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Trends in weather type frequencies across North America

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While 20th century changes in many individual meteorological variables are well documented, the trends in multivariate synoptic-scale air masses—or weather types—largely remain unexplored. Utilizing a recently developed gridded weather typing classification system, this research investigates the changes in the frequency of weather types (WTs) across North America, 1979–2017. Averaged across the study domain as a whole, Humid Warm WTs are occurring 22 more days per year, while Dry Warm WTs have increased by 10 days/year. These increases are offset mostly by decreased frequency of Dry Cool (–17 days/year) and Cool WTs (–21 days/year). The largest absolute changes are in the Canadian Archipelago, where the Warm WT is occurring 42 more days/year and the Cool WT is occurring 48 fewer times per year. In western Canada all humid types are occurring more frequently, including a Humid Cool type that is occurring 16 more days/year. The Desert Southwest US and northern Mexico show significant increases in Dry Warm WTs (+33 to +40 days/year). Cold front and warm front passages show increases in most of the US and decreases in most of Canada. Describing these secular changes to the frequency of intuitive weather types may be an effective means of communicating these climate trends to policymakers and the general public, especially considering their large magnitude.

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INTRODUCTION

During the past few decades the topic of climate change has received ample attention in the scientific, public and political arenas. Over the past century, the global average temperature has risen 0.85 °C,¹ with the strongest impact felt disproportionately in the Arctic region.^{2,3} Across the United States, the average temperature has increased about 1 °C since 1895, with the majority coming since 1970, and the rate of the rise has been increasing over that time.⁴ Rising temperatures have ushered in greater evaporation rates, giving rise to an overall increase in land-based precipitation in the mid-latitudes,¹ though with much greater spatial variability than the changes generally noted with temperature.

Among individual meteorological variables, most climate change research is focused on the trends in different metrics (means, maximums, minimums, extremes, etc.) of temperature and/or precipitation. Beyond this, however, trends in other variables have been noted. For instance, the absolute moisture content of the atmosphere—the link between rising temperatures and increased precipitation—has also correspondingly risen^{5,6} as relative humidity has stayed steady.⁶ Additionally, sea-level pressure has shown significant changes in low-latitude regions,⁷ wind speeds have generally declined,⁸ and many other atmospheric variables and phenomena have displayed significant changes in frequency or magnitude⁴ in recent decades.

This multivariate nature of the weather at any given location naturally underlies the concept of an air mass or weather type—a *category* of weather that defines the holistic atmospheric situation at a particular time. As noted in Lee and Sheridan (2015),⁹ this definition of a weather type is distinctly different from regional-scale atmospheric circulation pattern classifications, which are also commonly given this same moniker. Weather type categorizations have proven very useful in applied climatological research

examining the variability of numerous climate-related outcomes.⁹ Among the most well-studied outcomes are those concerning multivariate weather impacts on human mortality and morbidity,¹⁰ as it is the entire weather situation to which a person is exposed that will impact their health and well-being more-so than an individual weather element.¹¹ The most commonly used categorization of surface weather types is the Spatial Synoptic Classification (SSC),¹² which has been used to examine historical and future changes in both weather type frequency and human mortality.^{13–15} However, a more recent development in weather typing classification is the gridded weather type classification (GWTC).¹⁶ Since its development, it has been shown to relate to human health as well,¹¹ however, due to its relative infancy, long-term trends in the GWTC weather types have not yet been examined.

Thus, since temperature and precipitation trends over the last few decades are well-researched, but a changing climate can manifest itself in myriad ways, the simple aim of this research is to examine the changes in GWTC weather type (WT; Table 1) frequency over North America since 1979.

RESULTS

In the results below, the percentage-point change (%; from 1979–2017) and the number of occurrences (days) per year for each weather type are discussed. Separate analyses were also computed for traditional meteorological seasons. While calculated at individual points, for simplicity, results were also summarized for separate regions (Fig. 1) and discussed below.

