Measuring “weather whiplash” events in North America:

a new large-scale regime approach

Jennifer A. Francis, Woodwell Climate Research Center, Falmouth MA US

Natasa Skific, Rutgers University, New Brunswick, NJ US

Steven J. Vavrus, Center for Climatic Research, University of Wisconsin-Madison, Madison, Wisconsin US

Judah Cohen, Atmospheric and Environmental Research, Lexington, MA

Submitted to *Journal of Geophysical Research -- Atmospheres*

8 June 2021

Corresponding author: J. Francis, `jfrancis@woodwellclimate.org`, 732-688-2382

Key points

- We measure “weather whiplash” events (WWEs), defined as an abrupt transition from one large-scale atmospheric pattern to another.
- WWEs cause disruptive shifts in extreme temperatures and precipitation associated with particular atmospheric patterns.
- Warm-Arctic atmospheric patterns spawn more WWEs than cold-Arctic patterns, with robust future changes in frequency.

Key words: weather whiplash, extreme weather, Arctic, self-organizing maps, AI

Abstract

The term “weather whiplash” was recently coined to describe abrupt swings in weather conditions from one extreme to another, such as from a frigid cold spell to anomalous warmth or from drought to prolonged precipitation. These events are often highly disruptive to agriculture, ecosystems, and daily activities. In this study we propose and demonstrate a novel metric to identify weather whiplash events (WWEs) and track their frequency over time. We define a WWE as a transition from one persistent large-scale circulation regime to another distinctly different one, as determined using an objective pattern cluster analysis called self-organizing maps (SOMs). We focus on the domain spanning North America and the eastern N. Pacific Ocean. A matrix of representative atmospheric patterns in 500-hPa geopotential height anomalies is created. We analyze the occurrence of WWEs originating with long-duration events (defined as lasting 4 or more days) in each pattern, as well as the associated extremes in temperature and precipitation. A WWE is detected when the pattern two days following a long-duration event is substantially different, measured using internal matrix distances and thresholds. Changes in WWE frequency are assessed objectively based on reanalysis and climate model output, and in the future with climate model projections. Temporal changes in the future under RCP 8.5 forcing are more robust than in recent decades, with consistent increases (decreases) in WWEs originating in patterns with an anomalously warm (cold) Arctic.

Significance statement

When weather conditions shift abruptly after a long period of the same pattern – for example, from a spell of abnormally mild temperatures to extreme cold, or from a long dry period to a parade of storms – major disruptions to ecosystems and human activities often ensue. These types of shifts have recently been dubbed “weather whiplash” events. In this study we propose and demonstrate a new approach to measuring the frequency of these events based on continental-scale atmospheric regimes and their transitions. While the frequency of these events in recent decades has not changed substantially, our analysis of future model projections indicates robust increases and decreases in certain atmospheric patterns, particularly in those featuring an extremely warm or cold Arctic.

Introduction

The term “weather whiplash” has appeared frequently in recent media reports describing abrupt shifts from one type of weather extreme to another. These shifts typically consist of a severe cold spell being replaced by a period of above-normal temperatures, a prolonged drought followed by intense precipitation, or the reverse sequence in either case. A striking example of a whiplash event occurred in early September 2020 when a prolonged record-breaking heatwave over a large region of the central Rocky Mountains in the U.S. abruptly ended with a temperature drop exceeding 60°F in some areas along with several inches of snow. In 2018 a six-week cold spell in eastern North America flipped to a February heatwave that broke high temperature records from northern Maine to New Orleans and sent Bostonians flocking to the beaches (https://www.wunderground.com/cat6/summer-february-80-massachusetts-78-nyc). The disruptive “false spring” in March 2012 that struck the Midwest and lasted for several weeks was followed by killing freezes in April that wreaked havoc on fruit farmers, whose crops blossomed too early in March and were then damaged by the anomalous cold spell (https://medium.com/dose/whats-a-false-spring-b64cb977d59). Only a handful of studies has investigated these types of disruptive weather shifts, and as yet there is no consistent definition of a weather whiplash event, as distinct from the passage of fronts associated with progressive synoptic weather systems.

Metrics of variability are one approach used to assess whiplash events. An investigation of atmospheric temperatures during recent (1988/89 – 2014/15) winters (DJF) in the northern hemisphere by Cohen (2016) found that, consistent with previous studies (e.g., Screen 2014), daily winter near-surface temperature variability decreased in high latitudes (60°N-90°N), as would be expected with a weaker poleward temperature gradient owing to amplified Arctic warming. In contrast to most studies, Cohen (2016) also found that variability *increased* in low- to mid-latitudes (0-50°N), which was interpreted as a possible indication of increased weather whiplash. Larger variability in daily temperatures, however, suggests a timescale associated with fast-moving synoptic weather systems, such as frontal passages and changes in wind direction, rather than a shift from one persistent regime to another.

