Warm season thunderstorm rainfall estimation on the Canadian Prairies using lightning and gridded model data

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ABSTRACT: Thunderstorms are an important component of the water cycle on the Canadian Prairies, because they represent one of the mechanisms responsible for cycling moisture in the warm season between May and September. The Prairie landscape is extensive and diverse, and is comprised of six eco-climatic regions. A broad swath of the Boreal and Taiga regions, where station data are sparse, lie outside radar coverage but within coverage of the Canadian Lightning Detection Network (CLDN). Can lightning data be used to estimate seasonal thunderstorm rainfall over these data sparse regions?

This work estimates warm season thunderstorm rainfall using two methods. The first method derives thunderstorm rainfall from the gridded Canadian Precipitation Analysis (CaPA) product (6-hr temporal resolution and interpolated to a 0.2° x 0.2° grid) and concurrent cloud-to-ground lightning data from the CLDN. The second method derives rainfall amounts from previously developed rain-yield relationships constructed from a database of coincident 6-hrly rain gauge rainfall and cloud-to-ground lightning observations. Spatial patterns of thunderstorm rainfall from the two prediction schemes are assessed for three summers from 2009 to 2011. Additionally, several verification statistics over each eco-climatic region are calculated to assess the accuracy of the two approaches

INTRODUCTION

Thunderstorms over the Canadian Prairie Provinces are an important component of the hydrological cycle and forest fire activity. Varying amounts of convective rainfall and lightning can trigger flash floods (Soula et al. 1998) or ignite wildfires (Rorig and Ferguson, 1999). Numerous studies have been conducted to determine lightning-rainfall relationships over a wide variety of spatial and temporal scales using various measurement platforms. A summary of these findings can be found in Soula (2009). In Canada, Kochtubajda et al. (2013) conducted an exploratory study to examine lightning-rainfall relationships during warm seasons (April to October) from 1999-2003 across Canada’s ecozones using a database of coincident 6-hourly rain-gauge measurements and lightning data. Rain yields, determined for this period, ranged between 1.05×10^8 kg fl^{-1} and 41.5 $\times 10^8$kg fl^{-1} over western ecozones.

This wide range of rain yields, both within and between ecozones, poses a challenge for deciding on an appropriate rain yield relation for estimating thunderstorm rainfall. In this study we compare two approaches to derive thunderstorm rainfall. The first approach derives thunderstorm rainfall from the gridded Canadian Precipitation Analysis (CaPA) product (6-hr temporal resolution and interpolated to a 0.2° x 0.2° grid) and concurrent cloud-to-ground (C-G) lightning flash data from the CLDN. The second approach derives rainfall amounts on the same 0.2° x 0.2° grid from previously developed rain-yield relationships constructed from a database of coincident 6-hrly rain gauge rainfall and C-G lightning observations.

STUDY AREA

The Prairie Provinces (Fig. 1) of western Canada contain a diverse and extensive landscape with six ecozones, namely: Prairies (PR), Boreal Plains (BP), Boreal Shield (BS), Montane Cordillera (MC), Taiga Plains (TP) and Taiga Shield (TS). Extensive tracts of this region are data sparse, with widely separated surface stations and little or no radar coverage. The climate is characterized by short, warm summers and long, cold winters. Precipitation is extremely variable, ranging from 250 mm annually to slightly less than 700 mm. Summer thunderstorms are often severe, producing lightning, heavy rainfall, hail and tornadoes. The thunderstorm season is relatively short, with most locations experiencing lightning between May and September. One exception is the far southeastern corner of the Prairie ecozone where the thunderstorm season typically starts in late March and continues through the end of October (Burrows and Kochtubajda, 2010).

