Trends and Variability in Severe Snowstorms East of the Rocky Mountains*

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(Manuscript received 29 April 2013, in final form 16 April 2014)

ABSTRACT

The 100 most severe snowstorms within each of six climate regions east of the Rocky Mountains were analyzed to understand how the frequency of severe snowstorms is associated with seasonal averages of other variables that may be more readily predicted and projected. In particular, temperature, precipitation, and El Niño/La Niña anomalies from 1901 to 2013 were studied. In the southern United States, anomalously cold seasonal temperatures were found to be more closely linked to severe snowstorm development than in the northern United States. The conditional probability of occurrence of one or more severe snowstorms in seasons that are colder than average is 80% or greater in regions of the southern United States, which was found to be statistically significant, while it is as low as 35% when seasonal temperatures are warmer than average. This compares with unconditional probabilities of 55%–60%. For seasons that are wetter (drier) than average, severe snowstorm frequency is significantly greater (less) in the Northern Plains region. An analysis of the seasonal timing of severe snowstorm occurrence found they are not occurring as late in the season in recent decades in the warmest climate regions when compared to the previous 75 years. Since 1977, the median date of occurrence in the last half of the cold season is six or more days earlier in the Southeast, South, and Ohio Valley regions than earlier in the twentieth century. ENSO conditions also were found to have a strong influence on the occurrence of the top 100 snowstorms in the Northeast and Southeast regions.

1. Introduction

Temperatures in the United States and globally have increased more than 0.7°C since 1901, and the rate of warming since 1971 is 2–3 times higher (Blunden and Arndt 2012). The greatest rate of warming has occurred in the cold season, and there has been a reduction in the frequency of cold extremes (Trenberth et al. 2007). In association with warming temperatures, the intensity of extratropical storms has increased (Vose et al. 2014), and heavy precipitation events have increased in frequency and intensity in part because of the increasing capacity for water vapor in a warmer atmosphere (Kunkel et al. 2013a; Groisman et al. 2012).

These changes also have implications for the frequency and intensity of snowstorms in the United States. While warming temperatures and a reduction in cold extremes may lead to fewer snowstorms, particularly in regions where temperatures are marginally cold enough to support snowfall (Kunkel et al. 2009b), greater amounts of moisture and greater storm intensity could contribute to snowstorms of increased severity during periods of cold weather. In recent decades, major snowstorms have occurred even while temperatures have continued to rise, and in many cases, the impacts have been severe and widespread.

In the past two decades, three snowstorms each caused more than $1 billion in damages (NCDC 2014a).

* Supplemental information related to this paper is available at the Journals Online website: http://dx.doi.org/10.1175/JHM-D-13-068.s1.

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DOI: 10.1175/JHM-D-13-068.1

These included the "Storm of the Century," which brought heavy snow to more than 20 states from the deep South to New England in March 1993; a January 1996 storm that struck the mid-Atlantic and Northeast; and the Groundhog Day blizzard of 2011 that left from 25 to more than 50 cm of snow from the southern Great Plains to the upper Midwest. Other more localized storms with exceptionally heavy snowfall include the December 2004 storm that brought 25 cm of snow to southern Texas and the back-to-back snowstorms that struck the mid-Atlantic in 2010, shutting down the nation's capital with more than 100 cm of snow.

Mounting economic losses associated with severe snowstorms can be attributed in part to growth in population and infrastructure (Gamble et al. 2008), but there also is evidence that the frequency of major snowstorms has increased in recent decades. Kocin and Uccellini (2004) found an increase in the frequency of major snowstorms in the northeastern United States, and an analysis of the five biggest snowstorms in six climate regions of the United States from 1900 to 2010 found an approximate twofold increase in these storms when comparing the most recent 50 years to the previous 60 (Kunkel et al. 2013a).

Severe snowstorms as discussed in this paper are those with high snowfall amounts that affect large parts of one or more regions. Understanding how the frequency of severe snowstorms is affected by a warming climate is especially important given the economic losses and societal disruptions these storms can cause. The observational record of snowstorms collected since the start of the twentieth century provides historical perspective on the variation and change that has occurred as the climate has warmed. When combined with an analysis of seasonal temperature and precipitation patterns, the observational record can also be used to understand how the frequency of these storms are affected by year-to-year changes in the character of seasons.

In the continental United States there is great variability in mean seasonal temperature and precipitation from year to year. The year-to-year variability provides an opportunity for assessing how anomalous seasonal conditions affect the frequency of severe snowstorms and affords an opportunity to project the likelihood of future storms in a warmer world. For example, is the frequency of these storms diminished in seasons that are warmer than average or drier than average? Such an analysis can provide indications of how frequently severe snowstorms will occur in a future where winters that are today considered anomalously warm become the norm. Likewise, the interannual variability in precipitation provides a means for assessing the frequency of major snowstorms in seasons that are anomalously wetter or drier than average.

We recognize there are other factors not considered in this study that may influence the frequency and intensity of severe snowstorms. For instance, analyses have shown that midlatitude jet streams have been moving poleward in most regions of the Northern Hemisphere over at least the last three decades as global temperature has warmed (e.g., Hu and Fu 2007; Archer and Caldeira 2008; Fu and Lin 2011), which can affect the frequency and intensity of storms. There is observational and modeled evidence of a northward shift in storm tracks in the Northern Hemisphere (e.g., Bengtsson et al. 2006; Yin 2005), and Francis and Vavrus (2012) found a link between warming arctic temperatures and changes in large-scale circulation patterns that may contribute to extreme snowfall in the United States. Others (e.g., Deser et al. 2004; Magnusdottir et al. 2004) have used models to show arctic sea ice reductions and increases in surface temperature produce atmospheric circulation patterns that are favorable for winter storm development in the eastern United States.

Although such changes associated with a warming climate may influence the frequency and severity of snowstorms, understanding how seasonal temperature and precipitation on regional scales are related to severe snowstorms can provide important insights into how frequently and under what conditions severe snowstorms occur. We analyzed the top 100 (TOP100) snowstorms that occurred in each of six climate regions of the central and eastern United States from 1901 to 2013. These are synoptic-scale storms associated with midlatitude cyclones. Their selection is based on areal coverage and snowfall amount as computed using the Regional Snowfall Index (RSI; Squires et al. 2014) based on areal coverage (RSI_{area}) as described in section 2b. The occurrence of these storms and mean seasonal conditions during the 6-month cold season (November–April) is analyzed to determine how frequently severe snowstorms (i.e., TOP100) occur in otherwise unusually warm/cold and wet/dry seasons and if patterns of occurrence differ between regions. On average, snowstorms occur with greatest frequency during this 6-month period. The seasonal timing of these storms also is evaluated to determine the time of the cold season when severe snowstorms are most likely to occur and to note any trends. Because the presence of El Niño and La Niña can have a strong influence on seasonal conditions in large parts of the United States, the relationship between ENSO conditions and TOP100 snowstorms in each region is also investigated.

In section 2, an overview of snowfall data and storm identification procedures is provided. The analysis of the

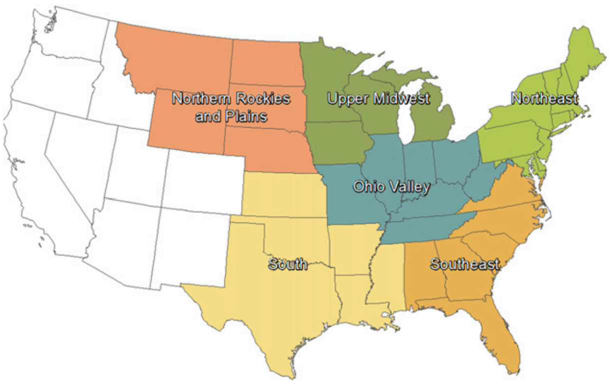

FIG. 1. The six easternmost climate regions included in this study.

