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A Canadian Hail Climatology Based on Elevation and the Hail-Thunderstorm Ratio

Scott D. Kehler. ORCID: 0000-0002-8961-381X
Matthieu Desorcy

Weatherlogics Inc. Winnipeg, Manitoba, Canada

Corresponding author email: scott@weatherlogics.com

Abstract

This paper examines the relationship between elevation and the hail-thunderstorm ratio. Hail data from the Weatherlogics Hail Database (WHD) was used to calculate the average annual hail hours in urban areas. The hail-thunderstorm ratio was then calculated as the quotient of average annual hail hours and average annual thunderstorm hours. The hail-thunderstorm ratio was calculated for all hail (diameter ≥ 5 mm) and severe hail (diameter ≥ 20 mm). The relationship between elevation and the hail-thunderstorm ratio was then examined, with coefficients of determination (r^2) of 0.78 and 0.65 found for all hail and severe hail, respectively. Using this relationship, the root-mean-square error between actual hail hours and predicted hail hours was found to be 0.6 and 0.2 hours, for all hail and severe hail, respectively. The relationships were then used to construct national hail climatologies for Canada using gridded elevation data and a thunderstorm hours climatology. A strong correlation of 0.98 was also found between annual hail hours and annual hail days, allowing for a “national hail days” climatology to be produced. A maximum in all hail hours and hail days was found along the Alberta foothills, with secondary maxima in the British Columbia interior and southern Prairies.

Key Points

1. In Canada, a majority of the variation in the hail-thunderstorm ratio can be explained by elevation.
2. The hail hours and hail days climatologies in this paper show a national maximum in hail occurrence along the lee of the Rocky Mountains in Alberta (Alberta foothills), with secondary maxima in the interior of British Columbia and the southern Prairies.

1. Introduction

Hail is a major source of insured losses in Canada. At the time this paper was written, hail was responsible for the second and eighth largest natural disasters in Canadian history, based on total insured losses. These two disasters both occurred in Calgary, Alberta – on August 5, 2024, and June 13, 2020. The August 5, 2024, hailstorm caused approximately CA\$3.25 billion in losses and the earlier June 13, 2020, storm caused CA\$1.3 billion in losses (Insurance Bureau of Canada). Other parts of Canada also receive damaging hail. For example, Winnipeg, Manitoba suffered a catastrophic hail event on August 24, 2023, causing more than 15,000 vehicle claims, which, up to that point, was the largest natural catastrophic event in the history of Manitoba Public Insurance. Furthermore, hail is responsible for significant agricultural yield losses, with crop insurance payouts on the Canadian Prairies totaling in the hundreds of millions of dollars annually (Canadian Crop Hail Association).

Despite Canada's hail risk, it is surprising that recent public hail data is very limited. As noted in Etkin (2018), Environment and Climate Change Canada (ECCC) weather stations now collect a trivial amount of hail data. Currently, Nav Canada's Human Weather Observation System (HWOS) at Canadian airports is the primary source of routine hail data. As of early 2025, there were 146 HWOS in Canada with the capability of reporting hail, although an analysis of the reporting efficacy of these stations is beyond the scope of this study. Recognising this data gap, Weatherlogics Inc. has collected national hail data in Canada since 2017, with a database of more than 10,000 reports between 2017 and the time of writing.

The earliest known Canadian hail climatology is from Environment Canada, based on station data from 1951-1980 (Phillips, 1990). This climatology was provided as a contour map and has an accompanying map showing average annual days with thunderstorms. Etkin and Brun (2001) produced another commonly used hail climatology for Canada, which was more recently updated in Etkin (2018). Etkin and Brun (2001) found that hail frequency was highest in Alberta, followed by Saskatchewan, and then Manitoba/British Columbia (tied).

The most recent Canadian hail climatology from Brunet and Brimelow (2024) shows the highest hail frequency in three areas: southeastern Saskatchewan and southwestern Manitoba, the Alberta Foothills, and southwestern Ontario. Each of these maxima locations averages between one and two hail days per year. Allen *et al.* (2020) notes that Canada has had hail observations since at least 1955, but the record contains many inconsistencies. ECCC mandated human collection of hail data from 1977 to 1993, and the Alberta Hail Project also collected high-quality observations in the 20th century. Since 1979, Allen *et al.* (2020) notes that Canadian spotter reports are biased toward population centres and concentrated in only four provinces.

The idea for this research originated from two observations. First, there appears to be a relationship between hail and elevation. To highly generalise past hail research, one tends to find a maximum in hail occurrence on the leeward side of the Rocky Mountains, running from Alberta southward in the Great Plains of the United States (e.g. Phillips, 1990; Etkin, 2001; Cintineo *et al.*, 2012; Murillo *et al.*, 2021). As one moves east from this area, hail frequency generally declines, as does elevation.

The second observation is that the thunderstorm climatology of a location provides a useful limit to the hail climatology, based on the assumption that all hail is produced by thunderstorms. There may be some occasional exceptions to this assumption for small hail, but for large hail this assumption is essentially universal.

The hail-thunderstorm ratio was commonly used in the middle of the 20th Century (e.g. Shands, 1944; Beckwith, 1960; Changnon Jr., 1962; Baughman and Fuquay, 1970; LaDochy, 1985), to describe the relationship between hail and thunderstorms. However, we were unable to find more recent studies using it, suggesting it has fallen out of favour. The reason for its decline is unknown, but it may be connected to the automation of weather observations, which has reduced the routine collection of hail data, making such calculations more difficult. These two observations were combined to formulate a simple research question: Can elevation data and a thunderstorm climatology be used to produce a reliable hail climatology?

The remainder of this paper is structured as follows:

- **Section 2** describes the data used in this paper;
- **Section 3** outlines our methods;
- **Section 4** shows the results;
- **Section 5** compares the results to other studies;
- **Section 6** is a discussion of the results;
- **Section 7** provides our conclusions.

2. Data

2.1. Weatherlogics hail database

To study our research question, it was first necessary to acquire a source of validated hail data. The Weatherlogics Hail Database (WHD) is such a source, providing a structured set of validated hail data for hailstorms in Canada since 2017.

The database contains the following fields: hail report time, latitude, longitude, maximum hail diameter, nearest city, province, quality-control flag, and unstructured notes. Importantly, the WHD includes hail of all sizes, starting at 3 mm in diameter. However, in this paper we exclude hail that is less than 5 mm in diameter, which is generally considered the minimum diameter for a hydrometeor to be classified as hail (AMS, 2024).

Weatherlogics staff collect hail data for the WHD from various sources, including social media, media reports, Meteorological Aerodrome Reports (METARs), Environment and Climate Change Canada severe weather summaries and reports, volunteer reports (e.g. Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS)), the Weatherlogics mobile app, and personal telephone calls to affected individuals or businesses.

The objective is to precisely and accurately document the largest hail that fell at a given location from a given hailstorm.

To ensure accuracy and precision, each report is validated to ensure it meets at least the quality-control level 1 (QC1) standard. For especially precise reports, there is also a quality-control level 2 (QC2). The standards for QC1 and QC2 reports are as follows:

QC1

- Report time is valid to within 15 minutes
- Maximum diameter is measured within 5 mm
- Location is valid to within 2,000 m

QC2

- Report time is valid to within 5 minutes
- Maximum diameter is measured to within 2 mm
- Location is valid to within 250 m

The QC1 and QC2 thresholds for time and location are validated by comparing the hail report to radar data (e.g. reflectivity, differential reflectivity, correlation

coefficient, and maximum estimated hail size). Hail reports that occur outside of radar coverage are validated by ensuring there was a nearby thunderstorm.

Such validation can include the use of satellite imagery, lightning detection, or nearby weather stations. These data sources are also used in some cases where radar data is insufficient to validate the report. Regardless of the validation source, the purpose is to ensure the hail report is reasonable and to determine its precision.

If the hail report clearly does not align with the observational data, the report is discarded. The validation data is not used as a substitute if the report itself cannot meet the quality-control thresholds. If the diameter is explicitly provided with a report, that value is entered into the WHD after validation. If the diameter is not explicitly provided, a secondary data source is needed, such as a photo with a reference object, from which the diameter can be determined. If such a secondary data source is unavailable, the report is assigned a diameter of -1, indicating the diameter is unknown. If the diameter can be determined by a primary or secondary means, it is then also compared to radar data to ensure it is reasonable.

Whether a report is classified as QC1 or QC2 is a judgement made by a trained staff member, based on comparisons with the validation data. Null cases are also included in the WHD, where hail was confirmed to have not occurred at a given location. These reports are given a diameter of 0.

At the time of writing, the database contained 10,997 reports from January 1, 2017, to October 1, 2024, with 9,864 reports having a verified diameter of 5 mm or larger, and 4,394 reports with a diameter of 20 mm or larger. This date range is also the time period over which the statistics in this study were calculated.

