

A Climatological Perspective of the February 2021 South-Central U.S. Arctic 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, arctic outbreak, ice storm

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 desig-

7 nated Winter Storm Uri and Winter Storm Viola by The Weather Channel.
8 Direct impacts from cold, snow, and ice were reported throughout the south-
9 ern and central states. As of October 2021, estimated damage from the
10 storms exceeded \$20 billion, making it the costliest winter weather event
11 in the U.S., surpassing the 1993 "Storm of the Century" (NOAA National
12 Centers for Environmental Information, 2021b; Kocin et al., 1995). It is esti-
13 mated that the storms caused hundreds of deaths, most occurring in Texas,
14 the state with the greatest impacts from the storms.

15 The notoriety of the event arose from the lack of preparedness and result-
16 ing widespread devastation. Additionally, there is an assumed likelihood that
17 climate change would decrease the occurrence of such freeze events (Osland
18 et al., 2021). While increased variability amidst a warmer temperature dis-
19 tribution could result in the same frequency in the magnitude of cold ex-
20 tremes previously observed (Rummukainen, 2012), average February maxi-
21 mum temperatures for the Contiguous United States had not been this cold
22 since 1989 (NOAA National Centers for Environmental Information, 2021a).
23 Other widespread cold outbreaks have occurred in U.S. history (Kocin et al.,
24 1988); however, the February 2021 event is arguably the most severe cold
25 event in the U.S. since the turn of the 21st century.

26 In this paper, we highlight the need for climate services in risk assess-
27 ment and increasing preparedness in the context of events such as the one
28 described in this paper. We begin with a synoptic analysis to provide a phys-
29 ical explanation of the event. The sequence of synoptic conditions necessary
30 for an event like this is not unprecedented, and there is no assumption that
31 they cannot happen in the future. A climatological analysis follows, where

32 the storm is placed in a historical context. Next, we examine the extent to
33 which similar events have occurred in the past and are likely to happen in the
34 future. We follow with a description of the observed wide-ranging impacts
35 that resulted from the event, including a discussion of why the event caused
36 such severe impacts. Finally, we propose how integrating climate services
37 into disaster risk management and hazard mitigation planning can reduce
38 the magnitude and severity of impacts for future events.

39 **2. Data and Methods**

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

46 *2.1. Analyzed wind and constant pressure charts*

47 For the synoptic analysis, we used the National Centers for Environmental
48 Prediction (NCEP) Climate-Forecast System Reanalysis (CFSR; 0.5°) (Saha
49 et al., 2010) to describe the mean, one standard deviation (1σ), and two
50 standard deviations (2σ) zonal-mean zonal wind climatology (1980–2010) for
51 60°N at 10 hPa. Superimposed upon the measure of climatological dispersion
52 in the zonal wind is the analyzed Global Forecast System (GFS; 0.5°) zonal-
53 mean zonal wind for the 2020/2021 season. All 250-hPa, 500-hPa, and mean
54 sea level pressure (MSLP) analysis maps were generated from the 0.5° NCEP
55 GFS. Standardized anomalies shown for specified variables are calculated

56 with respect to a 31-year (1979–2009) 0.5° NCEP CFSR climatology (Saha
57 et al., 2010).

58 *2.2. Observed station data*

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

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

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

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

96 Hourly freeze streaks, or the number of consecutive hours below freezing
97 for an event, were assessed using hourly station data from the NCEI Inte-
98 grated Surface Database (ISD). Stations with data through February 2021
99 and and records back to 1970 or earlier, were identified from ISD Station His-
100 tory. This resulted in 98 viable station locations. For each station, hourly
101 temperature values are examined first to determine if any station contained
102 a 3-hour reporting interval. If so, the two missing values are filled with the
103 average of the bounding values. Next, a query was completed for each winter
104 (Dec, Jan, Feb) to assess the completeness of the data for its entire period
105 of record. For all 98 stations, any streak longer than 24 hours in Feb 2021

106 is recorded. To compare the 2021 event to previous events with long freeze
107 streaks, we further refined the dataset to include stations with data before
108 1948, resulting in 84 stations. For the 84 stations starting in 1948, streaks of
109 values equal to or less than 0°C are identified with the progressively longest
110 such streaks reported. Streak length is counted as actual values reported or
111 interpolated from the three-hourly data. Finally, the year with the longest
112 freeze streak event is recorded as the record year for each station.

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

128 Storm summaries from the Weather Prediction Center and individual Na-
129 tional Weather Service offices were initially examined to determine the overall
130 spatial and temporal extent of freezing precipitation (i.e., freezing rain and

131 freezing drizzle) associated with this event. Hourly observations of freezing
132 precipitation were then obtained from first-order stations in these areas that
133 Changon (2002) determined were of sufficient quality for climatological anal-
134 yses. These observations were compared to the storm summaries to check
135 for consistency and accuracy. For the February 2021 event, the number of
136 hours of freezing precipitation were tallied at 17 stations across the study
137 region. Hourly amounts of freezing precipitation were also tallied. These
138 values were compared to climatological averages and extremes reported in
139 the peer-reviewed literature.

140 The total snowfall accumulation from 00 UTC 10 February to 00 UTC
141 20 February were calculated by adding the 24-hour snowfall accumulation
142 estimates from the NOAA National Operational Hydrologic Remote Sensing
143 Center’s National Snowfall Analysis (National Weather Service, 2021a) for
144 each day in the period and for our study area.

145 *2.3. Warnings, watches, and advisories*

146 Another measure of the spatial and societal impacts of the February 2021
147 event was examined by finding the total number of warnings, watches, and
148 advisories (WWAs) issued by local National Weather Service Forecast Offices.
149 WWAs spatial extents were retrieved from the Iowa Environmental Mesonet
150 Archived NWS Watch, Warnings, Advisories website (Iowa Environmental
151 Mesonet, 2021). First, geospatial data were downloaded for all WWAs issued
152 for the U.S. in 2021 (as of the download date, 17 April), then cropped to
153 our study area, and the date range was restricted to WWAs issued from 00
154 UTC 10 February up to but not including 00 UTC 20 February. The WWAs
155 phenomenon types were searched for any meteorological phenomenon related

156 to the winter weather outbreak; the end result included WWAs issued for
157 Blizzard, Freeze, Hard Freeze, Ice Storm, Wind Chill, Winter Storm, Winter
158 Weather, and Freezing Fog, totaling 10,213 WWAs in the study area. Other
159 phenomena searched for but not present in the data were Blowing Snow,
160 Extreme Cold, Avalanche, Freezing Rain, Freezing Spray, Frost, Heavy Snow,
161 Heavy Sleet, Lake Effect Blowing Snow, Lake Effect Snow, Sleet, Snow, and
162 Snow Squall. While the number of WWAs issued in the study area does
163 give a reference for the extent and severity of the storms, it is important to
164 note that the criteria for the different winter-weather related WWAs vary
165 by NWS Forecast Office to account for varying levels of preparedness and
166 acclimatization to winter weather within their county warning area (National
167 Weather Service, 2021c). As the study area for this paper ranges from the
168 Gulf Coast to the Great Lakes, the differences in the WWA criteria are large
169 but do provide insight into varying impacts expected across the geographic
170 area.

171 **3. Synoptic Overview**

172 *3.1. Precursors*

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

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

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

205 North America (Cohen et al., 2021). As a result, cold polar air and an as-
 206 sociated surface high-pressure system strengthened over Northern Canada.
 207 Aloft, the ridge-trough couplet interrupted the eastward flow of the polar
 208 jet stream and enabled terrain-channeled cold air to travel southward along
 209 the east side of the continental divide. An initial cold front on February
 210 5–7 brought the leading edge of the cold air into the Central U.S. Over the
 211 subsequent 10 days, the polar air plunged as far south as Brownsville, Texas
 212 (Fig 3).