TOP100 storms and seasonal conditions in which they occur are included in section 3. Discussion and conclusions are provided in section 4.

2. Data and storm selection

a. Snowfall data

The TOP100 snowstorms in each of six climate regions (Fig. 1) were identified using a multistep process. First a $1^{\circ} \times 1^{\circ}$ gridded dataset of daily average snowfall (Dyer and Mote 2006) was used to identify periods when heavy snowfall occurred across large parts of the United States. To create this gridded dataset, snowfall observations from the National Climatic Data Center's (NCDC) U.S. Summary of the Day datasets (DSI-3200; DSI-3206) were used. These datasets contain data primarily from the Cooperative Observer Program (COOP), which has operated since 1895 and provides the single largest source of daily climate observations. This network now has approximately 7500 stations reporting daily snowfall, and there are more than 3000 U.S. stations with snowfall observations in the early 1900s. Observations were quality controlled using criteria set forth by Robinson (1989).

Running 4-day totals were calculated from the daily snow values, and the largest totals were used to provide a first guess of high-impact snow events in each region. Daily weather maps [National Oceanic and Atmospheric Administration (NOAA) Central Library U.S. Daily Weather Maps project, www.lib.noaa.gov/collections/imgdocmaps/daily_weather_maps.html] and daily station snowfall data were then analyzed to produce a set of more than 500 snowstorms. Some storms affected a single region while larger storms covered three or more regions. In all, a total of 582 storms impacting at least one region was identified. A list of the TOP100 storms in each region is provided (Tables S1–S3 in the supplemental material).

Once the beginning and ending dates of storms were identified, daily snowfall observations were extracted from NCDC's Global Historical Climatological Network–Daily dataset (GHCN-D; Menne et al. 2012). The GHCN-D consists of 26 sources of Summary of the Day data, with more than 10 of these from the United States alone. However, most U.S. data originate from the COOP network.

All GHCN-D observations are routinely subjected to a series of automated quality control (QC) processes that are applied consistently throughout the period of record (Durre et al. 2010). Durre et al. (2008) describe the strategies for constructing the QC algorithms used in GHCN-D. Only snowfall values not flagged by the automated QC process were included in this analysis. Following quality control, the daily totals were summed across all days of each storm to obtain event totals. An additional layer of quality control was then applied to the event totals to further ensure the exclusion of erroneous storm totals. This was done within a geographical information system using a statistical test based on the local Moran's I index (Anselin 1995). This test is effective at identifying snowfall totals that are significantly different from neighbors. Values that were flagged as suspect are subsequently evaluated by a meteorological technician who determines if the differences are due to real features such as synoptic or topographic influences. Common errors identified with this technique are low storm snowfall totals due to missing daily observations and reports of zero within areas that clearly received measureable snowfall.

b. Calculating the magnitude of each snowstorm

Following quality control, the 100 largest storms in each region were identified using an algorithm that takes into account the amount of snowfall and the size of the area affected (Kunkel et al. 2013a). Our method is similar to the RSI (Squires et al. 2014), but it includes only snowfall amount (that exceeds thresholds specific to each region) and the area affected in determining the severity of a storm, while the RSI also includes the population affected. It does not distinguish between a storm that is centered on a major urban corridor and one that impacts lightly populated areas because the focus of this study is on assessing climatological trends associated with severe snowstorms rather than their societal impacts.

The equation used to calculate this index, $\mathrm{RSI}_{\mathrm{area}}$, is

$$\mathrm{RSI}_{\mathrm{area}} = \sum_{T=T_1}^{T_4} \left[\left(\frac{A_T}{\bar{A}_T} \right) \right], \qquad (1)$$

where T is the region-specific snowfall thresholds, A_T is the area affected by snowfall greater than threshold T, and $\overline{A}_T$ is the mean area affected by snowfall greater than threshold T.

The six climate regions referred to above and shown in Fig. 1 are the easternmost of the nine contiguous U.S. climate regions (Karl and Koss 1984). The region-specific snowfall thresholds T serve to calibrate RSI to each region. Snowfall observations for every location in a storm are placed into one of four threshold categories; light, moderate, heavy, and extreme. The thresholds vary based on the climatology of the region. For example, the snowfall thresholds for the South region are 5.1, 12.7, 25.4, and 38.1 cm, while thresholds for the Northeast region, which normally receives more snowfall, are 10.2, 25.4, 50.8, and 76.2 cm (Table 1).

These thresholds were set based on an objective method that best reproduced thresholds that were first established for the Northeast Snowfall Impact Scale using expert knowledge of Northeast snowstorms (Kocin and Uccellini 2004). The Northeast region thresholds were found to most closely match 10- and 25-yr return periods for 2-day accumulated snowfall totals averaged across the region. The first threshold is approximately one-quarter of the average 10-yr return period for 2-day snowfall amounts in the Northeast. The second threshold is approximately one-half of the average 2-day, 25-yr return period for the Northeast. The third and fourth thresholds are multiples of the second threshold. This relationship was applied to average return period statistics in each of the other regions to create snowfall thresholds specific to each region.

Each RSI_{area} value is calculated from a linear combination of four terms that represents the sum of normalized snowfall area for each of the four threshold categories. The area values are normalized using average snowfall amounts in each category for the largest 50 storms in each region. Normalizing the area for each threshold category by the mean value transforms these terms into ''percent of normal'' expressions with similar magnitudes. Using the mean area to normalize each term for each threshold category also helps to ensure that the final statistical distributions for all the regions are similar, despite large differences in regional snowfall climatologies and region area. This is a desirable attribute because it allows comparisons of snowstorms across regions. For example, a snowstorm in the Southeast may receive less snow than the Northeast for the same storm, but the Southeast totals may be more extreme within the context of the snowfall amounts that typically occur in the region.

TABLE 1. Regional thresholds (cm) used in Eq. (1).

Region	T1	T2	T3	T4
Northeast	10.2	25.4	50.8	76.2
Ohio Valley	7.6	15.2	30.5	45.7
Upper Midwest	7.6	17.8	35.6	53.3
Northern Plains	7.6	17.8	35.6	53.3
Southeast	5.1	12.7	25.4	38.1
South	5.1	12.7	25.4	38.1

3. Analysis

The number of TOP100 storms occurring in each decade within each region is shown in Fig. 2. In the four northernmost regions where cold season temperatures are the lowest [Table 2a; Northeast, Ohio Valley, upper Midwest, and northern Rockies and Great Plains (hereafter called Northern Plains)], the frequency of severe storms (i.e., TOP100 storms) was greater during the last five decades of the period than throughout the first six. Most notable is the upper Midwest, where half of the storms occurred between 1981 and 2013. Only 33 storms occurred during the first six decades of the twentieth century in this region, a statistically significant difference at the 1% level (99% confidence interval). In the Northern Plains region, 35 storms occurred between 1901 and 1960, only two more than occurred since 1990.

In contrast, the pattern of storms is more evenly distributed between the early and latter part of the record in the southern regions. Although 19 storms have occurred since 2001 in the South, more storms struck this region during the first half of the twentieth century (43) than the second half (38) of the century. The Southeast region is dominated by a large number of storms in the 1960s and 1970s; 30 storms occurred in those two decades alone. The three decades that followed were only slightly more active (27 storms) than the preceding three decades, which had 23 storms.

