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Heat Wave Trends in Canadian Regions

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ABSTRACT *Despite their widespread impacts, there has been limited work to quantify how heat waves have changed in Canada. With no standard definition of a heat wave, we consider two different types of heat waves: climatological heat waves defined by the exceedance of a climatological percentile threshold and heat-warning heat waves which are based on the absolute threshold criteria for issuing heat warnings in Canada. These two heat waves represent different types of events with different primary impacts. We find the type of heat wave strongly influences the number of heat waves each year and the regional patterns of where such events are more prevalent. After the evaluation of climatologies, considering station observations and spatially complete gridded datasets, trends in annual metrics of heat waves were calculated for Canadian regions. Climatological heat waves increased in frequency, duration, and cumulative intensity between 1961 and 2020 across the country and in most regions. Heat-warning heat waves have increased over Northern and Atlantic Canada.*

RÉSUMÉ *[Traduit par la rédaction] Malgré leur impact généralisé, peu de travaux ont été réalisés pour quantifier l'évolution des vagues de chaleur au Canada. En l'absence d'une définition normalisée d'une vague de chaleur, nous considérons deux types différents de vagues de chaleur: les vagues de chaleur climatologiques définies par le dépassement d'un seuil climatologique de percentile et les vagues de chaleur d'avertissement qui sont fondées sur les critères de seuil absolu pour l'émission d'avertissements de chaleur au Canada. Ces deux vagues de chaleur constituent différents types d'événements ayant des impacts primaires différents. Nous constatons que le type de vague de chaleur influe fortement sur le nombre de vagues de chaleur chaque année et sur les schémas régionaux dans lesquels ces événements sont plus fréquents. Après l'évaluation des climatologies, en tenant compte des observations des stations et des ensembles de données maillées spatialement complètes, les tendances des mesures annuelles des vagues de chaleur ont été calculées pour les régions canadiennes. Les vagues de chaleur climatologiques ont augmenté en fréquence, en durée et en intensité cumulée entre 1961 et 2020 dans l'ensemble du pays et dans la plupart des régions. Les vagues de chaleur avec avertissement de chaleur ont augmenté dans le nord du Canada et dans les provinces de l'Atlantique.*

KEYWORDS heat waves; Canada; regional trends; extremes

1 Introduction

Heat waves, or the occurrence of unusually high temperatures for several days in a row, have widespread impacts globally and in Canada. Heat waves have consequences for public health in terms of increased mortality and morbidity (Campbell et al., 2018), with the 2021 heat wave in western Canada (White et al., 2023) serving as a grim example. Concurrent heat waves and drought can be damaging to agriculture (Zampieri et al., 2017) and increase the risk of wildfires (Jain et al., 2024). A comprehensive list of heat wave impacts in Canada can be found in Smoyer-Tomic et al. (2003). With warming global temperatures, increases in extreme heat are a major concern for much of the population.

There is no single specific definition of a heat wave, though most definitions include the exceedance of some temperature threshold for multiple consecutive days. The American Meteorological Society Glossary refers to "a period of abnormally and uncomfortably hot and usually humid weather," but is not specific about how exactly to further define a heat wave (American Meteorological Society, 2025). Different ways to define heat waves can capture different types of events, with relevance to different impacts. Choosing relative

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thresholds (such as a climatological percentile) to determine heat waves enables a comparison across regions (Perkins & Alexander, 2013). Percentile thresholds may also have stronger signal-to-noise ratios (Zhang et al., 2011) and are more common for climate analyses. Climatological percentile thresholds are often defined based on rolling windows, identifying events that are extreme for a certain time of year (Perkins & Alexander, 2013) and these seasonal extremes may be particularly relevant for agriculture and wildfires. On the other hand, absolute thresholds can be chosen to be more relevant for specific impacts such as human health. Absolute thresholds can vary by region, but these events tend to occur mostly during the summer. Smith et al. (2013) found the spatial differences in average heat wave frequency over the United States were of a larger magnitude when absolute thresholds were used compared to relative thresholds. You et al. (2017) found a similar result in China, and also noted that quantifying heat wave trends depended strongly on the definition used.

Most existing literature on hot extremes in Canada is based on single-day temperature metrics. As such, hot extremes have increased in intensity and frequency over Canada, with increases in the annual maximum daily maximum temperature and the number of hot days (days over 30 °C) (Vincent et al., 2018; Zhang et al., 2019). This increase in annual maximum temperatures has been attributed to human influence (Wan et al., 2019). While some implications for heat waves can be inferred from single-day metrics, additional information on how the frequency and duration of events where multiple consecutive days exceed extreme heat thresholds is valuable for preparedness and adaptation. This quantification of observed changes in heat waves specifically has been limited over Canada and North America more broadly. In the Arctic, the area covered by heat waves has increased since 2002, with some of the strongest changes over the Canadian Arctic (Dobricic et al., 2020). Perkins-Kirkpatrick and Lewis (2020) identified increases in the frequency and cumulative intensity of heat waves for most global land regions. The only exception in their analysis was the Central North America region, which was also noted in the IPCC 6th Assessment Report (Seneviratne et al., 2021) to lack region-level trends in the annual maximum temperatures. Stewart et al. (2017) analyzed trends for heat events using various temperature thresholds at two stations in southern British Columbia, finding indications of increases though statistically significant changes were limited.

In this paper, we analyze climatologies and trends in heat wave metrics over Canada, summarizing nationally and regionally. The intent is to quantify how heat waves have changed over the past 50 years in Canadian regions, filling an information gap where previous work was either focused on single-day hot extremes or over very limited regions. Such information will be valuable for planning adaptation and resilience to continued warming. Canada covers a large area with a wide range of climates and a tailored analysis to Canadian regions will provide information not available from studies on the global domain. We consider the two different types of heat waves. We then compare heat wave climatologies over Canada from station-based observations with those calculated from two gridded products. The spatially complete datasets are used to calculate historical trends in heat wave metrics over all of Canada and its subregions.