Loecke et al. (2017) also focused on extreme precipitation events to define a weather whiplash index associated with drought-to-flood transitions. Focusing on the Upper Mississippi River basin, they calculated the index using the total precipitation from January to June of each year minus the total from July to December of the previous year divided by the total over both periods. They applied the index to identify events in projections by 30 of the models that participated in the climate model intercomparison project, version 5 (CMIP5) forced with representative concentration pathway (RCP) 8.5. They found that 19 of the models exhibited a robust positive trend in their index while the others had no significant trend.

The study by Swain et al. (2018) focused on regional precipitation extremes in California's rainy season (Nov.-Mar.), coining the term "precipitation whiplash" as a transition from anomalously dry to anomalously wet seasons in consecutive years. They analyzed a large number of climate simulations (forced with RCP8.5 conditions) created with the National Center for Atmospheric Research (NCAR) Community Earth System Model, CESM1. A whiplash event was identified when one rainy season with precipitation totals below the 20^{th} percentile during the pre-industrial period was followed by a season with totals exceeding the 80^{th} percentile. They found a significant increase in events over most of southern California, Mexico, and parts of northern California through the 21^{st} century, which implies increasing challenges for agencies that manage freshwater resources in that region.

He and Sheffield (2020) also focused on precipitation to develop a metric of whiplash, defining a drought-pluvial seesaw similar to Swain et al. (2018), in which dry spells were followed by wet spells (pluvials). They analyzed data from the past nearly seven decades (1950-2016) on a global scale for the spring/summer (April-September) season and for fall/winter (October-March).

Unlike Swain et al. (2018) who focused on consecutive wet seasons, this study investigated three-month lags in the drought-pluvial seesaw. They calculated the ratio of the frequency of events during the past 30 years (1987-2016) to that in the first 30-year period (1950-1979). Over North America, they found increased ratios over more than half of the area during the warm season along with a three-fold increase in frequency over about one-fifth of the region during the cold season, mainly in the central U.S. The authors note challenges, however, in interpreting the results owing to differing consistency of regional metrics for droughts and pluvials as well as disentangling the roles of natural variability and climate change.

We build on this growing body of research into disruptive and abrupt shifts in weather extremes, with a focus on a domain spanning North America and the eastern North Pacific Ocean. We demonstrate a novel approach to assess weather whiplash based on abrupt shifts in the large-scale circulation regime following the persistent dominance of one pattern. This method does not rely on measurements or simulations of precipitation or temperature, thereby avoiding uncertainties introduced by instrument error, local heterogeneity, and model physics associated with precipitation processes. For this study, we adopt the following definition of a weather-whiplash event (WWE): a long-lived (4 or more consecutive days), continental-scale pattern in the upper-level circulation that shifts abruptly (over 1-2 days) to a substantially distinct pattern, bringing a stark end to persistent weather conditions throughout the region. This definition eliminates confusion in the possible misidentification of WWEs caused by sharp, localized weather changes owing to synoptic features such as fronts, discreet disturbances (e.g., squall lines, tropical storms), and shifts in low-level winds from differing surface types (e.g., from onshore to offshore, downslope to upslope, or forest to grasslands). We submit that a WWE should be identified when one persistent and anomalous circulation pattern is replaced abruptly by a very different one, as distinct from the passage of fronts on synoptic time scales.

Data and Methods

We identify representative large-scale atmospheric patterns over the northeast Pacific Ocean/North American sector using a neural-network-based tool called Self-Organizing Maps (SOMs; Skific and Francis, 2012). The SOM algorithm ingests large, two-dimensional data sets and groups the fields into clusters or nodes of representative patterns found in the data. The patterns are arranged in a variable-size matrix according to their similarity with each other, with most similar patterns positioned near each other and most dissimilar patterns farthest apart. For this application we use daily fields of anomalies in the 500-hPa geopotential heights from 1948-2019 (~26,000 days) obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al., 1996). The spatial domain extends from 30°N-80°N and 180-60°W. Daily anomalies were calculated by subtracting the 72-year mean value for each gridpoint for that calendar day. We note that 500hPa height fields from other reanalyses are very similar (e.g., Archer and Caldeira 2008).

For this application, we chose a 4x3 SOM matrix, which balances sufficient representation of the atmosphere's dominant patterns with ease of displaying of results (**Fig. 1**). The algorithm places each daily field into the node with the most similar pattern. Once this so-called master SOM has been created, other fields of data can be mapped to the patterns, which is especially powerful for variables that are spatially and/or temporally discontinuous (e.g., cloud cover, precipitation, or extreme events). We take advantage of this tool to explore extreme temperatures and precipitation associated with each pattern. Changing frequencies of occurrence of the SOM nodes allow an assessment of trends in extreme conditions associated with each large-scale pattern. Air temperature at 925 hPa and precipitation data are also obtained from the NCEP/NCAR Reanalysis, which at the grid-box scale (2.5^o) should reasonably represent patterns of precipitation and changes over time.

