

Quantifying The Trend of Winter Cold Wave Changes in Toronto from 2011 To 2025

Yiren Wang *

Department of Chemistry, University of Toronto, Toronto, Ontario M5S 3H6, Canada

* Corresponding Author Email: wyr8240@gmail.com

Abstract. Winter extreme low-temperature events threaten urban operations and public health, but quantitative descriptive studies on changes in cold waves in Toronto are still relatively limited. Existing work mostly focuses on the perspectives of alerts and public health, or on winter temperature and case-specific circulation. Therefore, this article obtains the frequency and intensity of cold days/cold waves in Toronto from winters 2011 to 2025 and builds a linear regression between cold-day frequency and the seasonal mean temperature of non-cold days by using the baseline from 1981 to 2010 and calendar-day P10 to define a cold wave, then uses CMd/CWMI_d to characterize cold-wave event intensity. The results show that cold waves are unevenly distributed over the 15 years: 2014–2015 is the strongest and has the longest duration, while 2021–2024 almost have no cold waves, and found that the coldest single day does not necessarily occur within the strongest cold wave. With the linear regression, this article found that cold-day frequency decreases by about 3% per +1 °C of background warming ($R^2 \approx 0.46$). Overall, cold waves in Toronto show a weakening trend during 2011-2025, which is consistent with background warming. But because cold waves are also modulated by interannual circulation, the simple and consistent statistical framework used in this paper may serve as a basis for subsequently incorporating factors such as circulation mechanisms.

Keywords: Cold waves; Winter temperature; Linear regression.

1. Introduction

Cold waves, as one of the winter weather extreme phenomena, mainly represent a sudden outbreak of cold air, causing temperatures to drop significantly below seasonal norms and persist for several days [1]. Such events are driven by the southward intrusion of polar or high-latitude cold air and are typically accompanied by an upstream upper-level west-ridge/east-trough jet pattern together with sustained surface longwave radiative cooling [1-2]. Cold waves have many impacts on human activities, such as some research shows that the death rate during the lag period after a two-day cold wave increases by approximately 1.7% in 209 cities in the United States, and the 1998 cold wave in the United States and Canada left over 4 million people without power and damaged about 120,000 kilometers of power lines [3-4]. But recent research indicates that cold waves capable of affecting various regions may disappear in this century with a probability exceeding 90% [5]. These findings indicate that climate warming is causing the strongest cold waves to disappear or have largely vanished in mid-latitude regions.

Toronto, Canada's largest metropolitan area, is situated on the northwest shore of Lake Ontario (43.7°N, 79.4°W). Multiple studies show that global warming also impacts the weather in Toronto, such as precipitation and temperature patterns [6]. Because global warming not only affects winter temperatures and snowfall but also the occurrence and duration of cold waves. So, according to reasoning, the cold waves in Toronto may also gradually decrease with the temperature increase. However, few studies have explicitly quantified region-scale trends in cold-wave characteristics for Toronto; most prior work focuses on alerts or seasonal extremes [7].

Therefore, this study follows WMO recommendations by combining the locally adapted CSDI index from Canada, comprising four components: cold wave duration, frequency, intensity, and relationship with temperature. This analysis examines whether cold wave intensity and frequency have changed significantly in Toronto from 2011 to 2025 and how this trend is relevant to the

warming of the winter temperature in Toronto. It will help to present the trend and changes of the cold wave in Toronto with quantitative indicators.

2. Method

2.1. Data

This research uses the “Toronto Daily Weather (1937–2025)” dataset from the Kaggle platform and which dataset sourced from Weather Stats, selecting the period from 1991 to 2025 for analysis [8]. The research defined the winter season as the period from December to February, spanning from December 1 of the current year to February 28/29 of the following year, and the winter year is defined as the year where January and February. For example, the period from December 1990 to February 1991 is recorded as the winter of 1991. All dates are in Toronto local time. In conclusion, this research primarily used the maximum, minimum, and average temperatures (in °C) recorded from December to February for the years 1991-2025 within the dataset.

