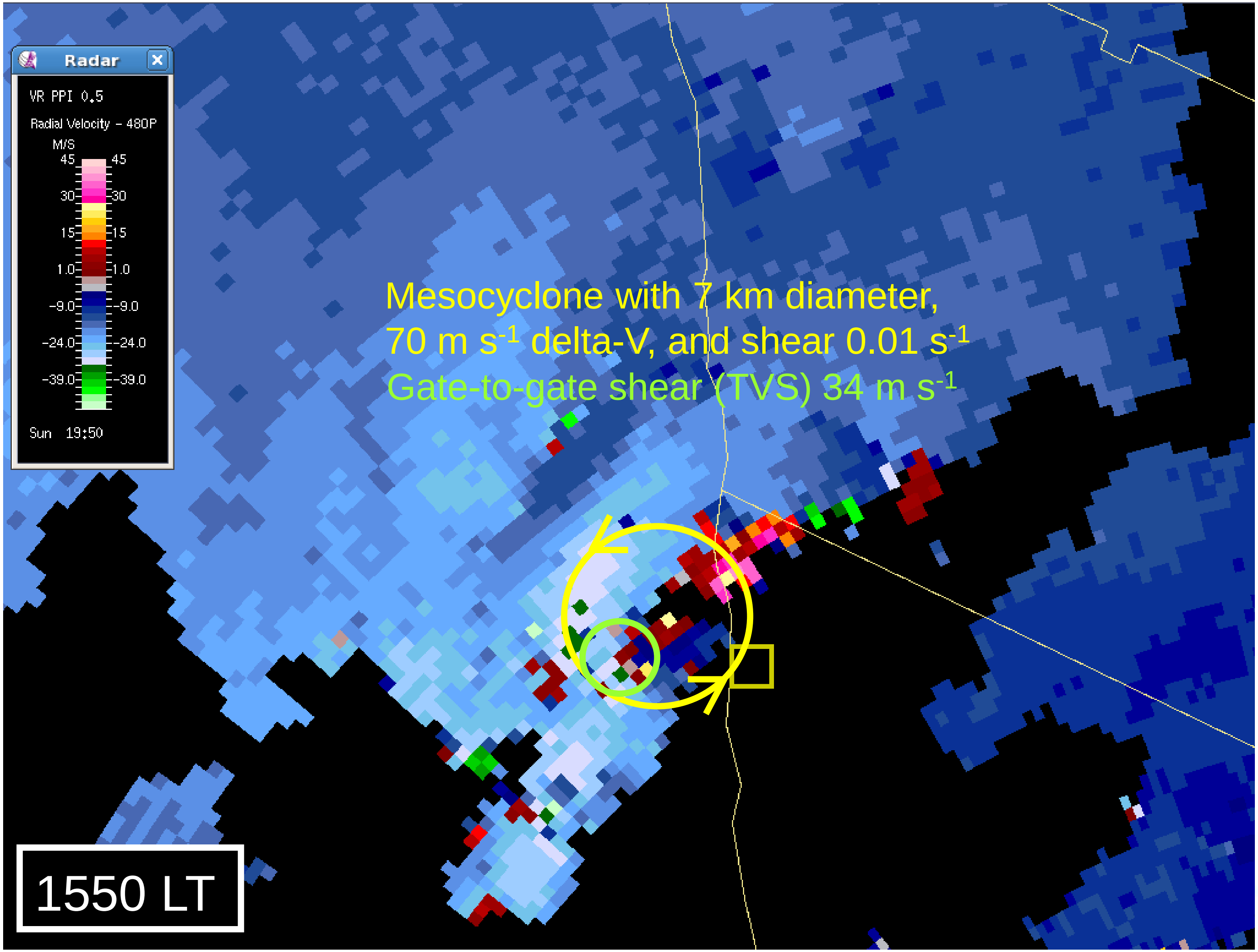
0.5° Doppler Precipitation Scan



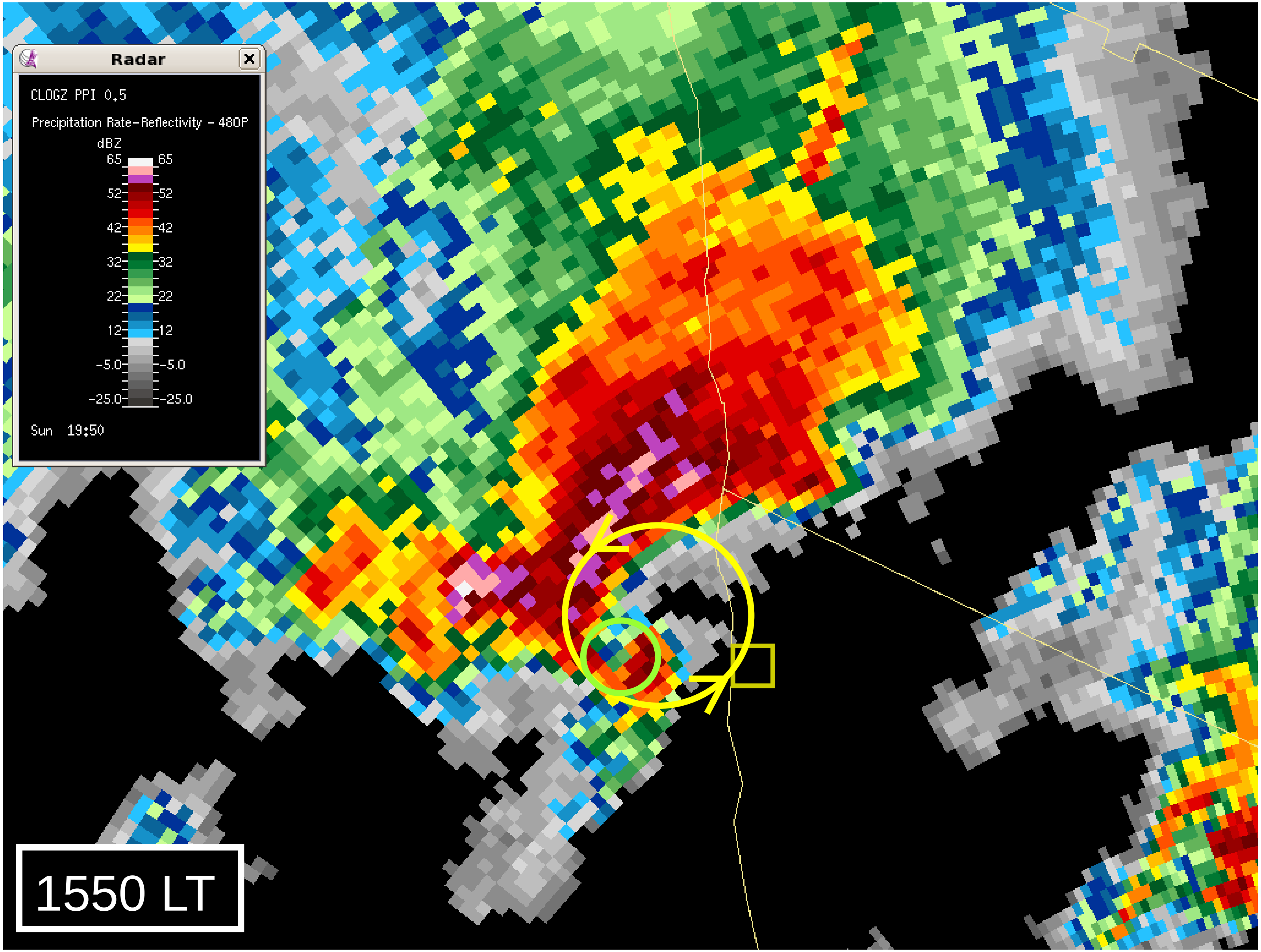
0.5° Doppler Velocity Scan



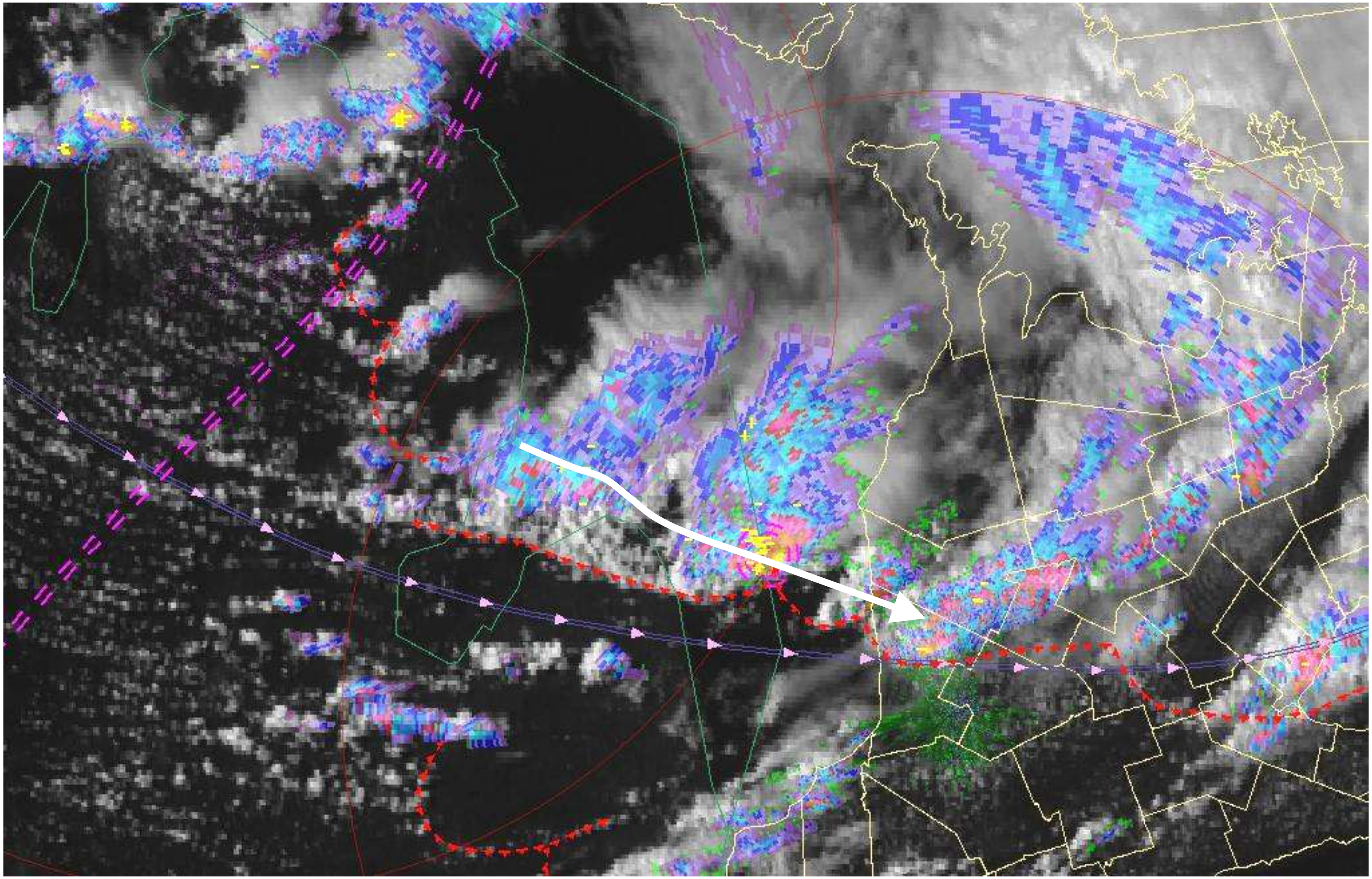
0.5° Doppler Velocity Scan



0.5° Doppler Precipitation Scan