In this study, we develop a novel metric for the detection of WWEs. We begin by identifying long-duration events (LDEs) during winter (January-March) and summer (July-September), defined as cases when the large-scale atmospheric pattern remains in one node of the SOM for four or more consecutive days (Francis et al., 2018; Vihma et al., 2019; Francis et al., 2020). The relatively small matrix was selected to ensure that adjacent patterns would be sufficiently distinct from each other and so consecutive days would be less apt to jump between nearby, similar patterns that typically characterize larger matrices. We then identify the node associated with the second day after each LDE and determine the Euclidean distance between the LDE node and the one containing the atmospheric pattern two days later as a measure of dissimilarity between the patterns. Based on examination of several actual WWEs (such as the example shown in **Figs. S1-S3** for 2-9 March 2019), the two-day time interval appears to be typical for a new pattern to become established after an LDE (conclusions are similar, however, for 1 and 3 days later). The LDE presented in **Figs. S1-S3** began on 27 February 2019, when a strong positive height anomaly persisted for 7 days across much of northern North America along with a negative anomaly over the central continent (**Fig. S1**). Two-meter air temperature anomalies associated with this weather regime exhibit a broad area of much-above-normal values across the Arctic along with much-below-normal temperatures from the Pacific Northwest extending across the continent to the southeastern U.S. (**Fig. S2**). Anomalies in precipitable water are generally positive across the southern states, while the northern tier and southern Canada are drier than normal (**Fig. S3**). Beginning on March 6^{th}, this pattern began to break down, and over a two-day period, shifted to a substantially different one in which low height anomalies invaded the northwest part of the continent as well as a large portion of the western U.S. This new regime ended the prolonged cold spell in the central and eastern states and marked the beginning of a period of intense and prolonged precipitation in the Midwest that caused record-breaking floods in eastern Nebraska and the surrounding region. The surge of moisture into the Upper Midwest is evident on March 8 and 9 in **Fig. S3**. In practical terms, a WWE is experienced when a persistent weather pattern ends abruptly and it is replaced by weather conditions that differ markedly from those in the prior persistent pattern, such as in this example and those described in the introduction.

We compiled the distribution of Euclidean distances from each LDE (about 2,015 of them from 1948 to 2019) to the node containing the pattern two days later and determined that the 50^{th} percentile distance value establishes a suitable threshold for identifying a WWE. As shown in **Table S1**, which displays results for winter, this value corresponds to a mean Euclidean distance of 1440 (a unitless metric internal to the SOM algorithm). This distance is approximately the same as between two non-adjacent nodes, such as nodes #1 and #3 (**Table S2**), thereby constituting a major pattern shift. For summer months, this threshold is 889, indicative of the reduced pattern contrasts in the warm season when the jet stream is farther poleward and the north-south temperature gradient is smaller. We then identify a WWE when the distance from the LDE node to the node two days later exceeds the seasonal threshold, which also enables us to quantify the WWE magnitude by the exceedance amount. The logic of this methodology is also illustrated in **Figs. 2, S4 and S5**. The histograms in **Fig. 2** display the node number containing the sample that occurs two days after an LDE during winter originating in each node in the matrix (the corresponding plot for summer months (not shown) is very similar). For example, the top left histogram indicates that the samples two days after LDEs occurring in node #1 fall most frequently into nodes #3 and #9. If a sample two days later falls in nodes other than #2 or #5 (the two nodes within the distance threshold from #1), a WWE is identified. Note that when the same node number as that of the initiating LDE appears in the histogram -- e.g., the histogram for node #1 has a bar in the node #1 location -- the pattern shifts away from node #1 on the first day then returns to node #1 on the 2^{nd} day. A similar set of histograms is shown in **Fig. S4**, but instead of displaying the node numbers for the sample two days later, the x-axis represents the Euclidean distance between the LDE node and the node containing the field 2 days later. One additional visualization of the Euclidean distances between nodes is presented in **Fig. S5**, a so-called Sammon map of the SOM matrix. The uneven distribution of distances between nodes is clearly evident, and this mapping shows that nodes #1 (warm Arctic) and #12 (cold Arctic) constitute the largest difference among the circulation patterns, while nodes #4 and #9 (cold or warm North Pacific) in the other two opposing corners also differ substantially.

Our analysis produces a total of 948 (annual), 239 (winter), and 228 (summer) WWEs over the 72-year record, which translates to an annual- or seasonal-mean frequency of 13.2, 3.3, and 3.2. These events are relatively rare because LDEs themselves occur infrequently (**Fig. S6**, and also see Francis et al., 2018; 2020).