Although the number of COOP stations was smallest during the first half of the twentieth century, the increase in severe snowstorms in four of the six regions during the latter half of the century is not believed to be due to an increase in observing stations. The smaller number of stations is accounted for through spatial interpolation and area averaging. This is further supported by the absence of a pattern of increasing snowstorm occurrence in the South and Southeast even though the number of observing stations also increased in these regions.

The higher frequency of severe snowstorms in the four northern regions has occurred in an environment of increasing surface air temperatures. From 1901 to 2013, cold season mean temperatures increased at a rate of 0.11°C decade^{-1} in the Northeast, 0.06°C decade^{-1} in the Ohio Valley, 0.11°C decade^{-1} in the upper Midwest, and 0.12°C decade^{-1} in the Northern Plains. The rate of increase since 1961 is from 2 to 5 times

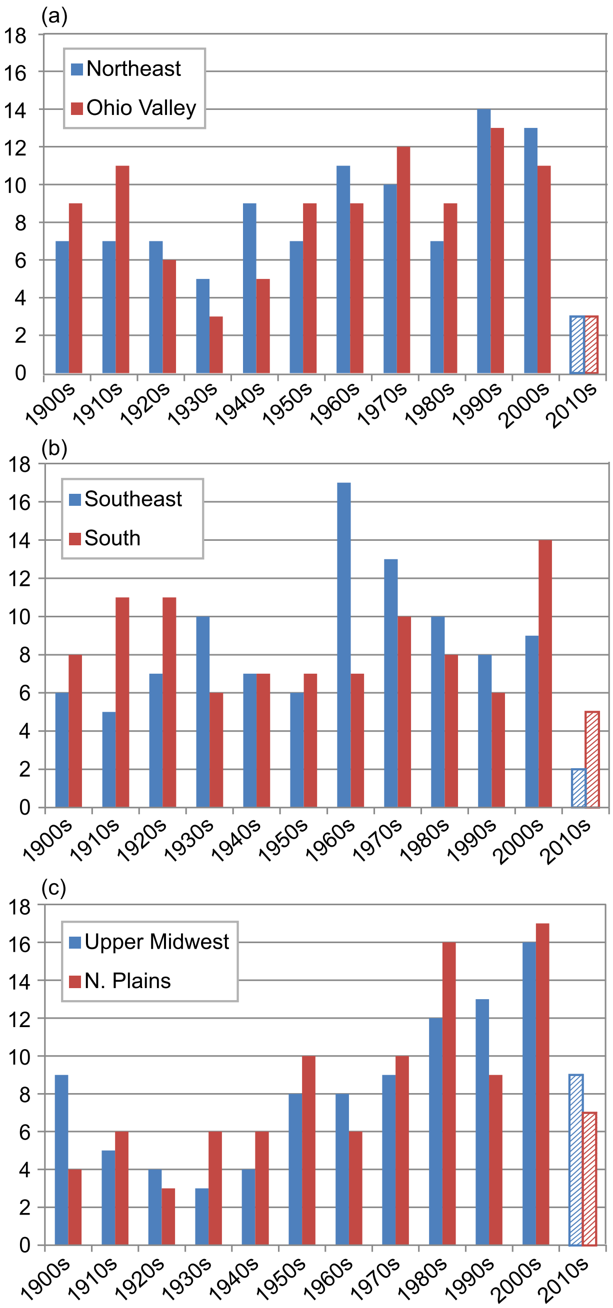

FIG. 2. Decadal frequency of TOP100 snowstorms in the (a) Ohio Valley and Northeast, (b) Southeast and South, and (c) upper Midwest and Northern Plains.

greater. Temperatures during the same period also increased in the Southeast and South regions (for Southeast, 0.01°C decade^{-1} and 0.19°C decade^{-1} from 1901 to 2013 and 1961 to 2013, respectively; for South, 0.02°C decade^{-1} and 0.20°C decade^{-1}; NCDC 2014b).

In the northern regions, the increase in seasonal temperatures does not appear to have negatively affected the frequency of severe snowstorms, and the frequency of storms in the Southeast and South in recent decades is consistent with multidecadal variability seen earlier in the twentieth century. It may seem counterintuitive that the frequency of severe snowstorms could remain the same or increase in a warming world, but there are several factors that can make this possible. Although mean temperatures have risen in the past century, winter temperatures have remained cold enough to support snowfall, particularly in northern regions (Table 2). In addition, severe snowstorms can occur during otherwise anomalously warm seasons as the short time scales with which snowstorms typically occur mean that a brief period of anomalously cold temperatures and the right combination of moisture and dynamics can produce a snowstorm during an otherwise warmer-than-average winter (Kunkel et al. 2013a). Furthermore, changes in circulation patterns and the poleward shift in storm tracks in recent decades (e.g., Yin 2005; Archer and Caldeira 2008; Francis and Vavrus 2012) could be a source of increasing frequency and intensity of snowstorms in some regions.

Table 3 provides a breakdown of the number of years in which TOP100 snowstorms occurred from 1901 through 2013, as well as the number of seasons (November–April cold season) that were cooler than the twentieth-century mean. In the Ohio Valley and Northeast regions, approximately half of the cold seasons in which at least one TOP100 snowstorm occurred were colder than average (Table 3a). The other regions had a slightly higher proportion of colder-than-average seasons. For seasons in which two or more snowstorms occurred, more than three-fourths were colder than average in the South and Southeast regions (Table 3b).

The mean seasonal temperature anomalies for each region are shown in Table 2 along with the seasonal anomalies averaged over years in which one or more (Table 2b) or two or more (Table 2c) TOP100 storms occurred. In all regions the mean seasonal temperature was colder than average for those seasons in which one or more of these storms occurred. The mean seasonal anomalies are even colder when averaged across seasons when two or more storms occurred (Table 2c), most notably in the Ohio Valley, Southeast, and South. The greater correspondence between colder-than-average conditions and the incidence of TOP100 snowstorms in these regions appears to reflect a greater importance of atmospheric patterns that persistently produce below-average temperatures as a prerequisite for snow, especially in milder climates. Persistent steering patterns that create colder-than-average seasonal temperatures increase the likelihood that temperatures will be cold enough in combination with sufficient precipitation to produce heavy snowfall.

TABLE 2. (a) Mean temperature during the November–April cold season and the std dev of the seasonal temperatures and precipitation during the twentieth century (1901–2000) for each of six climate regions. Mean temperature anomalies (departure from twentieth-century mean; °C and standardized values) and mean precipitation anomalies (mm and standardized values) for (b) years in which at least one TOP100 snowstorm occurred and (c) for years in which more than one TOP100 snowstorm occurred.