2.2. Method

To distinguish between seasonal background temperatures and cold wave events, 30-year climate daily mean winter temperatures are analyzed and used as the reference baseline for defining cold waves. This method follows the ETCCDI framework consistent with WMO guidelines, so the primary baseline period employed is 1981–2010 to analyze the cold wave from 2011 to 2025 [1,9]. Specifically, the average temperatures of every day during the winter months over 30 years are summarized separately according to calendar day, called dayT_summarized. Using this data sheet, the baseline average temperature (μ) and 10th percentile (P10) threshold of the calendar day are obtained. ± 2 -day window around the targeted day is used to smooth and estimate the typical temperature level and the 10th percentile (P10) and 25th/75th percentile (P25/P75) threshold for that day according to the reference of the stable baseline method [10]. The typical temperature level, called μ (Day), is calculated by calculating the average winter temperature of a calendar day within 30 years using the dayT_summarized sheet. And it represents the climate normal temperature of this calendar day regardless of the year difference [10]. These percentile thresholds (P10/P25/P75) are calculated based on the average summarized sheet. The temperature of every calendar day in this sheet is separately sorted from coldest to warmest, and then uses the interpolated quantile method to obtain the values of the percentile [11]. It can help to determine whether it is an index of cold day and quantify the intensity of the cold wave. In the classification of cold waves, the classification of Cold days is a necessary part of Cold waves: if the mean temperature of a day in winter is cooler than P10 of this day, it is defined as a cold day. According to recent research from another region, a cold wave is defined as a sequence of at least 2 cold days in this research [1].

The analysis primarily covers the period from 2011 to 2025, the number of cold days/ cold waves, cold waves frequency that defined as the proportion of cold days that form cold waves of this year relative to all cold days in this year and cold day frequency that defined as the proportion of cold days/ cold waves relative to the total number of valid days are mainly calculated and summarized for each winter from 2011 to 2025. And cold wave intensity can be measured by a recent method that is used in regional risk studies, called Cold Wave Magnitude Index (CWMId), which has been employed as an indicator of cold wave hazard intensity, and helps to compare risk attribution [12-13]. According to the daily scale approach based on IQR provided by NHESS in recent years, firstly, calculate the daily score for each day during the cold wave. The daily cold scale $CMD = (P75 - T_{mean}) / (P75 - P25)$ [12]. Then, add up the CMD of cold days in this cold wave section, and the event scale of this cold wave section can be obtained. The annual CWMId is the scale of the period with the largest cumulative scale among all the cold waves in that year. Additionally, because the cold wave may also have a relationship with temperature, this study also attempts to simply describe how background warming affects cold waves [14]. The background warming for each winter from 2011 to 2015 is calculated by using daily μ (day) and P10(day), and use dayT_summarized sheet to average

the difference of T_{mean} with $\mu(\text{day})$ called $T_{\text{mean}} - \mu(\text{day})$ of non-cold days in these years and then obtain the background warming amplitude of each winter excluding cold days relative to the baseline, that defined as B_t , and then do linear regression of the frequency of cold days against with B_t . This linear regression represents how the frequency of cold days is affected by the temperature warming.

To ensure interpretability and reproducibility, linear regression with annual indicators as dependent variables and calendar years as independent variables was used as the result analysis of this research, incorporating robust standard errors. A cold day excluded winter average temperature trend is used to regress against cold day/cold spell indicators, representing their relative relationship with background warming.

3. Result

3.1. Result and Discussion

According to the methods represented above, this study will quantify cold events in Toronto from 2011 to 2025 by defining cold spells as L2 (≥ 2 days). Annual results include total cold days, cold wave days, the proportion of cold wave days relative to cold days, and CWMId, which shows the cold wave intensity, and use linear regression to determine whether the warming effect on cold wave frequency.