Supercell / Pre-existing Boundary



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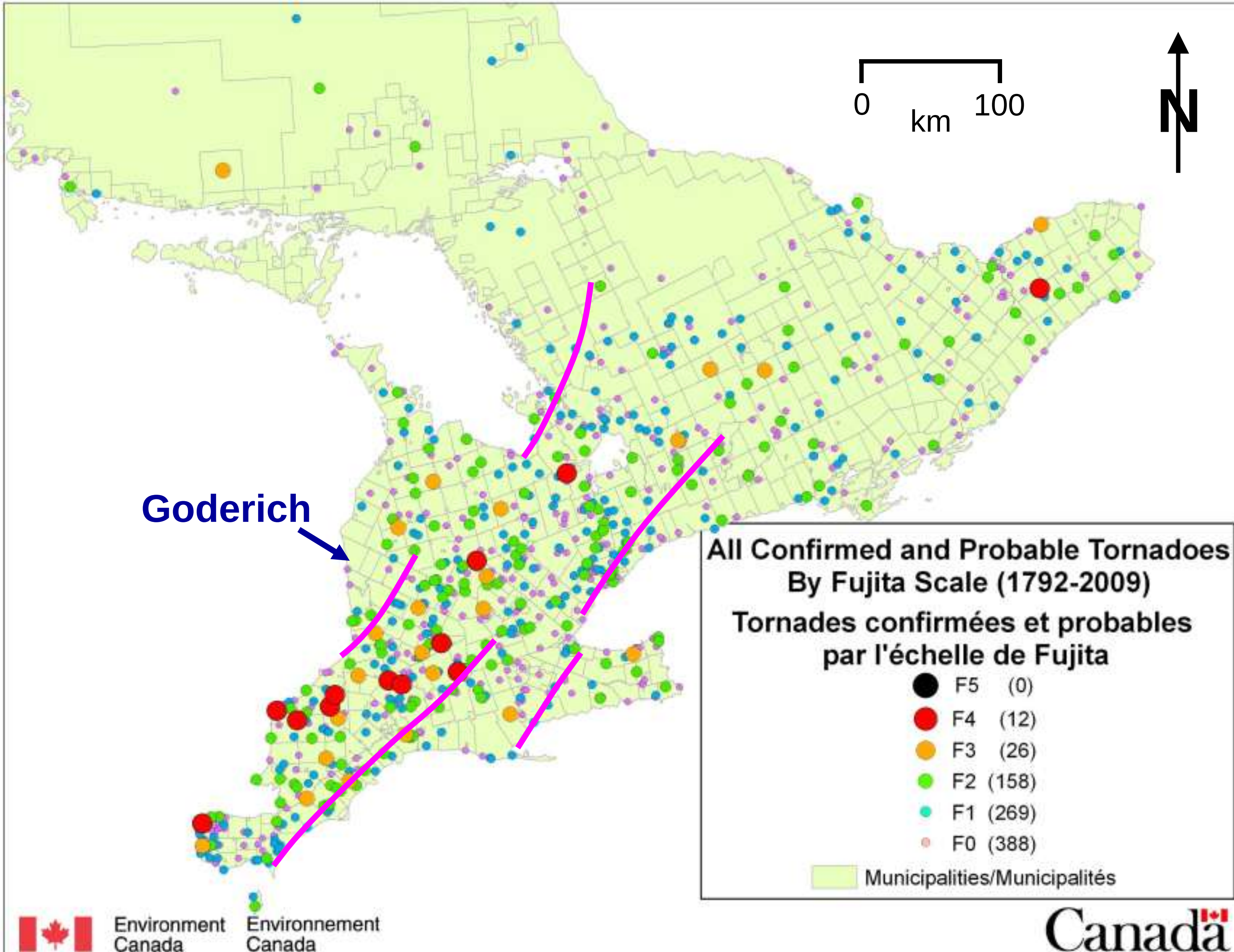
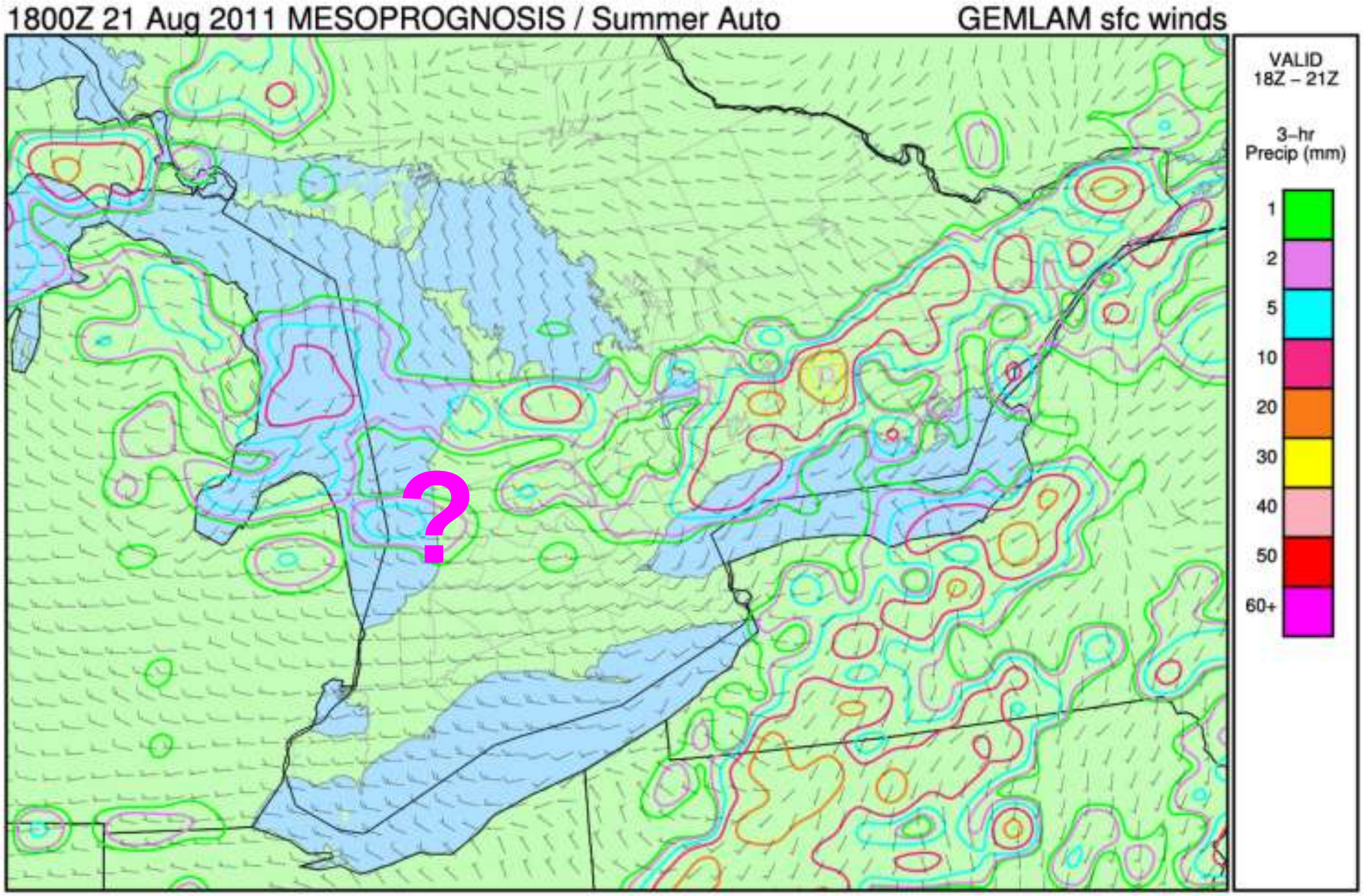
A Very Rare Event

- 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



Goderich
0 km 100
N
All Confirmed and Probable Tornadoes By Fujita Scale (1792-2009)
Tornades confirmées et probables par l'échelle de Fujita
F5 (0)
F4 (12)
F3 (26)
F2 (158)
F1 (269)
F0 (388)
Municipalities/Municipalités
Environment Canada
Environnement Canada
Canada