(a)	Mean temp (°C)	Mean std dev (°C)	Mean precipitation (mm)	Mean std dev (mm)
Northeast	−0.3	1.1	487.4	68
Ohio Valley	4.1	1.0	503.9	81
Upper Midwest	−3.2	1.3	241.0	41
Northern Plains	−2.7	1.3	129.8	18
Southeast	11.2	0.9	576.3	109
South	10.1	0.9	394.7	82
(b)	Mean temp anomaly (°C)	Mean standardized departure	Mean precipitation anomaly (mm)	Mean standardized departure
Northeast	−0.14	−0.1	10.7	0.2
Ohio Valley	−0.18	−0.2	1.3	0.0
Upper Midwest	−0.10	−0.1	14.0	0.3
Northern Plains	−0.13	−0.1	4.9	0.3
Southeast	−0.27	−0.3	6.6	0.1
South	−0.21	−0.2	4.2	0.0
(c)	Mean temp anomaly (°C)	Mean standardized departure	Mean precipitation anomaly (mm)	Mean standardized departure
Northeast	−0.23	−0.2	8.5	0.1
Ohio Valley	−0.39	−0.4	−3.1	0.0
Upper Midwest	−0.08	−0.1	20.1	0.5
Northern Plains	−0.27	−0.2	10.8	0.6
Southeast	−0.57	−0.6	74.0	0.7
South	−0.54	−0.6	16.9	0.2

When looking at the relationship between severe snowstorms and seasonal precipitation anomalies, more than 55% of the seasons in which at least one TOP100 snowstorm occurred were wetter than average in the upper Midwest, Northern Plains, and South regions (Table 3a). A greater percentage of the seasons were wetter than average when two or more TOP100 storms occurred in all regions except the Ohio Valley. In all regions, there were far fewer seasons in which conditions were both anomalously cold and wetter than average.

a. Conditional probabilities

In the two southern U.S. regions, colder-than-average seasonal conditions appear more important to the occurrence of a TOP100 storm than in the four northern regions. To better quantify the likelihood of occurrence during anomalously cold or warm seasons, and anomalously wet or dry seasons, conditional probabilities were calculated using a frequency analysis approach. For the 113 cold seasons between 1901 and 2013, those with temperature departures that were either more or less than one standard deviation from the mean were determined. The same was done for those either more or less than two standard deviations from the mean. Those seasons in which one or more TOP100 storms occurred were also determined. Using the following definition, calculations were made of the conditional probability that a TOP100 snowstorm will occur given seasonal temperatures that are anomalously cold or warm:

$$P(S_{100} \mid T_a) = P(S_{100} \text{ and } T_a)/P(T_a), \qquad (2)$$

where, S_{100} is a TOP100 snowstorm and T_a is a November–April seasonal temperature that was more than one standard deviation above (below) the twentieth-century mean.

The magnitude of seasonal variability is similar across the six climate regions. The smallest mean standard deviation is 0.9°C in the Southeast and South regions and the largest mean standard deviation is 1.3°C in the upper Midwest and Northern Plains regions (Table 2a). Within the six regions there were from 58 to 69 years in which one or more TOP100 storm occurred. As shown in Fig. 3a, the probability of such an occurrence is approximately 1 in 2. In those years in which the seasonal temperature for a region was more than one standard deviation below average, the likelihood of a TOP100 storm increased in every region except the Northeast and by as much as 26% in the South and 29% in the

TABLE 3. (a) Number of years in which one or more TOP100 snowstorms occurred and the fraction of those years that were cooler than the twentieth-century average, wetter than average, and cooler and wetter than average. (b) As in (a), but for those years in which more than one TOP100 snowstorm occurred.

(a)	No. of years with TOP100 storms	No. of storm years with below-avg seasonal temp	No. of storm years with above-avg seasonal precipitation	No. of storm years with below-avg seasonal temp and above-avg seasonal precipitation
Northeast	64	33 (52%)	33 (52%)	15 (23%)
Ohio Valley	59	30 (51%)	28 (48%)	14 (24%)
Upper Midwest	58	34 (59%)	37 (64%)	20 (35%)
Northern Plains	61	34 (56%)	35 (57%)	22 (36%)
Southeast	69	40 (58%)	34 (49%)	20 (29%)
South	62	41 (66%)	35 (56%)	23 (37%)
(b)	No. of multiple storm years with two or more TOP100 storms in same year	No. of multiple storm years with below-avg seasonal temp	No. of multiple storm years with above-avg seasonal precipitation	No. of multiple storm years with below-avg seasonal temp and above-avg seasonal precipitation
Northeast	25	13 (52%)	14 (56%)	7 (28%)
Ohio Valley	24	15 (62%)	10 (42%)	7 (29%)
Upper Midwest	27	15 (56%)	19 (70%)	10 (37%)
Northern Plains	24	15 (62%)	15 (62%)	11 (46%)
Southeast	19	15 (79%)	12 (63%)	10 (53%)
South	27	20 (74%)	16 (59%)	12 (44%)

Southeast. Conversely, the conditional probability of a TOP100 storm decreased in seasons that were anomalously warm, by as little as 9% in the Northern Plains and as much as 20% in the South and Southeast and 25% in the Northeast.

In both regions of the southern United States and Ohio Valley, the difference in conditional probability of a severe storm occurring in an anomalously cold season is much greater than during an anomalously warm season, that is, 35% greater for the Ohio Valley and 47%–49% greater for the Southeast and South. The difference in conditional probability between a colder-than-average season and a warmer-than-average season is also greater in the Northeast (25%), upper Midwest (22%), and Northern Plains (15%).

To determine if the conditional probability of severe snowstorm occurrence during anomalously cold and warm seasons based on the observational record is statistically distinguishable from what would occur by chance, a Monte Carlo analysis using a bootstrap technique (Wilks 2006) was conducted with 50 000 simulations. For each simulation, 100 years from the 113-yr record were randomly sampled with replacement. Thus, within each simulation, some years may have been sampled more than once and some years were not sampled at all. These 100 years were taken to represent years that had a TOP100 storm.

In most simulations, some years were randomly selected more than once, so the actual number of years with one or more storms was normally less than 100. The total number of years, typically 60 or fewer TOP100 storm years and some number of nonstorm years, always equaled 113 years. Each of the selected years has regional temperature anomalies associated with it, as was observed in the historical record. Thus, for each simulation and each region, the simulated conditional probability (CP_{ran}) of TOP100 storm occurrence in each type of season (warm, cool, near normal) was calculated using the same method applied to the observational record as described in Eq. (2).

A sampling distribution of CP_{ran} was produced for each region and type of season and the 5th and 95th percentile values were computed using the 50 000 simulations. The conditional probabilities from the observed record (CP_{obs}) that are less than (greater than) CP_{ran} at the 5th (95th) percentile are considered statistically significant at the 10% level (90% confidence interval). There are two such occurrences; for severe snowstorms occurring in seasons that are colder than average in the Southeast and South regions (Table 4a). These are also highlighted in Fig. 3a. Although conditional probabilities are higher (lower) in other regions in colder-than-average (warmer-than-average) seasons, they did not fall in the tails of the simulated distribution and are thus not statistically significant.

There were few seasons that were much colder or warmer than average (two standard deviations above or below average; not shown). Although the sample sizes were relatively small, there was a clear difference in the number of TOP100 storms that occurred in such

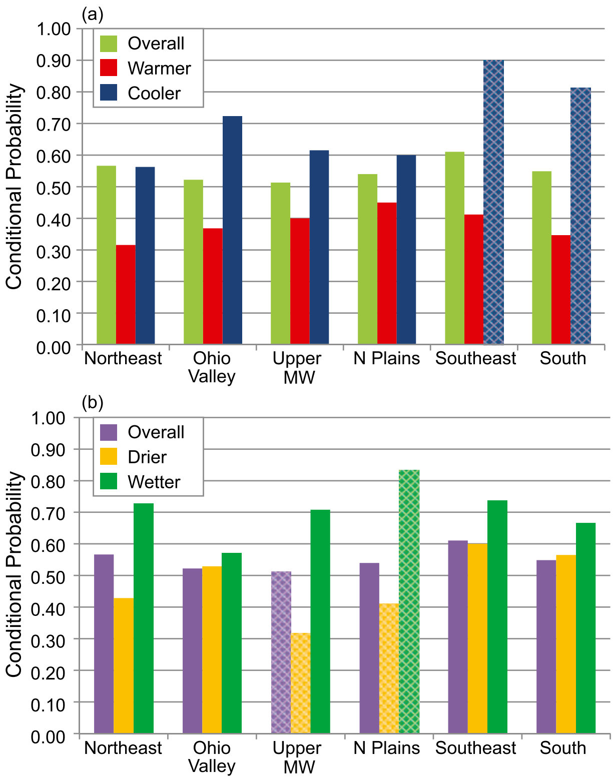

FIG. 3. Conditional probability of occurrence of one or more TOP100 snowstorms in any one season based on temperature, precipitation, and snowstorm data from 1901 to 2013. (a) Conditional probabilities of occurrence during any season, a warmer-than-average season, and a cooler-than-average season. (b) Conditional probabilities of occurrence during any season, a drier-than-average season, or a wetter-than-average season. Anomalously warm (cold) and wet (dry) are defined as those more than one std dev above (below) the November–April seasonal average. Hatched bars indicate those statistically significant using Monte Carlo analysis.

seasons. In two regions (the upper Midwest and South) there was one much warmer-than-average season in which a TOP100 storm occurred. No other region had a TOP100 storm in a much warmer-than-average season.

