ABSTRACT: Prior research evaluating snowfall conditions and temporal trends in the United States often acknowledges the role of various synoptic-scale weather systems in governing snowfall variability. While synoptic classifications have been performed in other regions of North America in applications to snowfall, there remains a need for enhanced understanding of the atmospheric mechanisms of snowfall in the central United States. Here we conduct a novel synoptic climatological investigation of the weather systems responsible for snowfall in the central United States from 1948 to 2021 focused on their identification and the quantification of associated snowfall totals and events. Ten unique synoptic weather types (SWTs) were identified, each resulting in distinct regions of enhanced snowfall across the study domain aligning with regions of sufficiently cold air temperatures and forcing mechanisms. While a substantial proportion of seasonal snowfall is attributed to SWTs associated with surface troughs and/or midlatitude cyclones, in portions of the southeastern and western study domain, as much as 70% of seasonal snowfall occurs during systems with high pressure centers as the domain’s synoptic-scale forcing. Easterly flow, potentially resulting in topographic uplift from high pressure to east of the domain, was associated with between 15% and 25% of seasonal snowfall in Nebraska and South Dakota. On average, 64.8% of the SWT occurrences resulted in snowfall within the study region, ranging between 40.1% and 93.5% by SWT. Synoptic climatological investigations provide valuable insights into the unique weather systems that generate hydroclimatic variability.

SIGNIFICANCE STATEMENT: By evaluating the weather patterns that are responsible for snowfall in the central United States, key insights can be gained into how and why snowfall varies and potentially changes over space and time. Using an approach that categorizes weather patterns based on their similarities, here 10 unique snowfall-producing weather patterns are identified and analyzed from 1948 to 2021. Each pattern resulted in different snowfall amounts across the central United States, varying substantially spatially and within the calendar year. Approximately 65% of the time that these weather patterns occur, snowfall is observed in the region. The majority of snowfall-producing weather patterns are associated with low pressure systems, but in some regions up to 70% of snowfall is associated with instances of high pressure in which winds can cause upward motions associated with topography.

KEYWORDS: North America; Synoptic climatology; Snowfall; Synoptic-scale processes; Climatology; Principal components analysis

1. Introduction

Snowfall is an important component of the climate system during the cold season of North America, contributing to water and energy budgets and impacting a variety of human and environmental systems. Especially in regions with ephemeral snow, there are challenges in predicting and preparing for the timing and magnitude of potentially multiple snowfall events per year. Such snowfall forecasting challenges can lead to detrimental environmental and societal hazards, primarily in the form of vehicular accidents, shipping and transportation disruption, and destruction of property and loss of life from excessive snowfall totals and snow removal attempts (Norton and Bolsenga 1993; Schmidlin 1993; Changnon et al. 2006). Because of the large impact of snowfall to North American climates, it is important to have a robust understanding of how snowfall varies within a region and what larger-scale processes are responsible for its variability and potential changes over space and time.

In the central United States, snowfall is common and is regularly observed over a 9-month period from September through May; however, snowfall is most prominent from November through April (e.g., Ford et al. 2022). Prior research indicates that there is a latitudinal gradient of snowfall during the average snow season in which snowfall totals of less than 40 cm (~16 in.) accumulate in the central U.S. states of Missouri and Kansas as compared with greater than 100 cm (~40 in.) in the northern U.S. states of South Dakota and Minnesota (Kunkel et al. 2009; Kluver et al. 2016). Over time, snowfall totals and events have significantly changed at annual and monthly scales in this region, where in western Nebraska, South Dakota, and Minnesota seasonal snowfall has increased by as much as 0.5 cm yr\(^{-1}\) from 1900 to 2009 (Kluver et al. 2016) while significantly decreasing
by approximately 1% yr⁻¹ in other central U.S. regions when evaluated from 1937 to 2007 (Kunkel et al. 2007). Further, the snowfall season appears to be shifting toward an earlier end with decreasing snowfall totals and events in March in the last 74 years, especially in Iowa (Suriano et al. 2023). Within these snowfall gradients and trends, snowfall exhibits further spatial variability with multiple homogeneous regions identified by prior work (Kluver and Leathers 2015). Of the seven distinct snowfall regions in the contiguous United States identified by Kluver and Leathers (2015), six of them occur, in part, within the six-state region of Missouri, Kansas, Iowa, Nebraska, Minnesota, and South Dakota. It was hypothesized by Kluver and Leathers (2015), and in subsequent research (e.g., Suriano et al. 2023) that these snowfall regions and associated variability may be partially attributed to preferential storm tracks and specific synoptic-scale atmospheric environments that result in spatially dependent snowfall signals. However, it remains unclear whether and what types of synoptic-scale systems contribute to seasonal and intra-annual variability snowfall in this region. This study will build upon the literature of synoptic climatologies in application to snowfall in evaluating the atmospheric forcing mechanisms of snowfall in this unique region.

