

**A BILLION DOLLAR FLASH FLOOD IN TORONTO –
CHALLENGES FOR FORECASTING AND NOWCASTING**

David Sills^{1*}, Arnold Ashton², Steve Knott², Sudesh Boodoo¹, Joan Klaassen^{2#},
Stéphane Bélair³ and Helen Yang²

¹Science and Technology Branch, Environment
and Climate Change Canada (ECCC), King City, ON
²Meteorological Service of Canada, ECCC, Toronto, ON
³Meteorological Service of Canada, ECCC, Dorval, QC

1. INTRODUCTION

Between 2000 UTC⁺ on July 8th and 0500 UTC on July 9th, 2013, a flash flood event affected the Greater Toronto Area (GTA) with the heaviest rain falling between 2020 and 2210 UTC. Observed rainfall accumulations for the event are shown in Fig. 1. Toronto Pearson International Airport recorded 126 mm, exceeding the 100-year return period storm for 30-min through 24-hr periods (Klaassen 2014).

During the storm, approximately 900,000 households lost power and more than 7,000 basements were flooded. Major highways had to be closed. Some 1400 people were stranded when their commuter train encountered floodwaters.

Additionally, more than 300 flights were cancelled at Pearson Airport, power outages closed Billy Bishop Airport in downtown Toronto, and the Toronto subway system was disrupted with stations experiencing significant flooding.

Fortunately, only minor injuries were reported with the event. However, there were approximately \$850M CDN in insured losses and at least \$150M CDN more in uninsured losses, making it a 'billion dollar storm' as well as the costliest natural disaster in Ontario history.

The goals of this paper are to describe the evolution of the event, the challenges for forecasters, and key indicators for nowcasting.

2. EVENT EVOLUTION

July 8th was expected to be a fairly typical summer day in the GTA with afternoon thunderstorms giving heavy downpours, possibly approaching the ECCC Ontario Storm Prediction Centre (OSPC) severe rainfall criterion of 50 mm h⁻¹.

By 1500 UTC, the Lake Ontario lake breeze had started to move onshore under a moderate southwest surface wind regime. Deep, moist convection began to develop northwest of the GTA at 1700 UTC, while the lake-breeze front continued to penetrate inland (Fig. 2). The OSPC issued a Special Weather Statement at 1731 UTC for regions north of the GTA, indicating the possibility of non-severe storms with rainfall rates of 30-40 mm per hour. The statement was updated to include the GTA at 1816 UTC after storms began to develop well west of the GTA, moving east.

After receiving a report of 50 mm of rain in 30-min associated with a storm in the Angus area north of the GTA, Severe Thunderstorm Warnings were issued for regions affected by those storms, which were moving slowly southeastward.

By 2000 UTC, a large area of precipitation-cooled air had begun to spread southwest of the cluster of storms, and the leading edge had intersected the lake-breeze front that had penetrated well inland (Fig. 3). At this point, the storm cluster changed from moving slowly toward the southeast to moving rapidly toward the south – and directly toward the GTA.

However, the path of the storms took them over the main ECCC radar serving the GTA, the C-band radar at King City. The resulting radome wetting caused severe attenuation, making the storms appear much less intense than they were

* Corresponding author address: David M. L. Sills,
Cloud Physics and Severe Weather Research Section,
ECCC, 14780 Jane Street, King City, Ontario, Canada,
L7B 1A3, David.Sills@canada.ca

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+ Local time (EDT) = UTC - 4 hours

in reality. At 2053 UTC, the first mention of flooding in Toronto was made via a Twitter post.

At 2132 UTC, the Severe Thunderstorm Warnings were allowed to expire. However, forecasters noted that between 2127 and 2145 UTC three consecutive special weather observations from Pearson Airport mentioned “very heavy” rain. Given that the inclusion of this modifier is quite rare there, forecasters decided to issue a Severe Thunderstorm Warning for the regions in the vicinity of the airport, including the City of Toronto, at 2151 UTC.

Fig. 4 shows the warned area with the location of the main storm over the GTA at 2100 UTC. In addition, the Toronto and Region Conservation Authority (TRCA) had issued a flood watch by 2130 UTC, based on the forecast rainfall, the nearly saturated soil, and the highly urbanized nature of the region. The OSPC does not issue flood watches or warnings, though discussions with TRCA are common in such situations.

It appears that significant flooding had already begun by the time the Severe Thunderstorm Warning was issued. Between 2230 and 2300 UTC, numerous Twitter posts were clearly showing widespread, catastrophic flooding. The TRCA issued a flood warning at 2320 UTC noting that flooding was occurring in low-lying areas of TRCA watersheds.

The Severe Thunderstorm Warning was allowed to expire at 0134 UTC on July 9th. By 0620 UTC, forecasters (on the next shift) were realizing the full impact of the event, and sent out an event summary noting that it had broken a long-standing record for single day rainfall at Pearson Airport associated with the passing remnants of Hurricane Hazel in 1954.

3. THE FORECASTING CHALLENGE

Forecasters are trained to look for synoptic-scale meteorological ingredients that can come together to produce flash flooding, with potential sometimes noted days in advance.

Maddox et al. (1979), for example, introduced a number of synoptic-scale patterns found to be related to seasonal flash flood events. The patterns involved troughs and ridges at mid-levels and the proximity to fronts at the surface.

Corfidi et al. (2003) developed a method whereby the motion of upwind-propagating mesoscale convective systems can be assessed by using the speed and direction of the low-level jet. When the resulting system speed is low, there is a greater chance of certain locations receiving rainfall over a longer period of time, increasing the potential for flash flooding.

Other ingredients include ‘coupled’ upper-level jets, high precipitable water values, and saturated soil from rainfall on the previous day.

For the July 8th case, nearly all of these ingredients appeared not to be a factor. Fig. 5 shows analyses at various levels of the atmosphere at 0000 UTC on July 9th. At the 250-hPa level, there is no evidence of upper-level jets in the Great Lakes region, though diffluent flow aloft could have contributed to lift over areas north of the GTA. At 500 hPa, a weak trough is located well east of the GTA while only a broad trough exists at the surface, thus no Maddox patterns are matched.

Wind speeds at the 850 hPa level in the vicinity of the GTA reached only 15 knots – a low-level jet having a minimum wind speed of 30 knots is not apparent within 1000 km of the GTA. In addition, while precipitable water values near the GTA reached into the low 40 mm near the time of the event, values were markedly higher both well to the east and west.

Quantitative precipitation forecasts by numerical weather prediction models were not helpful either. ECCC’s 10-km regional model predicted less than 15 mm of accumulated rainfall in the GTA (model results not shown). The higher-resolution (2.5 km) version of the model generated between 50 and 75 mm of accumulated rainfall north and west of the GTA and closer to 30 mm in northwestern Toronto. Even higher-resolution post-event runs of the model, with 1-km and 250-m horizontal grid spacing, failed to generate even half of the maximum observed accumulations.