In seasons that were much colder than average (standardized departure less than −2), there was a far greater percentage of seasons with TOP100 storms. There were two seasons with standardized temperature departures less than −2 in the Southeast region, and one or more TOP100 storms occurred in both. In the South region, there was one much-colder-than-average season since 1901 and a TOP100 storm occurred during that season. Two out of three much-colder-than-average seasons had one or more TOP100 storms in the Ohio Valley and Northern Plains regions. In the Northeast, there was one much-colder-than-average season with a TOP100 storm out of a total possible number of three. In the upper Midwest, there were two years with TOP100 storms out of four much-colder-than-average seasons.

In several regions, a similar analysis for precipitation showed a higher conditional probability of TOP100 storm occurrence in wetter-than-average seasons compared to seasons that were drier than average. In the Northeast, upper Midwest, Northern Plains, and Southeast the conditional probability of occurrence of a TOP100 storm during an anomalously wet season is greater than 70%, and the probability exceeds 60% in the South region (Fig. 3b). Applying a Monte Carlo analysis as described above for temperature, the conditional probabilities of severe snowstorms in wetter-than-average seasons and in drier-than-average seasons were found to be statistically significant in the Northern Plains region (Table 4b). The difference in conditional probability of a severe storm occurring in an anomalously wet season is more than 40% greater than during an anomalously dry season in this region. A low conditional probability of occurrence during a drier-than-average season also is significant in the upper Midwest (32%). Interestingly, the conditional probability during near-average seasons is significant in this region as well, indicative of a lower likelihood of severe snowstorm occurrence. In the South, Southeast, and Ohio Valley regions there is little difference in conditional probabilities during seasons that are anomalously wet or dry.

b. *Seasonal timing of TOP100 snowstorms*

TOP100 snowstorms were further analyzed to determine the months of the cold season when storm occurrence is most prevalent, how the seasonal timing of these storms has varied and changed since 1901, and how the timing of these storms is affected by anomalous seasonal temperature or precipitation.

As shown in Fig. 4, TOP100 storms primarily occur between December and March in all regions except the Northern Plains. In the Southeast, these snowstorms are most closely clustered in January and February. Only two have occurred before the first of December in the Southeast and only eight after the first of March. Early-season storms are found to be more common in the South region, where five occurred in November and two in October. This was a greater number of early-season TOP100 storms than seen in the Northeast (three) and the Ohio Valley (five). Severe early-season storms occurred frequently in the Northern Plains: 12 in November and 7 in the latter half of October, with the earliest storm beginning on 17 October in 1908. Late-season storms were seen even more frequently in this region: 19 in March and 15 in April. The upper Midwest had the second largest number of late-season storms (23), but perhaps surprisingly, only two of these were in April.

TOP100 storms have continued to occur in recent decades even though seasonal temperatures have been

TABLE 4. (a) Conditional probability of occurrence of TOP100 snowstorms based on 50 000 Monte Carlo simulations (5th and 95th percentiles) and based on the 1901–2013 observational record. Observed values below (above) the 5th (95th) percentiles determined from the Monte Carlo simulations are denoted in boldface font. Cooler seasons are the November–April seasons at least one std dev below the twentieth-century average. Warmer seasons are those at least one std dev above the twentieth-century average. Overall refers to any season irrespective of seasonal temperature. (b) As in (a), but for precipitation.

(a)

Region	Season	95th	5th	Observed
Northeast	Cooler	0.75	0.18	0.56
Northeast	Overall	0.65	0.24	0.57
Northeast	Warmer	0.73	0.18	0.32
Ohio Valley	Cooler	0.72	0.16	0.72
Ohio Valley	Overall	0.64	0.23	0.52
Ohio Valley	Warmer	0.72	0.16	0.37
Upper Midwest	Cooler	0.75	0.14	0.62
Upper Midwest	Overall	0.64	0.23	0.51
Upper Midwest	Warmer	0.71	0.17	0.40
Northern Plains	Cooler	0.75	0.15	0.60
Northern Plains	Overall	0.64	0.23	0.54
Northern Plains	Warmer	0.72	0.17	0.45
Southeast	Cooler	0.71	0.17	**0.90**
Southeast	Overall	0.64	0.23	0.61
Southeast	Warmer	0.73	0.15	0.41
South	Cooler	0.73	0.15	**0.81**
South	Overall	0.64	0.23	0.55
South	Warmer	0.70	0.18	0.35

(b)

Region	Season	95th	5th	Observed
Northeast	Drier	0.80	0.42	0.43
Northeast	Overall	0.66	0.53	0.57
Northeast	Wetter	0.75	0.45	0.73
Ohio Valley	Drier	0.77	0.44	0.53
Ohio Valley	Overall	0.66	0.52	0.52
Ohio Valley	Wetter	0.75	0.45	0.57
Upper Midwest	Drier	0.75	0.45	**0.32**
Upper Midwest	Overall	0.67	0.52	**0.51**
Upper Midwest	Wetter	0.74	0.46	0.71
Northern Plains	Drier	0.77	0.44	**0.41**
Northern Plains	Overall	0.66	0.53	0.54
Northern Plains	Wetter	0.76	0.44	**0.83**
Southeast	Drier	0.76	0.44	0.60
Southeast	Overall	0.66	0.53	0.61
Southeast	Wetter	0.76	0.44	0.74
South	Drier	0.74	0.46	0.57
South	Overall	0.66	0.52	0.55
South	Wetter	0.76	0.44	0.67

frequently warmer than average. The upper Midwest is particularly notable in that 12 TOP100 storms occurred in seasons that were more than one standard deviation warmer than average since 1999, while only three such storms occurred before 1990. TOP100 storms in seasons more than one standard deviation warmer than average have also occurred with increasing frequency in the past three decades in the Northeast, Ohio Valley, and Northern Plains regions. There was no such increase in the frequency of TOP100 storms during anomalously warm seasons in the Southeast, where all eight such events took place before 1980. The South region had 10 storms in anomalously warm seasons, four since 1999 and six storms before 1940. Across all regions there were only six warmer-than-average seasons with a TOP100 storm when the season was also drier than average.

While severe snowstorms during warmer-than-average seasons occurred relatively rarely in the Southeast and South, snowstorms were prevalent during anomalously cold seasons, as previously noted. Thirty TOP100 storms in the Southeast and 29 in the South region occurred in seasons that were more than one standard deviation colder than average. This compares to 23 in the Ohio Valley, 17 in the Northeast, and 14 in the upper Midwest and Northern Plains regions.