The use of synoptic classification as a means of isolating distinct modes of atmospheric variability is widespread and has been utilized for a variety of hydroclimatic applications, including snowfall (Karmosky 2007), snowmelt and rain-on-snow ablation (Leathers et al. 2004; Bednorz 2009; Suriano and Leathers 2018), extreme precipitation and streamflow (Kunkel et al. 2012; Siegert et al. 2017), and biogeochemical cycling (Siegert et al. 2021). The technique’s advantage is its ability to represent diverse atmospheric conditions as a single distinct weather type and allow for the development of pathways of physical forcing mechanisms connecting local- and regional-scale atmospheric and surface events to larger-scale atmospheric modes of variability (Yarnal 1993; Harman and Winkler 1991; Lee and Sheridan 2015). Using synoptic classification techniques, this paper will 1) isolate the primary synoptic-scale weather systems that generate snowfall in central United States and characterize their meteorological conditions, 2) describe the spatial snowfall pattern associated with each of the synoptic weather categories, and 3) quantify the proportion of total snowfall generated by each synoptic weather category. Developing a strong understanding of these atmospheric forcings can help to explain spatial variations in snowfall and sets the stage for future work exploring temporal changes in snowfall in future climates.

2. Method

a. Study site and snowfall data

This study evaluates snowfall conditions over the six-state region of Kansas, Missouri, Nebraska, Iowa, South Dakota, and the southern half of Minnesota identified from prior research as having contained high spatial and temporal variability and change in snowfall over the last 75–100 years (Kluver et al. 2016; Suriano et al. 2023). A larger domain was not selected to specifically focus on this region and the potential connections synoptic weather patterns have on partially explaining the modes of variation identified in Kluver and Leathers (2015). As described in greater detail within Suriano et al. (2023), daily snowfall observations were obtained from 134 meteorological stations within the study region from the National Centers of Environmental Information daily Global Historical Climatology Network-Daily dataset (GHCNd; Menne et al. 2012) from 1948 to 2021. A majority of snowfall stations were isolated from Kunkel et al. (2009) list of homogeneous snowfall stations that were identified as appropriate for long-term snowfall analysis. To increase the spatial resolution of stations and account for a number of stations from Kunkel et al. (2009) that are no longer operational, additional stations were identified, quality controlled, and supplemented into the dataset. Stations were required to have at least 90% nonmissing data over the 74-yr period. To assist in the contouring of snowfall information, a small number of observation stations outside the six-state region were included in the 134. Snowfall values were not extrapolated outside the study region. Figure 1 depicts the study region and the observation stations utilized, and Table S1 in the online supplemental material lists all 134 stations.

b. Synoptic classification

Synoptic weather types (SWT) associated with snowfall across the central United States were isolated using a daily temporal synoptic index (TSI; Kalkstein and Corrigan 1986) classification approach from 1948 to 2021. The TSI classification approach utilizes subdaily meteorological conditions from a single centrally located observation station to detect and cluster the main modes of synoptic-scale atmospheric circulation for a regional environment (Suriano and Leathers 2018). Prior research indicates stations within relatively close geographic proximity provide similar results (McCabe 1985; Suriano et al. 2020).
and are representative of a broad region on the order of a 1000 km radius. Omaha, Nebraska, was selected on the basis of its central location within the study domain and its minimal percentage of missing data (<1%). Here, 6-hourly observations (0900, 1500, 2100, and 0300 UTC) of air temperature, dewpoint temperature, sea level pressure, cloud cover and u- and v-wind vectors were obtained from the Omaha Eppley Airfield (WBAN: USW00014942, 41.31186°N, 95.90186°W). Four time steps per day (i.e., 6 hourly) was considered to be sufficient for capturing the synoptic-scale meteorological variability of a 24-h period (Siegert et al. 2021). Following procedures outlined in Sheridan (2002), attempts were initially made to supplement or interpolate any missing data using hourly observations immediately after or prior to the stated time. In total, 59 days of the 27,029 days (~0.2%) were excluded from analysis because of missing data.

Meteorological data were then arranged into an array (variable × day) for the November–April season and subjected to a P-mode unrotated principal component analysis (PCA) based on the correlation matrix, as noted in Kalkstein and Corrigan (1986). A P-mode PCA yields a (PC × variable) eigenvector loading matrix and subsequently a (PC × time) eigenvector score matrix that is desirable for this approach [see Yarnal (1993) for details on PCA modes]. Only November–April were utilized because of the limited role of May–October snowfall in the annual climatology. Principal components with eigenvalues greater than 1.0 were retained, because the orthogonal components are preferred over the original variables that are highly intercorrelated. Principal component scores, the mathematically weighted sums of the original variables by the correlation between the original variable and the component loading (Suriano et al. 2019), were automatically calculated and would be interpreted as the farther the score is from zero (either positive or negative), the greater the influence the specific principal component has on the days’ weather.