EC Hi-RES NWP Model



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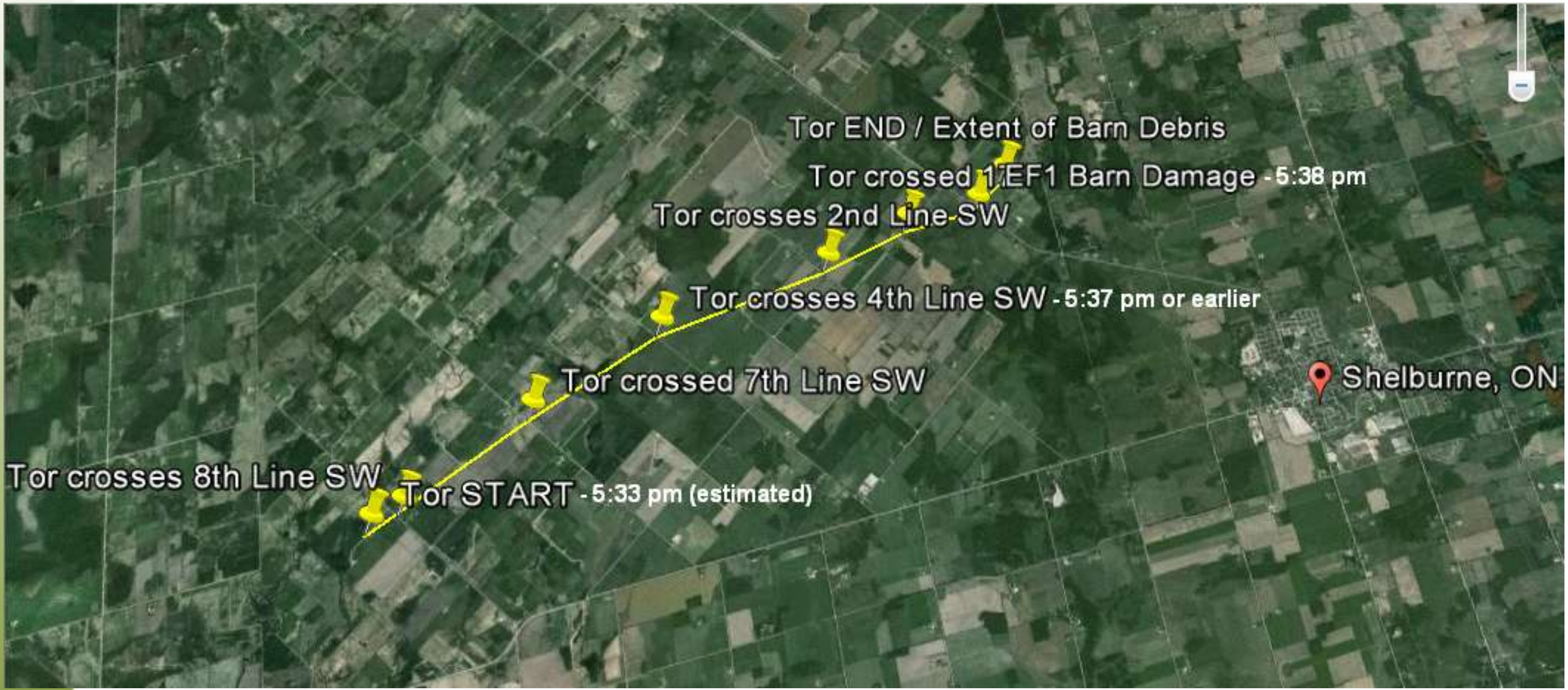
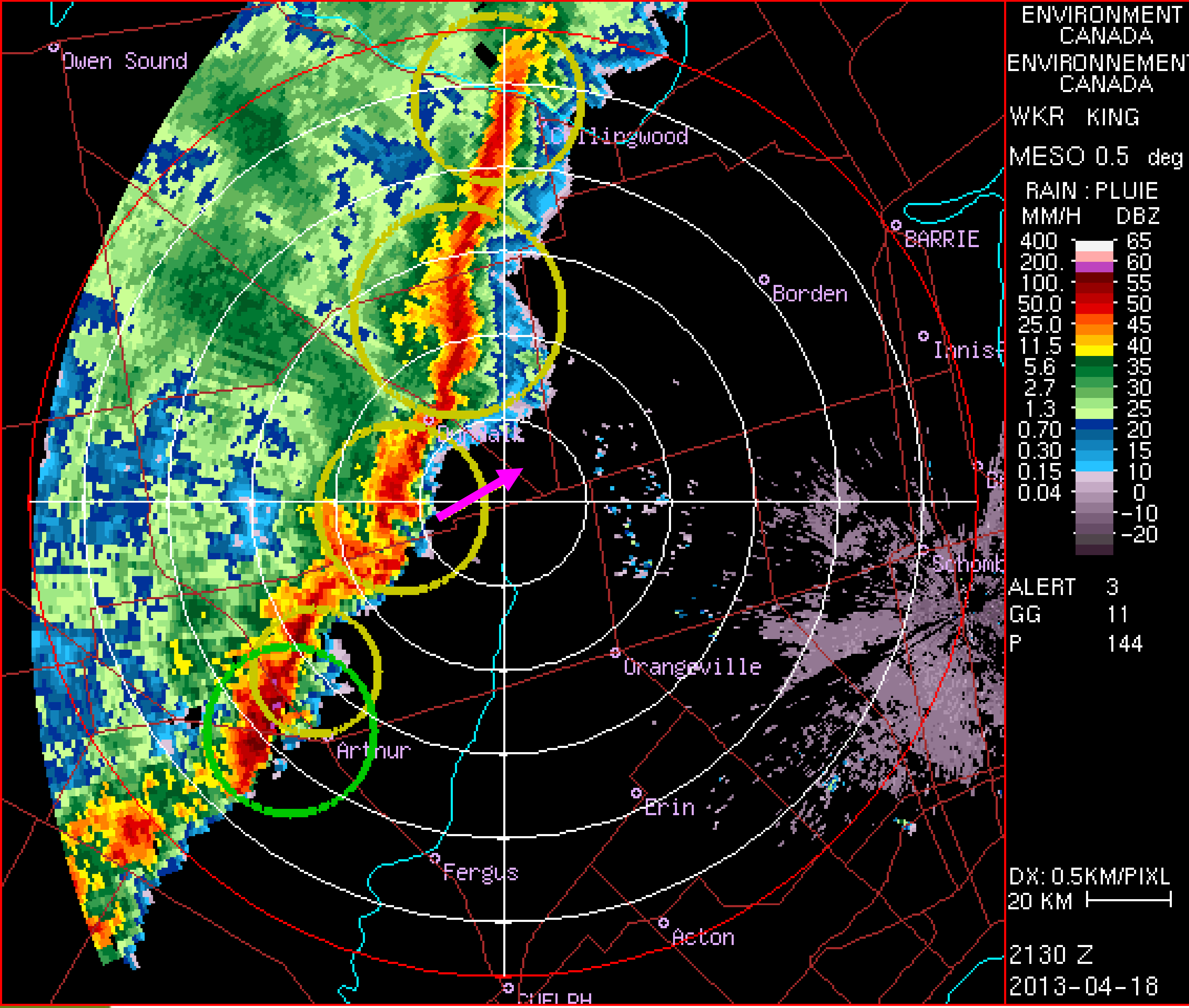
EC Alerts

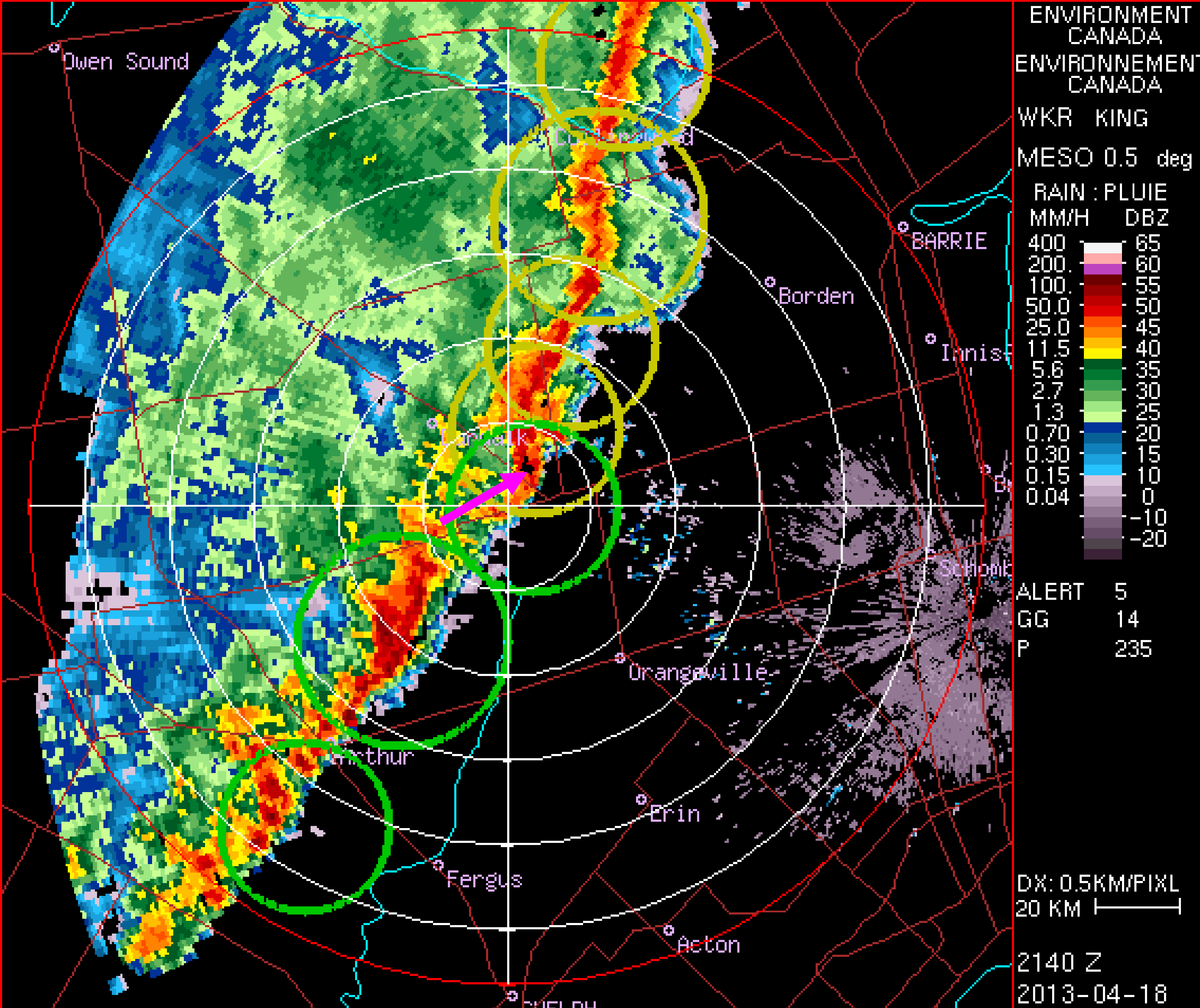
- Tornado began to impact Goderich at **3:55** PM
- **Severe Thunderstorm Watch** issued for Goderich: **2:02** PM
  - included the line “A tornado is possible”
  - lead time ~ 2 hours
- **Tornado Warning** issued for Goderich: **3:48** PM
  - “moving southeast at 75 km/h and will make landfall near 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


