

Examining the Characteristics and Evolution of Wintertime Temperature Whiplash Events in the U.S. Southern Plains

KATHERINE L. GIANNAKOPOULOS¹ AND JASON C. FURTADO^a

^a *School of Meteorology, University of Oklahoma, Norman, Oklahoma*

(Manuscript received 4 October 2024, in final form 10 October 2025, accepted 13 November 2025)

ABSTRACT: Rapid extreme temperature swings, termed “temperature whiplashes,” can lead to significant socioeconomic impacts. Few studies have considered temperature whiplashes over continental or global domains, but regional characteristics of temperature whiplash events and the potential for long-range predictions of such events remain to be studied. This study focuses on defining and characterizing temperature whiplash events in the U.S. southern plains during the winter. Two types of whiplashes are defined: 1) hot to cold and 2) cold to hot. Using the fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis from 1950 to 2023 during December–February, temperature whiplash events are defined using a temperature swing index (TSI), a measure of day-to-day changes in temperature, area-averaged across the southern plains. Days where the TSI exceeds the 90th percentile are labeled “high swing days” (HSDs). Temperature whiplash events occur when a HSD coincides with a highly negative (hot to cold) or positive (cold to high) shift in temperatures. Lagged geopotential height composites of hot-to-cold whiplashes illustrate an amplifying Rossby wave train and atmospheric blocking pattern in the North Pacific in the midtroposphere, coinciding with an increasingly distorted and “stretched” stratospheric polar vortex at 50 hPa. Coinciding with a statistically significant upward flux over eastern Siberia/western Alaska and downward flux over Canada, our results suggest possible stratospheric wave reflection prior to the HSD. These characteristics present particular forecasts of opportunity that may improve predictions of these extreme temperature events on a subseasonal to seasonal scale.

SIGNIFICANCE STATEMENT: Rapid changes in temperature within a few days, which we term “temperature whiplash events,” can have significant impacts on agriculture, transportation, and daily life. Although some past studies have looked at these temperature whiplash events on very large scales, regional events and their potential long-range prediction have not been quantified. This study focuses on temperature whiplash events in the southern plains of the United States, an area known for highly variable weather. Analyses of the atmospheric conditions reveal that stronger-than-normal high pressure builds in the North Pacific in the days leading up to the hot-to-cold temperature whiplash event, which helps to funnel colder air down into the southern plains days later. There are also precursor signals in the stratosphere, where the polar vortex shows signs of becoming more elliptical than circular in shape, a known precursor for cold-air surges into central North America. Together, these signals may be useful to improve our forecast skill of these very impactful extreme temperature events.

KEYWORDS: Extreme events; Stratosphere-troposphere coupling; Climate classification/regimes; Climate variability; Subseasonal variability

1. Introduction

Extreme temperatures remain a critical threat to global infrastructure and livelihoods, affecting economies, ecosystems, and public health. The Intergovernmental Panel on Climate Change Sixth Assessment Report reported a global trend of increasing warm extremes and decreasing cold extremes (Seneviratne et al. 2021). These trends have been exacerbated

by human influences, including increased greenhouse gas emissions (Seneviratne et al. 2021). For this reason, understanding precursors to and synoptic environments associated with warm and cold extremes are important areas of current research. In this study, we focus specifically on extreme temperature variability in North America during the cold season. Past research has suggested that variability in cold-air outbreaks (CAOs) in that domain is related to multiple mechanisms, including variability in the strength of the stratospheric polar vortex (SPV; e.g., Baldwin and Dunkerton 2001; Kolstad et al. 2010; Millin et al. 2022; Hanna et al. 2024; Agel et al. 2025) and variability in the North Pacific jet stream and associated wave trains (e.g., Winters et al. 2019; Park et al. 2024; Stone et al. 2025). However, while CAOs are decreasing in frequency and intensity over North America on the whole (e.g., van Oldenborgh et al. 2019; Smith and Sheridan 2020), there may be lower confidence in this declining trend for parts of eastern and Central United States, particularly over the last 2–3 decades (e.g., Cohen et al. 2023).

Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/JCLI-D-24-0572.s1>.

Giannakopoulos’s current affiliation: Gulf of Maine Research Institute, Portland, Maine.

Corresponding author: Katherine Giannakopoulos, kgiannakopoulos@gmri.org

DOI: 10.1175/JCLI-D-24-0572.1

© 2025 American Meteorological Society. This published article is licensed under the terms of the default AMS reuse license. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).

Brought to you by UNIVERSITY OF OKLAHOMA LIBRARY | Unauthenticated | Downloaded 09/27/26 07:06 PM UTC

North American CAOs are also frequently associated with blocking ridges near and over Alaska (e.g., Konrad and Colucci 1989; Westby and Black 2015; Cellitti et al. 2006; Xie et al. 2017; Millin et al. 2022; Hanna et al. 2024). In contrast, abnormal warm spells across North America during winter are not researched as extensively as CAOs. Limited studies on the topic indicate that winter warm spells are collocated with positive geopotential height anomalies. They often result in an atmospheric block over the affected region and are part of a much larger hemispheric-scale Rossby wave train (e.g., Dong et al. 2018; Tomczyk et al. 2019; Domeisen et al. 2023). Recent work by Grace et al. (2024) on two winter warm spells specifically in the southern Great Plains concluded that anomalous Alaskan ridging contributed to the winter warm spells, along with higher-than-average sensible and latent heat fluxes in different parts of the Great Plains.

Lately, a new form of extreme weather event has been proposed: temperature whiplash. Temperature whiplashes occur when near-surface temperatures rapidly transition from one persistent and anomalous temperature pattern to the opposite-signed temperature extreme. For example, in December 2013, Oklahomans experienced temperatures over 8°C above the climatological mean in Norman, Oklahoma, between 16 and 19 December 2013 (Oklahoma Mesonet 2024). However, this pattern abruptly shifted on 20 December 2013 with the emergence of a strong winter storm that plunged temperatures in Norman nearly 10°C below normal from 21 to 24 December 2013 (Oklahoma Mesonet 2024). Additionally, between 20 and 22 December 2013, Oklahoma received up to 2.5 cm of ice across the state (NWS 2013). Many Oklahomans were out of power, with Oklahoma Gas and Electric reporting 8950 power outages as of 2200 LT 21 December 2013 (News on 6 2013). Power outages when temperatures are substantially below normal pose a threat to human health, including an increased risk of hospitalizations when a power outage is paired with a cold event or ice storm, and can have impacts on health up to a week following the outage (Lin et al. 2021). This event serves as a prime example of how rapid changes in temperature can affect a region. Indeed, the U.S. southern plains is an area prone to very large temperature swings particularly during the winter (Yang et al. 2022). Thus, this region will be the focus area for this study.

Current literature on temperature whiplash events offers varied definitions and criteria for these extreme weather events. In considering a large domain, Francis et al. (2022) defined temperature whiplashes as “transitions from one persistent large-scale regime to a distinctly different one” through using self-organizing maps of 500-hPa geopotential height anomalies. The same study defined “long-duration events” (LDEs) as periods when the synoptic patterns remained in the same node for 4 or more days. Subsequently, a “weather whiplash” occurred when the 2 days following an LDE were notably different from the LDE (Francis et al. 2022). Considering 500-hPa geopotential heights anomalies is effective when considering continental-scale extremes, but the methodology overlooks local temperature variations by focusing on large-scale midtropospheric circulation variability. In contrast, Casson et al. (2019) studied a smaller domain (the Northeast United States) and defined a weather whiplash as periods in

the Northeast United States when the air temperature oscillates above and below freezing. This criterion was selected because the phase change from liquid to solid precipitation leads to more drastic human impacts (Casson et al. 2019). This impact-based approach favors local adaptations to such extreme events but cannot be generalized easily to other U.S. regions due to regional temperature differences. Additionally, resilience to cold weather varies between regions; thus, it cannot be assumed that adaptation is consistent for all regions. As such, a region-specific definition, one that considers a regional domain for its formulation but can be applied elsewhere, is a more appropriate approach for capturing local temperature variations while enabling direct comparisons across different regions.

Skillful prediction of temperature whiplash events remains a challenge, particularly at the subseasonal to seasonal (S2S) time scale where prediction skill is already low (Vitart and Robertson 2018). However, having skillful forecasts within this time frame is beneficial, as it allows for preemptive adaptation and mitigation of potential damages (Coughlan de Perez et al. 2016; Vitart and Robertson 2018). Although previous studies have identified possible S2S features for whiplashes including a meridional-oriented, amplified ridge/trough pattern over North America (Francis et al. 2022), and connections to modes of climate variability like the North Pacific Oscillation, Pacific–North American pattern, and ENSO related to temperature swings (Yang et al. 2022), such work for the U.S. southern plains remains incomplete. Indeed, understanding the mechanisms related to and identifying long-lead predictors of temperature whiplash events warrant attention due to their potential to disrupt ecosystems, infrastructure, and human health.

The objectives of this study are to 1) develop a novel, regional methodology to identify temperature whiplashes in the U.S. southern plains; 2) examine the trends in temperature whiplash events in the recent past; and 3) investigate the characteristic tropospheric and stratospheric circulations preceding and co-occurring with temperature whiplash events in the U.S. southern plains. Our statistical analysis of these events will fill a gap in the literature for such extreme temperature events for the U.S. southern plains and could be used for benchmarking and understanding the potential S2S prediction skill for such events within operational dynamical models. We hypothesize that atmospheric features connected to CAOs and winter warm spells, such as atmospheric blocking and stratosphere–troposphere interactions, are also important for temperature whiplash events. Additionally, we hypothesize that the U.S. southern plains may have different precursors than those that have been identified in previous works for larger scales because of local temperature variations. Such results have the potential to improve long-lead forecasts of such events in operational settings and to develop a dynamical framework for understanding extreme temperature variability in the U.S. southern plains.