Days with similar component scores exhibit similar synoptic-scale atmospheric conditions; thus, cluster analyses can be used to determine which days exhibit similar conditions. Prior research has identified within-group average linkage clustering as the most appropriate method for the TSI (Kalkstein et al. 1987), and thus this study’s method differs slightly from the original approach outlined in Kalkstein and Corrigan (1986) that utilized Ward’s clustering. A 10-cluster solution per season was utilized, where the clustering algorithm is based on the squared Euclidean distance. The 10-cluster solution was selected based on the range of typical number of solutions identified by other studies examining synoptic-scale environments of hydroclimatic variables (Hartnett 2021, 2022; Siegert et al. 2021; Suriano et al. 2020; among others) and is identified from other solutions as most appropriate for maximizing the number of clusters to sufficiently capture variability while minimizing the coercion of solutions and keeping the number manageable for meaningful analysis. To support the validity of a 10-cluster solution, a silhouette analysis was performed. The silhouette analysis measures the similarity of data points to its cluster solution relative to the surrounding clusters, with a positive value indicating an appropriate configuration (Rousseeuw 1987; Dickinson et al. 2021). Here, a silhouette score of 0.2 was achieved and indicates an appropriate number of solutions.

The resulting cluster solutions were visualized using composite maps of sea level pressure, 850-hPa temperature, and 500-hPa geopotential heights across all occurrences of each cluster using the ECMWF ERA5 hourly reanalysis (Hersbach et al. 2020). Composites for all variables were generated for 1800 UTC, providing an indication of atmospheric conditions at approximately local noon central standard time (CST; UTC – 6 h), the midway point of the midnight-to-midnight TSI classification. Given the scales analyzed, ERA5 provides appropriate resolution and is sufficient for analysis here. Each resulting cluster is assigned the name of an SWT from 1 through 10.

c. Analysis

Meteorological conditions from both reanalysis (ERA5) and raw station observations associated with each SWT were initially evaluated across the study region over the 74-yr period. Station observations were analyzed at seven different locations distributed across the study region [Minneapolis, Minnesota (USW00014922); Davenport, Iowa (USW0014923); Springfield, Missouri (USW00013995); Dodge City, Kansas (USW0013985); Scottsbluff, Nebraska (USW00024028); Pierre, South Dakota (USW00024025); and Omaha]. Daily snowfall observations across the study region were aligned with the daily synoptic climatology (i.e., the TSI) based on the calendar day of occurrence. Snowfall totals, event frequencies, and event magnitudes were calculated for each SWT at monthly scales and further scaled up to the November–April snow season. Here, “seasonal” will refer to the snow season, and climatological seasons will be referenced by name (e.g., spring). Descriptive statistics of spatial and temporal snowfall characteristics for each SWT are presented. In evaluating the snowfall events by SWTs, it became apparent that each SWT occurrence did not result in snowfall each time, despite general conditions suitable for snowfall on average. As such, the percentage of SWT days that generated snowfall anywhere within the study region was additionally evaluated during the study period. The term “snowfall days” refers to the days on which snowfall is observed at any of the stations within the study region. Further, ratios of total snowfalls within the region from each SWT were calculated.

3. Results

a. Synoptic weather types

The principal component analysis of the TSI yielded five principal components with eigenvalues greater than 1.0. The five principal components explained 80.0% of the seasonal variance. The individual principal components consistently load highly with specific meteorological variables. Principal component 1 loads highly with air temperature and dewpoint temperature (i.e., the air mass) explaining approximately 39.4% of variance. Principal component 2 loads highest with v- and u-component winds (17.1% variance explained), whereas component 3 loads highest with cloud cover conditions (11.4% variance explained). Principal component 4 loads highest with sea
level pressure fields (7.6% variance explained), and component 5 loads moderately with a variety of pressure and wind fields typically later in the calendar day (4.5% variance explained; not shown).

SWT 1, a 1030-hPa high pressure center above the northern Great Plains into Saskatchewan, Canada, aligned with the descending branch of a 500-hPa ridge over the Great Plains (label 1 in Figs. 2 and 3), generated the most amount of snowfall across the study region at 22.3% of the seasonal total on average. On average, 850-hPa air temperatures were below freezing for nearly all of the study region (Fig. 4, label 1) and small trough axis is apparent, oriented east to west, extending away from the Lake Michigan area toward the study region where enhanced surface convergence can occur. Spatially, snowfall is greatest in Iowa and Minnesota, where over 250 mm is observed each season from SWT 1 (Fig. 5, label 1). SWT 1 occurred an average of 16.4 days per season ($\mu = 6.3$), with 93.3% (15.3 days) resulting in snowfall within the domain.

