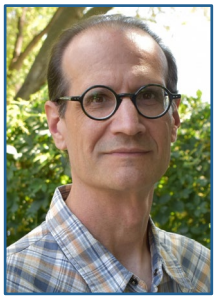
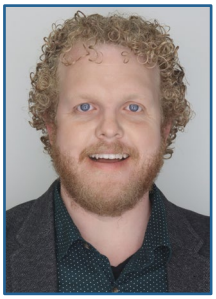
SEVERE THUNDERSTORM RESEARCH IN CANADA

SUMMARY: Improving the understanding, prediction, and mitigation of severe thunderstorms requires physics-based research conducted by interdisciplinary teams.









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On August 7, 1979, two violent F4 tornadoes struck the towns of Woodstock and Stratford, Ontario, damaging and destroying homes within minutes, injuring 141 people and causing three fatalities [1]. Thunderstorms on May 21, 2022, left a continuous path of widespread severe wind damage from Windsor to Quebec City, killing 16 people and causing power outages for millions of customers. The Calgary hailstorm of August 5, 2024 caused more than 3.2 billion Canadian Dollars in insured damage. Events like this demonstrate the destructive power of severe thunderstorms, which can produce tornadoes, large hail, flash floods, and damaging wind gusts within very short periods of time. Even small improvements in forecasting can have significant societal benefits, allowing individuals to protect themselves, their property and helping emergency services respond more effectively.

Understanding these storms requires a grounding in fundamental physics such as fluid dynamics, thermodynamics and electromagnetism. Predicting severe thunderstorms remains one of the most

challenging problems in atmospheric science. A key difficulty lies in the scale of the problem. A tornado may be only tens of meters wide, which is comparable to the width of a street, yet it forms within storm systems that can travel hundreds of kilometers. Meanwhile, weather prediction models typically operate at resolutions of several kilometers, leaving critical small-scale processes unresolved.

This article explores the physical processes behind thunderstorms, how they are observed and studied in Canada, and how research is evolving to meet future challenges.

THE PHYSICS OF THUNDERSTORMS

Thunderstorms form when three key ingredients are present: instability, moisture, and lift [2]. Instability occurs when a parcel of air becomes buoyant relative to its surroundings. It accelerates upward due to density differences. This is often quantified by Convective Available Potential Energy (CAPE), which measures the energy available for vertical motion. As air rises, it expands and cools. When it reaches its dew point temperature, water vapour condenses into liquid droplets. This phase change releases latent heat, warming the air parcel and increasing its buoyancy. If enough instability and moisture are present, this feedback process can lead to strong updrafts. Lift is required to initiate this process because the air in the lower-most part of the atmosphere tends to inhibit vertical motion, which is a common feature of severe storm days. A source of lift in a stably stratified lower atmosphere may arise from large-scale systems such as cold fronts or from smaller features such as surface heating or boundaries created by previous storms.

Once initiated, storm structure depends strongly on wind shear, which is the change in wind direction and speed with height. In weak shear environments, storms are short-lived. With moderate shear, storms organize into mesoscale systems such as squall lines, which can produce widespread wind damage. In strong vertical shear, supercells become likely. These are highly organized storms with rotating updrafts. These storms are responsible for many of the most severe weather events in Canada, including large hail and tornadoes [3].

A major challenge in thunderstorm physics is the interaction between processes across scales. Large-scale flow organizes the ingredients of storms and provides a suitable setting for storm formation, while small- and micro-scale processes such as droplet formation and hail growth contribute to their hazard impact. Numerical models solve the governing equations (Navier-Stokes equation, first law of thermodynamics, continuity equation) of atmospheric motion. They are crucial to bridge these scales. An example is the idealized Cloud Model 1 [4], which allows to test how small-scale changes in the environment influence the potential for high impact events.

OBSERVING THUNDERSTORMS AND THEIR IMPACTS IN CANADA

To understand the dynamics and structure of thunderstorms, they must first be observed. The most important tool for this purpose is the weather radar. Radar systems emit microwave pulses and measure the energy scattered back by precipitation particles. The timing of the return signal determines distance, while its strength indicates precipitation intensity. This relies on electromagnetic wave scattering, directly linking meteorology with physics. Modern Canadian radars are dual-

polarization Doppler systems, which transmit waves in both horizontal and vertical orientations. This allows differentiation between raindrops and hail, as well as measurement of wind velocity within storms. Features such as rotating updrafts can be detected in real time, providing crucial information for forecasting. Certain radar signatures are strongly associated with severe weather. For example, hook-shaped echoes and rotating winds often indicate rotation and possible tornado formation. These observations allow meteorologists to issue warnings with limited but valuable lead time.