ENVIRONMENT CANADA
ENVIRONNEMENT CANADA
WKR KING
MESO 0.5 deg
RAIN : PLUIE
MM/H DBZ
400 65
200. 60
100. 55
50.0 50
25.0 45
11.5 40
5.6 35
2.7 30
1.3 25
0.70 20
0.30 15
0.15 10
0.04 0
-10
-20
ALERT 3
GG 11
P 144
DX: 0.5KM/PIXL
20 KM
2130 Z
2013-04-18
Owen Sound
Collingwood
BARRIE
Borden
Orangeville
Arthur
Erin
Fergus
Acton
GUELPH


ENVIRONMENT CANADA
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WKR KING
MESO 0.5 deg
RAIN : PLUIE
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400 65
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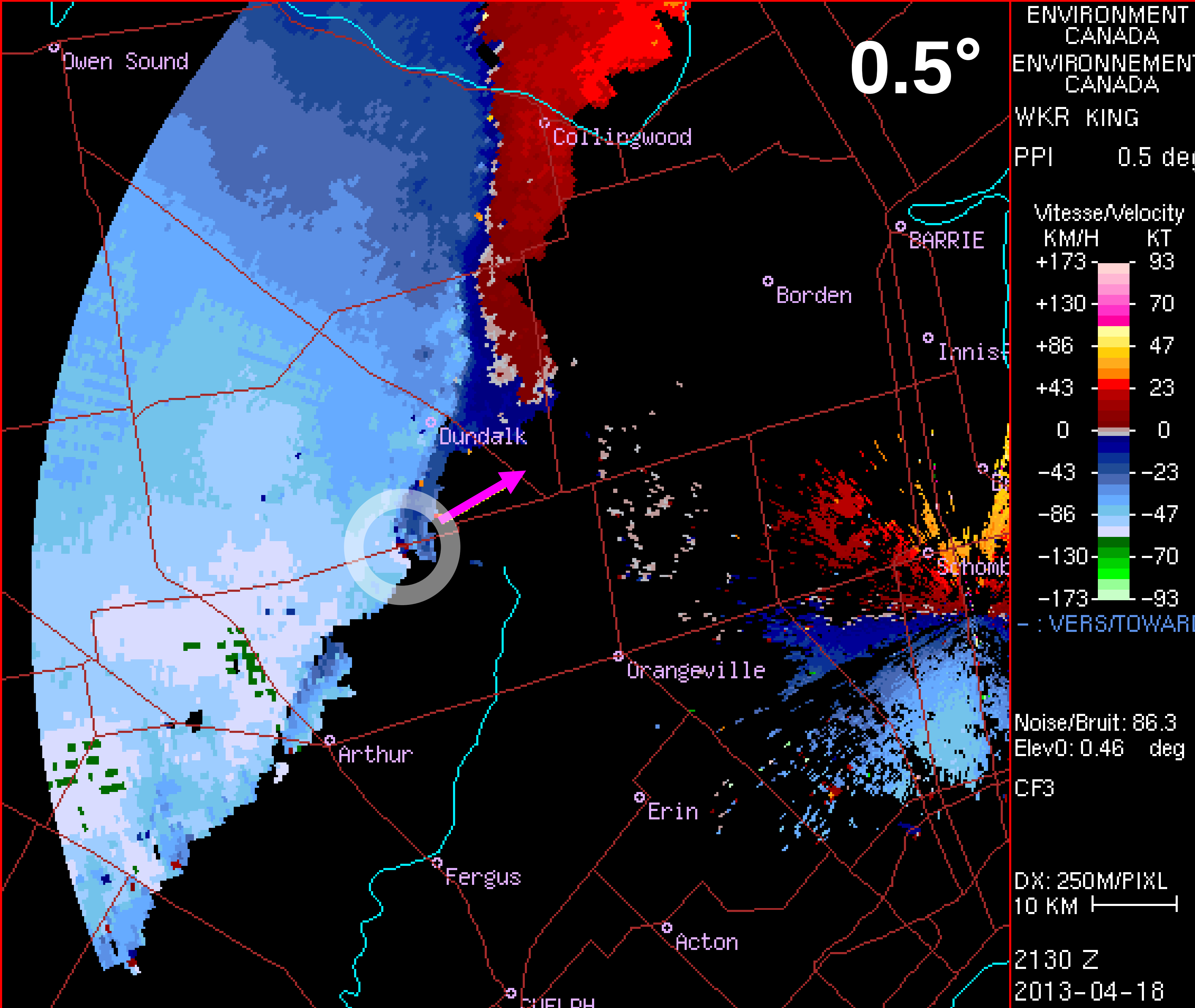
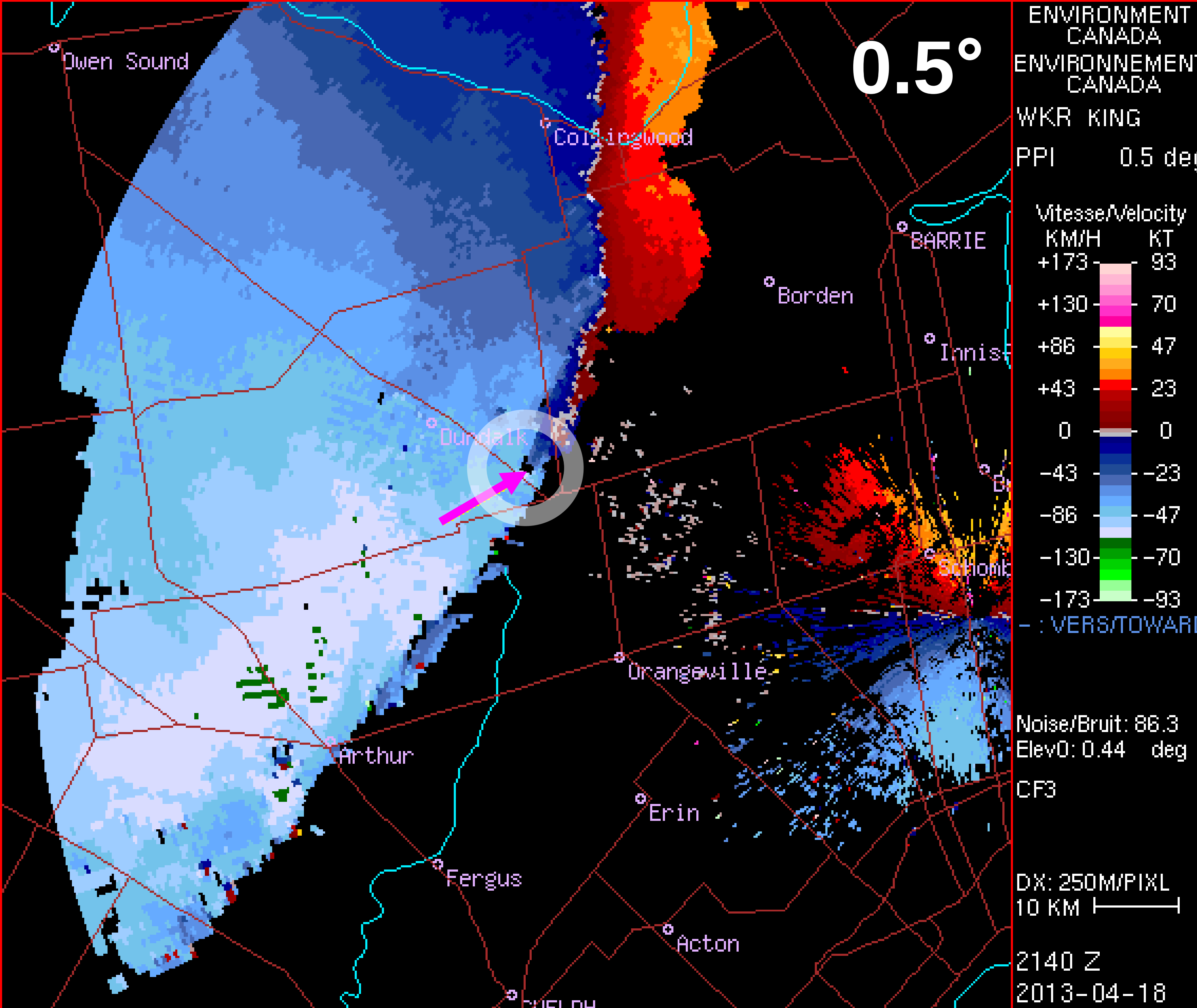
25.0 45
11.5 40
5.6 35
2.7 30
1.3 25
0.70 20
0.30 15
0.15 10
0.04 0
-10
-20
ALERT 5
GG 14
P 235
DX: 0.5KM/PIXL
20 KM
2140 Z
2013-04-18
Owen Sound
BARRIE
Borden
Orangeville
Erin
Fergus
Acton


