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North American Weather Regimes Are Becoming More Persistent: Is Arctic Amplification a Factor?

J. A. Francis[1], N. Skific[1], and S. J. Vavrus[2]

[1]Department of Marine and Coastal Sciences, Rutgers, The State University of New Jersey, New Brunswick, NJ, USA, [2]Center for Climatic Research, University of Wisconsin-Madison, Madison, Wisconsin, USA

Key Points:

- Long-duration (greater than or equal to 3 days) dry and wet spells measured at 17 U.S. stations generally occurred more frequently in recent decades
- The frequency of persistent large-scale circulation regimes over North America has increased for patterns with anomalously warm high latitudes
- Warm Arctic patterns have increased in frequency, suggesting increased occurrence of persistent patterns as rapid Arctic warming continues

Supporting Information:

- Supporting Information S1

Correspondence to:
J. A. Francis,
francis@imcs.rutgers.edu

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Abstract Rapid Arctic warming is hypothesized to favor an increased persistence of regional weather patterns in the Northern Hemisphere (Francis & Vavrus, 2012). Persistent conditions can lead to drought, heat waves, prolonged cold spells, and storminess that can cost millions of dollars in damage and disrupt societal and ecosystem norms. This study defines a new metric called long-duration events (LDEs)—conditions that endure at least four consecutive days—and takes two independent approaches to assessing seasonal changes in weather-pattern persistence over North America. One applies precipitation measurements at weather stations across the United States; the other is based on a cluster analysis of large-scale, upper-level atmospheric patterns. Both methods indicate an overall increase in LDEs. We also find that large-scale patterns consistent with a warm Arctic exhibit an increased frequency of LDEs, suggesting that further Arctic warming may favor persistent weather patterns that can lead to weather extremes.

Plain Language Summary Rapid Arctic warming and sea ice loss are expected to affect weather patterns around the Northern Hemisphere. An increased persistent of weather regimes is one hypothesized impact. Long-lasting weather conditions can lead to destructive extreme events, such as droughts, prolonged cold spells, heat waves, and flooding. This study uses daily precipitation measurements across the United States, as well as daily large-scale atmospheric patterns over the eastern Pacific and North America, to assess changes in weather-regime persistence and whether any changes are associated with a rapidly warming Arctic. We find an increased frequency in long-lived patterns in recent decades, especially those with abnormally warm high latitudes, suggesting that further Arctic warming may favor an increase in extreme events caused by prolonged weather conditions.

1. Introduction

In recent decades the Arctic has been warming at least twice as fast as the globe as a whole, a phenomenon known as Arctic amplification (Burt et al., 2015; Francis et al., 2017; Pithan & Mauritsen, 2014; Screen & Simmonds, 2010). The resulting weakening of the poleward temperature gradient between midlatitudes and the Arctic reduces the atmospheric potential energy that is a primary driver of zonal winds in the polar jet stream. A general slowing of westerly winds aloft has indeed been observed in midlatitudes (e.g., Coumou et al., 2015; Vavrus et al., 2017) and simulated by atmospheric models (e.g., Pedersen et al., 2016), with a great deal of regional and seasonal variability (Francis & Vavrus, 2015). It has been hypothesized that these reduced zonal winds will favor increased north-south meandering of the polar jet stream, which has also been observed using a variety of new metrics (Cattiaux et al., 2016; Di Capua & Coumou, 2016; Vavrus et al., 2017), although not uniformly around the Northern Hemisphere. It has also been hypothesized that naturally occurring jet stream ridges can be intensified by regional Arctic amplification if the ridge and the high-latitude heat anomaly are collocated in longitude (e.g., Cvijanovic et al., 2017; Francis et al., 2017; Kug et al., 2015; Osborne et al., 2017; Sung et al., 2016), favoring an amplified Rossby wave pattern. High-amplitude (north-south) planetary Rossby waves are known to progress eastward more slowly (Chen et al., 2015), causing weather regimes associated with those waves to be more persistent. Prolonged weather conditions can lead to a variety of extreme weather events such as drought, heat waves, cold spells, and storminess (Screen & Simmonds, 2014), some of which appear to be increasing in frequency (e.g., Diffenbaugh et al., 2017; National Oceanic and Atmospheric Administration's Climate Extremes Index, 2016; Gallant et al., 2014; Herring et al., 2016; Munich Re, 2015; National Academies of Sciences, 2016; Rahmstorf & Coumou, 2011; Wuebbles et al., 2014). Whether the waviness of the jet stream has changed and whether any such changes can be attributed to amplified Arctic warming (AAW) and/or other factors, however, has been a topic of active research and controversy in recent years (Barnes & Screen, 2015; Francis, 2017; McCusker et al., 2016).

