Spatiotemporal Trends in Winter Wind Chill Temperatures across Canada and the United States

NEIL F. LAIRD,[a] MATTHEW SINNENBERG,[b] MACY E. HOWARTH,[a] AND CAMERON W. CROWELL[a]

[a] *Department of Geoscience, Hobart and William Smith Colleges, Geneva, New York*
[b] *Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, Albany, New York*

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ABSTRACT: Wind chill temperature (WCT) is a widely recognized biometeorological variable that quantifies atmospheric conditions that have consequential impacts on many aspects of society, especially human health through exposure to winter conditions that can result in hypothermia, frostbite, and cardiorespiratory mortality. The spatial and temporal variations in WCT and extreme WCT (E WCT) (coldest 1%) were examined using hourly surface measurements collected at 133 stations across Canada and the United States during 40 winters (1979/80–2018/19). Most locations experienced an overall warming in both mean and extreme WCTs. The most substantial and statistically significant warming of mean WCT occurred across Alaska and the Canadian Northwest Territories with values of +3.2° to +6.4°C during the 40-winter time period. Statistically significant warming of mean WCT also occurred along the East Coast of Canada and the United States, as well as across the southeastern United States. Extreme WCT was found to be 10°–30°C colder than the mean WCT, and generally, the extreme WCT warmed at a greater rate than the mean WCT at locations. For example, extreme WCT warmed as much as +10.4°C during the 40-winter time period across portions of Alaska and the Canadian Northwest Territories. Warming air temperatures were found to have a large relative contribution to warming of mean and extreme WCTs with a smaller contribution coming from decreasing wind speeds (WS).

KEYWORDS: Winter/cool season; Climatology; Windchill

1. Introduction

Spatiotemporal changes in winter weather conditions are important to quantify since not all locations in both middle latitudes and polar regions are experiencing the same magnitude of change in atmospheric variables (e.g., Walsh and Chapman 1990; Vrac et al. 2014), and changing conditions will often have consequential impacts on many aspects of society. These impacts can relate to human health (e.g., Caminade et al. 2019), agriculture and biodiversity (e.g., McMeans et al. 2020), water availability (e.g., Milly et al. 2005; Woolway et al. 2020), socioeconomic conditions (e.g., van Ginkel et al. 2020), and energy systems (e.g., Perera et al. 2020). Wind chill temperature (WCT) is a widely recognized biometeorological variable with an extensive body of scientific literature exploring the relationship of WCT to human health, specifically exposure to winter conditions that result in hypothermia, frostbite, and cardiorespiratory mortality (e.g., Biem et al. 2003; Carder et al. 2005; Moore and Semple 2011). Additionally, WCT has been used to develop a large variety of predictive relationships to examine daily emergency ambulance services (e.g., Wong 2023), seasonal clothing demands (e.g., Oh et al. 2022), trends in tourism (e.g., Wang et al. 2022), winter highway traffic volume (e.g., Datla et al. 2013), and types of occupational construction accidents (e.g., Kang and Ryu 2019). The National Academies of Sciences has suggested that additional understanding of the attribution of variations in extreme cold-season weather events can be achieved by examining changes in WCT, as well as other severe weather indices [National Academies of Sciences, Engineering, and Medicine (NASEM) 2016]; however, research in this area has yet to be completed.

WCT was developed to quantify the physiological response of the human body to extreme winter conditions (e.g., Siple and Passel 1945; Lankford and Fox 2021) and is often used to evaluate the severity of winter weather since both wind speed (WS) and air temperature are incorporated into the calculation of WCT (Osczevski and Bluestein 2005). As the air temperature cools and/or the wind speed increases, the WCT decreases. Few studies have examined the spatial and temporal variations in WCT for locations in the United States. These studies have focused on specific regions, such as the north-central United States (Rieck and Binau 2008; Lussenden et al. 2014) and the southeastern United States (Soulé et al. 1992). Howarth and Laird (2017) examined the variation in WCT within the winter season across Canada and the United States and defined extreme WCT (E WCT) as the coldest 1% of the WCT frequency distribution. They found that the coldest extreme WCT values most often occur in the Hudson Bay region of Canada, with the largest changes in WCT within a winter occurring in north-central and northeastern North America.

A limited number of studies have examined long-term trends of WCT (e.g., Keimig and Bradley 2002; Mekis et al. 2015; Wang et al. 2019). The two studies that investigated long-term WCT trends over North America focused on high-latitude regions: (i) Alaska and northern Canada (Keimig and Bradley 2002) and (ii) across all provinces and territories of Canada (Mekis et al. 2015). Keimig and Bradley (2002) investigated WCT across a 40-yr time period (1953–93) and found 76% of locations had warming of monthly WCT, with many monthly mean WCT having increased by >5°C. Alaska and

Corresponding author: Neil F. Laird, laird@hws.edu

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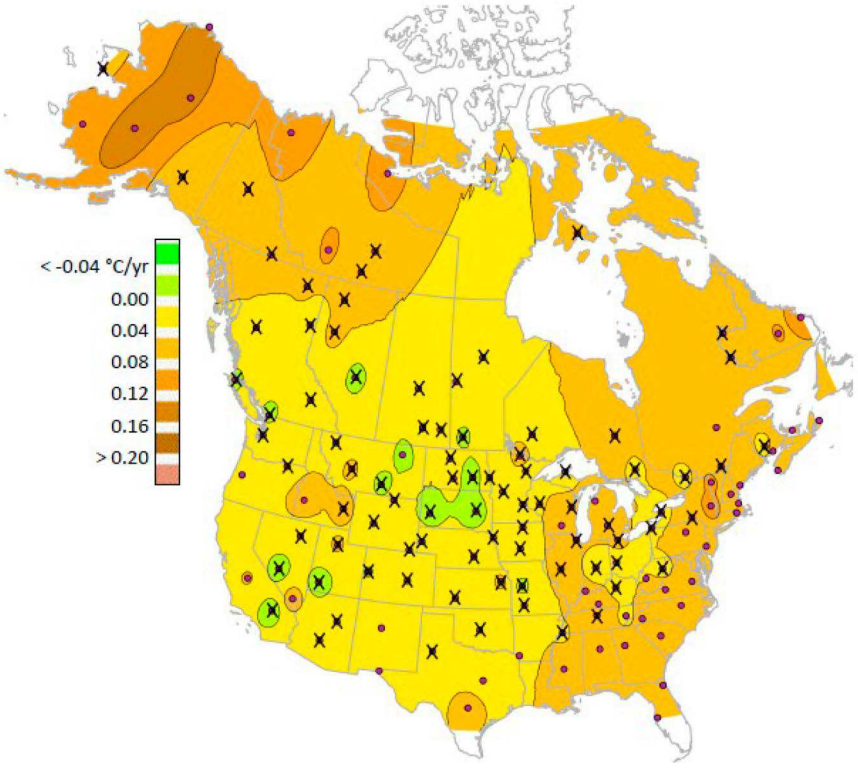

FIG. 1. Trend in annual mean WCT (°C yr^{-1}) across the 40-winter time period. Stations with WCT trends statistically different from a slope = 0.0 having a p value < 0.05 are shown with a filled circle, and stations with WCT trends not statistically different from a slope = 0.0 having a p value > 0.05 are shown with an X.

western Canada experienced the greatest warming of WCT, and central, eastern, and northern Canada experienced cooling of WCT or a smaller magnitude of warming. Additionally, Keimig and Bradley (2002) determined that the primary contribution to warming WCT was from warming air temperatures and a smaller influence from decreasing wind speeds. Mekis et al. (2015) examined trends in WCT for 1953–2012 at 126 stations across Canada and found that the number of days with at least one hourly WCT below −30°, −35°, −40°, and −45°C had significantly decreased at more than 76%, 71%, 61%, and 53% of the observing stations, respectively. They also found that the frequency of observations with WCT colder than −30°C had decreased significantly across all of Canada, except for a small number of coastal locations in eastern and western Canada.

Winter mean and minimum surface air temperatures in Canada and the continental United States have warmed during recent decades (e.g., Vincent et al. 2007, 2015; Wang et al. 2021). Observed winter surface air temperature trends are positive across Canada, with the largest warming [>4°C (50 $yr)^{-1}$] having occurred over northwestern Canada and smaller-amplitude warming [<1°C (50 $yr)^{-1}$] having occurred over the southwestern and eastern coastal regions during the time period from 1963 to 2012 (Deser et al. 2016). For the continental United States, surface air temperatures have warmed during all seasons with the greatest warming trends determined to be either during the spring {[0.14°C (10 $yr)^{-1}$] Brown and DeGaetano 2013} or during the winter {[1.17°C (100 $yr)^{-1}$] Lu et al. 2005}. Additionally, several studies have shown that climate variability in Arctic regions can influence the occurrence and severity of extreme winter weather conditions in midlatitude locations (e.g., Higgins et al. 2002; Cohen et al. 2020, 2021). Therefore, an examination of temporal and spatial changes in WCT across both Canada and the United States can help further understand whether regional differences exist.