Throughout most of the US and Canada, all cool WTs [Dry Cool (DC), Cool (C), Humid Cool (HC)] show substantial decreases, while all warm WTs [Dry Warm (DW), Warm (W), Humid Warm (HW)] show marked increased frequency from 1979–2017 (Fig. 2). In

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terms of magnitude, there is only a slight change in the frequency of transitional WTs [Cold Front Passage (CFP) and Warm Front Passage (WFP)], with both increasing in frequency in much of the US (significantly in parts of the West) and decreasing over all but the extreme western portions of Canada. On average across the study domain, of the 11 GWTC weather types, HW and DW showed the most widespread significant trends towards more frequent occurrences (+6.1 and +2.9%, respectively), at the expense of C and DC (−5.7 and −4.5% respectively), though with substantial geographic variability. On average across the domain of study, this equates to a net gain of +22 HW days/year (between the start and end of the record) and +10 DW days/year, at the

expense of −21 Cool days/year and −17 DC days/year (Fig. 2). Warm WT days also increased by 3.4% (+13 days/year) on average. Combined, across the domain as a whole, the three warm WTs have increased by 12.4% (+45 days/year) largely at the expense of the three cool WTs, decreasing by −11.8% (−43 days/year) over the 39-year period. Seasonally, the largest changes are in autumn, when WT frequencies change an average of over 37 days/season (Fig. 3). When year-over-year occurrences of WTs are examined, it should be noted that many of these trends are non-linear, especially the increase in HW and the decrease in DC (Fig. 4).

Spatially, the most widespread changes are noted in north-eastern Canada (Fig. 5), around Hudson Bay and the Canadian archipelago (Regions 7 and 9), especially with the HW, C and DC weather types. Here, frequency changes are on the order of +/− 23 to 30 days/year, with an average change of nearly +42 days/year for the Warm WT and −48 days/year (−13.1%) for the Cool WT across Region 9—the largest change of any WT in any region. Further, many of these changes are highly non-linear (Fig. S6). In these same regions, on a seasonal basis, the greatest magnitude of frequency changes comes in autumn (September–November) and winter (December–February). In autumn these areas have seen decreases of 6–14 days/season of each of the three cool WTs (HC, C and DC) and gaining 6 to 12 days/season of each of the warm WTs (HW, W, and DW) within that three month period (Table S3). In winter, the changes are heavily concentrated in extreme north-central Canada and the Canadian Archipelago (Region 9), where each of the cool and warm WTs change by at least +/− 8 days/season, with the Warm WT increasing by 17 days/season (about 40% of the annual change, Table S4). While frequency changes of these WTs in summer (June–August; Table S2) and spring (March–May; Table S1)—especially with decreased Cool WTs—also largely

Table 1. The 11 GWTC Weather Types, abbreviations and descriptions (relative to seasonal and geographical normal)

WT	Description
HC	Humid and Cool
H	Humid (normal temp)
HW	Humid and Warm
C	Cool (normal humidity)
S	Seasonal
W	Warm (normal humidity)
DC	Dry and Cool
D	Dry (normal temp)
DW	Dry and Warm
CFP	Cold Front Passage
WFP	Warm Front Passage