2 Methods

a *Heat wave definitions*

We consider two types of heat waves. The first is referred to as climatological heat waves and is based on climatological percentile thresholds for the May through September warm season. Following the recommendation of Perkins and Alexander (2013), we defined heat waves as at least three consecutive days where the daily maximum temperature exceeds the climatological 90th percentile. This climatological threshold was defined for each calendar day, using the 90th percentile of daily maximum temperatures from a 15-day window centred on the target day. This rolling window percentile means that climatological heat waves can occur at any time in the warm season and represent events that are anomalous for a particular time of year. We used the whole time period of 1961–2020 to define these percentiles in order to avoid inhomogeneities between years within and outside the base period that may have led to overestimated trends (Zhang et al., 2005).

The second type of heat wave is referred to as a heat-warning heat wave, which is based on human-health-relevant absolute thresholds. We used the criteria for heat warnings across Canada, which is the exceedance of absolute thresholds in both maximum and minimum temperatures for two or more consecutive days (Environment and Climate Change Canada, 2024, 2025). These absolute thresholds vary by region (Fig. S1) and were chosen for their relevance to human health impacts.

To summarize heat waves annually, we used the metrics described in Fischer and Schär (2010) and subsequently used in several climate studies of heat waves (Perkins & Alexander, 2013; Perkins-Kirkpatrick & Lewis, 2020). The heat wave frequency is defined as the number of days each year that meet the heat wave criteria. The heat wave number is the number of distinct heat waves each year. The heat wave duration describes the length of each year's longest heat wave. And the cumulative heat exposure is the cumulative sum across heat wave days of the amount the daily maximum temperature exceeds the threshold. This cumulative heat exposure describes heat wave intensity by considering the accumulation of heat exposure during the event.

Trends in annual heat wave metrics were calculated using the Mann-Kendall method over 1961-2020. Significance of the trends was assessed at the 90% confidence level, using a two-tailed test. At the regional level, the trends were very similar if a linear least squares method was used instead.

b *Data and processing*

Station observations in this analysis were from the third generation of homogenized temperature datasets from the Adjusted and Homogenized Canadian Climate Data

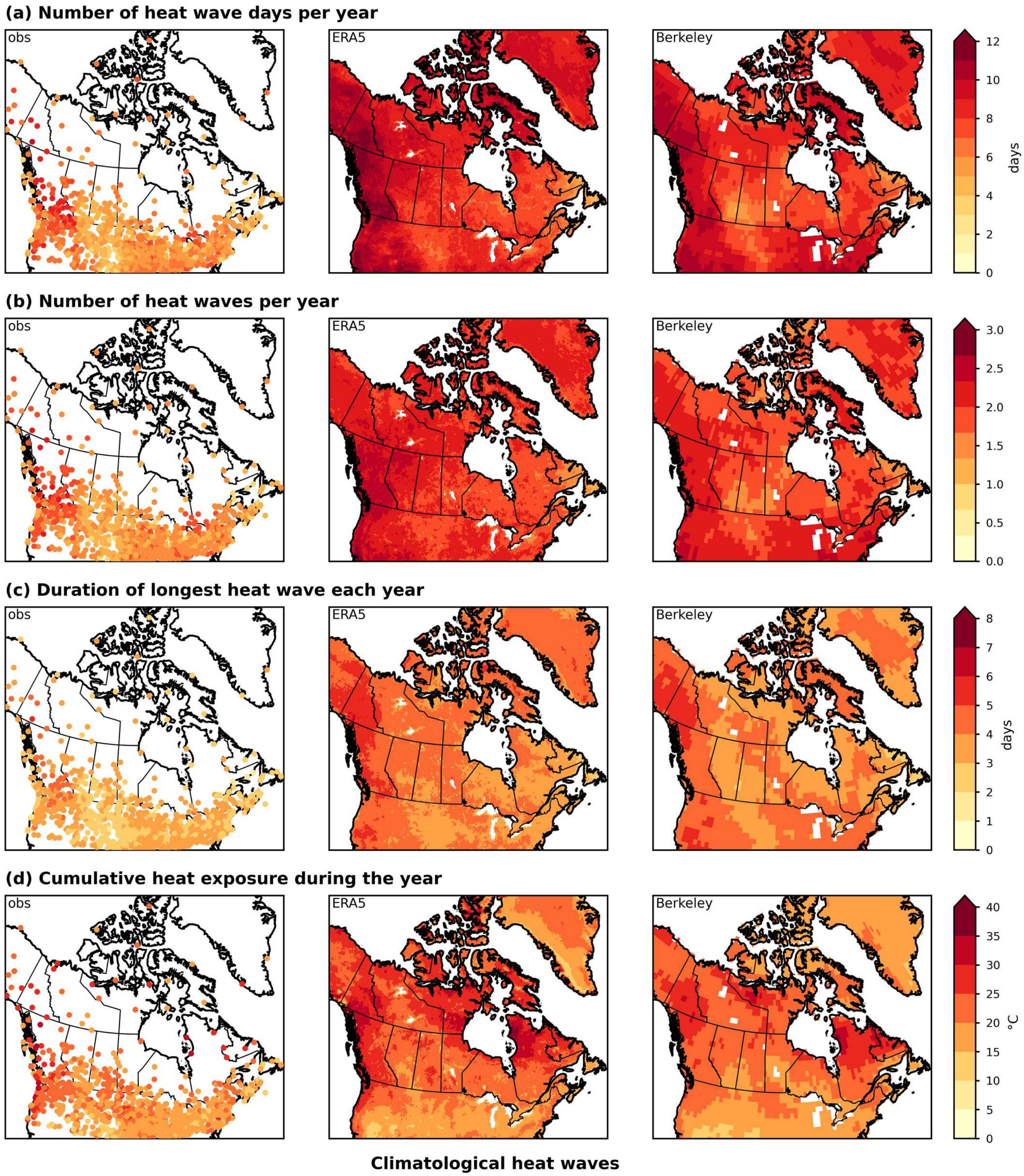

Fig. 1 Climatology (1961–2020) of heat wave metrics for climatological heat waves for each dataset at its original resolution.