Surface wind speeds have also changed across Canada and the United States during the most recent decades (e.g., Wu et al. 2018). Decreases in winter wind speeds have occurred in western Canada and parts of southern Canada, though increases occurred in the central Canadian Arctic (e.g., Tuller 2004; Wan et al. 2010). Decreasing surface wind speeds have also been observed across the continental United States (e.g., Klink 1999a,b; Pryor et al. 2009; Pryor and Ledolter 2010; Wu et al. 2018). Pryor et al. (2009) found negative trends for all seasons with a reduction in wind speeds of generally 1% $(yr)^{-1}$ from 1973 through 2005.

The current article presents a unique investigation of the spatial and temporal variations in WCT and extreme WCT across Canada and the United States while also examining the attribution of changes in WCT to changing surface air temperature and wind speed conditions. The results quantify trends

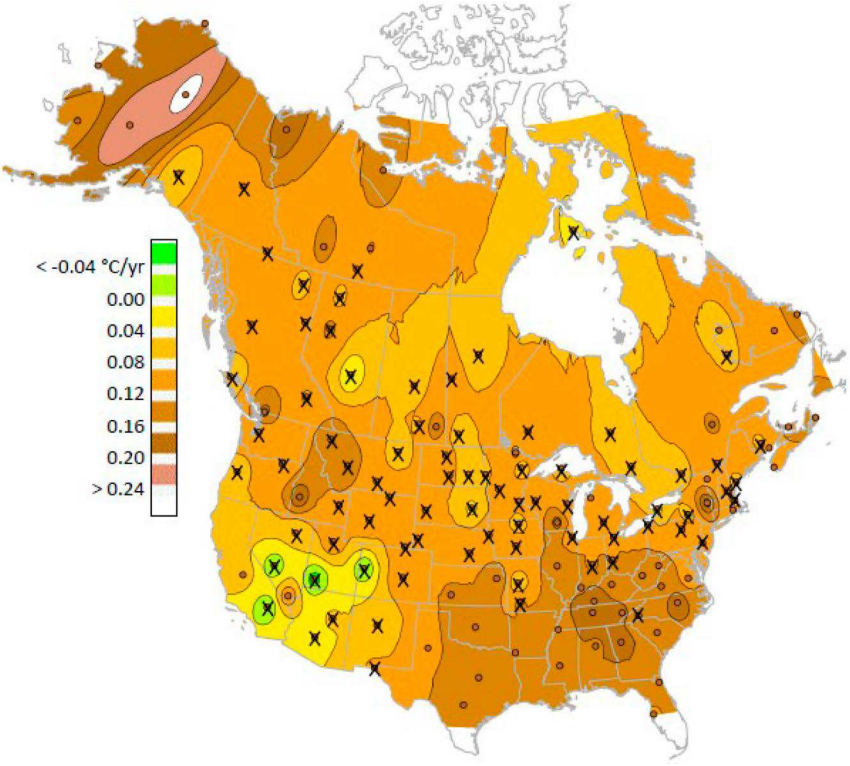

FIG. 2. Trend in annual extreme WCT (°C yr^{-1}) across the 40-winter time period. Stations with extreme WCT trends statistically different from a slope = 0.0 having a p value < 0.05 are shown with a filled circle, and stations with extreme WCT trends not statistically different from a slope = 0.0 having a p value > 0.05 are shown with an X.

in WCT and extreme WCT, as well as supply information to understand the potential influences on human health and a variety of other relationships that have been established with WCT as the primary predictive variable. Section 2 provides information about the data used and the analyses conducted. The results are presented in section 3, and a summary of the primary findings from the study is included in section 4.

2. Data and methodology

This study used integrated surface global hourly data (DSI–3505), which contains measurements of wind speed and direction, air temperature, humidity, sea level pressure, station pressure, present weather, and visibility, during a 40-yr time period for the winters (December–February) of 1979/80 through 2018/19. Data were obtained from the National Center for Environmental Information (NCEI: https://www.ncei.noaa.gov), and all data were quality controlled for extremes, consistency, and continuity (Smith et al. 2011). The winter months of December, January, and February were selected since the transitional months of November and March lacked the number of air temperature and wind speed observations at many stations in the range of values necessary to apply the WCT relation (Osczevski and Bluestein 2005).

Locations were selected across Canada and the United States to create a reasonably distributed arrangement of stations that provided continuous, long-term, observation records. The first criterion for selection required that stations had not moved the location more than 5 km during the study time period to reduce the possibility of inhomogeneity in the archived data. A second criterion, used by Keimig and Bradley (2002) and Howarth and Laird (2017), required a station to have at least 70% of hourly data reported to achieve temporal robustness and consistency of the hourly dataset at each surface station. Nearly all selected stations had consistent hourly data at a much greater percentage than the required 70% for the entire 40-winter time period. Using the two criteria, 133 stations across Canada and the United States were selected. Station locations are included on all maps presented in this article. Temporal analyses of surface station data were conducted based on both individual winters and four decades defined as the winters spanning 1979/80–1988/89 (decade 1: D1), 1989/90–1998/99 (decade 2: D2), 1999/2000–2008/09 (decade 3: D3), and 2009/10–2018/19 (decade 4: D4).

Several studies have examined long-term hourly data at stations in the United States for inhomogeneity, due to such things as instrumentation changes and shifts in station location. These studies have shown that temperature records for some stations are affected; however, the influences are often relatively minor or are inconsistent across the small subset of stations with identified inhomogeneity (Gaffen and Ross 1999; Robinson 2000; Brown and DeGaetano 2009, 2013).

Hourly observations have also been examined for discontinuities in the long-term records for Canadian surface stations (e.g., Vincent et al. 2007). They found that no changes in instrumentation, observing procedure, or exposure were associated with the few identified inhomogeneities in the temperatures and it was not necessary to adjust the temperature time series. For the current study, the hourly temperature data for the time period investigated were not adjusted for any of the 133 surface stations.

The method used to adjust the wind speed, if necessary, is the same as that employed in Howarth and Laird (2017) and the following text is derived from that study with minor modifications. Station histories were examined to determine whether there had been changes in anemometer height or location and whether wind speeds had been measured at a height of 10 m above the ground. Following Peterson and Hennessey (1978), Klink (1999a,b), and Pryor et al. (2009), wind speeds measured at nonstandard heights were adjusted to the standard 10-m height using the 1/7th wind power law assuming near-neutral stability and a flat relatively smooth surface. These adjustments were not required for all stations or time periods. When station data are required, the modifications to wind speed for most hourly observations were found to be small (e.g., generally <0.5 m s^{-1}) since height adjustments were typically on the order of 2 m and therefore resulted in only a very small change in wind speed.

The most current empirical WCT equation (Osczevski and Bluestein 2005), and the relationship used in this study, is

$$\mathrm{WCT} = 13.12 + 0.6215T - 11.37V^{0.16} + 0.3965TV^{0.16}, \quad (1)$$

where T is the air temperature (°C), V is the wind speed (km h^{-1}) measured at a height of 10 m, and WCT is reported in degrees Celsius. Equation (1) is valid for air temperatures of $-50°$ to 10°C and for wind speeds of 10–80 km h^{-1} (Osczevski and Bluestein 2005). Additionally, a complementary relation was implemented based on the use by Mekis et al. (2015) and Howarth and Laird (2017) to expand the examination of WCT in weak wind regimes (i.e., observation times when the wind speed was <10 km h^{-1}):

$$\mathrm{WCT} = T + \frac{-1.59 + 0.1345T}{5}V. \quad (2)$$

The determination of decadal mean winter (DMW) WCT used the defined ranges of air temperatures and wind speeds to derive WCT, while the DMW air temperatures and wind speeds were calculated using all available winter hourly observations. Extreme WCT is defined in this study as the coldest 1% of hourly WCT at each station. Both the annual and decadal extreme WCT were examined to explore, visualize, and quantify changes. Some analyses present decadal changes, as well as changes across the entire 40-winter time period, and were determined using the difference in DMW values as such: 1990s minus 1980s (change in the variable from D1 to D2), 2000s minus 1990s (change in the variable from D2 to D3), 2010s minus 2000s (change in the variable from D3 to D4), and 2010s minus 1980s (change across the entire time period from D1 to D4). For example, a positive value of DMW WCT change represents an increase (e.g., warming), and a negative value represents a decrease (e.g., cooling). Alternative analyses were conducted with differently defined time periods to examine the sensitivity of our analyses to the designated decades. While there were slight variations in the mean values, the overall changes throughout the entire time period were similar in showing both the direction of change (e.g., increase vs decrease) and the magnitude of change.

