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Examining trends in multiple parameters of seasonally-relative extreme temperature and dew point events across North America

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ABSTRACT:

Concurrent with the background rise in global mean temperatures, changes in extreme events are also becoming evident, and are arguably more impactful on society. This research examines trends in three components of seasonally-relative extreme temperature and humidity events in North America that directly influence human thermal comfort: event frequency, duration, and areal extent. Results indicate that for the majority of the study domain, changes in these events are in the expected direction with changes in means. Extreme heat events are generally increasing throughout the domain, with the largest changes in summer and autumn in the eastern portion of Canada and the US. Cold events are largely decreasing in these same locations and seasons, with additional widespread decreases in winter. Interestingly, significant increases in cold events are also evident in autumn in parts of the western US. Extreme humidity events are showing an even greater change than temperature events – nearly all of Canada and most of the US is seeing significant increases in extreme humid events and decreases in dry events, while the southwestern deserts show widespread significant increases in dry events, especially in winter and spring. Changes in event duration and spatial extent mimic these results. Importantly, this research demonstrates that there are regions that show changes to extreme events that differ from the overall changes in means, highlighting the importance of looking beyond climate averages to examine not only extreme events, but changes in higher-order statistical moments.

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/joc.6852

KEYWORDS:

extreme events; trends; climate change; North America; statistical moments

Funding Information: This research was supported by federal award number NA17OAR4310159, entitled “Developing extreme event climate change indicators related to human thermal comfort” from the National Oceanic and Atmospheric Administration’s Climate Program Office.

I. INTRODUCTION

The evaluation of climate changes, both observed and projected, has most frequently focused on the analysis of mean fields (e.g., IPCC report, Hartmann et al., 2013). Considering their relative infrequency, however, extreme weather events have a disproportionately greater impact on many biological systems (e.g., human health, agriculture, ecosystems) in comparison to climatic averages, yet are less-often studied and deserve more detailed analyses.

Among these infrequently occurring phenomena are extreme temperature events (ETEs). Both heat and cold events can have substantial impacts on human health (Sheridan & Allen, 2015) as well as other natural systems (e.g. Parmesan et al., 2000). Due to the sharp increases in human mortality that accompany extreme heat events (Shaposhnikov et al., 2014), changes in extreme heat events are examined more often than changes in extreme cold events. This asymmetry has only been exacerbated by climate change, and the projections of longer, stronger, and more expansive heat events in the future (Sheridan & Allen, 2015; Mitchell et al., 2016). Yet secular trends in cold event occurrence also merit study, as extreme cold has been shown to increase human mortality (Gasparrini et al., 2015), particularly in warmer climates that are less prepared to mitigate the impacts (Barnett et al., 2012; Smith & Sheridan, 2019). Extreme cold also increases energy demand, thus prolonged periods of extreme cold across large areas can be detrimental to the energy industry (Yang & Bou-Zeid, 2018).

Especially when considering applied climatological research in human health, trends in climate variables requires not only the consideration of temperature, but also humidity (Brown and DeGaetano, 2017; Vincent et al., 2007; Dahl et al., 2019), as it can interact synergistically with temperature to influence human thermal comfort (Andersen et al., 2012, Gosling et al., 2014, Steadman et al., 1984). In addition, persistent ETEs can lead to a build-up of thermal stress without any periods of relief, leading to negative outcomes (Lee et al., 2016; Turner et al., 2013); and a person's level of comfort with their native climate at a given time of year (i.e. acclimatization) will also impact the severity of ETE impacts on human health (Curriero et al., 2002). Further, from a public health point of view, the spatial extent of extreme events will dictate the raw number of people impacted, and the stress put on public health systems (Ebi & Bowen, 2016; Wang & Rosowsky, 2012).

Most of the near-surface weather variables impacting human thermal comfort have undergone mean changes due to anthropogenic forcing over the past few decades (Hartman et al., 2013). However, trends in the frequency, magnitude, and persistence of the extreme tails of the distributions of these variables are less well-researched, despite their impacts on society. To address these gaps, this research examines the trends in three different components (frequency, duration, and extent) of four seasonally-relative physical climate change indicators for North

America related to human thermal comfort: extreme temperature events and extreme dew point events, each for high (warm/humid) and low (cold/dry) extremes of the distribution.

II. DATA AND METHODS

To define ETEs and extreme dew point events (ET_DEs), daily mean 2-meter temperature and 2-meter dew point temperatures were retrieved from the North American Regional Reanalysis (NARR; Mesinger et al., 2006), 1979-2016 for all 18,661 land-based grid points in the domain (23°N to 83°N, 46°W to 167°W). The NARR dataset was chosen due to its widespread usage in prior research and its relatively fine scale spatial resolution (~32km) compared to other reanalyses. Seasonally-relative extreme event thresholds for each variable at each grid-point were computed using a three-stage process. First, monthly 5th and 95th percentiles (e.g. the 5th and 95th percentile of all January days, then all February days., etc.) were calculated for the 1981-2010 climate normal period; then each day in the entire timeseries was set to its representative monthly value (e.g. if the 5th percentile for Januaries was 10°C for a location, then each January day would be set to 10°C); and finally a 31-day centered-moving average was applied to smooth out the step-like discontinuities. The resulting smoothed curves were then used as baselines from which extreme event occurrences were defined: extreme warm events (XWEs) and extreme humid events (XHEs) occurred on days when the temperature/dew point was greater than the 95th-percentile curve, while extreme cold events (XCEs) and extreme dry events (XDEs) occurred on days when the temperature/dew point was less than the 5th-percentile curve. Again, this process is repeated separately for each grid-point.

Duration was calculated using a day-in-sequence approach that simply creates a daily-scale time series which counts consecutive occurrences of each event type at each location/gridpoint. Daily areal extent was calculated by determining the spatial set of grid points that met their own local percentile threshold for each of the four extreme events. To correct for the effect of latitude on the amount of space each gridpoint/grid-cell represents, each occurrence of a (binary) event was multiplied by the cosine of latitude at the location it occurred, the products of these multiplications were then summed by day across all locations and divided by the total area within the domain, to produce daily percentages of areal extent within the domain.

Trends for each parameter (frequency, duration, or extent) were calculated using Theil-Sen slope estimates on annual-level statistics, or where results are partitioned into seasons, then seasonal-annual level statistics (e.g. Winter 1979, Winter 1980, etc.), where n=38 years for all trend estimates. Event frequency trends used *summed* annual/seasonal events calculated at each gridpoint; event duration trends used *maximum* annual/seasonal event durations calculated at each gridpoint; and spatial extent trends used *mean* annual spatial extents calculated across all gridpoints. Statistical significance was determined using the non-parametric Mann-Kendall test for trend. Then, for all mapping, an individual gridpoint's significance was determined by controlling for the false detection ratio (Wilks, 2016), effectively requiring each local test to meet a stricter significance threshold (lower p-value) to achieve field significance, considering the 18,661 local tests being computed.

Seasons were defined as follows: winter from January through March, spring from April through June, summer from July through September, and autumn from October through December. While less traditional than using standard meteorological seasons, these seasonal delineations are not without precedent (e.g. Cohen et al., 2009). Moreover, the exact definition of a season's start and end date is partially subjective, spatially dependent, and currently undergoing change. For example, research has shown that over the last several decades, while winter and spring are ending earlier in the year, summer and autumn (especially) are ending later in the year (e.g. Kutta and Hubbart, 2016; Allen and Sheridan, 2016), and could be better captured by the seasonal definitions used herein by comparison to traditional seasons.

III. RESULTS AND DISCUSSION

3.1 – Extreme Temperature Events (ETEs)

Generally, the frequency of extreme heat events is increasing, while extreme cold events are decreasing (Table 1, Figure 1), similar to the results of nearly all recent research on temperature trends (e.g., Habeeb et al., 2015; Smith et al., 2013; Kanno et al., 2019; van Oldenborgh, et al., 2019). The majority of the statistically significant increases in heat events are in northeastern Canada (e.g. Quebec) and south through the northeastern quadrant of the US. Smaller regions of significant increases occur in northern Mexico through the southern plains, where the frequency of XWEs are increasing by 4-7 days per year per decade (just days/decade hereafter). While these are largely the same places experiencing decreases in absolute cold events (and at about the same rate), the latter changes extend farther northwestward into nearly all of northern Canada and are generally more spatially contiguous. Indeed, while about 1/3 of the domain is experiencing significant changes in XWEs (largely increases), well over half of the domain (about 56.5%, Table 2) is experiencing significant changes in XCEs (largely decreases). Compared to XWEs (+2.3 days/decade), XCEs are changing more across the domain as a whole (-2.6 days/decade). This result – that cold events are decreasing more than heat events are increasing – is also noted in previous research (e.g. Sheridan and Lee, 2018).

Seasonally, the largest increases in XWEs are found in summer (Figure 2), however, a decent portion of the XWE increases in the northeastern US (and the eastern US in general) occur outside of summer, particularly in autumn. While there are few areas of significance in any other season, both winter and spring do show anywhere from 0.5 to 1.5 more days/decade of increase in heat events, leading to the significant annual totals discussed above. The autumn increases in XWEs are focused around Hudson Bay, the province of Quebec and south through the upper Great Lakes. This result is likely tied to the delayed freeze up of sea-ice / lake-ice in these regions (Wang, et al., 2018; Andrews et al., 2018; Hochheim et al., 2010). In summer, unlike other seasons, XWEs represent absolute heat events (i.e. not necessarily seasonally-relative). In addition to Quebec, large increases are also seen in northern Mexico and a good portion of the desert southwestern US.

Decreases in seasonal cold events are most apparent in the eastern half of Canada in autumn, along with significant decreases in the Northeastern US in summer, and patchy decreases in these same areas in winter. Interestingly, a large portion of the western US is seeing *increases* in XCEs in autumn. While this result contradicts the overarching direction of trends, similar trends in cold weather have been noted in previous research (e.g. Lee and Sheridan, 2018), are projected to happen into the future (Vavrus et al., 2006), and have even been projected to occur slightly more frequently in the coming decades for some areas of the western US (Kodra et al., 2011). Nonetheless, this result warrants further examination.

Many of these changes are explained simply by changes in mean seasonal temperature trends (Figure 3, top). Large increases in temperature are occurring in the eastern half of Canada in summer and autumn – many of the same areas that are experiencing the increases in XWEs and decreases in XCEs. However, not all of the changes in ETEs are well correlated with patterns of mean temperature change, especially for XCEs in spring and summer (Table 2). Other changes (or lack of changes) in extreme events are better explained by examining the changes in both the seasonal temperature means and the *variability* (Figure 3, bottom). For example, there are also large increases in temperature in summer and autumn in north central Canada (west of Hudson Bay) and the Canadian archipelago, where seasonal temperatures are changing by upwards of 1.0°C or more per decade. However, in the Canadian islands, there is also a marked decrease in temperature *variability* (-0.5 to -0.7°C) in these seasons; and thus, while there is a large positive shift in the temperature distribution (which might suggest a dramatic increase in XWEs in these seasons), the concurrent narrowing of the distribution (e.g. Figure 4, top) is largely offsetting this shift and leading instead to significant decreases in XCEs, but few increases in XWEs in these areas. Decreases in Arctic cold-season variability have been cited in previous research examining extreme events, as Screen (2014) noted that northerly winds that usher in cold days are warming more rapidly than the southerly winds that bring warm days, partly leading to diminished subseasonal temperature variability.