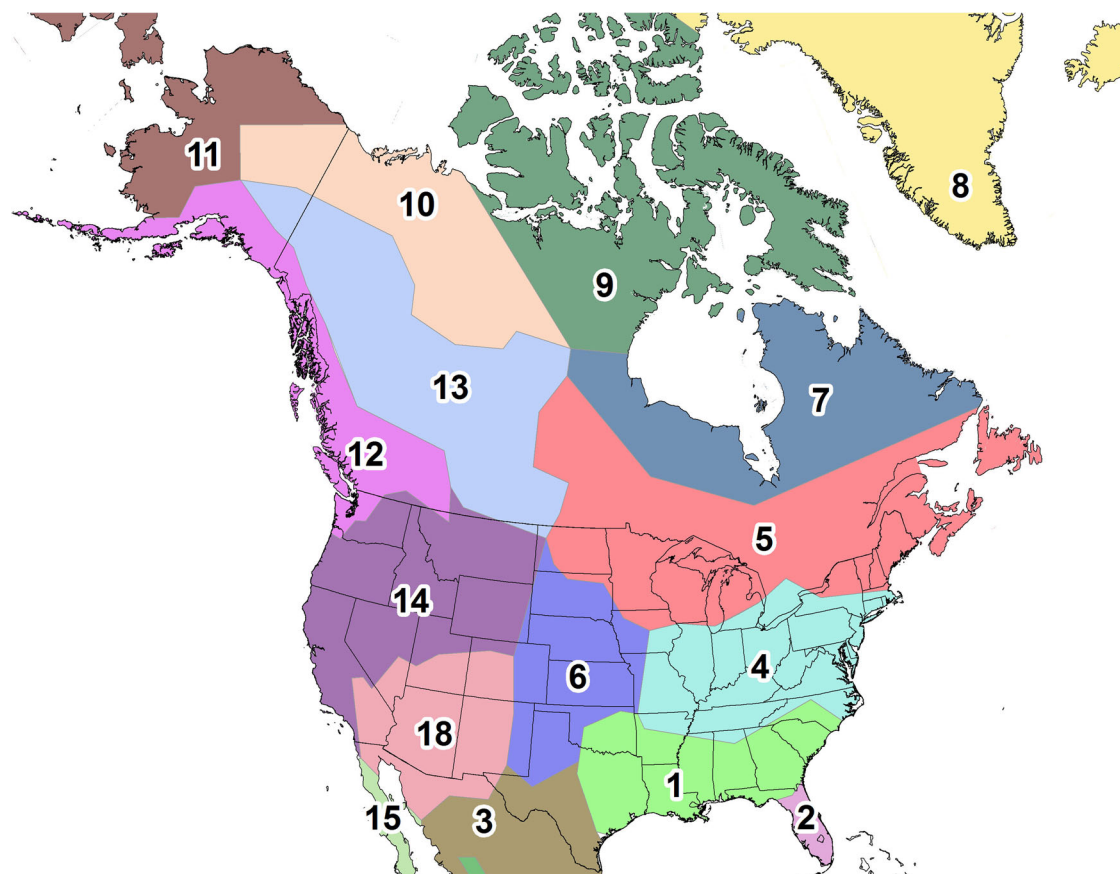


Fig. 1 The regions discussed in this research. Note that regions 16 and 17 are not included as they are located south of the study domain

REGION	HC	H	HW	C	S	W	DC	D	DW	CFP	WFP
1	-17	-15	13	-14	-12	9	-6	3	19	2	3
2	5	8	16	-13	-16	-2	-3	-11	2	0	2
3	-14	-13	16	-23	-29	12	-2	7	26	1	2
4	-11	-16	21	-16	-4	5	-14	8	19	0	2
5	-4	3	23	-15	2	11	-22	-1	9	-3	-3
6	-11	-13	9	-13	-10	3	-8	10	22	5	1
7	-10	1	23	-28	7	14	-29	7	19	-4	-3
8	-8	4	15	-20	3	19	-22	-2	9	-1	-1
9	-19	5	30	-48	-1	42	-31	-11	31	-2	-2
10	-1	12	16	-23	5	16	-22	-4	5	-2	-1
11	-9	4	16	-18	1	14	-16	-2	6	0	0
12	16	13	7	3	-4	-9	-4	-11	-16	0	1
13	16	21	16	-4	-2	-4	-16	-12	-14	-2	-1
14	7	4	6	-2	-7	-5	-4	-4	1	2	4
15	-22	-17	-15	-11	-10	4	4	15	40	1	2
18	-8	-18	-4	-12	-16	4	-1	11	33	5	3
AVG	-6	4	22	-21	-10	13	-17	-7	10	-2	0

Fig. 2 Annual change in the number of occurrences (per year) of each WT in each region, 1979 to 2017. Note that regions 16 and 17 are not included (as they are outside of the study domain). Darker reds (blues) indicate progressively more positive (negative) changes

	HC	H	HW	C	S	W	DC	D	DW	CFP	WFP	TOTAL
WINTER	-1.5	0.6	3.9	-4.2	-0.9	3.7	-5.1	-1.1	3.5	-0.3	-0.1	24.9
SPRING	-0.3	0.6	1.9	-3.8	-1.4	1.5	-2.3	-0.7	2.1	-0.1	0.1	14.7
SUMMER	-0.9	2.0	6.4	-4.5	-4.6	2.3	-2.5	-2.9	0.7	-1.0	-0.2	28.2
AUTUMN	-3.0	0.6	8.2	-7.6	-3.5	4.6	-4.2	-1.7	3.4	-0.4	-0.2	37.5

Fig. 3 Domain-wide average change in the number of occurrences per season for each WT, 1979 to 2017. The rightmost (Total) column is the summed absolute value of the changes for each season. Darker reds (blues) indicate progressively more positive (negative) changes