The same WWE metric is applied to output from climate model simulations. We analyze ten ensemble members from the NCAR Community Earth System Model Large Ensemble (CESM1) that span the historical period (1979–2005) as well as into the future (2006–2100) (Kay et al., 2015). Daily 500 hPa height fields were obtained from https://www.cesm.ucar.edu/projects/community-projects/MMLEA/. Historical runs incorporate observed natural and anthropogenic forcings, while future projections assume conditions defined by the RCP8.5 scenario (Riahi et al., 2011). Anomalies in future projections were calculated relative to the mean from 2006 to 2100.

Results

3.1 Mean patterns and changing frequencies of occurrence

The characteristic patterns in 500 hPa height anomalies across the domain for all months are displayed in the master SOM matrix (**Fig. 1**). Adjacent nodes are most similar to each other while those farthest apart are most dissimilar. Nodes along the edges of the matrix, and especially in the corners, occur most frequently. The percentages of winter (JFM) and summer (JAS) days belonging in each node are indicated over each map in the matrix. Winter days are more likely to exhibit patterns with large height contrasts, while summer days are fairly evenly distributed across the SOM.

Patterns in the upper-left part of the matrix feature positive height anomalies (ridging) in northern and western areas of the domain along with negative anomalies (troughing) in the east. The total number of days belonging in node #1 has increased during recent years (**Figs. 3, S7**), though not in winter (**Fig. 3b**). Anomalous temperature and precipitation patterns associated with each node can be used to ascertain weather conditions associated with each node. **Figure 4a** displays the number of days at each gridpoint in which anomalously high (> 1.5) temperatures occurred, and **Fig. 4b** indicates the occurrence of extremely low (< -1.5) temperatures associated with each pattern. The weather associated with node #1, for example, favors relatively dry, warm conditions in California, below-average snowpacks in western mountain ranges, and prolonged cold, wet spells in the Midwest and East (**Figs. 4, 5**). Nodes in the bottom-right part of the matrix feature the opposite anomaly pattern, with negative (positive) values spanning much of the high (middle) latitudes. Western states tend to be relatively cool and wet in these patterns, while the east experiences abnormally warm conditions. The total number of days belonging in these nodes, especially node #12, has declined in recent decades, particularly during winter (**Fig. 3**). In the upper-right and lower-left corners are opposing patterns featuring a strong zonal anomaly gradient, indicative of an amplified ridge/trough in each half of the domain. In terms of weather conditions, the strong western trough depicted in node #4, for example, tends to bring anomalously cold temperatures to Alaska along with stormy weather to the U.S. west coast. The opposite pattern in node #9 produces abnormally warm conditions along the west coast, cold temperatures in much of the central and eastern continent, and unsettled conditions in the eastern states.

As high latitudes warm disproportionately faster than midlatitudes, we find that patterns exhibiting positive (negative) high-latitude height anomalies are occurring more (less) frequently, especially in the most recent decades (**Fig. 3a and S7**). During winter months, the pattern featuring anomalous troughing in the west and ridging in the east (#4) is the only one that has occurred significantly more frequently (**Fig. 3b**), which is consistent with the region of strongest AAW during JFM presented in Fig. 1b of Francis and Vavrus (2012). During summer, nodes #1 and #3 are more common. Spring and fall also exhibit significant increases node #1 (not shown).

3.2 Recent changes in extremes

We focus first on the nodes with significant frequency changes during winter (#4 and #12) and examine the corresponding impacts on extreme temperatures and precipitation (**Fig. 4**). Increasing frequency of node #4 implies that warm winter extremes occurred more often across much of the domain, but especially in northcentral North America, while cold extremes were more prevalent over much of Alaska and the Gulf of Alaska. The decreasing frequency of node #12 suggests a reduction in anomalously warm temperatures across the mid-latitudes of the domain, along with less frequent intense cold spells in northern Canada and near Alaska. The changes in frequency of occurrence of these two patterns, therefore, result in opposing changes in the frequency of cold events in the Alaskan region. In terms of precipitation extremes (**Fig. 4c**), the increase in node #4 is associated with more frequent heavy events along the Pacific Northwest and northcentral Canada, while a decrease in node #12 would tend to offset these tendencies along the west coast.

During summer (**Fig. 5**), the increased frequency of node #1 suggests more (fewer) anomalously warm (cold) days along the west coast, Alaska, and high latitudes along with more frequent cold spells in the central and eastern parts of the continent, consistent with the declining trend in extreme summer heat over the Upper Midwest (Mueller et al., 2017). Unusually wet days are more likely in southern California, the southern Mississippi Valley, and the Canadian Maritimes. The increased occurrence of node #3 suggests more warm days in the Hudson Bay/Canadian archipelago region, more cool extremes in western U.S. states, and wet conditions along the west coast of Canada and southeast Alaska.