SWT 2, a 1007-hPa low in western Nebraska with cold front extended southward (label 2 in Fig. 2) generated the second lowest snowfall across the domain at 5.0% of the domain-wide average seasonal total. Air temperatures at 850 hPa were above freezing, on average, for all but portions of eastern Minnesota (label 2 in Fig. 4), contributing to snowfall being primarily contained to these northern regions (label 2 in Fig. 5). SWT 2 occurred an average of 19.3 days ($\mu = 6.3$) per

FIG. 2. The sea level pressure composite (hPa) for SWTs 1–10, 1948–2021. Red shades denote higher pressure, and blue shades denote lower pressure.
snow season, with 10.8 days, or 56.0%, resulting in snowfall. Snowfall was most common from SWT 2 in December, January, and March, respectively contributing 22.5%, 21.9%, and 18.8% to SWT 2's seasonal snowfall.

SWT 3 generated the third most, 13.2%, seasonal snowfall across the domain. SWT 3 exhibited a 1011-hPa low pressure system over eastern Nebraska (label 3 in Fig. 2) associated with a weak 500-hPa trough axis over the central United States (label 3 in Fig. 3) that yielded 850-hPa air temperatures at or above freezing from roughly 41°–42°N latitude south on average (label 3 in Fig. 4). SWT 3 occurred 18.9 days ($\sigma = 4.5$) on average per snow season. 14.4 (76.2%) of SWT 3 days resulted in snowfall within the domain, distributed similarly across from December through March (~19.5% each). Spatially, seasonal snowfall totals in excess of 150 mm are observed north of approximately 42°N latitude, with maximum seasonal snowfall observed in south-central South Dakota and central Minnesota in excess of 250 mm yr$^{-1}$ (label 3 in Fig. 5).

SWT 4, a 1008-hPa closed low over the Great Lakes region associated with a 500-hPa geopotential height trough over the central United States (label 4 in Figs. 2 and 3), yielded approximately 6.2% of seasonal snowfall in the domain. Occurring just 11.1 days per season ($\sigma = 3.4$), 8.8 days resulting in snowfall, SWT 4 exhibited the second lowest frequency of the 10 SWTs. Within the snow season, SWT 4 generated snowfall similarly each month from November to April (~16.7% each).
Spatially, seasonal snowfall less than 100 mm is observed for much of the domain, with the exception of northern Iowa and Minnesota (label 4 in Fig. 5).

SWT 5 was responsible for 5.1% of seasonal snowfall across the domain. SWT 5 is characterized by broad 1022-hPa high pressure over much of the study domain (label 5 in Fig. 2) resulting in weak flow around the high. SWT 5 was the most frequent of the SWTs, occurring 33.7 days (σ = 8) per snow season. Of those days, snowfall is observed 13.9 days, or 41.2% of the time. Per event, snowfall rates are minimal (<25 mm day\(^{-1}\); not shown), contributing to much of the domain experiencing less than 75 mm of snowfall from SWT 5 per season (label 5 in Fig. 5). Snowfall from SWT 5 was most prominent during March, where over 23% of snowfall days occurred.

SWT 6, a 1027-hPa high pressure center over Wisconsin (label 6 in Fig. 2) with below freezing 850-hPa air temperatures over the northern two-thirds of the domain (label 6 in Fig. 4), resulted in 10.9% of domain seasonal snowfall. The atmospheric configuration results in easterly flow across the domain, concentrating snowfall in South Dakota and Nebraska in excess of 150 mm, on average (label 6 in Fig. 5). SWT 6 occurred an average of 13.7 days (σ = 5.1) per snow season, 83.9% of them generating snowfall. Snowfall was most common from December through March with SWT 6, with the relative maximum occurring in February, corresponding to 24.7% of seasonal snowfall.

FIG. 4. The 850-hPa air temperature composite (K) for SWTs 1–10, 1948–2021. Red shades denote higher temperatures, and blue shades denote lower temperatures.
SWT 7 was associated with a 1031-hPa high pressure center bull’s eyed over the southern half of the study region with a 500-hPa trough axis extending south from central Ontario, Canada, south-southeast over the Great Lakes basin into the midsouth region of the United States (label 7 in Figs. 2 and 3). SWT 7 exhibited some of the coldest 850-hPa air temperatures of the SWTs, with all of the study domain below freezing on average. SWT 7 generated 8.6% of the domain’s seasonal snowfall, on average, where relatively higher snowfall totals of over 125 mm were observed in northern Iowa and southern Minnesota (label 7 in Fig. 5). SWT 7 occurred an average of 12.7 (± 4.9) days per season, with 10.3 of them, 81.1%, resulting in snowfall in the domain. Over 85% of SWT 7’s snowfall days occurred during climatological winter, with a majority (37.7%) occurring in January.