Firstly, Fig. 1 shows the interannual variation in cold waves and cold days. Orange bars represent cold wave days, while blue bars represent non-cold wave cold days. Their relative proportions indicate whether winter cold wave occurs as periods or isolated dates, and the green line indicates the year's warming compared with the baseline. As Fig. 1 shows, in the 2011–2025 winters, the number of cold days in Toronto was generally unevenly distributed and low. Including a total of 88 cold days identified, and found that when cold days > 4 days, cold waves accounted for approximately 59% to 93% of this year's winter cold days. This pattern, caused by Cold advection that produces cold days, often persists and is reinforced by snow radiation surface feedback. It justifies the use of continuous-day thresholds and event-intensity metrics such as CSDI and CWMId/CMd [15, 16].

Specifically, 2014 recorded the highest number of cold days at 21, with 7 cold waves that account for approximately 85% of this year's cold days. It is the highest number within the 15 years. 2015 experienced the longest cold waves, lasting 16 days from February 12 to February 28. It is also the sole cold waves in this year that account for approximately 84% of this year's cold days, and also causes two special trends: 2013 to 2014 and 2015 to 2016. The 2014 winter temperature had about a 3°C decrease in temperature compared to 2013 winter, and the quantity of cold days also had a 600% increase compared to 2013. This dramatic decrease is similar to that from 2024 to 2025, causing an increase in cold waves. Conversely, the 2014 winter temperature had about 4.3°C warming in 2016 compared to 2015, which led to a reduction in cold waves by approximately 79%. The increasing trend of cold waves with a decrease in background warming. The reason is that when an Alaskan ridge couples with an eastern North America trough, linear wind-driven persistent cold advection funnels polar air repeatedly into the Great Lakes. With tropospheric control, it is reinforced by surface radiative/snow-ice feedback to extend the cold waves [17].

Another decrease of cold waves with an increase of background warming caused by strong El Niño-caused warm winters in which jet-stream and storm-track shifts, compounded by long-term warming, made cold days or waves difficult to form [18]. That is also the reason why the 2023-2024 winter has fewer cold days with an increase in temperature warming which is based on the baseline shown in Fig. 1[19].

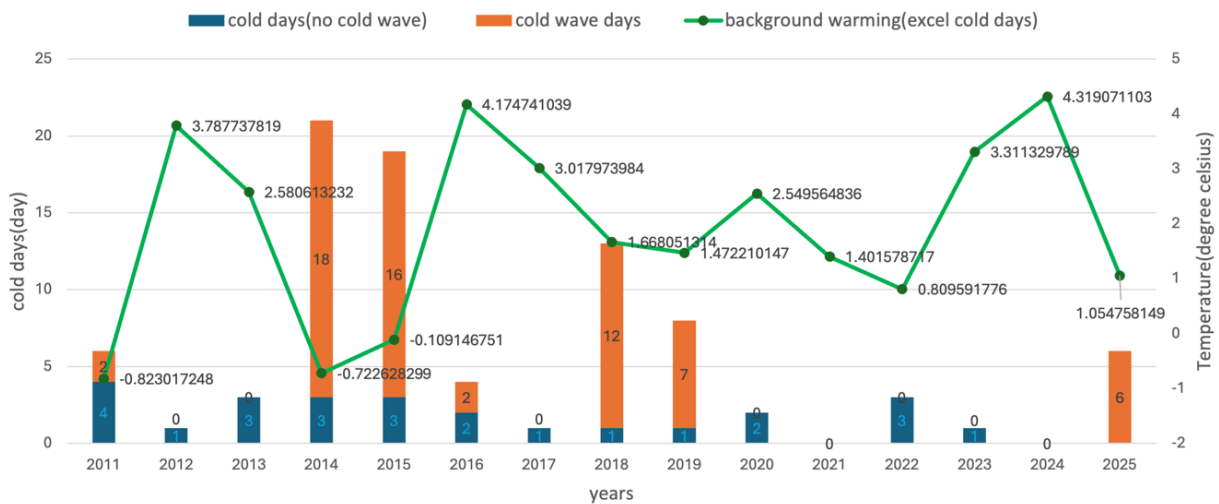


Fig. 1 2011-2015 Toronto DJF cold waves recording with background warming (Photo/Picture credit: Original).