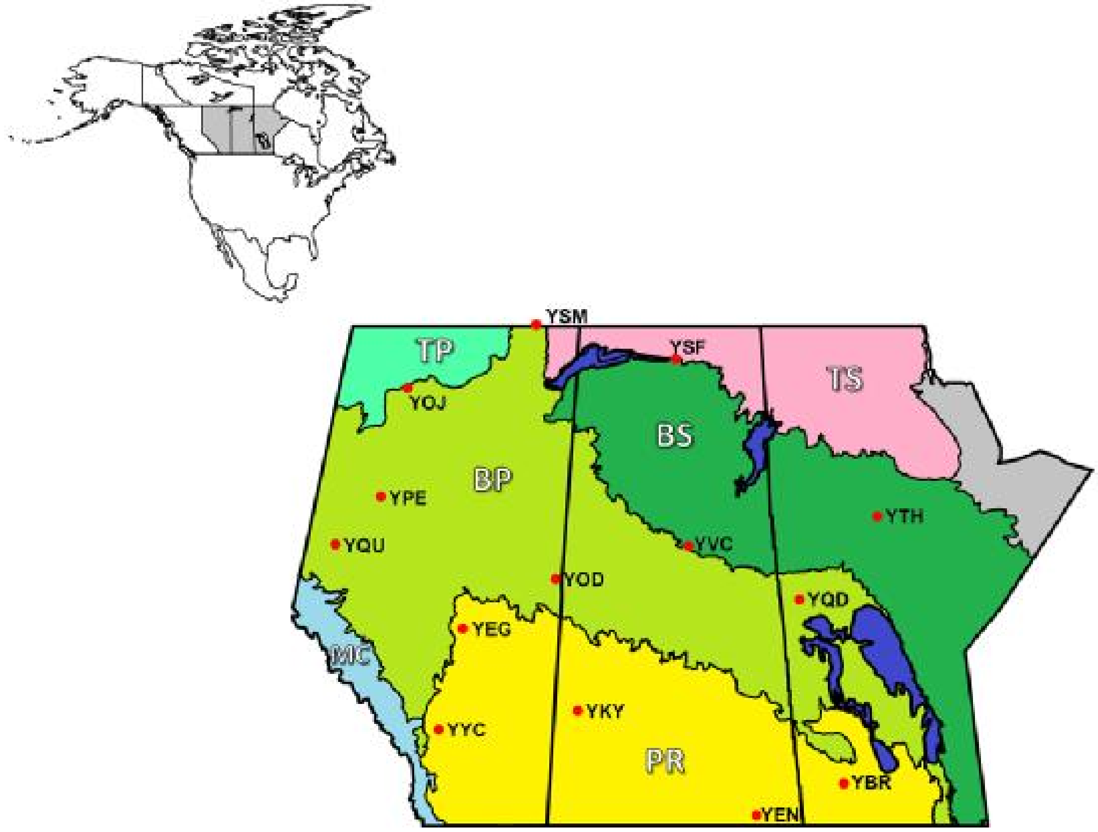


Fig. 1 Canadian Prairie Provinces (Alberta, Saskatchewan and Manitoba) study area, including the terrestrial ecozones. Locations of the surface rainfall stations used in this study are shown by red dots.

DATA AND METHODOLOGY

Several data sources were used to assemble a database of coincident 6-hourly observations of archived lightning flash and rainfall data. Lightning data were obtained from the Canadian Lightning Detection Network (CLDN). Rainfall data were extracted from the National Climate Data and Information Archive, operated and maintained by Environment Canada (2011). The CLDN is operated by Environment Canada and consists of both LPATS–IV and IMPACT–ES sensors. Quality-controlled flash data were provided by Vaisala Inc. Positive flash data were reclassified according to the criteria described in Burrows and Kochtubajda (2010).

The Canadian Precipitation Analysis (CaPA) product (6-hr temporal resolution and interpolated to a 0.2° x 0.2° grid) was used to capture the high spatial and temporal variability of warm season precipitation. CaPA is a merged precipitation product that uses observed precipitation from surface stations to nudge precipitation from the Canadian regional deterministic weather prediction system (Côté et al. 1998) using an optimal interpolation scheme (Mahfouf et al. 2007). If a C-G lightning flash is recorded within 0.1 degrees each side of a grid point for a given 6-hourly interval, then the accumulated rainfall predicted by CaPA during that time is classified as being thunderstorm rain. For each grid point, the total rainfall and associated total C-G lightning counts during the warm season months were then determined. For the second approach, thunderstorm rainfall amounts were calculated on a 0.2° x 0.2° grid using ecozone-specific rain-yield relationships derived by Kochtubajda et al. (2013) from a database of coincident 6-hrly rain gauge rainfall and C-G lightning observations. In this study, we used the C-G flash yields averaged for all stations in a given ecozone.