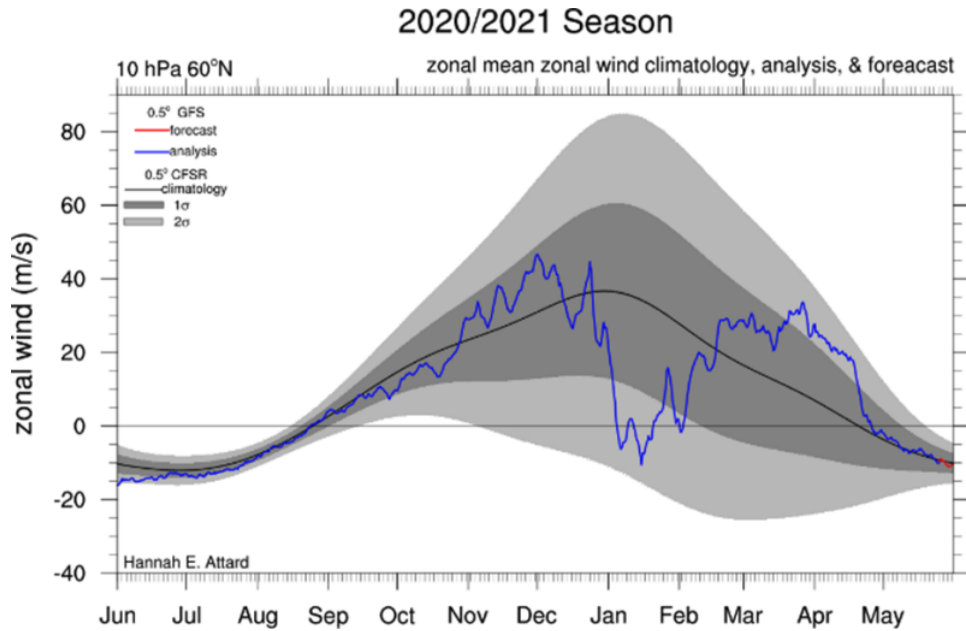


Figure 1: Zonal mean zonal wind climatology for 60°N at 10 hPa. The black line represents the climatological mean zonal wind (m/s), dark gray - one standard deviation zonal mean wind, and light gray - two standard deviation zonal mean wind from climatology. GFS zonal wind (blue line) describes a typical 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

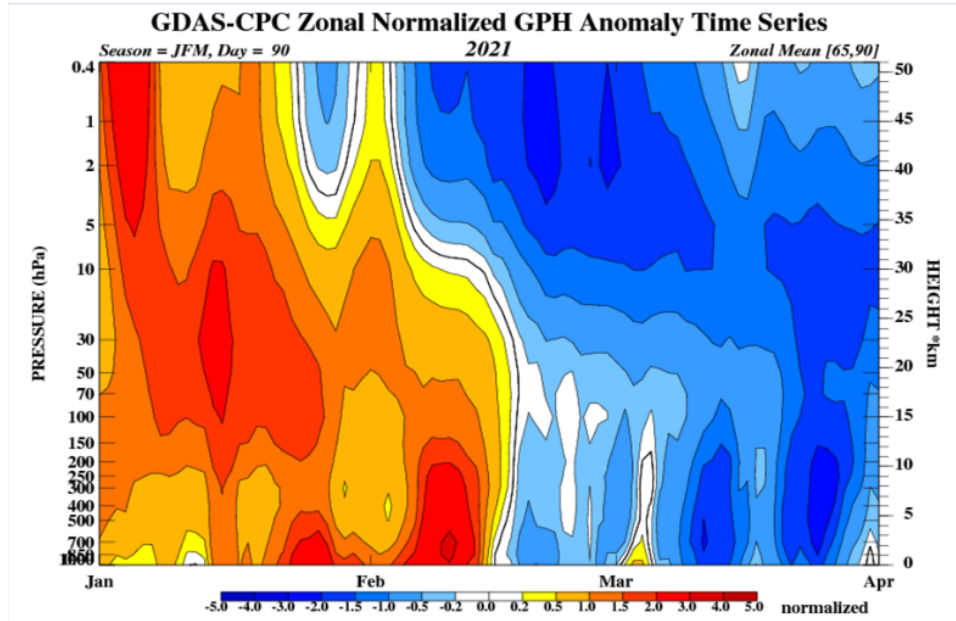


Figure 2: NCEP Global Data Assimilation System (GDAS)-Climate Prediction Center (CPC) standardized zonal (65–90 N) geopotential height anomalies during January-February-March 2021. Yellow-red colors show areas with positive height anomalies and light blue-dark blue show areas with negative height anomalies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

213 *3.2. Day-by-day summary*

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

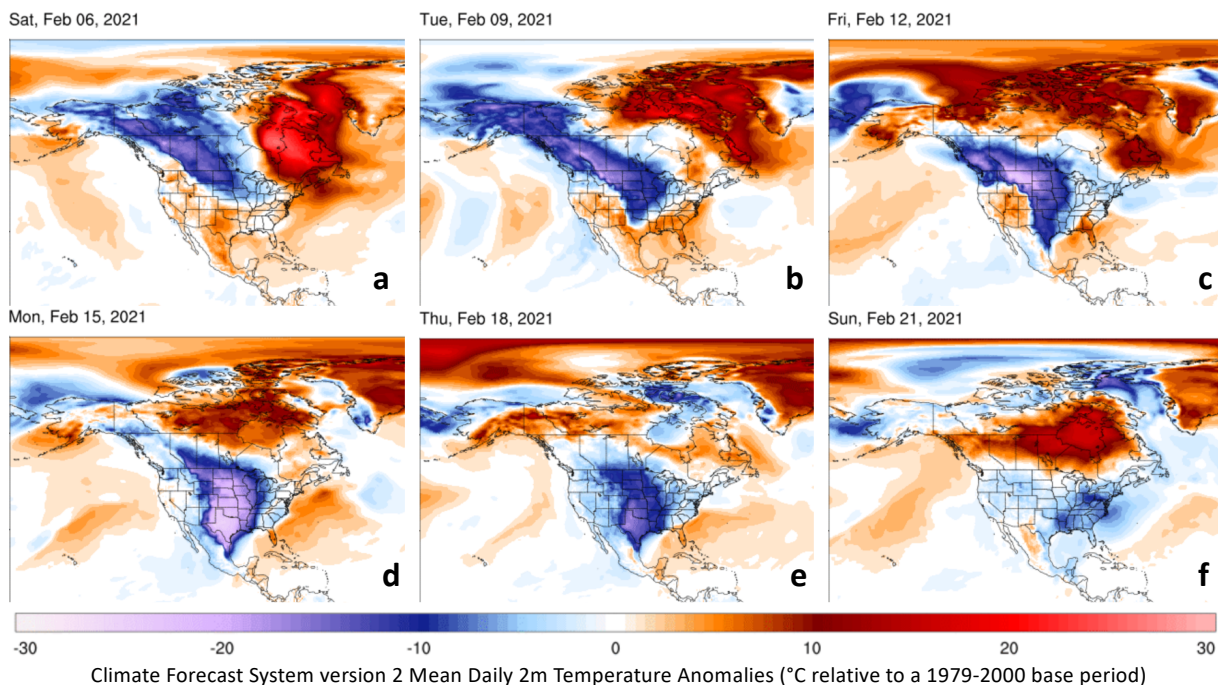


Figure 3: CFSv2 daily mean temperature anomalies near the surface (2 m) over North America for the duration of the event, starting on February 6 (a) through February 21 (f). Blue and purple colors denote below average temperature anomalies.

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

227 U.S (Fig 5a). At the surface, positive anomalies in mean sea level pressure
228 (MSLP), associated with the frigid air mass previously contained in north-
229 ern Canada and the Arctic, traveled south over the western High Plains (Fig
230 6a). Daily maximum surface temperatures for much of the Midwest were
231 more than 10°C below normal (1991–2020). During the day on 0000 UTC 9
232 February, the remnants of the vortex at 500-hPa shifted southeast, slightly
233 weakened, and covered a large portion of Canada. Associated cyclonic flow at
234 500-hPa around the area of low geopotential heights and northwesterly winds
235 from the ridge over Alaska continued to channel air down the east side of the
236 Rockies, enabling frigid air to advect into the U.S, particularly in the lower
237 troposphere. Daily mean surface temperatures from northern Texas, central
238 plains extending to the US/Canada border, and western Canada were 10°C
239 below normal (1979–2000) (Fig 3). The cold remnant vortices over Canada
240 blocked the eastward movement of the jet stream, and it remained south of
241 the U.S/Canada border over the central U.S.