In Canada, hail is often classified as severe or non-severe, depending on its diameter. ECCC defines severe hail as having a diameter of at least 20 mm. Throughout the remainder of this paper, we will use the term “all hail” to characterise any hail with a diameter of 5 mm or larger, and “severe hail” to characterise hail that has a diameter of 20 mm or larger. A map of all reports is shown in Figure 1, with severe reports shown as red triangles, and “non-severe” hail (5-19 mm diameter) shown as blue circles.

All Hail Reports in Canada

Blue circle: non-severe; Red triangle: severe

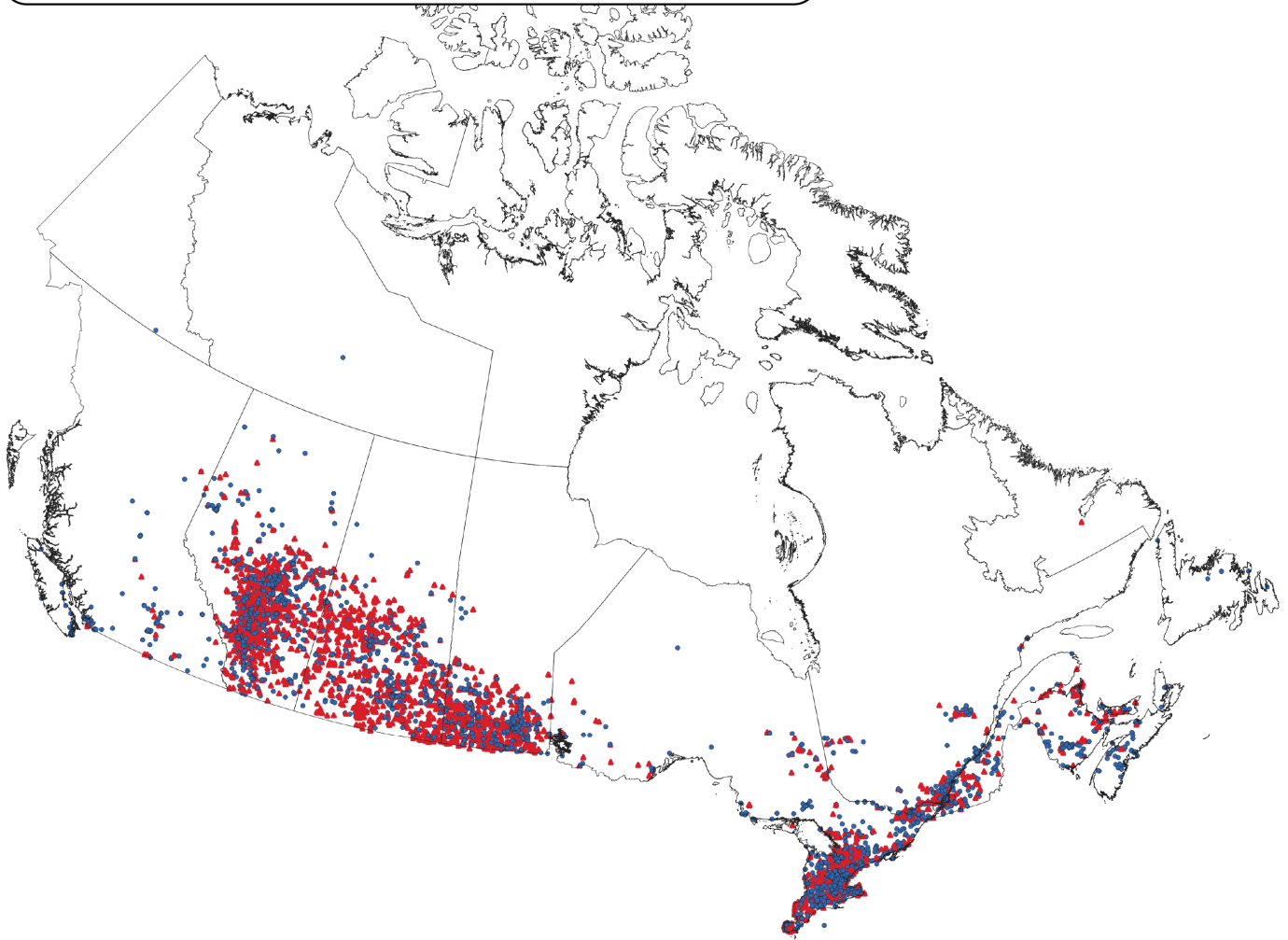


Figure 1: Hail reports from the Weatherlogics Hail Database between January 1, 2017, and October 1, 2024. Blue circles represent non-severe hail reports (diameter 5-19 mm), and red triangles represent severe hail reports (diameter 20 mm or larger).

2.2. Thunderstorm climatology

The thunderstorm climatology used in this paper is from the World-Wide Lightning Location Network (WWLLN). The WWLLN provides lightning data as an annual climatology of thunder hours. The climatology is provided on a 0.05° latitude/longitude grid. The climatology is based on lightning detection data from January 1, 2013, to December 31, 2023.

The performance of the WWLLN has been previously evaluated (Rodger *et al.*, 2004; Jacobson *et al.*, 2006; Lay *et al.*, 2007; Rudlosky and Shea, 2012) and, thus, we consider it reliable. More details are available in Virts (2024). A map of Canada's WWLLN thunder hours climatology is shown in Figure 2.

2.3. Elevation data

Elevation data at point locations were retrieved from the Canadian Digital Surface Model (CDSM). The CDSM provides elevation data on a 20 m grid based on data collected by the Shuttle Radar Topographic Mission. More details can be found in Natural Resources Canada (2018). Point elevation data was used to retrieve elevations at the centroid of urban areas.

Gridded elevation data was sourced from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) from the United States Geological Survey (USGS). The GMTED2010 data used in this paper was retrieved at 15-arc-second resolution. However, the data was later regridded to 0.05° to align with the WWLLN thunder hours climatology. More details can be found in Danielson and Gesch (2011). Gridded elevation data was used to produce national hail climatologies. Figure 3 shows the GMTED2010 data used in this paper.