Oppositely, increased autumn temperature variability may explain the significant increases in extreme cold events in autumn in the western US despite negligible changes to mean temperatures. This increased variability flattens the distribution of temperatures (e.g. Figure 4, middle), leading to both significant increases in cold events and patchy areas with slight increases in warm events as well. In addition, this area is seeing significantly more negative skew to the temperature distribution (not shown).

Finally, in summer in the southern High Plains through the lower Mississippi River valley, there is an area of significant increases in XWEs, but no change in XCEs. This change can only be explained by higher-order moments; as there are only minimal changes in means and variability, but very large and significant changes in skew (increased) and kurtosis (decreased) throughout this area which combine to produce this result (e.g. Figure 4, bottom). The importance of examining higher-order statistical moments – or the entire distribution of temperatures (e.g. Robeson, 2004) – when investigating temperature extremes has also been noted in previous research (Donat and Alexander, 2012; Lewis and King, 2017; Screen, 2014), though, seasonal-level analyses of these higher-order moments is sparse.

When examining the geography of ETE durations (Figure 5), there are quite a few similarities to the frequency results (Table 2), however, the spatial patterns are considerably more patchy and virtually no statistically significant areas of increased XWE durations exist on an annual basis. The greatest increases (significant or not) for XWEs are focused in the southern US and northern Mexico. The greater changes in duration are for XCEs, with 29.6% of the domain experiencing significant changes on an annual level, compared to about 1.2% of the domain experiencing significant changes in XWE duration. The XCE changes are focused in the Canadian archipelago (especially Baffin Island), the Prairie provinces (Saskatchewan and Alberta) and the central Plains states of the US, where XCE durations are decreasing by over 1 day per decade.

On a seasonal basis, the largest changes are in autumn throughout much of Canada, where XCEs are decreasing in duration and XHEs are increasing in duration by about 1 day per decade (Figure 6). Other areas of significant changes in duration are found for increased XHE duration in summer in northern Mexico, and decreased XCE durations in winter in the Canadian archipelago, the Great Lakes, and the High Plains of the central US – all areas and seasons that are exhibiting similar trends in event frequencies. The sign, patchiness and insignificance of the XWE *duration* trends compared to XWE *frequency* trends have been noted in previous literature in the US (Habeeb et al., 2015) and elsewhere (e.g. Perkins and Alexander, 2013). The general decrease in XCE duration is likely related to the systematic increase in temperatures, where fewer days exceed the 5th percentile threshold (Vose et al., 2017). Significant decreases in the duration of XCEs in the Canadian archipelago may be attributed to decreased sea-ice across the Labrador Sea and more persistent North Atlantic blocking (Chen & Luo, 2019; Hanna et al., 2018). However, while persistent blocking can result in prolonged periods of extreme cold both upstream and downstream of the block, Whan, et al. (2016) showed that the cold extremes associated with blocking episodes have trended warmer.

The spatial extents of both XWEs (+0.8%-points/decade) and XCEs (-0.7%-points/decade) are both changing significantly (Figure 7, Table 1). The signs of these changes are consistent throughout all seasons [with increased spatial extent in XWEs also being statistically significant ($p<0.05$) in all seasons], but the largest changes are seen in summer for XWEs (+1.1%-points/decade) and in winter for XCEs (-0.7%-points/decade). Changes in spatial extent are in the expected direction (XCEs decreasing and XWEs increasing) based upon previous research (e.g. van Oldenborgh et al., 2019; Smith and Sheridan, 2018).

Prior research (e.g. van Oldenborgh et al., 2019) suggests using a minimum 50-year period before climate changes can specifically be ascribed to anthropogenic global warming; and thus, it is plausible that some of the trends noted above could be related to internal climate variability (e.g. the Atlantic Multidecadal Oscillation, e.g. Lee, 2020) and accompanying shifts in atmospheric circulation patterns. However, it would seem likely that, even if ETE changes cannot be attributed to global climate change, it has exacerbated them. Moreover, large-scale circulation patterns undoubtedly impact extreme event frequency (Adams et al., 2020), but are themselves also impacted by background climate change (Horton et al., 2015), which adds more complexity to the question of ETE trend attribution – one that deserves attention in future research.

3.2 – Extreme Dew Point Events (ET_DEs)

Extreme dew point events (ET_DEs) – both low dew-point (extreme dry events; XDEs) and high dew point (extreme humid events; XHEs) – exhibit more complex spatial patterns than the ETEs both annually (Figure 1) and seasonally (Figure 8). The most apparent difference is the northeast-southwest dichotomy in the sign of the changes. Most of Canada (especially northern and eastern Canada) is experiencing fewer XDEs annually and in nearly every season, except spring. Increased frequencies of XHEs are occurring in these same areas in nearly every season, except winter. This contrasts slightly with others that have suggested increasing summer dew points throughout the eastern half of the US (e.g. Brown and DeGaetano, 2013), as other than the significantly increasing humidity trends in the extreme northeast, herein, little change in dew points is noted in other parts of the US. Oppositely, the desert regions of the southwestern US and northern Mexico are subjected to increased frequency of dry events in nearly every season but have seen relatively few significant changes in humid events, outside of patchy summer increases in XHEs. These results in the southern part of the domain are a function of both a decreasing mean dew point temperature in these locations (especially in winter and spring), along with increased variability in dew points in nearly all seasons, but especially in summer and autumn (Figure 9), leading to many more XDEs, but little change in XHEs. While higher order moments are also changing for dew points, they are mostly acting to amplify the signals noted above. For example, in summer in the western US, a more-negative skew is amplifying the decreasing mean and the increased variability in these locations – all leading to increased XDEs. And, similar to the changes in temperature events, as a result of decreasing variability, central Canada and the Canadian archipelago in winter and autumn are seeing negligible increases in XHEs compared to what might be expected from the mean trend in dew points alone. This also results in a much more dramatic and significant absolute change (decrease) in XDEs than in XHEs (increase).

When examining XHE and XDE durations, though more patchy and inconsistent, the same spatial patterns as those seen with XHE and XDE frequencies are apparent (Table 2), but there is little statistical significance (Figure 5, bottom; Figure 10). The largest cohesive areas of event duration change are seen for increased XDE durations in winter and spring in the southwestern part of the study area (of about -0.9 days/decade), though shorter autumn and winter XDEs are also noted in extreme north-central Canada (e.g. Baffin Island).

Of particular note is the summer in the western US, where both XDEs (dry) and XWEs (hot) are increasing in frequency in areas already prone to large wildfires, with both types of events also showing significantly increasing durations. Previous research (Lee and Sheridan, 2018; Knight et al., 2008; Kalkstein et al., 1998) has noted the relative increase of concurrently hot and dry weather in these areas already stressed by growing populations and a limited water supply. Further, both hot (XWEs) and humid (XHEs) events in autumn are also occurring substantially more frequently across much of the eastern half of the continent (especially eastern Canada), as well as becoming significantly longer. Considering the combined effects of both heat and humidity on human health, this should imply an increasing vulnerability to heat-related mortality over the last 4 decades in these regions; however, human adaptation over that time period has partially tempered this expectation (e.g. Sheridan and Dixon, 2017). To estimate the trends in combined temperature and humidity events, apparent temperature (Steadman, 1984) events were also examined, but revealed virtually identical spatial and nationally-averaged results as those found with temperatures, and were thus omitted. Nonetheless, such extreme hot and humid events are expected to increase into the future, putting more lives at risk (Dahl et al., 2019).

The changes in spatial extent of ET_DEs follows the general trends noted above for durations and frequencies of these events – XHEs are expanding (+0.7%-points/decade, p<0.01), and XDEs are contracting (-0.3%-points/decade, p=0.15). However, these statistics are a bit misleading, as within the entire domain, there are likely some areas that have increasing XDE extents (i.e. the southwest), while other areas have decreasing XDE extents (i.e. Canada), canceling each other out when averaged across the entire domain. The largest change in spatial extent among any of the extremes examined in this research is an increase in summer XHE extent (+1.3%-

points/decade), which is mainly attributable to the rapid increase since about 2000, over which time XHE extents have nearly doubled in size (Figure 11). One interesting note is that, in spring, both XHEs and XDEs have increasing trends, albeit, the latter is very minor and insignificant.

Though little research explicitly examines trends in extreme humidity events, these general changes in the various aspects of extreme dew point events are largely in agreement with previous research that suggests a warming atmosphere will accommodate additional absolute water vapor (Wentz et al., 2007) – implying a general increase in XHEs and decreased XDEs. This research also supports the spatial patterns of the trends in various humidity variables that are noted elsewhere, such as the trend towards drying (and increased XDEs) conditions in the desert regions of southwestern North America along with increased humidity (and XHEs) generally found elsewhere (Lee and Sheridan, 2018; Willet et al., 2008).

It is important to note that, while reanalyses should generally be used with caution with regard to trend estimation (e.g. Dee et al. 2016; Thorne and Vose et al., 2009; Behnke et al., 2016), our previous research suggests that reanalyses are reasonably accurate at identifying annual counts of extreme temperature events (based on apparent-temperature percentile thresholds), though some datasets are better than others (Sheridan et al., 2020). In order to verify the suitability of NARR for the research herein, we compared extreme events defined at 230 surface synoptic weather observation stations throughout North America with those at the nearest land-based NARR gridpoint. When aggregated to the annual level (the level at which trend statistics are measured herein), the rank-correlation between counts of year-over-year NARR extremes and station-based extremes are all moderate (XHE) to strong (XWE, XCE, XDE; Table 3), supporting the use of NARR for the investigation herein. And, while 17% of locations examined do have statistically significantly different XHE trends between stations and NARR (mostly in the eastern US – where XHE trends are overestimated by NARR), for XWE, XCE and XDE, fewer than 4% of the locations have significant differences in trends (Table 3, and Supplementary Material).

IV. SUMMARY AND CONCLUSIONS

While many of the results described above provide further confirmation of well-known trends in the climate, there are also several novel aspects of this research that provide a different perspective on these changes, including: the examination of trends in extreme events rather than means; the use of seasonally-relative event thresholds and seasonal stratification of the results; the investigation of not only changes in event frequency, but also of event duration and spatial extent; the analysis of changes in higher-order statistical moments (e.g. standard deviations, skew and kurtosis); and an evaluation of the agreement between reanalysis (NARR) and station-based observations in terms of identifying extreme events.

Generally, extreme warm events are increasing in frequency, duration and extent, while extreme cold events are decreasing in frequency, duration and extent throughout most of the study area. The greatest extreme temperature event changes are occurring in the eastern portions of Canada and the US, along with northern Mexico. Extreme humid events are increasing in frequency and duration throughout most of Canada and the northeastern quadrant of the US, while extreme dry events are decreasing in frequency and duration in these same areas. The trends in spatial extents of these extreme humid (dry) events are also generally increasing (decreasing). One notable difference is the marked increase in extreme dry event frequency and duration in the southwestern part of the domain. On average across the domain, the largest magnitude changes in of all these events are occurring in summer, with autumn and winter (especially for the extreme cold events and extreme dry events) following closely behind summer. Autumn has the most widespread significant changes in event frequency and duration, while the fewest changes are happening in boreal spring.