The quantitative precipitation forecast produced by forecasters at the US Weather Prediction Centre indicated the potential for heavy rain over extreme southwestern Ontario with over 20 mm possible, but only a few millimetres were expected in the GTA (Fig. 6).

Finally, with respect to antecedent conditions, non-severe showers and thunderstorms had affected the GTA daily since July 3rd in association with a stagnant synoptic-scale pattern. On July 7th, several non-severe thunderstorms tracked across the GTA, including the area around Pearson Airport, delivering 20-40 mm of rainfall. The TRCA considered the soil to be nearly saturated on July 8th, (D. Chekol, personal communication) and therefore somewhat sensitive to additional moisture input.

Overall, there was little indication based on synoptic-scale indicators, NWP model output and antecedent conditions that Ontario's most costly natural disaster might occur.

4. THE NOWCASTING CHALLENGE

Nowcasting, which for the purposes of this paper we define to be the description of weather from the current time out to two hours, typically involves the use of observations from one or more platforms. For severe weather nowcasting, such platforms include radar, satellite, lightning, surface weather stations and spotter/public reports. Data from these platforms must be monitored in an integrated way in order for forecasters to anticipate the development or detect the occurrence of severe weather.

On July 8th, forecasters at the OSPC made use of radar and a heavy rain report of 50 mm in 30 min north of the GTA to issue a Severe Thunderstorm Warning to the north of the GTA. As the storms progressed southward, forecasters continued to monitor radar and rain gauge data. However, such data appeared to indicate that accumulations in the GTA were consistent with what was specified in the Special Weather Statement (30-40 mm h⁻¹).

Forecasters also monitored the position of the Lake Ontario lake-breeze front, using radar data, visible satellite imagery and weather station observations. However, forecasters believed that thunderstorms would begin to dissipate after moving southeast across the lake-breeze front and into the relatively stable marine air.

Below, we look at four factors for nowcasting that appear to provide key information during this event, though forecasters were not able to incorporate such factors in real time due to tool limitations or their experimental nature at OSPC.

4.1 Mesoscale Boundaries and Interactions

Initially, the cluster of thunderstorms that developed to the north of the GTA was locally intense but disorganized, and heading in a southeasterly direction (see Fig. 2). Near 1900 UTC, the cold pool generated by the area of thunderstorms began moving southward and by 2000 UTC had collided with the lake breeze.

The 'triple point' at the intersection of the thunderstorm gust front and the lake-breeze front then served as a focus for the development of new convection, with warm, moist air from the southwest forced up and over the wedge-shaped area just west of the triple point (see Fig. 3).

As the gust front moved southward, the intersection/triple point also moved southward along the north-south-oriented lake-breeze front. Since the motion of the triple point controlled where new development occurred, it had the effect of changing the direction of motion of the cluster of storms from toward the southeast to toward the south, and directly toward the GTA.

The gust front also enhanced convective development to the north and west of the GTA (see Fig. 4). In fact, a new gust front from one of these thunderstorms moved east and interacted with the cluster of storms then over the GTA, resulting in even further intensification.

These mesoscale boundaries and their interactions clearly had a significant influence on storm development, movement and intensification during this event.

4.2 Lightning Jump

There is a growing body of research that indicates that a rapid increase in total lightning activity, known as a 'lightning jump', can indicate a strengthening thunderstorm updraft and provide lead time on the development of subsequent severe weather (e.g., Chronis et al. 2015). No total lightning network was available in the Toronto area in 2013, so lightning from the Canadian Lightning Detection Network (CLDN) was examined to see if such a jump could be detected before the onset of the flooding rains. While CLDN does detect both cloud-to-ground (CG) and in-cloud (IC) lightning (which together make 'total' lightning), the detection efficiency of IC lightning in

2013 was known to be relatively low (<20%).

Both CG and IC lightning generated by the flash-flood producing cluster of storms was identified and counted. Fig. 7 shows the resulting flash density between 1700 and 2320 UTC, with the estimated position of the Lake Ontario lake-breeze front at 1900 UTC superimposed. The marked change in direction of the storm cluster and the increase in lightning activity as the storms moved in the GTA are clear.

Fig. 8 shows the positive CG, negative CG, IC, and combined ('total') lightning counts during the period 1700-2320 UTC. Large, rapid increases in both IC and combined lightning can be seen near 2020 UTC and 2130 UTC, with a maximum flash rate near 130 flashes per minute. CG lightning also increased but large jumps are not apparent.

A lightning jump algorithm was applied to the combined lightning data to determine if observed increases qualified as true lightning jumps. The algorithm was a slightly modified version of that published by Schultz et al. 2009. Six jumps were found by the algorithm – four were smaller 'one-sigma' jumps, while two were determined to be significant 'two-sigma' jumps.

The first of these (LJ1) near 2020 UTC occurred when the gust front and lake-breeze front intersected and the storm cluster began to change direction. The rate of rainfall was noted to increase considerably after this time. The second (LJ5) near 2130 UTC occurred when storm cells with a gust front along the eastern edge began to interact with the main cluster of storms. The flash rate remained quite high after this jump.

Both of these lightning jumps occurred before or near the beginning of the flash flooding event, and well before the Severe Thunderstorm Warning was issued by the OSPC at 2151 UTC (see Fig. 8). As such, knowledge of these significant jumps may have led to an earlier warning of severe rainfall.

4.3 Radar Attenuation

Forecasters noted that, leading up to and during the flash flood event, returns from ECCC's King City C-band radar appeared to be suffering from severe attenuation. This was particularly noticeable when precipitation over the radar site resulted in radome wetting. Forecasters found that

returns from ECCC's Exeter C-band radar roughly 100 km to the west of the GTA gave higher rainfall rates, but the distance likely meant that the radar was not sampling the lower portions of the storms.

The US Buffalo S-band radar roughly 100 km to the southeast of the GTA typically has more reliable precipitation accumulation estimates due to S-band radars being less affected by attenuation by precipitation echoes. However, due to technical problems, that radar was temporarily not available in the radar viewing software that OSPC uses.

Boodoo et al. 2015 compared precipitation accumulation products from both the King City radar and the Buffalo radar for this event, including products using dual-polarization technology (still experimental for King City). A comparison of four different accumulation products is shown in Fig. 9.

The King City radar did indeed severely underestimate the precipitation accumulation in this case, with a maximum of less than 60 mm in the area where 126 mm was reported. When correcting for attenuation using dual-polarization data, the storm accumulation increased to over 150 mm (this product was generated post-event and was not available to OSPC forecasters in real time).