(AHCCD) (Vincent et al., 2020). The third generation temperature dataset contains 780 high quality station records that have been homogenized for use in evaluating long-term climatic changes. Station observations from the neighbouring United States were acquired from the Global Historical Climatology Network-Daily (GHCND) (Menne et al., 2012).

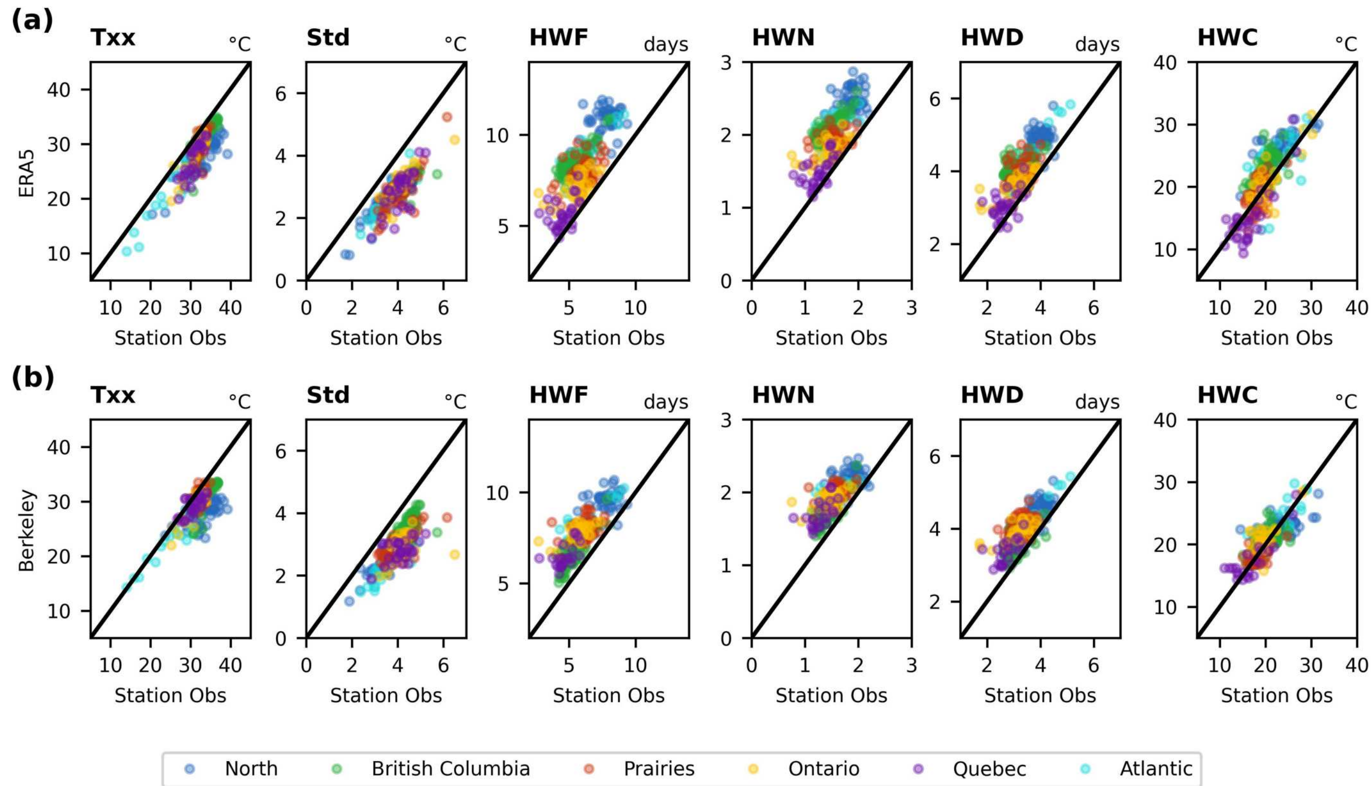

Fig. 2 Climatology (1961–2020) of the annual maximum daily maximum temperature (Txx), day-to-day standard deviation (Std), number of heat wave days per year (HWF), number of heat waves per year (HWN), duration of the longest heat wave each year (HWD), and cumulative heat exposure during the year. Heat wave metrics are based on the climatological heat wave definition. Values are plotted for each station against the value from the containing grid box from ERA5 (a) or Berkeley Earth (b). Points are coloured based on their location.

We required that each station is missing less than 10% of daily values during the warm season and no more than 5 years of missing data in total.

As station observations are sparse in many regions of Canada, especially in the North, we also considered two gridded datasets with full spatial coverage. The first is the ERA5 reanalysis (Hersbach, Bell, Berrisford, et al., 2020; Hersbach, Bell, Biavati, et al., 2023) which is available from 1940 at an 0.25 degree resolution. We extracted hourly maximum 2 m temperature and then calculated the daily maximum temperature. ERA5 is widely used in the analysis of extremes. It has been demonstrated to have a cold bias over land (Simmons et al., 2021) and in the Arctic (Rantanen et al., 2022) prior to 1967, but the comparison with other datasets improves with increased assimilated observations.

We also included the Berkeley Earth dataset (Rohde & Hausfather, 2020), which provides temperature variables on a 1.0 degree grid. The daily data are available from 1880. At least at the monthly and global scale, this dataset has been shown to compare well with other estimates of global temperatures (Gulev et al., 2021). Over Canada, Way et al. (2017) compared Berkeley Earth to adjusted and homogenized station data, finding a warm bias in monthly mean maximum temperatures overall and at most southern stations, but a cool bias in maximum temperatures across the North. They did not find significant differences in trends in maximum temperatures, although mean and minimum temperature trends were underestimated by the Berkeley Earth dataset (Way et al., 2017). Perkins-Kirkpatrick and Lewis (2020) used the daily-resolution Berkeley Earth dataset to analyze heat waves for global regions, finding good agreement on trends in heat waves with the station-based HadGHCND dataset where the latter had coverage.