The results presented herein must be viewed in light of the limitations of the data and methods utilized. One such limitation stems from the use of the underlying NARR dataset, as some previous research suggests avoiding the use of reanalysis for evaluating trends. While comparisons between station extremes and NARR extremes revealed moderate to strong correlations between annual counts of extreme events, it must be reiterated that the underlying data is still reanalysis (model)-based output, and thus, subject to model error. These differences are fairly trivial in most of the domain and most event types, but the XHE results in particular should be interpreted with caution, especially in the Southeastern US where trends diverge from those in previous research. Results in poorly sampled areas (e.g. extreme northern Canada) should also be treated with caution. Further, station-to-station differences in instrumentation and changes in station locations that feed data into the reanalyses have the potential to produce spurious leverage points in trend estimates or inconsistencies in trends across political borders (e.g. the summer mean dew point trends in Figure 9). Another limitation concerns the calculation of extreme event durations, and their trends. As described above, herein we used a day-in-sequence approach and then found the *maximum* duration event for each temporal partition (e.g. year and season). However, this method can lead to some events being spread across two seasons or two calendar years. For example, a 7-day event that began on 26 December 2001 would count as a 6-day event for autumn 2001, but also as a 7-day event for winter 2002. Since we used the maximum (as opposed to a mean) this would only be an issue if this event was indeed the maximum duration event for either of those temporal partitions. A final consideration regards how one defines an extreme event, as some examinations of extreme events require a spatial parameter be met, in that an event only is considered to have 'occurred' if it is spatially contiguous (as defined using one of a variety of different spatial thresholds). When calculating spatial extents herein, we chose to use a simple (latitude-adjusted) percentage of all grid-points that met their own local percentile thresholds on a given day (5th or 95th), without any requirement for spatial cohesiveness. Multiple ways of calculating events, durations and extents were considered, but each added complexity and had their own limitations, and for the sake of simplicity, the methods described above were ultimately chosen. While different techniques for defining these components would likely yield slightly different results, based upon the literature discussed above, the overall conclusions are unlikely to differ.

Given the background rise in global and regional mean temperatures, the general sign changes in these components of extreme events are largely unsurprising. However, this research also highlights the importance of examining various parameters of extreme events a bit more in depth. First, while the frequency of extreme events and their spatial extents are changing fairly substantially, significant changes in event duration are not nearly as widespread. Secondly, while one might expect changes to be consistent across seasons, this is not the case, and highlights the importance of both examining seasonally-relative extreme events [as opposed to absolute extremes – which would concentrate nearly entirely in winter (for cold and dry events) and summer (for warm and humid events)], and of stratifying these results by season. Herein, this method revealed some surprises. The best example is in the western US, where there is little statistically significant change in either XWEs or XCEs when examined across the entire dataset. However, when examined seasonally, there is a significant *increase* in cold events in autumn in the western US, which at the annual level is offset by the slight decreases in XCEs in summer and spring. Relatively few studies have examined seasonally-varying extreme temperature and dew point events [beyond some very notable events such as the extremely warm March 2012 event, with summerlike temperatures across in North America (Grumm et al., 2014) which yielded a false spring and steep agricultural losses (Ault et al., 2013)]. The results here show that there are significant trends in extreme events outside the core summer heat events and winter cold events, and the impacts of these events should be explored further.

Finally, while overall extreme humid and extreme warm events are increasing, this does not necessarily mean that extreme cold and extreme dry events are decreasing at similar rates. The best example is in the Canadian archipelago where XCEs are significantly decreasing, however, XWEs are only moderately increasing – a result amplified in winter and autumn. Considering the Canadian Arctic is one of the areas undergoing the most rapid increases in mean temperatures over recent decades, this result also underscores the importance of not assuming increases in mean temperatures will automatically result in increases in extreme heat events. Instead, trends in the higher order statistical moments (e.g. standard deviation, skewness, and kurtosis) might shed new light on the changing distributions of a climate variable, including changing frequencies of extreme events. Oppositely, even in the absence of changes in mean temperatures, significant changes in the extreme events may still be occurring due to changes in variability (e.g. changes in autumn XCEs in the western US without a significant change in mean). In this sense, focusing exclusively on changes in statistical means, without investigating these other statistical parameters or extreme events, runs the risk of missing aspects of our changing climate that might be even more important than changes in the average climate.

ACKNOWLEDGEMENTS

This research was supported by federal award number NA17OAR4310159, entitled “Developing extreme event climate change indicators related to human thermal comfort” from the National Oceanic and Atmospheric Administration’s Climate Program Office. The authors declare no conflict of interest, financial or otherwise. Raw extreme event data is available in the Mendeley Data Repository at http://dx.doi.org/10.17632/j7hp5tmcr7.1. We would like to thank the editor and the three anonymous reviewers for their comments in helping to improve this manuscript.

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TABLES

Table 1 – LEFT: Domain-wide (spatial) mean trends for extreme event frequency (top; units are change in days per year, per decade), duration (middle; units are change in days per event, per decade) and spatial extent (bottom; units are percentage-point change of areal extent per decade, as seen in Figures 7 and 11). Darker reds (blues) indicates increasingly more positive (negative) trends. RIGHT: Percentages of statistically significant ($p<0.05$) grid points for frequency and duration; and p-values for spatial extent trendlines (those seen in Figures 7 and 11). Increasingly darker reds indicate higher percentages of significant values (for frequencies and durations) or more significant p-values (for spatial extents).

Freq	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
XWE	0.31	0.37	0.74	0.49	2.27
XCE	-0.71	-0.16	-0.25	-0.50	-2.57
XHE	0.14	0.45	1.07	0.56	2.69
XDE	-0.52	0.02	-0.20	-0.44	-1.60
Duration	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
XWE	0.10	0.11	0.20	0.16	0.20
XCE	-0.21	-0.04	-0.07	-0.17	-0.34
XHE	0.03	0.08	0.22	0.15	0.20
XDE	-0.11	0.04	-0.06	-0.16	-0.16

Freq	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
XWE	1.0%	0.4%	15.0%	20.1%	33.8%
XCE	19.9%	2.4%	15.2%	28.6%	56.5%
XHE	0.3%	8.6%	40.4%	19.8%	51.1%
XDE	24.9%	16.9%	25.9%	29.9%	61.4%
Duration	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
XWE	0.9%	0.0%	4.1%	14.2%	1.2%
XCE	14.8%	0.1%	8.3%	20.8%	29.6%
XHE	0.3%	0.0%	12.1%	10.2%	2.8%
XDE	16.4%	8.4%	12.2%	16.7%	28.1%

Extent	Winter	Spring	Summer	Autumn	Annual
XWE	0.6%	0.6%	1.1%	0.6%	0.8%
XCE	-0.7%	-0.4%	-0.6%	-0.6%	-0.7%
XHE	0.2%	0.6%	1.3%	0.8%	0.7%
XDE	-0.4%	0.0%	-0.2%	-0.5%	-0.3%

Extent	Winter	Spring	Summer	Autumn	Annual
XWE	0.000	0.011	0.000	0.000	0.000
XCE	0.039	0.237	0.001	0.004	0.000
XHE	0.000	0.000	0.000	0.119	0.000
XDE	0.003	0.218	0.001	0.025	0.152

Table 2 – TOP LEFT: Pearson spatial correlations between trends in raw temperatures (dew points) and trends in the frequency of extreme temperature (dew point) events. BOTTOM LEFT: same as the top left, except using the trends in the duration of extreme temperature (dew point) events. RIGHT: Pearson spatial correlations between extreme event frequencies and extreme event durations. Bold and underlined values indicate statistical significance ($p<0.05$). Darker reds (greens) indicate increasingly positive (negative) correlations.

Freq	Winter	Spring	Summer	Autumn
XWE	**0.477**	**0.603**	**0.623**	**0.567**
XCE	**-0.589**	**-0.326**	**-0.349**	**-0.685**
XHE	**0.620**	**0.566**	**0.769**	**0.575**
XDE	**-0.723**	**-0.827**	**-0.737**	**-0.770**

Duration	Winter	Spring	Summer	Autumn
XWE	0.444	0.453	0.455	0.608
XCE	-0.592	-0.138	-0.190	-0.609
XHE	0.561	0.422	0.517	0.639
XDE	-0.720	-0.791	-0.589	-0.646

Freq vs. Duration	Winter	Spring	Summer	Autumn
XWE	0.830	0.780	0.784	0.832
XCE	0.745	0.670	0.716	0.784
XHE	0.696	0.714	0.759	0.761
XDE	0.822	0.861	0.795	0.815

Table 3 – Comparison between airport weather station observations of the four types of extreme events and NARR-based extreme events (at the nearest land-based gridpoint), averaged across all 230 locations examined. Annual rho is the Spearman rank-correlation of the annual counts of extreme events between station data and NARR data. Sig. Diff Trend is the percentage of locations (n=230) that have statistically significantly (p<0.05 after correcting for spatial autocorrelation) different trend estimates between stations and NARR.

