ARE FREEZING RAIN PATTERNS IN THE SOUTH CENTRAL UNITED STATES CHANGING?

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ABSTRACT

Daily surface climatological reports in conjunction with radiosonde data was analyzed from a period of 1950-2007 for five stations in the South Central United States. From this data, the annual number of possible snow, rain, and icy precipitation events was determined by analyzing characteristics of the troposphere for two mandatory radiosonde launches for each wintertime precipitation day. The number of "potentially significant freezing rain events" was also determined for each location. It was determined that there is an "ice belt" in which icy precipitation, which includes sleet, graupel, and freezing rain, is more likely to fall. This ice belt has moved northwest with time. The occurrence of potentially significant freezing rain events is not associated with this ice belt. Instead, the frequency of these events has its own trend and has been generally increasing, principally from the 1980s onward. However, there was a drastic decline in the number of these events in the early 2000s. This result is counterintuitive due to the fact that there have been several very damaging ice storms in the early and mid 2000s. The correlation between icy precipitation events/freezing rain and various teleconnections is also evaluated in this study.

1. INTRODUCTION

Recently, there have been a seemingly high number of intense ice storms over much of the continental United States. In the past decade, an area that has been significantly impacted by these ice storms is the South Central United States, including Texas, Oklahoma, Arkansas, and Kansas. In December of 2000, southeast Oklahoma, northeast Texas, and southwest Arkansas experienced a devastating ice storm with ice accumulations of up to 1". In 2002, two ice storms struck again. That year, a storm that struck in January caused over $100 million in damages and cut power to 255,000 residences and businesses (Sid Sperry, personal communication, 2008). Once again, in 2007, two ice storms produced tremendous amounts of damage in the same states. The ice storm that occurred on December 8-10th, 2007, hit the metropolitan areas of Oklahoma City and Tulsa, cutting power to about 630,000 customers, causing 29 deaths, and creating hundreds of millions of dollars in damage.

Due to this apparent increase in the frequency and intensity of ice storms in the given region, it is important to study the changes in the atmosphere in that region to see if ice storms are in fact becoming a bigger problem. To determine this, changes in frequency, intensity, and duration of freezing rain events needs to be studied. In this paper, possible changes in frequency are discussed.

Section 2 contains background information to this study and covers some previous research that has been completed on freezing rain. Section 3 covers the data and methodology. Section 4 presents the results of the three parts of this study. Section 5 provides a discussion of the results. Section 6 recommends ideas for future research. Section 7 states the conclusions drawn from this research.

2. BACKGROUND

Prior to this study, there has not been a lot of research on the changes in freezing rain patterns or ice storms. However, there has been some research that is related to this study. A climatology of freezing rain days in the continental United States has been completed (Changnon, 2003). This climatology delineates the average number of freezing rain days per year, the maximum number of freezing rain days per year, the peak months for freezing rain activity, as well as changes in the frequency of freezing rain for different regions of the continental United States from 1950-2000.

Changnon (2007) determined that there has been a problem with increasing catastrophic winter storms in the United States. He found that there has been a decrease in the number of winter storms that have been occurring; at the same time, the intensity and size of the storms has increased, as the recent storms have affected a larger number of states while causing a greater amount of damage. In the south, Changnon (2007) found that the number of storms has been decreasing overall, especially recently, while the damages from the winter storms have increased drastically.

Another study has also been completed on the relationship of sea surface temperatures (SSTs) with wintry precipitation (Ramos da Silva, 2005). From models and comparing SSTs with wintry precipitation events, it was found that warm SST anomalies are more likely to cause ice storms while cooler SSTs are more likely to be associated with snowstorms in the Southeast United States. Also, warmer SSTs seem more likely to produce more intense winter storms.

Zerr (1997) studied the thermodynamic profile of the atmosphere during different icy precipitation events. For the event to be classified as icy precipitation, there needed to be a melting layer present so that any ice crystals would melt to some extent. Zerr determined that the characteristics of the melting layer were much more important than the characteristics of the refreezing layer in determining the precipitation type. The melting layer needs to be deep and warm in order for the ice crystals to melt completely, making it difficult for the precipitation to refreeze when it falls back into a subfreezing layer once again. This idea of the importance of a deep, warm layer will be important for the second half of the analysis of the data later on in this paper.