242 By 0000 UTC 10 February, the cyclonic flow at 500-hPa remained largely
243 contained in Canada and the northern U.S. while northwesterly winds from
244 the ridge over Alaska continued to channel air down the east side of the
245 Rockies (Fig 4b). The 250-hPa flow remained roughly zonal across the cen-
246 tral U.S, and the jet stream retreated north to the Great Lakes region (Fig
247 5b). An upper-level shortwave trough moved eastward, deepening the exist-
248 ing trough and favoring surface cyclogenesis and precipitation across eastern
249 Texas and the Gulf Coast. As indicated by the high MSLP anomalies, the
250 surface cold front continued to travel southward and reached northern Texas
251 (Fig 6b). The cold air at the surface was shallow, especially across central

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

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

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

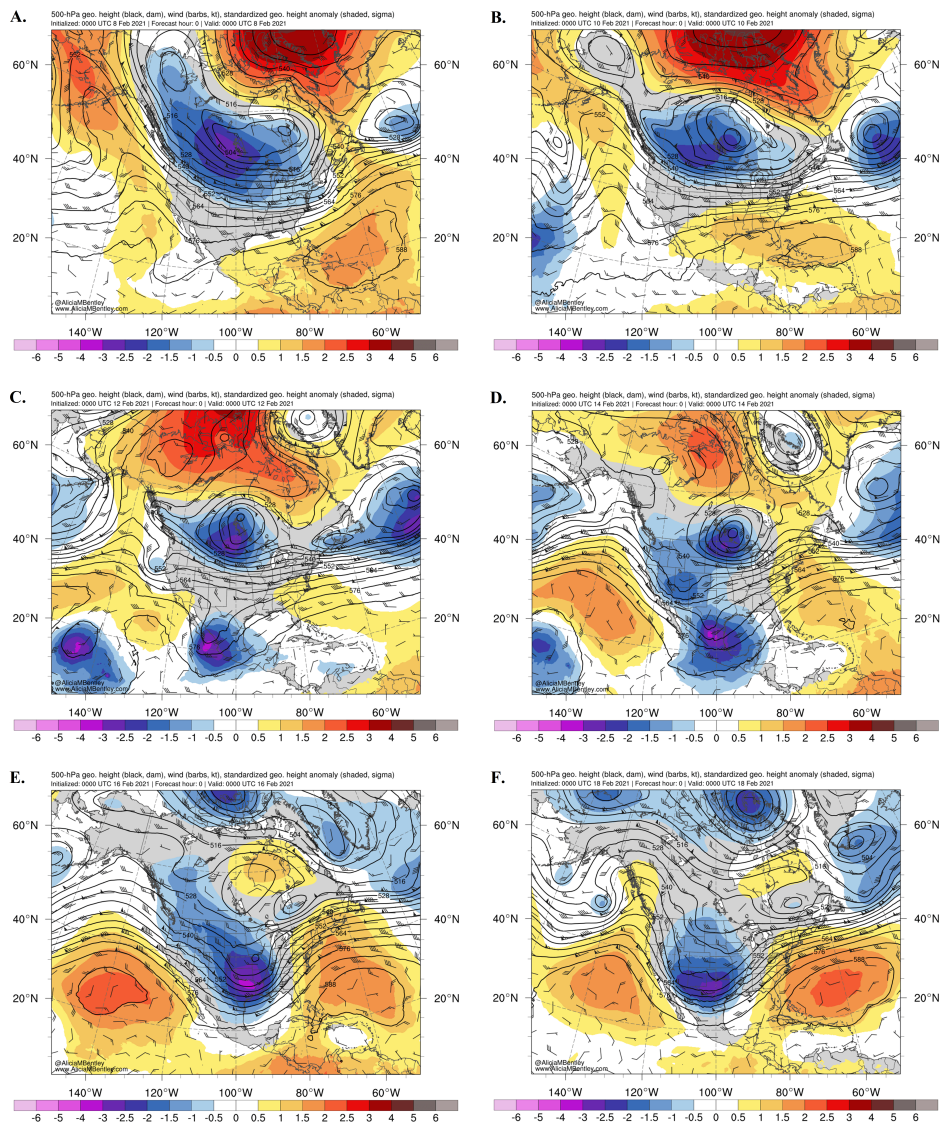


Figure 4: 500 hPa geopotential height (black lines, dam), wind (barbs, kt), and standardized geopotential height anomalies (shaded, sigma) for a) 00 UTC 8 February 2021, b) 00 UTC 10 February 2021, c) 00 UTC 12 February 2021, d) 00 UTC 14 February 2021, e) 00 UTC 16 February 2021, and f) 00 UTC 18 February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

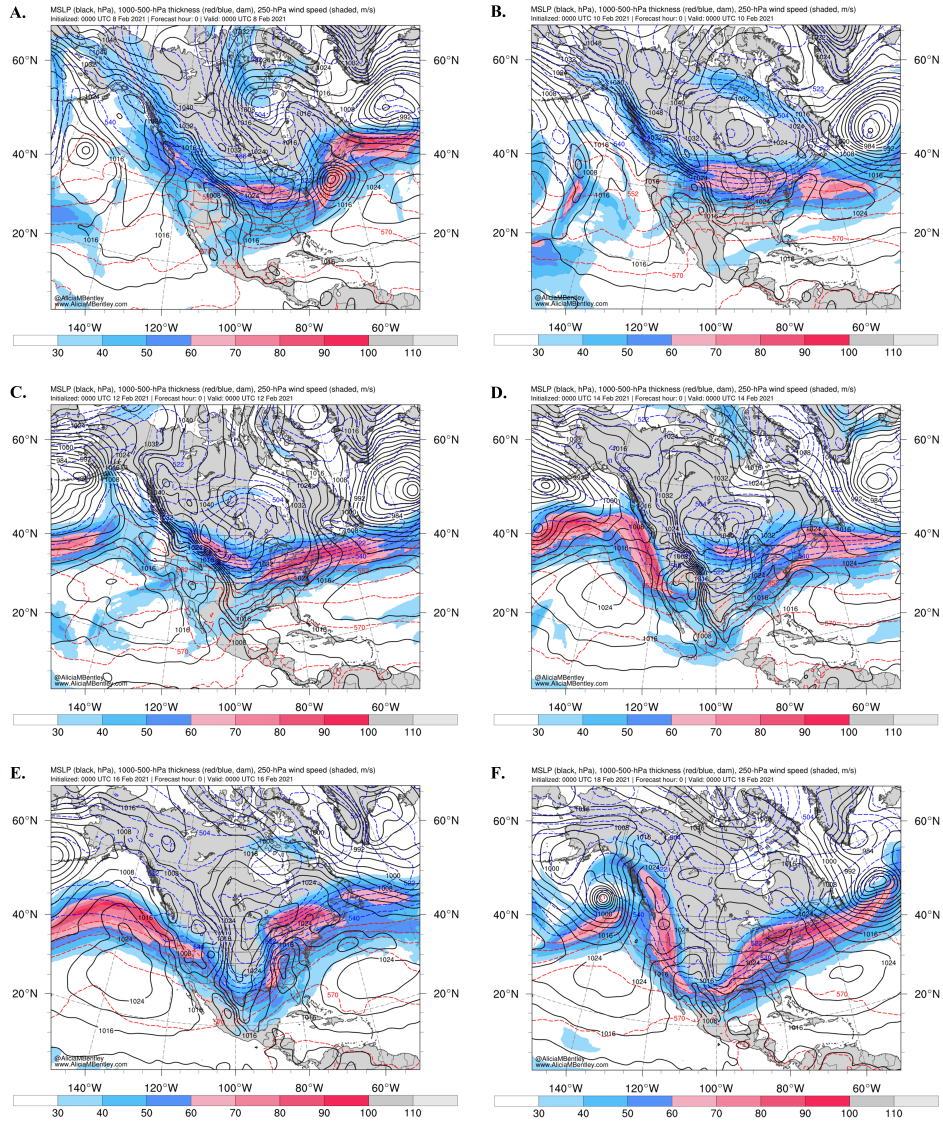


Figure 5: 250 hPa wind speed (shaded, m/s), mean sea-level pressure (black lines, hPa), and 1000–500 hPa thickness (red/blue dotted lines, dam) for same times as Fig 4. Image Credit: Dr. Alicia Bentley