Heat wave metrics were calculated at the station-level and for the grid boxes on the original resolutions of ERA5 and Berkeley Earth. For a regional analysis, heat wave metrics were calculated at the grid box level and then averaged over designated regions. We use the Canadian regions defined in Canada's Changing Climate Report (Bush & Flato, 2019) and add an additional region for southern Canada using land area below 60 °N.

3 Results

a *Climatologies*

Climatologies for climatological heat wave metrics are shown in Fig. 1, with heat waves calculated at each dataset's original resolution. Climatological heat waves were experienced across the country, with more heat waves along the west

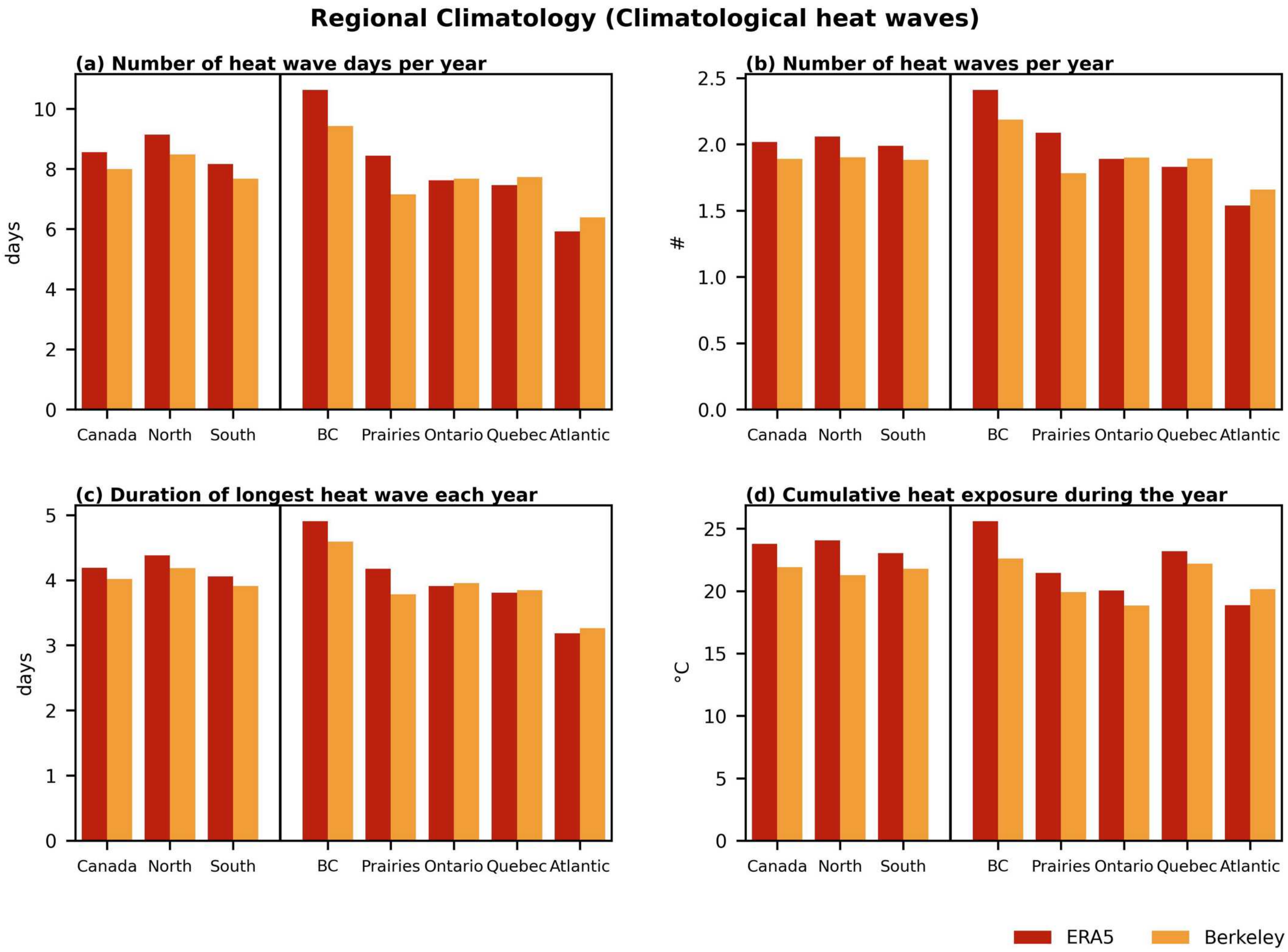

Fig. 3 Regional climatologies (1961–2020) for heat wave metrics for climatological heat waves. Results from ERA5 are shown in red and from Berkeley Earth in orange, calculated on the original resolution of the datasets. The regions are defined based on (Bush & Flato, 2019), with the addition of the "South" region defined as Canadian land with a latitude less than 60 °N.

coast and fewer in the Prairies and Atlantic Canada. The number of heat waves (Fig. 1b) and number of heat wave days (Fig. 1a) are smaller in the station observations than in the gridded datasets. However, the spatial patterns are generally consistent.

A more direct comparison between the station data and the gridded datasets is shown in Fig. 2, where each metric from a Canadian station location is plotted against the same metric from the corresponding grid box from each of ERA5 and Berkeley Earth. The average number of heat wave days, the average number of heat waves, and the average duration of the longest heat wave each year are larger in the gridded datasets for nearly all station locations. These patterns are similar across regions. Differences between the number of heat waves in the station data vs. the gridded datasets are consistent with differences in variability. The day-to-day standard deviation of daily maximum temperature is larger at point stations than in the gridded datasets (Fig. 2). With higher variability, there is less autocorrelation and it is more difficult to meet the three-day requirement for heat waves. Regional differences in variability (Fig. S2) also align with some of the spatial variations in the climatology, such as increased heat wave occurrence along the west coast where variability is lower.