While many recent studies have investigated the atmospheric response to Arctic sea ice loss (e.g., Cvijanovic et al., 2017; Deser et al., 2016; Knapp & Soulé, 2017; Kug et al., 2015; Lee et al., 2015; McCusker et al., 2016; Meleshko et al., 2016; Nakamura et al., 2015; Sorokina et al., 2016; Sun et al., 2016; Sung et al., 2016; Wang et al., 2018), the question of whether AAW is affecting the *persistence* of weather regimes has received little attention. The duration of various weather types has been explored (e.g., Screen, 2013; Screen et al., 2015; Zolina et al., 2013) with some indications that persistence has increased during summer in midlatitudes (e.g., Coumou et al., 2018; Pfleiderer & Coumou, 2017) while changes have varied in other seasons and regions. Here we define a new persistence metric to assess the frequency of long-duration events (LDEs). We apply this concept in two independent analyses over North America to investigate whether regime persistence has changed and if any relationship exists to regional AAW.

2. Data and Methods

While the concept of regime persistence seems simple, the selection of variables to use for this assessment is not. For example, station temperatures may seem like an obvious choice, but they suffer from local effects such as cloud cover, wind direction (especially near water bodies and mountains), soil moisture, and specific humidity. Precipitation is another candidate, but it can be extremely spotty at a single location, especially in summer when convective cells may affect only small areas. Pressure-level geopotential heights can also be used to assess overall regime type, but height anomalies do not necessarily correlate with surface weather conditions.

For this study we define LDEs to describe conditions that persist for at least four consecutive days—a threshold selected based on the observed distributions of duration lengths. Frequencies of events tend to decline markedly for periods longer than a few days. A constant threshold is desirable to enable application of the metric across different data sets and approaches. We apply this definition of LDEs to two distinct data sources: clusters of station measurements and large-scale upper-level atmospheric patterns.

Our first approach is to assess precipitation-based LDEs (PLDEs) at weather stations. We use daily precipitation data from 17 locations across the United States (Figure 1a), which provide a representative sampling of most geographic types. Data were obtained from the National Centers for Environmental Information (https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily). Each location spans approximately 50 km × 50 km (Figure 1b) with relatively homogenous surface conditions. We selected 8 to 12 individual stations within the area that have continuous data from at least 1950 through 2015. While precipitation at individual stations can be highly spatially variable on a given day, we reason that precipitation across a cluster of stations is a good indicator of a dry or moist weather regime. If all stations within a cluster record dry conditions on a given day, then the atmospheric conditions are not conducive to precipitation. Likewise, if any station within a cluster *does* record precipitation on a given day, the weather pattern is a potential precipitation producer. We therefore define dry spells and wet spells as follows: A dry PLDE is identified if all selected stations within a regional cluster report $\leq$0.01″ for four or more consecutive days, and a wet PLDE is tabulated when at least one station reports $>$0.01″ of precipitation during four or more consecutive days. (Thresholds of $\geq$5 days for PLDEs and $>$ 0.05″ for wet days were also tested. The study's conclusions were not affected.) Trends in the frequency of PLDEs are calculated for 1950–2015 and for 1996–2015, when AAW has been most pronounced.

Our second approach is to use the clustering tool known as self-organizing maps (SOMs) to identify changes in large-scale, upper-level patterns over the eastern Pacific/North America sector of the Northern Hemisphere (30–80°N, 180–60°W). Daily average 500-hPa geopotential height fields were obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research Reanalysis from 1948 to 2015 (Kalnay et al., 1996). Fields of 500-hPa heights from other reanalyses have been shown to be nearly identical (e.g., Archer & Caldeira, 2008). Daily anomalies were calculated by subtracting the 68-year mean value for each grid point for that calendar day then the spatial-mean height for each daily field was subtracted.