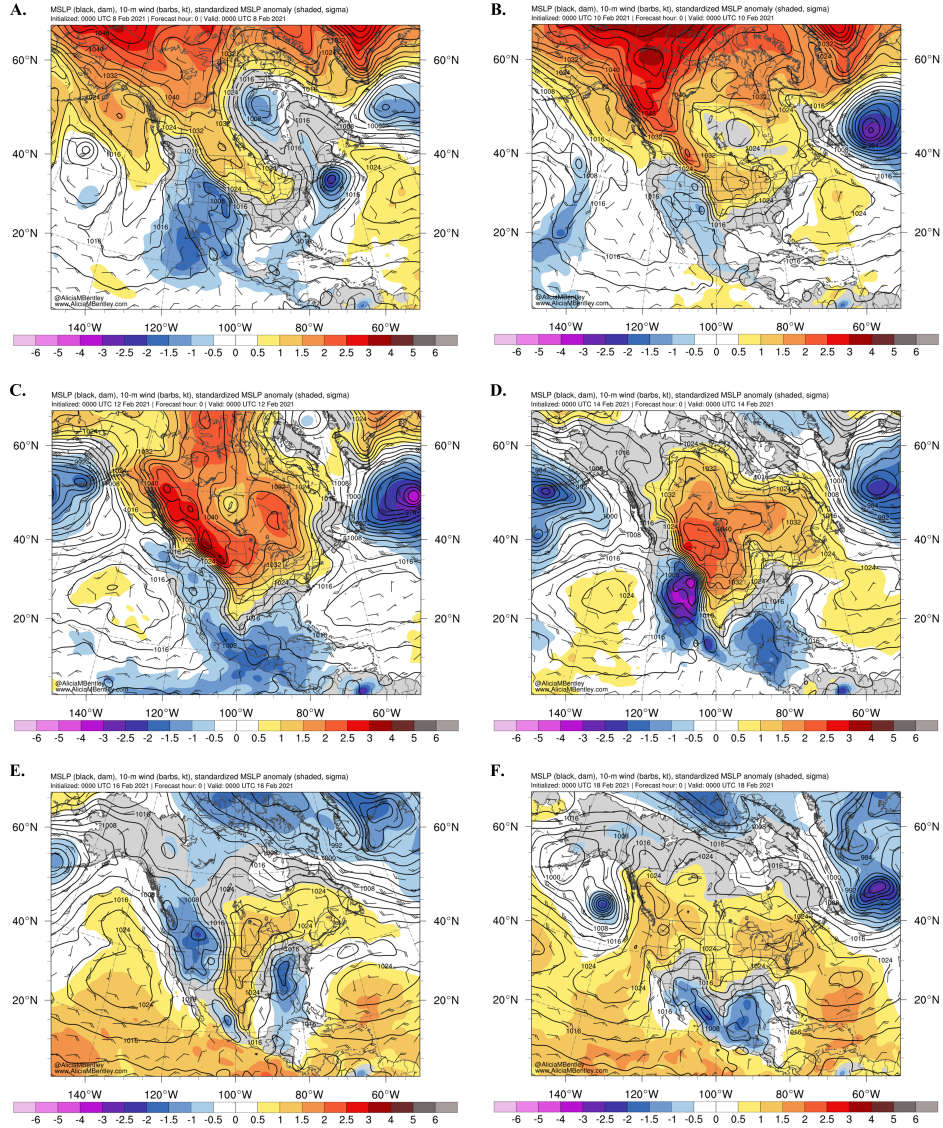


Figure 6: Mean sea level pressure (MSLP; black lines, dam), 10-meter wind (barbs, kt), and standardized MSLP anomaly (shaded, sigma) for same times as Fig 4. Image Credit: Dr. Alicia Bentley

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

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

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

300 The 500 hPa ridge-trough-ridge pattern weakened but remained persistent
301 across the U.S at 0000 UTC 18 February (Fig 4f). The surface low that

302 formed over the Gulf of Mexico moved southwest to northeast following the
303 upper-level flow (Fig 4f, Fig 5f), impacting the Southeast and Mid-Atlantic
304 before exiting the mid-Atlantic coastline around 1200 UTC 19 February.
305 Daily mean surface temperatures remained 10°C to 20°C below normal on
306 18 February across a large swath of the central U.S (Fig 3). By 2000 UTC
307 20 February, 500 hPa trough had eroded and the U.S. returned to a more
308 zonal pattern at 250-hPa, marking the end of the exceptional winter weather
309 outbreak; however, below average daily mean surface temperatures lingered
310 across the Gulf Coast until 24 February.

311 **4. Historical Perspective**

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

318 To put the storm into a historical perspective, we assessed the following
319 components: snowfall and ice accumulations (i.e., winter precipitation), the
320 magnitude of cold temperatures, and duration of cold temperatures. Figure
321 7 highlights the spatial extent of the storm, showing the total number of
322 warnings, watches, and advisories (WWAs) issued by the National Weather
323 Service during the duration of the event. A broad region received five or more
324 WWAs in the ten-day period, with a maximum of 15–16 WWAs throughout
325 southern Texas. Precipitation-related WWAs were most frequently-issued in

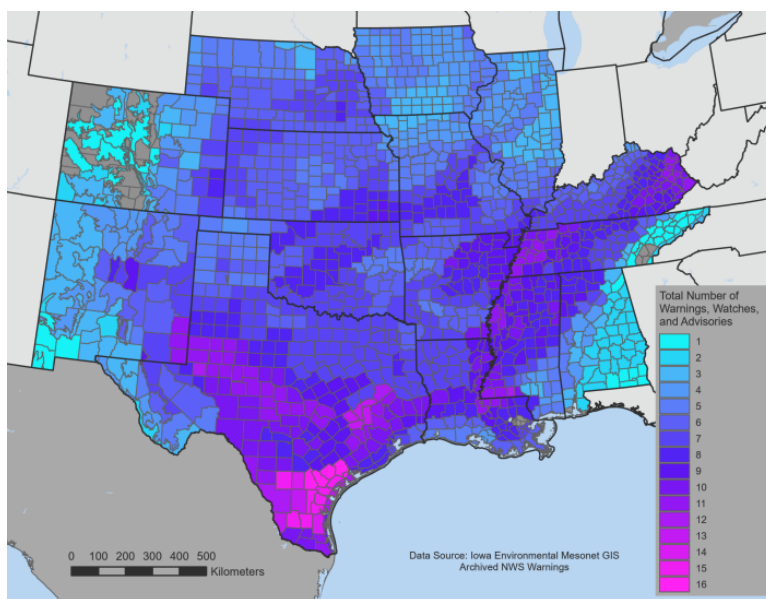


Figure 7: Total number of winter weather related warnings, watches, or advisories from 00 UTC 10 February to 23:59 UTC 19 February including blizzard, freeze, freezing fog, hard freeze, ice storm, wind chill, winter storm, and winter weather.

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

329 *4.1. Winter precipitation*

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

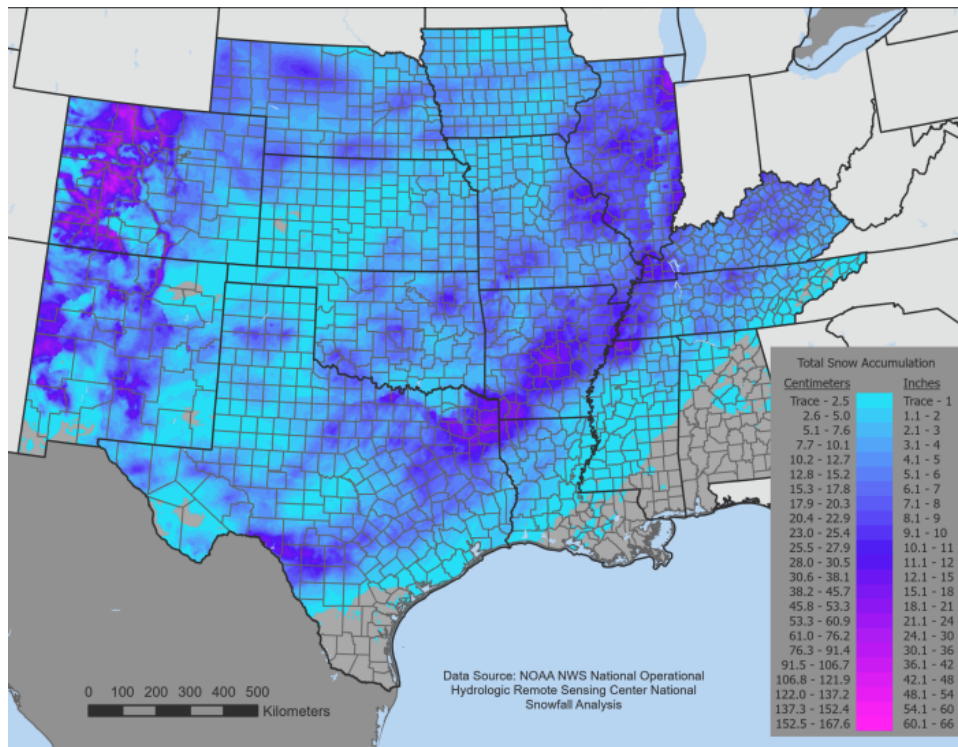


Figure 8: Total accumulated snowfall (cm and in) from 00 UTC 10 February to 23:59 UTC 19 February 2021, derived from NOAA NWS National Operational Hydrologic Remote Sensing Center National Snowfall Analysis.