SWT 8, exhibits a similar atmospheric configuration as SWT 2, with an elongated but southwest–northeast-oriented 1009-hPa low over North Dakota and southern Manitoba and a weak 500-hPa trough (label 8 in Figs. 2 and 3). The 850-hPa air temperatures are approximately 1°–2°C warmer during SWT 8 than SWT 2 (label 8 in Fig. 4) and surface troughing extended less far south for SWT 8 than it does for SWT 2. These differences resulted in SWT 8 generating just 2.9% of the seasonal snowfall of the domain, the lowest of the SWTs. Spatially, seasonal snowfall exceeds 100 mm in the northwestern extremes of South Dakota, with much of the domain experiencing less than 50 mm of snowfall per season from SWT 8 (Fig. 5, label 8). Further, SWT 8 was the third most frequent SWT at 21.5 days (± 8.6) per season; however, just 40.0% of days

![Seasonal snowfall map](image-url)
resulted in snowfall distributed similarly from November through March (~17.4% each).

SWT 9, an unclosed 1013-hPa surface trough extending from western Texas into the southern Missouri Valley amid primarily zonal midlevel flow (label 9 in Figs. 2 and 3), results in the second most seasonal snowfall of the SWTs across the domain at 18.5% of the total. The trough tracks northeast through the domain during the day, placing much of the region in the cool sector of the developing midlatitude cyclone where wrap-around snowfall is likely. Spatially, the relatively higher snowfall signals were concentrated in the northern and western portions of the domain, such that all of South Dakota, Minnesota, Nebraska, Iowa, and much of Kansas and northern Missouri observed at least 100 mm of snowfall from SWT 9 (Fig. 5, label 9). SWT 9 was the second most frequent SWT at Missouri where it contributed at least 25%, up to 32%, of seasonal snowfall in November, March, and April.

SWT 10, a 1000-hPa low pressure system centered over southern Wisconsin, contributed 5.0% of seasonal snowfall to the domain on average, the third least of the SWTs (label 10 in Fig. 2). SWT 10 was associated with a lifting 500-hPa trough over the Great Plains (Fig. 3, label 10), where a strong pressure gradient on the backside of the low resulted in northwesterly flow and below freezing 850-hPa air temperatures, on average, for the majority of the domain with the exception of southeastern Missouri (label 10 in Fig. 4). Snowfall totals of 125–190 mm were observed in eastern South Dakota and southern Minnesota, whereas regions of southern Missouri observed no snowfall from SWT 10 at any point during the 73-yr period (label 10 in Fig. 5). SWT 10 was the least frequent of the 10 SWTs, occurring just 3.3 (σ = 2.6) days per season. 93.6% of SWT 10 occurrences resulted in snowfall (3.1 days yr⁻¹), with maximum snowfall frequency occurring in March.

b. Proportions of snowfall attributed to SWTs

Each of the SWTs contributes to snowfall across the domain, with no one SWT resulting in more than 25% of the entire domain snowfall. However, SWTs had a relatively larger (and smaller) contribution to individual subregions within the domain (Fig. 6). SWT 1 was highly impactful for a large swath of the domain, where the southeastern half derived at least 25% of its seasonal snowfall from SWT 1, including a large southwest–northeast-oriented zone of snowfall contribution in excess of 33% from eastern Kansas into southern Iowa (label 1 in Fig. 6). Next, western Nebraska, western Kansas, and a relatively narrow region of eastern Nebraska including the city of Omaha were heavily impacted by SWT 9, to which more than one-quarter of seasonal snowfall was attributed (label 9 in Fig. 6). SWT 7 was the most impactful in extreme southeastern Missouri where it contributed at least 25%, up to 32%, of seasonal snowfall (label 7 in Fig. 6). Eastern South Dakota derived between 20% and 30% of its seasonal snowfall from SWT 3, with additional contributions of at least 10% from SWTs 2, 6, 9, and 10.

Within the snow season, variations in monthly snowfall contribution by SWT were detected. During climatological winter, SWT 1 consistently had the largest contribution to monthly snowfall, with 27.8%, 31.6%, and 26.3% of December, January, and February snowfall, respectively. Within the zone from eastern Kansas into northern Missouri to central Iowa, SWT 1 monthly contribution during winter exceeded 35%, on average. In November and the early spring months of March and April, SWT 1 only moderately contributed to monthly snowfall (<15%). During these shoulder months, SWT 9 was the most impactful of the 10 SWTs, with 27.8% of November snowfall and 26.4% and 35.4% of March and April snowfall, respectively, being attributed to SWT 9. SWTs 2, 3, 7, 8, and 10 did not exhibit substantial variation in contribution to monthly snowfall from November through April. SWT 4 ranged between 3% and 7% contribution from November through March, and then was attributed to over 12% of April snowfall. SWT 5 exhibited a distribution similar to SWT 4, with relatively lower contributions in the core winter month of January (2.6%) and maximum relative contribution in April with 14.4%. Conversely, SWT 6 exhibited relative minimum contributions in April at less than 1%, and its relative maximum in January at 14%. Figures S1–S6 in the online supplemental material provide the proportion of monthly snowfall, spatially, for each SWT relative to the month examined: November–April.