2. Data and methods

a. Reanalysis data

Data for this project originated from the fifth generation European Centre for Medium-Range Weather Forecasts atmospheric

TABLE 1. The ERA5 variables used in this study and associated analyses using those variables.

Analysis	Variables
TSI	2-m temperature
Height composites	Geopotential height: 500 and 50 hPa
RI and meridional heat flux ($v'T'$)	100-hPa temperature and 100-hPa meridional wind

reanalysis (ERA5; Hersbach et al. 2020). Six-hourly data from 1950 to 2023 on a $0.5^\circ \times 0.5^\circ$ grid were used for identifying temperature whiplash events. We restricted our analysis to exploring only boreal winter temperature whiplash events [i.e., December–February (DJF)], though the methodology for identifying temperature whiplash events described below could be extended to other seasons. The winter season was selected following other works on temperature whiplash, including the existing framework established in Yang et al. (2022). Anomaly fields were constructed by removing the long-term daily climatological values from the raw fields, where the climatology is computed from 1991 to 2020. For analyses of associated circulation patterns with and precursor patterns to temperature whiplash events, we use daily mean values and anomalies of the various fields. Table 1 lists the specific variables and their use in the study.

b. Defining temperature whiplash events

TSI

For this study, we followed Yang et al. (2022) in identifying temperature whiplash events. Specifically, we make use of the temperature swing index (TSI), defined as

$$\text{TSI} = \sqrt{\frac{1}{N-1} \sum_{n=1}^N [\text{SAT}(n+24\text{ h}) - \text{SAT}(n)]^2}, \quad (1)$$

where SAT represents the surface air temperature (in this study, we use 2-m temperature in lieu of surface temperature), n is an individual time step, and N is the number of time steps in a 24-h period (in this analysis $N = 4$). Yang et al. (2022) found that the TSI is proportional to the product of the eddy heat flux and the mean temperature gradient. This finding emphasizes that the TSI is not only directly related to the change in SAT itself but also rather the gradient in SAT. This relationship suggests that the patterns of TSI are likely to be different than those of SAT (Yang et al. 2022).

To begin defining temperature whiplash events, the TSI was calculated daily at each grid point within the U.S. southern plains domain, defined as $30^\circ\text{--}40.5^\circ\text{N}$ and $93^\circ\text{--}103.5^\circ\text{W}$ (Fig. 1a, blue box) between 1950 and 2023 over the DJF period. The boundaries of the U.S. southern plains domain were selected to include only points east of the Rocky Mountains and no points over the Gulf of Mexico. These values were then area averaged to get one “U.S. southern plains TSI” value for each day. Days when the U.S. southern plains TSI value was greater than the 90th percentile of the DJF U.S. southern plains TSI were termed “high swing days” (HSDs). The 90th percentile represents the most extreme temperature swings for our work. The actual day-to-day temperature anomalies were then considered to identify two different types of whiplashes: 1) hot to cold and 2) cold to hot. For a hot-to-cold whiplash, the following two conditions must be met:

- 1) The area-averaged 2-m temperature anomalies for the 4 days prior to the HSD must be positive.
- 2) The area-averaged 2-m temperature anomalies for the 4 days following the HSD must be negative.

Similarly, a cold-to-hot whiplash occurs when the following three conditions are met:

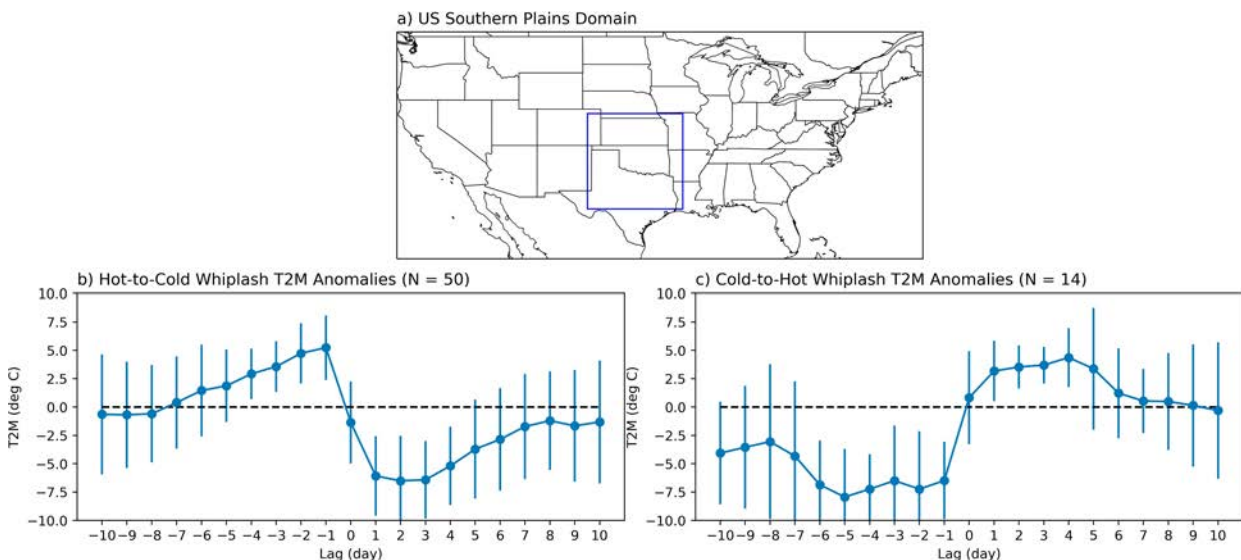


FIG. 1. (a) The U.S. southern plains domain (blue box). (b) Lag composite 2-m temperature anomalies ($^\circ\text{C}$) for hot-to-cold whiplashes from 1950 to 2023 ($N = 50$ events). (c) As in (b), but for cold-to-hot whiplashes ($N = 14$ events). Error bars represent one standard deviation in the composite mean for the given lag.

- 1) The area-averaged 2-m temperature anomalies for the 4 days prior to the HSD must be negative.
- 2) The area-averaged 2-m temperature anomalies the 4 days following the HSD must be positive.

With these definitions, we identified 50 hot-to-cold whiplash events and 14 cold-to-hot whiplash events over the period of the record. We hypothesize that the higher number of hot-to-cold whiplashes is related to the elevated number of cold fronts during the winter season (Lagerquist et al. 2020) and infrequent warm air advection (Schemm et al. 2018). The 4-day lead and lag period for the temperature trend criteria was selected based on Francis et al. (2022), who used a 4-day period to define LDEs. A “whiplash event” will thus be referred to as 4 days before the HSD, until 4 days following the HSD. We tested our definition using 3 and 5 days and found that using 5 days dramatically reduced the sample size of hot-to-cold whiplash events by half ($N = 25$). By contrast, using 3 days nearly doubled the sample size to $N = 91$ events. To retain both the extreme nature of temperature whiplash events and a sample size large enough for the statistical analysis, we will present results only for the 4-day lag results. However, there is little sensitivity in our overall conclusions if 3 or 5 days are chosen. Additionally, we tested the sensitivity of our choice of baseline period (1991–2020) used for calculating the 2-m temperature anomalies and thus identifying temperature whiplash events (e.g., choosing 1950–80 as a baseline period) and found little difference in the identification of events or overall aggregate statistics for the events.

In this manuscript, we will focus on the results for hot-to-cold whiplashes only. Select results for cold-to-hot whiplash events are available in the online supplemental material and will be referenced when appropriate.

c. Metrics for stratosphere–troposphere coupling

When considering mechanisms for wintertime temperature shifts in the Northern Hemisphere (NH) midlatitudes, variability in the SPV is one potential driver of subsequent changes in the tropospheric flow (e.g., Baldwin and Dunkerton 2001; Charlton and Polvani 2007; Cohen et al. 2021). The key forcing for extratropical stratosphere–troposphere coupling arises from vertically propagating Rossby waves from the troposphere into the stratosphere. To represent the vertical propagation of these Rossby waves, we use the meridional heat flux ($v'T'$). To account for only planetary-scale waves, $v'T'$ was filtered for wave-numbers 1–3 using a bandpass filter prior to analyses.

d. Statistical significance testing

To determine statistical significance in this study, we use a 5000-sample bootstrapping without replacement method and choose $p < 0.05$ as our threshold for significance. Random samples were selected from the entire period of record (i.e., 1950–2023), and locations of significance are located by hatching on spatial maps in the following sections.

3. Trends in temperature whiplash events

Figure 2 summarizes key trends in the TSI and HSDs ($N = 659$) in the U.S. southern plains from 1950 to 2019 (due

to only four winter seasons in the 2020s at the time of this study, the 2020s were excluded from decadal analyses). The magnitude of wintertime TSI is positively skewed, peaking around 5°C (Fig. 2a). The 90th percentile threshold is 8.58°C (Fig. 2a, dashed line). Of the 659 HSDs, 253 (38%) had a positive swing (i.e., a cold-to-hot swing) and 406% (62%) had a negative swing (i.e., a hot-to-cold swing). However, ~5.5% of cold-to-hot swings met the whiplash criteria outlined in section 2b, whereas ~11% of the hot-to-cold swings met the whiplash criteria. Possible reasons for this factor-of-two difference in swing types will be discussed later. Additionally, when considering the daily wintertime TSI by decade, there is little change between decades (Fig. 2b).