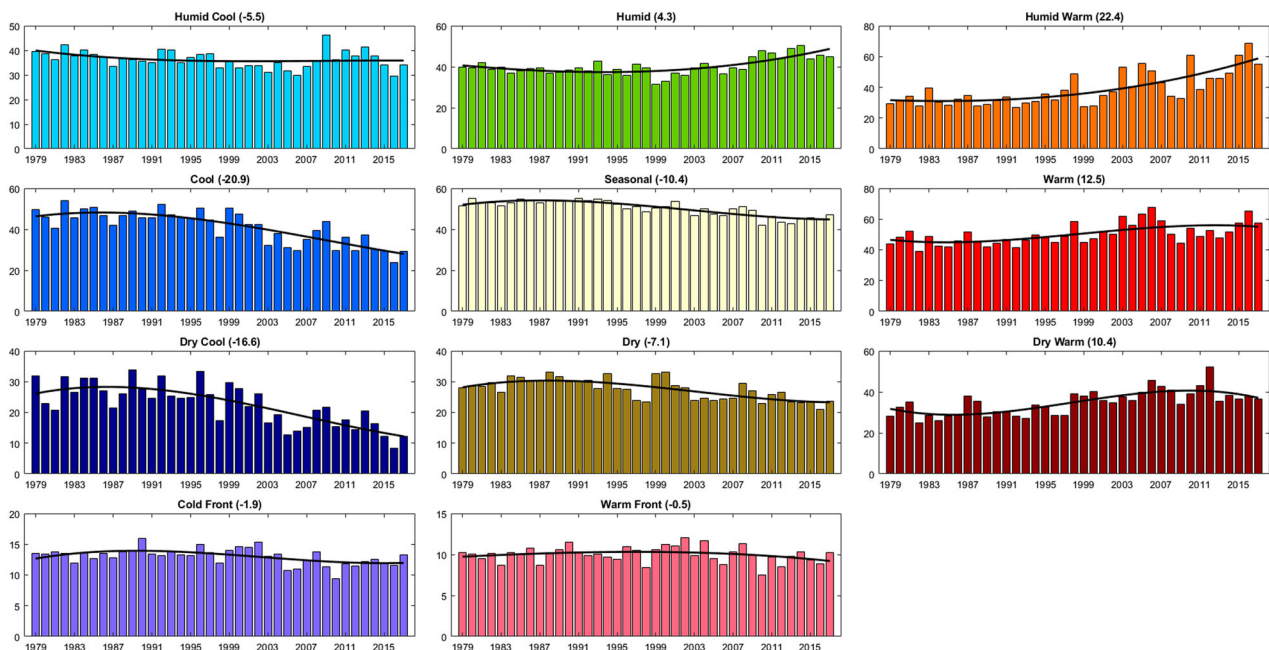


Fig. 4 Year-over-year plots of the number of occurrences of each WT averaged across the entire domain. The black line in each plot is a third-order polynomial fit to the underlying data in the bar graphs. Numbers in the title of each subplot indicate the total number of days/year change in each WT as calculated using Theil-Sen (and thus, match the numbers in Fig. 2). NOTE: the y-axis in each subplot can differ