4. Discussion

a. Alignment of SWT patterns and spatial snowfall distribution

In assessing the resulting snowfall fields attributed to each of the SWTs, it is seen that there are logical physical associations that can explain the spatial distribution and/or intensity of snowfall during the snow season. Six of the 10 SWTs are associated with a defined low pressure center or trough in and/or around the central United States, where the pattern of snowfall corresponds to the placement of the midlatitude cyclone within the region and its associated cold and cool sectors. In these instances, most snowfall is either in the northwest or northeast quadrant(s) of the system, aligning well with areas of wraparound snowfall and/or snowband formation (Baxter and Schumacher 2017). For example, SWT 10’s central low is over eastern Iowa, concentrating prime snowfall conditions in Minnesota and South Dakota, and to a lesser extent in Nebraska and Iowa. Missouri is typically within the warm sector of the system and generally experiences more limited snowfall from SWT 10 because of warmer temperatures. In comparison, SWT 2’s low is situated in western Kansas and tracks through the center of the study region to the northeast. This generally results in warmer and snow free conditions in Kansas, Missouri, and southern Iowa associated with the warm sector of the cyclone. Heavier snowfall is contained to the north and east on the backside of the low. SWT 8 has a similar, albeit less impactful, snowfall signal associated
with its weaker low to the north of the domain as SWT 2. Snowfall is contained to the northwest quadrant of the study region, as elsewhere typically remains above freezing during SWT 8 occurrences. The location of snowfall from SWT 9 and SWT 4 follow similar logic, aligning with the exact placement of the pressure centers and the corresponding temperature conditions necessary for snowfall.

The remaining four SWTs generate snowfall in a different, but still physically viable, manner. SWT 6’s high pressure in the northern and eastern areas of the study region places much of the domain in an area of easterly, or northeasterly, flow. Based on the pressure field, this generates cold air advection into the southern and western portions of the study region. While typically such advection suppresses precipitation, the easterly flow in this region results in topographic uplift as the elevation moves from some 150 m in the east to over 1500 m in the west. This has been shown to lead to and/or enhance precipitation in the Great Plains, and here snowfall totals are generally highest in these western regions.

While only moderately apparent from sea level pressure composite, evaluation of individual days of SWT 1 (not shown) indicate surface convergence in portions of the northern and eastern study region, particularly from Iowa extending out of the study region into Wisconsin and Michigan associated with a slight trough axis that forms during SWT 1 days angled east-to-west away from the Great Lakes basin. This likely contributes to additional precipitation in this region relative to other areas of the region, and snowfall totals are highest in these eastern

**FIG. 6.** Percentage of seasonal snowfall contribution by SWT (%), 1948–2021, for SWTs 1–10. Red shades denote a higher percentage of snowfall attributed to the individual SWT.
regions. Similar to SWT 1, there is a trough axis extending between the Great Lakes region and the study domain in conjunction with high pressure over eastern Kansas with SWT 7, likely leading to enhanced surface convergence and inducing precipitation. Snowfall totals are greatest in these northeastern regions, particularly in eastern Iowa and southern Minnesota. Elsewhere, on the western side of the high, snowfall is minimal, at less than 40–60 mm yr$^{-1}$ across multiple daily events. Collectively, approximately 47% of seasonal snowfall across the domain occurs during conditions where the dominant synoptic-scale feature over the region is high pressure.

Within each SWT, the pattern of snowfall further aligns with where 850-hPa air temperatures are predominantly below freezing, suggesting a higher probability for frozen hydrometeors. Some of the least productive SWTs with respect to snowfall were among the warmest, including SWT 2, 5, and 8, where 1800 UTC 850-hPa temperatures were above freezing for a majority of the domain. Note that 1800 UTC only corresponds to a single time-slice within the calendar day (noon CST) and that atmospheric conditions more suitable to frozen precipitation are possible at other times during the day. Further, there is inherent variability in the exact conditions within SWTs each time they occur (e.g., Suriano and Leathers 2021), and thus snowfall is not generated in the same location(s) each time an SWT occurs, as noted within the results. However, evaluating daily averaged surface conditions for each SWT at select surface stations supports this association (Table S2 in the online supplemental material). For example, in Pierre average daily air temperatures for SWT 3 were $-4.2^\circ C$, as compared with 6.6$^\circ C$ in Springfield. Per event, SWT 3 generated less than 25 mm of snowfall in Springfield (in many cases 0 mm) on average, as compared with nearly 60 mm per event in Pierre (not shown).