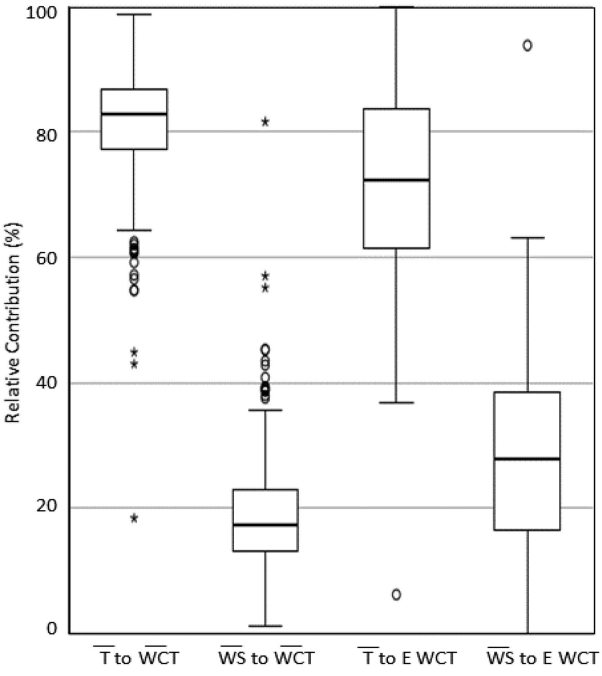

FIG. 3. Boxplot showing the percentage of relative contributions from annual mean air temperature and annual mean WS to variability of annual mean WCT or annual E WCT across the 40-winter time period for each of the 133 surface stations. The length of the box is the interquartile range of the data sample. The line across the central portion of the box represents the sample median. Values between 1.5 and 3.0 times the interquartile range from either end of the box are identified with open circles (o) representing outliers and extreme values are represented by stars (★).

A linear regression model was used to quantify the temporal trends in the annual mean values of WCT, extreme WCT, wind speed, and temperature across the 40-winter time period at each of the 133 stations. The linear regression analysis was implemented using data for each station to determine whether the trend (i.e., slope of the regression) was significantly different from no linear association (i.e., null hypothesis of slope = 0.0; no change in variable across the 40 winters) using an analysis of variance (ANOVA) and p value of <0.05 for significance testing with the rejection of the null hypothesis. Additionally, the determination of standardized coefficients from a multivariate linear regression analysis using data for each station allowed for examination of the relative contributions in the annual mean values of wind speed and temperature to changes in the annual mean values of WCT or extreme WCT across the 40-winter time period.

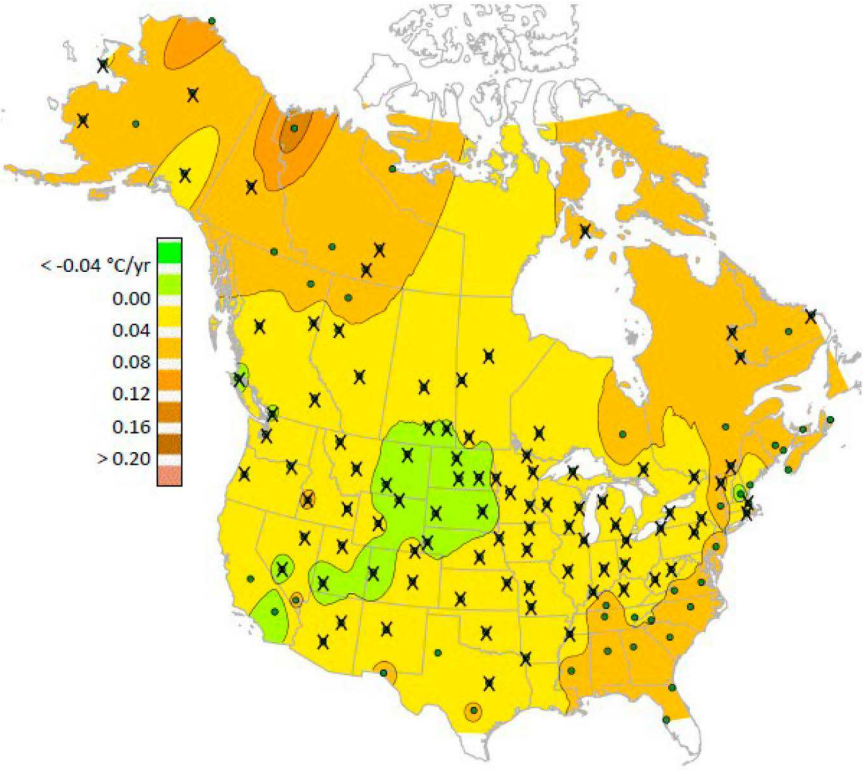

FIG. 4. Trend in annual mean air temperature (°C yr^{-1}) across the 40-winter time period. Stations with air temperature trends statistically different from a slope = 0.0 having a p value < 0.05 are shown with a filled circle, and stations with air temperature trends not statistically different from a slope = 0.0 having a p value > 0.05 are shown with an X.

Last, maps developed for this research were constructed within a geographic information system (GIS) framework using ArcGIS software with a similar approach, described here, to that of Howarth and Laird (2017). Derived parameters from the station data were objectively analyzed with an inverse distance weighting scheme in ArcMap using a variable search radius incorporating 15 data points and an output cell size of 60 km. Maps were developed using a North America Lambert Conformal Conic projection and masked to Canada and the United States.

3. Results

a. *WCT and extreme WCT trends*

Three combinations of changing air temperature and wind speed conditions can lead to a warming of WCT: (i) warming of temperature and decrease in wind speed, (ii) warming of temperature and increase in wind speed, or (iii) cooling of temperature and decrease in wind speed. A cooling in WCT can result from three combinations of changing air temperature and wind speed conditions: (i) cooling of air temperature and increase in wind speed, (ii) cooling of air temperature and decrease in wind speed, or (iii) warming of air temperature and increase in wind speed.

Most locations across Canada and the United States experienced warming of mean WCT across the 40-winter time period from 1979/80 through 2018/19 (Fig. 1). A localized region of the central United States was found to have an overall cooling of mean WCT of less than 0.04°C yr^{-1} The most substantial and statistically significant warming of mean WCT occurred across Alaska and the Canadian Northwest Territories with values between 0.08° and 0.16°C yr^{-1} (i.e., 3.2°–6.4°C during the 40-winter time period). Statistically significant warming of mean WCT also occurred along the East Coast of Canada and the United States at stations such as Cartwright, Newfoundland and Labrador; Boston, Massachusetts; and Philadelphia, Pennsylvania, as well as across the southeastern United States. These regions experienced warming of mean WCT between 0.04° and 0.08°C yr^{-1} Most other regions across Canada and the United States had warming mean WCT during the time period; however, warming trends in these regions were not statistically different from no change in mean WCT (i.e., slope = 0.0°C yr^{-1}) at a p value > 0.05.

Changes in annual extreme WCT across the 40-winter time period were found to have a similar spatial pattern to the mean WCT changes with a localized region of extreme WCT cooling in the southwestern United States and warming of extreme WCT across the remaining areas of Canada and the United States (Fig. 2). This magnitude of extreme WCT

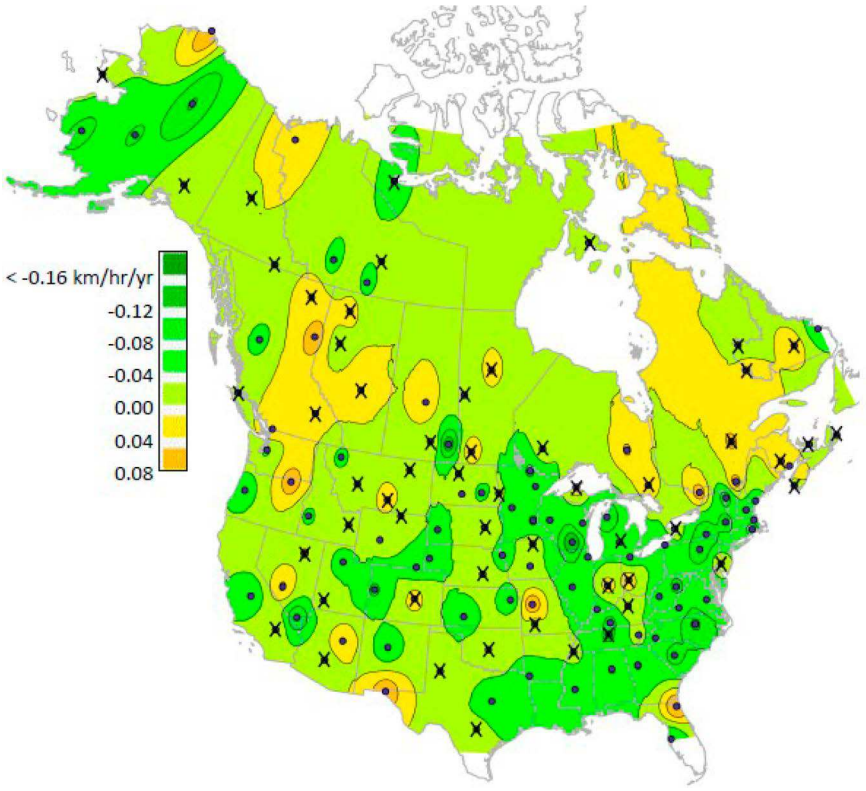

FIG. 5. Trend in annual mean WS (km h^{-1} yr^{-1}) across the 40-winter time period. Stations with WS trends statistically different from a slope = 0.0 having a p value < 0.05 are shown with a filled circle, and stations with WS trends not statistically different from a slope = 0.0 having a p value > 0.05 are shown with an X.

warming was mostly greater than the warming observed in the mean WCT. The most substantial and statistically significant regions of warming in extreme WCT occurred across Alaska and the Canadian Northwest Territories with values ranging from near 0.08° to 0.26°C yr^{-1} (i.e., 3.2°–10.4°C during the 40-winter time period), the Canadian Maritimes, the southeastern United States, and the south-central United States with the largest warming trends in these regions of approximately 0.20°C yr^{-1} (8°C during the 40-winter time period).