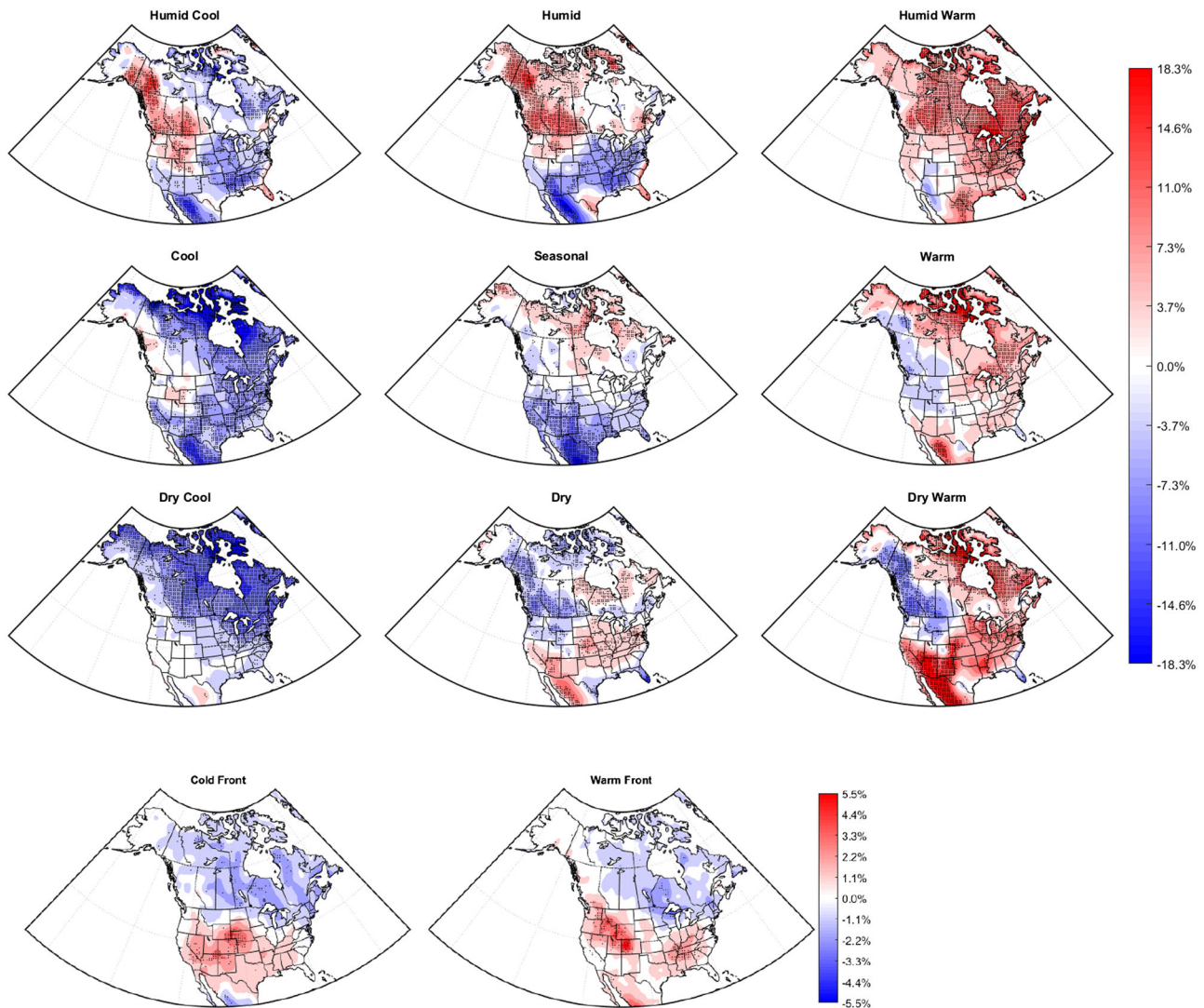


Fig. 5 The percentage-point change in the annual percent-frequency of occurrence of each WT over the period 1979–2017. Note that the 9 ‘core WTs’ share the large color bar, while the two ‘transitional WTs’ share the smaller colorbar. White areas indicate areas of near-zero change. Dots show locations of statistical significance ($p < 0.05$)

show these respective trends, their magnitude and geographic coverage are less than the changes in autumn and winter.

The significant frequency trends are largely in line with previous research discussing Arctic amplification.^{2,5} This region is experiencing 2–3 °C higher average temperatures over past few decades along with a nearly concordant rise in dew point temperatures (Fig. 6). Furthermore, the greatest increase in temperatures in these regions are largely seen in autumn³ as the air cools to temperatures lower than those at the sea surface, leading to a net transfer of excess heat to the lower troposphere. This net heat flux feeds back on itself, slowing sea ice growth in winter and changing surface albedo,¹⁷ leading to increased evaporation and greater atmospheric moisture—likely contributing to the substantial increases (decreases) in W and HW (C and DC) WTs in Northeastern Canada in these two seasons.

Separate from the Arctic, another major area of changed WT frequency is noted with the DW type in the Southern US and most of Northern Mexico, where this WT is occurring +26–40 more days per year on average. While experiencing lesser magnitude temperature changes (1–2 °C warmer) than the Arctic, when combined with a slight decrease in dew point over the same period, DW frequency has increased +7.0 to +10.9% in these areas annually, including 10–16 more DW days in spring and 5–9

more DW days in summer. For a location that is already hot, dry, facing water shortages, and experiencing increasing population,¹⁸ this trend is particularly problematic in terms of human health, especially with an aging population (e.g., refs. ^{19,20}). Furthermore, in southwestern Texas and northern Mexico (Region 3) in particular, much of the gain in both the W and HW WTs comes in summer, likely adding to this public health burden.

Contrasting with the rest of the study domain, Northwestern Canada shows a strong trend towards more frequent humid types [HC, Humid (H) and HW] at the expense of dry types [DC, Dry (D), and DW]. Nowhere is this more apparent than in Region 13, stretching from Saskatchewan to the Yukon-Alaska border, where the humid types occur anywhere from 16–21 more times per year currently, and all dry types occur 14–16 fewer times per year. Region 12 along the extreme west coast of Canada shows similar trends with all but DC. These trends are mostly a reflection of the changes in summer and, to a lesser extent, in spring. This apparent divergence from the trends noted in the rest of the country, however, are largely unsurprising considering the region’s negligible warming over the period, but its substantial rise in dew point since 1979 (Fig. 6). In the opposite corner of the continent, Florida also shows this same pattern (increased humid types, decreased dry types), with the exception of DW, as it too