	Annual rho	Sig. Diff. Trend

XWE	0.79	2.2%
XCE	0.84	0.4%
XHE	0.61	17.3%
XDE	0.76	3.5%

FIGURES

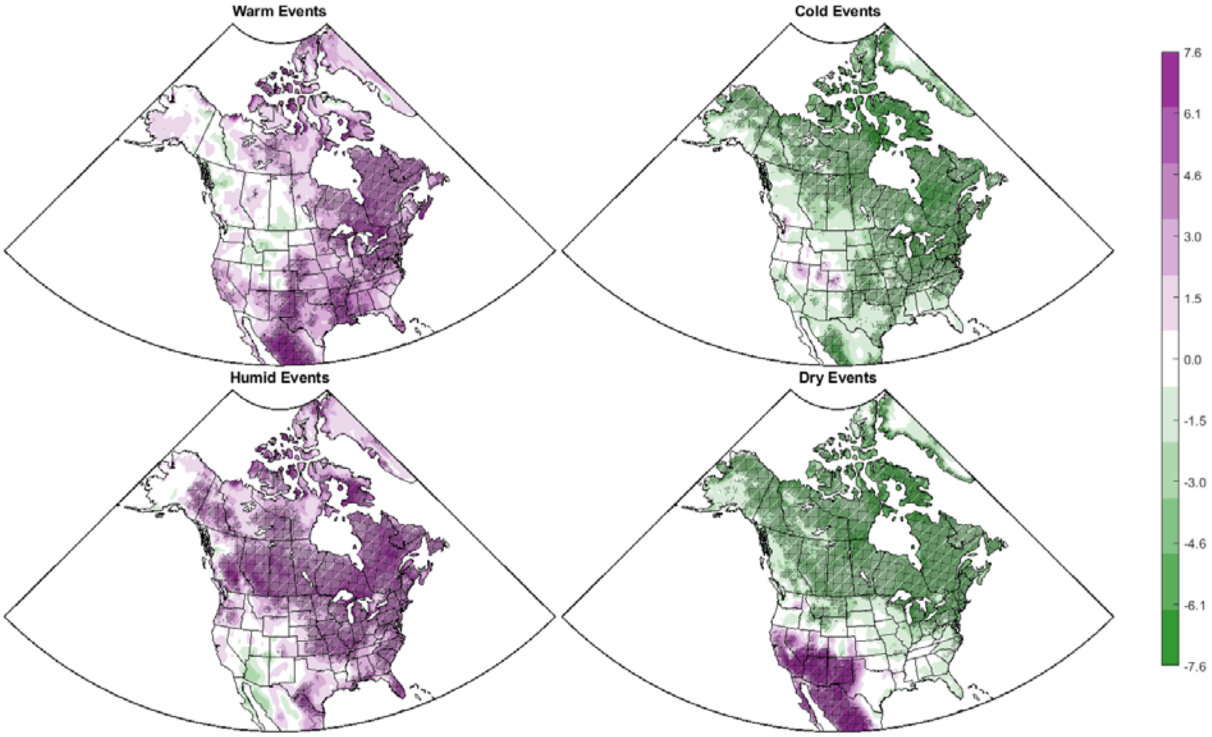
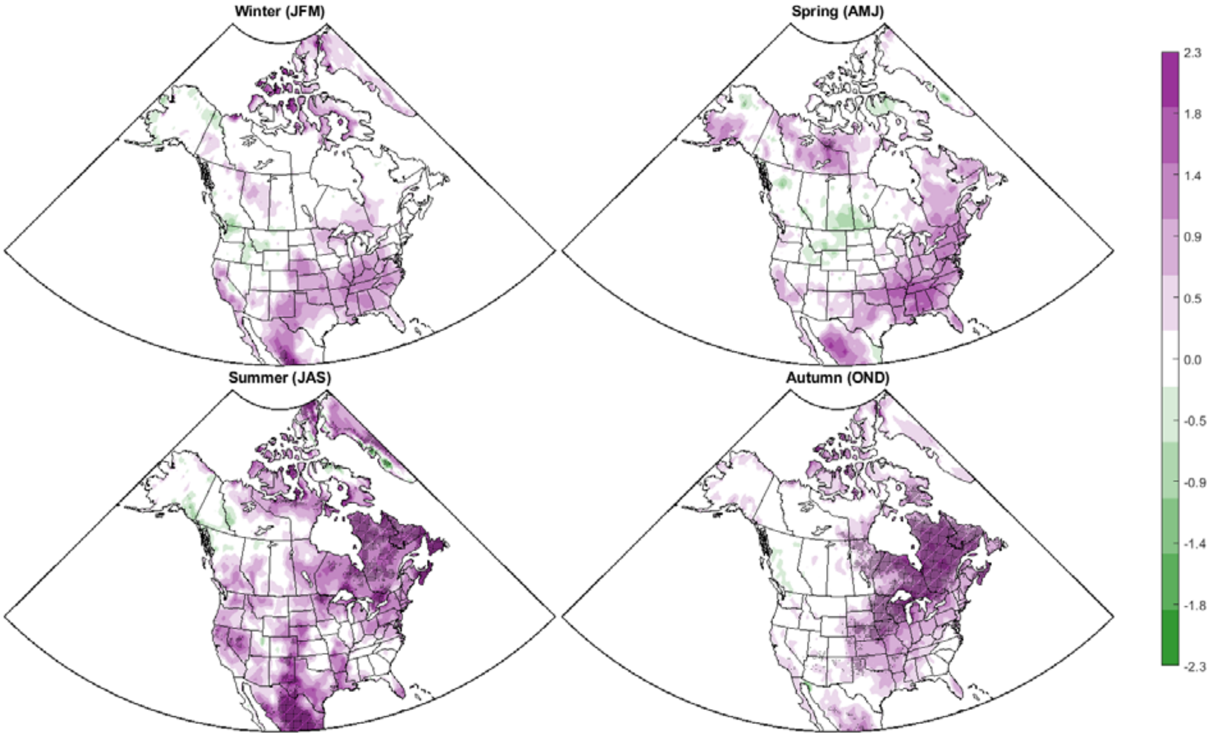


Figure 1 – Decadal change in annual event frequencies. Units are change in event-days per year, per decade. Stippling indicates statistical significance ($p<0.05$).


Winter (JFM)
Spring (AMJ)
Summer (JAS)
Autumn (OND)
2.3
1.8
1.4
0.9
0.5
0.0
-0.5
-0.9
-1.4
-1.8
-2.3

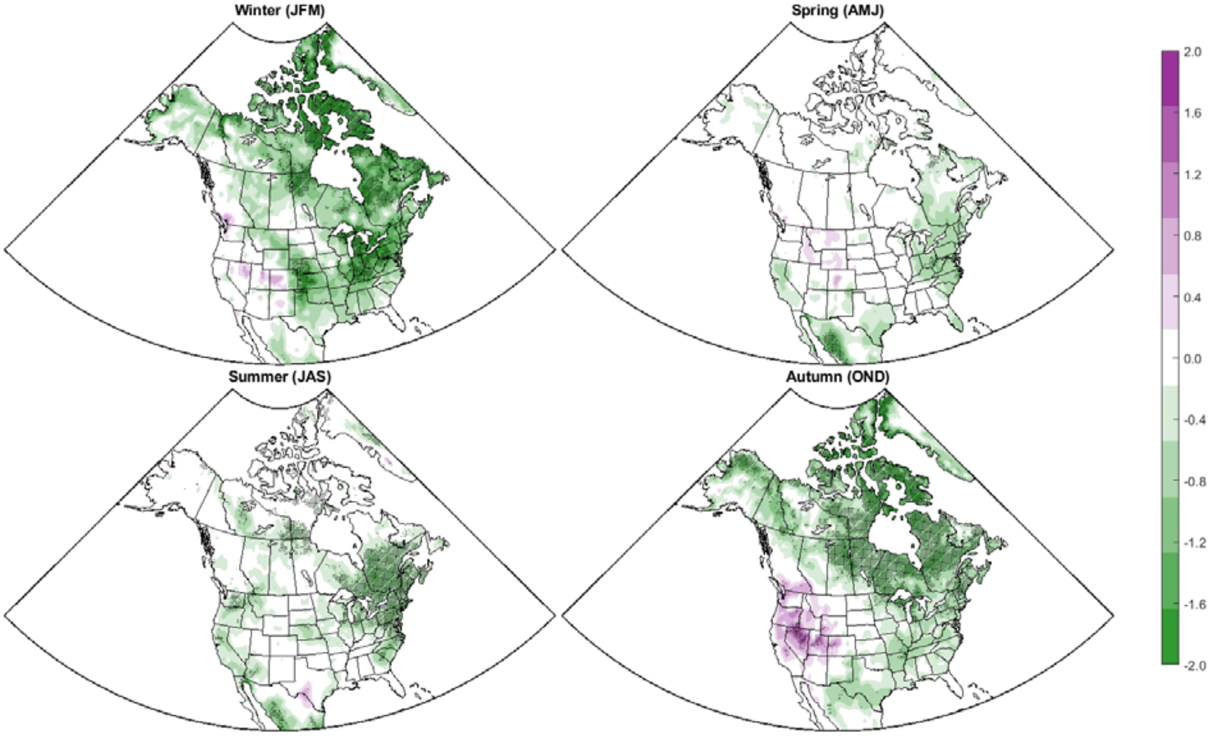
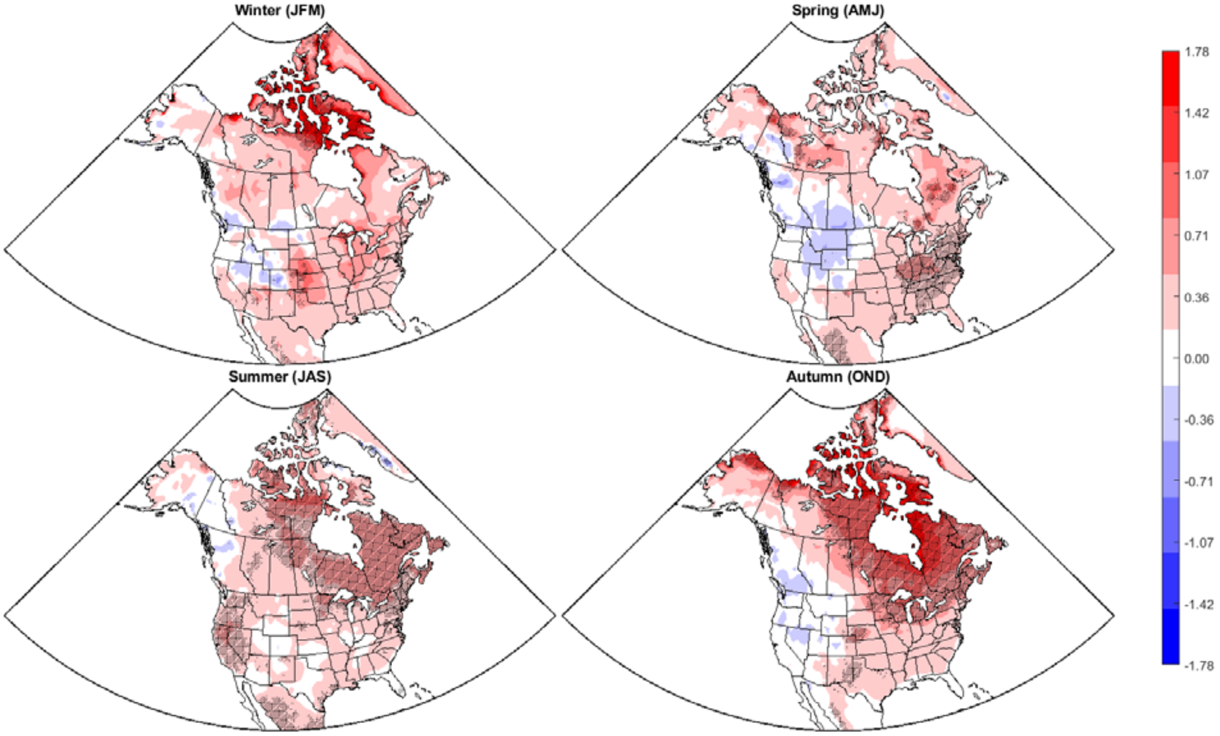


Figure 2 – Decadal changes in extreme 2m warm event frequencies (top four) and extreme 2m cold event frequencies (bottom 4), by season. Units are change in event-days per season, per decade. Statistically significant ($p<0.05$) values are shown with stippling. Note the different scale for the two types of events.