The Buffalo S-band radar accumulation product showed a maximum between 125 and 150 mm, while the attenuation-corrected version using dual-polarization data gave a maximum storm accumulation over 150 mm. In all cases, the radar data suggest that the highest accumulations were actually located just to the east of Pearson Airport, so the 126 mm measured there was likely lower than the maximum that fell in the area.

It is likely that the Severe Thunderstorm Warning would have been issued earlier if forecasters had access to attenuation-corrected precipitation accumulation products during the event.

4.4 Social Media

It was mentioned in Section 2 that flooding was reported with this event via Twitter posts as early as 2053 UTC. Many of these 'tweets' included a photo and enough description to positively identify the time and location. At the height of the event, the average volume of 'tweets' related to the GTA flooding was roughly one every ten seconds –

difficult to keep on top of, including the task of separating useful storm information from not-so-useful commentary.

Nevertheless, the first tweet to mention flooding was posted nearly an hour before the OSPC issued a warning, and could clearly be used to help with the detection of developing severe weather events. In fact, social media is likely most useful near the beginning of such events, before the volume increases substantially.

5. SUMMARY AND DISCUSSION

The following points summarize the results of this study:

- The catastrophic flash flood of 8 Jul 2013 in Toronto area had little in the way of synoptic-scale precursors and NWP QPF offered little help: *it seemed like just another day of typical sub-severe summer thunderstorms in the GTA*,
- Forecasters took cues from radar and from surface weather station observations in particular when issuing warnings,
- Mesoscale boundary interactions played a key role by focusing new convective development and intensifying updrafts,
- Total lightning jumps (a proxy for updraft intensification) appear to provide lead time for this event – even in the absence of a total lightning network,
- Dual-pol, S-band radar can greatly reduce attenuation problems, allowing better detection for such events, and
- Social media allowed relatively early event detection.

Overall, it is surprising and disconcerting that a billion dollar, ‘costliest-ever’ natural disaster was essentially not predictable given current forecasting techniques and technologies. Conceptual models that typically help forecasters identify flash flood ingredients at the synoptic-scale were not helpful in this case. NWP models are known to have difficulty with heavy precipitation and the details of mesoscale boundaries, particularly thunderstorm gust fronts, and evidence here suggests that increasing model resolution alone may not help. Clearly more research is needed to address these gaps.

However, as was shown above, there are some emerging detection and nowcasting techniques that appear to be promising. The ability to track

boundaries such as lake-breeze fronts in real time and correctly assess their influence is critical, and research is underway at ECCC to address this. Dual-polarization and/or S-band radars would greatly improve the value of the Canadian radar network for heavy rain events.

Monitoring lightning jump can potentially increase lead times for severe weather events, and a total lightning network was installed in the GTA in 2014 (the Southern Ontario Lightning Mapping Array, see Sills et al. 2015) to investigate this. Social media needs to be better harnessed for severe weather detection purposes, and that will involve looking for ways to automatically extract ‘signal’ from the ‘noise’, particularly near the beginning of an event.

Regarding warnings, greater collaboration between OSPC and local Conservation Authorities should also be explored. More consideration needs to be given to the impacts of heavy rain in highly urbanized areas such as the GTA, and how that might be handled with lower warning thresholds and/or special alert impact statements.

Finally, this event serves as a cautionary tale. High-impact flooding occurred in a marginally conducive synoptic-scale environment, mainly due to processes at the sub-synoptic scale. A future extreme rainfall event might be much better forecast, having synoptic-scale ingredients matching conceptual models and rainfall amounts well captured by NWP. But such an event may also have the potential for even greater amounts of precipitation. When (not if) such an event occurs in the highly urbanized GTA, the impacts could be much worse.

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REFERENCES

AMEC, 2014: July 8th, 2013 extreme rainfall event summary and analysis report. AMEC Americas Limited, 232 pp.

- Boodoo, S., D. Hudak, A. Ryzhkov, P. Zhang, N. Donaldson, D. Sills, and J. Reid, 2015: Quantitative precipitation estimation from a C-band dual-polarized radar for the 8 July 2013 flood in Toronto, Canada. *J. Hydrometeor.*, **16**, 2027–2044.
- Chronis, T., L. D. Carey, C. J. Schultz, E. V. Schultz, K. M. Calhoun, and S. J. Goodman, 2015: Exploring lightning jump characteristics. *Wea. Forecasting*, **30**, 23–37.
- Corfidi, S. F., 2003: Cold pools and MCS propagation: forecasting the motion of downwind-developing MCSs. *Wea. Forecasting*, **18**, 997–1017.
- Klaassen, J., 2014: July 8, 2013 Toronto and area extreme rainfall event: rainfall amounts and return periods. ECCC Technical Report, 15 pp.
- Maddox, R. A., C. F. Chappell, and L. R. Hoxit, 1979: Synoptic and meso- α aspects of flash flood events. *Bull. Amer. Meteor. Soc.*, **60**, 115–123.
- Schultz, C. J., W. A. Petersen, and L. D. Carey, 2009: Preliminary development and evaluation of lightning jump algorithms for the real-time detection of severe weather. *J. Appl. Meteor. Climatol.*, **48**, 2543–2563.
- Sills, D., H. Yang, and P. Joe, 2014: A Lightning Mapping Array in southern Ontario, Canada: uses for severe weather nowcasting. *Extended Abstracts, 27th AMS Conference on Severe Local Storms*, Madison, WI, Amer. Meteorol. Soc., Paper 83.