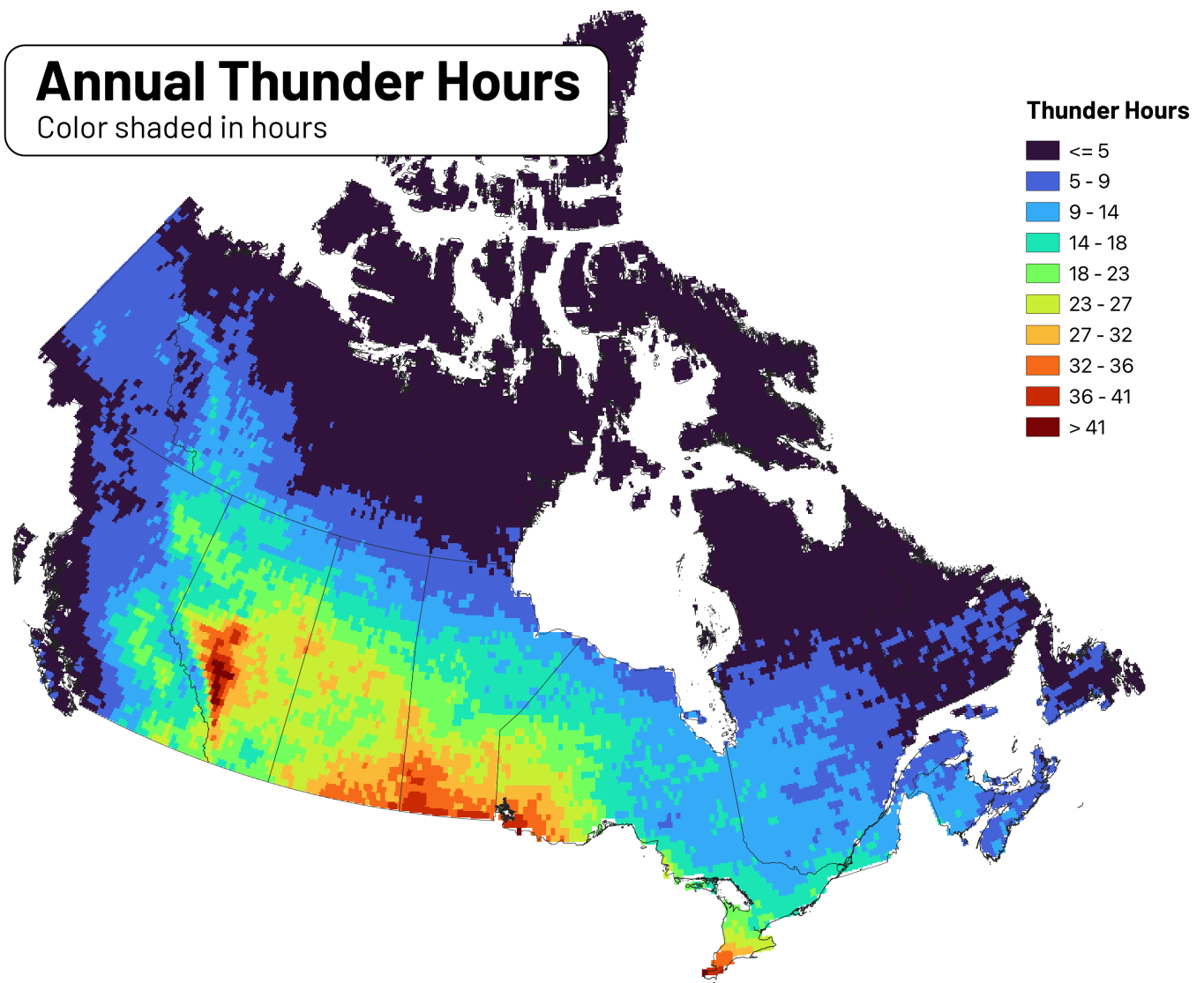


Figure 2: Average annual thunder hours from the World-Wide Lightning Location Network (Virts, 2024). Thunder hours are colour-shaded in hours.

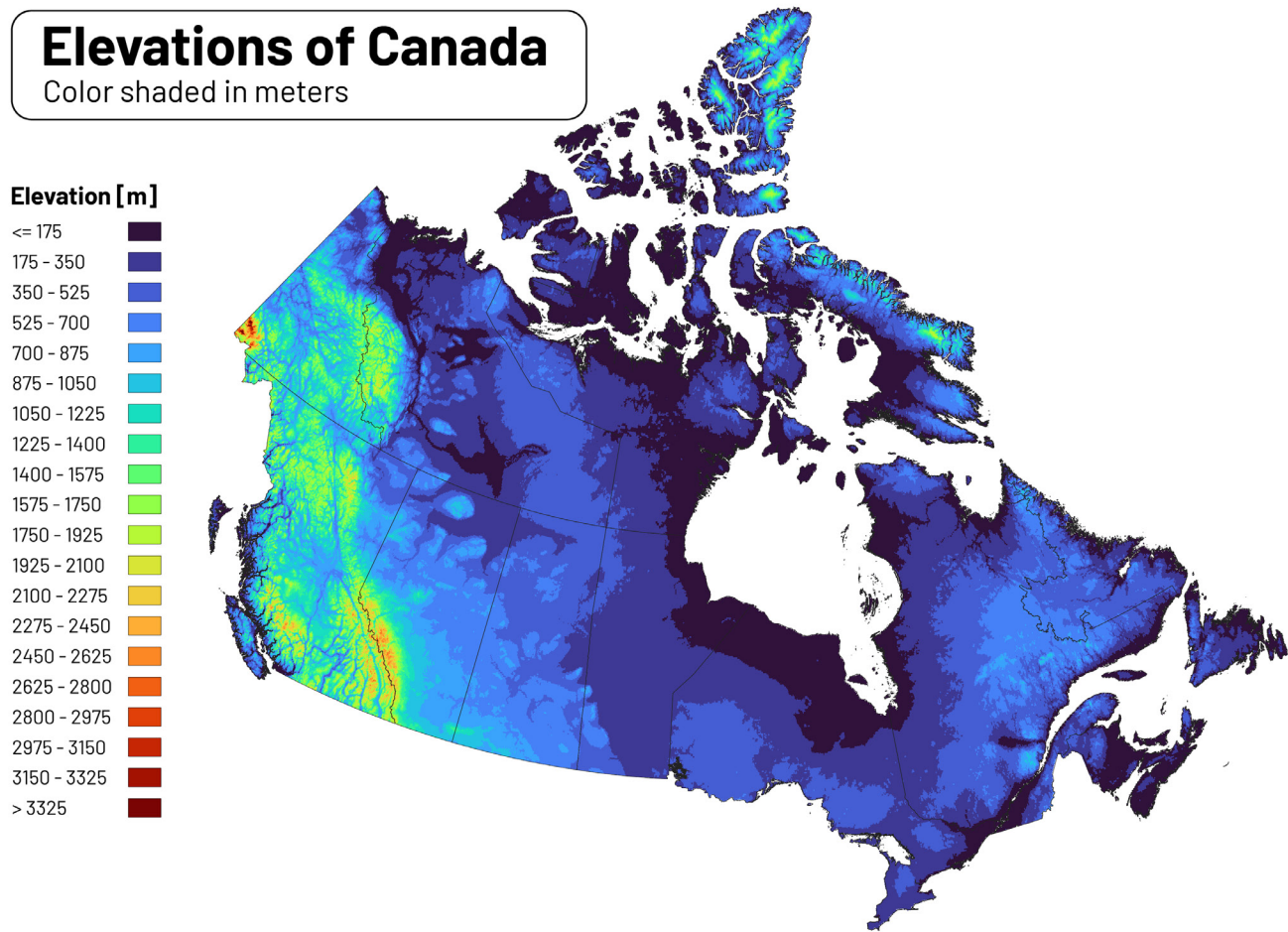


Figure 3: Elevation data over Canada from the Global Multi-resolution Terrain Elevation Data 2010 (Danielson and Gesch, 2011). Elevations are colour-shaded in metres.

3. Methods

3.1. Defining hail statistics

Hail days are commonly used in hail climatology literature. In this paper, we define a hail day to be any climate day in which hail occurs. A climate day in Canada starts at 0600 UTC and ends 24 hours later. We also use the concept of hail hours, which is analogous, except it refers to any hour in which hail occurs. It is important to note that neither hail days nor hail hours should be interpreted as a duration (i.e. a hail day does not mean hail persisted for a full 24 hours, nor does a hail hour mean hail persisted for an entire hour).

Another hail statistic we use frequently in this paper is the hail-thunderstorm ratio. The first known reference to the hail-thunderstorm ratio was in Shands (1944). It has since been used in many other climatological studies to quantify the proportion of thunderstorms that produce hail. This concept is useful, because as noted in the introduction, we assume the number of thunderstorm hours/days at a given location is also effectively the maximum possible number of hail hours/days. Therefore, the hail-thunderstorm ratio varies from 0 to 1, with a ratio of 1 meaning that all thunderstorms at a given location produce hail.

3.2. Defining urban study areas

Past research utilising hail reports has found that they are often biased toward population centres (e.g. Pehoski, 2013; Paulikas, 2014; Allen *et al.* 2017; Allen *et al.* 2020; Murillo *et al.* 2021). This is because hail reports require manual observation by a human observer, logically biasing reports toward higher population densities. Most of Canada consists of rural and remote lands, with very low population density. Therefore, the issue of a population bias is especially prevalent, with many hail reports in urban and agricultural areas and few or no reports in the vast Canadian Shield and arctic/subarctic regions (see Figure 1).

We observe that the high prevalence of hail reports in urban areas means that hail is most thoroughly sampled in those areas. As a result, this study utilises population centers and their reporting bias, similarly to Murillo and Homeyer (2019), to find a representative relationship between hail reports and other parameters, to then use over a larger area. We use the Statistics Canada definition

of an urban area, which requires a population of at least 1,000 and a population density of at least 400 persons per square kilometre. To identify urban areas, we use population data from the 2021 Canadian census (Statistics Canada). Figure 4 (top panel) shows all 362 urban areas in Canada as blue shaded areas.

3.3. Calculating the hail-thunderstorm ratio

To objectively determine the hail-thunderstorm ratio, it was first calculated for all possible sample sizes. This allowed us to objectively determine if a stable relationship exists between elevation and the hail-thunderstorm ratio as a function of the sample size. The first step in this approach was to calculate the number of all hail hours and severe hail hours for each urban area based on its administrative boundaries (see Figure 4). Next, the hail hours were normalised to an area of 100 km², the approximate resolution of the WWLLN thunderstorm hours climatology. If an urban area had an area of less than 100 km² no scaling occurred because scaling caused unrealistic hail-thunderstorm ratios to result (i.e. ratios greater than 1). Given that the average width of a hail swath (see Bell *et al.*, 2023) is approximately equal to the width of the normalised area (100 km², which corresponds to a 10 km x 10 km area), smaller areas should adequately capture all hail events. The result was normalised hail hours, for all hail and severe hail. *Note: While hail days are not part of our primary results, they are used in Section 5 and are calculated using the same approach.*

The normalised hail hours (for all hail and severe hail) were then divided by the annual thunderstorm hours for each urban area, resulting in the all hail-thunderstorm ratio and the severe hail-thunderstorm ratio. At this point, the relationship between elevation and the all hail-thunderstorm ratio and the severe hail-thunderstorm ratio, respectively, was calculated recursively starting with all urban areas that have at least one hail report, then all urban areas with at least two hail reports, and so on. At each recursion, the relationship between elevation and the hail-thunderstorm ratio was quantified using least-squares linear regression. The coefficient of determination r^2 was also calculated at each recursion, then plotted against the minimum hail sample size. The results of this process are shown in Figure 5.