Winter (JFM)
Spring (AMJ)
Summer (JAS)
Autumn (OND)
1.78
1.42
1.07
0.71
0.36
0.00
-0.36
-0.71
-1.07
-1.42
-1.78

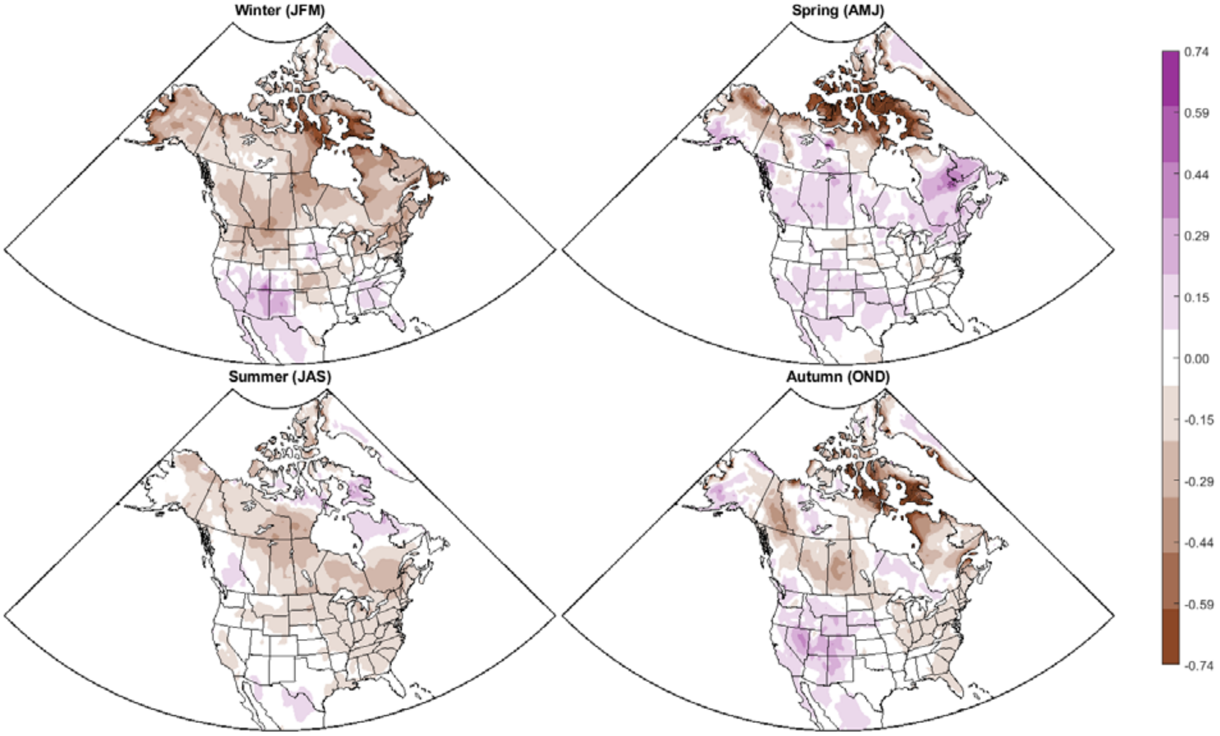


Figure 3 – Decadal changes in 2-m temperature means (top 4) and standard deviations (bottom 4), by season. Units are in Δ°C/decade. Statistically significant ($p<0.05$) values are shown with stippling.

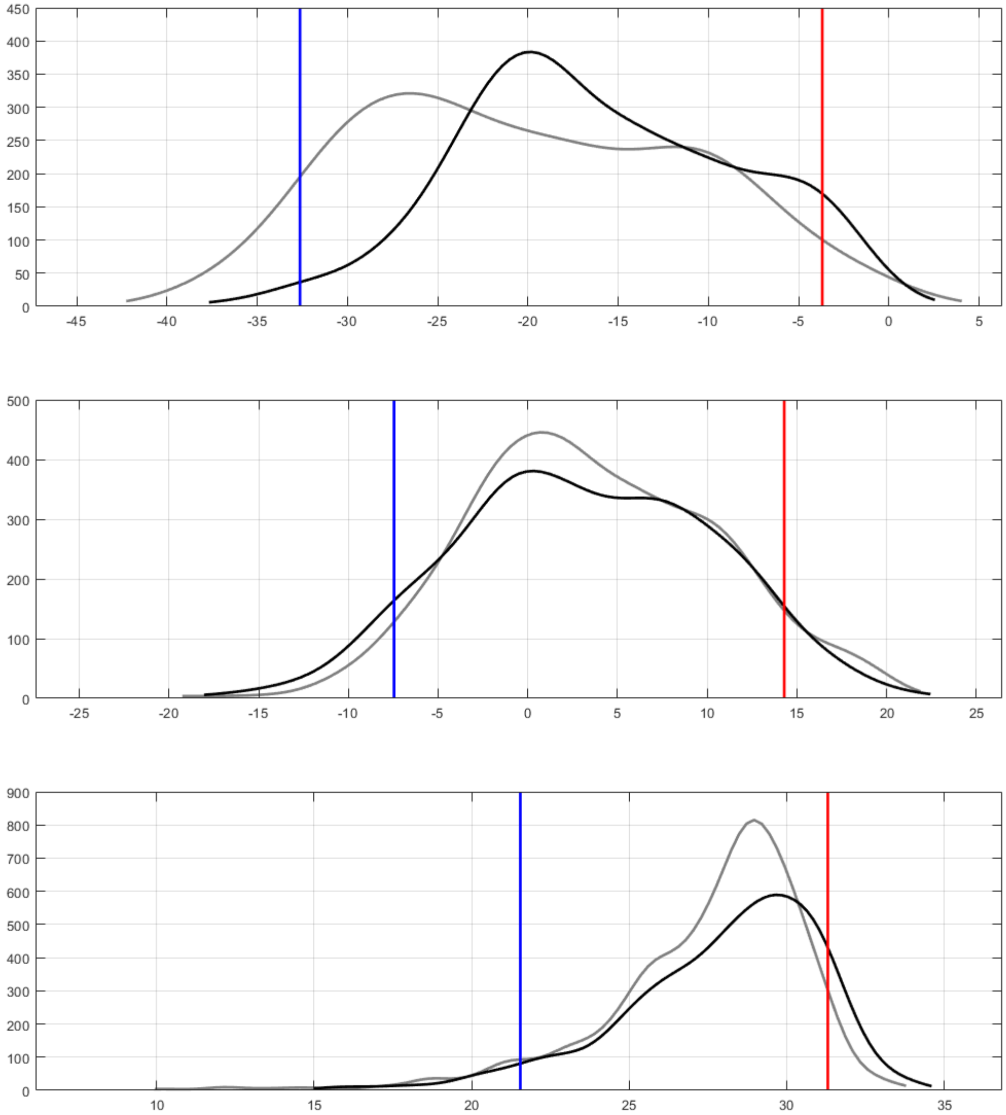


Figure 4 – Changes in 2-meter temperature distributions between the first half (1979-1997; gray lines) and last half (1998-2016; black lines) of the study period. Blue and red vertical lines denote thresholds for extreme temperature events (at the 5th and 95th percentiles). The top graphic shows temperatures for 5 northern Canada gridpoints in autumn. The middle graphic shows temperatures for 5 western United States gridpoints in autumn. The bottom graphic shows temperatures for 5 Southern Plains gridpoints in summer. The horizontal axes units are °C, the vertical axes are frequency counts. Note that both axes differ for each subplot.

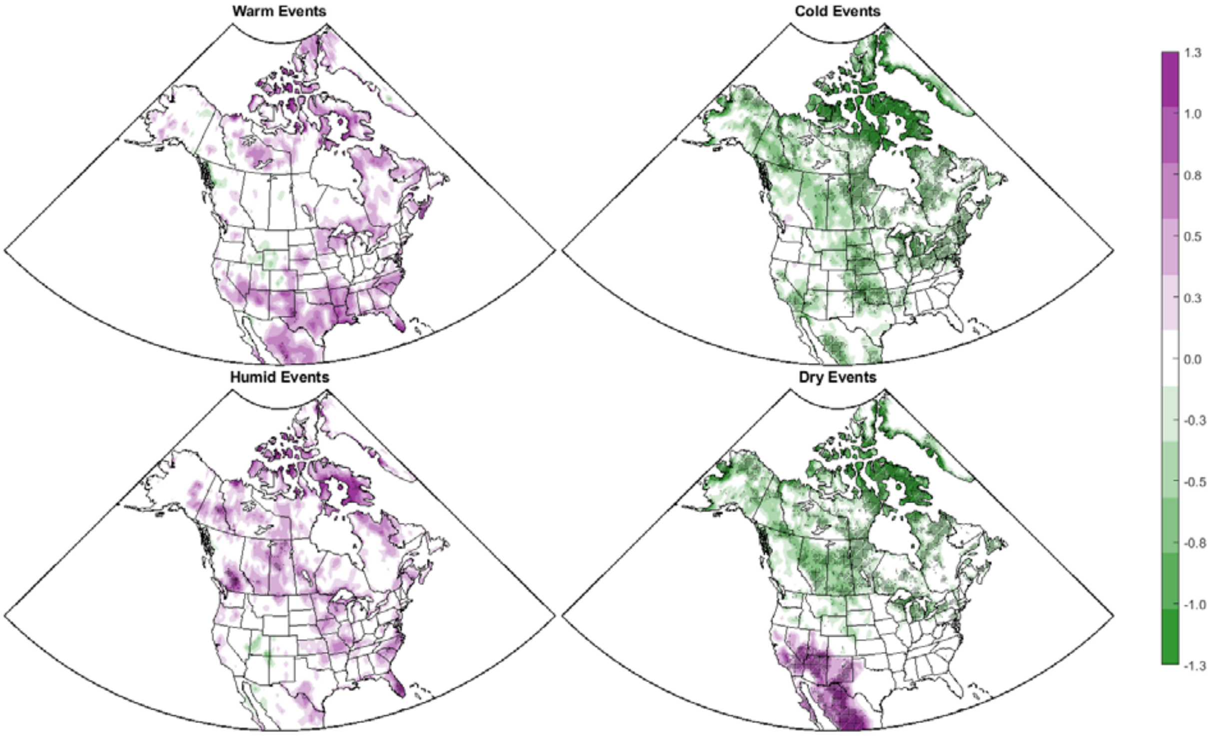
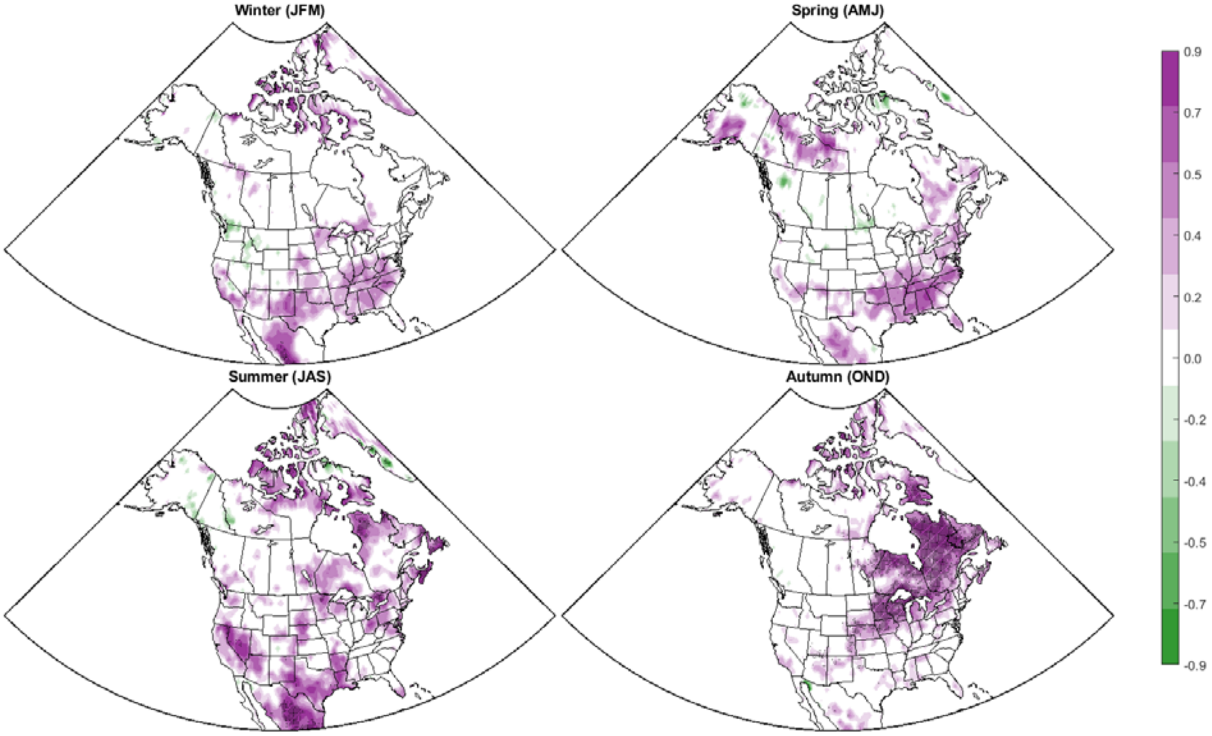


Figure 5 - Change in days per event, per decade. Stippling indicates statistical significance ($p<0.05$).