Quality-controlled synoptic surface rainfall measurements (amounts for 6-hourly periods ending at 1200, 1800, 0000, and 0600 UTC) from 14 principal weather stations (Fig.1) were used to validate the two methods. Due to the scarcity of stations, we were unable to represent the Montane Cordillera, Taiga Shield and Taiga Plains ecozones. Hourly weather reports from these weather stations were used to identify periods with thunderstorm activity. Thunderstorms are reported when either thunder is heard or when overhead lightning is observed (Environment Canada, 2013). All C-G flashes detected within the grid closest to each station were blocked into 6-hourly periods (for periods ending at 1200, 1800, 0000, and 0600 UTC) and paired with the coincident 6-hourly rainfall for the stations in the 2009-2011 study period. For each station, the total rainfall and associated total lightning counts during the warm season months were then determined.

RESULTS

The spatial patterns of CaPA-derived seasonal (May-Sept) rainfall and associated thunderstorm rainfall for 2009-2011 are shown in Figs. 2 and 3, respectively. The year-to-year rainfall variability is evident. For example, in Fig. 2 the Boreal Plains and Praire ecozones in 2009 are shown to be relatively dry (i.e., less than 200 mm), whereas in 2010 most zones (with the exception of the northwestern Boreal Plain) are quite wet (i.e., more than 350 mm). These patterns are consistent with the findings of Brimelow et al. (2014) who documented the widespread flooding observed over the Prairies in 2010 and 2011, and the significant drought regions in central and western Prairies in 2009. Of the three years, the thunderstorm rainfall estimated from CLDN and CaPA data is lowest in the Boreal Plains and Prairies in 2009 (Fig.3). Thunderstorms are shown to contribute greater amounts of rainfall (in excess of 100 mm) over the Boreal Plains and Prairie ecozones regions in 2010-11, and over the Boreal Shield in 2011. The highest thunderstorm rainfall amounts derived using CaPA and C-G flash data were predicted for 2010 (Fig 3).