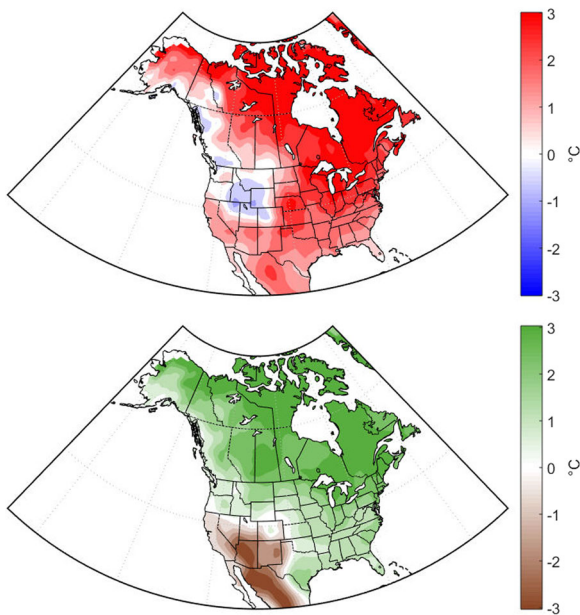


Fig. 6 Change in mean annual temperature (top) and dew point temperature (bottom), computed from Theil-Sen slope estimates of annually averaged monthly average temperatures (in °C) over the period 1979–2017. Darkest colors on both ends of each colorbar represent the 5th and 95th percentiles of distributions

has a slight increase in dew point and only a weak increase in temperature over the 39-year period.

Any seasonal geographic variability that does not show up in the annual analysis occurs mostly in the spring and is fairly minor (Fig. S2). Foremost are the uptick in HW days in the eastern US (+9 days/spring in Region 4, 43% of the *annual* total change in the region), the lack of decrease in Cool WTs throughout most of Canada, and the slight increase of DC in much of the northwest. Outside of spring, a significant increase in DC in the Desert Southwest in winter is also of note (Fig. S4). This last one is mostly offset by decreases in DC in other seasons yielding mostly insignificant annual changes. However, this can still be problematic, especially since the impact of weather types on human health often varies by season. For example, Lee (2015)¹¹ found that DC weather types in winter are related to increased mortality, while DW and HW weather types are related to decreased mortality. However, in summer, these impacts are opposite.²¹

The SSC has also been used in a number of papers to examine weather-type frequency changes in parts of North America. Among them, Vanos and Cakmak (2013)¹³ found similar changes in Canada to those found herein. Of note, a Dry Polar WT is significantly decreasing in frequency in most sub-regions of the country over the 60+ year period of record, especially in summer, where some regions are experiencing about 8 fewer Dry Polar days/summer. Oppositely, a Moist Tropical weather type was found to significantly increase in frequency over the same time period (by up to 5 days in some regions), especially in summer. Unfortunately, the SSC and GWTC are not directly comparable (the SSC is based on surface observations, while the GWTC is based on reanalysis and classifies spatiotemporally-relative differences from average on a fine-scale grid; please see Lee, 2014¹⁶ for a detailed discussion on the differences in these two classifications). Thus, especially in the Arctic regions, the Dry Polar weather type becomes nearly ubiquitous in the SSC, while the DC WT of the GWTC maintains a similar frequency throughout all seasons. Nonetheless, some similar results are noted herein, especially in southeastern Canada, where DC is declining and HW is increasing around +/- 5 to 10 days per summer.

Over the 1948–2005 time period, Knight et al., (2008)²² found widespread significant decreases in the SSC's Dry Polar WT in the eastern and western thirds of the US, increased frequency of a humid WT (Moist Moderate) in the Midwest and western US, and decreases in transitional weather throughout the country. While a few results herein [e.g., decreased DC (and C) in the northeastern US, and perhaps increased HW in the northeast] are similar to those found in Knight et al. (2008),²² their results are largely in contrast to the current research, especially in regards to transitional (WFP, CFP) weather, as this research finds slight increases in both transitional WTs across much of the US. Using a previous version of the SSC (the SSC1),²³ Kalkstein et al., (1998)²⁴ also found significant decreases in transitional weather across the US, along with increased winter Dry Polar and increased summer Moist Tropical, especially in the southeastern US. Both studies (refs 22,24) however, found locations in the desert southwest US had large summertime increases in a Dry Tropical weather type— analogous to the DW type herein. Both of these studies use time periods that end 10–20 years prior to the time series used in the current research, prior to the warmest years on record globally.²⁵ In more recent research evaluating summertime SSC WT frequencies, in the Midwestern US, Vanos et al., (2015)²⁶ found increasing Moist Tropical and decreasing Dry Polar WTs; and in eastern North America, Senkbeil et al., (2017)²⁷ found dramatic increases in summer Moist Tropical and large decreases in Dry Polar and transitional weather. However, these studies only determine trends over a regional domain and a single season.