The annual maximum daily maximum temperatures (Txx) are larger at point stations than the grid box values that represent areal averages (Fig. 2). For the average cumulative heat exposure, the gridded and station datasets compare well. Although the stations reach higher extreme temperatures (as shown with Txx), the event duration is smaller, which offset each other in terms of cumulative heat exposure. All patterns are consistent across regions.

Regional averages of the climatologies for climatological heat waves are shown in Fig. 3, using the original-resolution gridded datasets with full coverage. Climatological heat waves occurred on average about twice a year, with the average duration for the longest heat wave annually at about four days. Values for Northern and Southern Canada are

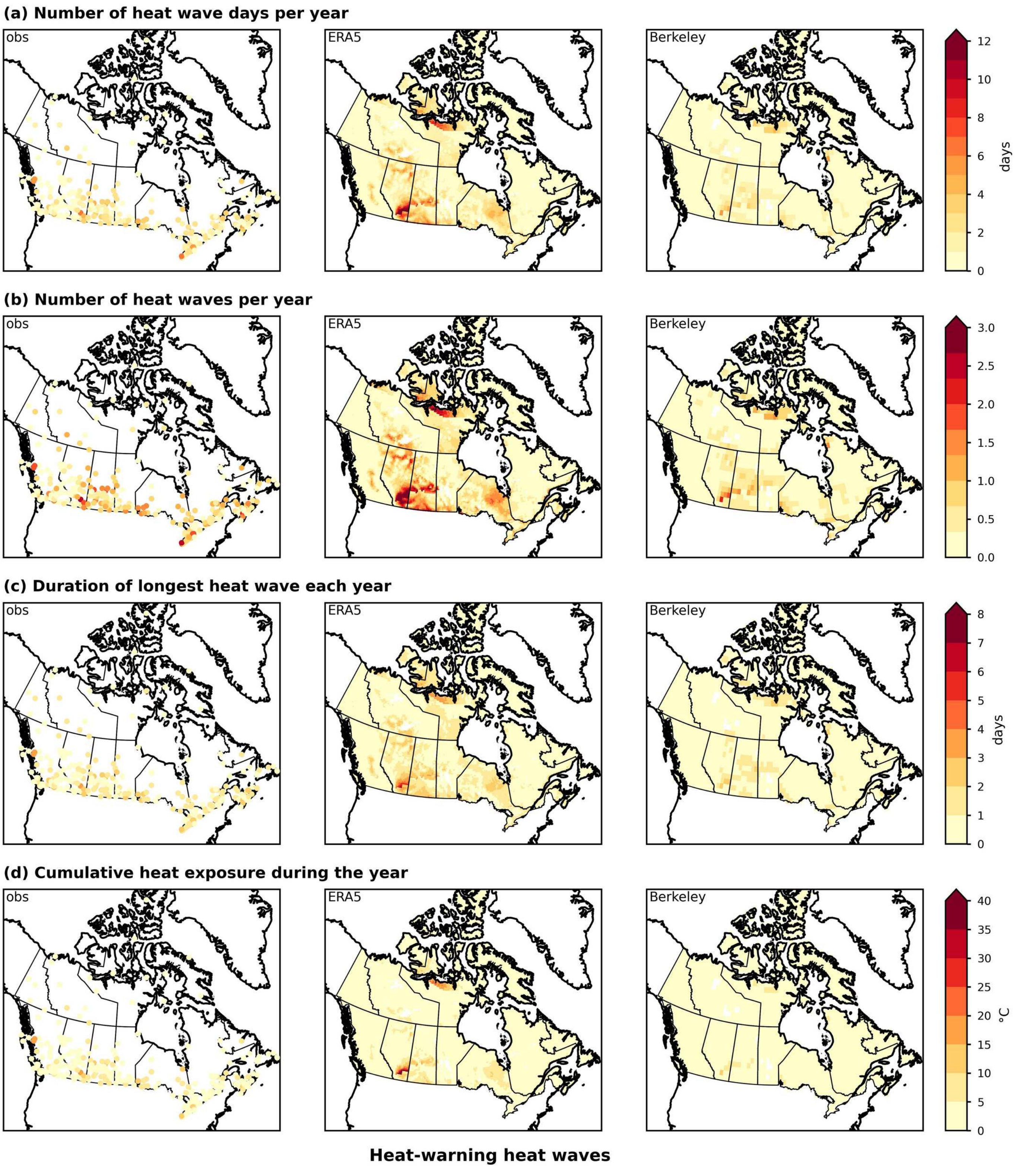

Fig. 4 Maps of climatologies of heat wave metrics as in Fig. 1 but for heat-warning heat waves. Heat waves were calculated and displayed on each dataset's original resolution. The colour scale was chosen to match that used in Fig. 1. Note that due to the heat wave criteria chosen to match heat warnings issued by Environment and Climate Change Canada, this metric is not calculated for any stations or grid boxes in the United States.