Figures 2c and 2d illustrate the frequency and magnitude of HSDs by decade, respectively. The frequency of HSDs (Fig. 2b) increased from the 1950s to 1970s, before declining and reaching a minimum in the 1990s, with 69 HSDs occurring. However, since the 1990s, there has been an increase in the number of HSDs. In the 2010s, 103 HSDs occurred, the most in any decade within our record. The Mann–Kendall test confirmed an increasing trend in the frequency of yearly HSD counts from 1990 to 2019 ($p < 0.05$). However, when extending the analysis to earlier start dates (e.g., 1950–2019, 1960–2019), the trend is no longer statistically significant. This suggests that the observed increase is not part of a consistent long-term trend but may reflect recent variability. Considering the HSD TSI magnitude by decade (Fig. 2d), there is minimal change over time and thus no significant trends detected.

Figure 2e displays some consistency in the number of hot-to-cold whiplashes per decade in early in the record, with 8, 7, and 9, respectively, in the 1950s, 1960s, and 1970s. The 1970s also featured four cold-to-hot whiplashes, which followed a decade with no cold-to-hot whiplashes (the 1960s). Indeed, the 1970s featured an increase in the amount of cold days over the U.S. southern plains, which may have led to more persistent cold anomalies, and therefore the potential for more whiplashes (Higgins et al. 2002, see their Fig. 6). However, following the 1980s, which had the smallest number of hot-to-cold whiplashes, there has been an increase again through the 2010s. The 2010s had nine hot-to-cold whiplashes, which tied the 1970s for the highest number observed in any decade. However, there is no significant trend in the number of hot-to-cold whiplashes per the Mann–Kendall test. The number of cold-to-hot whiplashes declined in the 1990s, and only one cold-to-hot whiplash has occurred each decade since.

The average TSI magnitudes on the HSD for both hot-to-cold and cold-to-hot whiplash events also exhibit variability (Fig. 2f). The TSI magnitude of hot-to-cold whiplash events was greater than 10.5°C before the 1980s but then declined to below 10°C on average in the 1980s and 1990s. The twenty-first century experienced a return to higher magnitudes, with magnitudes of 10.76° and 10.38°C in the 2000s and 2010s, respectively. The drop in magnitude in the 1980s and 1990s could be the result of teleconnection patterns. For example, the 1980s and 1990s featured an increased number of El Niño episodes, which may have reduced the temperature variability during these decades (e.g.,

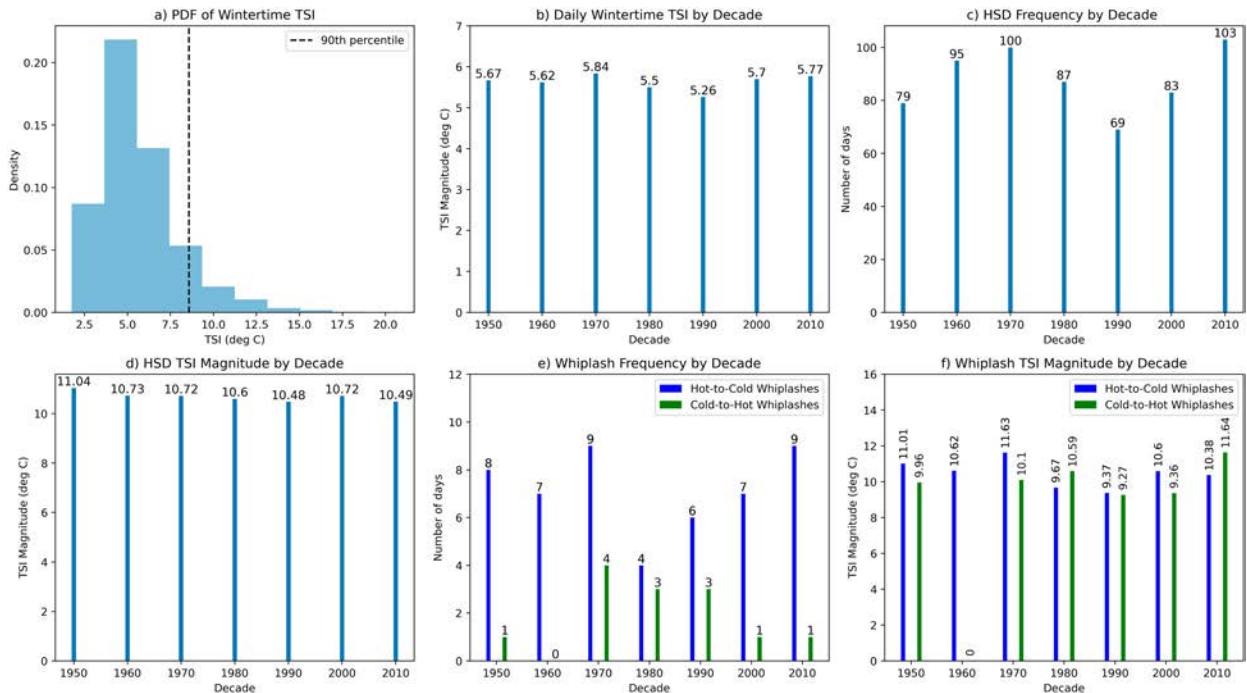


FIG. 2. (a) PDF of daily wintertime (DJF) TSI values ($^{\circ}\text{C}$) in the U.S. southern plains from 1950 to 2023 ($N = 6588$). Black dashed line represents the 90th percentile. (b) Average daily wintertime TSI magnitude ($^{\circ}\text{C}$) per decade ($N = 6588$). (c) Average HSD frequency (days) by decade from 1950 to 2023 ($N = 659$). The 1950 is denoted by years 1950–59 and so on. (d) As in (c), but for average HSD TSI magnitude ($^{\circ}\text{C}$). (e) Frequency (days) of hot-to-cold whiplashes (blue bars; $N = 50$) and cold-to-hot whiplashes (green bars; $N = 14$) by decade. (f) As in (e), but for the average TSI magnitude on the HSD ($^{\circ}\text{C}$).

Folland et al. 2001). This conclusion is supported by a lower average daily TSI during these decades (Fig. 2b). Overall, our results suggest that while the number of hot-to-cold whiplashes has varied since the 1980s, there are no statistically significant trends in frequency or magnitude in either whiplash type.

4. Midtropospheric and stratospheric flow composites associated with whiplash events

a. Hot-to-cold whiplash events

Having quantified recent trends in whiplash event frequency and magnitude over the U.S. southern plains, we next turn to examining characteristic atmospheric flow patterns associated with the whiplash events. We will focus here on such patterns for hot-to-cold whiplash events. Figure 3 presents composites of the lagged 500-hPa geopotential heights (Fig. 3, line contours) and anomalies (Fig. 3, shading) for hot-to-cold whiplashes (lag day 0 is the corresponding HSD). Days from -5 to -3 feature relatively zonal flow across the contiguous United States along with statistically significant ($p < 0.05$) positive height anomalies over the North Pacific and negative height anomalies over Alaska and northwestern Canada (Fig. 3a). The statistically significant positive height anomalies over the United States align with the preceding anomalously warm period in the hot-to-cold whiplash event. As the pattern progresses, a developing ridge in the North Pacific intensifies and moves eastward over Alaska (Fig. 3b, shading). Meanwhile, positive height

anomalies over Greenland and the North Atlantic weaken with time, replaced by increasing positive height anomalies over eastern North America (Fig. 3b). This Alaskan ridge amplifies the downstream flow, resulting in the anomalous trough deepening over the western United States and translating eastward into the U.S. southern plains between days $+1$ and $+3$ (Fig. 3c, shading). Positive height anomalies over the eastern United States during onset of the hot-to-cold whiplash events (Fig. 3b, shading) weaken with time as the overall North American continental pattern transitions to a more persistent Alaskan ridge/eastern North American trough pattern up to a week after the hot-to-cold whiplash event onset (Fig. 3d, shading).