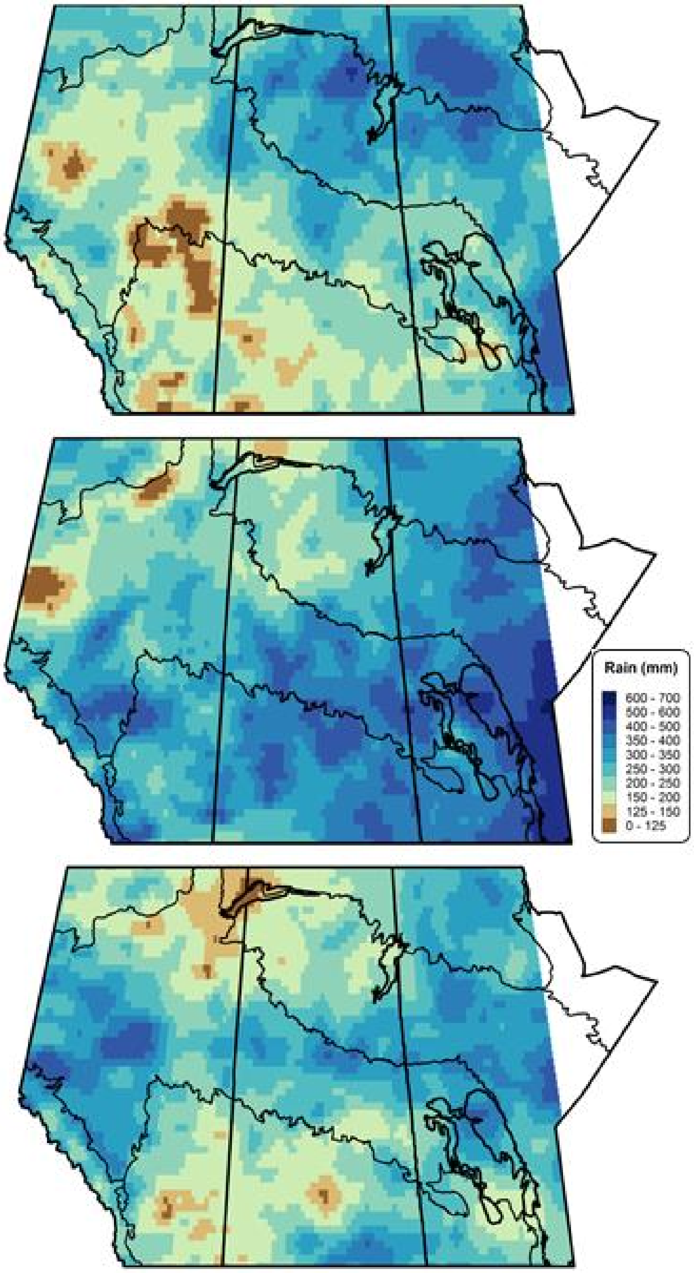


Fig. 2 The spatial patterns of CaPA-derived seasonal (May-September) rainfall for 2009 (top panel), 2010 (middle panel) and 2011 (bottom panel).