3. DATA AND METHODOLOGY

For this study, five locations around the South Central United States were chosen to represent the region. The locations that were chosen are Little Rock, AR; Ft. Worth, TX; Amarillo, TX; Dodge City, KS; and Oklahoma City, OK (Fig. 1). These locations were selected since they are rather evenly distributed throughout the region and should be representative of the area. All of the stations that were chosen are also the locations in the region that have the most complete radiosonde datasets from 1950 to the present. Some of the sites for the radiosonde launches have moved several times; for example, the Oklahoma City site has moved from Will Rogers World Airport to Tinker Air Force Base to Norman. However, these station moves have not been large enough distances to greatly affect the validity of the study.

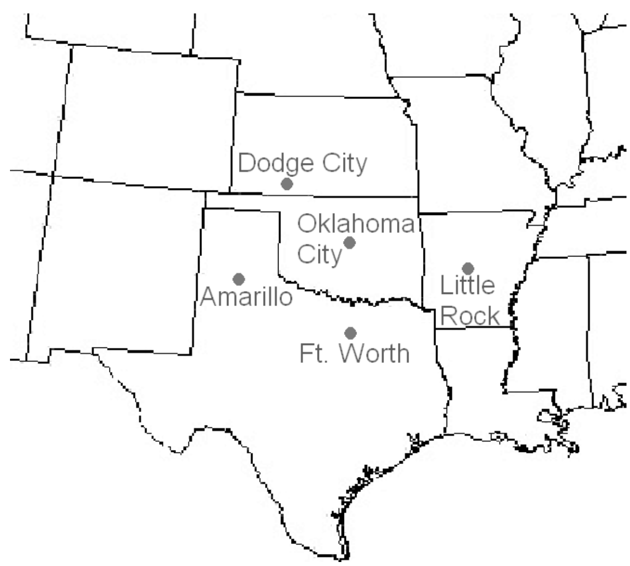


FIG.1. The locations of stations that are used in this study. This shows that stations are representative of the South Central United States.

For these stations, the *Global Surface Summary of the Day* (GSOD) was obtained from the National Climatic Data Center (NCDC) website. For a given day and station, the GSOD provides the mean temperatures, mean dew point, maximum temperature, several other conditions of the day, and indications of occurrences of several weather conditions. The weather conditions that the GSOD gives indicators of are fog, rain or drizzle, snow or ice pellets, hail, thunder, and tornado or funnel cloud. If the GSOD indicated that a given day had rain, drizzle, snow, and/or ice pellets, then that day would be determined to be a precipitation day for that station.

After this, the radiosonde archives for the stations were obtained. Two sources were used in acquiring this dataset: the Radiosonde Data of North America CD-ROM and the Integrated Global Radiosonde Archive (IGRA) from the NCDC website. The multiple datasets were used due to deficiencies if only one dataset was used. For instance, if only the IGRA dataset were used, then three years of data at Amarillo would be missing. In addition, in the earlier years of the IGRA dataset, the vertical resolution of the data is poor; on average, only about 20 upper air observations per sounding were archived in this dataset from 1950 to around 1970. The newer data from the IGRA has at least 40 observations per sounding, with some soundings having more than 100 observations. To compensate for this difference in the vertical resolution of data, much of the older data was replaced with archived radiosonde data from the Radiosonde Data of North America CD-ROM, since this data has about twice the data points. The difference in the resolution should not be an issue since the maximum temperature in a layer is archived if it is significant, such as a warm level with cooler air above and below that point, which is the case in any icy precipitation event.

The wintertime precipitation events were sorted into three categories by combining the radiosonde data with the precipitation days dataset, which was established from the GSOD. Wintertime precipitation was determined to occur in the months of November-April, to make sure that all wintry precipitation that occurs at all five stations is captured in this study. For a given day that had precipitation, the mandatory radiosonde launches (currently 0000z and 1200z) were examined to determine which type of precipitation would have theoretically occurred at that time. If the surface temperature was above freezing, the potential precipitation type was determined to be rain. If the surface temperature was below freezing, two precipitation types could occur: snow and icy precipitation. Snow would occur if the surface was below freezing and no upper air observation for that balloon launch was above freezing. Icy precipitation would occur if the surface was below freezing and any observation above the surface was above the freezing point. Theoretically, icy precipitation would include snow pellets, sleet, and freezing rain. A complete decision tree is shown in figure 2.