3.3 Observed changes in WWEs

Our new method of assessing WWEs begins with identification of long-duration events (LDEs) in reanalysis fields. We find that the most common patterns (**Fig. 1**) also tend to exhibit a higher occurrence of LDEs per year (**Fig. S6**), which is expected given that a larger number of days in one pattern increases the chances of three or more consecutive days occurring. Significant (>95% confidence) increasing trends in LDEs exist in node #1, while nodes #10 and #12 exhibit declining trends (while the f-test detected significant (>90%) trends in nodes #2 and #6, the number of LDEs is too small to be consequential). These findings are consistent with our earlier work on weather-regime persistence (Francis et al., 2018; Vihma et al., 2019; Francis et al., 2020). Specifically, Francis et al., 2018 found an increased occurrence of LDEs particularly in patterns featuring positive height anomalies in high latitudes of the North American domain, the same as that used in the present study. Increased LDEs in warm-Arctic nodes are consistent with the counterintuitive downward trend in extreme summer heat over much of the upper Midwest during recent decades, and the finding suggests that amplified Arctic warming favors more persistent weather conditions that can lead to extreme weather events.

The matrix of time series shown in **Fig. 6a** displays the frequency per year with which a WWE originates from an LDE in each node. The infrequency of WWEs (13.2 per year on annual average) and large interannual variability challenge the detection of frequency changes over the observational record, but a few nodes exhibit statistically significant trends. Nodes #1 and #12 initiate substantially more WWEs than do other nodes, and significant trends are evident for node #3 (increasing) and node #12 (decreasing). These trends are attributable mainly to the changes in frequency of these nodes (**Fig. 3**), in that LDEs are more likely to occur when a node becomes more prevalent, and vice versa.

<u>Winter:</u> Changes over time are more evident when assessed as differences in frequency between the two 20-year periods at the beginning and end of the observation record. During winter months (**Fig. 6b**), only node #9 exhibits a significant increase in WWEs, while those initiated in node #12 have declined. The pattern in node #9 features a strong meridional ridge/trough pattern across the continent, which according to **Fig. 2**, is most likely to shift to node #1 or #12 after a WWE (note node #10 is adjacent, thus does not qualify as a WWE), both of which are more zonal patterns. This transition would suggest that persistent warm, dry weather in the western states and cool conditions across central North America would likely transition to a more progressive synoptic regime in a WWE. The significant decrease in WWEs originating in node #12, in contrast, would suggest fewer abrupt transitions from broad western troughing/eastern ridging to patterns similar to either node #4 or #10, the two most likely nodes following an LDE in node #12. A WWE originating in the strong zonal jet conditions depicted by the pattern in node #12, featuring cold (warm) high (middle) latitudes, would most likely transition along one of two paths: 1) the cold migrates westward over the northeast N. Pacific and Alaska while warmth invades much of North America (node #4), or 2) the cold migrates eastward over northeastern North America, while warmth bulges northward into Alaska (node #10).

<u>Summer:</u> Our results suggest that WWEs originating in node #3 during JAS have increased (**Fig 6c**). An LDE in node #3 is most likely to shift to node #1 in a WWE (**Fig. S8**), which would replace anomalous troughing (ridging) in the northwestern (northeastern) parts of the continent with opposite height

anomalies. In terms of sensible weather, the increased frequency in WWEs from node #3 to node #1 shift anomalously high temperatures in the Hudson Bay region to Alaska and British Columbia, accompanied by increased negative anomalies throughout most of the western interior. Anomalously wet conditions shift from southeast Alaska and the British Columbia coast to southern California (**Fig. 5**). Note that a transition from node #3 to #1 in summer would be consistent with the reported increased precipitation extremes in western North America (Swain et al., 2018). A decrease in WWEs originating in nodes #4 and #10 has also occurred. An LDE in node #4 is most likely to shift to node #6 or #12 during a WWE. The shift in temperatures and precipitation from node #4 to #6 would reduce the likelihood of hot days over central Canada, reduce the likelihood of abnormally cool days over Alaska, and decrease the chances of heavy precipitation in western Canada while increasing chances in southeastern North America. A WWE that started in node #4 and shifted to #12 would also decrease hot days in central Canada but would also increase cold days over the northwest part of the domain, while heavy precipitation would increase from the Gulf of Mexico to New England A WWE that was initiated in node #12 is most likely to shift to node #10 or # 4. The most notable changes in extremes during a transition to #10 will be an increase in high-temperature extremes in the Gulf of Alaska, more widespread cool spells over the Rocky Mountains and High Plains, and a transition from anomalously wet to dry conditions along the coast of British Columbia. A shift from node #12 to #4 is likely to bring abnormally warm conditions to central Canada, a lower probability of anomalously cold days in the Arctic, and more focused heavy precipitation in the Pacific Northwest. The decreased frequency of WWEs originating in node #12 will mean fewer of these types of abrupt transitions.