The relative contributions of air temperature and wind speed changes to both changes of mean and extreme WCTs during the 40-winter time period were also examined. For most of the 133 surface stations, the variation in air temperatures explains a large portion of the variability in both mean WCT and extreme WCT, with median relative contributions of approximately 83% and 72%, respectively (Fig. 3). At few locations, however, changes in wind speed were found to be more influential than changes in air temperature. Not surprisingly, analyses of trends in annual mean surface air temperatures (Fig. 4) and annual mean wind speeds (Fig. 5) exhibit similar spatial patterns to trends in both annual mean WCT (Fig. 1) and annual extreme WCT (Fig. 2). The most substantial and statistically significant warming of annual mean surface air temperatures occurred in Alaska, Yukon, and Northwest Territories, as well as along the East Coast of the United States and Canada. Across most of these regions, the warming was between 0.04° and 0.08°C yr^{-1} during the 40-winter time period (Fig. 4). Comparatively, a larger number of stations across the United States and Canada experienced statistically significant changes in annual mean wind speeds with most locations having a trend of decreasing wind speed of less than 0.12 km h^{-1} yr^{-1} (4.8 km h^{-1} during the 40-winter time period) and two localized regions in eastern and western Canada having a trend of increasing wind speed of less than 0.08 km h^{-1} yr^{-1} (Fig. 5).

b. *DMW WCT, air temperature, and wind speed*

A warming in DMW WCT occurred at 68% (91) of surface locations across Canada and the United States from the 1980s (D1) to the 1990s (D2) (Fig. 6a). Of these locations, 95% (86) warmed in DMW temperature from D1 to D2, 66% (60) decreased in DMW wind speed, and 60% (55) warmed in DMW temperature and decreased in DMW wind speed. Across all locations where the DMW WCT warmed from D1 to D2, the mean change in DMW WCT was +1.0°C with mean changes in DMW air temperature and wind speed of +0.8°C and −0.6 km h^{-1}, respectively.

From the 1990s (D2) to the 2000s (D3), 78% (104) of surface locations across Canada and the United States warmed

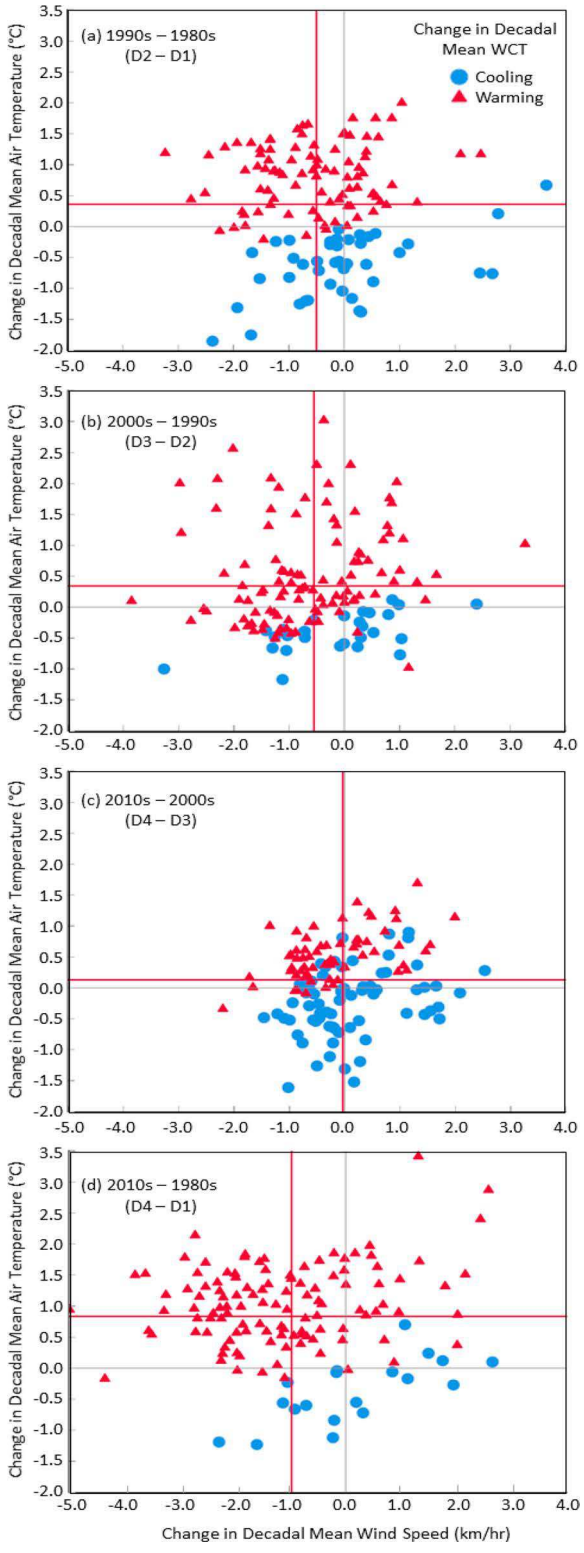

FIG. 6. Change in decadal mean winter WCT (a) from D1 to D2, (b) from D2 to D3, (c) from D3 to D4, and (d) from D1 to D4 with respect to change in decadal mean air temperature (°C) vs change in decadal mean WS (km h^{-1}). Locations that warmed in decadal mean winter WCT are represented by red triangles. Locations that cooled in decadal mean winter WCT are represented by blue circles. Red reference lines show mean values of changes in decadal winter air temperature and decadal winter WS for each time period.

in DMW WCT (Fig. 6b). Of these locations, 75% (78) warmed in DMW temperature, 71% (74) decreased in DMW wind speed, and 46% (48) both warmed in DMW temperature and decreased in DMW wind speed. Across all locations where the DMW WCT warmed from D2 to D3, the mean change in DMW WCT was +1.5°C with mean changes in DMW air temperature and wind speed of +0.9°C and −1.1 km h^{-1}, respectively.

From the 2000s (D3) to the 2010s (D4), 47% (63) of surface locations across Canada and the United States warmed in DMW WCT (Fig. 6c). Of these locations, 92% (58) warmed in DMW temperature, 65% (41) decreased in DMW wind speed, and 57% (36) both warmed in DMW temperature and decreased in DMW wind speed. Across all locations where the DMW WCT warmed from D3 to D4, the mean change in DMW WCT was +1.5°C with mean changes in DMW air temperature and wind speed of +1.2°C and −0.2 km h^{-1}, respectively.

The DMW WCT cooled at 32% (42) of surface locations from D1 to D2 (Fig. 6a). Of these locations, 95% (40) cooled in DMW temperature and 41% (17) experienced increasing DMW wind speed. There were 0.1% (2) of locations that both warmed in DMW temperature and increased in DMW wind speed, and 60% (25) of locations cooled in DMW temperature and decreased in DMW wind speed. Across all locations where the DMW WCT cooled from D1 to D2, the mean change in DMW WCT was −0.8°C with mean changes in DMW air temperature and wind speed of −0.63°C and −0.03 km h^{-1}, respectively.

From D2 to D3, 22% (29) of locations cooled in DMW WCT (Fig. 6b). Of the locations that cooled in DMW WCT, 90% (26) of locations cooled in DMW temperature, 45% (13) increased in DMW wind speed, and 35% (10) of locations both cooled in DMW temperature and increased in DMW wind speed. Across all locations where the DMW WCT cooled from D2 to D3, the mean change in DMW WCT was −0.3°C with mean changes in DMW air temperature and wind speed of −0.4°C and −0.2 km h^{-1}, respectively.

From D3 to D4, 53% (70) of locations cooled in DMW WCT (Fig. 6c). Of the locations that cooled in DMW WCT, 69% (48) of locations cooled in DMW temperature, 43% (30) increased in DMW wind speed, and 24% (17) of locations both cooled in DMW temperature and increased in DMW wind speed. Across all locations where the DMW WCT cooled from D3 to D4, the mean change in DMW WCT was −0.5°C with mean changes in DMW air temperature and wind speed of −0.2°C and 0.1 km h^{-1}, respectively.

Although some locations experienced both a warming and cooling of DMW WCT during portions of the 40-winter time period, the large majority of locations experienced an overall warming in WCT (Fig. 6d). When considering changes in

TABLE 1. DMW WCT changes with changes in DMW temperatures (TMP) and wind speeds (WS) across the 133 surface stations located in Canada and the United States.

Time period	Stations with DMW WCT warming (%)	DMW WCT change @ warming locations (°C)	DMW TMP change @ warming locations (°C)	DMW WS change @ warming locations (km h^{-1})	Stations with only DMW TMP warming (%)	Stations with only DMW WS decrease (%)	Stations with DMW TMP warming and WS decrease (%)
D1–D2	68	+1.0	+0.8	−0.6	95	66	60
D2–D3	78	+1.5	+0.9	−1.1	75	71	46
D3–D4	47	+1.5	+1.2	−0.2	92	65	57
(Total) D1–D4	86	+1.4	+1.0	−1.2	86	76	65
Time period	Stations with DMW WCT cooling (%)	DMW WCT change @ cooling locations (°C)	DMW TMP change @ cooling locations (°C)	DMW WS change @ cooling locations (km h^{-1})	Stations with only DMW TMP cooling (%)	Stations with only DMW WS increase (%)	Stations with DMW TMP cooling and WS increase (%)
D1–D2	32	−0.8	−0.6	−0.0	95	41	36
D2–D3	22	−0.3	−0.4	−0.2	90	45	35
D3–D4	53	−0.5	−0.2	+0.1	69	43	24
(Total) D1–D4	14	−0.4	−0.4	+0.2	79	47	26

DMW WCT across the entire time period (i.e., from D1 to D4), 86% (114) of locations had warming of DMW WCT, 86% (115) of locations had air temperatures warm, 76% (101) of locations experienced a decrease in wind speeds, and 65% (87) of locations had both air temperatures warm and a decrease in wind speeds. A summary of the DMW WCT, temperature, and wind speed changes is provided in Table 1.