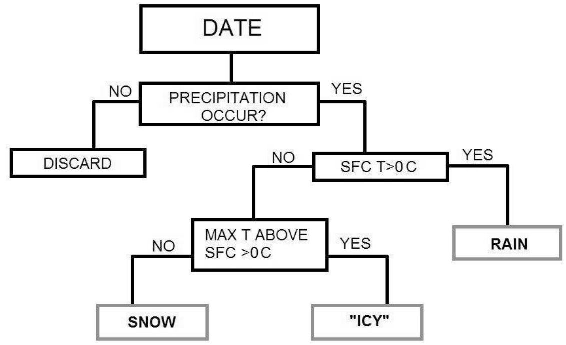


FIG. 2. A decision tree, showing how a radiosonde launch is determined to be a certain type of event. For the second section of this study, the "MAX T ABOVE SFC" was raised to ≥4°C for a ZR event.

From this point forward in this article, any time that a certain precipitation was determined from a mandatory radiosonde launch on a precipitation day, it will be called an "event" for simplicity, even though it has not been determined that the particular type of precipitation actually fell at that location on that given date. It is also important to note that the number of events that occurred does not reflect the number of days that certain precipitation occurred. Instead, the number of events is simply the number of times that the tropospheric conditions indicated that a certain type of precipitation fell. For each precipitation day in winter, two events occurred.

4. RESULTS

a. WINTERTIME PRECIPITATION "EVENTS"

Over the time period of the dataset, four out of the five stations had experienced a period of time when there was a marked increase in the frequency of icy precipitation events. Little Rock, AR, and Ft. Worth, TX, showed a clear increase in the late 1970s (Fig. 3a,b). Shortly after that increase, the occurrence of icy precipitation events quickly decreased in Little Rock, AR, and continued to decrease up through present. At the same time, the frequency of icy precipitation events in Ft. Worth, TX, slightly decreased after the peak in the late 1970s, but the overall higher incidence of icy events continued through the middle 1990s.

In Amarillo, TX, and Dodge City, KS, there was a marked increase in the frequency of icy precipitation events in the late 1980s and early 1990s (Fig. 3c,d). At the same time, during this period, there was a notable decrease in the occurrence of rain events at both of these stations. In the early 2000s, the incidence of icy precipitation events decreased significantly at these two cities, and the number of icy events returned to the long-term average. In both of these locations, there was a local maximum in the frequency of snow events that occurred during the period of heightened icy events. However, both Dodge City and Amarillo have shown a downward trend in the occurrence of snow events from the 1950s onward, particularly after the middle 1980s.

Oklahoma City, OK, is different from the other five stations. There has not been a time period when there was a substantial increase in the frequency of icy precipitation events followed by a substantial decrease in icy events (Fig. 3e). Instead, there have been several small maxima in the number icy events. However, none of the periods of increased icy precipitation frequency are impressive. Still, it is interesting to note that Oklahoma City does have an increasing number of wintertime rain events. At the same time, there has been a decrease in the frequency of snow events, particularly after 1980. The downward trend in the annual number of snow events that is shown in Oklahoma City resembles the trend shown in the composite of all five sites (Fig. 3f). Overall, there also seems to be a slight increase in the number of icy precipitation events, but this increase has not appeared to continue into the 2000s.

b. POTENTIALLY SIGNIFICANT FREEZING RAIN "EVENTS"

In order to better differentiate freezing rain events from other icy precipitation events, such as graupel and sleet, the method initially used was modified slightly for the next section of the study. Previously, icy precipitation was determined to have occurred if the surface was below freezing while any upper-air observation was above freezing (Fig. 2) on a precipitation day. For this part of the study, a radiosonde launch would be classified as a "potentially significant freezing rain event" (henceforth referred to as "ZR event") if the surface was below freezing and any observation aloft was greater than or equal to 4°C.