The SOM algorithm is a neural-network technique that reduces the dimension of a large data set by organizing it into a two-dimensional array or matrix (Kohonen, 2001). It groups the daily fields into a small number of

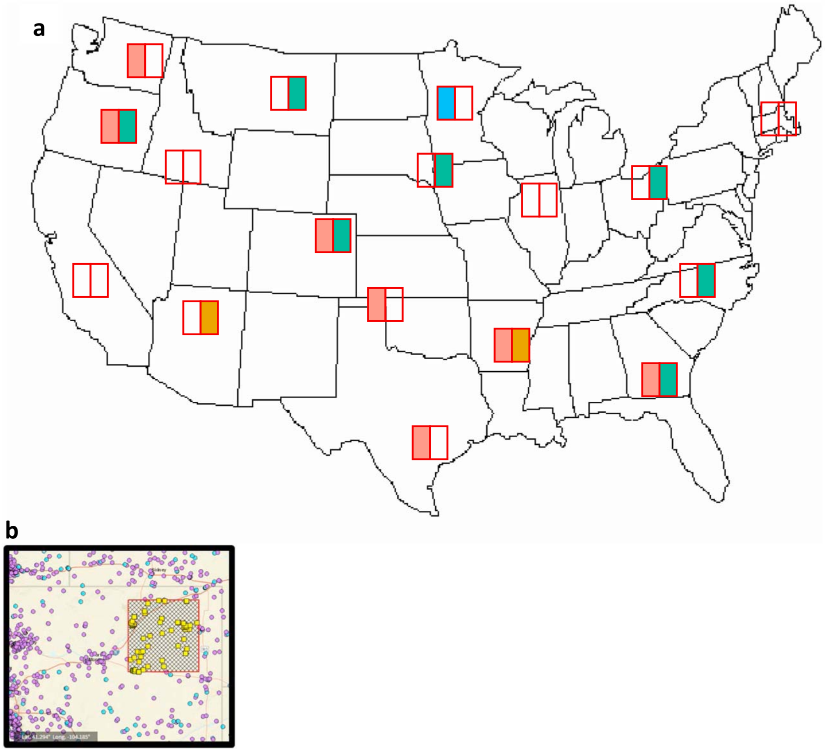

Figure 1. (a) Locations of 17 regions where station data are used to assess dry and wet PLDEs. The left side of split boxes is shaded pink (blue) if annual trend in frequency of dry PLDEs from 1996 to 2015 is significantly positive (negative) at confidence >95%. The right side of split boxes is shaded green (gold) if trend in frequency of wet PLDEs is significantly positive (negative). (b) Example of station locations within region located in NE Colorado. Only stations with continuous data from before 1950 to 2015 are selected for analysis. (Data are obtained from https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily.)

clusters or nodes (matrix size chosen according to the application [see Skific & Francis, 2012]; in this case we selected a 3 × 4 matrix) that represent the range of dominant patterns existing in the original data set. Each cluster is displayed as a geophysical field (in this case, maps of 500-hPa height anomalies), and the representative patterns are grouped in the matrix according to their similarity to each other, with adjacent patterns being most similar. Further detail on the application of SOMs in atmospheric research is available from Skific and Francis (2012) and Skific et al. (2009a, 2009b).

The relative frequency of occurrence of each pattern is also calculated, and changes in pattern frequency over time can be assessed. Because it is known which days belong in each cluster, the distribution of consecutive days that the atmosphere resides in a particular node of the SOM can be calculated, thereby quantifying the frequency of circulation-based LDEs (CLDEs) for each pattern in the matrix, as well as changes in those frequencies. As with the station data analysis, a CLDE is identified when four or more consecutive days reside in a node. Persistence metrics can also be related to other variables corresponding to the days that belong in each pattern, such as a metric of AAW based on daily 2-m temperature data from the National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis, the difference in temperature anomalies between the Arctic (70–90°N) and midlatitudes (30–60°N) in the SOM domain. Values of the daily Arctic oscillation (AO) index were also obtained from National Oceanic and Atmospheric Administration's Climate Prediction Center at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml.