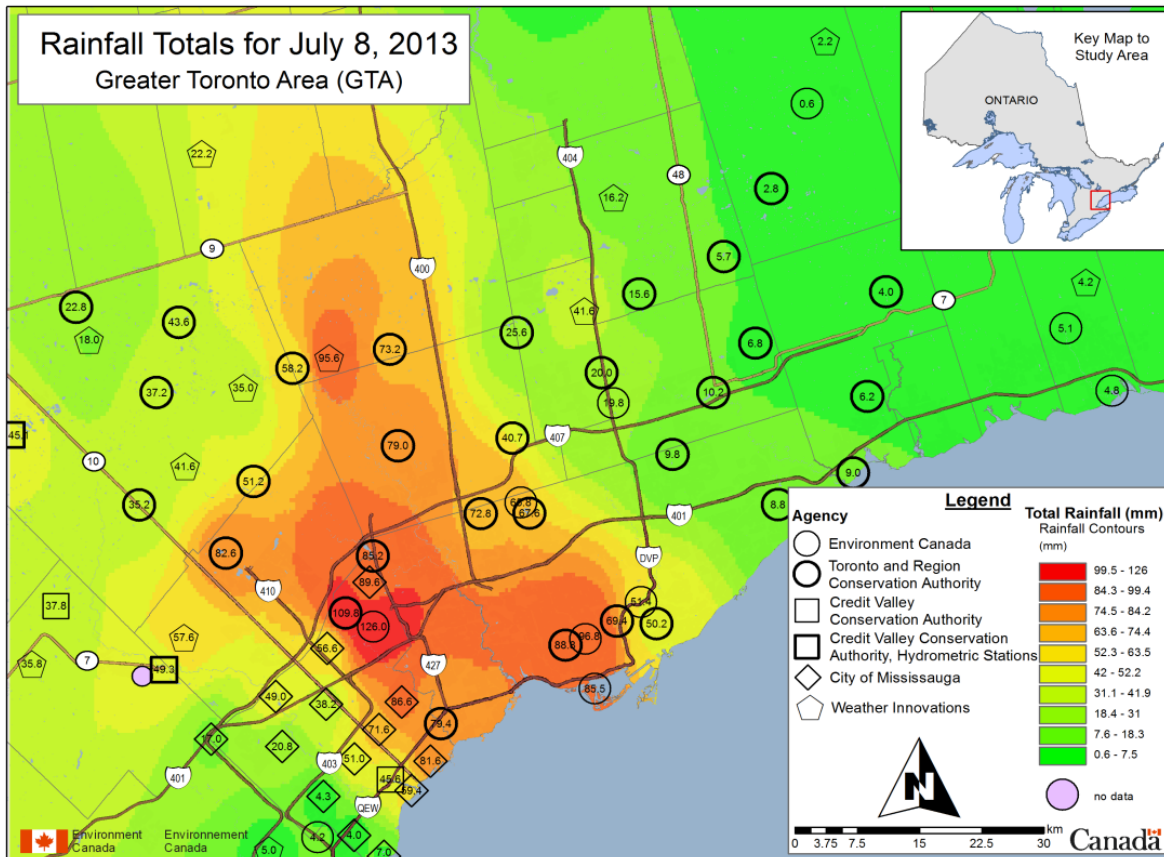


Figure 1. Rainfall totals in mm for the 8 Jul 2013 flash flood event, from Klaassen 2014. Although City of Toronto rain gauges were not included in this analysis, their Martin Grove gauge – just east of Pearson Airport – recorded 138 mm over the duration of the event (AMEC 2014).

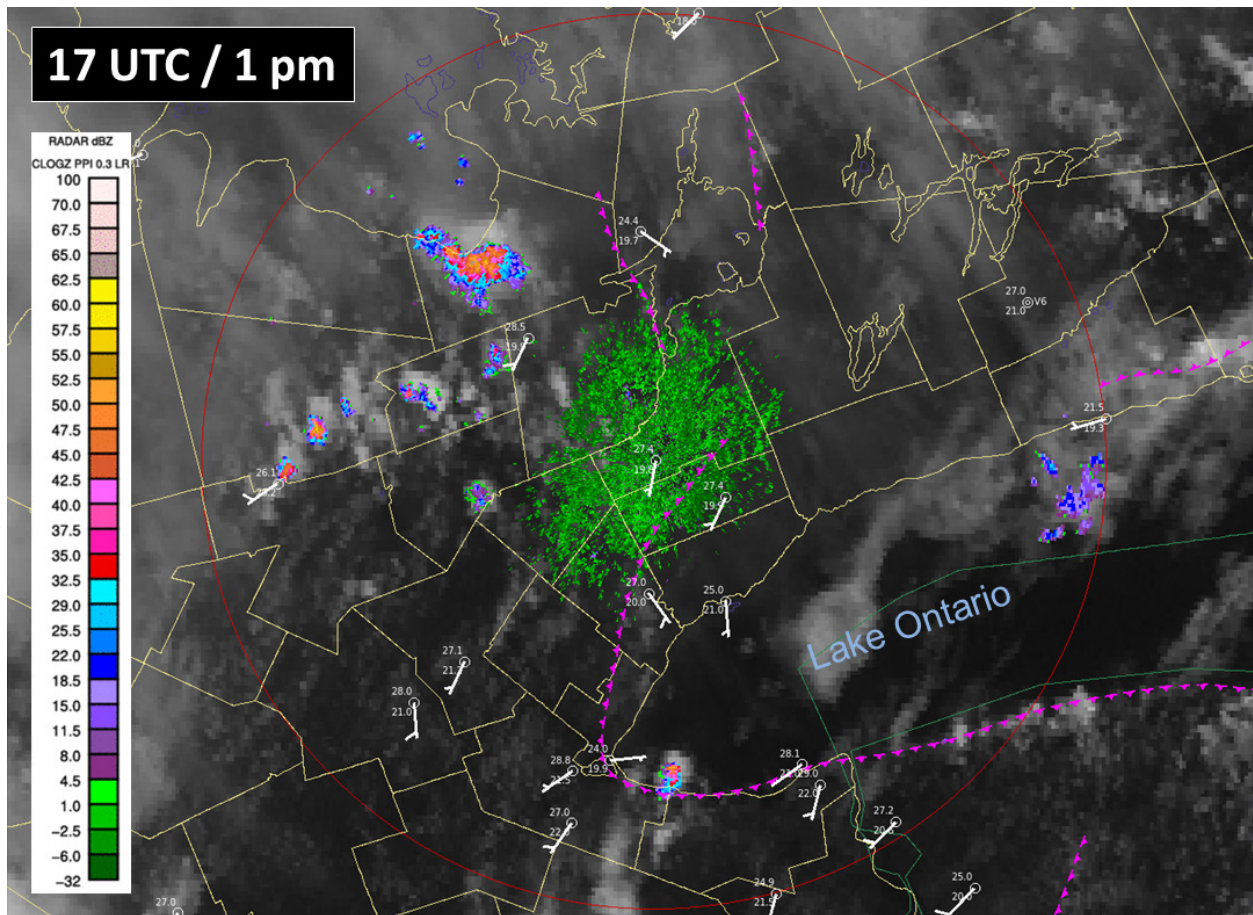


Figure 2. Composite plot at 1700 UTC showing King City radar data, GOES-13 visible channel satellite data, surface observations in standard weather station plotting format, and the estimated positions of lake-breeze fronts (magenta lines). The thin red circle indicates the Doppler range of the King City radar. OSPC warning regions are shown by the yellow outlines (no alerts were valid at this time).