Winter (JFM)
Spring (AMJ)
Summer (JAS)
Autumn (OND)
0.9
0.7
0.5
0.4
0.2
0.0
-0.2
-0.4
-0.5
-0.7
-0.9

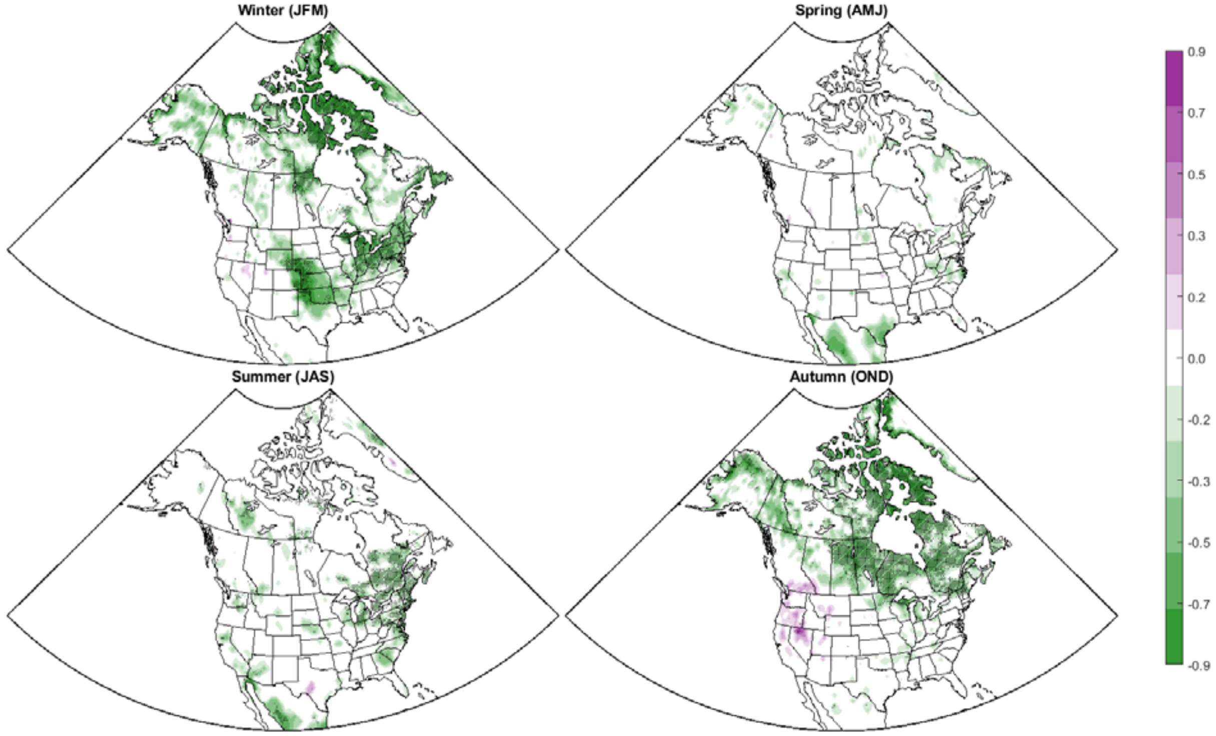


Figure 6 – Decadal changes in extreme 2m warm event durations (top four) and extreme 2m cold event durations (bottom 4), by season. Units are change in days per event, per decade. Statistically significant (p<0.05) values are shown with stippling.

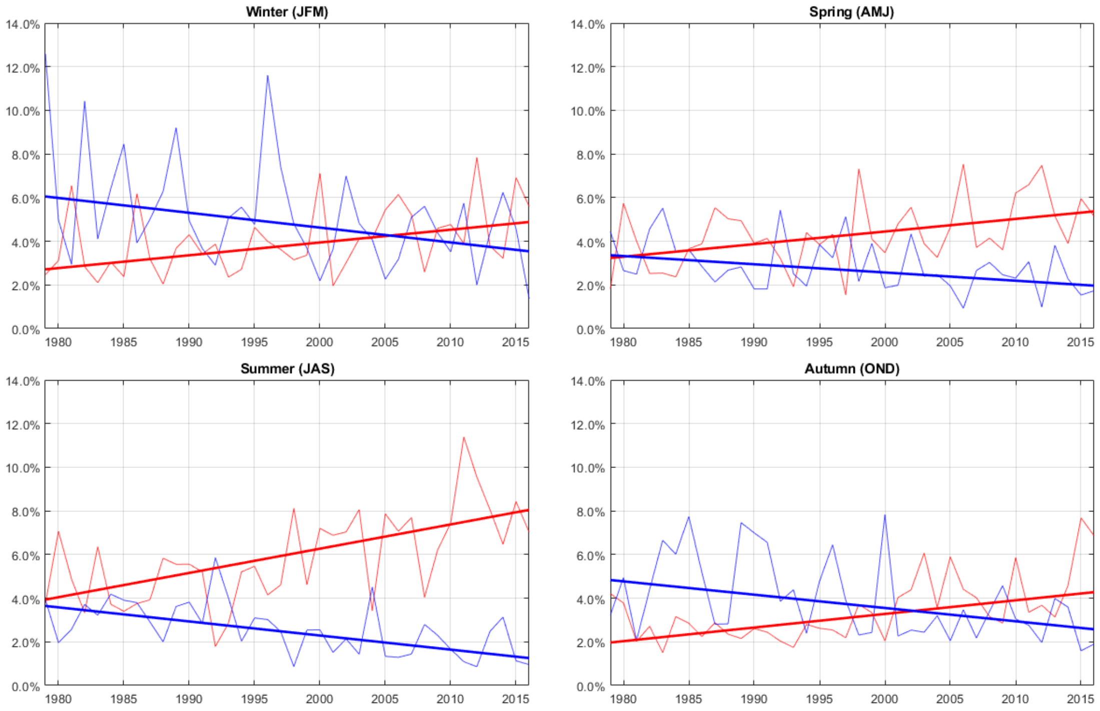
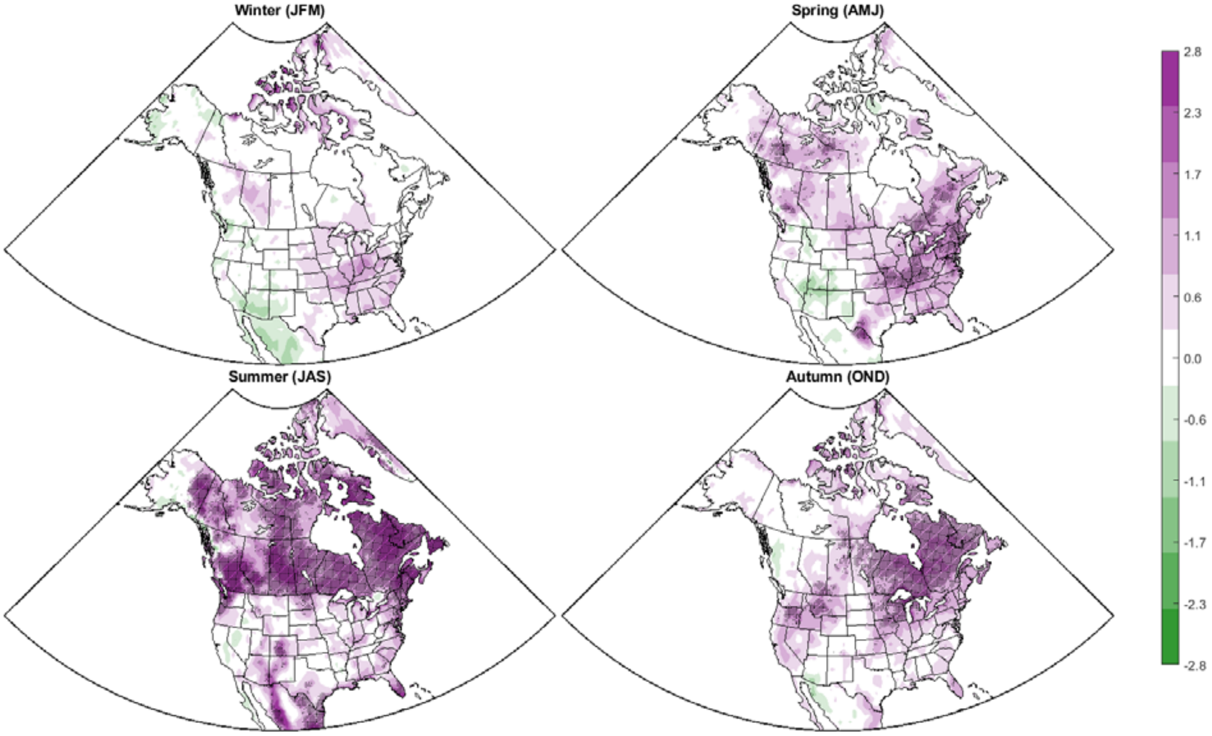


Figure 7 – Time series (thin lines) and linear trend line (thick lines) for extreme 2m warm event spatial extents (red) and extreme 2m cold event spatial extents (blue), by season. Y-axis units are latitude-corrected percentage of area (within the domain) covered.