For all hail and severe hail, the value of r^2 initially increases as the sample size increases, but then stabilises. We therefore consider a location to be well sampled if the number of reports is within the stable region – that is, at least 41 reports for all hail and at least 28 reports for severe hail.

There is a possibility that this technique could systematically exclude regions that are not hail prone (i.e. have few or no hail reports), biasing the results. However, we will show later that this approach still includes locations with normalised hail hours close to zero, mitigating this concern. Furthermore, Figure 1 shows that extensive hail data is available in parts of Canada that are not thought to be especially hail-prone (e.g. southern Ontario and Quebec), suggesting that regions at lower perceived hail risk are still being represented.

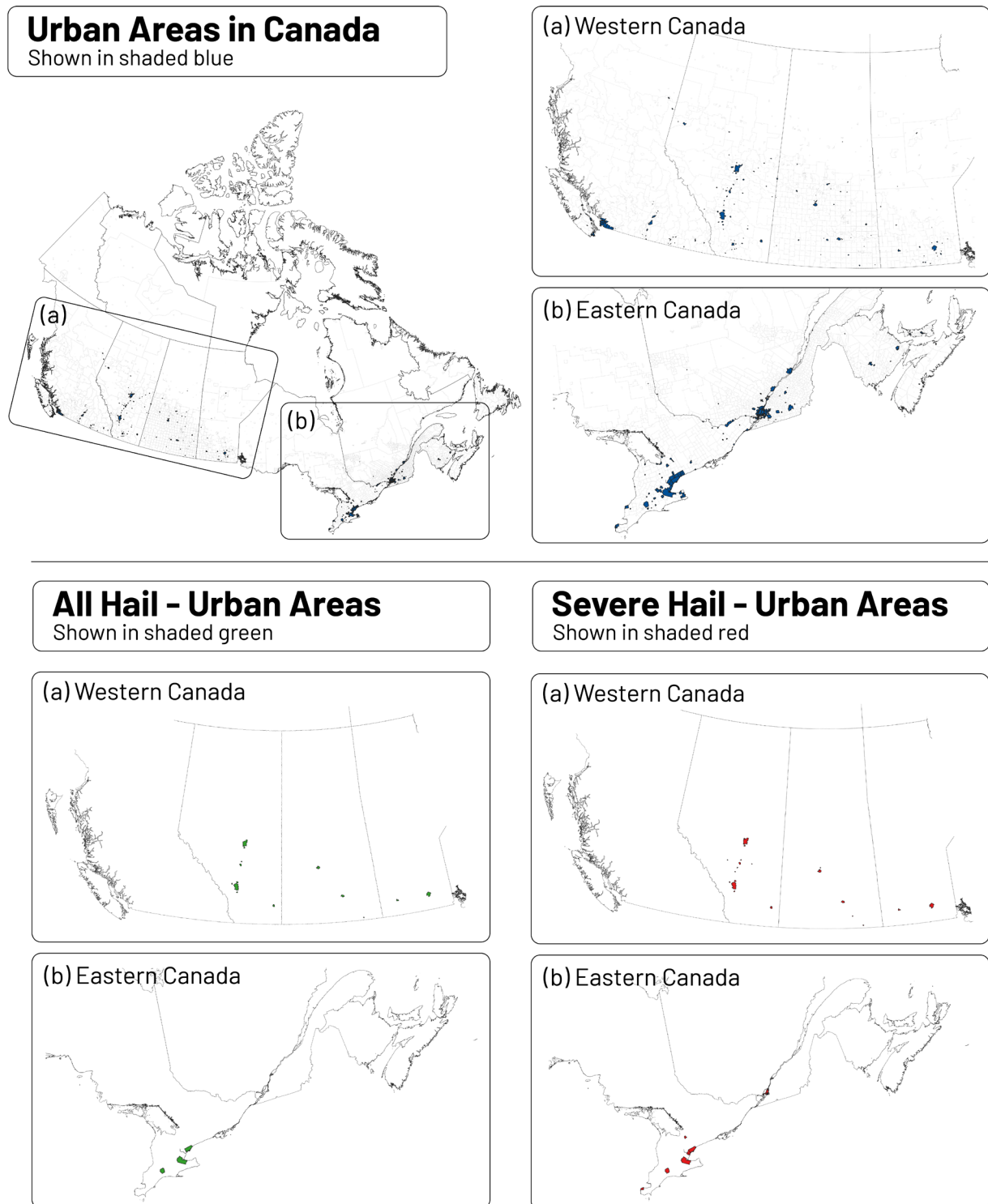


Figure 4: All urban areas are shown in the top panel in blue shading, based on the Statistics Canada definition. The lower-left panel shows all urban areas used to calculate statistics for all hail (in green shading) and the lower-right panel is the same but for severe hail (in red shading).

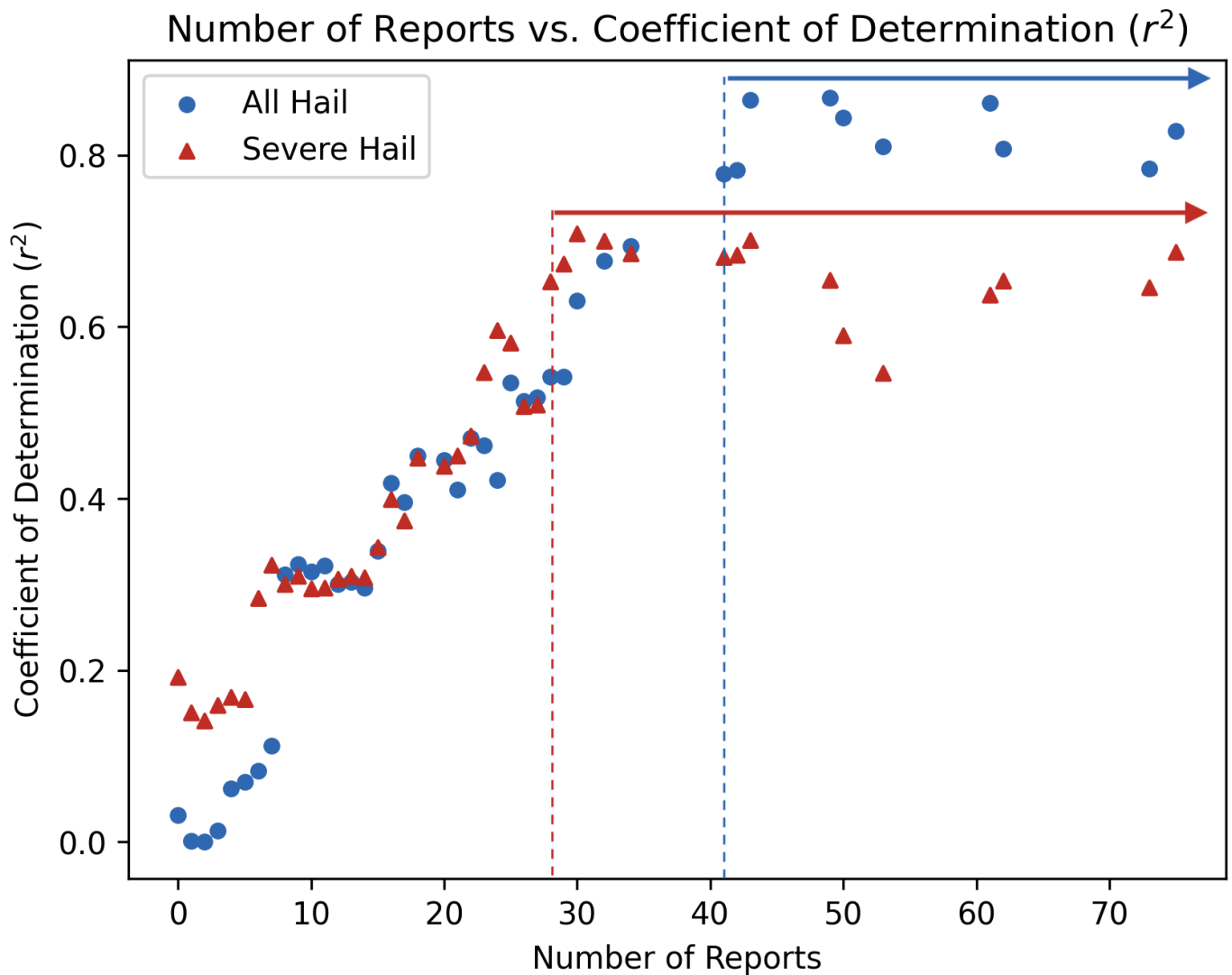


Figure 5: The x-axis shows the minimum number of reports used to compute the coefficient of determination (r^2) while the y-axis shows the value of r^2 . The purpose of the graph is to identify the minimum number of reports (samples; n) that are needed to produce a stable relationship between elevation and the hail-thunderstorm ratio. The blue dashed line and arrow indicate that at least 41 reports were needed for a stable relationship using all hail reports. The red dashed line and arrow indicate that at least 28 reports were needed for a stable relationship using only severe hail reports.