3. Results

3.1. Station Data

Changes in the number/year of dry and wet PLDEs at each of 17 locations across the United States are presented in Tables 1 and 2 for the period from 1996 to 2015 and for the longer record from 1950 to 2015 in

Table 1
Recent Trends in Dry PLDEs (number per year × 10) 1996–2015

Location	JFM	AMJ	JAS	OND	ANN
Massachusetts	−0.5	1.8	0.5	0.5	1.4
NE Ohio	−1.6	1.1	0.9	−0.1	0.1
N. Carolina	4.6	−1.2	−2.6	1.5	2.7
S. Georgia	3.4	3.9	−0.4	5.4	1.2
Minnesota	−3.3	−5.6	−0.9	−2.6	−12.7
E. Montana	−0.2	−0.4	1.1	1.2	2.1
NW Iowa	3.9	−1.9	0.9	0.9	3.7
N. Illinois	3.2	−1.8	4.4	−1.6	5.2
NE Colorado	3.9	4.9	3.2	6.4	18.9
Oklahoma	5.8	4.2	4.7	8.8	23.6
SE Arkansas	−0.7	4.3	3.9	3.6	1.1
SE Texas	2.4	1.8	2.0	3.4	9.8
E. Washington	0.4	1.3	4.0	0.8	7.5
Oregon	1.0	1.1	2.3	2.8	7.5
S. Idaho	0.5	−1.1	0.1	−1.1	−1.5
California	−2.3	−0.3	−0.5	1.9	1.1
Arizona	−2.8	−2.6	−0.5	2.1	−3.0

Note. ANN = annual.

Tables S1 and S3 in the supporting information. Seasonal and annual trends are listed, and results are grouped into eastern, central, and western regions. A geographical representation of statistically significant (>95% confidence) annual trends in PLDEs from 1996 to 2015 is shown in Figure 1a.

Annual trends in dry PLDEs since 1996 are significantly positive in 7 of 17 locations (41%), and only one location exhibits a decreasing frequency. Results for the period since 1950 are similar (35% increasing/12% decreasing). The spatial distribution map indicates that increasing PLDEs tend to occur in the southeast, south-central, and northwest areas of the United States. Given the ongoing drought in the southwestern United States, it may seem surprising that those locations do not exhibit increasing trends, but this is because the dry periods there tend to endure for several months at a time and thus the annual frequency of individual PLDEs is small. We do find, however, that the mean duration of long dry spells in these locations has increased significantly (difference from 1976–1995 to 1996–2015) in winter, spring, and fall (Table S2), while dry spell duration has generally decreased elsewhere. Changes in PLDE frequency can differ from changes in duration, as the distributions of PLDE duration may also shift. The seasonal distribution of positive trends in dry PLDEs is fairly even (Table 1). The probability that 28 of 85 table cells have positive trends by chance is near zero according to a binomial distribution test ($N = 85$, $p = 0.05$) to determine field significance (Wilks, 1995). These results suggest that dry PLDEs have occurred more frequently since the middle twentieth century and particularly so during the last few decades.

The occurrence of wet PLDEs has also increased since 1996, with significant positive trends spanning most of the country except for New England and the southwest (Figure 1, right side of boxes). Annually, 41% (12%) of locations exhibit significantly increasing (decreasing) trends. The preponderance of positive trends is evident in Table 2, and once again, the probability of finding 30 of 85 (35%) positive values by chance is near zero. Over the longer period back to 1950, positive trends occur mainly in the central United States and northeast (Table S3), and a smaller fraction of trends is negative (5/85, 6%) as compared to the period since 1996 (11/85, 13%). We also note that the mean duration of PLDEs has generally increased (Table S4).

Table 2
Same as Table 1 but for Wet PLDEs

	JFM	AMJ	JAS	OND	ANN
Massachusetts	2.4	1.3	0.4	0.2	3.6
NE Ohio	9.1	8.4	8.2	7.0	32.3
N. Carolina	3.4	8.0	7.6	5.0	22.9
S. Georgia	5.8	7.5	7.9	4.0	25.3
Minnesota	−0.3	0.2	−0.4	1.8	1.2
E. Montana	2.3	1.7	0.8	2.4	7.1
NW Iowa	1.9	2.7	2.1	0.5	6.8
N. Illinois	−1.5	1.3	−1.1	2.2	1.4
NE Colorado	1.6	3.1	4.7	4.7	9.8
Oklahoma	−0.6	3.2	2.6	0.4	5.7
SE Arkansas	−3.7	−5.2	−4.8	−3.3	−17.1
SE Texas	0.6	−0.1	1.0	−1.9	−0.4
E. Washington	2.7	3.9	−2.6	2.3	5.1
Oregon	1.5	2.9	0.2	2.7	5.8
S. Idaho	−2.6	−0.4	−1.0	4.1	−0.5
California	−4.0	0.1	−0.3	2.8	−1.0
Arizona	−5.1	−4.4	2.2	−4.1	−11.6

Note. ANN = annual.