STRATOSPHERIC WAVE REFLECTION

Amplified, horizontally propagating Rossby waves can also propagate vertically and enter the stratosphere. When they do, the waves often either break or reflect. Breaking waves in the stratosphere can result in weakening the SPV through deposits of heat and momentum, which subsequently can influence the tropospheric circulation days to weeks later via a downward propagation of the anomalies (e.g., Baldwin and Dunkerton 2001; Kidston et al. 2015). Wave reflection, however, occurs within a layer in the stratosphere where there is negative vertical zonal-mean zonal wind shear, directing vertically propagating waves back down into the troposphere (e.g., Kodera et al. 2008; Perlwitz and Harnik 2003; Matthias and Kretschmer 2020; Harnik 2009). This process is relatively

Composite of Lagged 500 hPa Geopotential Heights and Anomalies for Hot-to-Cold Whiplashes (N=50)

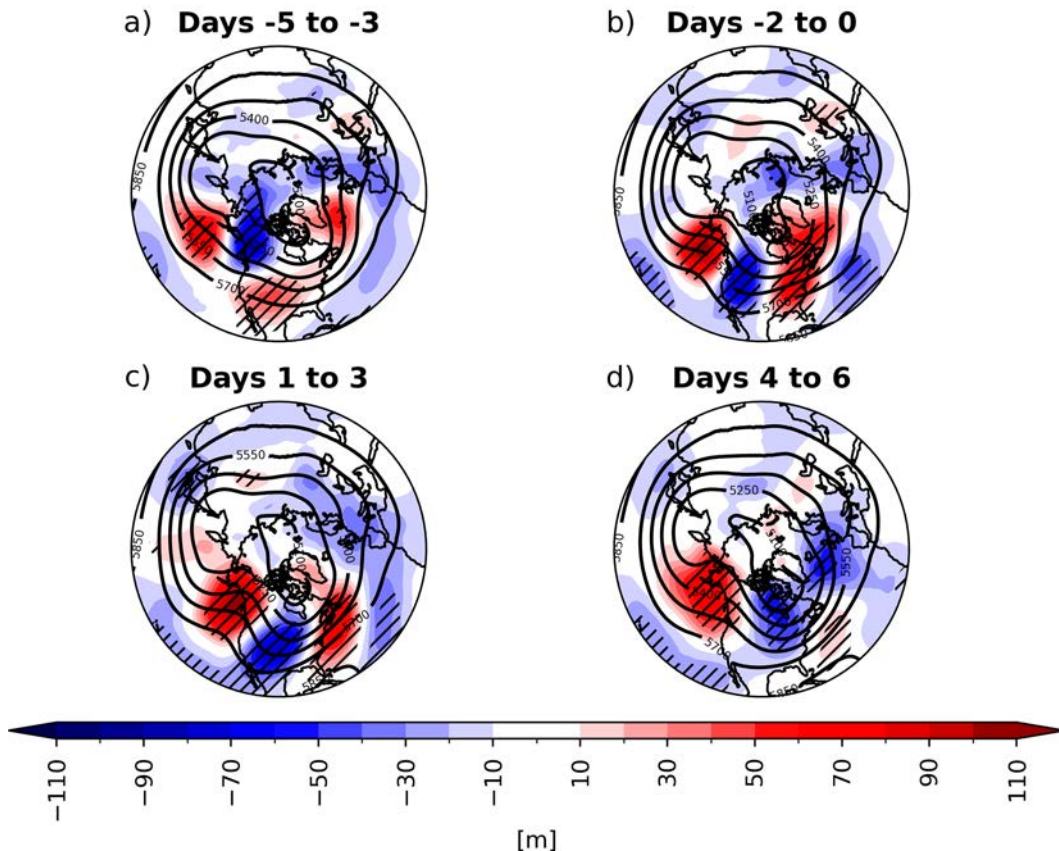


FIG. 3. Lag composites of 500-hPa geopotential heights (line contours; m) and anomalies (shading; m) for hot-to-cold whiplash events ($N = 50$) for (a) days from -5 to -3 , (b) days from -2 to 0 , (c) days from 1 to 3 , and (d) days from 4 to 6 . Hatching represents anomalies significant at the $p < 0.05$ level based on bootstrapping. Line contour interval is 150 m. Day 0 represents the onset of the hot-to-cold whiplash event (see text). Negative lags represent days before onset; positive lags represent days after onset.

faster in time than the breaking waves/downward propagation mechanism and can induce blocking over Alaska and changes in the jet stream downstream over North America (Matthias and Kretschmer 2020; Messori et al. 2022; Millin et al. 2022). It can also result in a more elongated SPV structure (e.g., Matthias and Kretschmer 2020; Cohen et al. 2022; Ding et al. 2023; Millin et al. 2022).

Figure 4 presents lag composites of 50-hPa geopotential heights and height anomalies relative to the HSD. Leading up to the hot-to-cold whiplash event, there are negative height anomalies over the Beaufort Sea and Siberia and positive anomalies over the North Atlantic Ocean and northeastern Russia (Fig. 4a, shading). Just before the HSD, significant positive height anomalies extend across eastern North America with negative height anomalies to the west (Fig. 4b, shading). The negative anomalies in particular amplify over time, specifically across Hudson Bay and into the Central United States (Figs. 4c,d, shading). Coupled with the concurrent weak (though statistically insignificant) positive anomalies in the

Eastern Hemisphere, the overall structure of the SPV starts somewhat distorted in shape and then appears to elongate or “stretch” into North America as time goes on. This stretching is also somewhat evident in the height contours themselves (Fig. 4, line contours) as they become more meridionally oriented over North America with time. This elongation of the SPV suggests that stratospheric wave reflection may be at play during the hot-to-cold whiplash events.

To quantify wave reflection, we use the reflection index (RI) from Matthias and Kretschmer (2020), defined as

$$RI = (\nu'T')_{\text{Siberia}}^* - (\nu'T')_{\text{Canada}}^*, \quad (2)$$

where $\nu'T'$ is the meridional eddy heat flux at 100 hPa, the prime notation indicates the perturbations from the zonal mean, and the asterisk denotes the area-averaged standardized anomalies. When using this index to examine wave reflection, positive $\nu'T'$ over Siberia (45° – 75° N, 120° – 185° E) and negative $\nu'T'$ over Canada (45° – 75° N, 225° – 300° E)

Composite of Lagged 50 hPa Geopotential Heights and Anomalies for Hot-to-Cold Whiplashes (N=50)

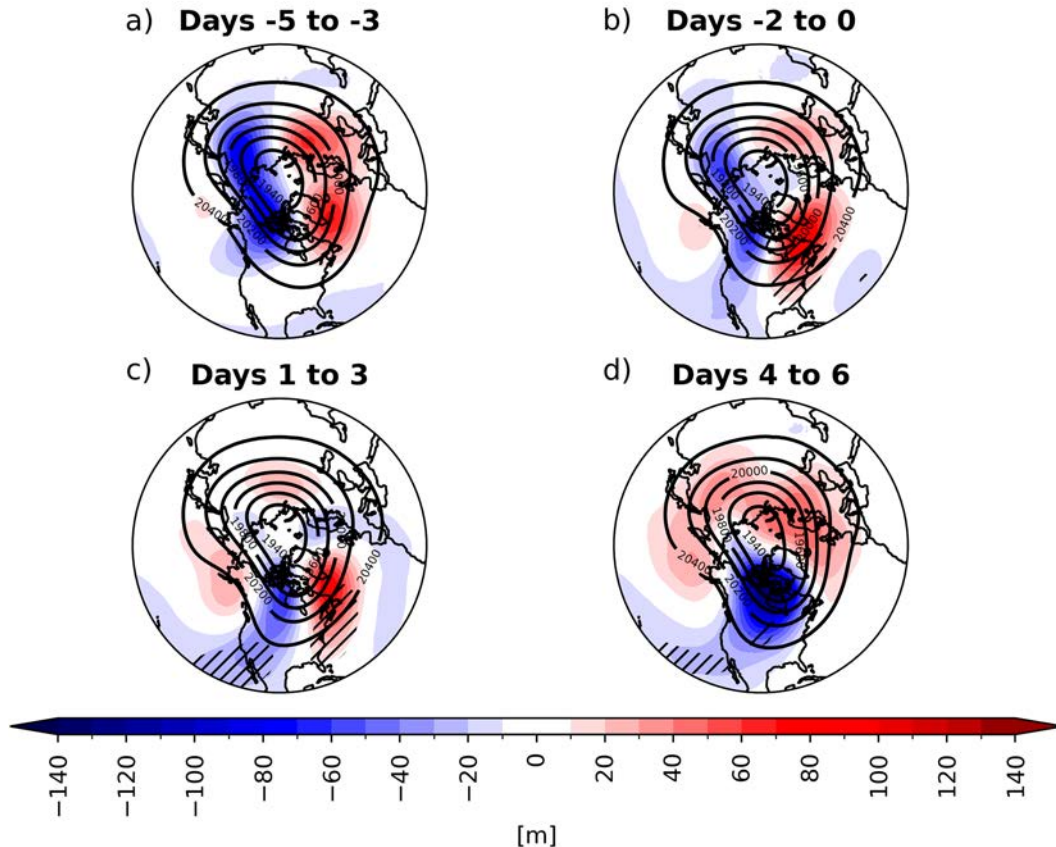


FIG. 4. As in Fig. 3, but for 50-hPa geopotential heights and anomalies.

lead to a positive RI value (Matthias and Kretschmer 2020). To be considered a reflection day, we required $RI > 1$, as done in prior studies (e.g., Messori et al. 2022; Millin et al. 2022).