Regarding intensity, as shown by comparing Fig. 2 and Fig. 1, the total intensity of cold wave events is proportional to the total number of cold waves in the season, and a more negative intensity indicates a stronger event. According to Fig. 2, in these years, the overall event intensity of the 2015 winter is recorded as the strongest among the 15 years (about -32.33), and the second one is 2014 at about -31.77 , and moderate-scale events also occurred in 2018 and 2019. 2015 exhibited the highest single-event intensity within a season, which corresponds to the longest cold-wave duration within the 15 years. Typically, the season's strongest cold wave corresponds to the day with the lowest CMD. However, the coldest day in 2014 and the coldest day in 2025 did not occur during the strongest cold-wave events. The observation that the coldest day (CMD) is not always in the strongest cold waves reflects that the difference in control scales of only single cold days or cold days to form cold waves. The season's strongest cold wave is governed by persistent cold advection that cumulates by magnitude and duration, but the coldest single day is often set by clear, calm nights over fresh snow that induce strong radiative cooling, so the coldest day can occur in a weaker cold wave. [15,16] (Figs. 1–2).

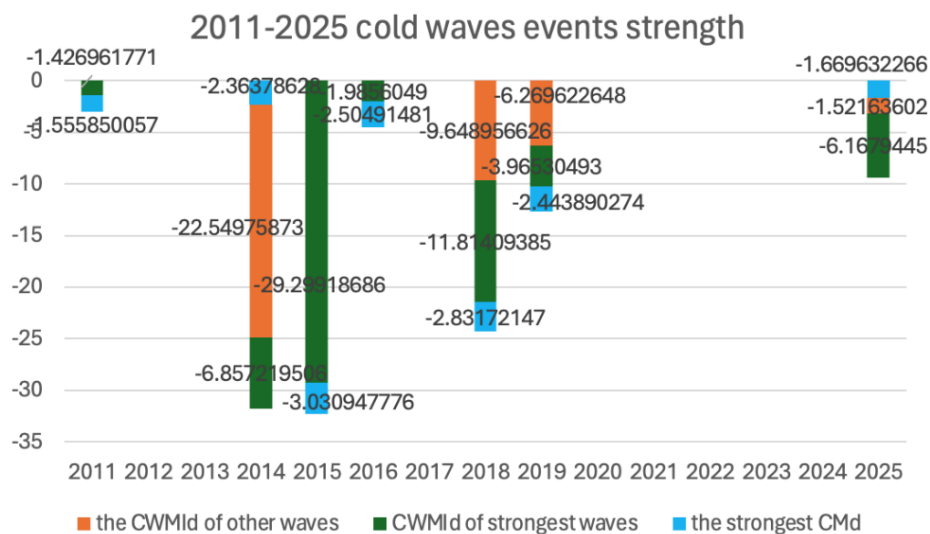


Fig. 2 2011-2015 Toronto DJF winter cold wave event strength (Photo/Picture credit: Original).

Finally, as shown in Fig. 3 about the linear regression of cold day frequency with warming based on the baseline. It was found that the cold days decreased by approximately 3% for every $1\text{ }^{\circ}\text{C}$ increase in temperature, indicating that cold days' frequency has a negative proportionality with temperature. When temperatures approached $0\text{ }^{\circ}\text{C}$ relative to the baseline, the cold-day frequency was around 12%. Overall, warming exhibits a relatively linear decreasing relationship with cold-end

frequency, with an R-squared value of approximately 0.46. The moderate R^2 of this linear regression indicates that not only does the temperature affect the cold wave frequency, but also other factors. It consists with recent studies have found that although the Arctic is warming rapidly, the intensity of cold waves in mid-latitudes such as Toronto has not shown a consistent warming trend. Therefore, the warming is not the only reason for the decreasing trend of cold waves; circulation patterns such as AO/NAO mentioned above also have a significant impact [20]. These relationships should be interpreted as associations rather than strict proportionalities. In conclusion, cold-wave events during 2011–2025 were unevenly distributed but show a relatively decreasing trend and are proportional to cold-wave intensity; the background warming of cold days shows a significant negative correlation with cold-end indicators.