0.5°
ENVIRONMENT CANADA
ENVIRONNEMENT CANADA
WKR KING
PPI 0.5 deg
Vitesse/Velocity
KM/H KT
+173 93
+130 70
+86 47
+43 23
0 0
-43 -23
-86 -47
-130 -70
-173 -93
- : VERS/TOWARD
Noise/Bruit: 86.3
Elev0: 0.46 deg
CF3
DX: 250M/PIXL
10 KM
2130 Z
2013-04-18
Owen Sound
Collingwood
BARRIE
Borden
Dundalk
Orangeville
Arthur
Erin
Fergus
Acton


0.5°
ENVIRONMENT CANADA
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-130 -70
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- : VERS/TOWARD
Noise/Bruit: 86.3
Elev0: 0.44 deg
CF3
DX: 250M/PIXL
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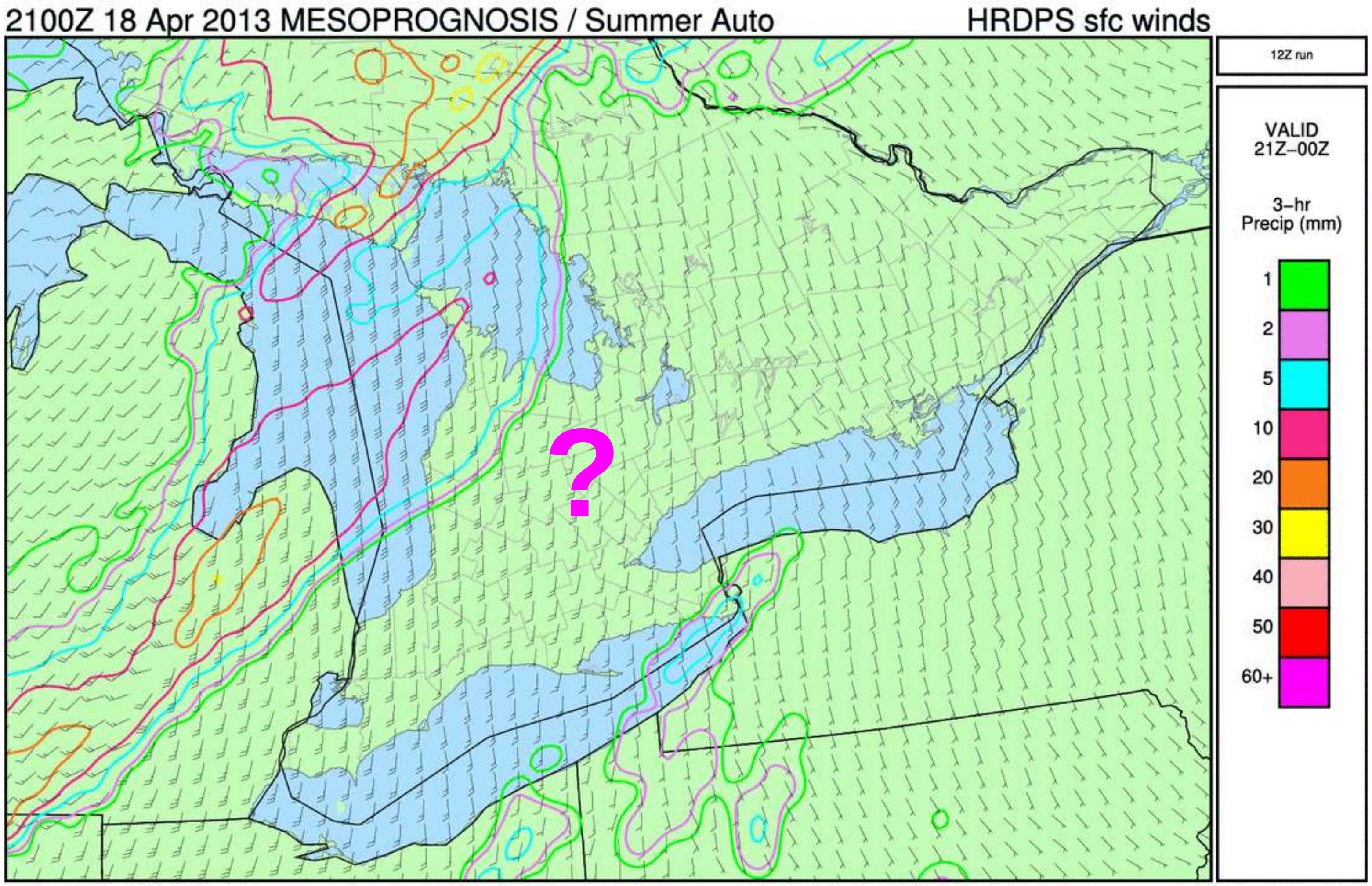
EC Hi-RES NWP Model