4. Results

Table 1 summarises the results of implementing our methods. We identified 15 urban areas that were well-sampled for all hail and 20 urban areas that were well-sampled for severe hail. Data from Table 1 were then plotted as elevation vs. the all-hail thunderstorm ratio (severe hail-thunderstorm ratio), with the results shown in Figure 6. The least-squares regression line is also shown in Figure 6 to quantify the relationship.

Table 1: This table shows the hail statistics that were calculated for each urban area as annual averages. Normalised (norm) days or hours are per 100 km². Columns showing ratios represent the hail-thunderstorm ratio (proportion of thunderstorms that produce hail).

Reference Data					Hail Days		All Hail			Severe Hail		
Urban area name	n	Land area [km ²]	Elevation [m]	Annual Thunderstorm Hours	All Hail Days	Norm All Hail Days	All Hail Hours	Norm All Hail Hours	All hail ratio	Severe Hail Hours	Norm Severe Hail Hours	Severe hail ratio
Airdrie, AB	61	84.4	1093.4	28.4	3.0	3.0	3.8	3.8	0.13	0.8	0.8	0.026
Brandon, MB	60	79.0	381.4	36.6	2.5	2.5	3.0	3.0	0.08	0.9	0.9	0.024
Calgary, AB	833	820.6	1042.6	25.3	16.0	1.9	24.4	3.0	0.12	7.0	0.9	0.034
Cochrane, AB	48	31.6	1144.1	29.1	2.8	2.8	3.5	3.5	0.12	1.0	1.0	0.034
Edmonton, AB	237	765.6	672.4	27.3	8.4	1.1	12.0	1.6	0.06	2.0	0.3	0.010
Estevan, SK	42	18.3	567.5	34.5	0.9	0.9	0.9	0.9	0.03	0.4	0.4	0.011
Hamilton, ON	49	1118.3	115.7	22.3	2.9	0.3	3.8	0.3	0.02	0.5	0.0	0.002
Innisfail, AB	33	19.4	944.0	27.9	-	-	-	-	-	0.9	0.9	0.031
Lacombe, AB	40	20.6	849.9	30.7	-	-	-	-	-	0.8	0.8	0.024

Table 1 continued

Leduc, AB	28	42.3	728.6	27.1	-	-	-	-	-	0.4	0.4	0.014
London, ON	83	420.5	269.0	30.9	3.5	0.8	4.4	1.0	0.03	0.9	0.2	0.007
Medicine Hat, AB	41	112.0	679.8	18.2	1.6	1.4	2.0	1.8	0.10	0.4	0.4	0.018
Okotoks, AB	52	38.5	1065.8	24.9	3.2	3.2	3.5	3.5	0.14	0.8	0.8	0.030
Olds, AB	31	14.9	1032.1	30.8	-	-	-	-	-	0.9	0.9	0.028
Red Deer, AB	72	104.3	851.3	28.7	3.5	3.4	3.8	3.6	0.13	1.1	1.1	0.038
Regina, SK	108	178.8	576.8	26.9	3.1	1.7	3.5	2.0	0.07	0.6	0.3	0.013
Rocky Mtn House, AB	29	13.1	1007.2	36.4	-	-	-	-	-	0.8	0.8	0.021
Saskatoon, AB	74	226.6	485.0	21.2	3.0	1.3	3.6	1.6	0.08	0.9	0.4	0.018
Toronto, ON	72	631.1	167.9	19.5	3.9	0.6	4.5	0.7	0.04	1.2	0.2	0.010
Winnipeg, MB	236	461.8	232.7	33.8	6.5	1.4	8.0	1.7	0.05	1.9	0.4	0.012

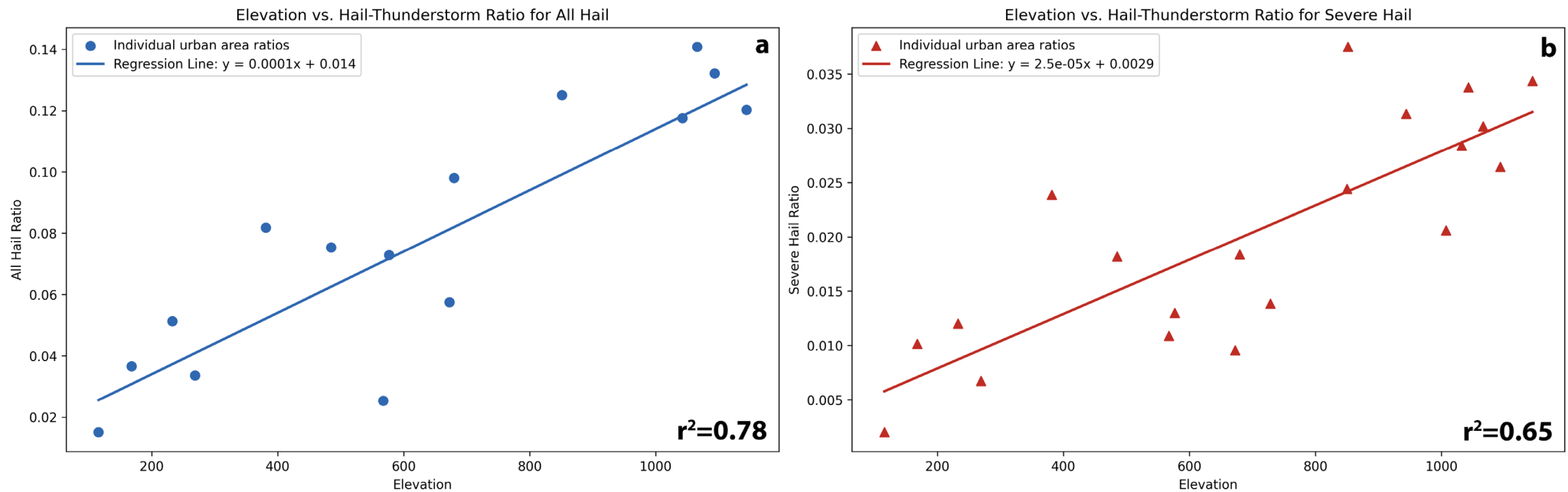


Figure 6: (a) This plot shows the elevation (m) as the independent variable and the all hail-thunderstorm ratio as the dependent variable, with urban area ratios from Table 1 plotted as blue circles. The least-squares linear regression line is plotted in solid blue. All locations with at least 41 hail reports are plotted, per the analysis in Section 3 (3.3). (b) This plot shows the elevation (m) as the independent variable and the severe hail-thunderstorm ratio as the dependent variable, with urban area ratios from Table 1 plotted as red triangles. The least-squares linear regression line is plotted in solid red. All locations with at least 28 hail reports are plotted, per the analysis in Section 3 (3.3).

The equations of the least-squares regression lines in Figure 6 are shown below:

Equation 1: All hail-thunderstorm ratio = $0.00010x + 0.014$

Equation 2: Severe hail-thunderstorm ratio = $0.000025x + 0.0029$

Where x is the elevation in meters.

The values of r^2 for elevation vs. the all hail-thunderstorm ratio and the severe hail-thunderstorm ratio are 0.78 and 0.65, respectively. The root-mean-square error (RMSE) between the normalised hail hours data in Table 1 and the predictions from Equations 1 and 2 are 0.6 and 0.2 hours for normalised all hail hours and normalised severe hail hours, respectively.

We further performed a leave-one-out cross-validation (LOOCV) of the model. The LOOCV systematically excluded one location from the fitting of the linear regression model and then calculated the average error (RMSE) between the predicted and actual hail-thunderstorm ratios.

The results of the cross validation yielded an RMSE of 0.021 for the all hail-thunderstorm ratio model and 0.0064 for the severe hail-thunderstorm ratio. These results show that elevation can be used to explain a majority of the variation in the hail-thunderstorm ratio for all hail and severe hail. Using these relationships, we produced full geographical distributions over Canada.