Although Fig. 4 shows that storms are occurring in otherwise anomalously warm seasons, particularly in the northern regions of the United States, the figure also suggests that in regions such as the Southeast and Ohio Valley, storms in recent decades are occurring with less frequency late in the season than was the case in the middle and early decades of the twentieth century. To determine whether TOP100 snowstorms have not occurred as late in the season in recent decades, the median date of occurrence was calculated within three periods of 37 or 38 years (1901–38, 1939–76, and 1977–2013; Fig. 5). As shown in Fig. 5, in three regions the median date of the last occurrence was earlier in the most recent multidecadal period than in both preceding multidecadal periods. In the Southeast, South, and Ohio Valley regions, the median date of occurrence was six or more days earlier when compared to any previous multidecadal period. Although the statistical significance of this is difficult to determine, the overall pattern of earlier snowstorm dates is consistent with what would be expected as warming spring temperatures create conditions more favorable for rain rather than snow, particularly in the warmer climate regions where the phase of precipitation is most sensitive to increasing temperatures (Räisänen 2008; Brutel-Vuilmet et al. 2013).

c. *Influence of ENSO on TOP100 snowstorm occurrence*

El Niño–Southern Oscillation (ENSO) strongly influences temperature, precipitation, and snowfall patterns in the United States during the winter (Ropelewski and Halpert 1986; Kunkel and Angel 1999). During El Niño episodes, anomalously warm sea surface

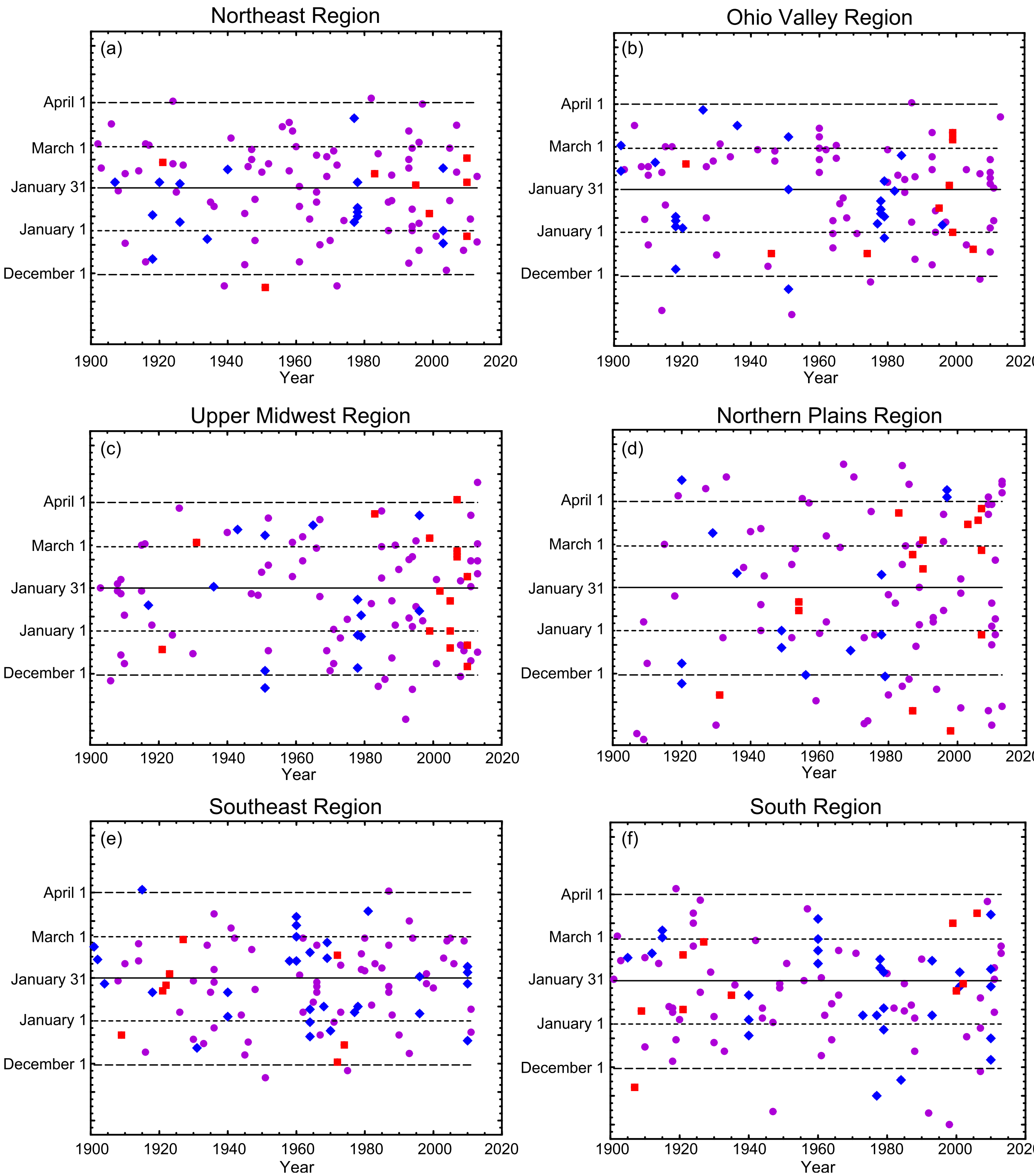

FIG. 4. The time of season and year each TOP100 snowstorm occurred from 1901 to 2013. The occurrence of each snowstorm is shown by a circle, square, or diamond. A red square indicates the storms that occurred in seasons that were one or more std dev warmer than average. A blue diamond represents the storms that occurred in seasons that were one or more std dev cooler than average. Purple circles indicate storms that occurred in all other seasons. The central point of the November–April cold season is 31 Jan.

temperatures in the eastern equatorial Pacific Ocean cause shifting atmospheric patterns that favor above-average precipitation in much of the southern United States and the Northeast while the Ohio Valley and upper Midwest are drier than average. Temperatures are more frequently below average during an El Niño episode in much of the South, Southeast, and Ohio Valley. Snowfall patterns are similarly influenced with

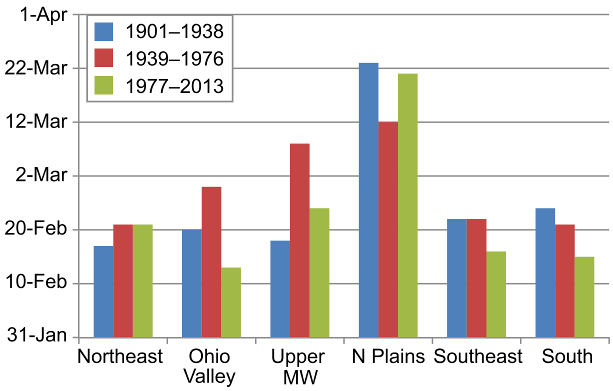

FIG. 5. Median date of occurrence for late-season storms. Late-season storms are those that occur in the second half of the cold season (February–April).

snowier-than-average seasons more common in the Southeast, Northeast, and parts of the South. Seasonal snowfall is typically below average in the upper Midwest and Northern Plains regions.

During La Niña, wetter-than-average seasons are more common in the Ohio Valley and upper Midwest while the winter is typically drier than average in much of the Southeast. However, areas from northern Alabama to Arkansas are often wetter than average. Seasonal temperatures are frequently warmer than average in the Southeast and South during La Niña episodes while below-average temperatures occur most frequently in the upper Midwest and Northern Plains. In keeping with these patterns, above-average seasonal snowfall is common in northern New England, the upper Midwest, and parts of the Northern Plains and the Ohio Valley during La Niña episodes.

Because of the strong influence of ENSO on temperature and precipitation patterns, one might expect ENSO to influence the frequency of TOP100 snowstorms; with more (fewer) severe snowstorms during the phase that favors above (below)-average seasonal snowfall. To assess this possibility, we identified seasons with moderate-to-strong El Niño and La Niña episodes from 1901 through 2013 and calculated conditional probabilities in each region and each phase of ENSO as a measure of the likelihood of TOP100 storm occurrence in warm, cold, and neutral phases.