We find that within 10 days before and including the HSD, 24 out of 50 hot-to-cold whiplash events feature at least 1 day of favorable reflection conditions (i.e., $RI > 1$). To illustrate the period of possible reflection mechanism, Fig. 5 presents lagged composites of meridional heat flux at 100 hPa ($v'T'$) prior to the hot-to-cold whiplash HSD. Positive, statistically significant meridional heat flux (i.e., upward wave flux) centered over the Bering Strait develops around 8 days before the hot-to-cold whiplash events, increasing in magnitude over time (Figs. 5a,b). Then, on days from -2 to 0 , positive significant $v'T'$ over eastern Siberia and western Alaska is juxtaposed with negative significant $v'T'$ values over Canada (Fig. 5c). This $v'T'$ pattern suggests that Rossby waves are propagating vertically over eastern Siberia/western Alaska and returning into the troposphere over Canada, the characteristic pattern for wave reflection (e.g., Matthias and Kretschmer 2020). Note that several events also feature favorable stratospheric wave reflection conditions during positive lags (i.e., after the onset of the hot-to-cold whiplash event), which may indicate

longevity of the cold temperature anomaly portion of the whiplash (though not a “whiplash” event itself). As wave reflection is detected in 48% of our events, its implications for temperature whiplash events in the U.S. southern plains may be important and warrant further consideration. To explore how this compares to a typical 10-day period, we selected 10 000 ten-day periods during November–March from 1950 to 2023 and found that an $RI \geq 1$ occurred 5039 times (50.39%). Our results are not definitive as to the role of stratospheric wave reflection in hot-to-cold whiplash events; its occurrence in 24 out of 50 cases aligns with its climatological frequency, suggesting it may be one of several contributing factors rather than a dominant driver.

b. Cold-to-hot whiplash events

While cold-to-hot whiplash events are less frequent than hot-to-cold whiplash events during our study period, they have distinct atmospheric features. Unlike the hot-to-cold whiplash events, cold-to-hot whiplash events evolve from a decaying blocking pattern (Fig. S1). While a ridge exists over Alaska from days -5 to -3 , the ridge is located farther north and is more expansive, extending over the Chukchi and Bering Seas, and featuring positive geopotential height

Composite of Lagged 100 hPa $V'T'$ for Hot-to-Cold Whiplashes ($N = 50$)

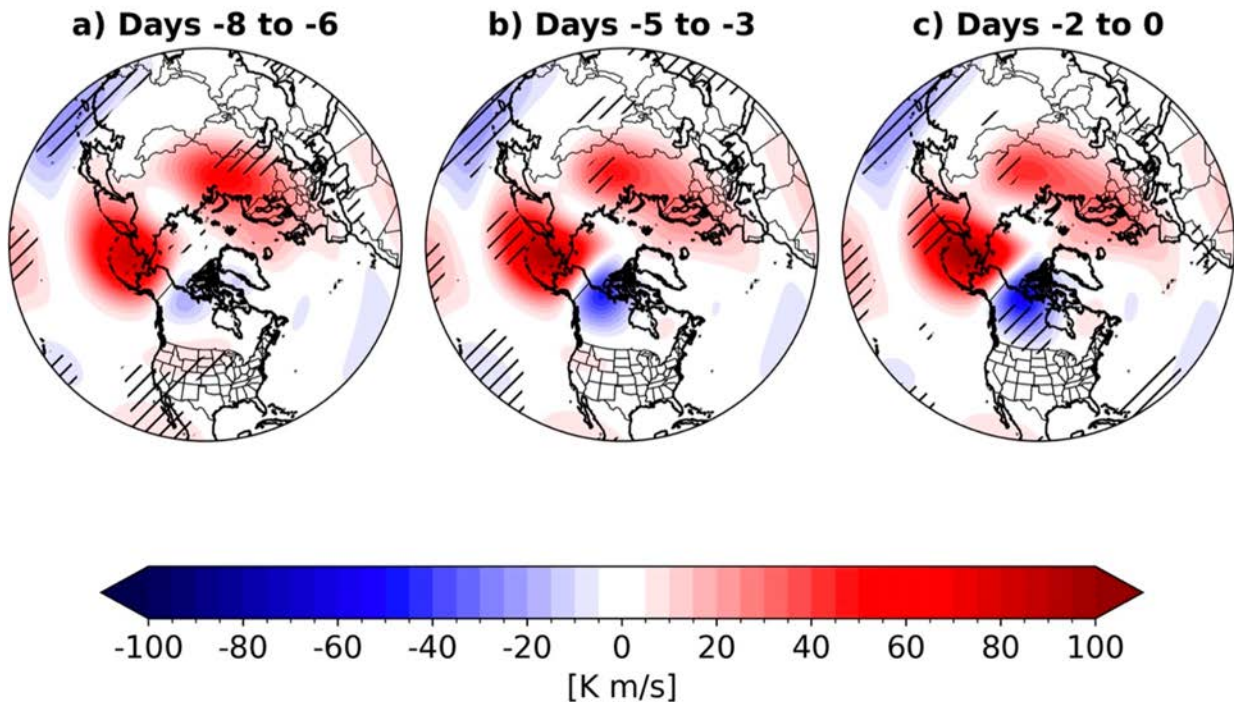


FIG. 5. Lag composites of 100-hPa $v'T'$ (wavenumbers 1–3; K m s^{-1} ; shading) for hot-to-cold whiplashes ($N = 50$) for (a) days from -8 to -6 , (b) days from -5 to -3 , and (c) days from -2 to 0 . Hatching denotes anomalies are significant at the $p < 0.05$ level. Red shading indicates a positive (upward) flux, and blue shading indicates a negative (downward) flux. Negative lags indicate days before the hot-to-cold whiplash event HSD. Day 0 represents the HSD/hot-to-cold whiplash event onset day.

anomalies extending across the North Pacific Ocean and into northern Siberia (Fig. S1a). This ridge does not persist through the whiplash event and dissipates completely by days 4–6 (Fig. S1d). The breakdown of this ridge leads to a relaxation of the downstream atmospheric flow, with an existing anomalous trough over the United States and Canada lifting and moving eastward into the Atlantic Ocean (Fig. S1c). The 500-hPa flow becomes more zonal, and positive geopotential height anomalies emerge over the U.S. southern plains, which is linked with the period of anomalous warmth in the cold-to-hot whiplash.

In the stratosphere (Fig. S2), there are three statistically significant areas of anomalies: 1) a negative height anomaly in northern Canada and Greenland, 2) a positive height anomaly in Siberia, and 3) a positive height anomaly in northwestern Europe and the North Atlantic Ocean. This pattern develops between days -5 and -3 (Fig. S2a), and the negative anomaly intensifies, reaching its peak intensity during just before the cold-to-hot whiplash onset (Fig. S2b). The presence of robust negative geopotential height anomalies near the core of the SPV suggests a strong SPV on and following the HSD. Negative geopotential height anomalies that extend farther

south into Canada and the United States prior to the HSD suggest the SPV may have been stretched and weaker before the cold-to-hot whiplash event (Figs. S2a,b). Following the HSD, the anomaly pattern persists through day 6, although the negative geopotential height anomaly recedes northward, restoring a more circular shape for the SPV (Figs. S2c,d). Note that the 50-hPa anomalies are an order of magnitude larger than the hot-to-cold whiplash anomalies, but this may be because of the smaller sample size of cold-to-hot whiplash events relative to the hot-to-cold whiplash events. Favorable wave reflection conditions were not present in cold-to-hot whiplashes (not shown).

5. Connecting whiplash events to weather regimes

Weather regimes represent recurrent, long-lasting atmospheric flow patterns over a specific region and can offer value for medium- and long-range forecasts of sensible weather, including on the S2S time scale (e.g., Michelangeli et al. 1995; Charlton-Perez et al. 2018; Vigaud et al. 2018; Lee et al. 2019; Millin et al. 2022). Past research has identified such weather regimes for the Atlantic–European sector (Vautard 1990;

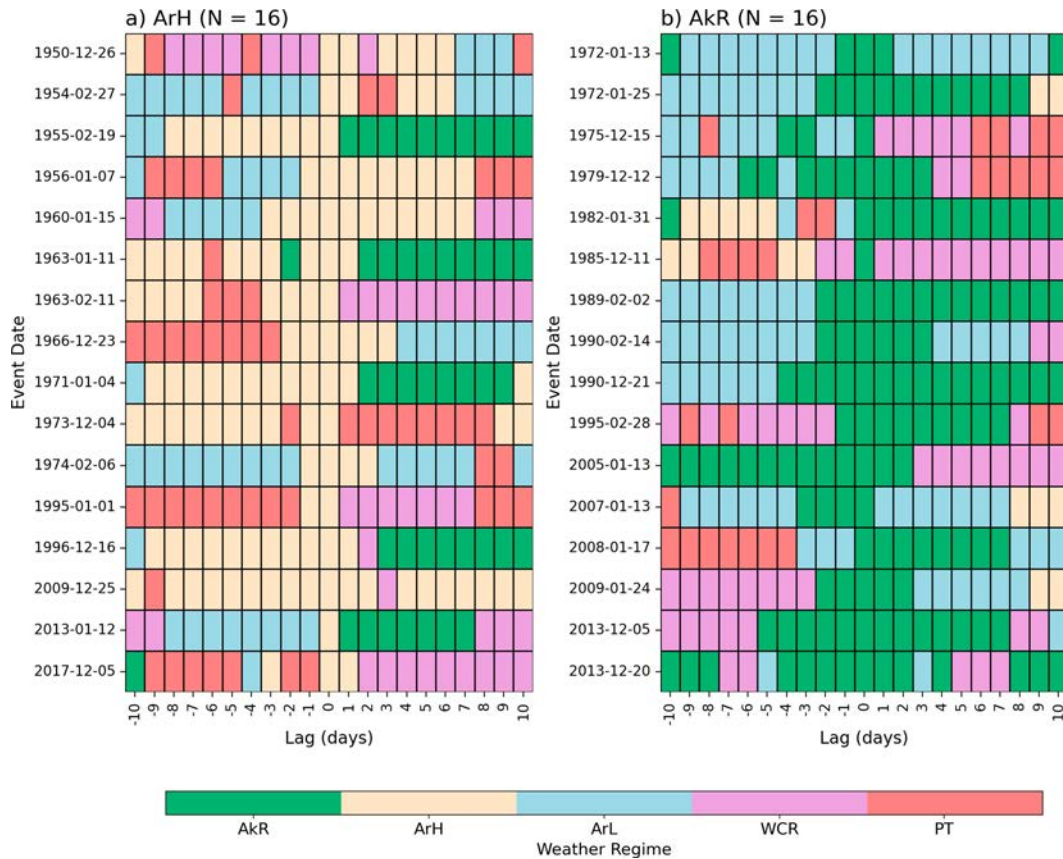


FIG. 6. Daily evolution of North American winter weather regimes for hot-to-cold whiplashes during which the HSD is in the (a) ArH and (b) AkR regimes. Lags are relative to the HSD; lag 0 represents the HSD.