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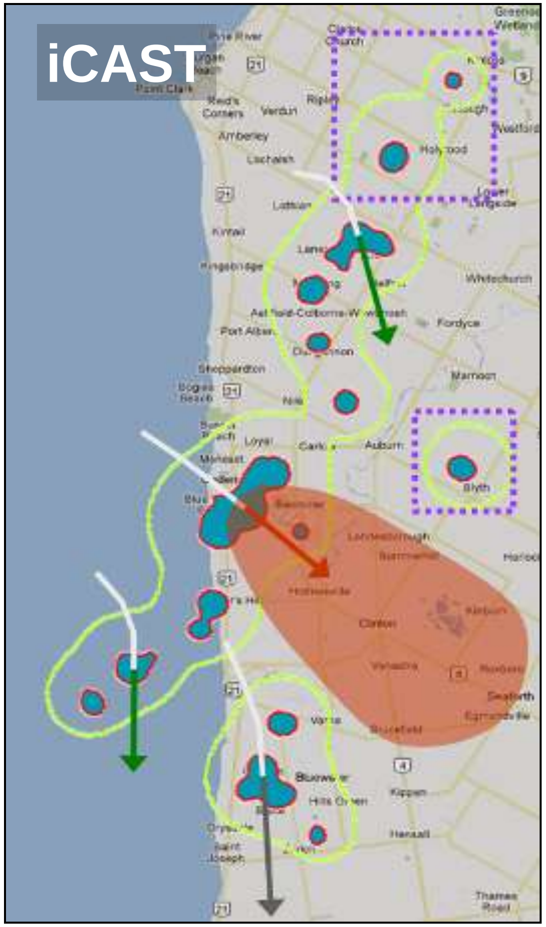
EC Alerts

- 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



Mesoscale / Storm-Scale

ID	Dist	Dir	Location	Mean Vel (Km/Hr)	Radar	Rank Weight	Rank T+10	Rank T+20	Rank T+30	Hail (mm)	MESH (mm)
347	231km	WNW	Tobermory	298/30	WGJ	3.8	4.4	5.1	5.8	38	22
349	305km	NNW	Tobermory	282/28	WGJ	2.4	2.6	2.8	3.0	11	10
348	318km	WNW	Tobermory	277/33	WGJ	2.3	2.6	2.9	3.2	7	8
345	18km	WSW	Nicolet	283/36	WMN	1.8	1.3	0.8	0.4	3	5
341	326km	WNW	Tobermory	359/10	WGJ	1.8	2.1	2.2	2.4	3	5
350	285km	SSE	Thunder Bay	N/A	WGJ	1.6	1.6	1.6	1.6	0	8

Human-machine mix:

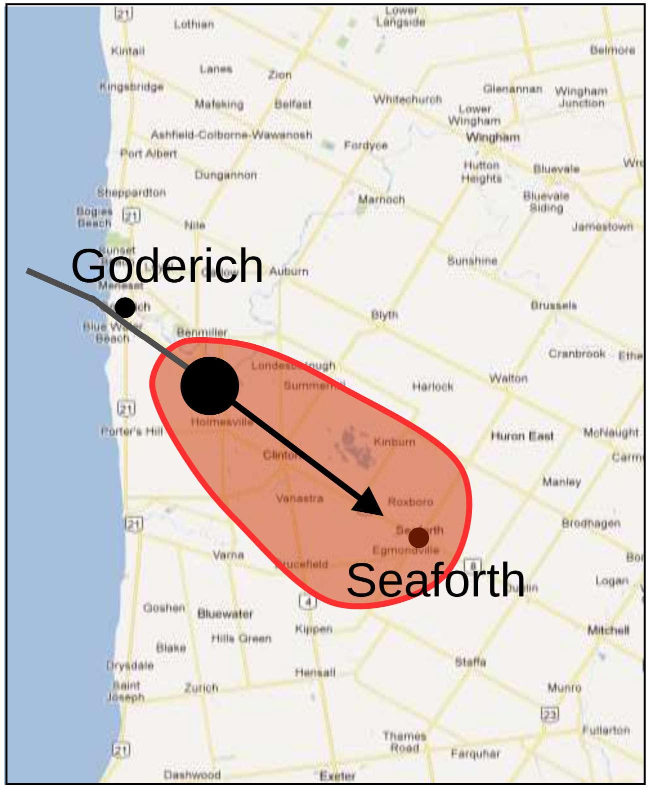
- *Interactive* 'Storm Attributes Table' used to rank storms – *smart filter*
- *Modifiable* 30-min *nowcast* 'rank weight' – *warn on nowcast*
- Storm track nowcasts and intensity trends determine if a *first-guess warning area* is generated, modified by forecaster as necessary

Warning Generation

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 SEAFORTH AT 8:05 PM EDT.



En français aussi!

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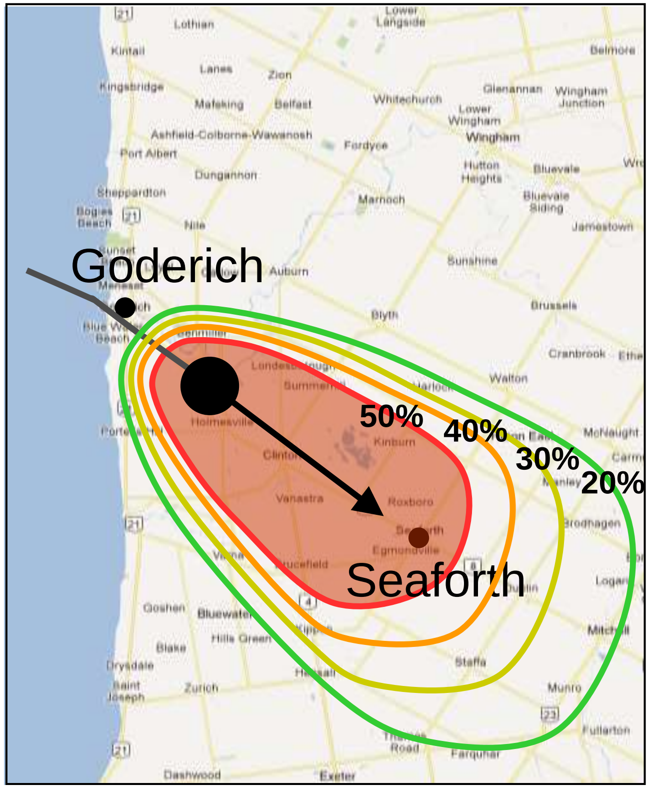

Are tornadoes increasing in frequency / intensity?