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

340 To objectively assess how extreme and severe this storm was, we used
 341 the NOAA NCEI database of Regional Snowfall Index (RSI) (Squires et al.,
 342 2014). RSI is a regionally-specific index that takes spatial extent, snowfall
 343 totals, and population into account to estimate the total impact of the storm.
 344 RSIs are assigned a category 1 through 5, similar to the Saffir-Simpson scale

345 used for tropical cyclones. According to the database, the two snowstorms
346 associated with this event each ranked as category 3 for the Southern region
347 (encompassing KS, OK, TX, AR, LA, and MS), suggesting major impacts.
348 The first storm (Feb. 13–16) ranked as a category 2 storm for the Ohio
349 Valley (which includes MO, IL, KY, and TN from our study region) and
350 category 1 for the Upper Midwest (which includes IA from our study region)
351 and the Northern Rockies and Plains (which includes NE from our study
352 region), while the second storm (Feb. 16–20) was rated category 1 for the
353 Ohio Valley and the Northeast.

354 Based on the historical distribution of winter storms assigned an RSI
355 category, dating back to 1900, 8% of storms rank at a category 3 or higher.
356 Only 3% of all storms rank as a category 4 or 5. All category 3+ storms
357 since 2010 in the Southern region have occurred in pairs, and all in February:
358 2010 (both category 4), 2011 (both category 4), and 2013 (both category 3).
359 According to the database, the 2021 storms both brought at least 5 cm (2
360 in) of snow to more people than any other Southern storms in the database.
361 These storms rank 19th and 22nd out of 151 storms in the Southern region.
362 Hence, storms of this size and magnitude have a large enough probability of
363 occurrence in the future that they should be considered in hazard mitigation
364 planning.

365 In addition to snow, cold temperatures associated with this event also
366 contributed to freezing precipitation across portions of the Southern Plains,
367 Lower Mississippi Valley, and Southeast U.S. Arctic fronts and anticyclones,
368 which were dominant synoptic features during the cold outbreak, are also
369 the most common synoptic types associated with freezing precipitation in

370 these regions. These types of freezing precipitation patterns typically result
371 in widespread ice accumulation (Rauber et al., 2001; Changnon, 2003).

372 Figure 9 shows the number of hours of freezing precipitation, which in-
373 cludes both freezing rain (FZRA) and freezing drizzle (FZDZ), recorded be-
374 tween 7–18 February at first-order weather stations with quality FZRA and
375 FZDZ data as determined by Changon (2002). These values were mostly
376 above average (Cortinas Jr. et al., 2004; McCray et al., 2019) but not record-
377 breaking (Houston and Changnon, 2007). Though FZRA is less common at
378 these locations than in other parts of the U.S., e.g. Great Lakes, North-
379 east (Changnon and Karl, 2003), a greater proportion of events are of long
380 duration (i.e. 6–18 hours) (McCray et al., 2019), including those that oc-
381 curred in February 2021. The maximum in FZDZ observations across parts
382 of Oklahoma and Missouri is consistent with climatology (Cortinas et al.,
383 2004).

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

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

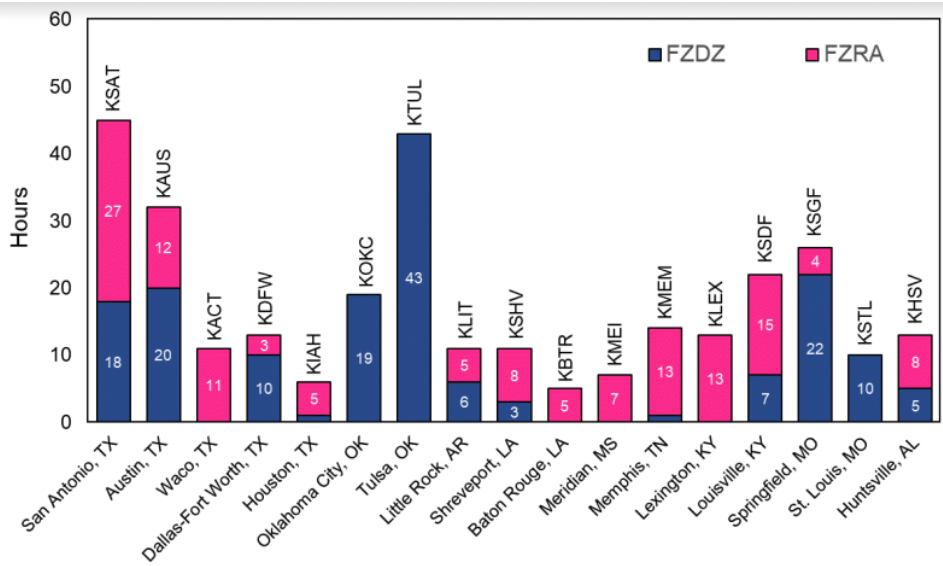


Figure 9: Number of hours with freezing precipitation (FZRA and FZDZ) at first-order stations with quality freezing precipitation data from 7–18 February 2021. Values < 3 h are not labeled inside the bars. Station identifiers are located above each bar.

395 itation per year (Cortinas Jr. et al., 2004) and, in some cases, may only
396 experience freezing precipitation once every 5–10 years (Changnon and Karl,
397 2003). Therefore, while the occurrence of freezing precipitation near the Gulf
398 Coast was climatologically notable, it was not unprecedented.

399 *4.2. Temperature extremes*

400 Perhaps the most notable aspect of this event was the cold temperatures.
401 The cold extremes, combined with the wintry precipitation, exacerbated the
402 severity of the storm. Table 1 shows the total number of cold temperature
403 records broken during the event. It’s not uncommon for significant cold air
404 outbreaks to result in a large number of record cold temperatures across a
405 region. As a recent example, over 6,000 cold temperature records (for both
406 low maximum and low minimum temperatures) were broken in February
407 2011. In December 1983, there were over 28,000 cold temperature records
408 broken. Focusing on Texas, where the widespread cold extremes were most
409 impactful, 192 monthly records were broken in the February 10–19, 2021 time
410 period (i.e., the lowest maximum or minimum temperature ever reported
411 in February at a station occurred in that period). For December 19–28,
412 1989, Texas had 322 monthly records broken, which was 130 more than the
413 February 2021 event. While the large number of stations with record cold
414 temperatures in February 2021 was significant, it was not unprecedented.

415 This storm was more unusual due to the length of time temperatures
416 remained below freezing. Across Texas, many stations set records with six to
417 ten consecutive days below freezing (Fig 10). Some stations in the Central
418 Plains and Midwest observed 11–15 consecutive days below freezing, and one
419 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.

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

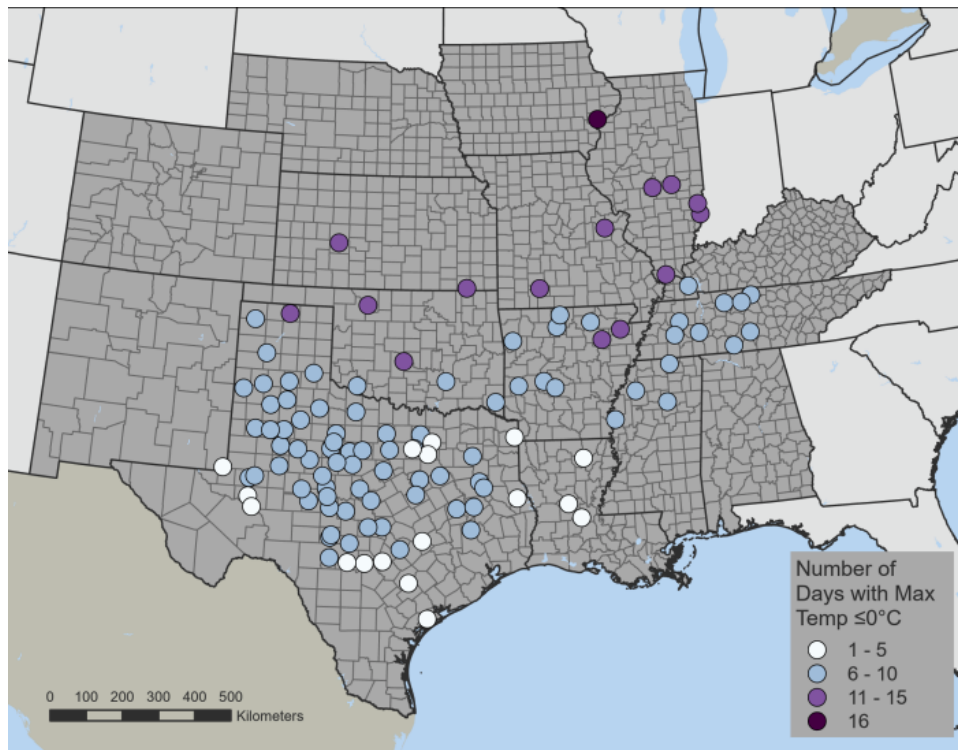


Figure 10: Stations within the GHCN-daily dataset which set an all-time station record for number of consecutive days with observed maximum surface temperatures at or below 0°C during February 2021.

