A Climatological Perspective of the February 2021 South-Central U.S. Cold Outbreak

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Abstract

In February 2021, a widespread cold-air outbreak, with two associated winter storm systems, impacted the South-Central United States. After a comprehensive summary of the synoptic setup and a day-by-day analysis of the event, we assess the significance of the storm from a climatological perspective. Concerning winter precipitation, there were isolated instances of record snowfall accumulations. While freezing rain and freezing drizzle both occurred, total freezing precipitation accumulations did not exceed a one-in-50

year event. The duration of the cold was notable - many stations across the region broke records for the highest number of consecutive days below freezing. When analyzing hourly temperature observations, we found that the February 2021 event was the record longest duration of hours below freezing for 12 stations. Nearly 6,000 daily temperature records were broken by this event. We next summarize significant impacts of this event. While we find that this event was extreme, most aspects of this storm were not unprecedented. Even in the context of a warming climate, cold events such as this should be considered when assessing risk and hazard mitigation planning. The magnitude of impacts associated with this event suggests a lack of preparedness that needs to be addressed. Finally, we discuss the importance of using climate services in planning for future extreme events. While there are documented benefits to users engaging with climate service providers and integrating climate information into their decision-making, the February 2021 event serves as an example of the failures that can occur when there is a barrier between decision-makers and climate service providers. We recommend continued and enhanced efforts to remove those barriers.
Keywords: climate extremes, climate services

1. Introduction

From 10 - 19 February 2021, a major Arctic cold air outbreak, accompanied by two widespread winter storm systems, affected much of the central U.S with extremely cold temperatures, snow, and ice. The overall event was dubbed the Valentine's Week Winter Outbreak by the Houston/Galveston National Weather Service office, while the two individual storms were designated Winter Storm Uri and Winter Storm Viola by The Weather Channel. Direct impacts from cold, snow, and ice were reported throughout the southern and central states. As of October 2021, estimated damage from the storms exceeded $20 billion, making it the costliest winter weather event in the U.S., surpassing the 1993 "Storm of the Century" (NOAA National Centers for Environmental Information, 2021b). It is estimated that the storms caused hundreds of deaths, most occurring in Texas, the state with the greatest impacts from the storms.

The notoriety of the event arose from the lack of preparedness and resulting widespread devastation. Additionally, there is an assumed likelihood that climate change would decrease the occurrence of such freeze events (Osland et al., 2021). While increased variability amidst a warmer temperature distribution could result in the same frequency in the magnitude of cold extremes previously observed (Rummukainen, 2012), average February maximum temperatures for the Contiguous United States had not been this cold since 1989 (NOAA National Centers for Environmental Information, 2021a). Other widespread cold outbreaks have occurred in U.S. history (Kocin et al., 1988); however, the February 2021 event is arguably the most severe cold event in the U.S. since the turn of the 21st century.

In this paper, we highlight the need for climate services in risk assessment and increasing preparedness in the context of events such as the one described in this paper. We begin with a synoptic analysis to provide a physical explanation of the event. The sequence of synoptic conditions necessary for an event like this is not unprecedented, and there is no assumption that they cannot happen in the future. A climatological analysis follows, where the storm is placed in a historical context. Next, we examine the extent to which similar events have occurred in the past and are likely to happen in the future. We follow with a description of the observed wide-ranging impacts that resulted from the event, including a discussion of why the event caused such severe impacts. Finally, we propose how integrating climate services into disaster risk management and hazard mitigation planning can reduce the magnitude and severity of impacts for future events.

2. Data and Methods

For our study, we've limited our analysis to the following states, where impacts and extremes were most widespread and significant: Alabama, Arkansas, Colorado, Illinois, Iowa, Kansas, Kentucky, Louisiana, Mississippi, Missouri, Nebraska, New Mexico, Oklahoma, Tennessee, and Texas. Station selection, data analysis, and investigation of impacts were done for each state in our focus area.

2.1. Analyzed wind and constant pressure charts

For the synoptic analysis, we used the National Centers for Environmental Prediction (NCEP) Climate-Forecast System Reanalysis (CFSR; 0.5°) (Saha et al., 2010) to describe the mean, one standard deviation (1σ), and two standard deviations (2σ) zonal-mean zonal wind climatology (1980–2010) for 60°N at 10 hPa. Superimposed upon the measure of climatological dispersion in the zonal wind is the analyzed Global Forecast System (GFS; 0.5°) zonal-mean zonal wind for the 2020/2021 season. All 250-hPa, 500-hPa, and mean sea level pressure (MSLP) analysis maps were generated from the 0.5° NCEP GFS. Standardized anomalies shown for specified variables are calculated with respect to a 31-year (1979–2009) 0.5° NCEP CFSR climatology (Saha et al., 2010).

2.2. Observed station data

Observed station data for temperature and snowfall were acquired from the Global Historical Climatology Network Daily (GHCN-D) dataset (Menne et al., 2012b) archived by the National Centers for Environmental Information (NCEI). GHCN-D consists of over 96,000 stations worldwide (Huang et al., 2017) and has been extensively used in assessments that require daily data such as cold snaps (Menne et al., 2012a). For inclusion in this study, GHCN-D stations were required to contain at least 50 complete years of data, including February 2021 (i.e., started in 1970 because 2021 is not complete yet). While other studies typically required an 80% completeness threshold for GHCN-D (Higgins et al., 2007; Huang et al., 2017), our analysis required a 83% completeness threshold per month (i.e., fewer than five missing days per month).

Using the GHCN-D, two analyses were performed. First, the summation of the consecutive days below freezing and, second, the number of daily temperature records broken by the February 2021 event. For consecutive days below freezing, a moving window summation approach was implemented where the first observed day with a daily maximum temperature equal to or less than 0°C initiated the event, and every subsequent day with a daily maximum temperature remaining equal to or less than 0°C added to the total. For example, if a station observed a daily maximum temperature less than 0°C on January 1st, that was counted as day one. If the daily maximum temperature remained at or below 0°C at that station until January 7, and on

January 7 the temperature rose above 0°C, the streak of consecutive freezing days for that event would be six (e.g., 1–6 January = six consecutive days).

To calculate the number of daily temperature records broken by the February 2021 event, the created time series of consecutive days below freezing (created in the above-mentioned step) for each station were sorted by consecutive days below freezing and date of occurrence. If the largest sum of consecutive days of at or below freezing daily maximum temperatures occurred or ended in February 2021, it would be counted as a new record attributed to this event. Similar to other NCEI Extremes Tools, the first occurrence date for an all-time streak is recorded, and subsequent ties, if any, do not replace the first occurrence. For example, if a daily temperature record streak of 15 days occurred in 1975 and then another daily streak of 15 days occurred in 1985, the 1975 streak date would remain the record holder. The same approach is implemented here, meaning any February 2021 streak record listed as the record holder (no ties) for that station.

Hourly freeze streaks, or the number of consecutive hours below freezing for an event, were assessed using hourly station data from the NCEI Integrated Surface Database (ISD). Stations with data through February 2021 and and records back to 1970 or earlier, were identified from ISD Station History. This resulted in 98 viable station locations. For each station, hourly temperature values are examined first to determine if any station contained a 3-hour reporting interval. If so, the two missing values are filled with the average of the bounding values. Next, a query was completed for each winter (Dec, Jan, Feb) to assess the completeness of the data for its entire period of record. For all 98 stations, any streak longer than 24 hours in Feb 2021 is recorded. To compare the 2021 event to previous events with long freeze streaks, we further refined the dataset to include stations with data before 1948, resulting in 84 stations. For the 84 stations starting in 1948, streaks of values equal to or less than 0°C are identified with the progressively longest such streaks reported. Streak length is counted as actual values reported or interpolated from the three-hourly data. Finally, the year with the longest freeze streak event is recorded as the record year for each station.

Long-term records on a climate division scale were assessed using the Applied Climate Information System (ACIS) data, primarily drawn from the GHCN-D database. The purpose of this assessment was to compare the 2021 cold with cold events dating back to the 1890s. First, within each county, the station with the greatest (longest POR) amount of data was identified. Daily data for that core station was used for a given winter season if no more than five days were missing. Otherwise, data was chosen from the next-longest-record station with nearly complete data located within 30 m (100 ft.) of elevation of the first core station. Second, a time series of winter extrema (lowest minimum temperature of the season, etc.) was created using this pieced-together county record. Next, all counties whose geographical centers lay within a given climate division were grouped, and a time series of average annual extrema was created using the method of Foster (2011) that iteratively estimates missing data from correlations with other stations in the division and calculates the average annual extrema across all counties in the division.

Storm summaries from the Weather Prediction Center and individual National Weather Service offices were initially examined to determine the overall spatial and temporal extent of freezing precipitation (i.e., freezing rain and freezing drizzle) associated with this event. Hourly observations of freezing precipitation were then obtained from first-order stations in these areas that Changon (2002) determined were of sufficient quality for climatological analyses. These observations were compared to the storm summaries to check for consistency and accuracy. For the February 2021 event, the number of hours of freezing precipitation were tallied at 17 stations across the study region. Hourly amounts of freezing precipitation were also tallied. These values were compared to climatological averages and extremes reported in the peer-reviewed literature.

The total snowfall accumulation from 00 UTC 10 February to 00 UTC 20 February were calculated by adding the 24-hour snowfall accumulation estimates from the NOAA National Operational Hydrologic Remote Sensing Center's National Snowfall Analysis (National Weather Service, 2021a) for each day in the period and for our study area.

2.3. Warnings, watches, and advisories

Another measure of the spatial and societal impacts of the February 2021 event was examined by finding the total number of warnings, watches, and advisories (WWAs) issued by local National Weather Service Forecast Offices. WWAs spatial extents were retrieved from the Iowa Environmental Mesonet Archived NWS Watch, Warnings, Advisories website (Iowa Environmental Mesonet, 2021). First, geospatial data was downloaded for all WWAs issued for the U.S. in 2021 (as of the download date, 17 April), then cropped to our study area, and the date range was restricted to WWAs issued from 00 UTC 10 February up to but not including 00 UTC 20 February. The WWAs phenomenon types were searched for any meteorological phenomenon related to the winter weather outbreak; the end result included WWAs issued for Blizzard, Freeze, Hard Freeze, Ice Storm, Wind Chill, Winter Storm, Winter Weather, and Freezing Fog, totaling 10,213 WWAs in the study area. Other phenomena searched for but not present in the data were Blowing Snow, Extreme Cold, Avalanche, Freezing Rain, Freezing Spray, Frost, Heavy Snow, Heavy Sleet, Lake Effect Blowing Snow, Lake Effect Snow, Sleet, Snow, and Snow Squall. While the number of WWAs issued in the study area does give a reference for the extent and severity of the storms, it is important to note that the criteria for the different winter-weather related WWAs vary by NWS Forecast Office to account for varying levels of preparedness and acclimatization to winter weather within their county warning area (National Weather Service, 2021c). As the study area for this paper ranges from the Gulf Coast to the Great Lakes, the differences in the WWA criteria are large but do provide insight into varying impacts expected across the geographic area.