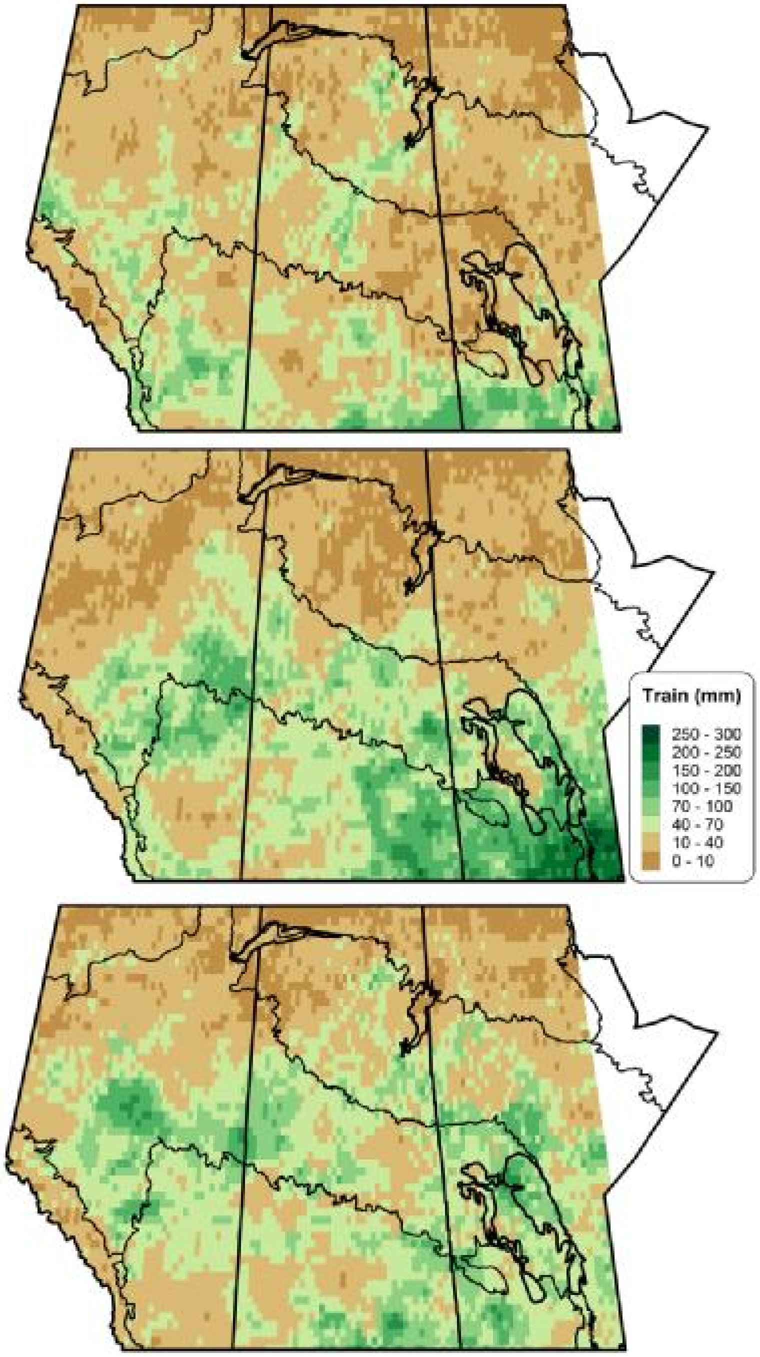


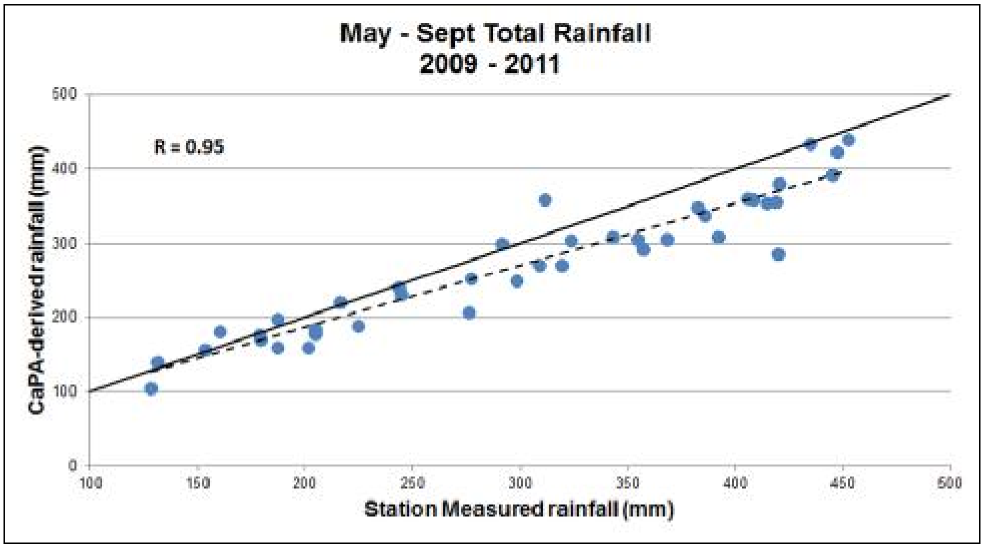
Fig. 3 The spatial patterns of CaPA-derived thunderstorm rainfall totals from May to September for 2009 (top panel), 2010 (middle panel) and 2011 (bottom panel).

Table 1: Summary of CaPA rainfall, cloud-to-ground (CG) flash counts and relative thunderstorm rain contribution averaged over grid points within each ecozone for the warm season (May-September). “Train” represents the relative contribution of thunderstorm rainfall to the seasonal total. Values in parentheses are the maximum percentages of “Train” for each ecozone.

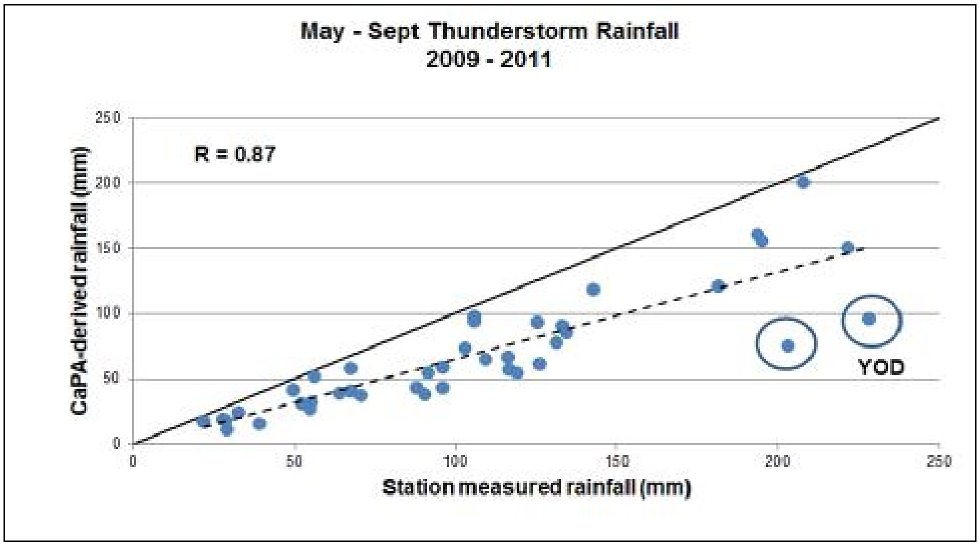
	2009			**2010**			**2011**		
	CaPA (mm)	**CG flashes**	**Train (%)**	**CaPA (mm)**	**CG flashes**	**Train (%)**	**CaPA (mm)**	**CG flashes**	**Train (%)**
PR	188.1	160.1	26.2 (67.0)	347.5	283.9	21.0 (56)	249.6	192.2	21.0 (51.2)
BP	227.3	118.3	13.7 (46.3)	299.8	188.0	14.8 (49.5)	276.5	158.2	18.2 (54.1)
BS	323.9	77.1	8.4 (39.2)	331.8	85.3	9.6 (51.3)	246.3	85.2	15.8 (42.8)
MC	212.1	123.3	14.3 (45.7)	284.8	68.6	7.2 (20.1)	291.4	98.1	10.2 (31.9)
TP	254.9	66.0	5.6 (22.4)	257.7	93.2	7.1 (16.4)	199.2	65.2	10.7 (38.6)
TS	327.1	19.4	3.3 (23.3)	308.6	27.7	3.6 (16.6)	219.9	44.8	10.2 (39.5)