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

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

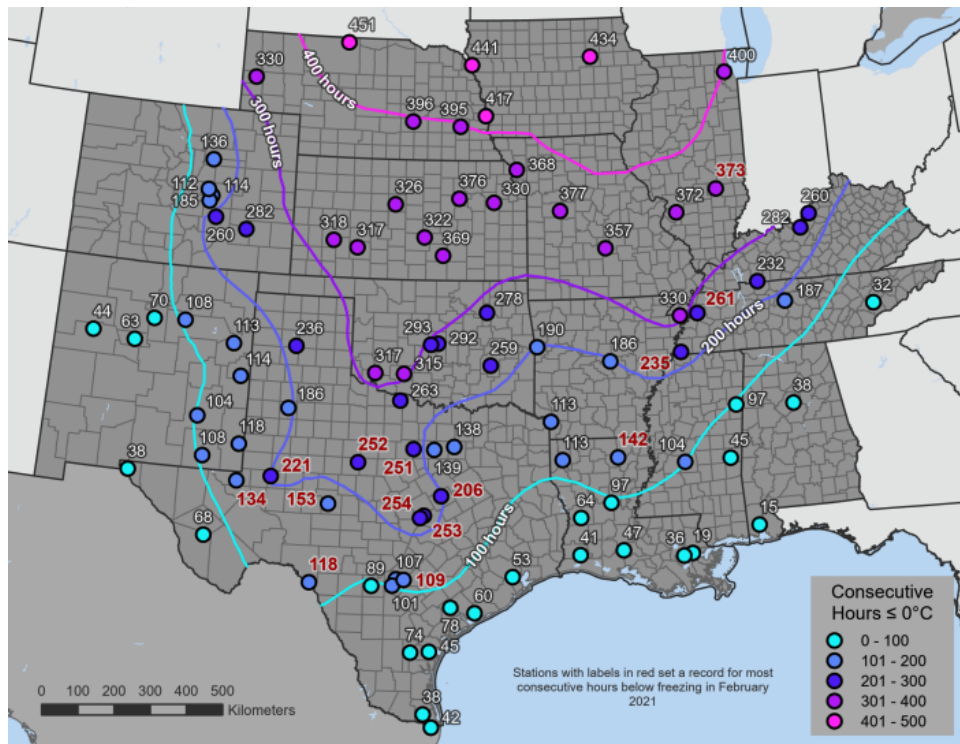


Figure 11: The longest hourly streak (consecutive hours) with surface temperatures at or below 0°C reported during February 2021 at NCEI Integrated Surface Database (ISD) stations. Hours in red set the station record for longest hourly streak for that station. Stations with records for 1948-2021 are shown.

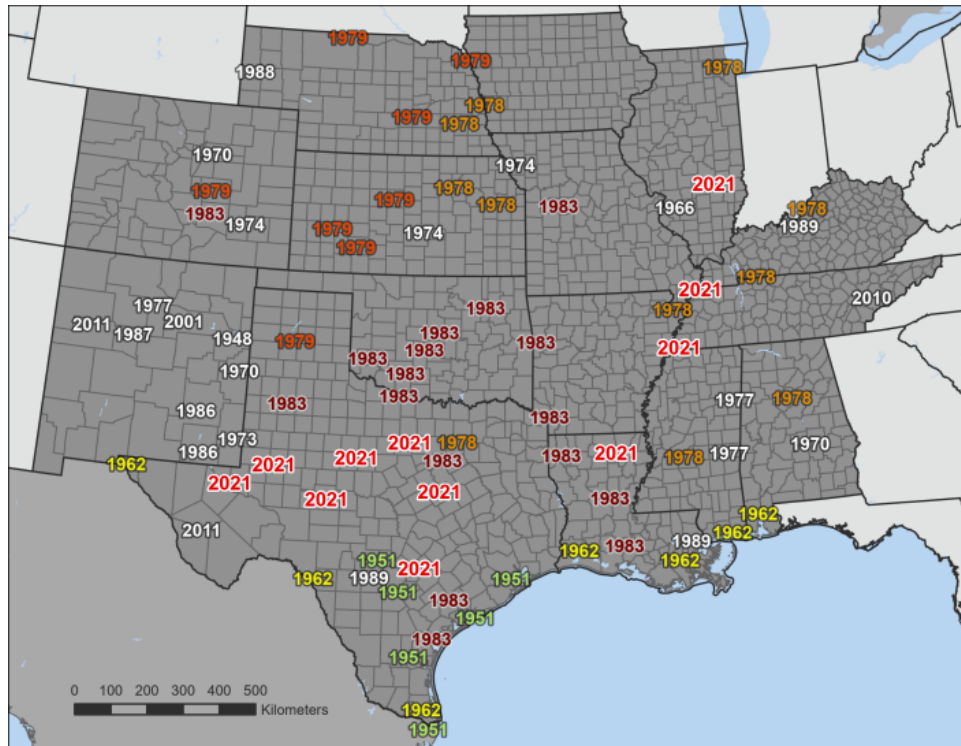


Figure 12: Year with the record hourly streak event of surface temperatures at or below 0°C. Any event in which 5 or more stations set a record streak are color-coded to show the spatial extent. Any year that 4 or fewer stations set a record are labeled in white. Stations with records for 1948-2021 are shown.

443 time series ranks 2021 as the most extreme. The February 2021 event stands
444 out as most unusual for its persistently low daily maximum temperatures, as
445 is also reflected in the consecutive hours below freezing discussed above. The
446 7-day average maximum temperature ranks as first or second coldest across a
447 vast expanse of the central United States from Iowa to Texas and from New
448 Mexico to Mississippi.

449 Figure 14 shows which year holds the record for each of these tempera-
450 ture extremes in each climate division, except for those without sufficiently
451 complete data in 1899. The extreme cold wave in February 1899 holds the
452 greatest number of records across the region, with minimum temperature
453 records being especially notable. At seven climate divisions in the region
454 (North Central and Northeast Arkansas, Western and Central Kentucky,
455 Southwest and Northeast Louisiana, and the West Central Plains of Mis-
456 souri), February 1899 holds all twelve extreme cold records considered here.
457 The other two cold waves holding more records than 2021 are December 1983
458 and December 1989. The former was most notable for persistently low maxi-
459 mum temperatures, while the latter was most extreme in its two-day average
460 temperatures. By sheer number of climate division records, top fives, or top
461 tens, the February 2021 cold event is the fourth most extreme on record. It is
462 also the only cold event besides February 1899 that holds all twelve all-time
463 records in a particular climate division: in central Oklahoma, the February
464 2021 cold was more extreme in all twelve metrics than any other event on
465 record.

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

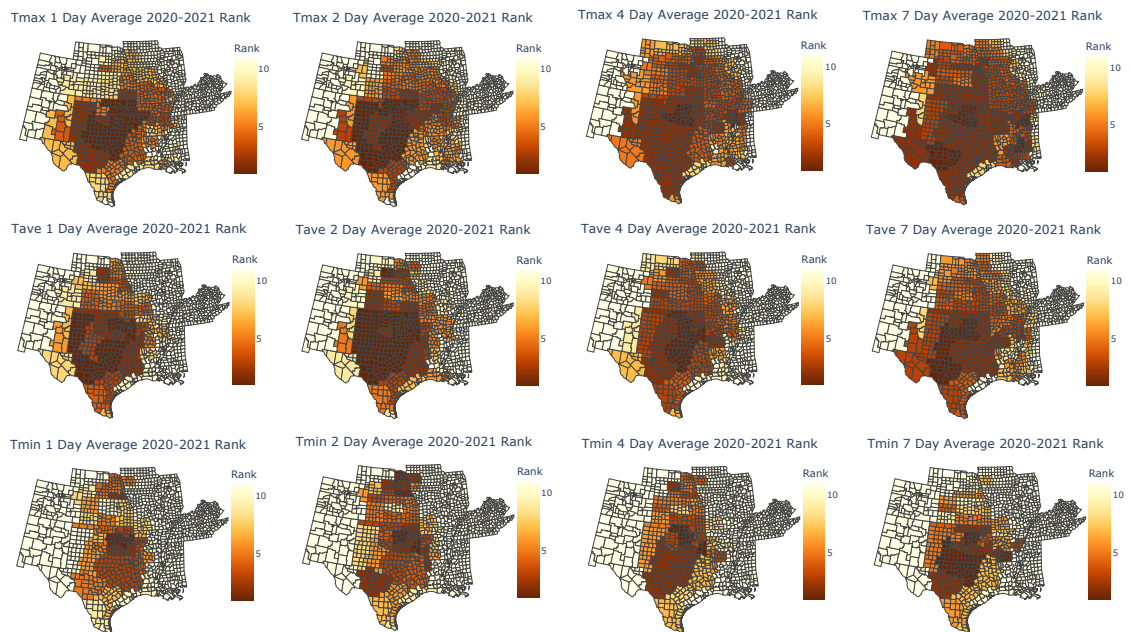


Figure 13: Historic rank of February 2021 cold extreme daily maximum (Tmax), average (Tave) and minimum (Tmin) temperatures, averaged over 1, 2, 4, or 7 days, among climate division composite temperature records. Most such records go back to the 1890s.