The coldest DMW WCT values for D1, D2, D3, and D4 were located in northern Canada, north of Hudson Bay (Fig. 7). Mean values of WCT in this area ranged from −28°

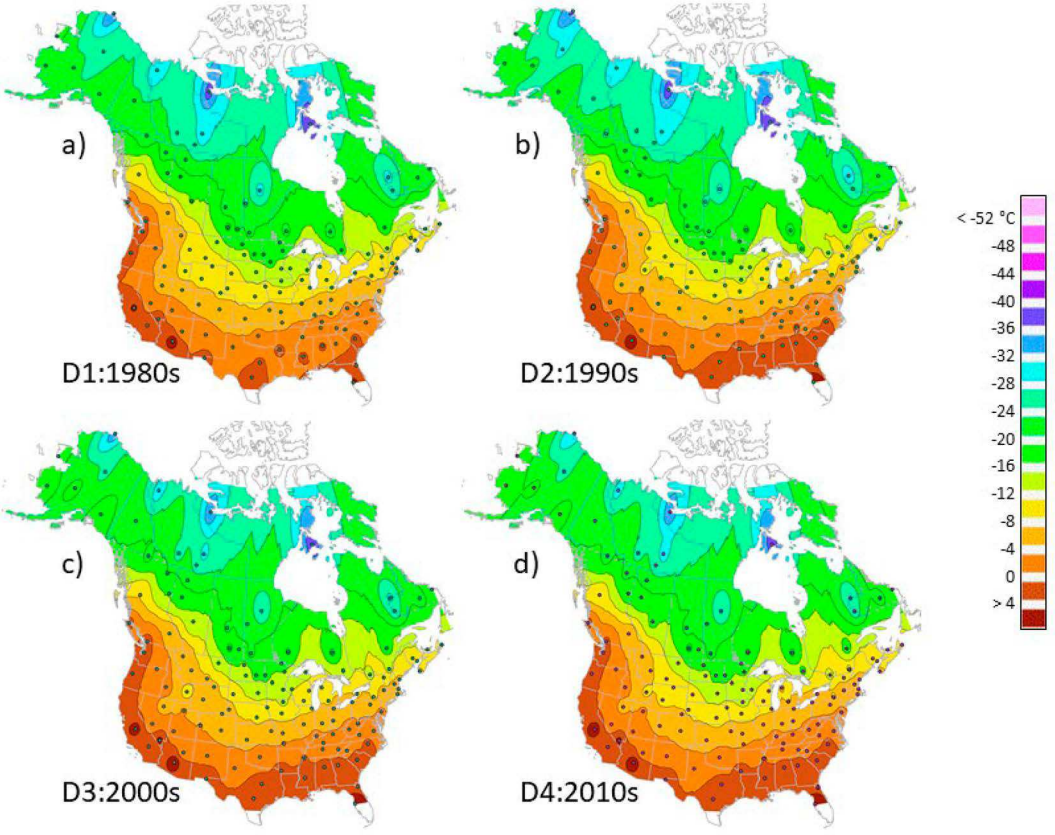

FIG. 7. Decadal mean winter WCT (°C) for (a) D1, (b) D2, (c) D3, and (d) D4. Station locations are shown with filled circles.

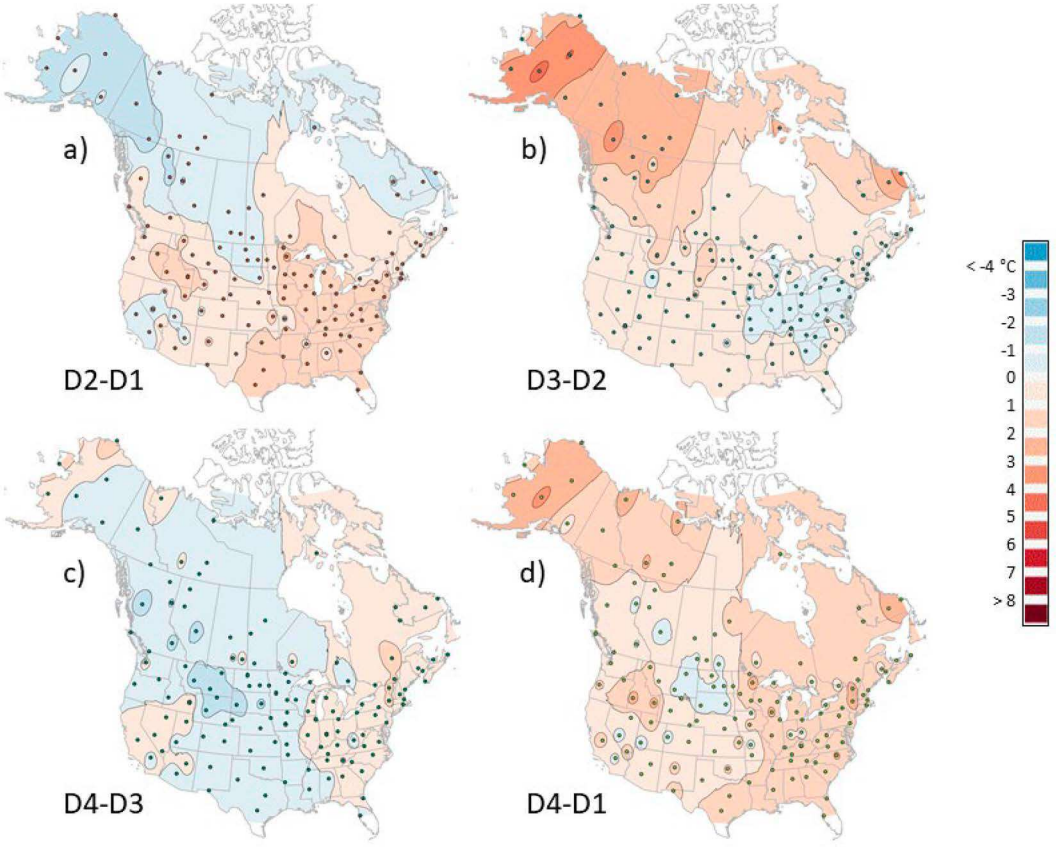

FIG. 8. Change in decadal mean winter WCT (°C) from (a) D1 to D2, (b) D2 to D3, (c) D3 to D4, and (d) D1 to D4 (change across the entire 40-winter time period). Positive values indicate a warming of the decadal mean winter WCT, and negative values indicate a cooling of decadal mean winter WCT.

to −36°C. Alaska had DMW WCT values ranging from near −36°C in the north to about −16°C across southern portions of the state. Cold WCT extended equatorward through the interior continent with the Rocky Mountains to the west. Below freezing (0°C), DMW WCT values were found across all of Canada and most of the United States, except for southernmost locations and along the West Coast throughout California, western Oregon, and western Washington. Mean values of WCT were generally −8° to −12°C across most of the states of Colorado and Nebraska. In eastern Canada and the eastern United States, the spatial pattern of DMW WCT was zonally oriented with slightly warmer WCT extending northward into the Great Lakes region, likely indicating winter airmass modification by the Great Lakes. The states of Michigan and New York had DMW WCT from −4° to −12°C, and much of the southeastern United States had mean WCT values warmer than −4°C.

From D1 to D4, the DMW WCT warmed over nearly all of Canada and the United States, with the exception of isolated locations in the southwest United States and the central plains region including Montana, North Dakota, and South Dakota (Fig. 8d). The greatest warming during this period occurred in northeastern Canada and Alaska, which warmed 2°–4°C. From D1 to D2, DMW WCT warmed by 1°–2°C in much of the United States and southeastern Canada and cooled in Alaska and northern Canada by 1°–2°C (Fig. 8a). From D2 to D3, warming of DMW WCT occurred over most regions by 1°–4°C, while a portion of the eastern United States cooled by about 1°C (Fig. 8b). From D3 to D4, DMW WCT cooled by 1°–2°C over most of Canada and the United States. Slight warming of 1°–2°C occurred in western Alaska, the southwestern United States, and most of eastern North America.

The spatial distributions of DMW air temperatures had a similar pattern to that of DMW WCT, although air temperatures were typically 8°–12°C warmer (Fig. 9). DMW air temperatures below freezing (0°C) extended southwestward into northern Nevada, as far south as Kansas in the U.S. Great Plains region, and eastward to the mid-Atlantic coastal region. The changes in DMW air temperatures across decades were generally smaller than changes in WCT, although the spatial patterns of these changes are similar (Fig. 10). From D1 to D4 (i.e., change across the entire four decades), the DMW air temperatures warmed over most of Canada and the United States, with the greatest warming (2°–3°C) in eastern Canada and the region of Alaska and northwestern Canada (Fig. 10d).