3. Synoptic Overview

3.1. Precursors

The features that produced the record-breaking mid-February 2021 cold air outbreak began aligning many weeks before the onset of frigid temperatures and wintry precipitation across the U.S. In early January 2021, the upper stratosphere in the Northern Hemisphere rapidly warmed in response to planetary-scale waves that disrupted the normal circulation. These events, termed sudden stratospheric warming (SSW) events, occur on average six times per decade during the Northern Hemisphere winter (Charlton and

Polvani, 2007). Major SSW are known to significantly weaken or reverse the typically strong westerly stratospheric circulation known as the stratospheric polar vortex (Butler et al., 2017; Baldwin et al., 2021). The stratospheric polar vortex is a thermally driven stratospheric wind system that develops primarily in winter with the strongest winds near 60°N (Waugh et al., 2017). The probability of a cold air outbreak increases after SSW events (Butler et al., 2017; Baldwin et al., 2021), and the potential surface impacts can linger for 30–60 days (Baldwin and Dunkerton, 2001).

The connection between the winter stratospheric wind system and surface cold air outbreaks is complicated (Waugh et al., 2017), and assessing the statistical linkages between the two is beyond the scope of this paper. However, similar to the January 2021 event, SSW events can result in negative anomalies in the Arctic Oscillation (AO) (Butler et al., 2017). Negative AO values generally indicate a weak and amplified jet stream. On February 10–11, the AO index was –5.3, tying 5 February 1978 and 13 February 1969 for the lowest observed daily value since records began in 1950 (NOAA, National Centers for Environmental Information 2021). After the stratospheric wind system deteriorated and eventually reversed in early to mid-January 2021 (Fig 1, positive height anomalies propagated downward from the stratosphere (over the North Pole) that helped dislodge sections of the tropospheric polar vortex, displacing it equatorward (Fig 2). The remnant vortices traveled south, aided by an amplified 500-hPa trough extending from northern Canada to the central U.S. on 5 February and an amplified 500-hPa ridge to its west. During early to middle February, the stratospheric vortex attained more of a stretched character, with a southward plunge of the vortex circulations into

North America (Cohen et al., 2021). As a result, cold polar air and an associated surface high-pressure system strengthened over Northern Canada. Aloft, the ridge-trough couplet interrupted the eastward flow of the polar jet stream and enabled terrain-channeled cold air to travel southward along the east side of the continental divide. An initial cold front on February 5–7 brought the leading edge of the cold air into the Central U.S. Over the subsequent 10 days, the polar air plunged as far south as Brownsville, Texas (Fig 3).

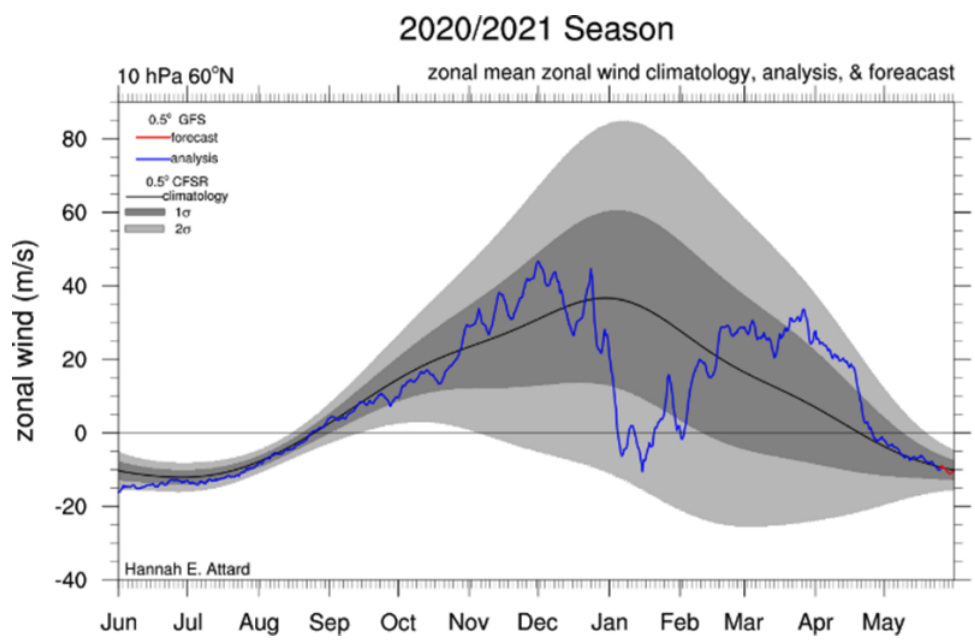

Figure 1: Zonal mean zonal wind climatology for 60°N at 10 hPa. The black line represents the climatological mean zonal wind (m/s), dark gray - one standard deviation zonal mean wind, and light gray - two standard deviation zonal mean wind from climatology. GFS zonal wind (blue line) describes a typical northern hemisphere circulation when > 0 m/s (westerly component) and denotes a reversal of northern hemisphere circulation when $<$ 0 m/s (easterly component). Image Credit: Dr. Hannah E. Attard

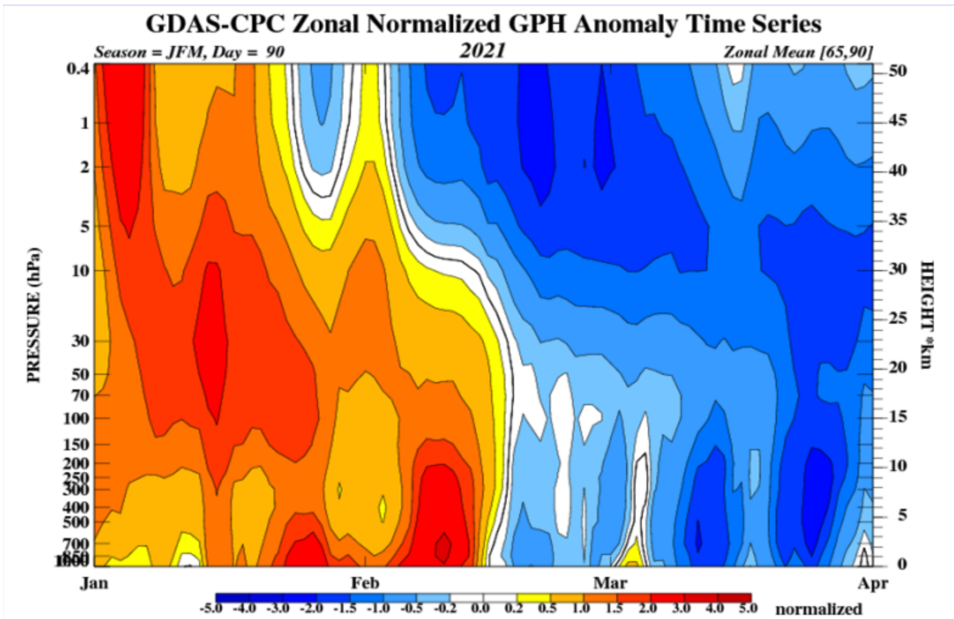

Figure 2: NCEP Global Data Assimilation System (GDAS)-Climate Prediction Center (CPC) standardized zonal (65–90 N) geopotential height anomalies during JFM 2021. Yellow-red colors show areas with positive height anomalies and light blue-dark blue show areas with negative height anomalies in the atmosphere. https://www.cpc.ncep.noaa.gov/products/stratosphere/strat-trop/

3.2. Day-by-day summary

On 0000 UTC 8 February, an amplified 500-hPa pattern was in place from Alaska (ridge) to the central U.S. (trough) and the high-latitudes in northeastern Canada (ridge) (Fig 4a). Over Alaska, the 500-hPa ridge provided northwesterly winds that encouraged the southward movement of cold air from higher latitudes. Simultaneously, a broad area of low geopotential heights over northwestern Canada, representing a frigid and dense air mass, slid southwest in association with the deepening 500-hPa trough across central and western North America. The frigid air mass and associated low

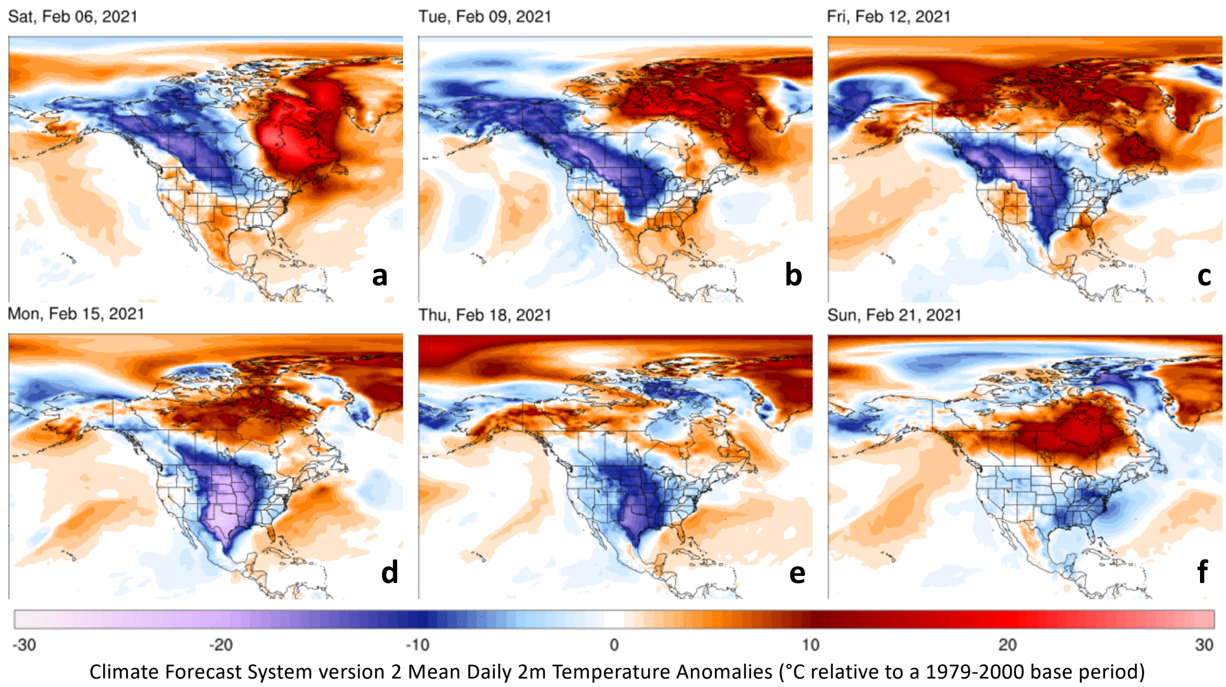

Figure 3: CFSv2 daily mean temperature anomalies near the surface (2 m) over North America for the duration of the event, starting on February 6 (a) through February 21 (f). Blue and purple colors denote below average temperature anomalies.