3.4 Model-simulated WWEs, past and future

The same analysis method is applied to ten ensemble members produced by the CESM. Daily fields of 500 hPa geopotential height anomalies are mapped onto the characteristic patterns in the master SOM that were derived from reanalysis output. The closest matching node is identified for each simulated daily field. It should be noted that a master SOM created using model fields produces a very similar matrix of patterns (**Fig. S9**). Moreover, our previous work (Francis et al., 2020) demonstrated that three models participating in the Climate Model Intercomparison Project – version 5 (CMIP5) successfully captured monthly distributions of days belonging in each node as well as frequencies of LDEs during the years included in the historical period (1979-2005).

In terms of changes in WWEs over the historical period, we find CESM simulations agree reasonably well with changes observed in the reanalysis output (**Fig. S10**). Given the large interannual variability in WWEs (**Fig. 6a**) and the fact that the 1995-2005 period is relatively early in the era of the climate-change signal generally and the emergence of AAW specifically (node #1), it is not surprising that changes over two relative short periods do not align perfectly.

To further demonstrate the utility of this approach, next we explore projected future changes in WWEs, assuming RCP 8.5 forcing conditions in CESM. Our findings presented in **Fig. 7** suggest robust changes in the number of WWEs will occur from the beginning of the 21st century (2006-2030) to the end (2076-2100) during winter and summer seasons. Nodes #1 and #3 exhibit robust increases in both seasons, while WWEs originating in node #12 are projected to decrease significantly. These changes can be attributed to a combination of changing frequency of occurrence of each node (**Fig. S11**) as well as changes in the probability (number of WWEs/number of days in a node) of a WWE originating in each node (**Fig. S12**). Patterns with positive height anomalies over northern and northeastern North America are projected to not only occur more frequently (**Fig. S11**), but also to spawn a higher frequency of WWEs in a warmer world. To check for intermodel consistency, we also analyze output from three of the models included in the CMIP5 generation. We find they project changes in WWEs similar to those from the CESM runs (**Fig. S13**). These findings point toward an increased occurrence of regime-based WWEs in the future, as patterns with positive height anomalies in high latitudes become more common and are also more likely to initiate WWEs, while those with negative anomalies in Arctic regions will occur less frequently and are less likely to spawn WWEs.

Finally, we calculate the annual mean Euclidean distances separating the two nodes participating in a WWE, based on CESM output from 2006 to 2100 (**Fig. S14**). This metric provides an indication of the severity of a WWE, as a larger Euclidean distance would represent a more dramatic shift in the pattern. We find that 7 of 12 nodes exhibit statistically significant trends; five with declining trends and two with increasing trends. The preponderance of negative trends may result from the ongoing decrease in the poleward temperature/height gradient as high latitudes warm faster than lower latitudes and the corresponding reduction in airmass contrast. This explanation is supported by the fact that patterns with low height anomalies in the Arctic (nodes #11 and #12) exhibit increasing trends, reflecting larger airmass contrasts when the Arctic is anomalously cold.

Summary and Conclusions

Abrupt shifts from one anomalous weather condition to another substantially different one are disruptive to agriculture (e.g., thaw/freeze episodes that can cause early budding on fruit trees), winter recreation enterprises, management of municipal utilities, animal behavior, and a variety of human activities. The term "weather whiplash" recently entered the public discourse to describe these types of shifts, but a commonly accepted definition has yet to emerge. In this study we propose a characterization that differentiates normal frontal passages, which often usher in marked but short-lived weather changes, from more disruptive events in which a persistent and anomalous weather regime is abruptly replaced by another strikingly different one. Whiplash events typically involve a persistent winter cold spell that is supplanted by a winter heatwave, a prolonged drought followed by days of storminess, or the reverse order of these transitions.

In this study, we demonstrate a new method to identify and trace weather whiplash events (WWEs) based on characteristic large-scale patterns of daily upper-level (500 hPa) geopotential height anomalies over the domain encompassing the northeast North Pacific Ocean and North America. Patterns are objectively determined from 72 years of daily height fields (from NCEP/NCAR reanalysis), and each day is classified into a matrix of representative clusters or nodes by a neural-network-based tool called self-organizing maps (**Figs. 1 and S9**). Persistent long-duration events (LDEs) are identified when a string of four or more consecutive days occurs in a single cluster. A WWE is then diagnosed when the pattern two days following a LDE transitions to a cluster that is sufficiently different from the one where the LDE occurred, as measured by the Euclidean distance between clusters in the matrix. Extreme temperatures and heavy precipitation associated with each pattern in the matrix are also characterized. This information is used to describe the expected shift in weather conditions before and after a WWE.