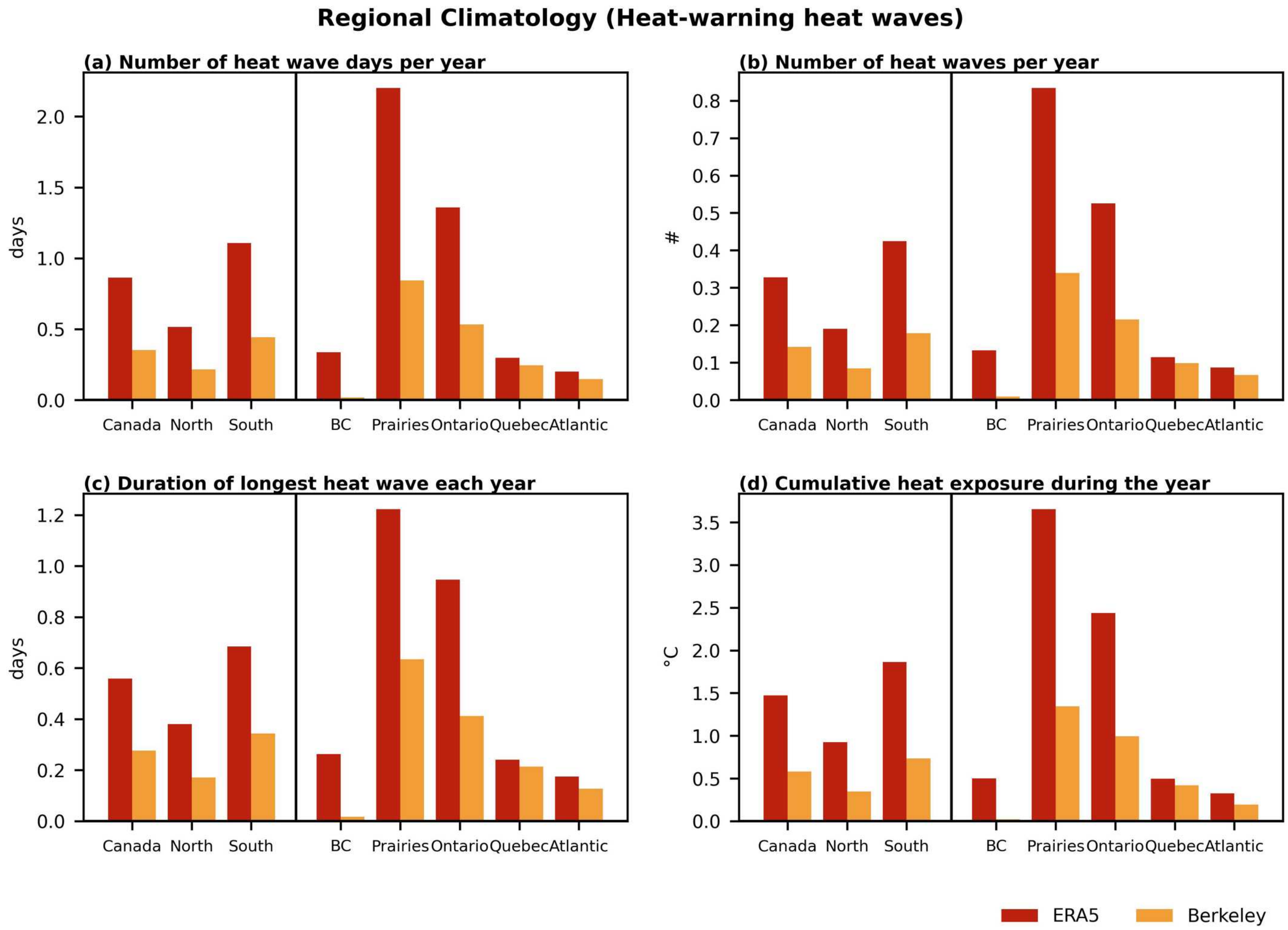

Fig. 5 Regional climatologies as in Fig. 3, but for heat-warning heat waves. Note that the vertical scales here are smaller than in Fig. 3.

similar to the means for Canada as a whole. Of the Southern regions, British Columbia experienced the most and longest heat waves, while the means for these metrics were smaller in Quebec and Atlantic Canada. The climatologies are similar between ERA5 and Berkeley Earth, though ERA5 is often slightly larger.

Heat-warning heat wave climatologies are shown in Figs. 4 and 5. There are many fewer heat-warning heat waves on average than climatological heat waves. There is also a notable difference in regional patterns between the two types of heat waves. It should be recognized that in addition to the switch to absolute thresholds which limit the focus to peak summertime, the heat warning definition is also more restrictive in requiring both maximum and minimum temperatures to exceed particular thresholds during the event.

For heat-warning heat waves, the southern Prairies is a hot spot, with more than two per year on average in some locations. The Prairies are also the region of the country with the highest values for annual maximum temperatures (Fig. S3). Parts of Ontario and the far North experienced more than one heat wave per year on average. The rest of the country, in particular Quebec, Atlantic Canada, and along the west coast averaged less than one heat-warning heat wave every two years. Note that the absolute thresholds vary by region (Fig. S1) and there may be spatial inhomogeneities at the boundaries between thresholds.

ERA5 shows more heat-warning heat waves than both Berkeley Earth and the station data. Dataset resolution and the temperatures representing grid box averages play a role in the difference in heat wave climatologies between the ERA5 and Berkeley Earth datasets. The absolute thresholds for heat waves in this approach are fixed and these extreme temperatures will be reached less often for temperatures averaged over larger regions. Despite point stations reaching higher temperatures than grid box averages (Fig. S3), the smaller number of heat waves at the stations compared to ERA5 may be related to the same difference in the daily maximum temperature variability discussed previously.

b *Trends*

Trends in the heat wave metrics for climatological heat waves are presented for 1961–2020 in Fig. 6. Averaged regionally,