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We (unfortunately) don't know,

and likely won't for a long time!

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Canada

Are tornadoes increasing in frequency / intensity?

We (unfortunately) don't know,

and likely won't for a long time!

- Low sample size (rare events)
- Numerous artifacts in data (tornadoes vs. downbursts, EC resources, rise of commercial electronics, storm chasers, etc.)

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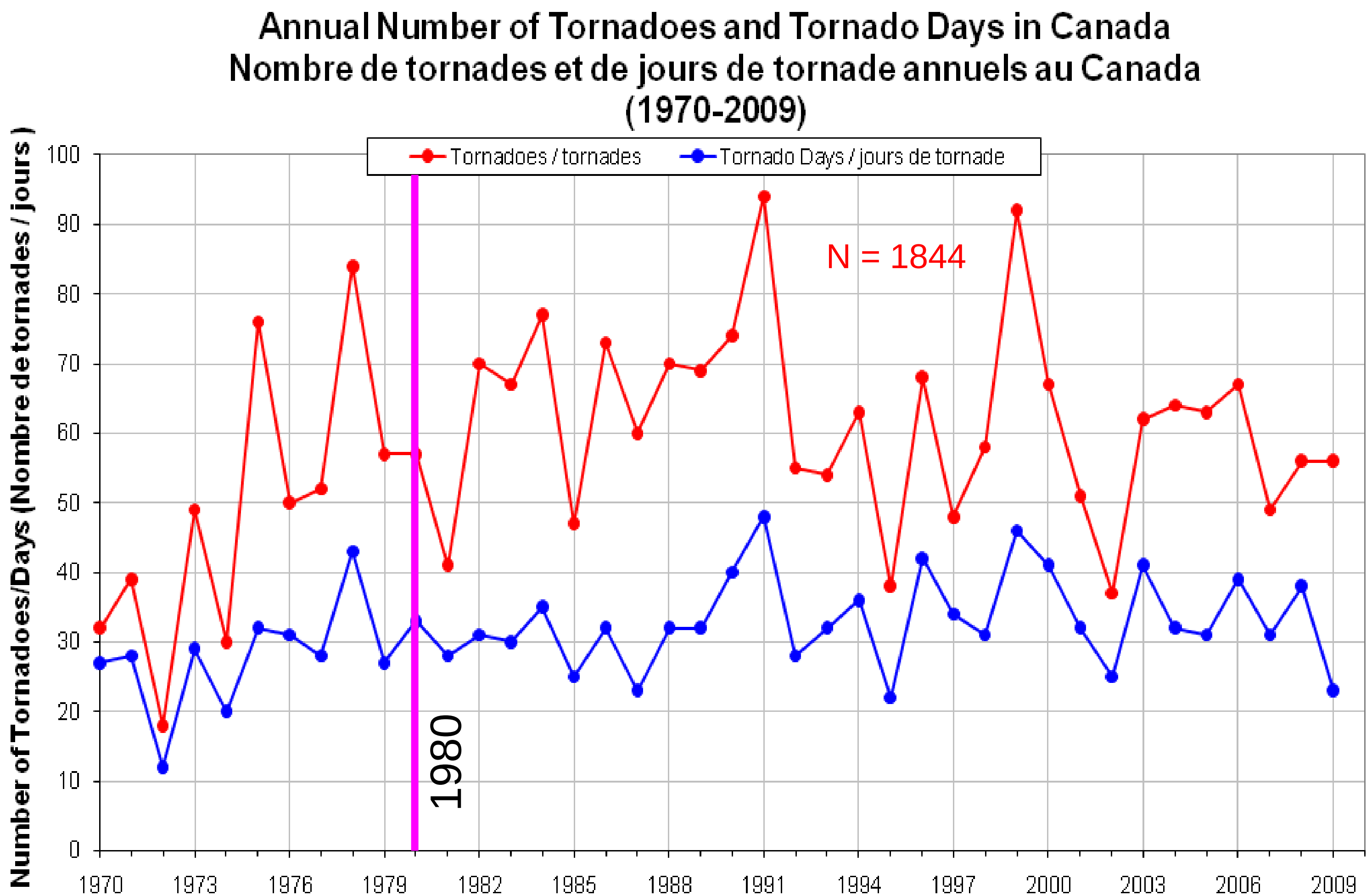
Canada

Are tornadoes increasing in frequency / intensity?



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Environnement Canada

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- Ed Mahoney / Jim LaDue (NWS Warning Decision Training Branch)

References

Brooks, H. E. and C. A. Doswell III, 2001. Some Aspects of the International Climatology of Tornadoes by Damage Classification. *Atmospheric Research*, **56**, 191-201.

Cheng, V. Y. S., G. B. Arhonditsis, D. M. L. Sills, H. Auld, M. W. Shephard, W. A. Gough and J. Klaassen, 2013. Probability of Tornado Occurrence across Canada. *Journal of Climate*, in press.

Etkin, D., S.E. Brun, A. Shabbar and P. Joe, 2001. Tornado Climatology of Canada Revisited: Tornado Activity During Different Phases of ENSO. Int. J. Climatology, 21, 915-938.

Fujita, T.T., 1981. Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.,* **38**, 1511-1534.

Lee, B. D., and R. B. Wilhelmson, 1997: The numerical simulation of non-supercell tornadogenesis. Part II: Evolution of a family of tornadoes along a weak outflow boundary. J. Atmos. Sci., **54**, 2387-2415.

References (*cont'd*)

Lemon, L.R. and C.A. Doswell III, 1979: Severe thunderstorm evolution and mesocyclone structure as related to tornadogenesis. *Mon. Wea. Rev*., **107**, 1184-1197.

McDonald, J. and K. C. Mehta, 2006. A Recommendation for an Enhanced Fujita Scale (EF-Scale), Revision 2. Wind Science and Engineering Research Center, Texas Tech University, Lubbock, TX, 111 pp.

Markowski, P. M., E. N. Rasmussen, and J. M. Straka, 1998: The occurrence of tornadoes in supercells interacting with boundaries during VORTEX-95. *Wea. Forecasting,* **13,** 852–859.

Markowski, P. M., Y. Richardson, J. Marquis, R. P. Davies-Jones, J. Wurman, K. Kosiba, P. Robinson, E. N. Rasmussen, and D. Dowell, 2012b: The pretornadic phase of the Goshen County, Wyoming, supercell of 5 June 2009 intercepted by VORTEX2. Part II: Intensification of Low-level Rotation. *Mon. Wea. Rev.,* **140**, 2916-2938.

References (*cont'd*)

NBC, 2011. Users Guide - National Building Code of Canada (NBC) Structural Commentaries (Part 4 of Division B); issued by the Canadian Commission on Building and Fire Codes, National Research Council of Canada, Ottawa, Ontario. Tornado Prone Map and Commentary contributed by Environment Canada (Adaptation and Impacts Research, Cloud Physics and Severe Weather Research; Science and Technology Branch), Toronto, ON.

Newark, M. J., 1984. Canadian Tornadoes, 1950-1979. *Atmosphere-Ocean,* **22,** 343-353.

Sills, D. M. L, S. J. Scriver and P. W. S. King, 2004. The Tornadoes in Ontario Project (TOP). Preprints, *22nd AMS Conference on Severe Local Storms*, Hyannis, MA, American Meteorological Society, CD-ROM Paper 7B.5.

Questions?

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