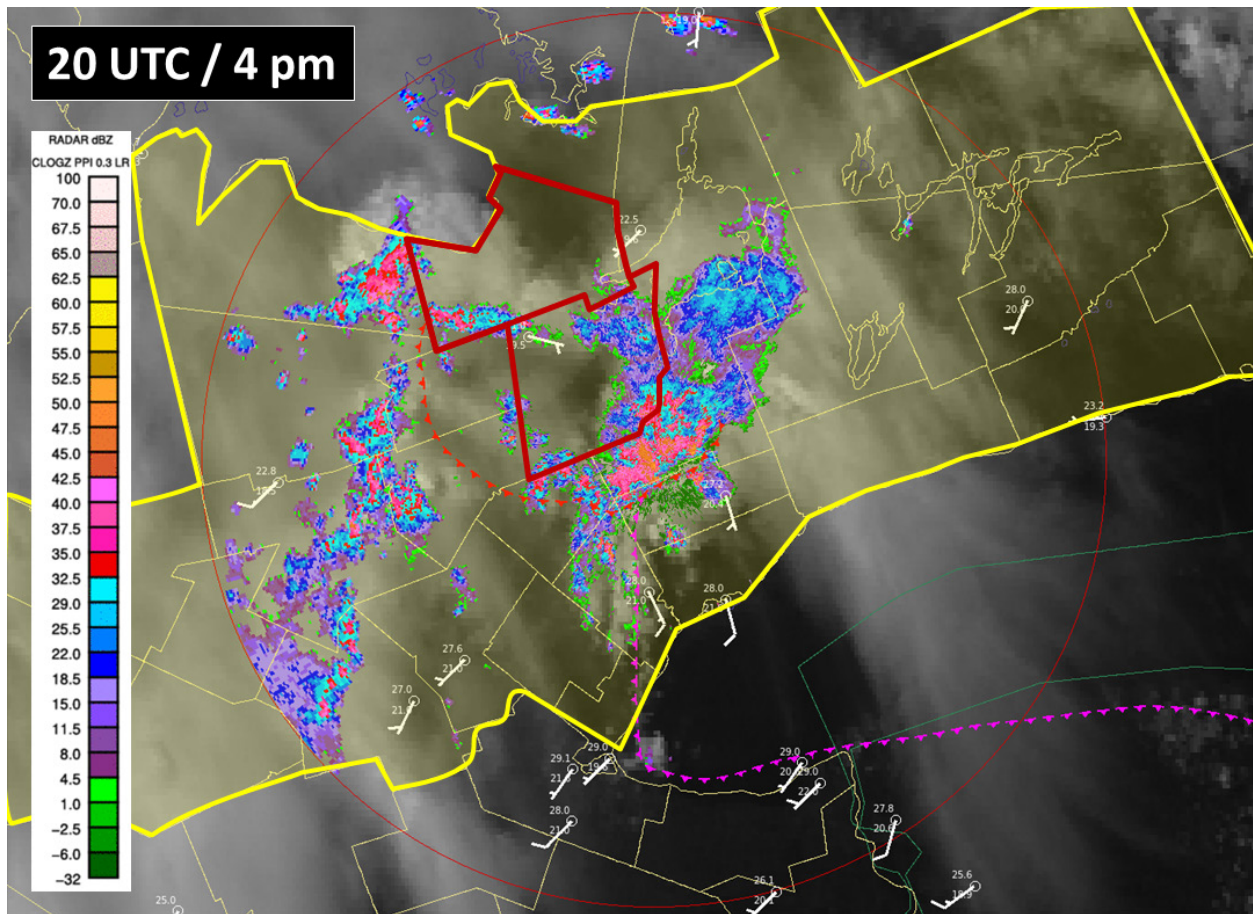
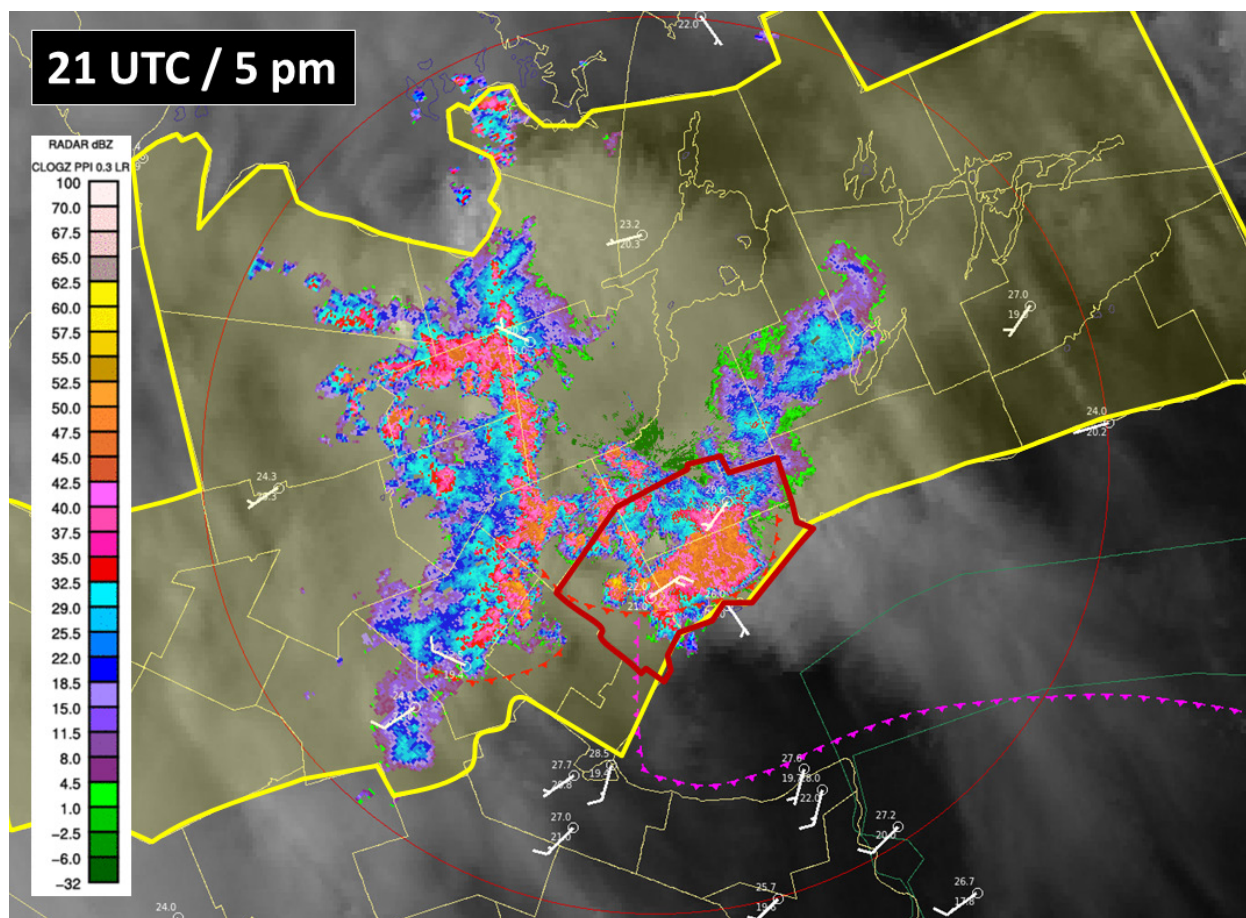


Figure 3. As in Fig. 2 except for 2000 UTC. The Special Weather Statement covers the regions highlighted in yellow, while Severe Thunderstorm Warnings are in effect for the regions highlighted in red. The estimated position of a thunderstorm gust front is also shown (red line).