heights at 500 hPa shifted southeast into Manitoba and Ontario. The longitudinal extent and strength of the cold 500 hPa air mass was notable, covering nearly all of Canada with geopotential height anomalies $< -2\sigma$. The jet stream was located near the U.S./Canada border in the western U.S. but extended from the northwest to the southeast, stretching across the central

U.S (Fig 5a). At the surface, positive anomalies in mean sea level pressure (MSLP), associated with the frigid air mass previously contained in northern Canada and the Arctic, traveled south over the western High Plains (Fig 6a). Daily maximum surface temperatures for much of the Midwest were more than 10°C below normal (1991–2020). During the day on 0000 UTC 9 February, the remnants of the vortex at 500-hPa shifted southeast, slightly weakened, and covered a large portion of Canada. Associated cyclonic flow at 500-hPa around the area of low geopotential heights and northwesterly winds from the ridge over Alaska continued to channel air down the east side of the Rockies, enabling frigid air to advect into the U.S, particularly in the lower troposphere. Daily mean surface temperatures from northern Texas, central plains extending to the US/Canada border, and western Canada were 10°C below normal (1979–2000) (Fig 3). The cold remnant vortices over Canada blocked the eastward movement of the jet stream, and it remained south of the U.S/Canada border over the central U.S.

By 0000 UTC 10 February, the cyclonic flow at 500-hPa remained largely contained in Canada and the northern U.S. while northwesterly winds from the ridge over Alaska continued to channel air down the east side of the Rockies (Fig 4b). The 250-hPa flow remained roughly zonal across the central U.S, and the jet stream retreated north to the Great Lakes region (Fig 5b). An upper-level shortwave trough moved eastward, deepening the existing trough and favoring surface cyclogenesis and precipitation across eastern Texas and the Gulf Coast. As indicated by the high MSLP anomalies, the surface cold front continued to travel southward and reached northern Texas (Fig 6b). The cold air at the surface was shallow, especially across central

Texas, i.e., the dense air did not reach above 900-hPa in the 0000 UTC Fort Worth sounding. Behind the front, northerly winds supplied cold, dense air from a surface anticyclone over Iowa. Daily maximum surface temperatures across portions of northern Texas, central Oklahoma, and Kansas remained roughly 10°C below normal (1991–2020). Since roughly 4 February, minimal movement in the broad 500-hPa zonal pattern had occurred over North America; however, that changed by 11–12 February, as upstream, two shortwaves encroached.

By 0000 UTC 12 February, a shortwave arrived along the Pacific coast (Fig 4c, Fig 5c), traveling southeast into the trough. At the surface, the terrain-channeled cold air along the east side of the Rocky Mountains continued to advect into the central U.S. (Fig 6c), where daily mean surface temperatures extending from southern Texas to the southern plains and Canada remained at least 10°C below normal (1979–2000) (Fig 3). In fact, nearly the entire state of Montana observed daily mean surface temperature less than 15°C below normal. Encouraging even colder air temperatures was snow cover over Canada and the northern U.S that increased albedo and permitted sustained radiative cooling of the air that was funneled south (not shown).

On 13–14 February, the shortwave trough, embedded in the jet stream with winds $>$ 77 ms-1 (150 kts) at 250-hPa (Fig 5d), moved over the Western CONUS. At 500-hPa (Fig 4d) Arctic air continued to travel south into the central and southern U.S. (Fig 6d). The shortwave also deepened the 500-hPa trough, and it moved southward into southern California while the jet stream relocated south along the Pacific coast on 0000 UTC 14 February.

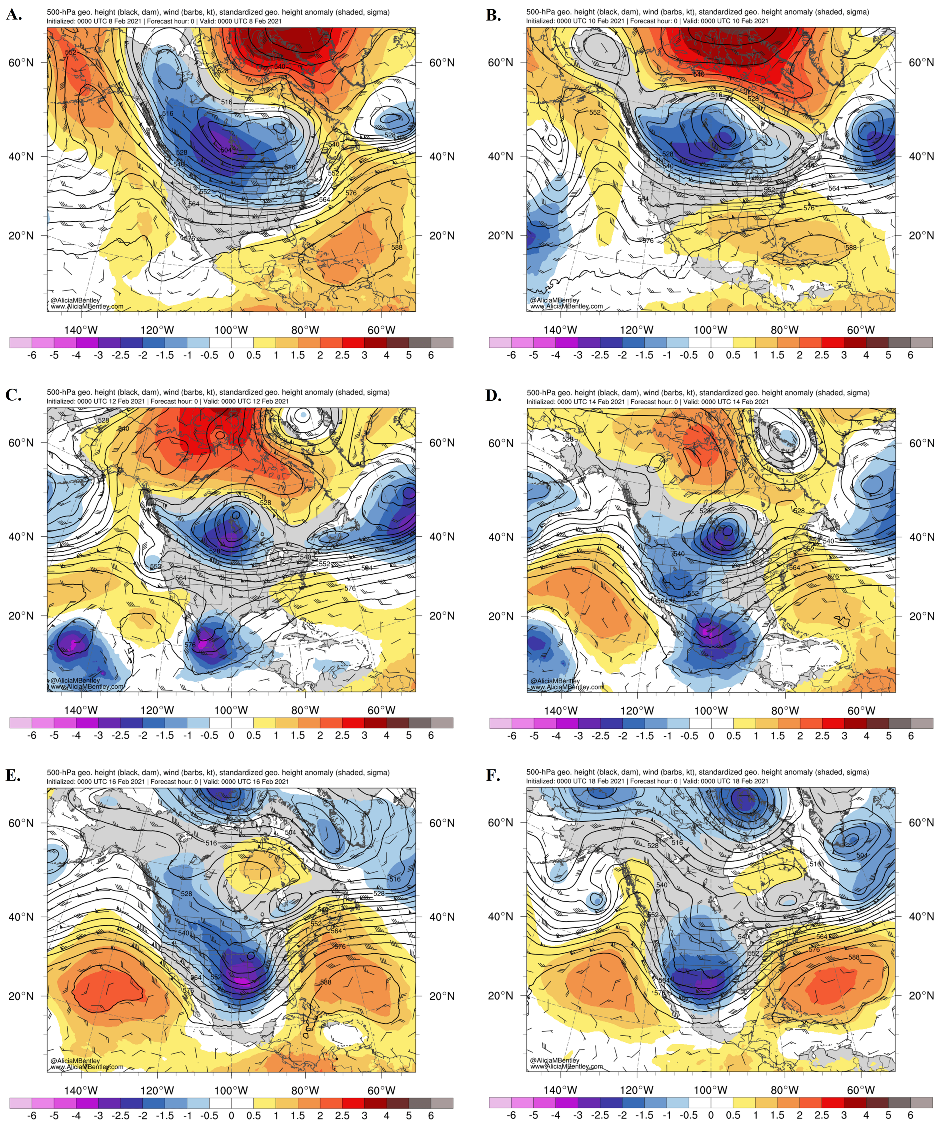

Figure 4: 500 hPa geopotential height (black lines, dam), wind (barbs, kt), and standardized geopotential height anomalies (shaded, sigma) for a) 00 UTC 8 February 2021, b) 00 UTC 10 February 2021, c) 00 UTC 12 February 2021, d) 00 UTC 14 February 2021, e) 00 UTC 16 February 2021, and f) 00 UTC 18 February 2021. Image Credit: Dr. Alicia Bentley

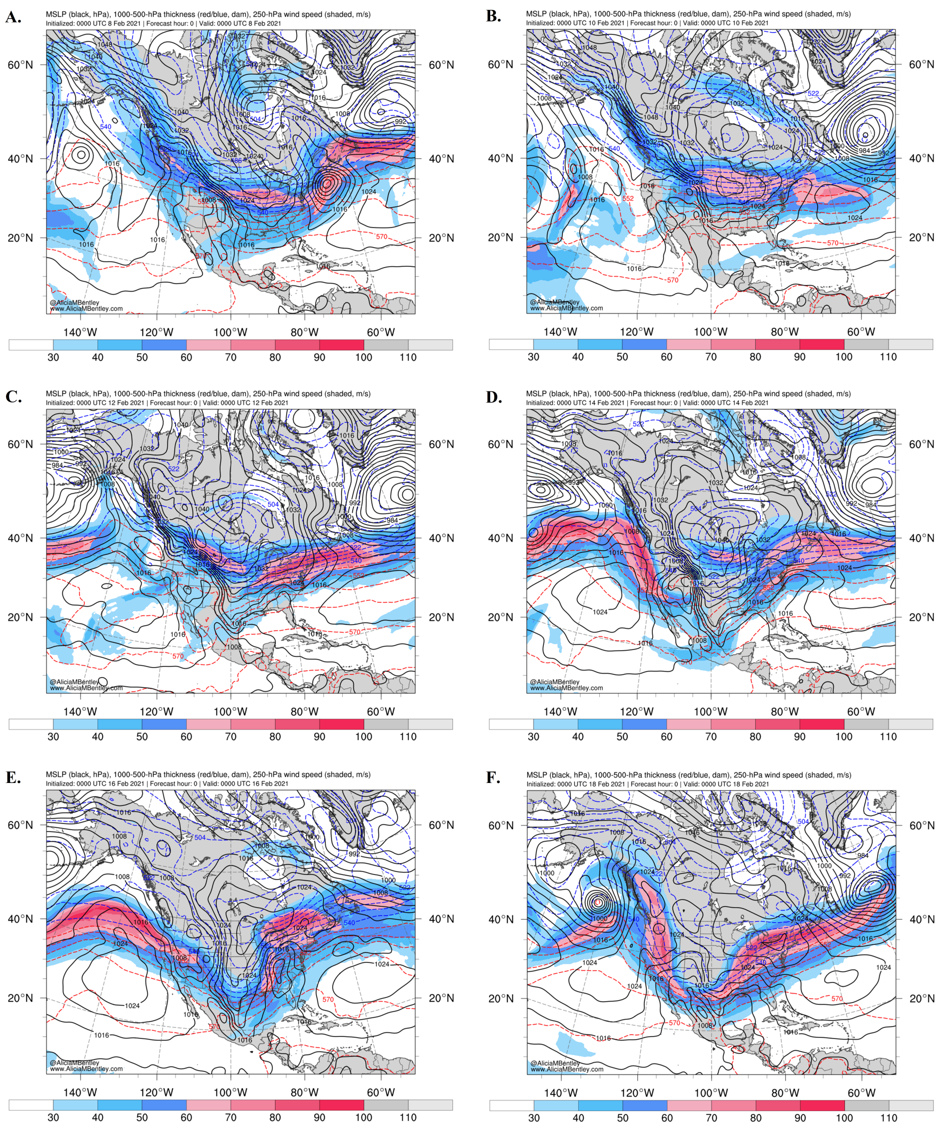

Figure 5: 250 hPa wind speed (shaded, m/s), mean sea-level pressure (black lines, hPa), and 1000–500 hPa thickness (red/blue dotted lines, dam) for same times as Fig 4. Image Credit: Dr. Alicia Bentley