The phase of ENSO was determined by calculating 3-month running means of sea surface temperature in the Niño-3.4 region from November through April. Moderate-to-strong El Niño (La Niña) events (hereafter, msElN, msLaN, respectively) were identified when at least three 3-month periods were more than 1.0°C above (below) average. Based on this definition, there were 20 moderate-to-strong El Niño episodes and 20 moderate-to-strong La Niña events from 1901 through 2013 (Table 5).

TABLE 5. Seasons (ending year) in which moderate-to-strong ENSO events occurred as defined by 3-month running means of SSTs in the Niño-3.4 region. Any November–April season with at least three such 3-month running means more than 1°C above (below) average is defined as msElN (msLaN) season.

El Niño	La Niña
1903	1904
1906	1909
1912	1910
1915	1911
1926	1917
1931	1918
1941	1925
1958	1934
1964	1939
1966	1943
1969	1950
1973	1956
1983	1971
1987	1974
1988	1976
1992	1989
1995	1999
1998	2000
2003	2008
2010	2011

Although there are many methods for identifying moderate-to-strong ENSO events, those identified here are similar to those based on other ENSO definitions (e.g., Trenberth 1997; Larkin and Harrison 2005; Kunkel et al. 2009a).

Based on the storms that occurred since 1901, there is an approximate 1-in-2 chance in each region that one or more TOP100 snowstorms will occur during years in which neutral ENSO conditions are present (not shown), while there is an approximate 1-in-5 chance that two or more storms will occur (Fig. 6a). While the likelihood of occurrence of one or more storms does not significantly differ between ENSO phases in most regions (not shown), ENSO conditions have a strong influence on the occurrence of two or more TOP100 storms in a season (Fig. 6). The conditional probabilities are generally much higher during msElN episodes in the eastern United States: 40% in the Northeast (statistically significant) and 35% in the Southeast. Conditional probabilities of 30% in the Ohio Valley and South regions also stand out, although not statistically significant. The conditional probability during an msLaN episode is as low as 5% in the Southeast (statistically significant), which is indicative of a low likelihood of multiple TOP100 snowstorms in a moderate-to-strong cold phase of ENSO. Values were also low in the South and Northeast regions but were not statistically significant. The Southeast region is also notable for significantly low conditional probability of a TOP100 snowstorm during

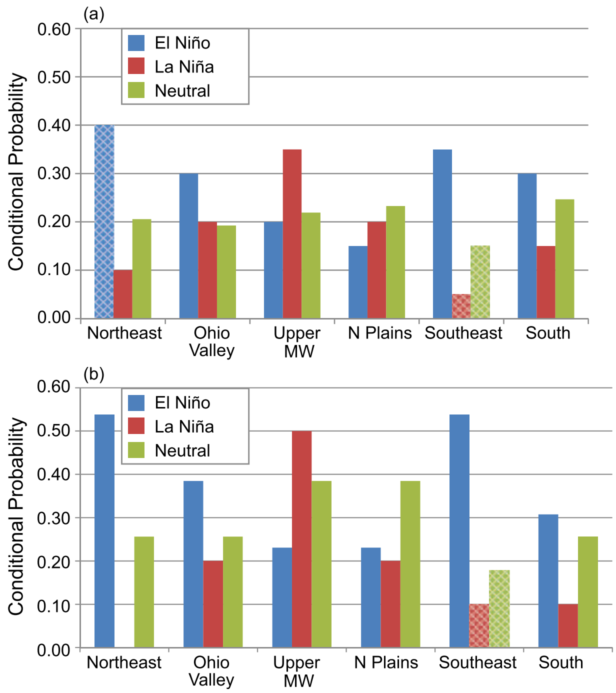

FIG. 6. (a) Conditional probability of occurrence of TOP100 snowstorms during El Niño, La Niña, and ENSO neutral conditions (calculated over the period 1901–2013). (b) As in (a), but for the period 1950–2013. Hatched bars indicate statistical significance.

neutral ENSO conditions. The only regions in which the conditional probability during an msLaN episode exceeds that of an msElN is in the upper Midwest and Northern Plains, where the conditional probability of occurrence was 35% and 20%, respectively.

A feature that stands out in this analysis is the much greater occurrence of TOP100 storms during msElN events since 1950 (Table 6). For example, in the Northeast, Ohio Valley, and upper Midwest regions, all but one of the msElN seasons in which more than one TOP100 storms occurred were after 1950. In the Southeast and Northern Plains there was no msElN season before 1950 in which multiple TOP100 storms occurred. Overall, 85% of the El Niño seasons in which multiple TOP100 storms occurred were after 1950. La Niña seasons in which TOP100 storms occurred were more evenly distributed between pre- and post-1950 periods (48% and 52%, respectively).

Performing the same analysis only on the storms that occurred since 1950 (Fig. 6b), a similar pattern emerges, but the differences between El Niño and La Niña are more pronounced. In the Southeast and Northeast, the conditional probability of two or more TOP100 storms occurring during an msElN exceeds 50% while it is 10% during an msLaN in the Southeast. In the Northeast, no msLaN season since 1950 had two or more TOP100 storms. The upper Midwest is the only region where the conditional probability of multiple TOP100 snowstorms is highest during msLaN episodes since 1950 (50%).

The higher likelihood of severe snowstorms in the Southeast during msElN is consistent with the observed relationship between ENSO and snowfall. An active southerly storm track with above-average precipitation increases the chances that cold outbreaks will combine to produce severe snowstorms. The relationship between El Niño and snowfall is not as strong in the Northeast, but our results are not at odds with recent findings. For instance, Patten et al. (2003) found an increase in the number of days with heavy snowfall for a majority of stations in the Northeast corridor and New England compared to neutral ENSO conditions. Other studies have found above-average snowfall on average in the Northeast during weak-to-moderate El Niño episodes. Northeast seasonal snowfall is often above average during weak-to-moderate El Niño episodes, which is consistent with our findings of an increasing likelihood of the most severe snowstorms in this region. However, strong El Niño events typically result in fewer intrusions of arctic air in the Northeast and below-average seasonal snowfall. But while seasonal snowfall is typically below average, short cold outbreaks can combine with moisture from the southern branch of the jet stream to produce severe snowstorms (Bradbury et al. 2003).

4. Discussion and conclusions

In the twenty-first century, severe snowstorms will occur in an environment of increasing temperatures and, in many regions, increasing precipitation. Mean annual temperatures in the contiguous United States are projected to increase from 2° to 4°C by the middle of the twenty-first century, with the greatest warming from the Great Plains to the Northeast (Kunkel et al. 2013c). The number of much-warmer-than-average seasons is expected to increase while the frequency of much-colder-than-average seasons decreases.

Although temperature is only one variable that determines if a major snowstorm will occur, it is a dominant factor, especially in the Southeast and South regions, the climatologically warmest regions in this study. The frequency of snow and mean seasonal snowfall is lowest in the warmest climate regions of the United States because temperatures are seldom cold enough for snow to fall. As temperatures continue to warm during the twenty-first century, the rain/snow line is expected to move farther north (Karl et al. 2009).

In the Southeast and South, our analysis showed that a difference in mean seasonal temperature of 1.8°C or

TABLE 6. (a) El Niño seasons in which one and two or more (boldface) TOP100 storms occurred. (b) As in (a), but for TOP100 storms occurring during La Niña seasons.