Canada has a long history of radar development [1]. Research led by J. Stewart Marshall at McGill University in the 1940s established key relationships between rainfall and drop-size distributions that are still used today. The modern Canadian radar network now consists of 32 Doppler radars, greatly improving national coverage. Radar research remains important to maximize its benefit.

Other observational tools complement radar. Satellites provide a large-scale view of storm systems and can detect water vapour and cloud features in various wavelengths. This can be used, for example, to locate jet streams, areas of enhanced lift and vertical wind shear. Lightning detection networks provide additional information about storm intensity. After severe events, researchers analyze damage patterns using drones and ground observations. These surveys improve essential understanding of storm impacts and help refine models and building standards.

CURRENT CANADIAN RESEARCH EFFORTS

Thunderstorm research in Canada has expanded significantly in recent years through coordinated field programs and interdisciplinary collaboration. A major development is the establishment in 2024 of the Canadian Severe Storms Laboratory (CSSL) at Western University, which brings together meteorologists, physicists, engineers, and social scientists to study severe weather and its impacts. Meteorologists and physicists focus on understanding the atmospheric processes behind thunderstorms using, for example, numerical models to analyze storm environments [5] and simulate storm dynamics (Fig. 1d,e). Engineers use observations of damage patterns to improve building codes, develop better representations of wind and vortex behaviour, and conduct controlled experiments. Social scientists study the human dimension of severe wind, including how risk is perceived, how people prepare and keep themselves safe during hazard exposure, and how social and structural impacts are experienced to foster improvements in early warning processes and protective action decision-making [6]. The CSSL hosts several major initiatives: The Northern Tornadoes Project documents tornadoes and downbursts across Canada, including in remote regions, using tools such as damage surveys and machine learning to better understand frequency and risk (Fig. 1a-c) [7]. The Northern Hail Project investigates hail events by collecting hailstones in the field and analyzing their size, shape, impact, and climatology [8]. Techniques such as 3D scanning and printing allow controlled experiments on hail damage and sensor development. The Northern Mesonet Project aims to better monitor severe convective storms by increasing the spatial density of real-time advanced weather observations and enhancing data availability and quality for severe weather analysis and prediction. In addition, the CSSL offers undergraduate research opportunities, combining fieldwork and research to train students across disciplines (Fig. 2) [9].

Furthermore, experimental facilities such as the WindEEE Dome enable controlled simulations of downbursts and tornado-like flows, offering insight into how buildings and vegetation respond to extreme winds.