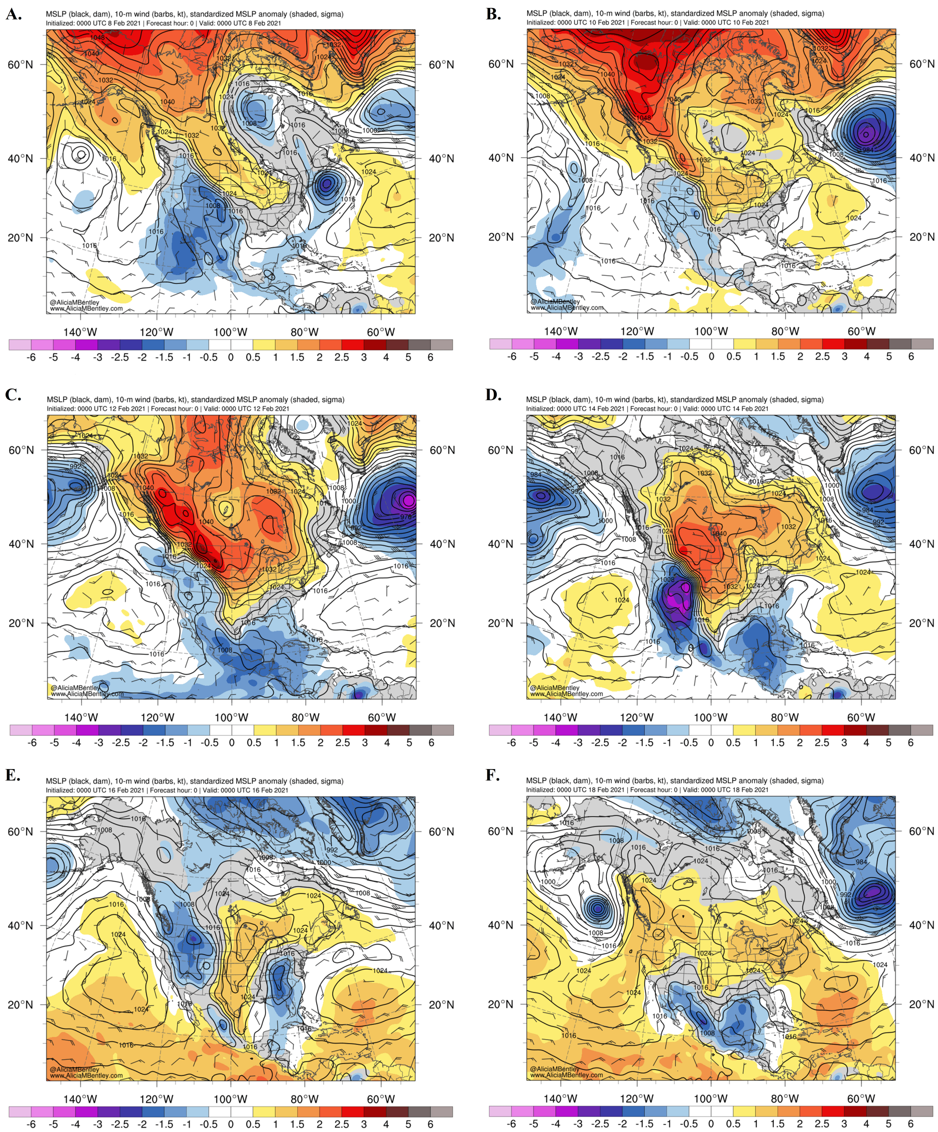

Figure 6: Mean sea level pressure (MSLP; black lines, dam), 10-meter wind (barbs, kt), and standardized MSLP anomaly (shaded, sigma) for same times as Fig 4. Image Credit: Dr. Alicia Bentley

Simultaneously, a second shortwave embedded in the jet stream upstream – west of the Pacific Northwest – traveled south.

By 1200 UTC 14 February, low geopotential heights were evident at 700-hPa near the Four Corners in a region of upper-level divergence and rising air associated with the left exit region of a jet streak at 250-hPa (Fig 5d). By 0000 UTC 15 February, the jet stream dipped as far south as southern Texas and northern Mexico. The 500-hPa trough axis was negatively tilted, aiding low-level cyclogenesis in the far southwestern Gulf of Mexico beginning around 0000 UTC 15 February. The coldest day of the event for most locations was 15 February. Daily mean surface temperatures from southern Texas to the central/northern plains were 10°C to 15°C below normal with embedded areas across Texas greater than 20°C below the climatological average (Fig 3). In Oklahoma City, the observed daily maximum temperature was -15.5°C on 15 February, roughly 28°C below normal.

On 16 February at 0000 UTC, the 500 hPa ridge-trough-ridge pattern was locked in across the U.S. with height anomalies $< -3\sigma$ across northeastern Texas (Fig 4e). A second shortwave tracked through the southwestern U.S. (Fig 5e) and another surface low-pressure system began to organize in the Gulf of Mexico off the coast of southern Texas associated with the right front quadrant of a $>$ 77 ms-1 (150 kts) jet streak situated over eastern Texas. The surface low-pressure system strengthened over the southwest Gulf of Mexico on 16–17 February and began to move northeastward towards the Southeast U.S (Fig 6e) following the divergence region of the jet stream.

The 500 hPa ridge-trough-ridge pattern weakened but remained persistent across the U.S at 0000 UTC 18 February (Fig 4f). The surface low that formed over the Gulf of Mexico moved southwest to northeast following the upper-level flow (Fig 4f, Fig 5f), impacting the Southeast and Mid-Atlantic before exiting the mid-Atlantic coastline around 1200 UTC 19 February. Daily mean surface temperatures remained 10°C to 20°C below normal on 18 February across a large swath of the central U.S (Fig 3). By 2000 UTC 20 February, 500 hPa trough had eroded and the U.S. returned to a more zonal pattern at 250-hPa, marking the end of the exceptional winter weather outbreak; however, below average daily mean surface temperatures lingered across the Gulf Coast until 24 February.

4. Historical Perspective

The severity, spatial extent, and long duration of this event resulted in a widespread disaster. The number and magnitude of resulting impacts, further detailed in the next section, leads to two important questions: 1) what is the historical and climatological significance of this storm, and 2) what is the probability of occurrence of future storms of similar severity and size?

To put the storm into a historical perspective, we assessed the following components: snowfall and ice accumulations (i.e., winter precipitation), the magnitude of cold temperatures, and duration of cold temperatures. Figure 7 highlights the spatial extent of the storm, showing the total number of warnings, watches, and advisories (WWAs) issued by the National Weather Service during the duration of the event. A broad region received five or more WWAs in the ten-day period, with a maximum of 15–16 WWAs throughout southern Texas. Precipitation-related WWAs were most frequently-issued in

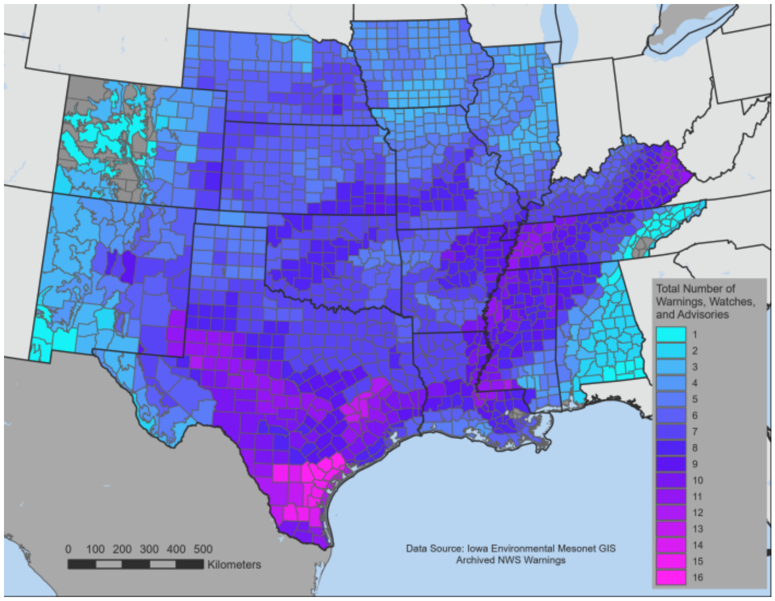

Figure 7: Total number of winter weather related warnings, watches, or advisories from 00 UTC 10 February to 23:59 UTC 19 February including blizzard, freeze, freezing fog, hard freeze, ice storm, wind chill, winter storm, and winter weather.

western Texas and in a swath from eastern Kentucky southwestward into western Tennessee and extending into Mississippi. Cold-related WWAs were more frequent along the Gulf Coast areas and especially in south Texas.