From D1 to D2, the DMW temperatures warmed by 1°–2°C across most of the United States and southeastern Canada,

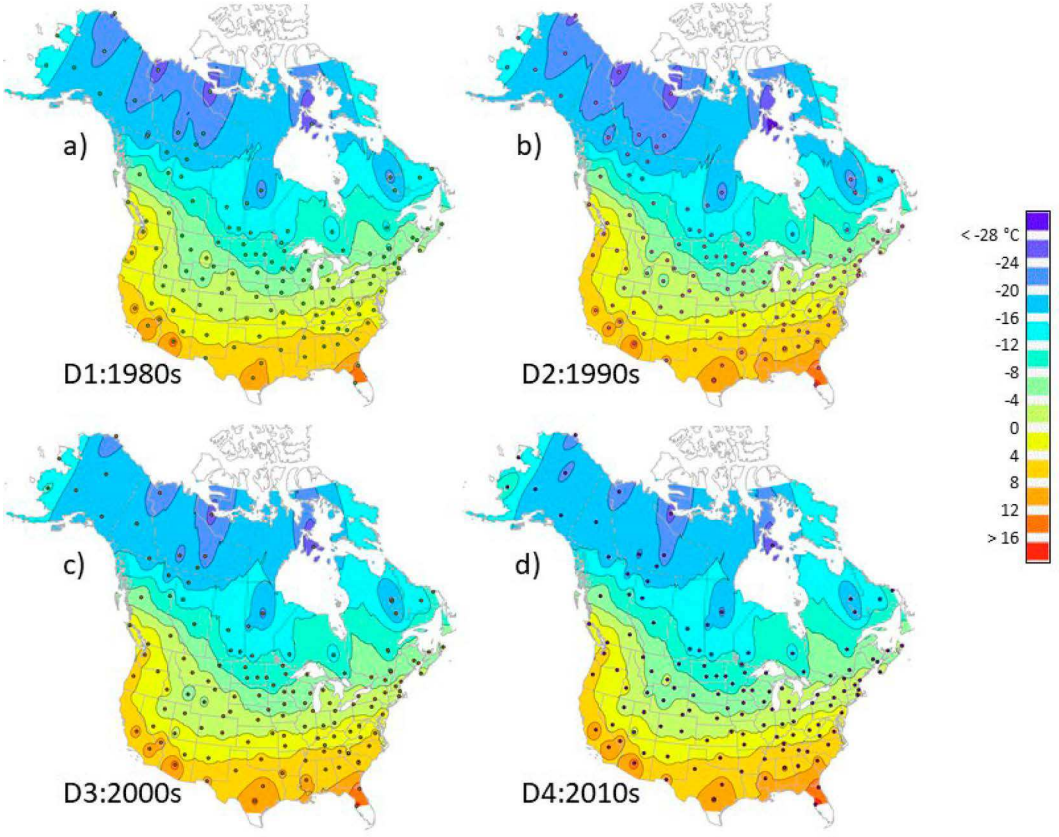

FIG. 9. Decadal mean winter air temperatures (°C) for (a) D1, (b) D2, (c) D3, and (d) D4.

with the greatest warming over the eastern half of the United States (Fig. 10a). During this time period, DMW air temperatures cooled by less than 2°C in Alaska and northern Canada. From D2 to D3, DMW temperatures cooled by less than 1°C in the eastern United States and some of the western United States and warmed by less than 3°C across the remaining areas, especially in eastern Canada and Alaska (Fig. 10b). From D3 to D4, the interiors of Canada and the United States experienced a cooling of less than 1°C for DMW air temperatures (Fig. 10c). A portion of eastern Alaska and along the West Coast in southern British Columbia and the states of Washington and Oregon also had cooling of less than 1°C. Most other regions experienced warming DMW air temperatures of less than 1°C.

DMW wind speeds displayed greater spatial heterogeneity than air temperature and WCT (Fig. 11). DMW wind speeds were typically faster over the eastern two-thirds of the United States and Canada with the fastest wind speeds (16–20 km h^{-1}) over the central United States. Slower DMW wind speeds (4–12 km h^{-1}) were observed west of the Rocky Mountains. Across the entire period (i.e., from D1 to D4), the DMW wind speeds slowed by less than 4 km h^{-1} over much of the United States and Canada (Fig. 12d). From D1 to D2, DMW wind speeds decreased over much of Canada and the eastern United States by less than 2 km h^{-1}. DMW wind speeds increased by less than 3 km h^{-1} in the western half of the United States and in southwestern Canada (Fig. 12a). From D2 to D3, DMW wind speeds decreased by less than 3 km h^{-1} across much of the United States and Canada, with some localized exceptions of increasing wind speeds, generally less than 1 km h^{-1}, in eastern Canada (Fig. 12b). A small decrease of less than 1 km h^{-1} was observed across most of the United States and central Canada from D3 to D4 (Fig. 12c) and a widespread region over western Canada and Alaska experienced increases of DMW wind speeds of less than 2 h^{-1} during this time period.

c. *Decadal extreme WCT*

Decadal extreme WCT was determined using the distribution of hourly WCT values within each decade (D1, D2, D3, or D4). Extreme WCT (Fig. 13) for each decade was generally found to be 10°–30°C colder than the DMW WCT (Fig. 7) across the 133 stations with a mean difference of approximately 20°C. Values of extreme WCT below freezing (0°C) were found across all of Canada and the United States and extended into the range of −44°C to near −58°C for most of northern Canada and Alaska (Fig. 13). The minimum of the extreme WCT values was −58°C and occurred in both Kugluktuk, Nunavut, Canada (north-central Canada), and Coral Harbor (north of Hudson Bay) during several of the defined decades. The spatial distributions of the extreme WCT (Fig. 13) clearly show the areas corresponding

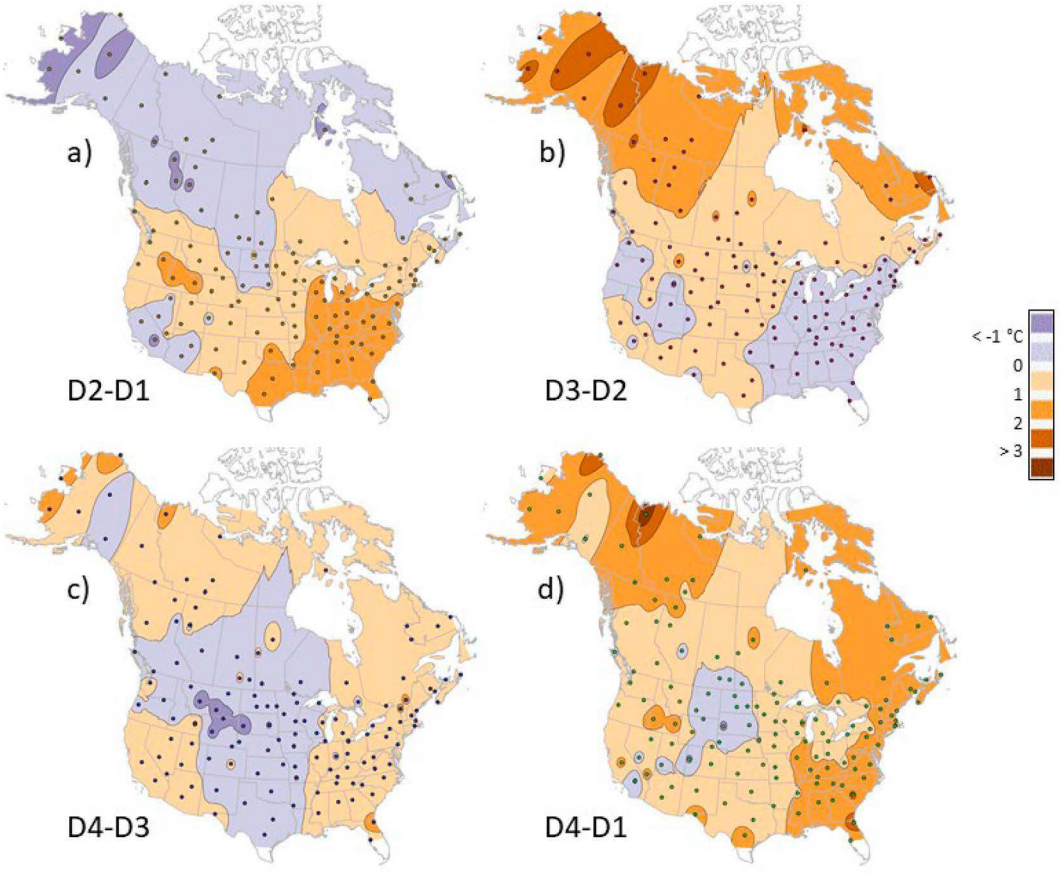

FIG. 10. Change in decadal mean winter air temperatures (°C) from (a) D1 to D2, (b) D2 to D3, (c) D3 to D4, and (d) D1 to D4 (change across the entire 40-winter time period). Positive values indicate a warming of the decadal mean winter air temperatures, and negative values indicate a cooling of decadal mean winter air temperatures.

to Arctic airmass development over north-central Canada and the typical pathway of Arctic airmass intrusion southward into the central Great Plains region of the United States during intense cold-air outbreaks (e.g., Brunnschweiler 1952; Cellitti et al. 2006; Hartig et al. 2023).