Figure 7a (7b) shows the all (severe) hail-thunderstorm ratio mapped for all of Canada using the gridded elevations data. Figure 8 (9) takes the gridded hail-thunderstorm ratios from Figure 7 and calculates all (severe) hail hours based on its product with the thunder hours data.

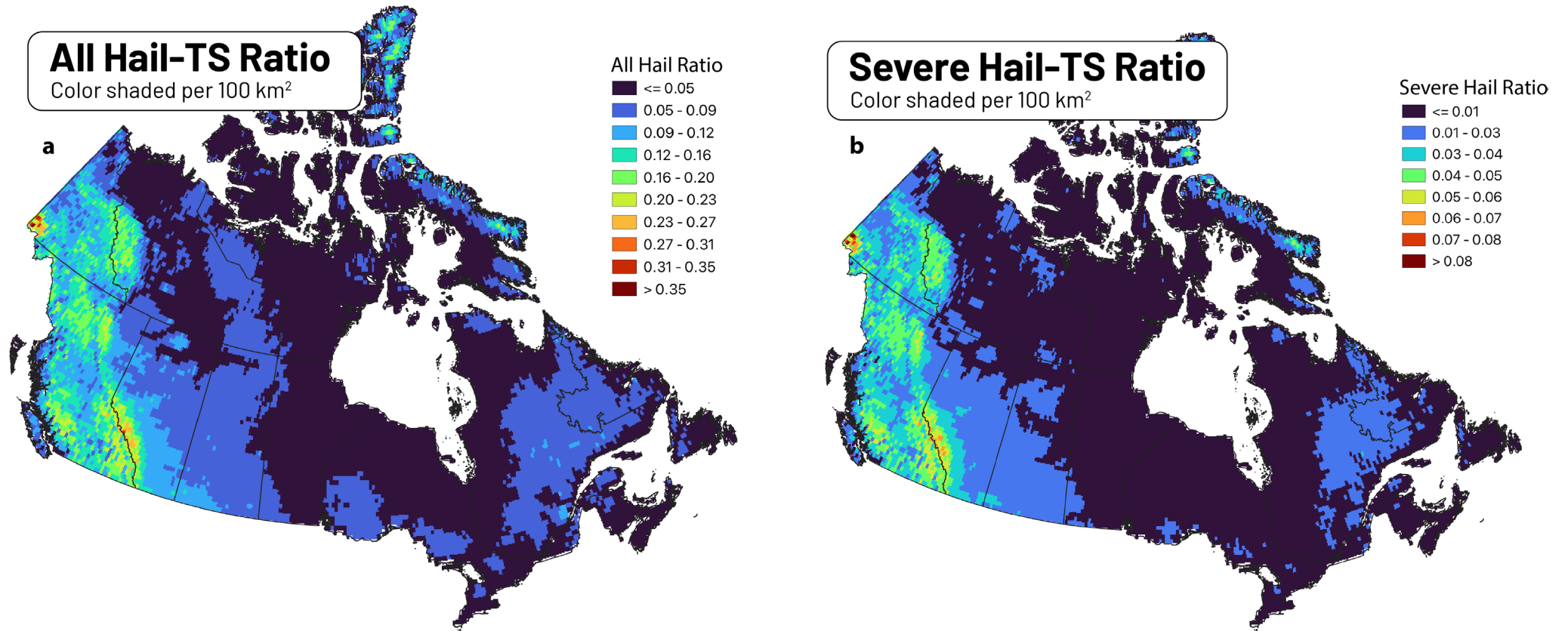


Figure 7: (a) The all hail-thunderstorm ratio calculated using Equation 1 and the gridded elevation data described in Section 2(2.3). (b) The severe hail-thunderstorm ratio calculated using Equation 2 and the gridded elevation data described in Section. 2(2.3).

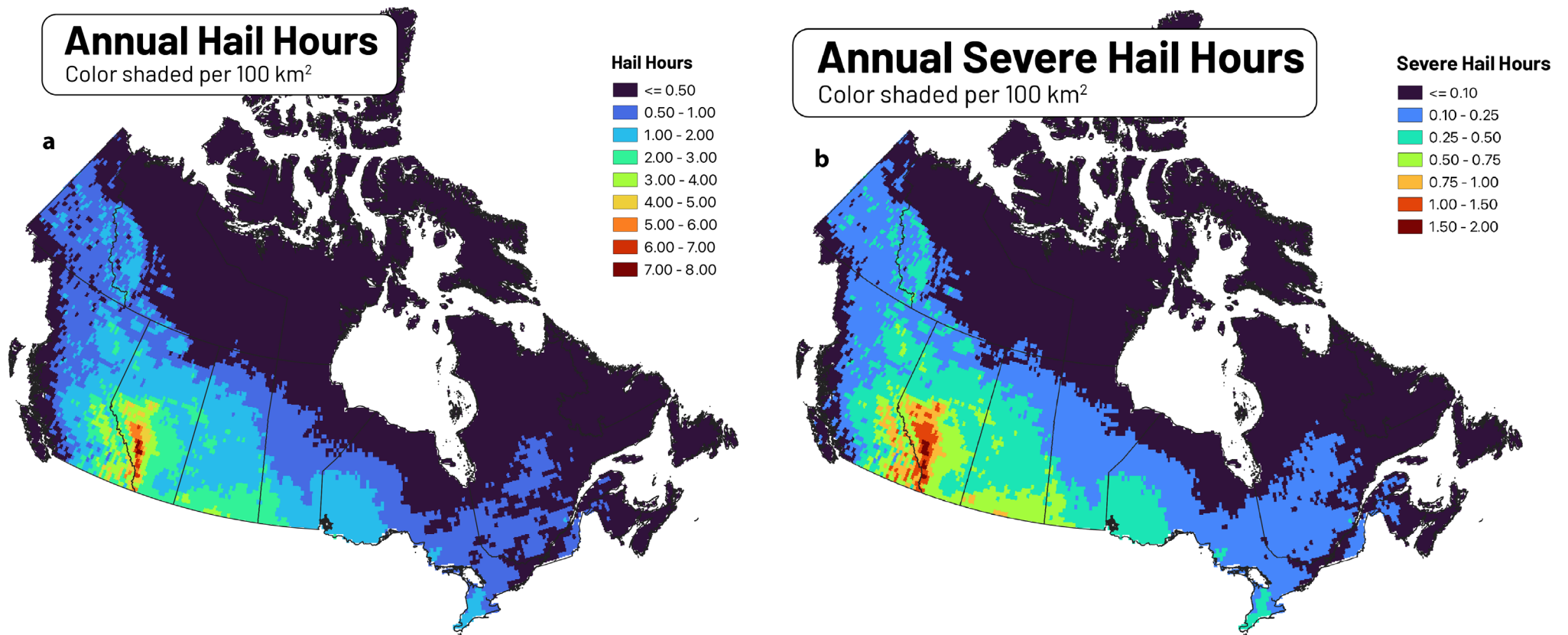


Figure 8: (a) Map of annual hail hours (colour-shaded) per 100 km² based on the product of the all hail-thunderstorm ratio, calculated using Equation 1 with the gridded elevation data described in Section. 2(2.3), and thunder hours, as described in Section 2(2.2). (b) As in (a) except for severe hail hours calculated using Equation 2.

5. Comparisons to other studies

5.1. Hail-thunderstorm ratio comparison

LaDochy (1985) is the only known study that produced hail statistics in Canada that are comparable to those herein. The thunderstorm-hail ratios in LaDochy (1985) were calculated for six locations in Manitoba (0 to 473 m). We converted these to the hail-thunderstorm ratio by taking their reciprocal – they ranged from 0.05 (Churchill, MB; 0 m) to 0.12 (Thompson, MB; 224 m).

Outside of Canada, Shands (1944) found hail-thunderstorm ratios of 0.04 in Washington, D.C. (0-125 m) and 0.08 in Kansas City, Missouri (219-311 m). Beckwith (1960) calculated the hail-thunderstorm ratio for Denver, Colorado which was described as ranging from 1/8 (0.13) for a point location to 1/1.7 (0.59) for the City of Denver and surrounding area (1,564-1,667 m). Changnon (1962) calculated the hail-thunderstorm ratio in Illinois (85-376 m), which varied from 0.03 to 0.07 at point locations. Although Baughman and Fuquay (1970) did not explicitly use the hail-thunderstorm ratio, they documented 25 thunderstorms in the Rocky Mountains of Montana (1,850-2,200 m) and found that 10 produced hail, giving a hail-thunderstorm ratio of 0.40.