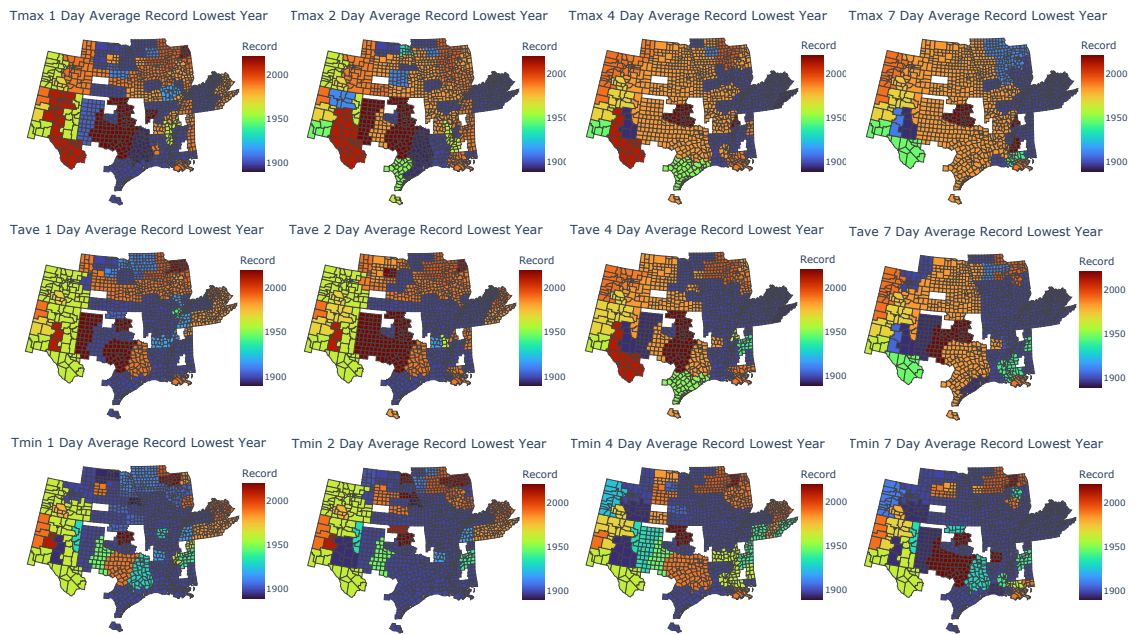


Figure 14: The year with the most extreme cold maximum, average, and minimum temperatures, averaged over 1, 2, 4, or 7 days, in the climate division composite time series of seasonal extremes. Time series that do not extend back to the February 1899 cold event are excluded.

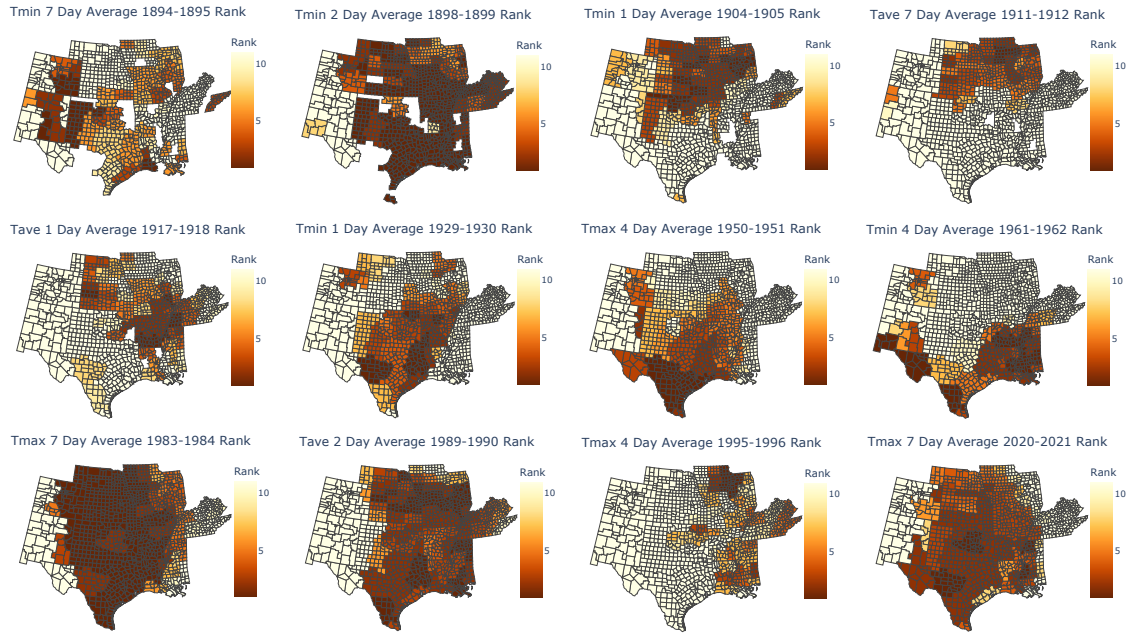


Figure 15: The top ten rankings within climate divisions of the most extreme cold events, 1890 to present. For each cold event, the most extreme combination of duration and metric (minimum, average, or maximum temperature) is shown.

468 event is most extreme (Fig 15). The four events in 1899, 1983, 1989, and 2011
 469 affected the largest geographical areas, with February 1895 and December
 470 1929 nearly as widespread. February 1951 and January 1962 were extreme
 471 mainly in southern states, February 1905 and January 1912 were particularly
 472 unusual in northern states, and January 1918 and February 1996 primarily
 473 impacted states bordering the Mississippi River.

474 A recent study by Doss-Gollin et al. (2021) used reanalyses to compare
475 the intensity of cold snaps since 1950 in Texas on the basis of the expected
476 impact on electricity demand for heating within the Texas Interconnection
477 power grid. They found that February 2021 ranked second behind December
478 1989, with December 1983 and February 1951 nearly as severe.

479 **5. Impacts**

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

487 *5.1. Energy*

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

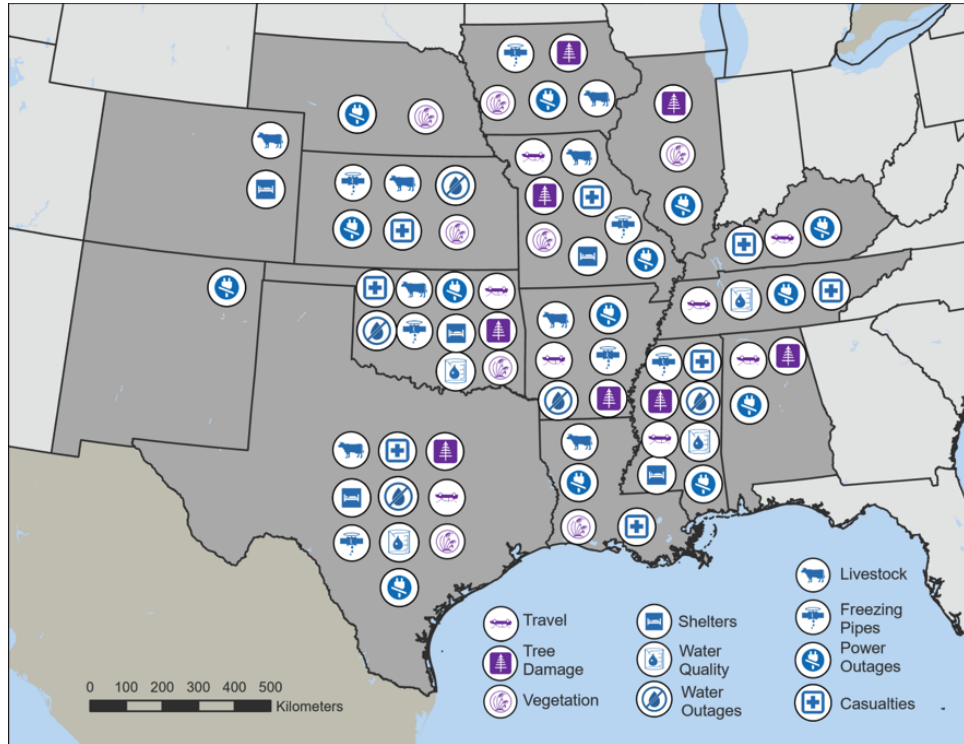


Figure 16: Major impacts from the February winter weather and cold outbreak in the South-Central US. Impacts were grouped into ten categories and color-coded based on whether the impacts were due mainly to ice/snow (travel, tree damage, vegetation) or cold temperatures (shelters, water quality, water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