Extreme WCT warmed over most of Canada and the United States during the four-decade time period (Fig. 14d); however, certain regions experienced short-term cooling of extreme WCT within that time period (Figs. 14a–c). From D1 to D2, extreme WCT experienced warming at 68% (91) of surface locations across Canada and the United States (Fig. 14a). From D1 to D2, extreme WCT warmed by 1°–3°C in much of the United States, especially in the southeast and south-central plains of the United States. Extreme WCT cooled in eastern and western Canada by 1°–2°C. From D2 to D3, 95% (126) of surface locations across Canada and the United States had warming of extreme WCT (Fig. 14b). The greatest warming in extreme WCT was observed in western Canada and Alaska (3°–7°C), as well as the northwest United States. In central and eastern Canada, the coldest 1% of WCT warmed by 1°–3°C. From D3 to D4, only 34% (45) of surface locations experienced warming of extreme WCT (Fig. 14c). The magnitude of cooling was relatively small at stations, ranging from 1° to 4°C with the mean change in extreme WCT for these locations of −1.4°C. The south-central United States, the Great Lakes region, and over Oregon and western Idaho experienced the greatest magnitude of cooling with decreases in extreme WCT of 2°–4°C during D3 to D4.

Given the widespread warming of extreme WCT from D2 to D3 (Fig. 14b), as well as regions across Canada and the United States alternating between warming and cooling during the periods of D1 to D2 (Fig. 14a) and D3 to D4 (Fig. 14c), an overall warming of extreme WCT occurred over the entire four decades across nearly all of Canada and the United States (Fig. 14d). From D1 through D4, 97% (129) of surface locations warmed in extreme WCT. The greatest warming of extreme WCT (3°–5°C) occurred across the central and southeastern United States and most of Alaska. Only a slight cooling of extreme WCT occurred from D1 to D4, generally less than 1°C, and was limited to a few isolated locations across Canada and the United States.

4. Discussion and conclusions

WCT is a widely recognized biometeorological variable that has been used in previous studies to examine relationships to

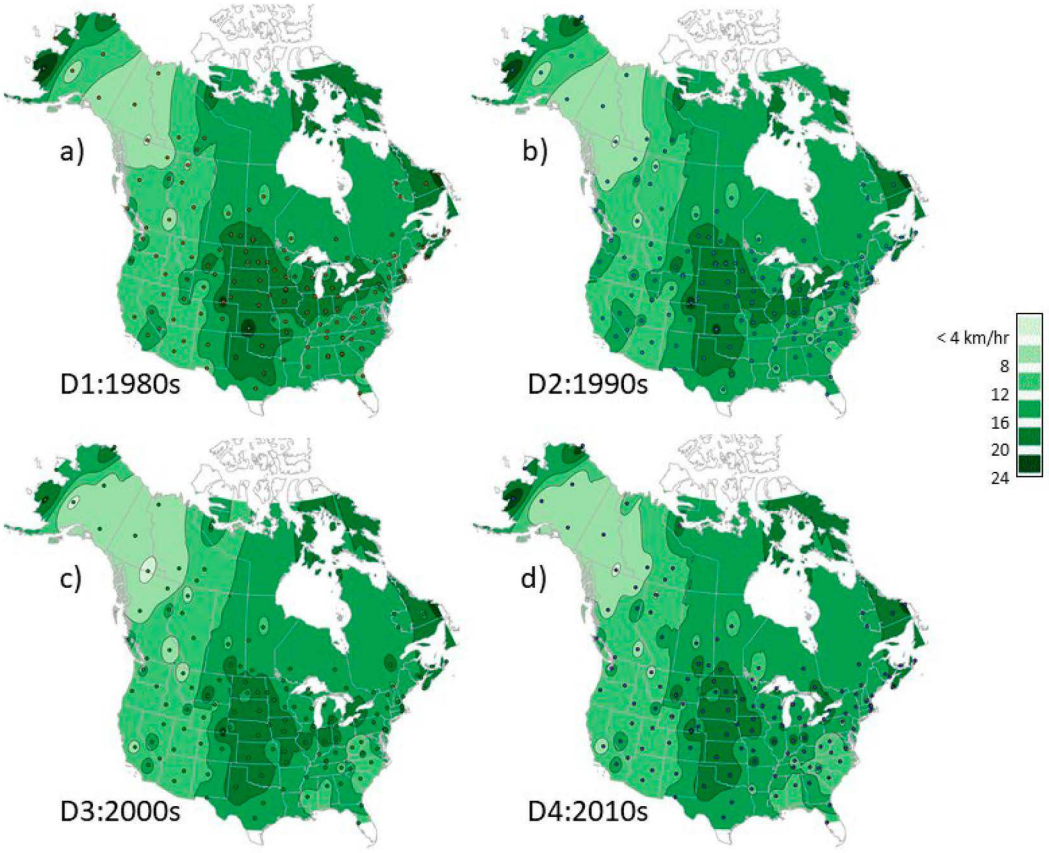

FIG. 11. Decadal mean winter WS (km h^{-1}) for (a) D1, (b) D2, (c) D3, and (d) D4.

human health, daily emergency ambulance services, seasonal clothing demands, trends in tourism, winter highway traffic volume, and types of occupational construction accidents. WCT could also be used to understand the attribution of variations in extreme cold-season weather since WCT is derived from both air temperature and wind speed (NASEM 2016). WCTs across Canada and the United States were examined during the meteorological winter months (December–February) from 1979/80 through 2018/19, with a focus on spatial and temporal changes of the mean and extreme WCTs. The identified changes in WCT across Canada and Alaska from the current study share similarities to the results of Keimig and Bradley (2002) that focused on afternoon WCTs across a larger range of months (October–April) and an earlier time period (1953–93), as well as the results of Mekis et al. (2015) that focused on severe WCT frequency across Canada from 1953 to 2012.

The current study has expanded the understanding of changing WCT by examining decadal variations and trends of both the mean WCT and extreme WCT. The primary conclusions from the current research include the following:

- The most substantial and statistically significant warming of mean WCT occurred across Alaska and the Canadian Northwest Territories with values between 0.08° and 0.16°C yr^{-1} (i.e., 3.2°–6.4°C during the 40-winter time period). Statistically significant warming of mean WCT was also located along the East Coast of Canada and the United States, as well as across the southeastern United States.
- Extreme WCT for each decade was generally found to be 10°–30°C colder than the mean WCT, with a mean difference of approximately 20°C. Extreme WCT warmed at a greater rate than mean WCT. The most substantial and statistically significant regions of warming in extreme WCT occurred across Alaska and the Canadian Northwest Territories with values ranging from near 0.08° to 0.26°C yr^{-1} (i.e., 3.2°–10.4°C during the 40-winter time period).
- Most locations in Canada and the United States experienced an overall warming in WCT. Across the four decades, 86% of locations had warming of DMW WCT, 86% of locations had air temperatures warm, 76% of locations experienced a decrease in wind speeds, and 65% of locations had both air temperatures warm and a decrease in wind speeds.
- During the four decades, the coldest mean WCT values were located in northern Canada, north of Hudson Bay. DMW values of WCT in this area ranged from −28° to −36°C. Alaska had DMW WCT values ranging from near −36°C in the north to about −16°C across southern portions of the state. Below freezing (0°C), DMW WCT values were found across all of Canada and most of the United