These studies are not directly comparable to each other, or to our results, because the hail-thunderstorm ratios were calculated at different spatial scales. Long (1980) provides a thorough description of why the spatial scale is important for hail statistics. However, one can subjectively note that the lowest elevations (e.g. Churchill, MB / Washington D.C. / Illinois) tend to have the lowest hail-thunderstorm ratios, while the highest elevations (e.g. Montana / Denver, CO) tend to have the highest hail-thunderstorm ratios.

These previous studies are in general agreement with the elevation-hail relationship described in this paper.

5.2. Hail days climatology comparison

Since the hail-thunderstorm ratio is no longer widely used in hail climatology studies, it was also desirable to subjectively compare our results to more recent hail climatologies. However, most studies use hail days, rather than hail hours.

In this paper, hail days weren't used in earlier analyses because we were unable to source a gridded thunderstorm days climatology. However, normalised hail days

were computed for urban areas, as shown in Table 1. For all hail, the correlation between normalised hail hours and normalised hail days is 0.98 ($r^2=0.95$). The high degree of correlation is reasonable, since hailstorms are typically short-lived and isolated, meaning most hail days will only have one hail hour. We therefore transformed our all-hail hours climatology to an all-hail days climatology using the linear relationship (least-squares linear regression) between all hail hours and all hail days, as shown in Equation 3.

The relationship between all hail hours and all hail days is shown in Figure 9. The hail days climatology for all hail is shown in Figure 10.

Equation 3: All hail days = $0.84 \times \text{All hail hours} - 0.025$

The climatology of Phillips (1990), provides both the annual days with thunderstorms and hail, allowing approximate hail-thunderstorm ratios to be calculated. Subjectively, hail-thunderstorm ratios are highest around Prince George, BC with a ratio of ~0.25 (five hail days and 20 thunderstorm days). A secondary maximum is found in central Alberta, along the foothills, where the hail-thunderstorm ratio is ~0.20 (five hail days and 25 thunderstorm days).

In general, the hail-thunderstorm ratio is minimised where elevations are lowest (coastal areas/eastern Canada) and in areas where there is a lack of thunderstorm days (e.g. the arctic). Since the spatial scales used in the Phillips (1990) climatology are different from those used here, direct comparisons of the hail-thunderstorm ratio cannot be made. However, the hail-thunderstorm ratio appears to have a positive relationship with elevation in the Phillips (1990) climatology, in general agreement with our results.

The statistics in Etkin and Brun (2001) are also not directly comparable to our results, or to Phillips (1990), but we can subjectively note that all three studies find common provinces where hail frequency is maximised (i.e. the four western-most provinces). The climatology update by Etkin (2018) provides average hail days by month for various regions of Canada. However, as also noted in Etkin (2018), the number of hail reporting stations declined to a trivial number after 2007.

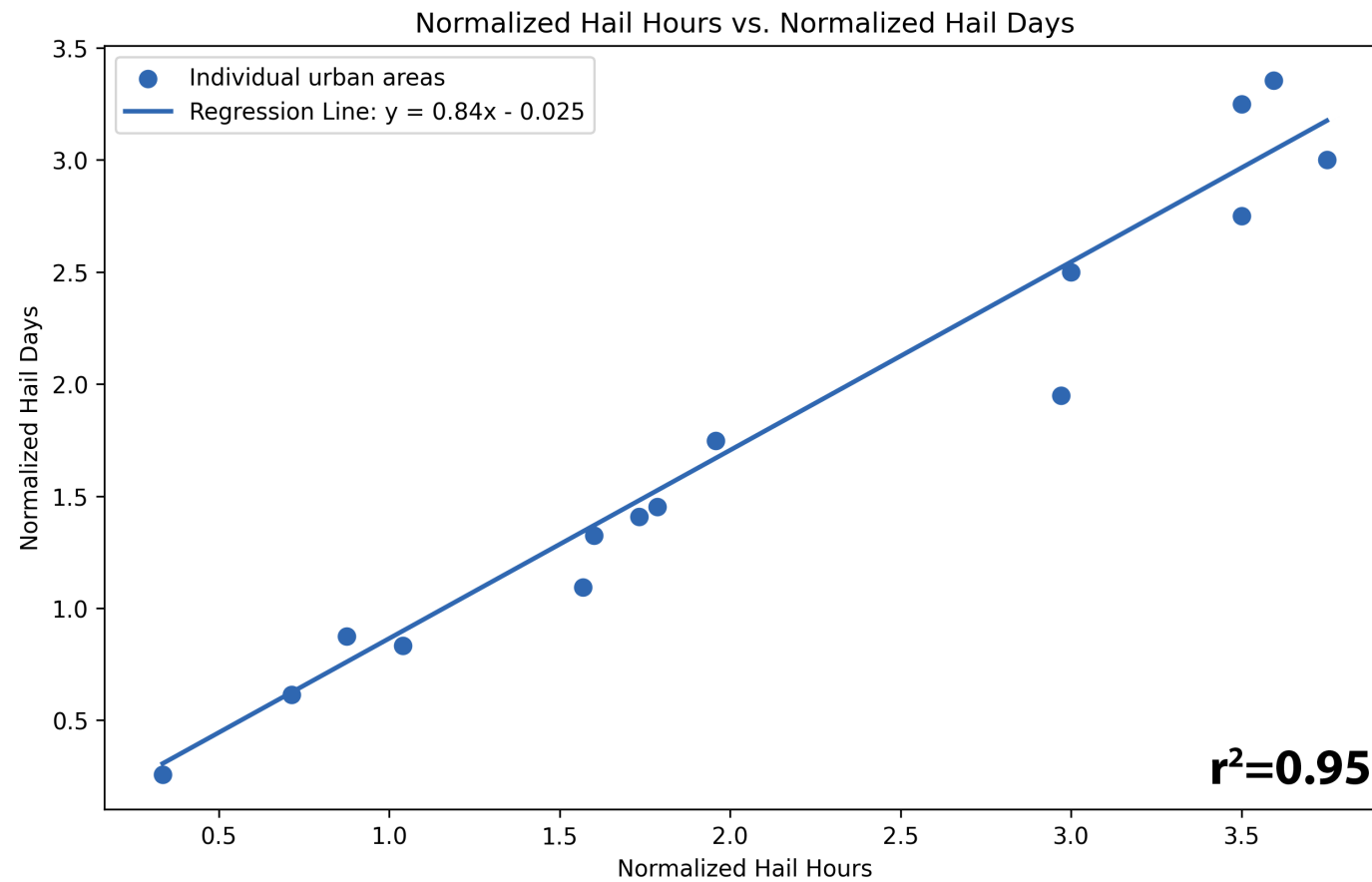


Figure 9: Scatterplot showing the relationship between normalised all hail hours and normalised all hail days for the same urban areas as in Figures 6 and 7. This relationship was used to produce Figure 10.