4.1. Winter precipitation

Total snow accumulation for the ten-days of February 10–19 (Fig 8) were between 5–25 cm for much of the region. A swath of maximum snowfall greater than 25 cm extended across central Texas, northeast through Arkansas, and into west Tennessee. According to NCEI data, all-time records for single-day snowfall coincided with these swaths. For isolated locations, such as Texarkana, TX (which received 44 cm of snowfall during the event), this was their snowiest event on record. There were isolated instances of

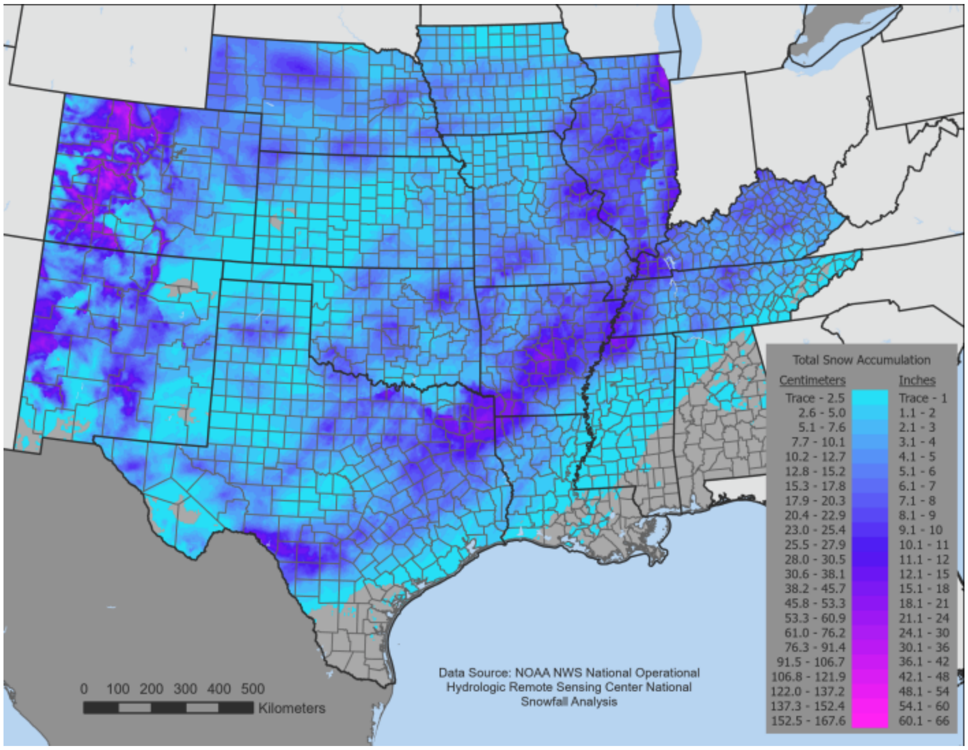

Figure 8: Total accumulated snowfall (cm and in) from 00 UTC 10 February to 23:59 UTC 19 February 2021, derived from NOAA NWS National Operational Hydrologic Remote Sensing Center National Snowfall Analysis.

three-day total snowfall amounts located around the AR-LA-TX border (not shown) that exceeded 20 cm, which is extremely rare, according to snowfall climatology for GHCN-D stations in that region.

To objectively assess how extreme and severe this storm was, we used the NOAA NCEI database of Regional Snowfall Index (RSI) (Squires et al., 2014). RSI is a regionally-specific index that takes spatial extent, snowfall totals, and population into account to estimate the total impact of the storm. RSIs are assigned a category 1 through 5, similar to the Saffir-Simpson scale used for tropical cyclones. According to the database, the two snowstorms associated with this event each ranked as category 3 for the Southern region (encompassing KS, OK, TX, AR, LA, and MS), suggesting major impacts. The first storm (Feb. 13–16) ranked as a category 2 storm for the Ohio Valley (which includes MO, IL, KY, and TN from our study region) and category 1 for the Upper Midwest (which includes IA from our study region) and the Northern Rockies and Plains (which includes NE from our study region), while the second storm (Feb. 16–20) was rated category 1 for the Ohio Valley and the Northeast.

Based on the historical distribution of winter storms assigned an RSI category, dating back to 1900, 8% of storms rank at a category 3 or higher. Only 3% of all storms rank as a category 4 or 5. All category 3+ storms since 2010 in the Southern region have occurred in pairs, and all in February: 2010 (both category 4), 2011 (both category 4), and 2013 (both category 3). According to the database, the 2021 storms both brought at least 5 cm (2 in) of snow to more people than any other Southern storms in the database. These storms rank 19th and 22nd out of 151 storms in the Southern region. Hence, storms of this size and magnitude have a large enough probability of occurrence in the future that they should be considered in hazard mitigation planning.

In addition to snow, cold temperatures associated with this event also contributed to freezing precipitation across portions of the Southern Plains, Lower Mississippi Valley, and Southeast U.S. Arctic fronts and anticyclones, which were dominant synoptic features during the cold outbreak, are also the most common synoptic types associated with freezing precipitation in these regions. These types of freezing precipitation patterns typically result in widespread ice accumulation (Rauber et al., 2001; Changnon, 2003).

Figure 9 shows the number of hours of freezing precipitation, which includes both freezing rain (FZRA) and freezing drizzle (FZDZ), recorded between 7–18 February at first-order weather stations with quality FZRA and FZDZ data as determined by Changon (2002). These values were mostly above average (Cortinas Jr. et al., 2004; McCray et al., 2019) but not record-breaking (Houston and Changnon, 2007). Though FZRA is less common at these locations than in other parts of the U.S., e.g. Great Lakes, Northeast (Changnon and Karl, 2003), a greater proportion of events are of long duration (i.e. 6–18 hours) (McCray et al., 2019), including those that occurred in February 2021. The maximum in FZDZ observations across parts of Oklahoma and Missouri is consistent with climatology (Cortinas et al., 2004).

The vast majority (>90%) of FZRA and FZDZ observations at these locations were light (<2.5 mm/hr), which is consistent with climatology (Houston and Changnon, 2007). Additionally, none of the accumulated FZRA and FZDZ totals at these locations exceeded the approximate 50-year recurrence interval for extreme ice accumulation (>25 mm), though some locations (e.g. Austin, TX; Meridian, MS; Huntsville, AL; Louisville, KY) did come close, i.e. within 2–3 mm (Jones et al., 2002; Changnon, 2003).

The most unusual observations of freezing precipitation in February 2021, from a climatological perspective, were found along the northern Gulf Coast, extending from southeastern Texas to southern portions of Louisiana and Mississippi. These areas typically experience <5 hours of freezing precip-

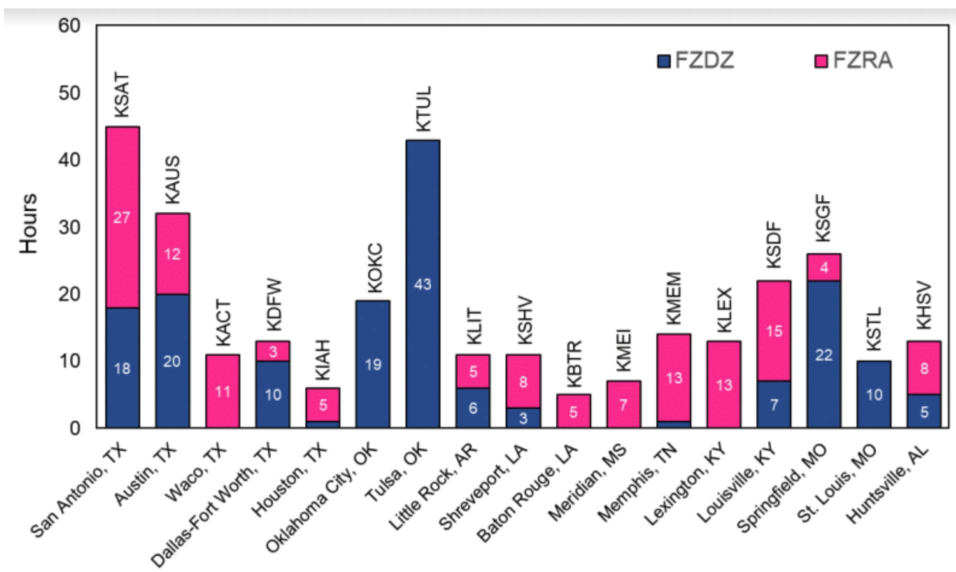

Figure 9: Number of hours with freezing precipitation (FZRA and FZDZ) at first-order stations with quality freezing precipitation data from 7–18 February 2021. Values < 3 h are not labeled inside the bars. Station identifiers are located above each bar.

itation per year (Cortinas Jr. et al., 2004) and, in some cases, may only experience freezing precipitation once every 5–10 years (Changnon and Karl, 2003). Therefore, while the occurrence of freezing precipitation near the Gulf Coast was climatologically notable, it was not unprecedented.

4.2. Temperature extremes

Perhaps the most notable aspect of this event was the cold temperatures. The cold extremes, combined with the wintry precipitation, exacerbated the severity of the storm. Table 1 shows the total number of cold temperature records broken during the event. It's not uncommon for significant cold air outbreaks to result in a large number of record cold temperatures across a region. As a recent example, over 6,000 cold temperature records (for both low maximum and low minimum temperatures) were broken in February 2011. In December 1983, there were over 28,000 cold temperature records broken. Focusing on Texas, where the widespread cold extremes were most impactful, 192 monthly records were broken in the February 10–19, 2021 time period (i.e., the lowest maximum or minimum temperature ever reported in February at a station occurred in that period). For December 19–28, 1989, Texas had 322 monthly records broken, which was 130 more than the February 2021 event. While the large number of stations with record cold temperatures in February 2021 was significant, it was not unprecedented.

This storm was more unusual due to the length of time temperatures remained below freezing. Across Texas, many stations set records with six to ten consecutive days below freezing (Fig 10). Some stations in the Central Plains and Midwest observed 11–15 consecutive days below freezing, and one station in Iowa set a record with 16 consecutive days below freezing. We

Variable	Daily	Monthly	All-time
Max Temp	3,612	320	75
Min Temp	2,311	257	66
Total	5,923	577	141

Table 1: Number of daily, monthly, and all-time records set for daily observations in the study area for February 10-19, 2021. Maximum temperature records denote a high temperature colder than all previous high temperatures for the day (column 1), for the entire month of February (column 2), or all-time (column 3). Minimum temperature records denote a low temperature colder than all previous low temperatures for the same columns.

compared the duration of the event to other cold events through analysis of hourly reporting stations. Figure 11 shows the duration of the freeze event in continuous hours below freezing. The longest consecutive run of hours exceeded 400 h at sites in Nebraska, Iowa, and northern Illinois, with the two longest runs at 451 h at Valentine, NE and 441 h at Sioux City, IA. Some stations along the immediate Gulf Coast had durations under 24 hours, including 15 h at Mobile, AL and 19 h at New Orleans-Lakefront Airport. Figure 12 shows the year of the record-breaking number of hours below freezing for each station. For the 2021 event, the record was broken for seven locations in Texas, one in Louisiana, two in Tennessee, and one in Illinois. Other than the 2021 event, the 1983 event was the record setter at many locations, primarily in Oklahoma. Events in 1978 and 1979 were the record setters in the northern reaches of the study area, and events in 1951 and 1962 were prominent at sites near the coast. For perspective, the longest run below freezing in our records for these sites was 1273 straight hours below