While a 39-year period of record is used to evaluate the significance of WT trends, this still is considered a fairly short temporal domain to be confident in this being a true climate change signal. The use of Theil-Sen slope estimates (described below) in lieu of simple linear regression largely mitigates the influence of potential high-leverage outliers on these results.²⁸ However, in order to gauge the influence of starting and ending points a bit further, we ran the same analyses multiple times, each time omitting 1–3 years at the beginning and/or 1–3 years at the end. The overall spatial pattern of the slopes was virtually identical when averaging the results from this alternative time domain analysis, and nearly 89% of the continent remains unchanged with regard to statistical significance/insignificance of the slopes (Fig. S5). As with all secular examinations of any component of the climate system, other decadal and interdecadal forcing agents (e.g., teleconnections and oscillations) are undoubtedly contributing to *short-term* fluctuations in WT frequency. A detailed analysis of such factors is outside the scope of this research, but they were examined in Lee (2016)²⁹ with regards to their impact on wintertime weather type frequencies.

As would be expected, many of the above results are largely in agreement with the general changes in temperatures or dew points over this time period (e.g., where dew points and temperatures are both rising, we generally see increases in HW and decreases in DC); many pattern correlations between WT frequency and these two variables are $r > |0.5|$ (Table S5). However, there are also more subtle changes noted here that a simple univariate analysis of either individual meteorological variable is unable to elucidate. For example, increased DW in the Desert Southwest is offset by significant decreases of multiple WTs (and not only HC, as would be expected); and decreases in DC in Canada are offset by increases in both HW and DW in the east, and increases in the Humid WT and even HC in the West. Moreover, CFP and WFP changes are not well correlated with either temperature or dew point trends (Table S5), yet are important meteorological phenomena leading to dramatic short-term weather variability affecting the mid-latitude population. All of these additional analyses reveal that depending on location and the WT of interest, there is considerable variability in the association between background warming and the trends in these WTs, highlighting the value of such an analysis.

DISCUSSION

Using a recently developed surface weather typing classification, this study explores the changes in multivariate atmospheric conditions across North America since 1979. Largely in line with previous research, across all seasons and most locations, warm weather types have shown a significant increase in frequency since 1979, especially Dry Warm weather types in the southern and western US and northern Mexico, and Humid Warm weather types northeastern Canada. Humid Cool weather types have shown significantly increased frequency in northwestern Canada. Contrary to the limited previous research exploring interdecadal trends in weather types, a few significant areas of trends were noted with transitional weather types, as increases in cold fronts and warm fronts were found throughout much of the US, and decreases shown in much of Canada.

It is important to note that the relatively short, 39-year record available for this research underlies two key limitations. First, trend calculations on this short of a time-span can be substantially altered by outlier data near the beginning or end of the period. The technique used and additional analyses undertaken both acted to mitigate the impacts of this issue on the conclusions, but nonetheless, the results should be interpreted within the scope of this limitation. Further, without a much longer period of record of GWTC data, it is also difficult to attribute the multi-decadal trends found herein specifically to a changing climate, or another natural multi-decadal climate oscillation.

When using a univariate analyses with individual meteorological variables (e.g., temperature) to study interdecadal trends, increased high temperature events nearly universally mean a decrease in low temperatures events. However, with weather types, this dichotomy is not necessarily present—increased Humid Warm types are not always at the expense of decreased Dry Cool WTs—as no WT can be considered a true ‘opposite’ of another. While there is, expectedly, a correlation between the spatial patterns of GWTC slopes (in Fig. 5) and slopes in temperatures and dew points (in Fig. 6), the absolute magnitude of these correlations varies substantially by WT, indicating the unique contribution of this WT-based perspective to indicator research.

While unsurprising in terms of the geographic location and sign of these trends, the *magnitude* of the change in WT frequency is unexpectedly large. To climatologists, 2–3 °C changes in temperature and/or humidity (e.g., in northern Canada) are definitively substantial. However, a 30–40 day change per year in a particular weather type’s frequency at the expense of another may be a more efficacious means of communicating such trends to policymakers and the general public.