Winter (JFM)
Spring (AMJ)
Summer (JAS)
Autumn (OND)
2.8
2.3
1.7
1.1
0.6
0.0
-0.6
-1.1
-1.7
-2.3
-2.8

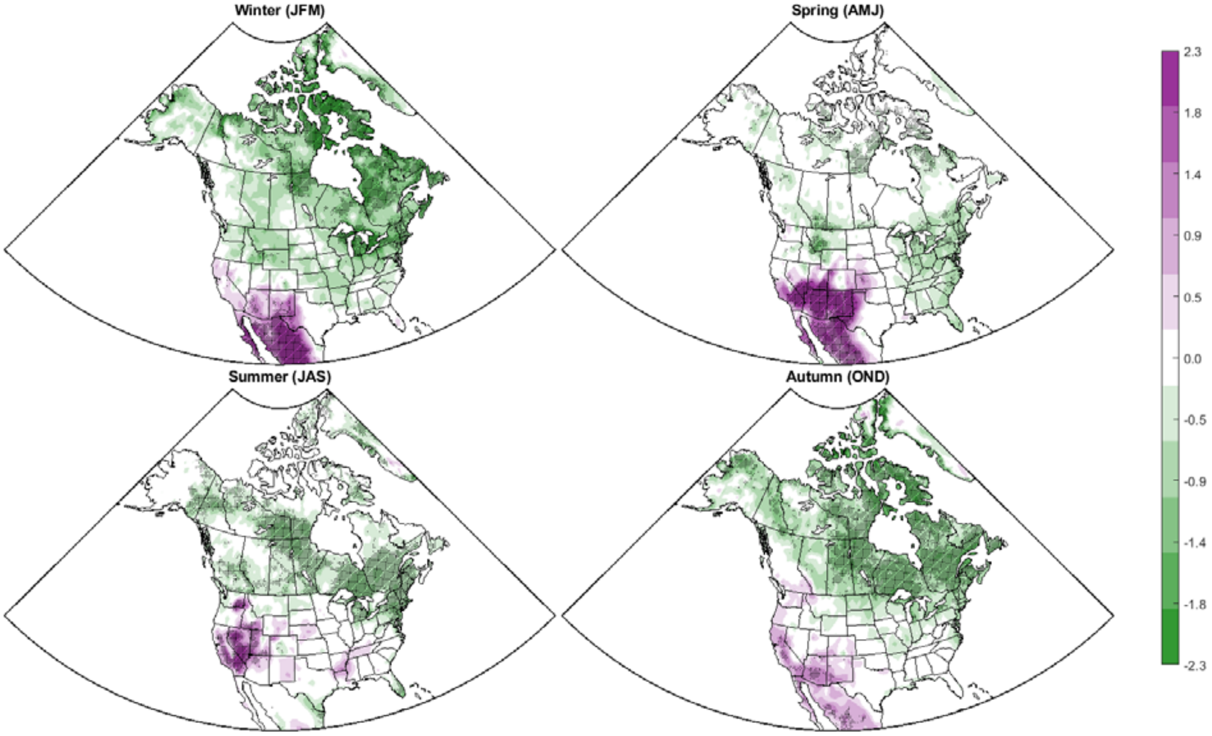
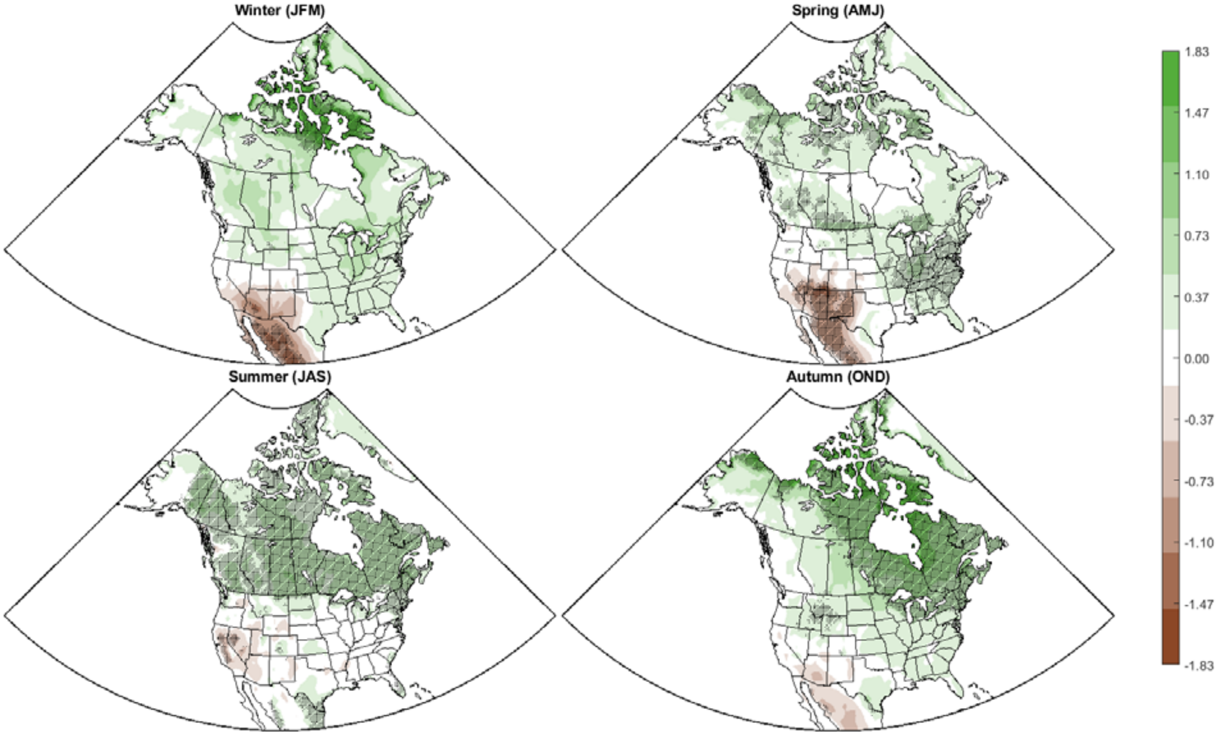


Figure 8 – Decadal changes in extreme 2m humid event frequencies (top four) and extreme 2m dry event frequencies (bottom 4), by season. Units are change in days per season, per decade. Statistically significant ($p<0.05$) values are shown with stippling. Note the different scale for the two types of events.


Winter (JFM)
Spring (AMJ)
Summer (JAS)
Autumn (OND)
1.83
1.47
1.10
0.73
0.37
0.00
-0.37
-0.73
-1.10
-1.47
-1.83

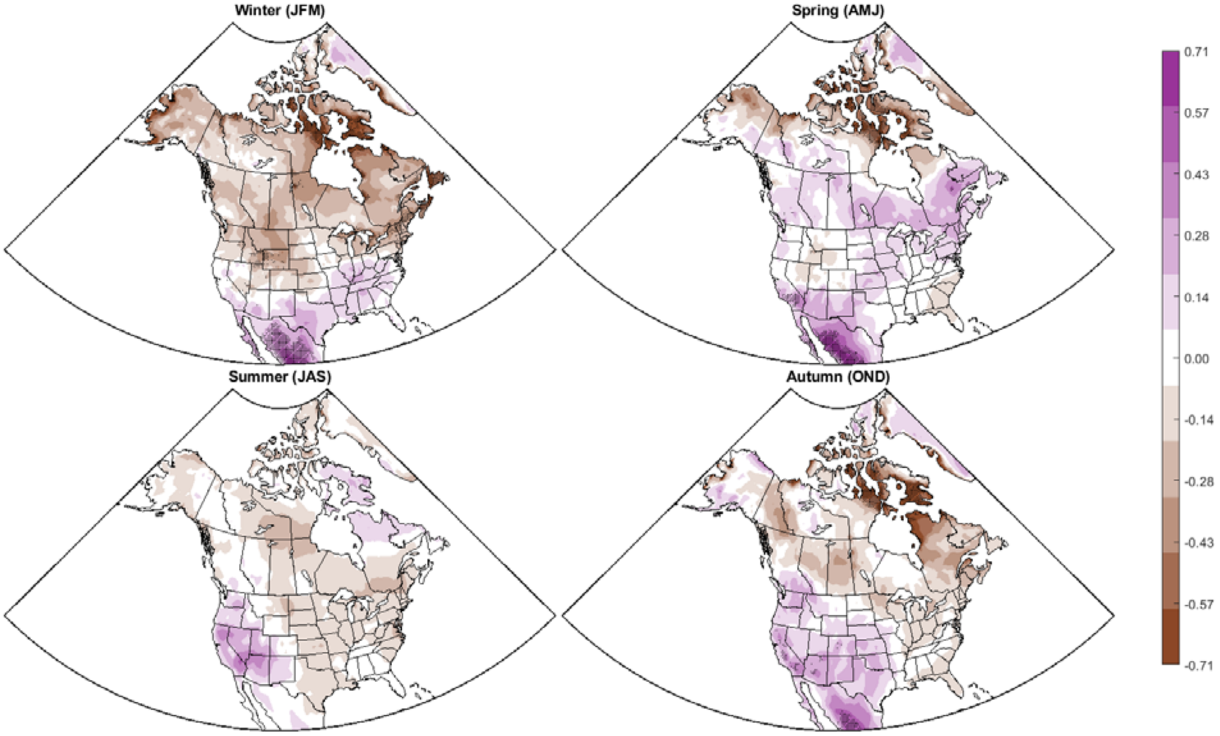
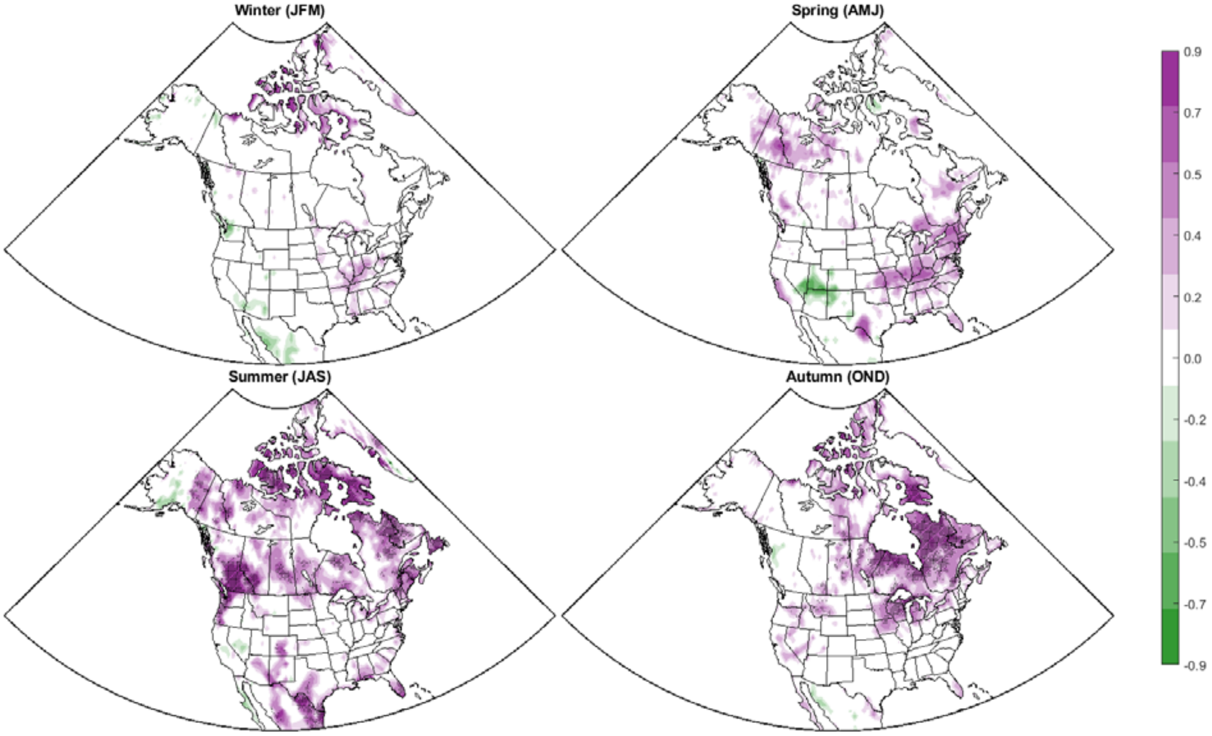


Figure 9 – Decadal changes in 2-m dew point means (top 4) and standard deviations (bottom 4), by season. Units are in Δ°C/decade. Statistically significant ($p<0.05$) values are shown with stippling.