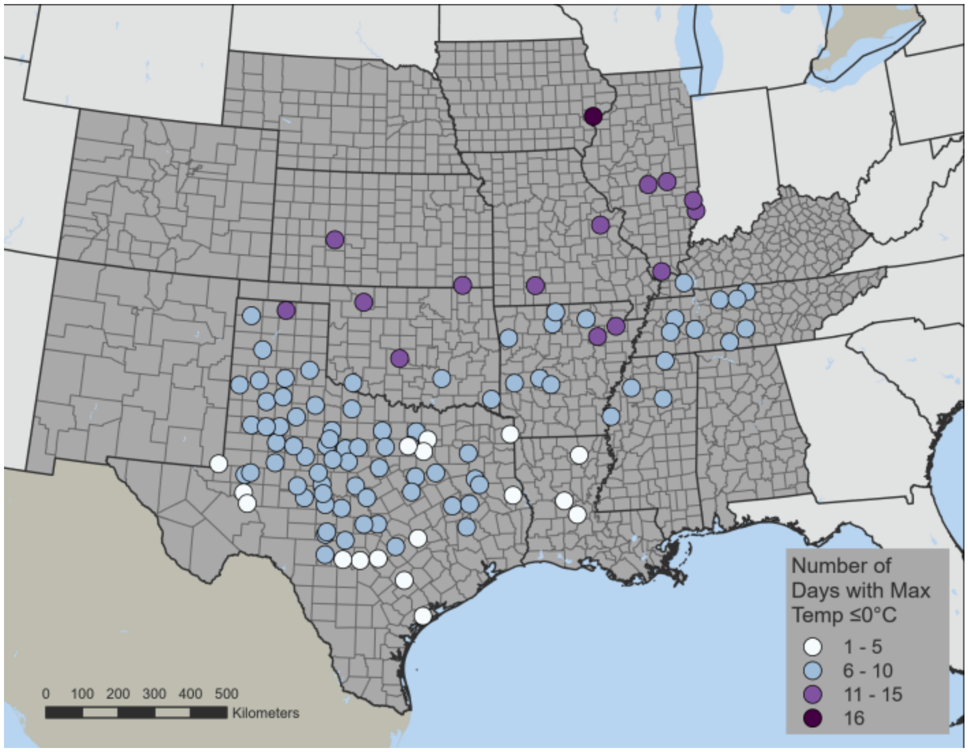

Figure 10: Stations within the GHCN-daily dataset which set an all-time station record for number of consecutive days with observed maximum surface temperatures at or below 0°C during February 2021.

freezing at Waterloo, IA from December 29, 1978 through February 20, 1979 - a total of 53.04 days. In contrast, Valley International Airport in Harlingen, TX had its longest run in 1962 at 63 hours - 2.62 days.

When considering lowest daily maximum, minimum, or average temperatures, averaged over 1, 2, 4, or 7 days' duration, the February 2021 cold event consistently ranks among the 10 most extreme events in the historical record (1890 to present) from northern Nebraska to southern Texas (Fig 13). In every metric, there is at least one climate division where the composite

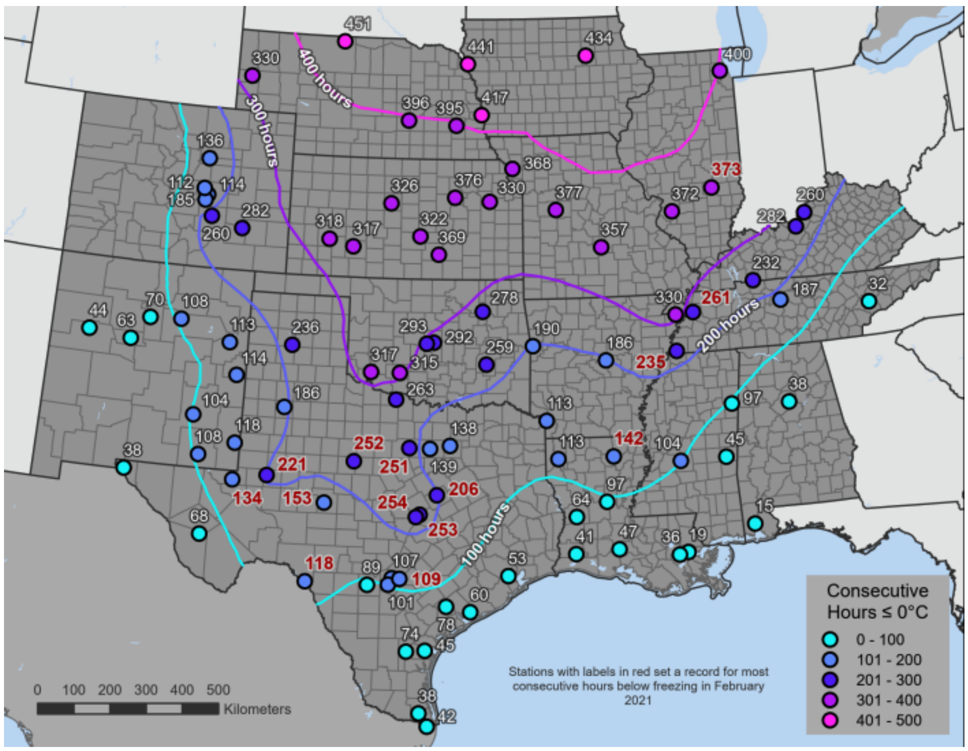

Figure 11: The longest hourly streak (consecutive hours) with surface temperatures at or below 0°C reported during February 2021 at NCEI Integrated Surface Database (ISD) stations. Hours in red set the station record for longest hourly streak for that station.

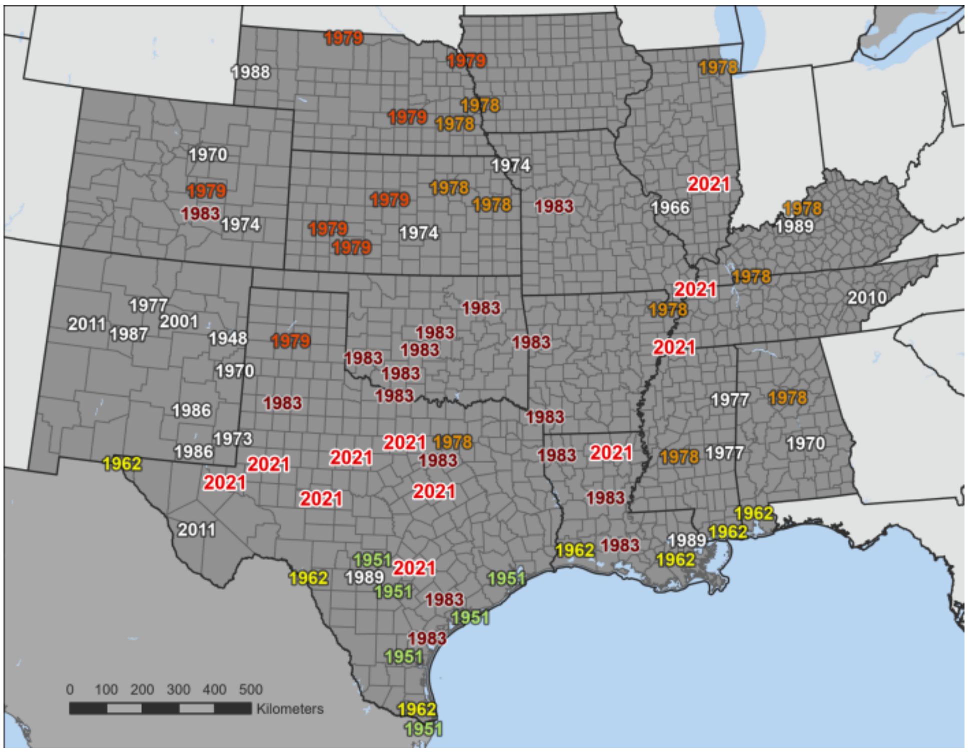

Figure 12: Year with the record hourly streak event of surface temperatures at or below 0°C. Any event in which 5 or more stations set a record streak are color-coded to show the spatial extent. Any year that 4 or fewer stations set a record are labeled in white.

time series ranks 2021 as the most extreme. The February 2021 event stands out as most unusual for its persistently low daily maximum temperatures, as is also reflected in the consecutive hours below freezing discussed above. The 7-day average maximum temperature ranks as first or second coldest across a vast expanse of the central United States from Iowa to Texas and from New Mexico to Mississippi.

Figure 14 shows which year holds the record for each of these temperature extremes in each climate division, except for those without sufficiently complete data in 1899. The extreme cold wave in February 1899 holds the greatest number of records across the region, with minimum temperature records being especially notable. At seven climate divisions in the region (North Central and Northeast Arkansas, Western and Central Kentucky, Southwest and Northeast Louisiana, and the West Central Plains of Missouri), February 1899 holds all twelve extreme cold records considered here. The other two cold waves holding more records than 2021 are December 1983 and December 1989. The former was most notable for persistently low maximum temperatures, while the latter was most extreme in its two-day average temperatures. By sheer number of climate division records, top fives, or top tens, the February 2021 cold event is the fourth most extreme on record. It is also the only cold event besides February 1899 that holds all twelve all-time records in a particular climate division: in central Oklahoma, the February 2021 cold was more extreme in all twelve metrics than any other event on record.

Another way of comparing historic cold snaps is with the geographical distribution of top ten rankings for the particular value for which each notable

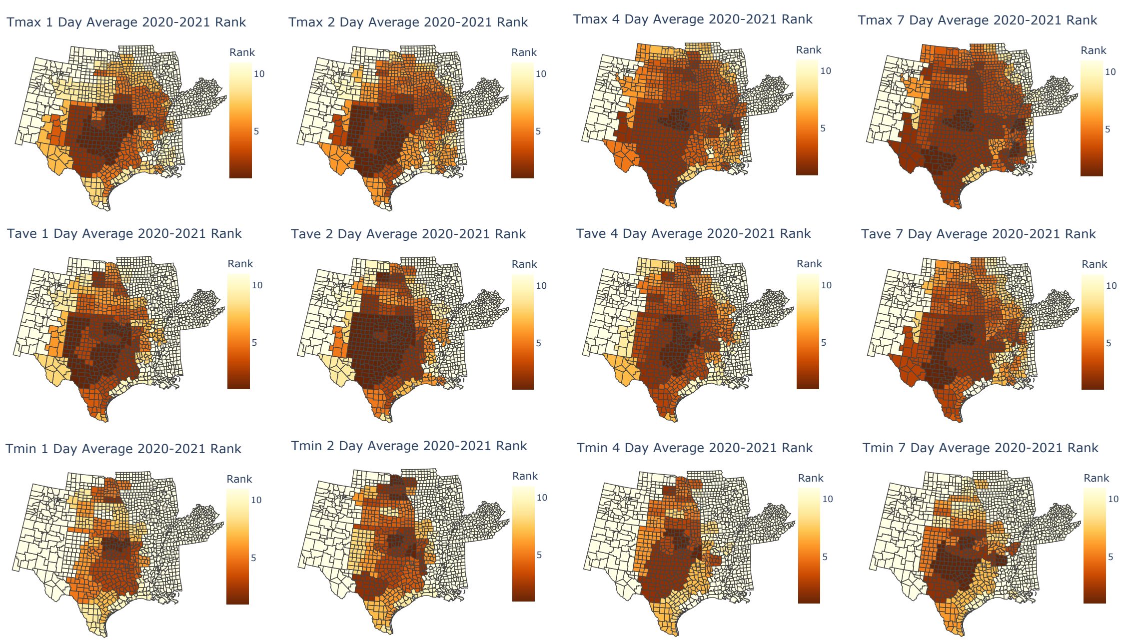

Figure 13: Historic rank of February 2021 cold extreme daily maximum (Tmax), average (Tave) and minimum (Tmin) temperatures, averaged over 1, 2, 4, or 7 days, among climate division composite temperature records. Most such records go back to the 1890s.