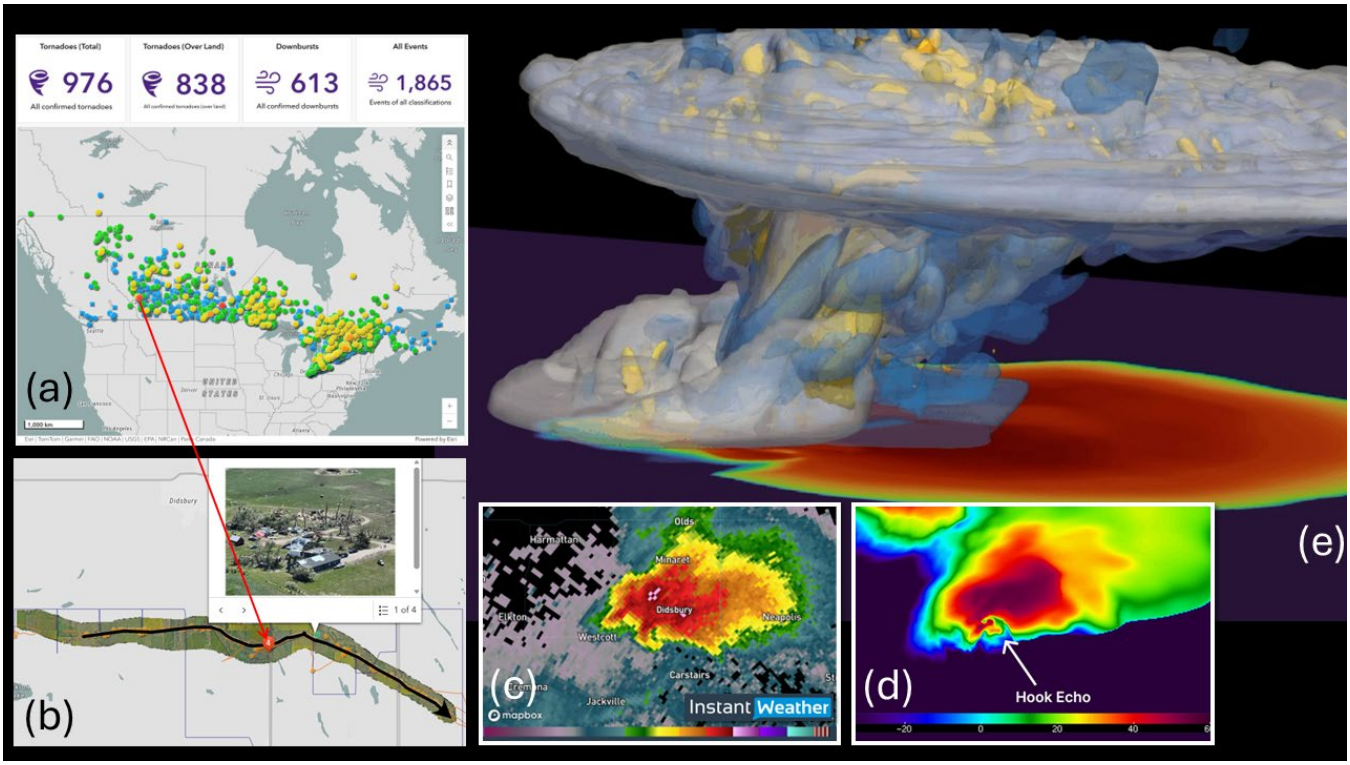


Figure 1. (a) Northern Tornadoes Project Dashboard displaying all events between 2017 and May 2026 (Screenshot taken May 24, 2026). Colors indicate tornado strength. (b) Event Summary of the Didsbury EF4 tornado occurring on July 1, 2023 with tornado path and drone photo taken of damage along the path. (c) Radar Reflectivity (dBZ) of the Didsbury EF4 tornado case on July 1, 2023, observed by the CASSM (Strathmore, AB) radar at an elevation of 0.3955° at 15:53 EDT. Image: Instant Weather, data: Environment Canada. (d) Radar Reflectivity (dBZ) at lowest model level (z=125 m) of a numerical simulation of the Didsbury EF4 tornado case using Cloud Model 1. (e) 3D visualization of the simulated thunderstorm displayed in (c) at another, earlier timestep. Gray: Cloud; Yellow: Vertical Vorticity; Blue: Rain; Shaded: Reflectivity at lowest model level. Visualizations in (d,e) by Luna Awad and Keya Raval.



Figure 2. Impressions from the CSSL summer internship fieldwork and damage surveys [9]. Photos originally published at https://uwo.ca/cssl/internships (May 31, 2026).

FUTURE OF THUNDERSTORM RESEARCH

Future thunderstorm research in Canada will be significantly influenced by technological progress and climate change. A warmer atmosphere can hold more moisture (Clausius-Clapeyron equation) and according to the Intergovernmental Panel on Climate Change (IPCC) extreme precipitation is projected to increase across Central and East North America with high confidence while trends for other parts of the continent cannot be clearly stated [10]. For severe thunderstorms, downbursts, tornadoes and lightning strikes, future changes are still unclear, although observations indicate a reduction in the number of days when tornadoes occur, but an increase in days with ≥30 (E)F1+ tornadoes in the USA [11]. However, there is medium confidence that severe storms will become more frequent and that the storm season will become longer in the USA. Future projections of severe thunderstorms in Canada are an active area of research, and while there are uncertainties, the scientific consensus points to more intense storms, with regionally variable changes in frequency over the coming decades.

Furthermore, advances in computing are enabling higher-resolution models that can better resolve storm-scale processes, while machine learning techniques are being integrated with physics-based models to optimize predictions. Improved observational systems, including denser sensor networks

and enhanced radar capabilities, will also play a critical role. Together, these developments will help address current limitations in severe weather prediction.

HOW PHYSICISTS CAN CONTRIBUTE

Thunderstorm research is deeply rooted in physics. Fluid dynamics governs storm structure and turbulence, thermodynamics explains convection and phase changes, and electromagnetism plays a key role for radar observations and lightning. Physicists can contribute through numerical modeling, data analysis, and improving observations through novel and improved instrumentation. Storm simulations involve solving the Navier–Stokes equations, while radar interpretation requires understanding electromagnetic scattering. Studying physics not only provides a foundation in fundamental concepts and their applications but also builds skills in physical interpretation, programming, experimentation, and data analysis. Furthermore, physics students can get involved in research and field internships of the CSSL [9] or graduate programs of several Canadian Universities. Interdisciplinary collaboration and teamwork are essential. Combining physics with other scientific fields allows for a more complete understanding of severe weather and its impacts.

CONCLUSIONS

Severe thunderstorms are complex phenomena that combine processes across multiple scales. From early radar research to modern interdisciplinary efforts, Canada has made significant contributions to understanding these storms. Despite this progress, challenges remain, particularly in predicting small-scale processes and extreme impacts. As climate change continues to influence weather patterns, improving our understanding of severe thunderstorms will become increasingly important. For physics students, this field offers an opportunity to apply fundamental principles to real-world problems with direct societal impact. Continued research and collaboration will be essential for improving resilience to severe weather in Canada.

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