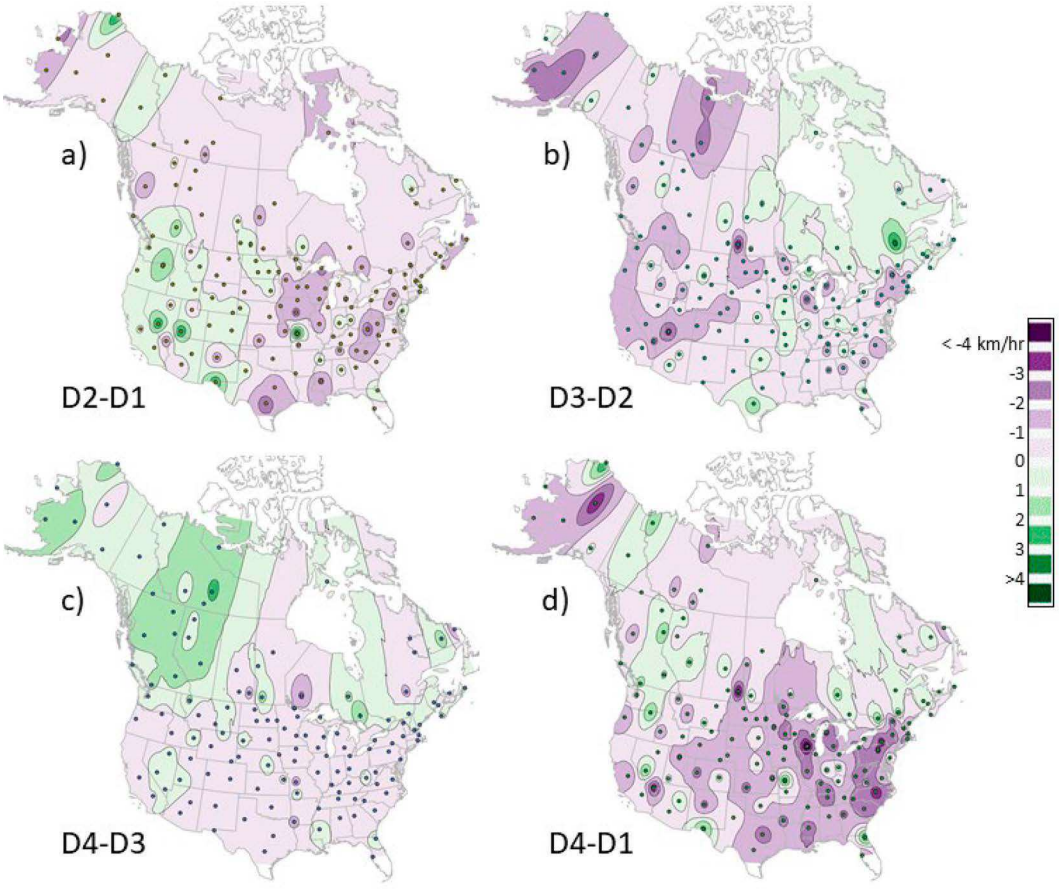

FIG. 12. Change in decadal mean winter WS (km h^{-1}) from (a) D1 to D2, (b) D2 to D3, (c) D3 to D4, and (d) D1 to D4 (change across the entire 40-winter time period). Positive values indicate an increase in WS, and negative values indicate a decrease in WS.

States, except for southernmost locations and along the West Coast of the United States.

- Similar to Keimig and Bradley (2002), the current study determined the primary contribution to warming of mean and extreme WCTs was from warming air temperatures with a smaller influence from decreasing wind speeds. For most of the 133 surface stations, the variation in air temperatures was found to explain a large portion of the variability of both mean WCT and extreme WCT with median relative contributions of approximately 83% and 72%, respectively.

The warming in both mean and extreme WCT values suggests that intense cold-air outbreaks (CAOs) are warming and/or becoming less frequent. In addition, the changes in mean and extreme WCTs across the United States support findings that extreme CAOs are less frequent and less severe than in previous decades (e.g., Peterson et al. 2013; Sillmann et al. 2013a,b; Kunkel et al. 2015; Screen et al. 2015) and that CAOs may have less of an equatorward extent than in the past (e.g., Smith and Sheridan 2020). Although examining the association of the trends of mean and extreme WCT values with changes in the frequency, intensity, and equatorward extent of extreme CAOs is beyond the scope of the current study, this is a topic of future research that can address the relation of large-scale atmospheric circulation and dynamics to warming mean and extreme WCTs.

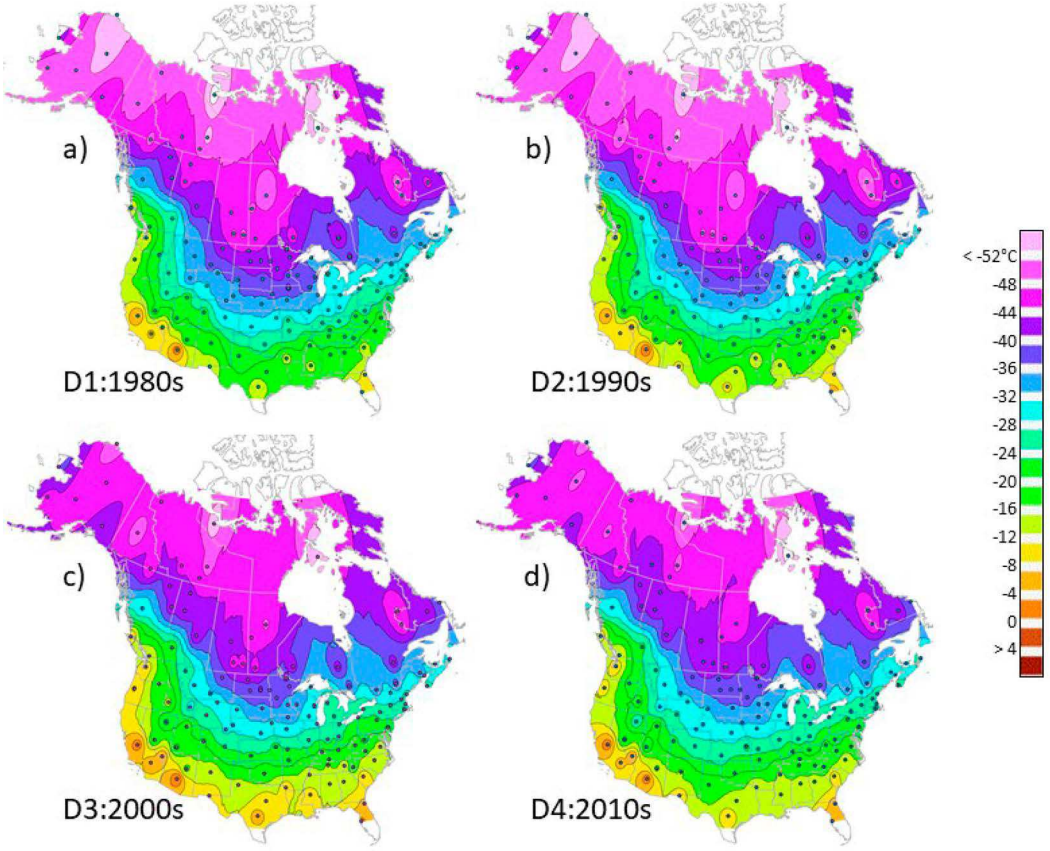

FIG. 13. Decadal extreme WCT (°C; coldest 1%) for (a) D1, (b) D2, (c) D3, and (d) D4.

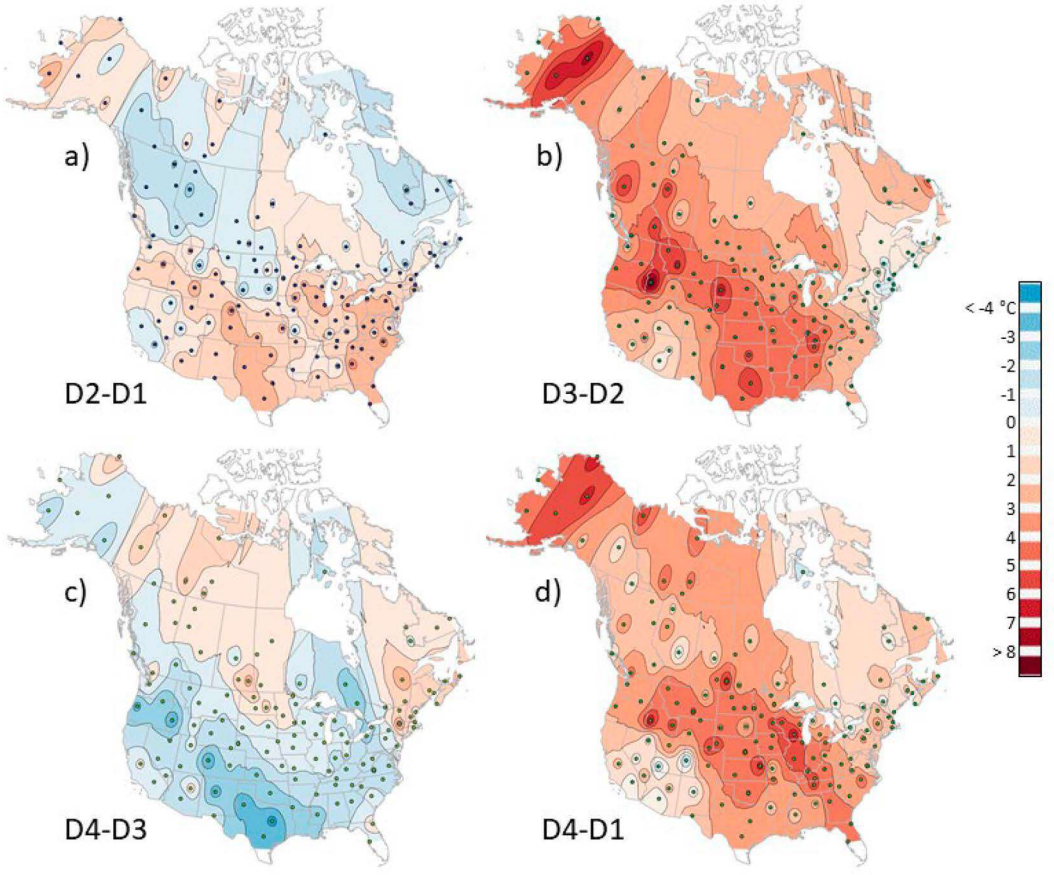

FIG. 14. Change in the decadal extreme WCT (°C; coldest 1%) from (a) D1 to D2, (b) D2 to D3, (c) D3 to D4, and (d) D1 to D4 (change across the entire 40-winter time period). Positive values indicate a warming in the E WCT, and negative values represent a cooling of the E WCT.

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