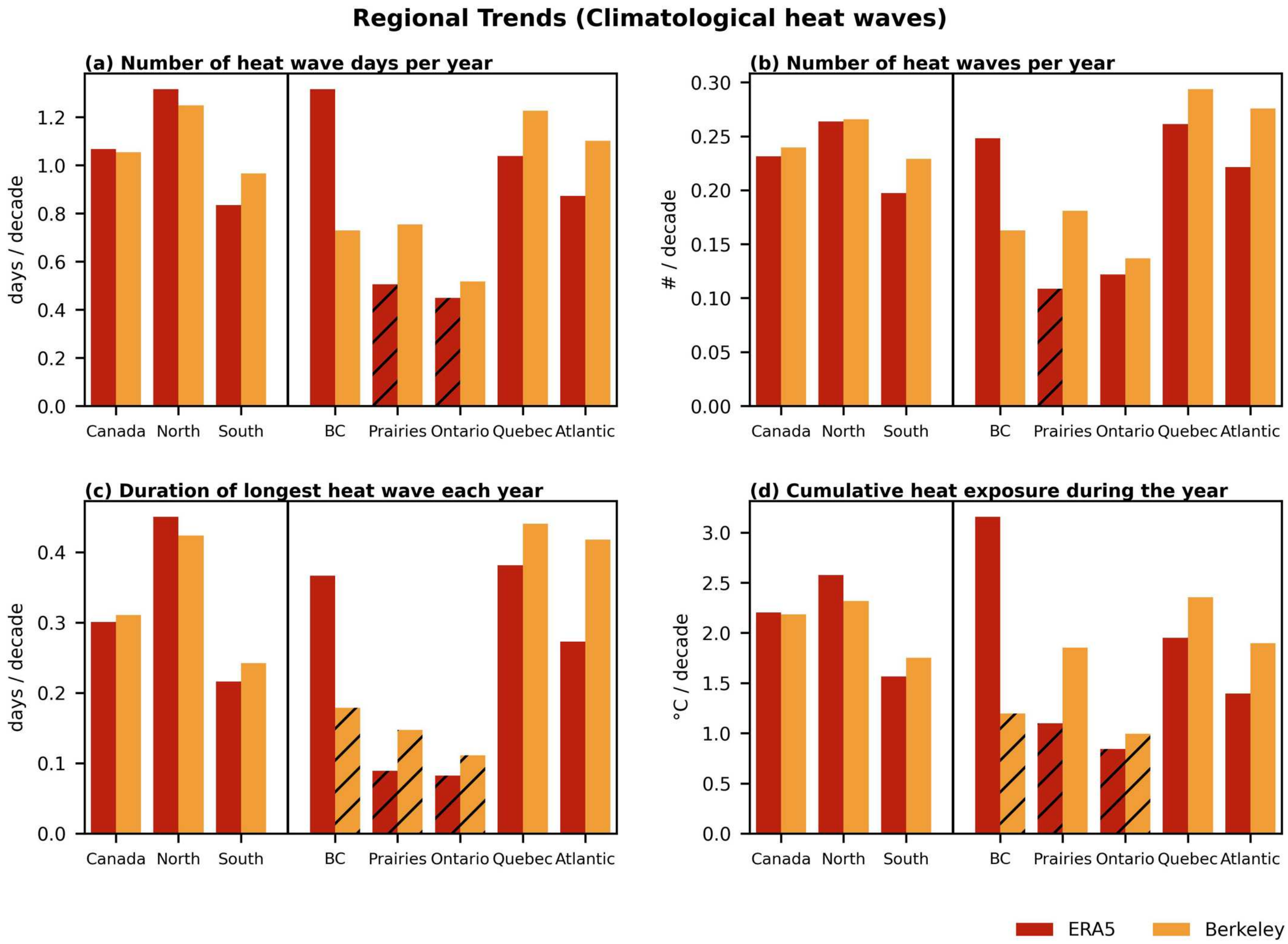

Fig. 6 Regional trends in heat-wave metrics for climatological heat waves for ERA5 (red) and Berkeley Earth (orange). Hatching indicates trends are not significant at the 10% level.

metrics of climatological heat waves have increased across Canada as a whole and the North and South separately. Nationally, the number of heat wave days in a year has increased at a rate of about 1 d per decade (Fig. 6a). A rate of change of about 0.25 heat waves per decade (Fig. 6b) equates to an increase in the average number of heat waves per year of 1.5 over the 60-year period. The duration of the longest heat wave increased at a rate of almost a third of a day per decade (Fig. 6c). And the cumulative heat exposure increased at around 2 °C per decade (Fig. 6d). In all metrics, the trends are stronger in the North and slightly weaker in the South compared to the nation-wide changes.

ERA5 often shows larger regional trends in climatological heat waves compared to Berkeley Earth, which is consistent with the larger climatology and the potential influence of biases in the first few years. Despite some regional disagreement between datasets in the magnitude of trends, there is much more confidence in the direction. Most regional trends are significant at the 90% confidence level. Even with some areas of slightly negative trends in the Prairies, when averaged regionally the trends in heat wave metrics are positive.

We note the use of the entire 1961–2020 period as the base period for determining the percentile threshold. Using a 1961–1990 base period instead means the time series may be subject to an inhomogeneity at the end of the base period as described in Zhang et al. (2005). A comparison of the trends using different base periods is shown in Fig. S4, where regional trends are overestimated when not accounting for the base period sampling issue.

Regional trends for heat-warning heat waves are shown in Fig. 7. Both ERA5 and Berkeley Earth agree on significant increases in all heat-warning heat wave metrics over the North. Trends at the national scale are significant for the Berkeley Earth dataset but not for ERA5. For other regions, most trends are positive in both datasets across all heat wave metrics, though few are significant. In the Prairies, ERA5 and Berkeley Earth disagree on the direction of change, though neither is significant.