3.2. SOM Analysis of Large-Scale Patterns

A separate approach to assessing the persistence of weather regimes is based on the frequency of LDEs in large-scale atmospheric patterns (CLDEs) as represented by 500-hPa geopotential height anomalies. Patterns in the upper-left section of the SOM matrix (Figure 2) exhibit anomalous ridging in the Pacific sector of the Arctic, consistent with observed AAW in recent decades. Lower-left patterns feature positive height anomalies that extend farther south into the northeast Pacific, a familiar pattern associated with the ongoing drought in the American west. Both patterns are accompanied by negative height anomalies (troughing) over eastern North America. Patterns on the right side of the SOM exhibit negative height anomalies in the northeast Pacific and western Arctic along with predominantly positive anomalies in eastern North America. The monthly node distributions are shown in Figure S1, indicating that corner (center) patterns occur more frequently during cold (warm) months.

The number of days that belong in each SOM cluster is shown in Figure 3a. The most frequently occupied nodes are in the four

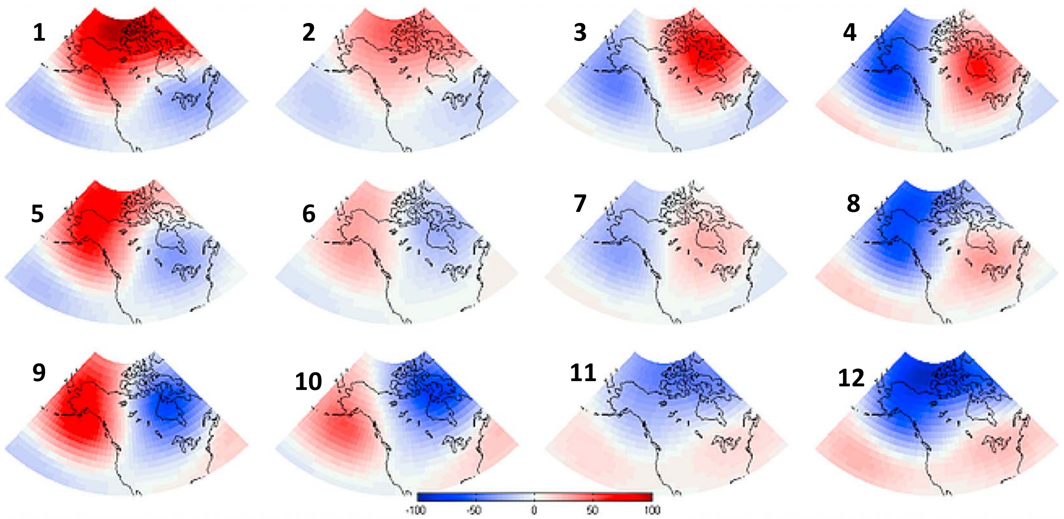

Figure 2. Representative patterns of 500-hPa height anomalies (m) derived using self-organizing maps. Numbers are for convenient reference in the text. Daily data from the NCEP/NCAR reanalysis from 1948 to 2015 were used to create the SOM matrix.

corners, particularly the upper left and lower right. To investigate whether the relative occurrence of atmospheric patterns has shifted during the recent decades, we calculate the frequency change (days in a node/total days in a period × 100%) from 1976–1995 to 1996–2015 (Figure 3b). The frequency of AAW-like patterns (nodes 1–5) has increased, along with nodes 3 and 4 that feature positive anomalies over the Canadian archipelago and troughing over northwest North America. Patterns with negative height anomalies in high latitudes (nodes 10–12) accompanied by troughing along the west coast (node 7) occurred less often. Overall, these findings indicate more frequent AAW-like patterns, associated with negative AO indices, along with less frequent patterns with negative high-latitude height anomalies and positive AO indices (Figure S4).

We now investigate changes in CLDE occurrence by identifying events with four or more consecutive days in each node. The mean number of CLDEs per year in each node is presented in Figure 3c. Patterns along the top and bottom rows of the SOM exhibit the highest frequency of CLDEs, similar to the overall frequency of occurrence of the nodes shown in Figure 3a. This relationship is evident in the plot of CLDE probability (Figure 3e), the mean annual ratio of CLDEs to days in the node. Nodes with high CLDE frequency are also the nodes with high probabilities of a CLDE.