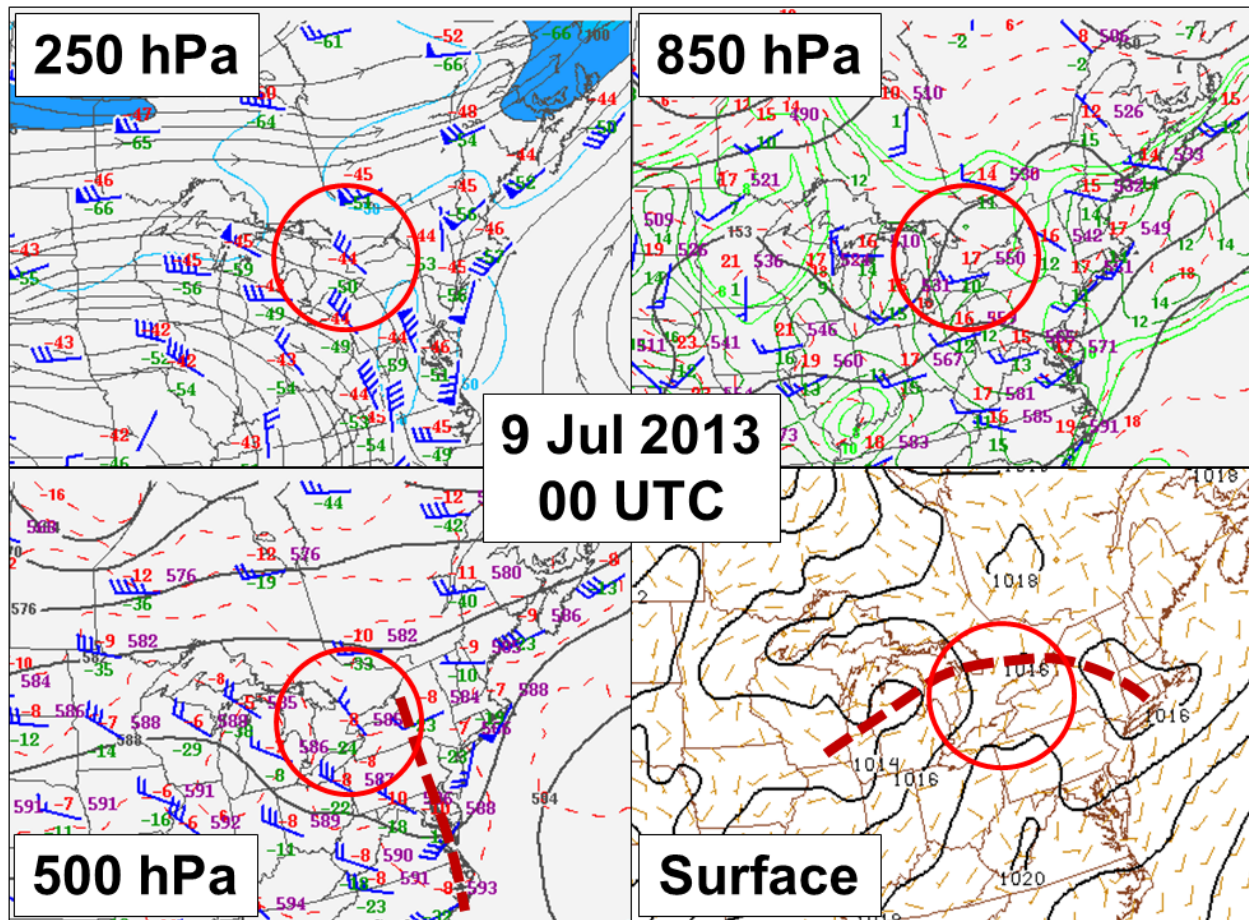


Figure 5. Analysis maps provided by the US Storm Prediction Centre. The broken dark red lines indicate a trough while the red circle is centred over the Greater Toronto Area.