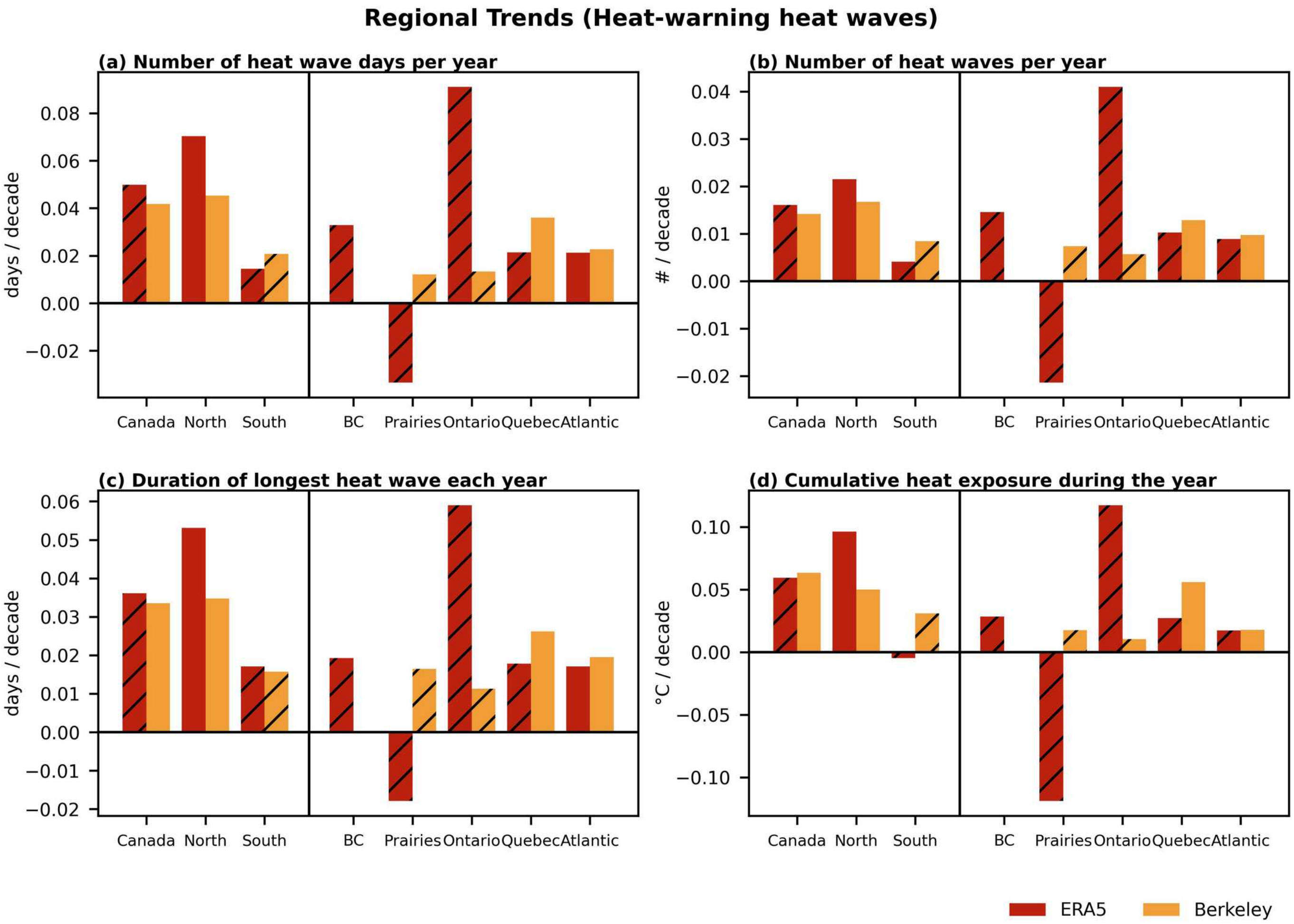

Fig. 7 As in Fig 6 but for the heat-warning heat waves. Note the vertical scale is smaller than in Fig 6.

4 Discussion and conclusions

We investigated climatologies and trends in heat waves over Canada, to determine if/how these impactful events have changed historically at national and regional scales. There is no standard definition of a "heat wave" and this term can be broadly applied. We considered two types of heat waves that represent different types of events. Climatological heat waves consider daily maximum temperatures that exceeded a seasonally varying climatological 90th percentile threshold for at least three days in the warm season of May to September. These events encompass both peak summer hot extremes and multi-day events that are hot for a particular time of year. The latter can be especially impactful for wildfires and agriculture. The second type of heat wave is a heat-warning heat wave that is defined based on two consecutive days where both daily maximum and minimum temperatures exceed regionally varying absolute temperature thresholds. The criteria are those used to trigger heat warnings in Canada and are most relevant to human health impacts. Heat-warning heat waves are generally limited to the hottest time of the year. These two heat waves represent different types of extreme heat events and may not be directly comparable.

Climatological heat waves occurred on average about twice a year, with more heat waves in western Canada, somewhat aligning with the regions of the country with the smaller day-to-day variability in maximum temperatures and less amplitude in the seasonal cycle. Climatological heat waves have increased in frequency, duration, and cumulative heat exposure over Canada as a whole from 1961-2020. Many regions also experienced significant increases in climatological heat waves, with the strongest changes in Northern Canada. Heat-warning heat waves occur on average once every several years, with more heat waves in the regions of the country that experience the hottest summer temperatures. Heat-warning heat waves have increased in frequency, duration, and cumulative exposure over the North, as well as in Atlantic Canada for frequency and duration.

While station-based metrics may be more relevant to temperatures experienced by an individual or at the local scale, the sparse station coverage and need for spatially complete data for the country necessitate the use of alternate gridded products. Full spatial coverage is especially important to ensure regional averages are representative. Full-coverage gridded results are presented using two different datasets and while there is broad agreement in the heat wave climatologies and direction of trends, some regional differences in magnitude were demonstrated. Berkeley Earth is based on station data and kriging methods to achieve spatial completeness, with an approach that allows for the use of short records (Rohde et al., 2013; Rohde & Hausfather, 2020). In contrast, ERA5 is a reanalysis product, where the spatial field is constructed by the underlying forecast model while regularly assimilating various observations. Both the different initial resolutions and different methods for producing spatially complete fields can explain some of the differences between these two data products. Even if differences between the two datasets influence the larger uncertainty in the magnitude of heat wave trends, agreement on the direction of trends gives higher confidence that heat waves have increased over Canada.

The term "heat wave" can apply to different types of events and we have demonstrated that climatologies and trends in heat waves over Canada depend on, at a high-level, what is considered to be a heat wave. As such, care should be taken to consider the needs of particular applications and the appropriate type of heat wave before making actionable decisions based on results like those presented here. We can expect increases in heat waves for much of the country with continued global warming, especially for regions and events where there are significant increases over the historical period.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Supplemental data

Supplemental data for this article can be accessed at https://doi.org/10.1080/07055900.2025.2521501

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