Michelangeli et al. 1995) and linked these regimes to applications in S2S prediction of temperature and precipitation patterns and even energy production and use (e.g., Grams et al. 2017; Matsueda and Palmer 2018; Domeisen et al. 2020; Büeler et al. 2021; Rantanen et al. 2023; Millin et al. 2024). For this work, we use the boreal winter North American winter weather regimes derived by Millin et al. (2022) and relate them to our temperature whiplash events. To create these regimes, Millin et al. (2022) used *k*-means clustering on the 12 leading principal component time series of the 500-hPa linearly detrended geopotential height anomalies over North America between 1950 and 2021 (expanded to 2023 for this work). The five North American weather regimes are 1) the Arctic high (ArH) regime, 2) the Arctic low (ArL) regime, 3) the Alaskan ridge (AkR) regime, 4) the Pacific trough (PT) regime, and 5) the West Coast ridge (WCR) regime. Daily classification of weather regimes during each winter day from 1950 to 2023 was done based on the minimum Euclidean distance between daily mean 500-hPa geopotential height anomaly maps over North America and each cluster's centroid. More information on the characteristic midtropospheric flow patterns and frequency of occurrence of these regimes can be found in Millin et al. (2022, see their Fig. 4).

Cross listing our 50 hot-to-cold whiplash event start dates with the daily weather regime classifications, three North

American winter weather regimes emerge as predominantly coinciding with the onset date for these whiplash events: ArH (16 events), AkR (16 events), and ArL (10 events). The PT (3 events) and WCR (5 events) regimes occur far less frequently and are thus not evaluated further. Note that the WCR loading pattern closely resembles that of the AkR and, while not formally tested, may lead to similar conclusions. For cold-to-hot whiplash events, 6 of the 14 events featured the AkR regime on onset date, followed by WCR (3 events), PT (3 events), and ArL (2 events). Both whiplash types yield small sample sizes for each regime, so while statistical significance is difficult to determine, these patterns still offer useful qualitative insights on event evolution and favorability for wave reflection.

Figure 6 depicts the daily evolution of the midtropospheric flow pattern over North America as represented by our weather regimes during hot-to-cold whiplash events, stratified by the regime classification on the HSD: ArH (Fig. 6a) and AkR (Fig. 6b). Our two most frequent regimes on the HSD of hot-to-cold whiplash events, the AkR and ArH regimes, have been identified in previous research as conducive to cold events, with the coldest events occurring during an AkR regime (Millin et al. 2022; Lee et al. 2019; Messori et al. 2022). To understand how each type is developed, we examine how the weather regimes evolve leading to and following the HSD.

The evolution of hot-to-cold whiplash events associated with the ArH regime (Fig. 6a) shows that 10 out of the 16 ArH-related events feature at least 1 day of the PT regime before the HSD. This finding is similar to the results in Millin et al. (2022), who found that 8 of the 18 CAOs they identified as ArH related also transitioned from the PT regime to the ArH regime. The ArH regime is generally associated with a weaker SPV, which leads to the absorption of wave energy as opposed to reflection (Millin et al. 2022). However, of the 16 ArH hot-to-cold whiplash events, 7 exhibited RI values greater than 1 in the 10 days preceding the HSD, indicating the potential for wave reflection events; future work is needed to understand these potential reflecting cases. Nevertheless, the events ultimately transition to a regime associated with a stronger SPV (the AkR, WCR, and ArL regimes), suggesting there may be an increase in SPV strength occurring over time.

Conversely, the AkR regime has been identified in multiple studies as conducive to wave reflection (e.g., Messori et al. 2022; Millin et al. 2022; Lee et al. 2019; Ding et al. 2023). This finding is also present in our study, as 10 of the 16 AkR hot-to-cold whiplash events showed $RI > 1$ within 10 days of the HSD. This regime is favorable due to its accompanying strong SPV. Messori et al. (2022) found that wave reflection events were most likely to occur during a transition from a PT to AkR regime. Interestingly, only 6 of the 16 AkR events had at least 1 day of the PT regime before the HSD. However, given that Messori et al. (2022) examined long-duration reflection events, the comparison may not be entirely equitable. Transitions for our AkR events were generally from the ArL and WCR regimes, and like the PT, they are favorable for stronger SPV states, supporting the likelihood of wave reflection (e.g., Lee et al. 2019; Millin et al. 2022).

6. Discussion and conclusions

Temperature whiplash events pose a significant threat to society through added stress to infrastructure (Yang et al. 2022; Francis et al. 2022), increased mortality (Lee et al. 2018), and other harmful health impacts, including respiratory and cardiovascular impacts, when temperatures fluctuate rapidly (Liu and Ho 2024; Ponjoan et al. 2021). This study defined temperature whiplash events over a regional domain (the U.S. southern plains) to allow for potential improved preparation for these extreme weather events. Our methodology can be applied to other domains, facilitating future work in this area. The TSI is also a useful metric for temperature whiplashes, as shown in this and prior work. Indeed, operational forecasting and climate models such as the Geophysical Fluid Dynamics Laboratory's seasonal prediction system demonstrate skill in prediction of the TSI at long leads, suggesting the potential for subseasonal forecasts of temperature whiplash events (Yang et al. 2022). This conclusion is bolstered with our examination of the precursors to and evolution of temperature whiplash events in the U.S. southern plains.

In this work, we defined two types of whiplash events in the U.S. southern plains: hot to cold and cold to hot. Hot-to-cold whiplashes occurred more frequently than cold-to-hot whiplashes over the last seven decades, possibly due to a greater

number of cold fronts and limited warm air advection during the winter season (Schemm et al. 2018; Lagerquist et al. 2020). The number of HSDs has increased since the 1990s, which is notable considering the general decrease in temperature variability over recent decades (e.g., Screen 2014; Rhines et al. 2017; Blackport et al. 2021; Dai and Deng 2021). Our hot-to-cold whiplash findings also support the conclusions by Francis et al. (2022), who found that the AkR regime pattern is associated with weather whiplash events (Figs. 3 and 6). Additionally, Francis et al. (2022) also found that further Arctic warming is expected to increase the amount of weather whiplashes. While this study focused on the U.S. southern plains domain, examining temperature whiplashes over other regions would provide more context on regional precursors, trends in whiplash events, and offer additional relevance to their S2S predictions.

The midtropospheric flow patterns associated with temperature whiplash events are type dependent. Hot-to-cold whiplash events feature an increase in anomalous ridging across the North Pacific throughout the event, which induces a deep, expansive trough over the Central United States (Fig. 3). The southward digging of this trough over time leads to the cold spell of the hot-to-cold whiplash event. The evolution of the 500-hPa geopotential height patterns can also be characterized through North American winter weather regimes. The two regimes that are most commonly associated with hot-to-cold whiplashes on the HSD are the ArH and AkR regimes (Fig. 6). Relating temperature whiplash events to these large-scale, recurrent patterns is a valuable way to extend the work to S2S prediction, as regimes serve as convenient methods to verify and track with time over individual ridges and troughs. Such regimes also provide excellent forecasts of opportunity during which prediction skill for significant temperature and precipitation events is enhanced on subseasonal time scales (e.g., Jennrich et al. 2024).

In this work, we focused on extratropical NH stratosphere–troposphere coupling and variability in the SPV as one such driver. Our results suggest that stratospheric wave reflection may occur within the 10 days preceding the HSD, especially within 5 days. Indeed, Ding et al. (2023) identified wave reflection as a precursor to North American cold-air events, which occurred 5–25 days after strong wave reflection events. However, this wave reflection is not as prevalent or persistent as shown in, for example, Matthias and Kretschmer (2020) or Messori et al. (2022). This quicker stratospheric wave reflection episode is consistent with the findings of Millin et al. (2022), who also found that stratospheric wave reflection was a key feature preceding the onset of the AkR regime. Indeed, the AkR-related hot-to-cold whiplash events also tended to align more with favorable stratospheric wave reflection conditions. By contrast, ArH-related hot-to-cold whiplash events featured a weak SPV (Fig. 6a; Baldwin and Dunkerton 2001; Kolstad et al. 2010; Millin et al. 2022). Therefore, stratospheric wave reflection may offer potential subseasonal prediction skill of some temperature whiplash events for the U.S. southern plains, but other mechanisms also need to be considered. The weather regime framework may be a convenient

way to facilitate the exploration of other such mechanisms of temperature whiplash events.

While we additionally examined cold-to-hot whiplashes, the relatively small sample size did not lead to distinct conclusions about their precursors. Their 500-hPa height composites featured an opposite pattern to that of the hot-to-cold whiplashes, with a dissipating atmospheric block in the midtroposphere over the Chukchi and Bering Seas (Fig. S1) and a strengthening SPV, which matches the associated weather regime evolution for these events (Fig. S3). Note that cold-to-hot temperature whiplashes may not have temperature anomalies as strong or persistent as hot-to-cold swings, and therefore, the proposed whiplash criteria may be too limiting to adequately represent them. Future work should continue efforts to categorize and classify cold-to-hot whiplash event precursors and addressing these questions, perhaps with the use of large-ensemble projects [e.g., CESM2 large-ensemble projects (LENS); Rodgers et al. 2021].