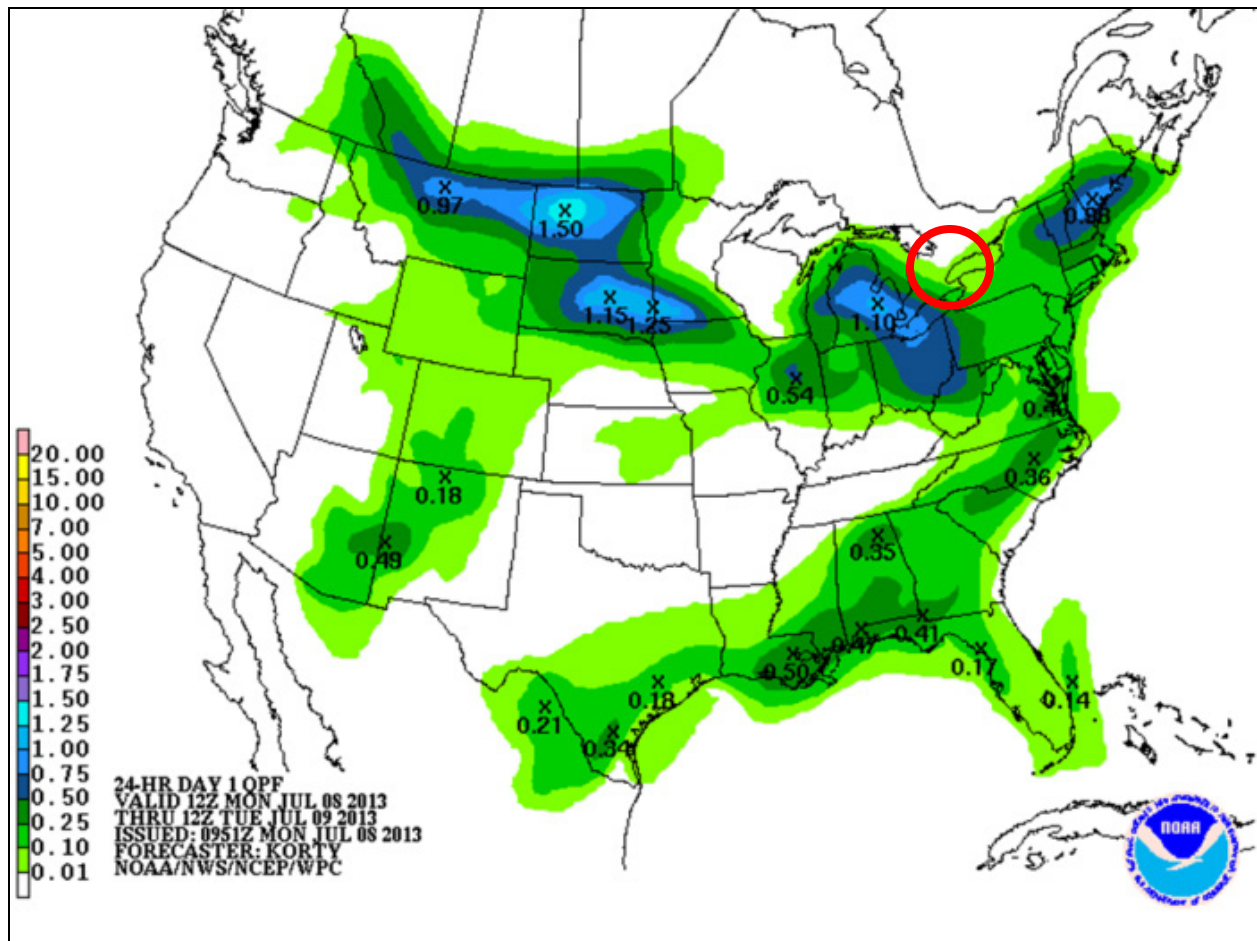


Figure 6. The 24-hour Day 1 Quantitative Precipitation Forecast (QPF) map generated by the US Weather Prediction Centre, showing a QPF bulls-eye over southern Michigan into extreme southwestern Ontario, but very little rainfall expected in the Greater Toronto Area (red circle).

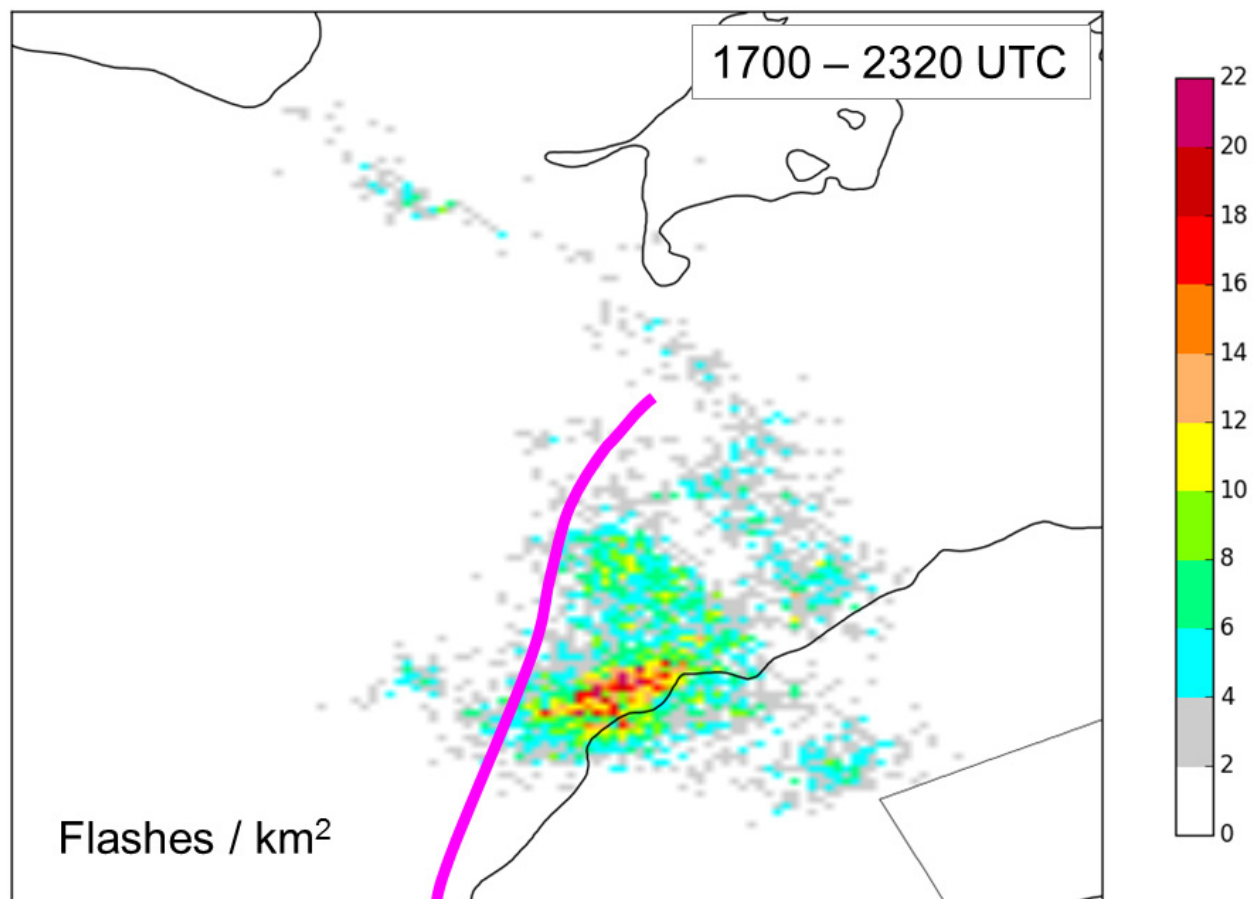


Figure 7. Lightning flash density using lightning data from the Canadian Lightning Detection Network over the period 1700-2320 UTC on 8 Jul 2013. The magenta line represents the estimated position of the Lake Ontario lake-breeze front at 1900 UTC.