Winter (JFM)
Spring (AMJ)
Summer (JAS)
Autumn (OND)
0.9
0.7
0.5
0.4
0.2
0.0
-0.2
-0.4
-0.5
-0.7
-0.9

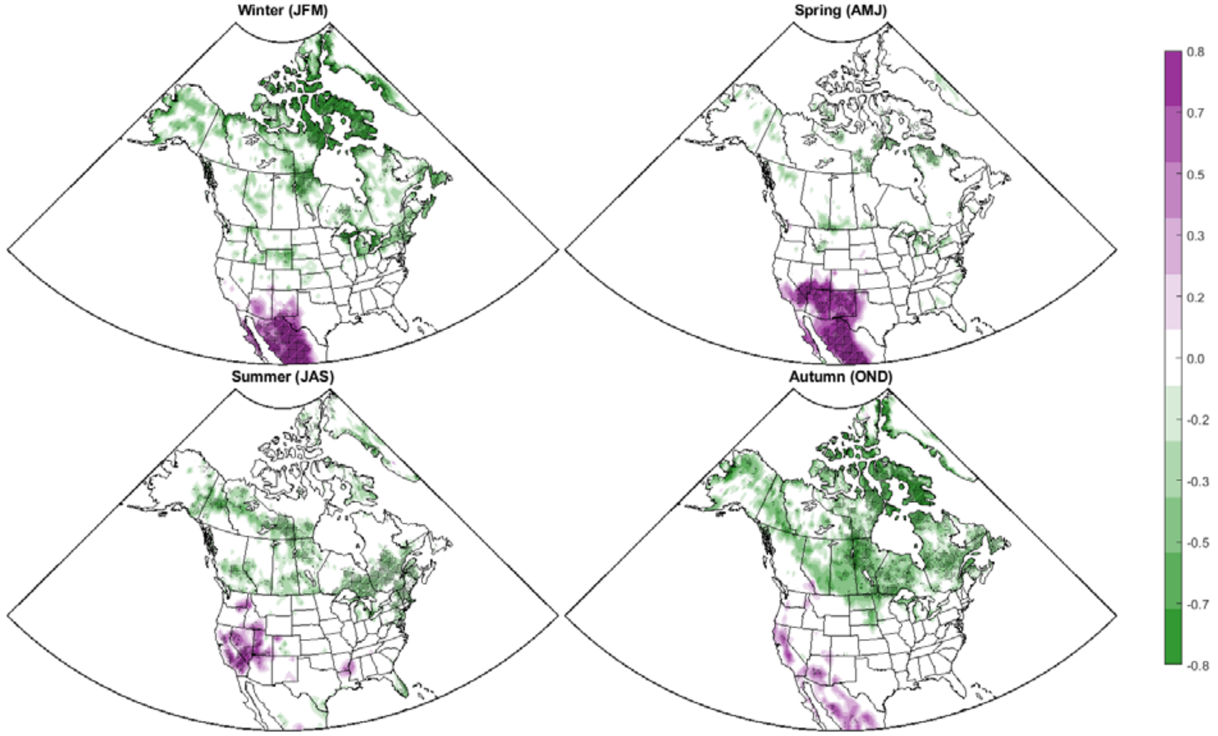


Figure 10 – Decadal changes in extreme 2m humid event durations (top four) and extreme 2m dry event durations (bottom 4), by season. Units are change in days per event, per decade. Statistically significant ($p<0.05$) values are shown with stippling.

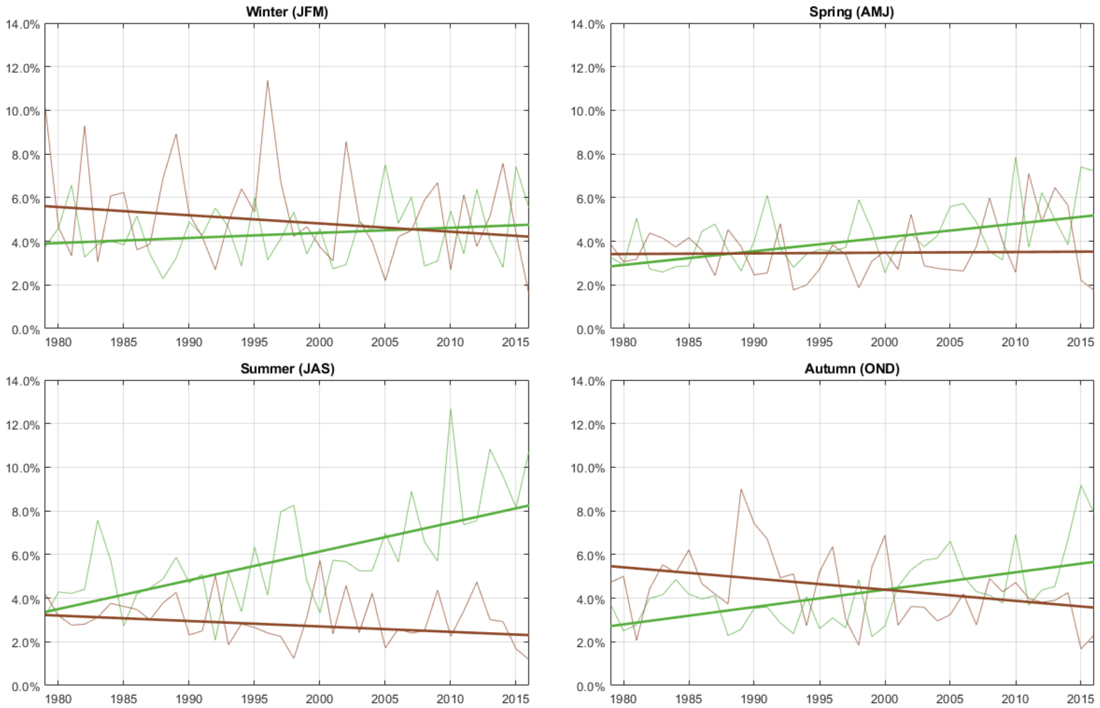
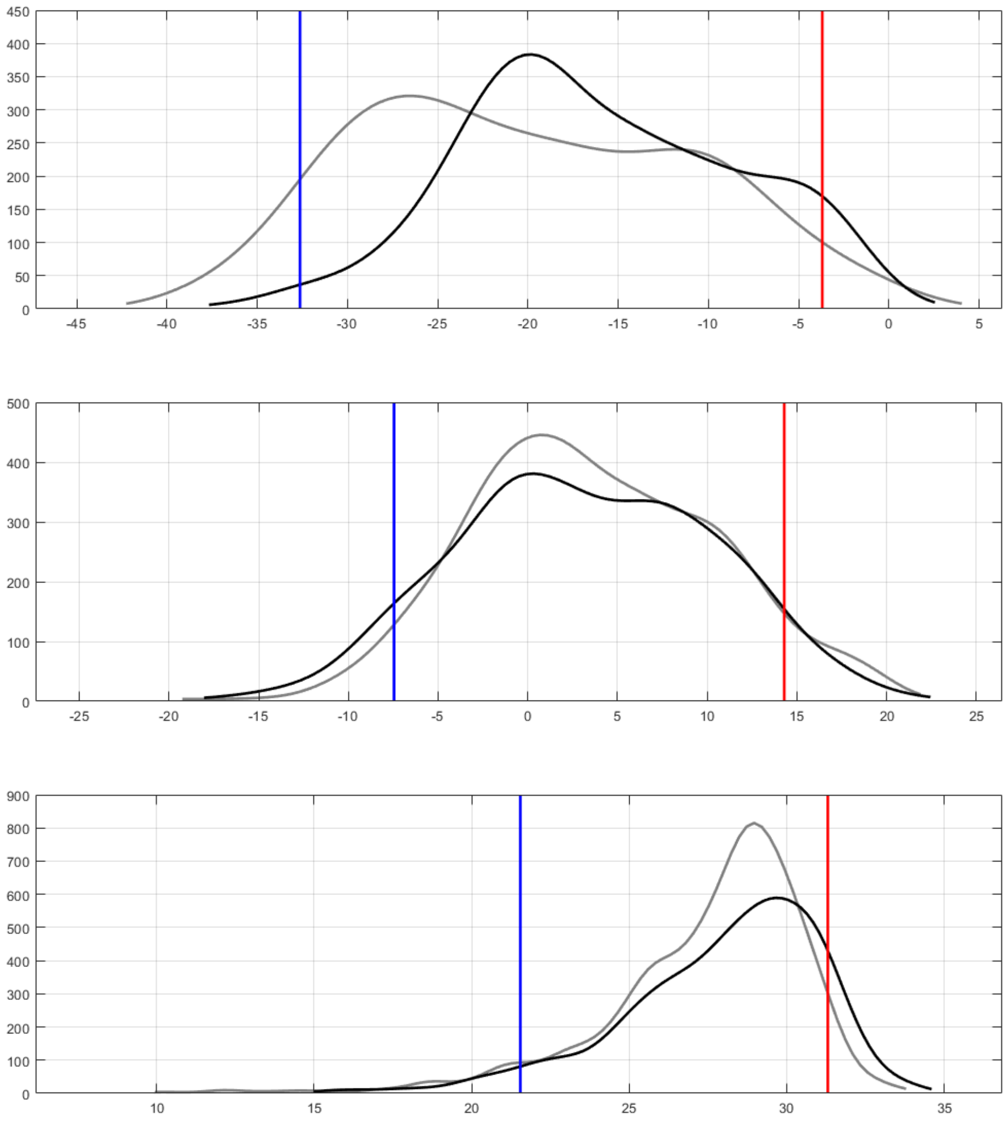


Figure 11 – Time series (thin lines) and linear trend line (thick lines) for extreme 2m humid event spatial extents (green) and extreme 2m dry event spatial extents (brown), by season. Y-axis units are latitude-corrected percentage of area (within the domain) covered.

Examining trends in multiple parameters of seasonally-relative extreme temperature and dew point events across North America

Cameron C. Lee*, Omon Obarein, Scott C. Sheridan, Tyler E. Smith, Ryan Adams



This research examines trends in three components of seasonally-relative extreme temperature and humidity events in North America: frequency, persistence, and areal extent. While many changes in these events are in the expected direction, opposite extremes are not changing with the same magnitude, and trends vary markedly by season. Most importantly, some regions show changes to *extreme* events that differ from the overall changes in *means*, highlighting the importance of examining not only extreme events, but changes in higher-order statistical moments.