Somewhat surprisingly, temperature whiplash events in the U.S. southern plains showed little direct connection to classical modes of climate variability known to contribute to winter weather patterns. For example, we found no statistically significant relationships between whiplash events and ENSO, the Arctic Oscillation, the North Atlantic Oscillation, or the Pacific–North American pattern (not shown). These statistics do not discount that such patterns may exist during select whiplash events (e.g., the ArH regime has ties to the negative phase of the Arctic Oscillation). Moreover, Yang et al. (2022) found that the seasonal TSI could be connected to multiple climate modes on a continental scale. This finding suggests that while climate modes may be used to predict temperature variability on long time scales and over large domains, smaller domains and smaller swing time scales require considering different drivers. Future work may focus on this linkage and extending that to potential changes in whiplash events and teleconnection links in a future warmer climate.

Acknowledgments. We thank the National Science Foundation EPSCoR Grant OIA-1946093 for their support of this work. We would also like to thank the anonymous reviewers for their constructive feedback. Furthermore, we thank Oliver Millin for his helpful suggestions surrounding this work. The whiplash databases and relevant analyses are available at <https://doi.org/10.5281/zenodo.15066402>.

Data availability statement. The ERA5 reanalysis dataset was obtained from the Copernicus Climate Data Store at <https://cds.climate.copernicus.eu>.

REFERENCES

- Agel, L., J. Cohen, M. Barlow, K. Pfeiffer, J. Francis, C. I. Garfinkel, and M. Kretschmer, 2025: Cold-air outbreaks in the continental US: Connections with stratospheric variations. *Sci. Adv.*, **11**, eadq9557, <https://doi.org/10.1126/sciadv.adq9557>.
- Baldwin, M. P., and T. J. Dunkerton, 2001: Stratospheric harbingers of anomalous weather regimes. *Science*, **294**, 581–584, <https://doi.org/10.1126/science.1063315>.
- Blackport, R., J. C. Fyfe, and J. A. Screen, 2021: Decreasing sub-seasonal temperature variability in the northern extratropics attributed to human influence. *Nat. Geosci.*, **14**, 719–723, <https://doi.org/10.1038/s41561-021-00826-w>.
- Büeler, D., L. Ferranti, L. Magnusson, J. F. Quinting, and C. M. Grams, 2021: Year-round sub-seasonal forecast skill for Atlantic–European weather regimes. *Quart. J. Roy. Meteor. Soc.*, **147**, 4283–4309, <https://doi.org/10.1002/qj.4178>.
- Casson, N. J., and Coauthors, 2019: Winter weather whiplash: Impacts of meteorological events misaligned with natural and human systems in seasonally snow-covered regions. *Earth's Future*, **7**, 1434–1450, <https://doi.org/10.1029/2019EF001224>.
- Cellitti, M. P., J. E. Walsh, R. M. Rauber, and D. H. Portis, 2006: Extreme cold air outbreaks over the United States, the polar vortex, and the large-scale circulation. *J. Geophys. Res.*, **111**, D02114, <https://doi.org/10.1029/2005JD006273>.
- Charlton, A. J., and L. M. Polvani, 2007: A new look at stratospheric sudden warmings. Part I: Climatology and modeling benchmarks. *J. Climate*, **20**, 449–469, <https://doi.org/10.1175/JCLI3996.1>.
- Charlton-Perez, A. J., L. Ferranti, and R. W. Lee, 2018: The influence of the stratospheric state on North Atlantic weather regimes. *Quart. J. Roy. Meteor. Soc.*, **144**, 1140–1151, <https://doi.org/10.1002/qj.3280>.
- Cohen, J., L. Agel, M. Barlow, C. I. Garfinkel, and I. White, 2021: Linking Arctic variability and change with extreme winter weather in the United States. *Science*, **373**, 1116–1121, <https://doi.org/10.1126/science.abi9167>.
- , —, —, J. C. Furtado, M. Kretschmer, and V. Wendt, 2022: The “polar vortex” winter of 2013/2014. *J. Geophys. Res. Atmos.*, **127**, e2022JD036493, <https://doi.org/10.1029/2022JD036493>.
- , —, —, and D. Entekhabi, 2023: No detectable trend in mid-latitude cold extremes during the recent period of Arctic amplification. *Commun. Earth Environ.*, **4**, 341, <https://doi.org/10.1038/s43247-023-01008-9>.
- Coughlan de Perez, E., and Coauthors, 2016: Action-based flood forecasting for triggering humanitarian action. *Hydrol. Earth Syst. Sci.*, **20**, 3549–3560, <https://doi.org/10.5194/hess-20-3549-2016>.
- Dai, A., and J. Deng, 2021: Arctic amplification weakens the variability of daily temperatures over northern middle-high latitudes. *J. Climate*, **34**, 2591–2609, <https://doi.org/10.1175/JCLI-D-20-0514.1>.
- Ding, X., G. Chen, P. Zhang, D. I. V. Domeisen, and C. Orbe, 2023: Extreme stratospheric wave activity as harbingers of cold events over North America. *Commun. Earth Environ.*, **4**, 187, <https://doi.org/10.1038/s43247-023-00845-y>.
- Domeisen, D. I. V., C. M. Grams, and L. Papritz, 2020: The role of North Atlantic–European weather regimes in the surface impact of sudden stratospheric warming events. *Wea. Climate Dyn.*, **1**, 373–388, <https://doi.org/10.5194/wcd-1-373-2020>.
- , and Coauthors, 2023: Prediction and projection of heatwaves. *Nat. Rev. Earth Environ.*, **4**, 36–50, <https://doi.org/10.1038/s43017-022-00371-z>.
- Dong, L., C. Mitra, S. Greer, and E. Burt, 2018: The dynamical linkage of atmospheric blocking to drought, heatwave and urban heat island in southeastern US: A multi-scale case study. *Atmosphere*, **9**, 33, <https://doi.org/10.3390/atmos9010033>.
- Folland, C. K., and Coauthors, 2001: Observed climate variability and change. *Climate Change 2001: The Scientific Basis*, J. T. Houghton et al., Eds., Cambridge University Press, 101–181.
- Francis, J. A., N. Skific, S. J. Vavrus, and J. Cohen, 2022: Measuring “weather whiplash” events in North America: A new large-scale