We assess the number of WWEs that originate from LDEs occurring in each node during all months (**Fig. 6a**), as well as changes in WWE frequency during winter (JFM; **Fig. 6b**) and summer (JAS; **Fig. 6c**). The clusters dominated by high or low height anomalies spanning high latitudes tend to spawn the most WWEs (nodes #1 and #12). Patterns featuring a distinct meridionally oriented dipole of height anomalies (primarily nodes #3/4 and #9/10) also produce a relatively large number of WWEs.

Changes in WWEs over time are more robust in future model projections assuming minimal abatement of carbon emissions (**Fig. 7**) than during past decades. WWEs originating in nodes #1 and #3 increase significantly from 2006-2030 to 2076-2100 during both winter and summer, while those originating in node #12 decrease significantly. Increasing WWEs are projected for nodes with positive height anomalies in high latitudes, while WWEs will decrease when the Arctic is anomalously cold.

Using extreme temperature and precipitation patterns associated with each node, we analyzed the sensible weather shifts that are likely to occur in nodes where WWEs become more or less likely. In addition to illuminating specific weather transitions in particular regions, we find more generally that a WWE originating in node #1 (large positive height anomalies in high latitudes) is most likely to shift to nodes #3 or #9 (**Fig. 2**), both of which are substantially more meridional in character. This finding suggests that a persistent episode of strong AAW is likely to be followed by a more amplified upper-level circulation pattern. Interestingly, WWEs originating in nodes #1 and #3 are likely to jump between these two nodes, resulting most notably in repetitious cold spells in midlatitudes of North America and fluctuating wet/dry periods in west-central regions. During summer months, WWEs originating in nodes #1 and #3 will produce similar shifts in temperatures and precipitation, but with somewhat less distinct contrasts (**Fig. 5**). Shifts in temperature and precipitation extremes associated with WWEs initiated in each node for any season can be assessed using this methodology.

Our objective in this paper was to demonstrate a new approach to measure the occurrence of WWEs, which large-scale atmospheric patterns are more or less likely to initiate them, the extreme weather conditions associated with the patterns before and after a WWE, and how their frequency may change in the future as greenhouse gas concentrations continue to rise. Future efforts will examine WWEs in other sectors of the globe and investigate relationships between WWE frequency and changes in the climate system, such as rapid Arctic warming, disruptions of the stratospheric polar vortex, and fluctuations in natural climate oscillations. Because WWEs tend to cause abrupt and disruptive shifts in weather conditions, a better understanding of these events – and the extremes associated with them – will better enable preparations by decision-makers that will lessen their impacts.

Acknowledgments

The authors are grateful to anonymous reviewers of a previous version of this manuscript. J. Francis and N. Skific are grateful to the Fund for Climate Solutions at the Woodwell Climate Research Center for supporting this research. J. Cohen is supported by the US National Science Foundation grant PLR-1901352. S. Vavrus is supported by the US National Science Foundation grant OPP-2043727.

Data availability statement

No data sets were created as a part of this investigation.

References

Archer, C. L., & Caldeira, K. (2008). Historical trends in the jet streams. *Geophys. Res. Lett., 35*, doi:10.1029/2008GL033614.

Cohen, J. (2016). An observational analysis: Tropical relative to Arctic influence on midlatitude weather in the era of Arctic amplification, *Geophys. Res. Lett.*, *43*, doi:10.1002/2016GL069102.

Francis, J.A., Skific, N. & Vavrus, S.J. (2020). Evidence for increased persistence of large-scale circulation regimes over Asia in the era of amplified Arctic warming, past and future, *Nature Sci. Rpts., 10*, doi:10.1038/s41598-020-71945-4.

Francis, J. A., Skific, N. & Vavrus, S.J. (2018). North American weather regimes are becoming more persistent: Is Arctic amplification a factor? *Geophys. Res. Lett.*, *45*. doi:10.1029/ 2018GL080252.

Francis, J.A., & Vavrus, S.J. (2012). Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys. Res. Lett.*, *39(6),* doi:10.1029/2012GL051000.

He, X. & Sheffield, J. (2020). Lagged compound occurrence of droughts and pluvials globally over the past seven decades. *Geophys. Res. Lett., 47*, doi: 10.1029/2020GL087924.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-year Reanalysis project. *Bulletin of Am. Met. Soc.*, *77(3),* 437–472, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., et al. (2015). The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability, *Bulletin of the American Meteorological Society*, *96*(8), 1333-1349.