b. Comparison of analysis with existing synoptic climatologies

The various synoptic-scale weather systems associated with snowfall in the central United States are similar in nature to the types of systems associated with snowfall in other midlatitude regions. The majority of synoptic-snowfall analysis to date has focused on the role of cyclonic systems inducing snowfall to a particular study region. Grundstein (2003) determined that high snow-water-equivalent (SWE) snowpack years were more typically associated with colder and drier airmass where enhanced frequency of mid-to-low-level troughing (700 hPa) across the United States leads to higher SWE in the northern Great Plains. Baxter and Schumacher (2017) focused their analysis on single-handed cyclones that generated snowfall in the central United States, finding approximately 98 snowbands over a 5-yr period, where nearly twice as many were observed to the northeast of the surface low than to the northwest. In New York State, there has been extensive work assessing the synoptic-scale conditions associated with snowfall, where the role of cyclonic systems is emphasized in comparison with lake-effect snowfall (Hartnett 2021, 2022; Ellis and Suriano 2022, among others). Here, we find that 6 of the 10 snowfall-producing SWTs are associated with cyclonic systems.

The results of this study suggest that the role of high pressure systems on central United States snowfall is substantial. Particularly in southern Missouri and Kansas, snowfall from SWTs with a dominant feature of high pressure accounts for approximately 40%–70% of seasonal totals. Elsewhere, snowfall from these SWTs still exceed 35% in central and western Nebraska and South Dakota. The role of easterly flow in enhancing snowfall in the western portions of the study region is apparent, with approximately 16%–24% of seasonal snowfall (150–200 mm per season) in these regions being attributed to the easterly flow and subsequent topographic associated with SWT 6. While not necessarily focused on the role of high pressure systems, other studies have identified easterly flow leading to enhanced snowfall totals in other regions, as observed here, including in New York (Suriano et al. 2019), the central Mediterranean Sea coast (Mora et al. 2016), and in Yeongdong, South Korea (Nam et al. 2014), among others.

In comparing the results here with those of the identified homogeneous snowfall regions of Kluver and Leathers (2015), some spatial similarities are seen. Region 1 (Kluver and Leathers 2015) is concentrated in the southeast extreme portions of the study domain, where snowfall occurs in southeastern Missouri, and then outside the study domain into the Tennessee Valley. This aligns closely to the snowfall fields associated with SWT 7, and to a lesser extent SWT 5, where over 25% of snowfall in eastern Missouri is attributed to these types. Region 2 (Kluver and Leathers 2015) consists of Kansas, southern Nebraska, and northeastern Missouri, including areas outside the study domain in Colorado, Oklahoma, and the Southwest. This spatially aligns with the snowfall fields of SWT 9, associated with a forming Oklahoma low, delivering over 25% of snowfall in western Nebraska and Kansas. Kluver and Leathers’s (2015) region 3 partially resembles the spatial pattern of snowfall associated with SWT 1, where over a third of seasonal snowfall in central Missouri is associated with the SWT. Region 5 (Kluver and Leathers 2015) is restricted to northeastern Nebraska, southeastern South Dakota, portions of southern Minnesota, and portions of northern Iowa. Here, this resembles the snowfall fields from SWT 4 with snowfall maximums in northeastern portions of the domain. It is possible for the snowfall patterns from SWTs 1 and 3 that are more southerly in nature within their range of natural variations may further contribute to this region. Kluver and Leathers’s (2015) region 7 corresponds to the northern portions of the study domain, including much of South Dakota and Minnesota plus areas in Montana, North Dakota, and Wisconsin. The snowfall patterns associated with SWT 10, 2, and 3 all spatially align with this region. While present within the study region here, the role of specific SWTs contributing uniquely to Kluver and Leathers’s (2015) region 6 was not overly apparent. This may be due to their spatial footprint being limited to just eastern Iowa, and/or were not sufficiently distinct from the snowfall fields of SWT 1.

Intrasasonally, there are unique contributions of individual SWTs to regional snowfall. SWT 9, for example, was responsible for the most snowfall across the domain in March, ranging between 18% and 22% of monthly snowfall in the
northern and southeastern subregions, to nearly 45% in western Kansas and southwestern Nebraska. Approximately 30%–35% of March snowfall in Iowa is associated with SWT 9. Comparatively, SWT 9 only modestly contributes to snowfall during the core winter months, where SWT 1 dominates snowfall contribution for much of the domain. Prior research has indicated March snowfall has significantly declined over the last 70 years in Iowa, northern Missouri, and eastern Nebraska in association with significant reductions in snowfall-producing events with time (Suriano et al. 2023). Based on these findings and the role that SWT 9 plays with March snowfall in this region, it is plausible that the long-term changes to SWT 9’s frequency and/or inherent meteorological conditions may be driving the observed declines in snowfall. Evaluation of this potential is warranted and is the subject of a separate investigation.

c. Limitations

There has been extensive analysis documenting the challenges associated with historical snowfall observations in the United States (e.g., Kunkel et al. 2009; Robinson 1989; among others). Often, challenges arise from erroneous measurement practices, changes in time-of-day reporting, turnover of observers, and missing data during adverse conditions. Care is taken to ensure quality controlled snowfall observations are analyzed in this study, including focusing heavily on stations deemed by Kunkel et al. (2009) to be homogeneous and appropriate for long-term trend analysis and only incorporating stations with at least 90% nonmissing data. Additionally, there arises the potential for there to be a slight mismatch between the daily snowfall observations and that of the daily synoptic calendar, as previously reported by Suriano and Leathers (2017) because snowfall events do not necessarily confine themselves to standard 24-h calendar days and station reporting times may have changed over time (e.g., Kunkel et al. 2007). As such, it is possible for some snowfall to be attributed to two different SWTs that occur in succession.