Table 1 indicates that the greatest contribution to total warm season rainfall from thunderstorms is over the Prairie ecozone at 21% to 26%, with thunderstorms in some grid cells contributing up to 67% of the warm season CaPA rainfall. For the three study years, the Boreal Plains, Boreal Shield, Prairie and Montane Cordillera received very similar warm season rainfall amounts, however, the relative contribution from thunderstorm rainfall over the Prairie was the highest, followed by the Boreal Plains. The C-G flash counts and thunderstorm rainfall typically decrease with increasing latitude, with the Taiga Plains and Taiga Shield experiencing the least thunderstorm activity and lowest thunderstorm rainfall contributions (10% or less) of all the ecozones.

Seasonal and thunderstorm rainfall measured at selected manned weather stations across the study area (Fig. 1) were used to validate the CaPA-derived total rainfall and thunderstorm rainfall estimates for the warm seasons from 2009-2011. Figure 4a, b shows that the correlation coefficients were 0.95 and 0.87 for the seasonal rainfall and thunderstorm rainfall, respectively. These values suggest that CaPA captures the year-to-year variability and variability between ecozones quite well. However, two exceptions are noted when the CaPA-derived thunderstorm rainfall was significantly underestimated at Thompson (YTH) in August 2011 and Cold Lake (YOD) in July 2010. An inspection of the July rainfall record at YOD revealed that thunderstorms accounted for 70% of the total monthly accumulation (130.4 mm of 186.1 mm) on four days during the July 12-19, 2010 period. The station reported 80.8 mm of rainfall on the 19th while CaPA, in contrast, indicated an accumulation of only 0.1 mm. An examination of the radar data over YOD on July 19 found that the observed heavy rainfall was due to an isolated and slow moving thunderstorm over the station. The disparity between the station rainfall and CaPA rainfall at YOD was not an isolated case and our data suggests that CaPA tends to underestimate rainfall from heavy thunderstorm events. For example, of the 22 heavy thunderstorm events (> 25 mm) measured at the 14 stations for 2009-2011, the mean CaPA thunderstorm rainfall was only 55% of the mean station rainfall.



(a)



(b)

Fig.4. Scatterplots and correlation coefficients between the station measured and (a) CaPA-derived seasonal totals and (b) thunderstorm rainfall total at the grid point closest to each station. Two instances when the CAPA-derived thunderstorm rainfall was significantly underestimated are circled. A diagonal 1:1 line (solid), the linear best fit line (dashed), and the linear correlation coefficient (R) are indicated in the figures.