497 thick ice accumulations on trees and power lines, particularly across south-
498 ern states. In Texas, generation capacity was lost at natural gas, coal, and
499 nuclear power plants due to the direct impacts of cold on exposed equipment
500 and the loss of natural gas supply due to both direct impacts and loss of
501 electricity at natural gas wellheads, while wind turbines also lost capacity
502 due to buildup of ice on blades (Busby et al., 2021). At one point on the
503 16th, nearly 5 million electric customers across Texas, Louisiana, and Okla-
504 homa were without power due to a combination of controlled power outages
505 and damaged infrastructure, with 4.5 million of those outages occurring in
506 Texas alone (U.S. Department of Energy, 2021). Power outages caused by
507 ice accumulations on trees and power lines were also highly impactful across
508 parts of Kentucky (National Weather Service, 2021b), as well as Arkansas,
509 Mississippi, and Tennessee (Johnson, 2021).

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

516 *5.2. Human health*

517 In many areas, human health was put at risk due to water pressure loss
518 from burst pipes that froze from the extreme temperatures. For instance,
519 Memphis Light, Gas and Water (Tennessee) issued a system-wide boil wa-
520 ter notice, as critical infrastructure such as hospitals and the international
521 airport reported low pressures (Tennessee Emergency Management Agency,

522 2021). Water outages and water quality were also a concern across Arkansas,
523 Louisiana, Oklahoma, and Texas (Bertrand and Speizer, 2021). Additionally,
524 this event caused several water main breaks on Jackson, MS’s well and sur-
525 face water systems, prompting boil water advisories that remained in effect
526 for over a month after the storm (The City of Jackson, Mississippi, 2021).

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

533 The long duration and severity of this event resulted in many fatalities.
534 While NOAA NCEI (2021) lists the death toll estimate at 172, there are
535 conflicting reports on the actual number of deaths that could be directly or
536 indirectly attributed to this event. According to the Texas Department of
537 State Health Services, as of July 13, 2021, the number of Texans who died
538 as a result of the storm was estimated at 210. Most of the fatalities were
539 attributed to hypothermia, while some were caused by vehicle accidents, car-
540 bon monoxide poisoning, the exacerbation of chronic illnesses, falls, and fire
541 (Texas Department of Emergency Management, 2018). Aldhous et al. (2021)
542 ran a simplified model on mortality data from the Centers for Disease Con-
543 trol to assess the number of excess deaths in Texas during and immediately
544 following the storm. They estimate that the number of people who died
545 as a result of the storm (directly and indirectly) may actually be closer to
546 700 (with an uncertainty range of 426–798 deaths). Overall, six weather-

547 related fatalities were reported in Tennessee by the Tennessee Department of
548 Health (Tennessee Emergency Management Agency, 2021). Weather-related
549 fatalities were also reported in Oklahoma, Kansas, Missouri, Kentucky, Mis-
550 sissippi, and Louisiana.

551 *5.3. Agriculture and wildlife*

552 The agriculture sector (including both farms and livestock) was also sig-
553 nificantly impacted by the storm. Many crops sustained damage from the
554 extreme temperatures and ice accumulations. For instance, citrus and veg-
555 etable crop producers in Texas endured incredible losses – at least \$230 mil-
556 lion and \$150 million, respectively (Schattenberg, 2021). The fruits and
557 vegetables that made up the majority of losses included oranges, grapefruits,
558 lemons, limes, onions, leafy greens, and watermelons. AgriLife Extension and
559 the Texas Nursery and Landscape Association were also exploring losses by
560 the green industry, including landscaping trees, shrubs, annuals, and peren-
561 nials. The sugarcane crop was also impacted in Texas and Louisiana (U.S.
562 Department of Agriculture, 2021). Farther north, slowed winter wheat devel-
563 opment was reported, with concerns of damage from leaf burn or winterkill
564 in Kansas (Lin et al., 2021) and Nebraska (Dutcher, 2021). It is important
565 to note that loss data are preliminary, and damage estimates are still be-
566 ing assessed. Additionally, it would be difficult to ultimately attribute crop
567 damage to extreme cold in areas that have also experienced drought impacts
568 during the same time period.

569 Livestock losses were also widespread. This event caused a challenging
570 start to the calving season. High death loss of new calves was reported in
571 Arkansas, Colorado, Louisiana, and Texas but was minimal in Minnesota,

572 Nebraska, and Ohio where extreme cold is more common (U.S. Department
573 of Agriculture, 2021). Fortunately, the extreme temperatures were forecast
574 well in advance, which gave livestock producers time to act; otherwise, cat-
575 tle/calf losses would have been much higher. Reports also indicate significant
576 losses in the poultry industry (Berkhout, 2021). Besides livestock deaths, the
577 event negatively impacted the livestock industry infrastructure (Schatten-
578 berg, 2021) and increased feed requirements and feed costs (Dutcher, 2021).
579 In addition to livestock, there were significant losses of wildlife throughout
580 the region, including birds and fish (Bertrand and Speizer, 2021).

581 **6. Discussion and Conclusions**

582 The synoptic setup for this event began well in advance with an SSW
583 event. A subsequent AO anomaly in early February was a record-tying -5.3
584 magnitude, suggesting an extremely strong and cold event would occur. The
585 two winter storms, ranked as category 3 events by the Regional Snowfall
586 Index, were rare (especially in recent records), but not unprecedented. The
587 number of hours of freezing precipitation recorded across the study area was
588 not extreme or unusual based on previous climatological studies. In addi-
589 tion, the intensity and total amount of freezing precipitation did not exceed
590 established thresholds for extreme ice loads based on climatology. Never-
591 theless, the timing and duration of freezing precipitation likely exacerbated
592 the impacts associated with the bitterly cold temperatures and snow that
593 dominated this event.

594 The extreme and prolonged cold set many specific records across the
595 region, including the number of hours below freezing. Considering extreme

596 cold events in the central and south-central United States since the 1890s,
597 the event appears to have been exceeded in overall severity only by events in
598 February 1899, December 1983, and December 1989.

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

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

621 in weather patterns. This will limit both hazards frequency and intensity.”

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

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

642 A simple stationary analysis implies a return period of 6 years for the
643 2011 event based on data through 2011, indicating that similar events should
644 have been anticipated in the near future. An event equivalent to 2021 would
645 have been assessed at a return period of 61 years. However, the climate

646 is changing, and a nonstationary analysis with time or global mean surface
647 temperature as a covariate would have implied a 10–12 year return period for
648 2011 and a 300-700 year return period for 2021. Climate expertise would be
649 necessary to make sense of the large differences between these two types of
650 analyses, future projections based on downscaling of global climate models
651 (Deser et al., 2014), and the relevance of evidence that more recent changes at
652 high latitudes may be altering the odds (Cohen et al., 2021; Yin and Zhao,
653 2021), and to work with policymakers to determine an appropriate target
654 for resiliency. Climate services are also necessary to identify an appropriate
655 measure of the weather-related threshold corresponding to the breakdown in
656 power distribution in 2021, which happened well before the lowest average
657 daily temperature was achieved. An assessment of risk based only on the
658 most extreme aspects of the 2021 event would underestimate grid vulnera-
659 bility.

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

668 The successful integration of climate information into decision-making is
669 documented. The Fourth National Climate Assessment lists many examples
670 of federal, state, tribal, and local agencies implementing climate adaptation

671 plans (USGCRP, 2018). These implementations can lead to tangible improve-
672 ments at the community level. For example, Vogel et al. (2016) describe the
673 actions that communities have taken that resulted in observable reductions
674 in vulnerabilities to climate extremes. These examples highlight the benefits
675 of users engaging with climate service providers and incorporating climate
676 information into their plans.

677 Perhaps because climate services have been primarily focused on the
678 capability-driven approach for a longer span of time (Hewitt and Stone,
679 2021), there exists a division between the data provider and the data user.
680 This approach is more “top down,” where the provider assumes the needs of
681 a passive receiver of information, then develops and disseminates informa-
682 tion based on that initial idea. A demand driven approach requires increased
683 engagement between provider and user throughout every stage of the climate
684 service to be developed and implemented - a more “bottom up” approach.

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

696 it will not be used.

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

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