(a)

Northeast	Ohio Valley	Upper Midwest	Northern Plains	Southeast	South
1903	1903	1903	1915	1915	1903
1906	1906	1906	1931	1926	1912
1926	1912	**1915**	1966	1931	**1915**
1941	**1915**	1926	1969	1941	**1926**
1958	1926	1931	**1973**	1958	**1964**
1964	1931	1966	1983	**1964**	**1966**
1966	**1964**	1969	**1987**	**1966**	1973
1969	1966	1973	1988	**1969**	1987
1983	1983	1983	1998	**1973**	**1988**
1987	**1987**	**1988**	2003	1983	1992
1988	**1988**	1992	**2010**	**1987**	1998
1995	1995	**1995**		1988	2003
2003	1998	**2010**		**1998**	**2010**
2010	**2003**			2003	
	2010			**2010**	

(b)

Northeast	Ohio Valley	Upper Midwest	Northern Plains	Southeast	South
1910	1909	**1909**	**1909**	1904	1909
1917	**1910**	**1910**	1910	1909	**1910**
1918	1917	1917	1918	1910	1917
1925	**1918**	1918	**1943**	1918	**1918**
1934	1934	1943	1956	1934	1956
1939	1971	1950	1974	1971	1971
1950	1974	**1971**	1976	1974	1999
1956	**1999**	**1989**	**1989**	2000	2000
1971	**2011**	**1999**	**2011**	**2011**	**2011**
1974		**2008**			
1999		**2011**			
2011					

more (0.9°C warmer or colder than average) results in a 45%–50% difference in the likely occurrence of a TOP100 storm, assuming no change in variability. In the South region, the conditional probability of a TOP100 storm decreases from 81% in a colder-than-average season to 35% in a warmer-than-average season. In the Southeast, it decreases from 90%–41%, while the conditional probability decreases by 35% in the Ohio Valley and from 15% to 25% in the other three regions between colder- and warmer-than-average seasons. A summary of these and other important seasonal influences on TOP100 snowstorm occurrence is included in Table 7.

A 2°–3°C increase in mean temperature that is projected to occur in large parts of the southern United States by the middle of the twenty-first century (Kunkel et al. 2013c) is of a similar magnitude to the difference in mean seasonal temperature that is associated with the historical 45%–50% difference in conditional probability of occurrence of a TOP100 storm in the Southeast and South. Other factors, principally available moisture and synoptic-scale forcing, are essential to the occurrence of snowstorms. While the location and availability of these is projected to change with northward shifts in prevailing storm tracks, making conditions less favorable for severe snowstorm development, our results indicate that warming temperatures will further reduce the likelihood that severe snowstorms will occur. The large difference in TOP100 snowstorm frequency during warmer-than-average seasons in the Southeast and South suggests warming temperatures will contribute to significantly fewer severe snowstorms by the middle of the twenty-first century in those regions, in contrast to the northern United States, where such changes are not evident using the historical relationship as a guide to the future.

In addition to an overall reduction in the number of severe snowstorms, warming temperatures also are likely to affect the seasonal timing of these storms. As temperatures warm, spring conditions occur earlier, as reflected by a trend toward earlier dates of the last frost of the season (Easterling 2002), earlier spring snowmelt

TABLE 7. Seasonal conditions leading to a higher/lower likelihood of TOP100 snowstorms in each region. Conditional probabilities calculated over the 1901–2013 period based on the TOP100 storms in each region are shown in parentheses. Statistically significant values in italicized font.

	Seasonal conditions leading to higher likelihood of (a) TOP100 storm(s)	Seasonal conditions leading to lower likelihood of (a) Top100 storm(s)
Northeast	Wetter than average (73% likelihood of at least one severe snowstorm); *El Niño (40% likelihood of at least two severe snowstorms)*	Drier than average (43% likelihood of at least one severe snowstorm); La Niña (10% likelihood of at least two severe snowstorms)
Ohio Valley	Colder than average (72% likelihood of at least one severe snowstorm)	Warmer than average (37% likelihood of at least one severe snowstorm)
Upper Midwest	Wetter than average (71% likelihood of at least one severe snowstorm); La Niña (35% likelihood of at least two severe snowstorms)	*Drier than average (32% likelihood of at least one severe snowstorm)*; El Niño (20% likelihood of at least two severe snowstorms)
Northern Plains	*Wetter than average (83% likelihood of at least one severe snowstorm)*	*Drier than average (41% likelihood of at least one severe snowstorm)*
Southeast	*Colder than average (90% likelihood of at least one severe snowstorm)*; El Niño (35% likelihood of at least two severe snowstorms)	Warmer than average (41% likelihood of at least one severe snowstorm); *La Niña (5% likelihood of at least two severe snowstorms)*
South	*Colder than average (81% likelihood of at least one severe snowstorm)*	Warmer than average (35% likelihood of at least one severe snowstorm)

(Karl et al. 2009) and river ice breakup (Magnuson et al. 2000), and earlier plant bloom dates (Schwartz et al. 2006). Our analysis of TOP100 storms in three 37–38-yr periods found results consistent with these indicators. The median dates of late-season storms occurred at least 6 days earlier in the most recent multidecadal period than in either of the previous two periods in the Ohio Valley, Southeast, and South regions. As temperatures continue to warm, late-season conditions will be less frequently suitable for snowfall, reducing the frequency of major snowstorms late in the cold season, particularly in the warmest climate regions.

While temperatures are expected to warm in all areas of the United States, by the middle of the twenty-first century precipitation is projected to increase in far northern parts of the United States. But in central and southern sections, there is uncertainty about the direction of change (Kunkel et al. 2013c). There is also great uncertainty about the magnitude of any changes. For example, projections for winter precipitation in the Northeast vary from a decrease of 6% to an increase of 20% among 15 climate models (Kunkel et al. 2013b,c). As our results show, wetter-than-average seasons increase the likelihood of major snowstorms, most significantly in the Northern Plains. Projections of an increasing trend in precipitation in the far northern United States during the cold season would appear favorable for the development of major snowstorms in that region since temperatures are more likely to remain cold enough to support snowfall than in warmer climate regions. The lack of confidence in the direction of precipitation changes in other regions means that assessment of future changes are best assessed based on temperature relationships alone.

Regardless of the long-term trends in both temperature and precipitation, there will continue to be year-to-year variability, in part because of the influence of ENSO conditions. Our analysis showed that the likelihood of a TOP100 snowstorm increased (decreased) in all but the upper Midwest and Northern Plains regions when a moderate-to-strong El Niño (La Niña) event occurred. The difference in conditional probability between an El Niño and La Niña episode was greatest in the Southeast and Northeast regions, exceeding 40% in one analysis (Table 7). Although the future frequency of El Niño events is unclear, understanding this relationship between severe snowstorm frequency and ENSO events can be helpful for extreme seasonal predictions.

While these results provide insights into the effect that interannual to multidecadal changes in climate can have on the frequency of severe snowstorms, much work remains to fully understand the relationship between snowstorms and mean climate conditions. Future efforts could focus on extending these analyses to include a broader spectrum of snowstorms. In addition, an analysis of storms that occur with temperatures above and below freezing can be performed to determine if a shift to warmer storms, particularly in the southern regions, can explain the reduction in the number of TOP100 storms in recent decades. Also given the strong influence of the North Atlantic Oscillation/Arctic Oscillation on winter climate conditions, efforts to better understand its relationship to severe snowstorms, particularly in regions of the eastern United States, will be an important component of future studies.

Acknowledgments. The authors thank Sara Veasey and Debi Riddle for their support in the preparation of this manuscript and for the thoughtful recommendations of anonymous reviewers who helped us to significantly improve the manuscript.

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