We now explore changes in CLDE occurrence from pre-AAW years (1976–1995) to recent decades that exhibit strengthening AAW (1996–2015). The percentage change in CLDE frequency is shown in Figure 3d, indicating an increase (decrease) in CLDEs for nodes that also exhibit a general increase (decrease) in the number of days that belong in that cluster. While the similarity between Figures 3d and 3b suggests that the shift in circulation patterns has been a dominant factor driving changes in CLDEs, the CLDE changes are approximately double those for pattern frequency. The change in probability of a CLDE occurring when the atmosphere resides in a particular pattern is shown in Figure 3f. Positive and negative values are fairly equally split among the nodes, suggesting that changing probabilities have less influence on changes in CLDEs.

It is challenging to compare results from the two persistence metrics owing to increasing trends in both dry and wet spells in some locations. Precipitation frequency patterns mapped to the SOM are shown in Figure S6 for reference.

A measure of AAW based on daily near-surface air temperature anomalies (see section 2) is mapped onto the SOM matrix in Figure S5. Consistent with the patterns of 500-hPa anomalies in Figure 2, positive AAW values correspond with nodes on the left side while negative values map to patterns on the right. The node with the strongest AAW (upper-left corner) is also the node with the largest increase in CLDEs, and conversely, the node with weakest AAW (lower-right corner) also exhibits the largest decline in CLDEs. The association holds when segregated by season (Figure S2). The patterns with positive height anomalies in the Hudson Bay