An assessment of warm season thunderstorm rainfall estimation

An independent method to estimate thunderstorm rainfall from the C-G flash data described in Kochtubajda et al. (2013) was used to evaluate CAPA derived thunderstorm rainfall. Ecozone-specific average rain yields were applied to the seasonal lightning counts at each grid point to generate predicted thunderstorm rainfall maps over the study area for each of the warm seasons in 2009-2011. Rain yields ranged between 1.92 x10^8 kg fl^{-1} and 3.29 x10^8kg fl^{-1}. As an example, the predicted thunderstorm rainfall map for the warm season of 2010 is illustrated in Fig. 5.

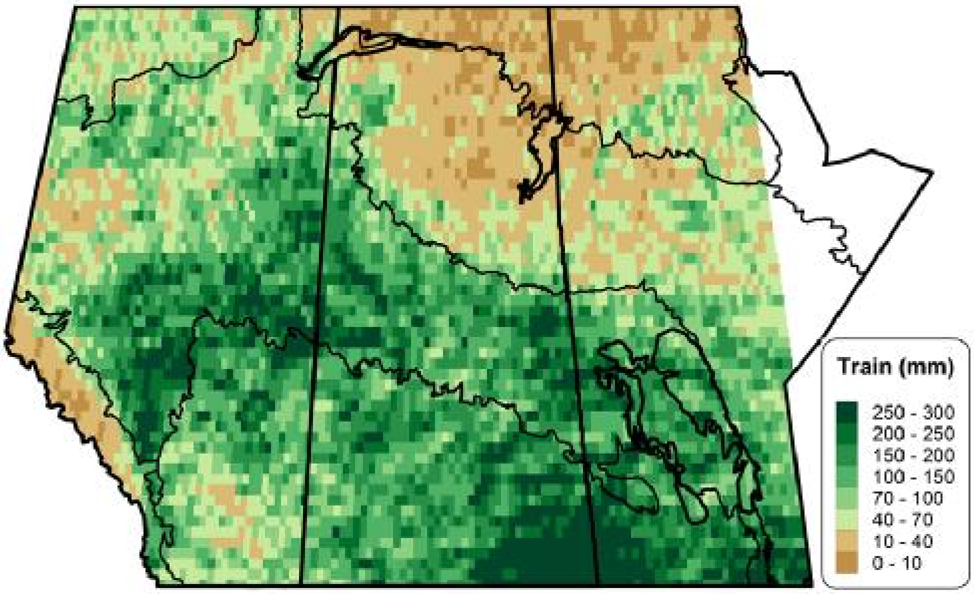


Fig. 5. Predicted thunderstorm rainfall map for the warm season of 2010 using ecozone average lightning-rainfall relationships calculated by Kochtubajda et al. (2013).

Figure 5 suggests that the thunderstorm season over the Prairie Provinces in 2010 was very active. McDonald (2011) reported that thunderstorm activity in the 2010 warm season was high, especially across central Alberta and into central and southern Saskatchewan. A comparison of the spatial patterns of the CaPA-derived thunderstorm rainfall map (Fig. 3 middle panel) and the predicted thunderstorm rainfall map (Fig. 5) finds that the areas of greatest rainfall in the Boreal Plains and Prairie ecozones are reasonably captured in both fields. Both fields also suggest a relatively dry region in the western portions of the Prairie ecozone. Overall though, the CaPA derived rainfall amounts are much lower.

Figure 6 shows the scatterplot for station measured and predicted thunderstorm rainfall using the C-G flash relationships (at the grid point closest to each station) for the 2009-2011warm seasons, yielding a correlation coefficient of 0.66. The measured thunderstorm rainfall averaged over the 14 stations is 104.3 mm, whereas the predicted thunderstorm rainfall using the C-G flash relationships is 115.7 mm. We also estimated the thunderstorm rainfall using CaPA-derived rain-yields averaged over each ecozone; rain yields ranged between 0.98 x10^8 kg fl^{-1} and 1.95 x10^8kg fl^{-1}. Using this approach, the linear correlation coefficient and the predicted thunderstorm rainfall averaged over the 14 stations were 0.67 and 55.8 mm, respectively. By comparison, the CaPA-derived thunderstorm rainfall averaged over the 14 stations was 68.7 mm.