- regime approach. *J. Geophys. Res. Atmos.*, **127**, e2022JD036717, <https://doi.org/10.1029/2022JD036717>.
- Grace, T. M., K. Pegion, and J. B. Basara, 2024: Atmospheric and surface dynamics during winter warm spells in the Southern Great Plains: Insights from the 2021 case study. *J. Geophys. Res. Atmos.*, **129**, e2024JD040856, <https://doi.org/10.1029/2024JD040856>.
- Grams, C. M., R. Beerli, S. Pfenninger, I. Staffell, and H. Wernli, 2017: Balancing Europe's wind-power output through spatial deployment informed by weather regimes. *Nat. Climate Change*, **7**, 557–562, <https://doi.org/10.1038/nclimate3338>.
- Hanna, E., and Coauthors, 2024: Influence of high-latitude blocking and the northern stratospheric polar vortex on cold-air outbreaks under Arctic amplification of global warming. *Environ. Res.: Climate*, **3**, 042004, <https://doi.org/10.1088/2752-5295/ad93f3>.
- Harnik, N., 2009: Observed stratospheric downward reflection and its relation to upward pulses of wave activity. *J. Geophys. Res.*, **114**, D08120, <https://doi.org/10.1029/2008JD010493>.
- Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. *Quart. J. Roy. Meteor. Soc.*, **146**, 1999–2049, <https://doi.org/10.1002/qj.3803>.
- Higgins, R. W., A. Leetmaa, and V. E. Kousky, 2002: Relationships between climate variability and winter temperature extremes in the United States. *J. Climate*, **15**, 1555–1572, [https://doi.org/10.1175/1520-0442\(2002\)015<1555:RBCVAW>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<1555:RBCVAW>2.0.CO;2).
- Jennrich, G., D. Straus, M. Chelliah, and C. Baggett, 2024: Ensemble predictability of week 3/4 precipitation and temperature over the United States via cluster analysis of the large-scale circulation. *Wea. Forecasting*, **39**, 1531–1544, <https://doi.org/10.1175/WAF-D-23-0065.1>.
- Kidston, J., A. A. Scaife, S. C. Hardiman, D. M. Mitchell, N. Butchart, M. P. Baldwin, and L. J. Gray, 2015: Stratospheric influence on tropospheric jet streams, storm tracks and surface weather. *Nat. Geosci.*, **8**, 433–440, <https://doi.org/10.1038/ngeo2424>.
- Kodera, K., H. Mukougawa, and S. Itoh, 2008: Tropospheric impact of reflected planetary waves from the stratosphere. *Geophys. Res. Lett.*, **35**, L16806, <https://doi.org/10.1029/2008GL034575>.
- Kolstad, E. W., T. Breiteig, and A. A. Scaife, 2010: The association between stratospheric weak polar vortex events and cold air outbreaks in the Northern Hemisphere. *Quart. J. Roy. Meteor. Soc.*, **136**, 886–893, <https://doi.org/10.1002/qj.620>.
- Konrad, C. E., II, and S. J. Colucci, 1989: An examination of extreme cold air outbreaks over eastern North America. *Mon. Wea. Rev.*, **117**, 2687–2700, [https://doi.org/10.1175/1520-0493\(1989\)117<2687:AE0ECA>2.0.CO;2](https://doi.org/10.1175/1520-0493(1989)117<2687:AE0ECA>2.0.CO;2).
- Lagerquist, R., J. T. Allen, and A. McGovern, 2020: Climatology and variability of warm and cold fronts over North America from 1979 to 2018. *J. Climate*, **33**, 6531–6554, <https://doi.org/10.1175/JCLI-D-19-0680.1>.
- Lee, S. H., J. C. Furtado, and A. J. Charlton-Perez, 2019: Winter-time North American weather regimes and the Arctic stratospheric polar vortex. *Geophys. Res. Lett.*, **46**, 14892–14900, <https://doi.org/10.1029/2019GL085592>.
- Lee, W., and Coauthors, 2018: Mortality burden of diurnal temperature range and its temporal changes: A multi-country study. *Environ. Int.*, **110**, 123–130, <https://doi.org/10.1016/j.envint.2017.10.018>.
- Lin, S., and Coauthors, 2021: The immediate effects of winter storms and power outages on multiple health outcomes and the time windows of vulnerability. *Environ. Res.*, **196**, 110924, <https://doi.org/10.1016/j.envres.2021.110924>.
- Liu, S., and H. C. Ho, 2024: Effects of socioeconomic status and greenspace on respiratory emergency department visits under short-term temperature variations: An age-stratified case time-series study. *Soc. Sci. Med.*, **343**, 116613, <https://doi.org/10.1016/j.socscimed.2024.116613>.
- Matsueda, M., and T. N. Palmer, 2018: Estimates of flow-dependent predictability of wintertime Euro-Atlantic weather regimes in medium-range forecasts. *Quart. J. Roy. Meteor. Soc.*, **144**, 1012–1027, <https://doi.org/10.1002/qj.3265>.
- Matthias, V., and M. Kretschmer, 2020: The influence of stratospheric wave reflection on North American cold spells. *Mon. Wea. Rev.*, **148**, 1675–1690, <https://doi.org/10.1175/MWR-D-19-0339.1>.
- Messori, G., M. Kretschmer, S. H. Lee, and V. Wendt, 2022: Stratospheric downward wave reflection events modulate North American weather regimes and cold spells. *Wea. Climate Dyn.*, **3**, 1215–1236, <https://doi.org/10.5194/wcd-3-1215-2022>.
- Michelangeli, P.-A., R. Vautard, and B. Legras, 1995: Weather regimes: Recurrence and quasi stationarity. *J. Atmos. Sci.*, **52**, 1237–1256, [https://doi.org/10.1175/1520-0469\(1995\)052<1237:WRRASQ>2.0.CO;2](https://doi.org/10.1175/1520-0469(1995)052<1237:WRRASQ>2.0.CO;2).
- Millin, O. T., J. C. Furtado, and J. B. Basara, 2022: Characteristics, evolution, and formation of cold air outbreaks in the Great Plains of the United States. *J. Climate*, **35**, 4585–4602, <https://doi.org/10.1175/JCLI-D-21-0772.1>.
- , —, and C. Malloy, 2024: The impact of North American winter weather regimes on electricity load in the central United States. *npj Climate Atmos. Sci.*, **7**, 254, <https://doi.org/10.1038/s41612-024-00803-1>.
- News on 6, 2013: Freezing rain brings power outages in northeastern Oklahoma. *News on 6*, 21 December, <https://www.newson6.com/story/5e3636df2f69d76f62054c12/freezing-rain-brings-power-outages-in-northeastern-oklahoma>.
- NWS, 2013: The winter storm of December 20–22, 2013. Accessed 6 May 2024, <https://www.weather.gov/oun/events-20131220>.
- Oklahoma Mesonet, 2024: Long-term averages in Oklahoma (temperature). Accessed 6 May 2024, <https://www.mesonet.org/index.php/pastdata/mesonetaveragesgraphs>.
- Park, M., N. C. Johnson, and T. L. Delworth, 2024: The driving of North American climate extremes by North Pacific stationary-transient wave interference. *Nat. Commun.*, **15**, 7318, <https://doi.org/10.1038/s41467-024-51601-5>.
- Perlwitz, J., and N. Harnik, 2003: Observational evidence of a stratospheric influence on the troposphere by planetary wave reflection. *J. Climate*, **16**, 3011–3026, [https://doi.org/10.1175/1520-0442\(2003\)016<3011:OE0ASI>2.0.CO;2](https://doi.org/10.1175/1520-0442(2003)016<3011:OE0ASI>2.0.CO;2).
- Ponjoan, A., and Coauthors, 2021: Extreme diurnal temperature range and cardiovascular emergency hospitalisations in a Mediterranean region. *Occup. Environ. Med.*, **78**, 62–68, <https://doi.org/10.1136/oemed-2019-106245>.
- Rantanen, M., S. H. Lee, and J. Aalto, 2023: Asymmetric warming rates between warm and cold weather regimes in Europe. *Atmos. Sci. Lett.*, **24**, e1178, <https://doi.org/10.1002/asl.1178>.
- Rhines, A., K. A. McKinnon, M. P. Tingley, and P. Huybers, 2017: Seasonally resolved distributional trends of North American temperatures show contraction of winter variability. *J. Climate*, **30**, 1139–1157, <https://doi.org/10.1175/JCLI-D-16-0363.1>.
- Rodgers, K. B., and Coauthors, 2021: Ubiquity of human-induced changes in climate variability. *Earth Syst. Dyn.*, **12**, 1393–1411, <https://doi.org/10.5194/esd-12-1393-2021>.

- Schemm, S., M. Sprenger, and H. Wernli, 2018: When during their life cycle are extratropical cyclones attended by fronts? *Bull. Amer. Meteor. Soc.*, **99**, 149–165, <https://doi.org/10.1175/BAMS-D-16-0261.1>.
- Screen, J. A., 2014: Arctic amplification decreases temperature variance in northern mid- to high-latitudes. *Nat. Climate Change*, **4**, 577–582, <https://doi.org/10.1038/nclimate2268>.
- Seneviratne, S. I., and Coauthors, 2021: Weather and climate extreme events in a changing climate. *Climate Change 2021: The Physical Science Basis*, V. Masson-Delmotte et al., Eds., Cambridge University Press, 1513–1766.
- Smith, E. T., and S. C. Sheridan, 2020: Where do cold air outbreaks occur, and how have they changed over time? *Geophys. Res. Lett.*, **47**, e2020GL086983, <https://doi.org/10.1029/2020GL086983>.
- Stone, J., M. Gervais, K. A. Bowley, and C. Zarzycki, 2025: Identifying, tracking, and evaluating mechanisms of North American cold air outbreaks (CAOs) using a feature tracking approach. *Mon. Wea. Rev.*, **153**, 153–168, <https://doi.org/10.1175/MWR-D-23-0265.1>.
- Tomczyk, A. M., A. Sulikowska, E. Bednorz, and M. Pórolniczak, 2019: Atmospheric circulation conditions during winter warm spells in central Europe. *Nat. Hazards*, **96**, 1413–1428, <https://doi.org/10.1007/s11069-019-03621-4>.
- van Oldenborgh, G. J., E. Mitchell-Larson, G. A. Vecchi, H. de Vries, R. Vautard, and F. Otto, 2019: Cold waves are getting milder in the northern midlatitudes. *Environ. Res. Lett.*, **14**, 114004, <https://doi.org/10.1088/1748-9326/ab4867>.
- Vautard, R., 1990: Multiple weather regimes over the North Atlantic: Analysis of precursors and successors. *Mon. Wea. Rev.*, **118**, 2056–2081, [https://doi.org/10.1175/1520-0493\(1990\)118<2056:MWROTN>2.0.CO;2](https://doi.org/10.1175/1520-0493(1990)118<2056:MWROTN>2.0.CO;2).
- Vigaud, N., A. W. Robertson, and M. K. Tippett, 2018: Predictability of recurrent weather regimes over North America during winter from submonthly reforecasts. *Mon. Wea. Rev.*, **146**, 2559–2577, <https://doi.org/10.1175/MWR-D-18-0058.1>.
- Vitart, F., and A. W. Robertson, 2018: The sub-seasonal to seasonal prediction project (S2S) and the prediction of extreme events. *npj Climate Atmos. Sci.*, **1**, 3, <https://doi.org/10.1038/s41612-018-0013-0>.
- Westby, R. M., and R. X. Black, 2015: Development of anomalous temperature regimes over the southeastern United States: Synoptic behavior and role of low-frequency modes. *Wea. Forecasting*, **30**, 553–570, <https://doi.org/10.1175/WAF-D-14-00093.1>.
- Winters, A. C., L. F. Bosart, and D. Keyser, 2019: Antecedent North Pacific jet regimes conducive to the development of continental U.S. extreme temperature events during the cool season. *Wea. Forecasting*, **34**, 393–414, <https://doi.org/10.1175/WAF-D-18-0168.1>.
- Xie, Z., R. X. Black, and Y. Deng, 2017: The structure and large-scale organization of extreme cold waves over the conterminous United States. *Climate Dyn.*, **49**, 4075–4088, <https://doi.org/10.1007/s00382-017-3564-6>.
- Yang, X., T. L. Delworth, L. Jia, N. C. Johnson, F. Lu, and C. McHugh, 2022: On the seasonal prediction and predictability of winter surface Temperature Swing Index over North America. *Front. Climate*, **4**, 972119, <https://doi.org/10.3389/fclim.2022.972119>.