SWTs represent composites of over 70 years, and thus internal variations in meteorological conditions are present within the range of natural distribution. There are instances in which conditions for snowfall within an SWT may be more/less conducive for snowfall than the composited conditions. Should SWTs exhibit long-term changes, as shown as possible in other work, it is possible for trends in snowfall to be attributed to trends in the SWTs. This hypothesis is being investigated in a separate study currently. Further, the TSI procedure relies on the selection of a single point location in generating principal components and subsequent clusters. Prior research has indicated stations in close geographic proximity yield similar TSI results (e.g., Suriano et al. 2020); however, there arises the potential for TSI results to differ should the station location not be sufficiently representative of the surrounding region with respect to elevation. While Omaha represents a central location to the study region and has a relatively representative elevation (Table S1 in the online supplemental material), it is possible a station selected from a different (higher or lower) elevation may yield different results.

5. Conclusions

This study utilized synoptic classification techniques to identify and analyze the key weather systems that generated snowfall within the central United States over a 74-yr period of 1948–2021. Specific objectives were to 1) isolate the primary synoptic-scale weather systems that generate snowfall in the central United States and characterize their meteorological conditions, 2) describe the spatial snowfall pattern associated with each of the synoptic weather categories, and 3) quantify the proportion of total snowfall generated by each synoptic weather category and the percentage of weather category occurrences leading to snowfall.

Through established approaches, 10 synoptic weather types (SWTs) were isolated from observational conditions. Each of the SWTs exhibited unique atmospheric conditions, with 6 of the 10 SWTs being associated with low pressure systems and/or surface troughs over the study region. For such systems associated with surface troughs and low pressure centers, snowfall tends to be greatest in the northwest and northeast quadrants of the central low, regardless of where it is within the region, in alignment with where enhanced uplift is expected and sufficiently cold surface and 850-hPa air temperatures are observed. The remaining SWTs had high pressure as the dominant atmospheric feature, creating conditions suitable for snowfall through either topographic uplift and/or surface convergence away from the central zone of high pressure. In some regions, as much as 68%–70% of seasonal snowfall was associated with these high pressure snowfall patterns, including some 20%–25% of seasonal snowfall in the western portions of the study region attributed to topographic uplift associated with the easterly flow of SWT 6.

While there is some spatial overlap, the snowfall fields associated with each SWT are relatively unique. There is variability where, and how much, snowfall is observed during each occurrence of the SWTs spatially; each SWT does not yield snowfall during each occurrence. While events could have been narrowed to just snowfall yielding days, the decision to include nonsnowfall days was purposeful to evaluate the proportion of occurrences yielding snowfall by SWT. The percentage of SWT days that lead to snowfall vary by SWT, ranging between 40% and 93%. Future research could evaluate the potential for changes in this percentage with time, based on prior research suggesting significant changes in the snow-to-rain precipitation ratio across the United States during the observational period (Feng and Hu 2007) and projected changes in future climate scenarios (Notaro et al. 2014).

During the snow season, approximately one-half of the SWTs had substantial variation in their relative contributions to monthly snowfall. Most prominently, SWT 1 and SWT 9 dominated the proportion of monthly snowfall across the domain in the core winter month (SWT 1) and during the transition months (SWT 9). In both cases, upward of 45% of monthly snowfall was attributed to one of these two types in large portions of the study domain. In March, shown previously to have exhibited significant decreases in snowfall over the last 70 years (Suriano et al. 2023), SWT 9 is associated with the highest proportion of snowfall, 25%–45%. The evaluation of these contributions to monthly and
seasonal snowfall is of particular interest for future study, where the potential role of a warmer atmospheric environment influencing snowfall within SWTs can be investigated.

Acknowledgments. Partial support for this research was provided by the Ogden College of Science and Engineering at Western Kentucky University and the Office of Research and Creative Activity at the University of Nebraska Omaha. The authors do not have any conflicts of interests that are not apparent by their listed affiliations.

Data availability statement. Snowfall data used in this study are publicly available at the Climate Data Online web portal (https://www.ncdc.noaa.gov/cdo-web/). Hourly meteorological conditions used to generate the synoptic classifications are also publicly available from this same web portal.

REFERENCES


Norton, D. C., and S. J. Bolsenga, 1993: Spatiotemporal trends in lake effect and continental snowfall in the Laurentian Great