Lehmann, J., F. Mempel, and D. Coumou (2018), Increased occurrence of record-wet and631

record-dry months reflect changes in mean rainfall, Geophysical Research Letters, 45,632

doi:10.1029/2018GL079439.

Loecke, T. D., Burgin, A.J., Riveros-Iregui, D.A., Ward, A.S., Thomas, S.A., Davis, C.A. & Clair, M.A.S. (2017). Weather whiplash in agricultural regions drives deterioration of water quality, *Biogeochemistry, 133*(1), 7–15.

Mueller, N. D., Rhines, A., Butler, E. E., Ray, D. K., Siebert, S., Holbrook, N. M., & Huybers, P. (2017). Global Relationships between Cropland Intensification and Summer Temperature Extremes over the Last 50 Years, *Journal of Climate*, *30*(18), 7505-7528.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., & Rafaj, P. (2011). A scenario of comparatively high greenhouse gas emissions. *Clim. Change, 109*, doi:10.1007/s10584-011-0149-y.

Screen, J. A. (2014). Arctic amplification decreases temperature variance in northern mid- to high-latitudes, *Nat. Clim. Change*, *4*, 577–582, doi:10.1038/nclimate2268.

Skific, N. & Francis, J.A. (2012). ”Self-Organizing Maps: A Powerful Tool for the Atmospheric Sciences” in Applications of Self-Organizing Maps, ISBN 978-953-51-0862-7, edited by M. Johnsson, doi:10.5772/54299.

Swain, D.L., Langenbrunner, B., Neelin, J.D., & Hall, A. (2018). Increasing precipitation volatility in twenty-first-century California. *Nat. Clim. Change* 8**,** 427–433, doi: 10.1038/s41558-018-0140-y.

Vihma, T., Graversen, R., Chen, L., Handorf, D., Skific, N., Francis, J.A. et al. (2019). Effects of the tropospheric large-scale circulation on European winter temperatures during the period of amplified Arctic warming. *Int. J. of Climo.,* 1-21, doi: 10.1002/joc.6225.

Figure Captions

Figure 1: Representative patterns in daily 500-hPa geopotential height anomalies [m, shaded] for all months from 1948-2019 calculated using Self-Organizing Maps. The domain covers 30ºN-80ºN and 180-60ºW (midlatitude North America/NE Pacific). Percentages indicate the frequency of occurrence of each node during winter months (JFM). Numbers to left of each node are for reference purposes. Data to generate the SOM were obtained from the NCEP/NCAR Reanalysis (Kalnay et al., 1996).

Figure 2: Distributions of days (y-axis) of node number (1-12, x-axis) corresponding to two days following an LDE in a particular node. Matrices correspond to node placement in master SOM shown in Fig. 1, indicated with bold numbers in upper left corners.

Figure 3: Change in the frequency of occurrence (days) of each node from 1961-1989 to 1991-2019 during (a) all months and (b) winter months (JFM). The small (large) Xs indicate changes that are statistically significant with 90% (95%) confidence.

Figure 4: Winter (JFM) temperature extremes associated with each node of the master SOM. (a) Number of days (shading) that air temperature anomalies at 925 hPa exceed 1.5 . (b) Number of days that air temperature anomalies at 925 hPa fall below 1.5 . Data are from the NCEP/NCAR reanalysis.

Figure 5: Winter (JFM) precipitation extremes associated with each node of the master SOM. Shading indicates number of days that daily precipitation anomalies exceed 1.5 . Data are from the NCEP/NCAR reanalysis.

Figure 6: (a) Time series of weather whiplash events (WWEs) per year during winters (JFM) from 1949 to 2019 (x-axis), derived using data from the NCEP reanalysis. Bold solid (dashed) lines indicate trend significance with 95% (90%) confidence. (b) displays differences in the number of WWEs during two 20-year intervals: 1950-1969 to 2000-2019. The X indicates statistical significance > 95% based on student's t-test.

Figure 7: Timeseries of Euclidean distances (y-axis, unitless) between the node in which an LDE occurs and the node that contains the daily field two days after the LDE, averaged over winter months (JFM) each year from 1950 to 2019 (x-axis). Bold (thin) trend lines are significant at 95% (90%).

Figure 8: Changes in the number of winter (JFM) WWEs from 1979-1989 to 1995-2005 in (a) NCEP/NCAR reanalysis output and in historical simulations

from three global climate models: (b) CCSM4, (c) CanESM2, and (d) GFDL-CM3. The small (large) Xs indicate statistical significance $> 90\%$ ($> 95\%$) based on a student's t-test.

Figure 9: Projected changes in the number of winter (JFM) WWEs from 2006-2030 to 2076-2100 in (a) CCSM4, (b) CanESM2, and (c) GFDL-CM3. The Xs indicate statistical significance $> 95\%$ based on a student's t-test.