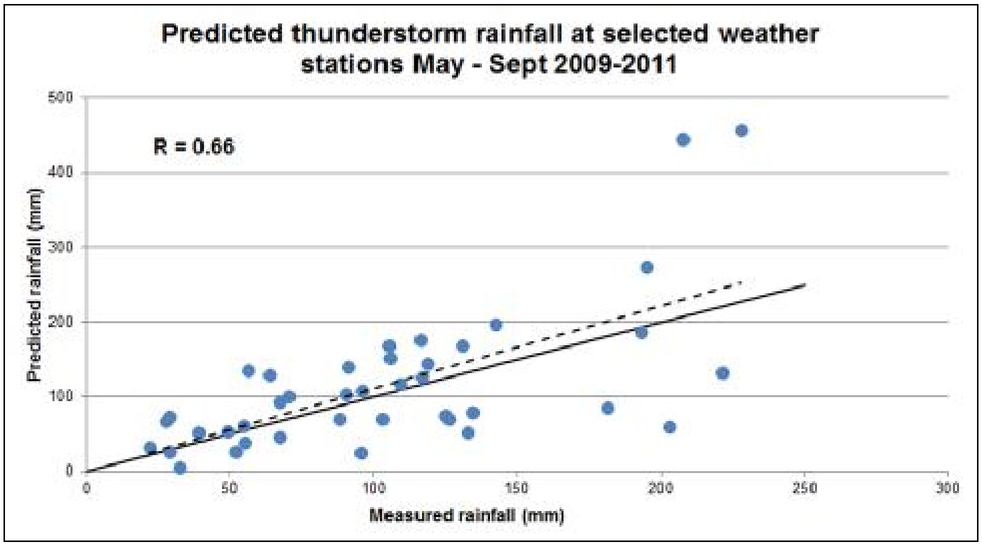


Fig. 6. Scatterplot between measured and predicted thunderstorm rainfall using the rain yields from Kochtubajda et al (2013). The grid point closest to each station was used. The diagonal 1:1 line (solid), the linear best fit line (dashed), and the linear correlation coefficient (R) are indicated in the figure.

DISCUSSION AND CONCLUSIONS

The primary objective of this research was to determine whether or not C-G flash data could be used either alone, or in concert with CaPA rainfall, to estimate seasonal thunderstorm rainfall over data sparse regions. Our analysis suggests that both methods show promise, and that the C-G flash relationships are robust even when applied at a spatial high resolution. Also, there is a high degree of correlation between thunderstorm rain estimates from both methods against those from 14 manned weather stations. The CaPA method, however, markedly underestimates the thunderstorm rainfall amounts, whereas the C-G flash yield method tends to overestimate the thunderstorm rainfall. So the CaPA and C-G flash yield techniques may represent the lower and upper bounds of thunderstorm rain estimates, respectively.

Certain limitations of these methods need to be kept in mind. For example, currently all the rainfall in a 6-hr window with lightning is attributed to thunderstorm rainfall and flash yields derived using point measurements are applied over large areas. While there is promise in using coincident CaPA and C-G flash data to determine seasonal thunderstorm rainfall at a high spatial resolution, we found that CaPA sometimes grossly underestimates the rainfall at locations affected by isolated (or slow moving) thunderstorms. This is likely because the current assimilation scheme in CaPA rejects those observations that differ significantly from the model-derived background precipitation field, which in turn may be biased low during convective events because current NWP models still struggle to correctly predict the timing and location of isolated thunderstorms, especially in weakly forced situations. Work is underway on developing version 3 of CaPA (Fortin et al. 2014), in which quantitative precipitation estimates from the Canadian radar network are also assimilated. Preliminary results indicate that this approach reduces the negative bias of warm season CaPA rainfall observed in this study.

Future work will address some of the shortcomings in the current methodology by using 3-hourly satellite-derived rainfall (e.g., CMORPH or GPM) at a high spatial resolution, or using hourly rainfall data from an extensive network of stations in Alberta to improve the C-G flash rainfall yields. A significant portion of the thunderstorm rainfall in this region is from so-called “dry” thunderstorms (i.e., rainfall amounts <3 mm), but our work suggests that the C-G flash rainfall yield may differ for “dry” events and those with more than 3 mm. Thus calculating separate C-G flash yields for these two categories could further improve the thunderstorm rainfall estimates.

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