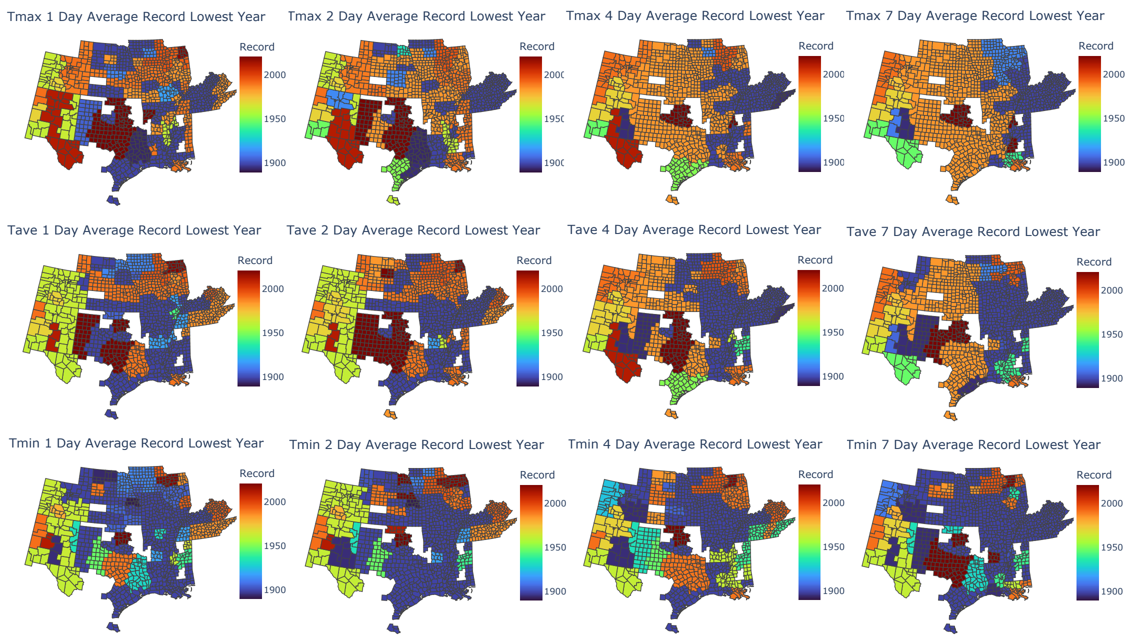

Figure 14: The year with the most extreme cold maximum, average, and minimum temperatures, averaged over 1, 2, 4, or 7 days, in the climate division composite time series of seasonal extremes. Time series that do not extend back to the February 1899 cold event are excluded.

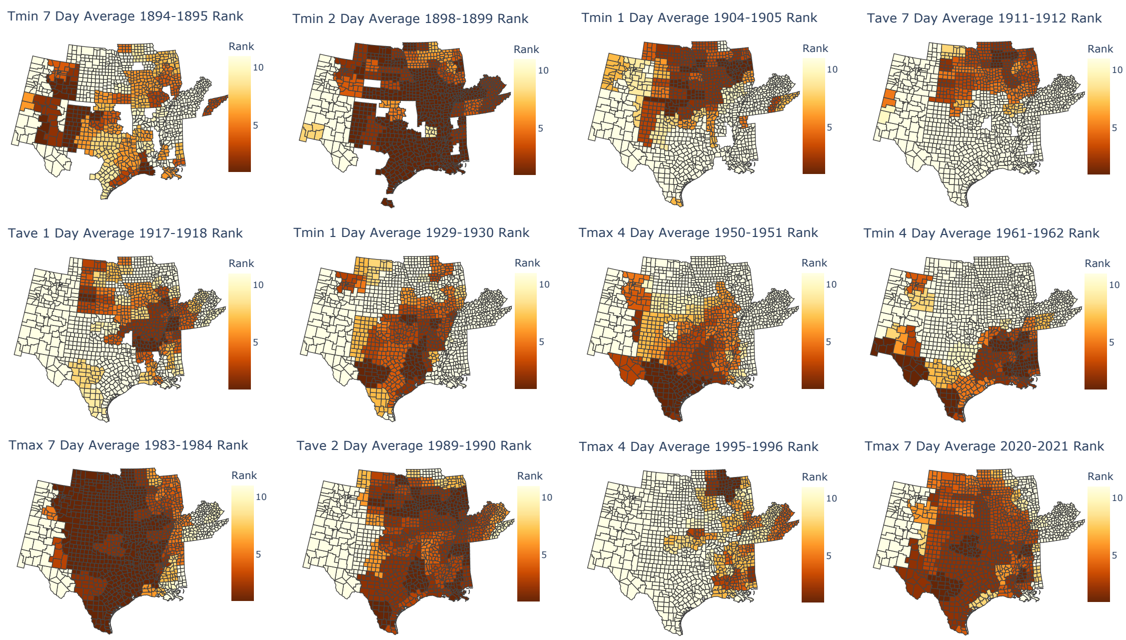

Figure 15: The top ten rankings within climate divisions of the most extreme cold events, 1890 to present. For each cold event, the most extreme combination of duration and metric (minimum, average, or maximum temperature) is shown.

event is most extreme (Fig 15). The four events in 1899, 1983, 1989, and 2011 affected the largest geographical areas, with February 1895 and December 1929 nearly as widespread. February 1951 and January 1962 were extreme mainly in southern states, February 1905 and January 1912 were particularly unusual in northern states, and January 1918 and February 1996 primarily impacted states bordering the Mississippi River.

A recent study by Doss-Gollin et al. (2021) used reanalyses to compare the intensity of cold snaps since 1950 in Texas on the basis of the expected impact on electricity demand for heating within the Texas Interconnection power grid. They found that February 2021 ranked second behind December 1989, with December 1983 and February 1951 nearly as severe.

5. Impacts

The February 2021 event is noteworthy given the widespread impacts that occurred from extreme cold, ice, and snow (Fig 16). Its spatio-temporal extent contributed to it becoming the costliest winter storm event on record for the U.S., with damage losses exceeding $20 billion and surpassing the March 1993 "Storm of the Century" (Kocin et al., 1995; NOAA National Centers for Environmental Information, 2021b). Impacts are organized by type and described below.

5.1. Energy

The energy sector was arguably most impacted by this event. The cold wave placed high demands on power grids, forcing many large utility companies such as the Southwest Power Pool (SPP), the Electric Reliability Council of Texas (ERCOT), and the Midcontinent Independent System Operator (MISO) to implement controlled power outages to manage the load (U.S. Department of Energy, 2021). According to a statement from Barbara Sugg, Southwest Power Pool's president and CEO, the week of February 15th was "the most operationally challenging week we've ever faced in our 80-year history" (Southwest Power Pool, 2021). Some power outages were caused by

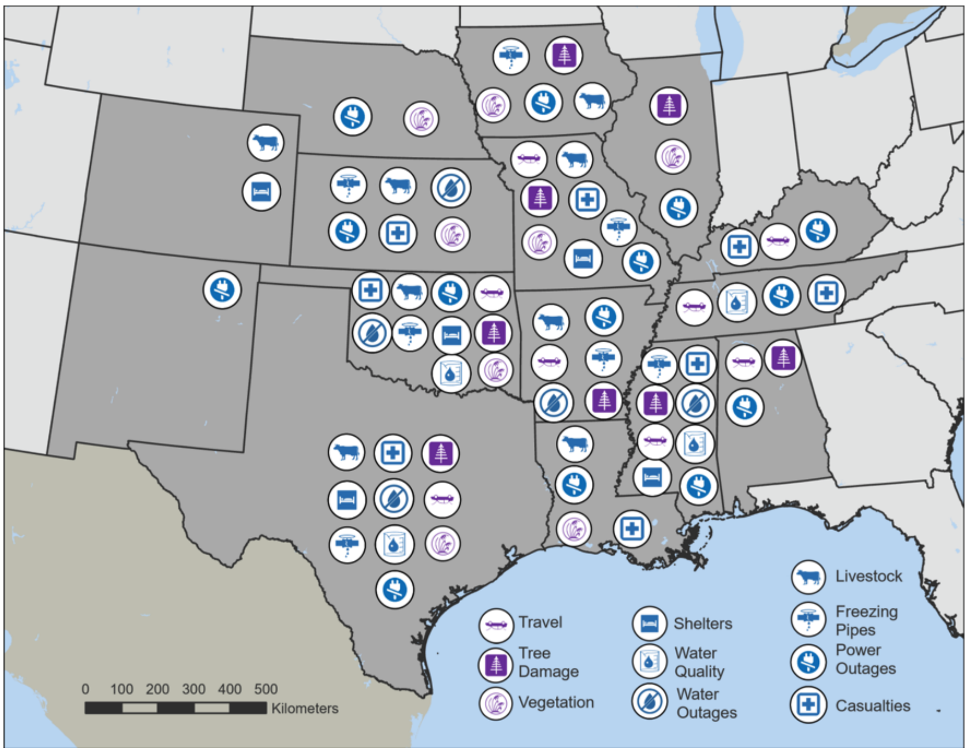

Figure 16: Major impacts from the February winter weather and cold outbreak in the South-Central US. Impacts were grouped into ten categories and color-coded based on whether the impacts were due mainly to ice/snow (travel, tree damage, vegetation) or cold temperatures (shelters, water quality, water outages, livestock, freezing pipes, power outages, casualties). Each state is labeled with the icons of the impacts reported there.

thick ice accumulations on trees and power lines, particularly across southern states. In Texas, generation capacity was lost at natural gas, coal, and nuclear power plants due to the direct impacts of cold on exposed equipment and the loss of natural gas supply due to both direct impacts and loss of electricity at natural gas wellheads, while wind turbines also lost capacity due to buildup of ice on blades (Busby et al., 2021). At one point on the 16th, nearly 5 million electric customers across Texas, Louisiana, and Oklahoma were without power due to a combination of controlled power outages and damaged infrastructure, with 4.5 million of those outages occurring in Texas alone (U.S. Department of Energy, 2021). Power outages caused by ice accumulations on trees and power lines were also highly impactful across parts of Kentucky (National Weather Service, 2021b), as well as Arkansas, Mississippi, and Tennessee (Johnson, 2021).