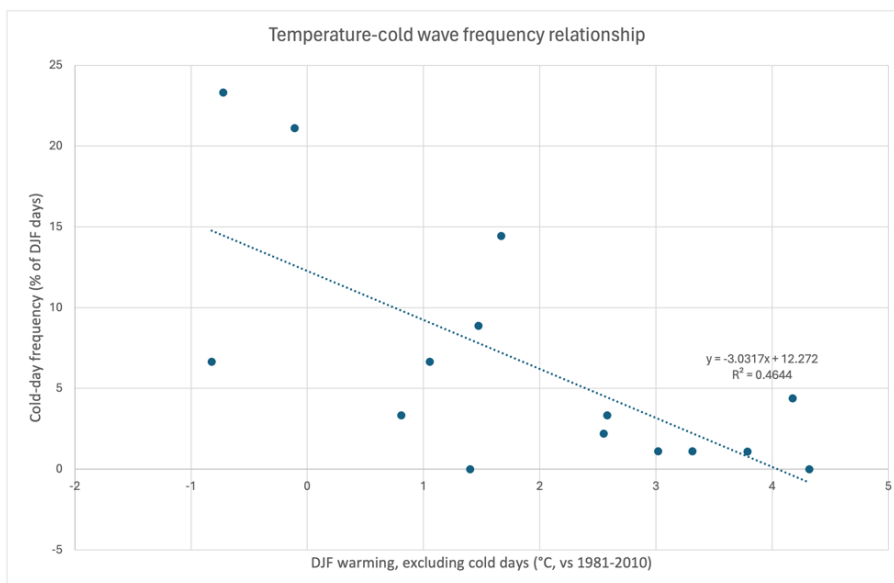


Fig. 3 2011–2025 Toronto DJF winter Temperature–cold wave frequency relationship (Photo/Picture credit: Original).

3.2. Limitation

The methodological limitations also remain; the baseline should be updated from 1981–2010 to 1991–2020 according to WMO guidance. This research does not use the new baseline because of the small interval between 2021 to 2025. And also need better regression method and consider more factors that may affect cold wave, such as station differences, human influence like urbanization, and residual effects after events [1][14]. So future work should extend the analysis with better-specified regressions and additional predictors. Such as longer windows (\pm days), distributed-lag diagnostics, and circulation-condition matching in the supplement, together with threshold sensitivity such as L3/P15 to assess robustness [5].

4. Conclusion

Under a fixed baseline (1981–2010) and quantification threshold (P10), L2 (≥ 2 days) and CWMId/CMD, this research quantifies the winter cold wave in Toronto from 2011 to 2025. The results show that cold waves generally uneven distribution and have large fluctuations between years. As the number of cold days increases, cold days mostly occur as processes rather than isolated days. The total seasonal intensity rises with the superposition of the number of segments and duration. Long-term cold waves may affect more than multiple cold waves, and in some years, the coldest day is not in the strongest cold waves because the reason for causing long duration of cold wave and strong strength of a single cold day is not the same. Moreover, warming temperatures will lead to a reduction in the frequency of cold waves. It was shown that the background temperature change after excluding the cold day was approximately linear and negatively correlated with the cold day

frequency by about -3 percentage points /°C. However, according to R², the differences between different years were still affected by other factors, such as AO/NAO and underlying surface feedback modulation. This article supplements the more detailed magnitude evidence of the cold wave in Toronto, it analyzes the nature of the cold wave in Toronto, and provides repeatable quantifiable records (frequency, duration, intensity and their statistical relationship with background warming) of the cold end in downtown Toronto during winter from 2011 to 2025, offering baselines and reusable methods for subsequent research and monitoring. However, the sample period was relatively short, and there was a zero-event year, and the conclusion was that it was related but not causal. The single-station sequence is affected by urbanization and the station site environment. The threshold and window width selection will change the values. Subsequently, baselines from 1991 to 2020 can be updated in parallel to conduct L3/P15 sensitivity and multi-station comparisons. Circulation factors such as AO/NAO were incorporated and separated from urbanization, and a counting/distribution lag model was attempted to enhance robustness and predictability.

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