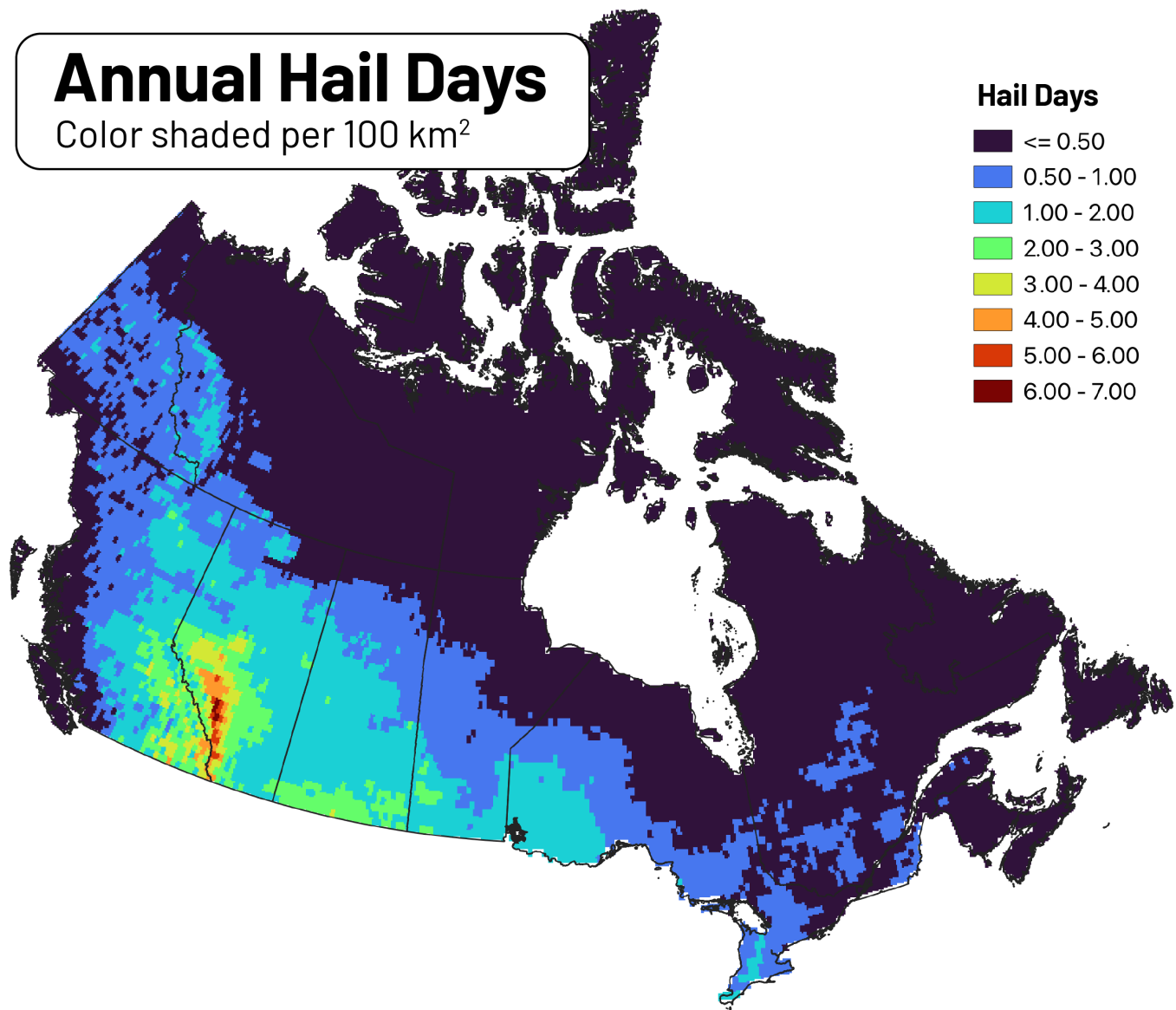


Figure 10: Map of all hail days (colour shaded) per 100 km², calculated using gridded all hail hours from Figure 8 and the relationship to hail days given in Equation 3.

The maps in Etkin (2018) show maxima surrounding many specific reporting stations, suggesting that the hail data suffers from severe biases toward the remaining stations. The maps of hail days are also provided by month; therefore, it is difficult to conclude how it compares to our results, or previous studies.

The climatology provided by Brunet and Brimelow (2024) allows for the most direct comparison with our results (our results are per 100 km², which is equivalent to their 10 km resolution). We generally find hail to be more frequent, especially along the Alberta foothills (maximum 6-7 hail days vs ~1 day) and in southern Saskatchewan (maximum 2-3 days vs ~1 day). We find approximately the same number of hail days in southwestern Ontario (maximum 1-2 days vs ~1 day).

As noted by Brunet and Brimelow (2024), their approach relies on a lightning proxy and therefore the hail climatology appears to follow the lightning (i.e. thunderstorm) climatology, hence their three maxima in the most lightning-prone parts of Canada, which can also be seen in our Figure 2.

6. Discussion

This paper has provided results which quantified the relationship between elevation and the hail-thunderstorm ratio using linear regression. Determining why elevation has a relationship with the hail-thunderstorm ratio is beyond the scope of this paper. Instead, we offer some speculation on why this relationship might exist, which may be useful to formulate future research questions.

In this paper we have not provided any evidence that elevation physically affects a thunderstorm's propensity to produce hail. Rather, we think it is most likely that elevation simply serves as a useful proxy for other physical processes that determine the propensity of a thunderstorm to produce hail. For example, higher elevation regions may have a lower freezing level height, which allows hail to reach the ground more readily.

A good example of this is the local maximum in hail days over the southern Appalachian Mountains in the Storm Prediction Center hail climatology (NOAA, 2024). Since the southern Appalachians are near the Atlantic coast, surrounded by regions of relatively low elevation, they would not normally be considered hail prone. Similarly, European climatologies also tend to show a maximum in hail occurrences around major mountain ranges such as the Alps and Pyrenees (e.g. Battaglioli *et al.*, 2023; Giordani *et al.*, 2024).

The lower freezing level in mountainous environments also affects the overall thermodynamic environment in which a thunderstorm operates, which may have other less obvious impacts on hail generation. Kunz and Puskeiler (2010) have also shown that flow modification from such mountain ranges produces convergence areas near and immediately downstream, which results in localised hail climatology maximums.

As operational meteorologists and storm chasers, we have anecdotally observed that thunderstorms, especially supercells, seem to have different characteristics in high elevation locations, such as Alberta or the US High Plains (the portion of the Great Plains nearest the Rocky Mountains).

For example, our operational experience suggests that high-elevation supercells tend to more frequently be of the low-precipitation variety, whereas eastern Canadian/US supercells are more often high precipitation. If these observations are accurate, the lower precipitation

volume in the updrafts of low-precipitation supercells would reduce water loading, potentially causing them to have systematically stronger updrafts, thereby supporting larger hail.

While not specifically studying different types of supercells, Bunkers *et al.* (2020) notes that supercells in general tend to have higher hail-wind ratios (i.e. more hail reports than wind reports) and notes a maximum in hail reports at times of year when mid-level temperatures are coolest. The hail-wind ratios calculated by Bunkers *et al.* (2020) are also maximised in higher elevation areas, notably in the Great Plains, but also locally enhanced along parts of the Appalachian range and parts of the intermountain west.

Bunkers *et al.* (2020) also hypothesises that storm mode plays a role as to why more hail is observed at higher elevations. Cellular storm modes (e.g. multicells and supercells) are more common over high elevations and produce severe hail more frequently than severe wind. We have made similar observations in Canada, with cellular storm modes frequently observed at the higher elevations along the Alberta foothills during the summer months. As cellular storms mature and advance eastward into lower elevations of the Canadian Prairies, cold pools consolidate, and storm modes often become more linear – and thus less favoured to produce hail.

We also speculate that storm mode partly explains why the relationship between elevation and the severe hail-thunderstorm ratio is lower than with the all hail-thunderstorm ratio.

As noted by Allen *et al.* (2020), supercell thunderstorms are known to be responsible for the majority of severe hail events and these storms may account for a larger portion of hail events at lower elevations.

Finally, we note that the Rocky Mountains frequently serve as a convenient geographic boundary in hail climatologies, with a maximum in hail occurrence typically found along their leeward side. Due to their significant relief, the Rocky Mountains have well-known impacts on atmospheric dynamics; for example, by causing perturbations to Rossby waves via the conservation of potential vorticity and lee-cyclogenesis (Stull, 2000).

Such processes affect the dynamics of environments in which thunderstorms operate, suggesting that these

effects may help explain the observed relationship with elevation. We end this discussion by reiterating that this section is purely speculative. The objective of this speculation is to present ideas that could form the basis of future research.

7. Conclusion

This study explored the following question: Can elevation data and a thunderstorm climatology be used to produce a reliable hail climatology? Using WHD in-situ hail reports from January 1, 2017 to October 1, 2024, the WWLLN thunder hours climatology, and CDMS/GMTED2010 elevation data, our results demonstrate that elevation has a useful relationship with the hail-thunderstorm ratio. The value of r^2 for this relationship was found to be 0.78 for all hail and 0.65 for severe hail.

Since high-quality hail data is sparse, and often suffers from biases, this relationship provides a reliable and simple method to calculate hail statistics at any location in Canada, given elevation data and a thunderstorm climatology.

Geographically, we found a national maximum in hail occurrence along the lee of the Rocky Mountains in Alberta (Alberta foothills), with secondary maxima in the interior of British Columbia and the southern Prairies. However, we cannot and do not conclude that elevation is the physical cause of hail variability. We speculate that elevation serves as a useful and convenient proxy for other meteorological factors, which are the true physical causes of this variability.

Future research could expand on our findings by investigating the applicability of Equations 1-3 in different climates and geographies. There is also a lack of recent studies which use the hail-thunderstorm ratio. More of these types of studies, especially ones that use a comparable spatial scale, could also increase the robustness of these findings.

Lastly, we encourage further exploration of the speculative explanations for the elevation vs. hail-thunderstorm ratio relationship provided in the discussion.

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Declarations

Conflicts of Interest: Scott D. Kehler and Matthieu Desorcy are owners of Weatherlogics Inc.

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Data Availability

- The thunder hours data are available from the WWLLN (<http://www.wwlln.net>).
- The point elevation data are available from Natural Resources Canada (<https://natural-resources.canada.ca/science-and-data/science-and-research/geomatics/topographic-tools-and-data/web-services/elevation-api/17328>).
- The gridded elevation data are available from the United States Geological Survey (<https://www.usgs.gov/coastal-changes-and-impacts/gmted2010>).
- The Weatherlogics hail database is available from Weatherlogics Inc. This data is not publicly available. Please contact the corresponding author for details.

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