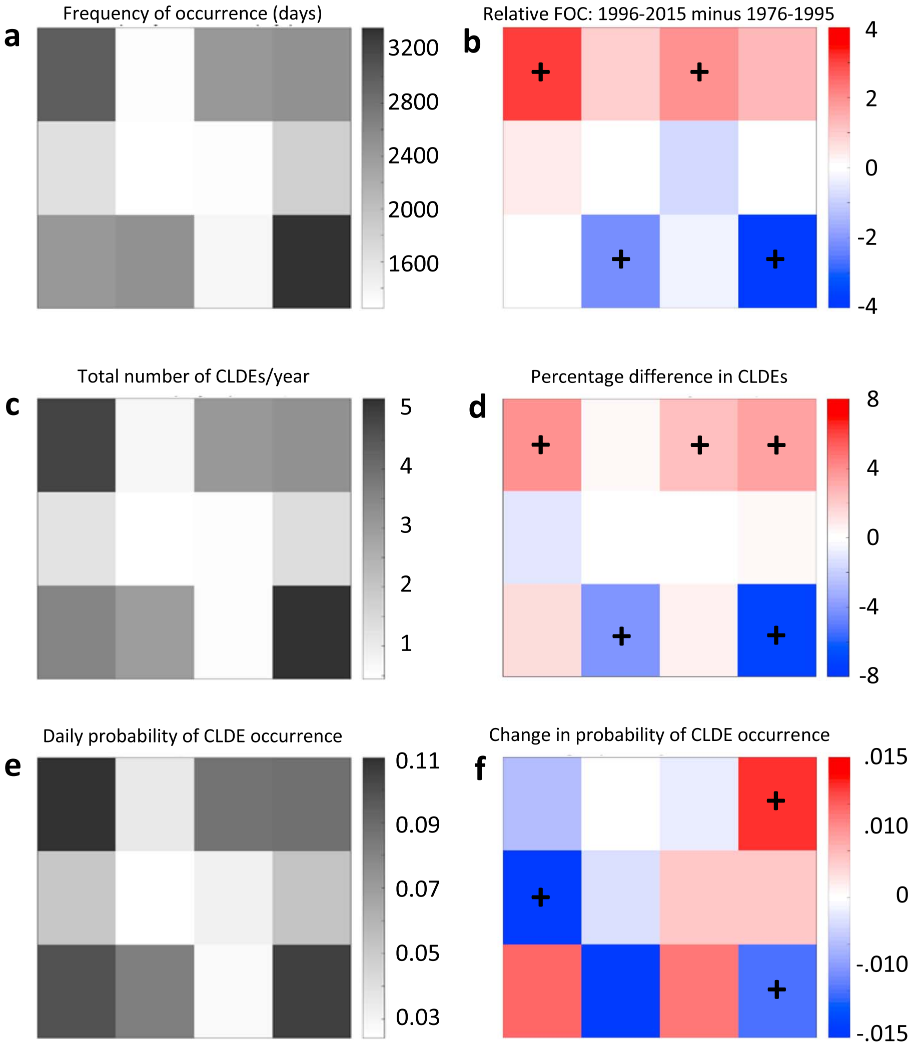

Figure 3. (a) Total number of days that belong in each node. (b) Percentage change in the number of days in each node from early (1976–1995) to late (1996–2015) period. (c) Total number of long-duration events (CLDEs) per year occurring in each node from 1948 to 2015. (d) Change in number of CLDEs per node from early to late period weighted by total CLDEs in each 20-year period (%). (e) Annual probability that an CLDE occurs in each node (mean ratio of number of CLDEs to days per year in each node). (f) Change in probability of CLDE occurrence from early to late period. Plusses indicate statistical significance at >90% confidence.

region also indicate more frequent CLDEs. These findings suggest that as the Arctic continues to warm disproportionately in the future (e.g., Barnes & Polvani, 2015), the frequency of CLDEs may also increase, favoring more persistent weather regimes across North America.

4. Conclusions

We have presented two independent lines of evidence suggesting that weather regimes over North America are becoming more persistent. The first is based on daily measurements of precipitation at 17 clusters of weather stations across the United States, which we argue is a reasonable proxy for large-scale weather regimes. We find that the frequencies of long-duration (≥ 4 consecutive days) dry and wet spells exhibit a preponderance of increasing trends, particularly since the mid-1990s. More frequent dry spells tend to occur mainly in the southeast, south-central Midwest, and northwest during summer and autumn, with decreasing tendencies in the northern Midwest. The duration of dry spells is generally decreasing except in the southwest during winter through summer and in the southeast during autumn. We find a few cases where PLDE frequency increases while the mean duration of PLDEs decreases, indicating that the increased frequency occurs predominantly in the shorter end of the distribution in those cases. The frequency of long-duration wet spells is also increasing overall, with particularly significant trends in the southeast, south-central Midwest, and northwest, with no strong seasonal preference. The north-central Midwest again runs counter to the general tendencies, exhibiting a decreasing frequency. In terms of duration, wet PLDEs increased significantly in much of the east, supporting the findings of Guilbert et al. (2015), as well as across the northern Midwest in winter and spring. The preponderance of increasing trends in both dry and wet PLDEs during summer is consistent with the mechanism of quasi-resonant wave amplification (Coumou et al., 2018, 2014; Kornhuber et al., 2017; Kretschmer et al., 2016; Mann et al., 2017), as well as with the findings of Pfleiderer and Coumou (2017). Across seasons, the overall increase in PLDEs is consistent with observed increases in waviness of the upper-level flow over North America (Cattiaux et al., 2016; Di Capua & Coumou, 2016; Vavrus et al., 2017).

Our second approach to measuring weather-regime persistence explores the frequency of long-duration, large-scale, upper-level patterns. We use daily reanalysis fields of 500-hPa anomalies over the eastern Pacific and North America to identify the most representative patterns using self-organizing maps then analyze the frequency with which the atmosphere occupies each pattern for consecutive days. CLDEs are tabulated, and changes over time are analyzed for each pattern. Consistent with many lines of evidence that AAW has increased in recent decades (e.g., Francis et al., 2017; Screen & Simmonds, 2010), we find that patterns associated with a warm (cold) Arctic have increased (decreased) in frequency. Patterns featuring positive anomalies over the Canadian archipelago along with troughing over northwest North America have also increased, consistent with an observed deepening of the Aleutian low (Gan et al., 2017) and a warming trend in the Hudson Bay region (Figure S3). Both AAW+ and AAW− types of patterns tend to favor CLDEs, most likely because those patterns occur most often, thereby increasing the odds of the atmosphere dwelling in that pattern for several consecutive days. The overall shift in pattern frequency toward AAW+ conditions without a robust change in daily CLDE probability suggests that the changing frequency of large-scale circulation patterns is a primary driver of change in CLDEs, though the frequency change in CLDE is approximately double that for pattern frequency change. These results suggest that future intensification of AAW may be one factor that favors an increased frequency of persistent weather regimes. Ongoing work will apply these approaches to model projections of future conditions assuming a continuation of rising concentrations of greenhouse gases, which will fuel an even warmer Arctic.

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