In addition to the outages, the imbalance of supply and demand for heat and power caused by prolonged cold temperatures drove up the cost of electricity and natural gas. This event caused natural gas prices to reach near record highs at several trading hubs throughout the Plains and the South (York, 2021). In some locations, the high cost will be recouped over a period of months or years from natural gas customers (Black Hills Energy, 2021).

5.2. Human health

In many areas, human health was put at risk due to water pressure loss from burst pipes that froze from the extreme temperatures. For instance, Memphis Light, Gas and Water (Tennessee) issued a system-wide boil water notice, as critical infrastructure such as hospitals and the international airport reported low pressures (Tennessee Emergency Management Agency, 2021). Water outages and water quality were also a concern across Arkansas, Louisiana, Oklahoma, and Texas (Bertrand and Speizer, 2021). Additionally, this event caused several water main breaks on Jackson, MS's well and surface water systems, prompting boil water advisories that remained in effect for over a month after the storm (The City of Jackson, Mississippi, 2021).

Public health was a concern for homeless populations in urban areas. Due to extremely cold temperatures, homeless shelters and warming centers were offered and used in many major metropolitan areas, such as Denver, Houston, Kansas City, Chicago, and Minneapolis-St. Paul. Bertrand and Speizer (2021) also noted how the storm disproportionately impacted the health of individuals in low-income communities and communities of color.

The long duration and severity of this event resulted in many fatalities. While NOAA NCEI (2021) lists the death toll estimate at 172, there are conflicting reports on the actual number of deaths that could be directly or indirectly attributed to this event. According to the Texas Department of State Health Services, as of July 13, 2021, the number of Texans who died as a result of the storm was estimated at 210. Most of the fatalities were attributed to hypothermia, while some were caused by vehicle accidents, carbon monoxide poisoning, the exacerbation of chronic illnesses, falls, and fire (Texas Department of Emergency Management, 2018). Aldhous et al. (2021) ran a simplified model on mortality data from the Centers for Disease Control to assess the number of excess deaths in Texas during and immediately following the storm. They estimate that the number of people who died as a result of the storm (directly and indirectly) may actually be closer to 700 (with an uncertainty range of 426–798 deaths). Overall, six weather-related fatalities were reported in Tennessee by the Tennessee Department of Health (Tennessee Emergency Management Agency, 2021). Weather-related fatalities were also reported in Oklahoma, Kansas, Missouri, Kentucky, Mississippi, and Louisiana.

5.3. Agriculture and wildlife

The agriculture sector (including both farms and livestock) was also significantly impacted by the storm. Many crops sustained damage from the extreme temperatures and ice accumulations. For instance, citrus and vegetable crop producers in Texas endured incredible losses – at least $230 million and $150 million, respectively (Schattenberg, 2021). The fruits and vegetables that made up the majority of losses included oranges, grapefruits, lemons, limes, onions, leafy greens, and watermelons. AgriLife Extension and the Texas Nursery and Landscape Association were also exploring losses by the green industry, including landscaping trees, shrubs, annuals, and perennials. The sugarcane crop was also impacted in Texas and Louisiana (U.S. Department of Agriculture, 2021). Farther north, slowed winter wheat development was reported, with concerns of damage from leaf burn or winterkill in Kansas (Lin et al., 2021) and Nebraska (Dutcher, 2021). It is important to note that loss data are preliminary, and damage estimates are still being assessed. Additionally, it would be difficult to ultimately attribute crop damage to extreme cold in areas that have also experienced drought impacts during the same time period.

Livestock losses were also widespread. This event caused a challenging start to the calving season. High death loss of new calves was reported in Arkansas, Colorado, Louisiana, and Texas but was minimal in Minnesota, Nebraska, and Ohio where extreme cold is more common (U.S. Department of Agriculture, 2021). Fortunately, the extreme temperatures were forecast well in advance, which gave livestock producers time to act; otherwise, cattle/calf losses would have been much higher. Reports also indicate significant losses in the poultry industry (Berkhout, 2021). Besides livestock deaths, the event negatively impacted the livestock industry infrastructure (Schattenberg, 2021) and increased feed requirements and feed costs (Dutcher, 2021). In addition to livestock, there were significant losses of wildlife throughout the region, including birds and fish (Bertrand and Speizer, 2021).

6. Discussion and Conclusions

The synoptic setup for this event began well in advance with an SSW event. A subsequent AO anomaly in early February was a record-tying -5.3 magnitude, suggesting an extremely strong and cold event would occur. The two winter storms, ranked as category 3 events by the Regional Snowfall Index, were rare (especially in recent records), but not unprecedented. The number of hours of freezing precipitation recorded across the study area was not extreme or unusual based on previous climatological studies. In addition, the intensity and total amount of freezing precipitation did not exceed established thresholds for extreme ice loads based on climatology. Nevertheless, the timing and duration of freezing precipitation likely exacerbated the impacts associated with the bitterly cold temperatures and snow that dominated this event.

The extreme and prolonged cold set many specific records across the region, including the number of hours below freezing. Considering extreme cold events in the central and south-central United States since the 1890s, the event appears to have been exceeded in overall severity only by events in February 1899, December 1983, and December 1989.

The meteorological extremes of this event, while remarkable, are not truly unprecedented (Doss-Gollin et al., 2021). However, the magnitude of the associated impacts suggests a lack of preparedness for this scale of event. Out of the 19 winter storms that ranked as billion dollar disasters in NOAA's database (back to 1980) this was the costliest, even when accounting for inflation. If the combination of long-duration extreme cold temperatures and widespread snowfall and ice accumulations is within a probable range of occurrence, would it be reasonable to expect communities to be more prepared to mitigate the impacts? According to Doss-Gollin et al. (2021), the answer is yes. They found that, even though temperatures during the December 1989 event were more intense (and would have put more demand on the power supply), there were fewer than three hours of rolling blackouts in Texas.

It is common practice for state entities to develop hazard mitigation plans at the state level that can propose and implement actions to reduce the severity of impacts. These will usually include local hazards that pose some moderate risk of occurring and resulting in damage and impacts. The State of Texas Hazard Mitigation Plan (2018), for example, contains a comprehensive list of hazards that have previously resulted in damage and losses. This plan not only details the impacts from these hazards, but forecasts potential future losses. As quoted in the plan, "Winter weather and extreme cold are the only two hazards with expected decreases in future losses due to variations in weather patterns. This will limit both hazards frequency and intensity."

In the southern region, particularly along the Gulf Coast, the hazards that pose the greatest risk (due to damage potential, loss of life, and frequency of occurrence) include floods, hurricanes, and tornadoes. A larger percentage of planning and monetary resources would likely be directed to the hazards of higher risk. Even as noted in Texas's state hazard mitigation plan, the risk of winter weather and extreme cold events is decreasing, and therefore it could be assumed that fewer resources would focus on these hazards. As evidenced by the magnitude of impacts from the February 2021 event, an increased effort in planning for these types of events would be beneficial, because vulnerability from such events is clearly high.

Extreme cold weather led to rolling blackouts in Texas in February 2011, a full decade before the event that is the subject of this paper. Many of the problems during 2021 were similar to, but more extreme than, problems that arose in 2011, according to federal regulators (Friedman et al., 2021). Some of the recommendations made in the wake of the 2011 event are now being adopted as rules by the Public Utilities Commission of Texas (Douglas, 2021). The importance of climate services in recognizing this vulnerability can be illustrated by considering return periods for a simple cold wave metric: the lowest average daily temperature at Oklahoma City OK, Abilene TX, and San Antonio TX, each of which have complete data from 1890 to present.

A simple stationary analysis implies a return period of 6 years for the 2011 event based on data through 2011, indicating that similar events should have been anticipated in the near future. An event equivalent to 2021 would have been assessed at a return period of 61 years. However, the climate is changing, and a nonstationary analysis with time or global mean surface temperature as a covariate would have implied a 10–12 year return period for 2011 and a 300-700 year return period for 2021. Climate expertise would be necessary to make sense of the large differences between these two types of analyses, future projections based on downscaling of global climate models (Deser et al., 2014), and the relevance of evidence that more recent changes at high latitudes may be altering the odds (Cohen et al., 2021; Yin and Zhao, 2021), and to work with policymakers to determine an appropriate target for resiliency. Climate services are also necessary to identify an appropriate measure of the weather-related threshold corresponding to the breakdown in power distribution in 2021, which happened well before the lowest average daily temperature was achieved. An assessment of risk based only on the most extreme aspects of the 2021 event would underestimate grid vulnerability.

Given the importance of climate services, how should they be provided? Hewitt and Stone (2021) differentiate between a demand-driven approach to providing climate services and a capability-driven climate services approach. The latter has been in practice for a long time, as making climate data widely available and accessible was a top priority. With a demand-driven approach, climate services are more targeted, and climate information is delivered based on the needs of a specific user and in a way that allows the user to make improved decisions.

The successful integration of climate information into decision-making is documented. The Fourth National Climate Assessment lists many examples of federal, state, tribal, and local agencies implementing climate adaptation plans (USGCRP, 2018). These implementations can lead to tangible improvements at the community level. For example, Vogel et al. (2016) describe the actions that communities have taken that resulted in observable reductions in vulnerabilities to climate extremes. These examples highlight the benefits of users engaging with climate service providers and incorporating climate information into their plans.

Perhaps because climate services have been primarily focused on the capability-driven approach for a longer span of time (Hewitt and Stone, 2021), there exists a division between the data provider and the data user. This approach is more "top down," where the provider assumes the needs of a passive receiver of information, then develops and disseminates information based on that initial idea. A demand driven approach requires increased engagement between provider and user throughout every stage of the climate service to be developed and implemented - a more "bottom up" approach.

Through a series of surveys and interviews of European decision-makers, Bruno Soares et al. (2018) found that the biggest barrier between climate service providers and users is whether the users perceive the information to be useful to their organizations, while cost and availability of climate information were not as important. While recent advances have been made in the realm of demand-driven climate services, and climate service providers have increased efforts to meet specific needs (Hewitt and Stone, 2021), one hurdle that can't be ignored is a potential user's willingness to receive climate information and make decisions based on that information. Even if the information is available and credible, if the user has not been engaged in the development of the service, and they don't consider the information useful, it will not be used.

The extreme events and subsequent impacts in February 2021 clearly indicate there is a need for climate services to address extremes that may be perceived as lower risk. Advances in forecasting and risk communication are meaningless if there are no actions implemented to prepare for and respond to climate and weather extremes. Climate service providers and decision-makers (with public or private institutions) should continue work to address the risks of many hazards.

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