METHODS

Daily gridded weather typing classification (GWTC)¹⁶ data were obtained for each day from 1 January 1979 through 30 December 2017 for each of 9027 grid points, representing every other grid point in the North American Regional Reanalysis (NARR)³⁰ data set that is within 100 km of land. Developed by Lee (2014),¹⁶ the GWTC uses 3-hourly (8-times daily) values of six near-surface atmospheric variables (2-meter temperature, 2-meter dew point, sea level pressure, total column cloud cover, 10-meter wind speed and wind direction) from NARR to classify each day at a location into one of 11 seasonally-relative and geographically-relative weather types (WTs; Table 1). While 9 of the 11 WTs are defined mostly by their temperature and dew point characteristics, two types represent transitional situations typical of the changes experienced during warm front (WFP) or cold front passages (CFP). As described in Lee (2014),¹⁶ there is a three stage process for calculating the GWTC. First, cyclical seasonal curves of means and standard deviations for each variable are calculated individually for each location. These statistics are used to compute deseasonalized z-scores for each variable, forming the basis for the initial classification into one of the 11 types. A second stage uses principal components analysis and discriminant function analysis to hone the classification, and help sort ‘borderline’ days into optimal categories. A final

step in the classification applies a geographical smoother in order to improve spatial consistency. Differing from a traditional air mass classification, the GWTC identifies weather situations that are relative to normal for a season and a location. For example, a Dry Cool (DC) weather type simply means that the weather is drier and cooler than average for the time of the year for that location. In a more poleward location a DC-type day is going to be, on average, colder than DC at lower latitudes, even on the same date; similarly, a DC weather type in winter is going to be colder than in summer, even in the same location. This relativistic nature of the GWTC allows the classification scheme as a whole to maintain ample frequency of each WT throughout all seasons and locations. All GWTC data are publicly available at: www.personal.kent.edu/~cclee/gwtcdata.html free of charge.

Separately at each location, percent frequency of the counts of each WT in each year (1979–2017) were tabulated and then subjected to Theil-Sen Slope estimation along with bootstrap-derived 95% confidence intervals (using the normal approximated interval with bootstrapped bias and standard error). The Theil-Sen slope estimation is a nonparametric statistical analysis that calculates the median value of all pairwise slopes between the points in the dataset, and is thus robust against outliers in comparison to traditional linear analyses.³¹ The confidence intervals were converted to p-values using the method described in Altman and Bland (2011)³² in order to compute the field significance ($\alpha_{\text{field}} = 0.05$) of these trends, by controlling for the false discovery rate.³³ Essentially, this technique necessitates each local test to meet a stricter requirement (i.e., a lower p-value) in order to be considered significant relative to the multiple tests conducted across the spatial domain. In the results discussed above, all percentages refer to percentage-point changes in average frequency over the entire period, computed by multiplying the Theil-Sen slope estimates by 38 (years in the study, minus 1). These percentage-point changes were then mapped, with significant values shown with dots. Accordingly, multiplying these results by 365 yields the change (from the start of the period to the end of the period) in the number of occurrences (days) per year for each weather type, also discussed above. This process was also repeated for varying time-domains, leaving out the first 1–3 years and/or the last 1–3 years to examine robustness of the method against high-leverage outliers. The averaged slopes and p-values from these repeated analyses are presented in supplementary material (Fig. S5).

To help *visualize* nonlinear trends, year-over-year bar graphs of WT frequencies were superimposed with a third-order polynomial fit to the underlying data (however, no numeric results presented above are based upon this polynomial). Monthly means of 2 m temperatures and dew points were obtained from the NARR data set as well to help analyze causes behind spatial patterns of WT frequency trends. Pearson-based pattern correlations between slopes of weather types and local Theil-Sen slopes of annual temperatures and dew points were also computed and tabled in supplementary material. All above correlations were calculated for the 6397 land-based grid points of the GWTC. All aforementioned analyses were completed in Matlab.

A regionalization of the GWTC domain was undertaken in order to spatially summarize the resulting trends in WT frequency. Average monthly frequency for each of the 11 weather types in each of the 12 months (132 columns) were computed for each of the 9027 locations (rows) for 1979–2015. These frequencies were then subjected to principal components analysis and the TwoStep Clustering component in SPSS Statistical Software³⁴—the same regionalization method described in Lee (2014),¹⁶ but with the full GWTC spatial domain. These statistically derived regions were used as a reference from which the final regions were drawn in ArcMap (Fig. 1).

DATA AVAILABILITY

All GWTC data used in this research are freely available from the lead author’s website at: www.personal.kent.edu/~cclee/gwtcdata.html. All raw NARR data used in this research are freely available from NOAA at: www.esrl.noaa.gov/psd/data/gridded/data.narr.monolevel.html.

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AUTHOR CONTRIBUTIONS

C.C.L. contributed to the research and writing of this manuscript. S.C.S. contributed to the writing of this manuscript.

ADDITIONAL INFORMATION

Supplementary information accompanies the paper on the *npj Climate and Atmospheric Science* website (<https://doi.org/10.1038/s41612-018-0051-7>).

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