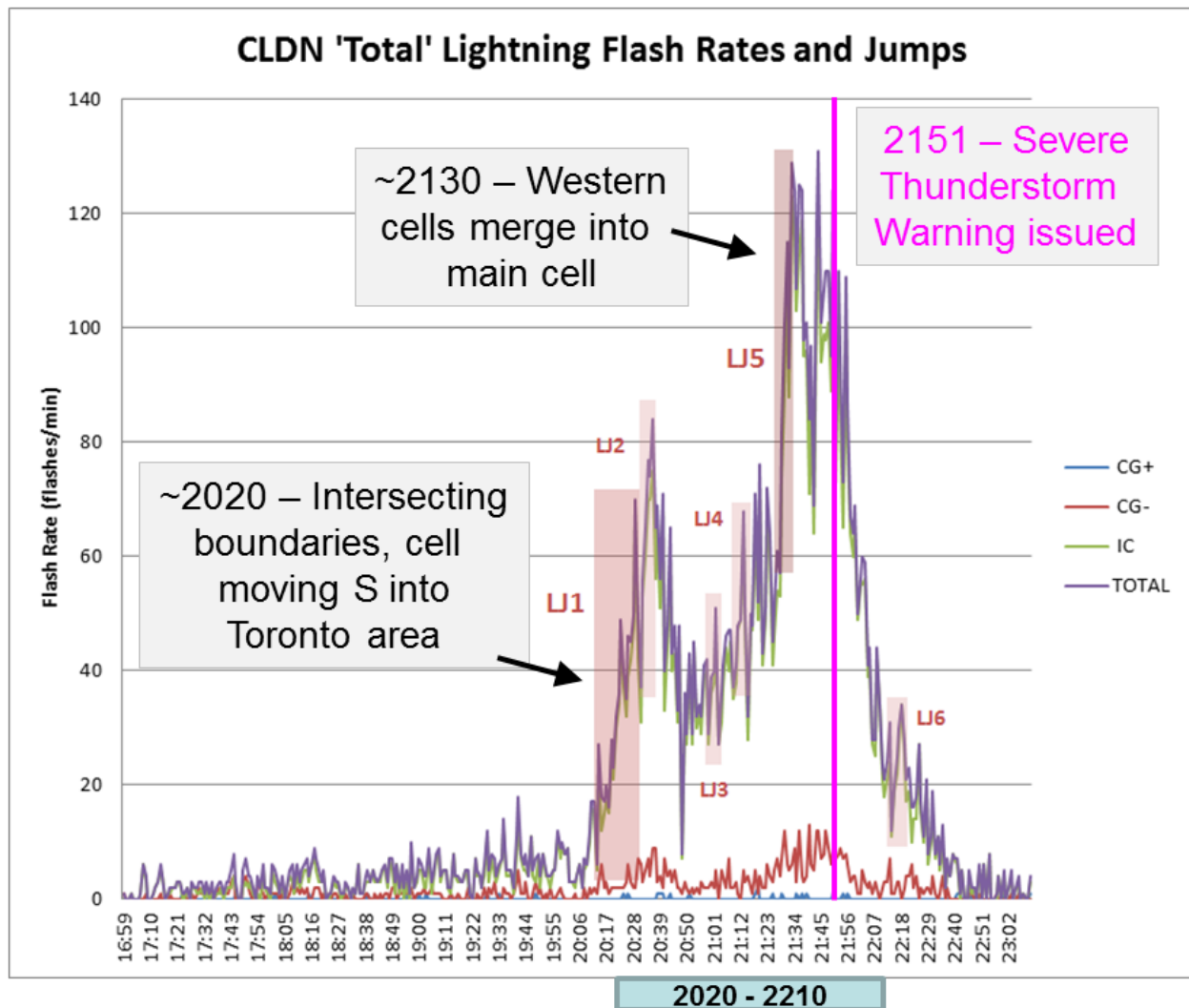


Figure 8. Graph showing counts of positive CG, negative CG, IC and combined ('total') lightning associated with the flash flood-producing cluster of storms. Times are in UTC. Lightning jumps detected by an algorithm are shown as labelled pink boxes. The blue box indicates the duration of the highest rain rates. The magenta line indicates the time when the OSPC issued a Severe Thunderstorm Warning.

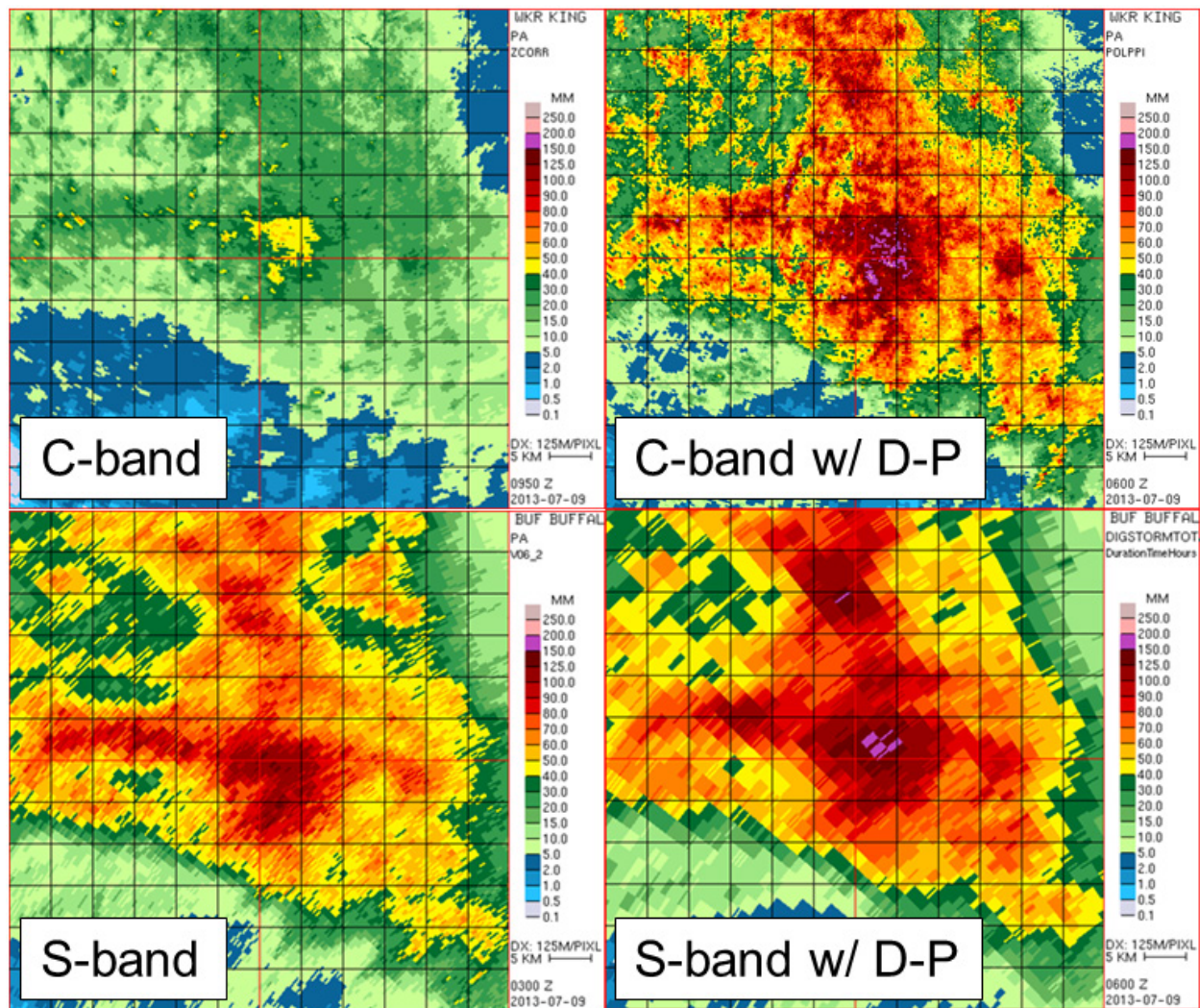


Figure 9. Storm total precipitation accumulations in mm for the 8 Jul 2013 event using four different approaches: C-band, C-band with dual-polarization data, S-band, and S-band with dual-polarization data. The accumulation maps are centred on Pearson Airport. The 'C-band' accumulation at top left is what OSPC forecasters could access in real time via their radar viewing software.