This temperature was chosen as the dividing line between ZR events and non-significant freezing rain events due to research by Zerr (1997). Since melting characteristics of a profile are the most important factor in distinguishing freezing rain events from ice pellets, a characteristic of the melting layer was picked to discriminate freezing rain from other wintry precipitation. When the maximum temperature in a melting layer is 4°C or higher, it is likely t hat any ice crystals falling though the layer will melt completely. Also, the warmer the maximum temperature in a layer, the deeper the layer is likely to be to completely melt an ice crystal falling through it. Since all the ice crystals melt, there is nothing for the precipitation to refreeze onto when the raindrop falls into the subfreezing layer once again, making it unlikely that the raindrop will refreeze and turn into ice. Consequently, the raindrop will become supercooled and freeze on contact with the surface, resulting in freezing rain. Also, a warmer layer will be able to hold more water

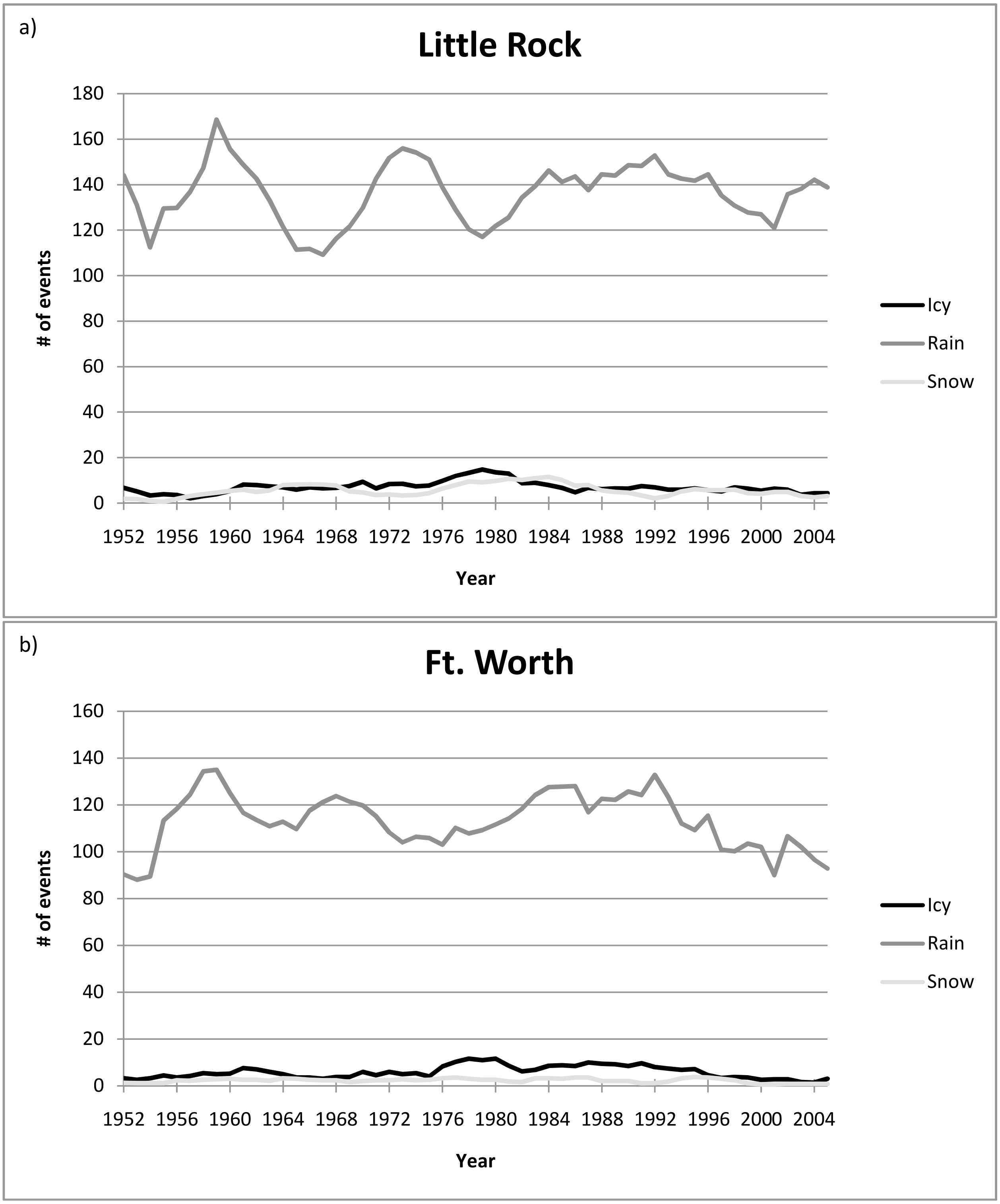


FIG 3. a,b. a) Shows the 5-year running mean (to factor out a lot of white noise) of the annual number of radiosonde indicated icy, rain, and snow events at Little Rock, AR. b) Same description as for a), for Ft. Worth, TX. Notice in both graphs the peak in icy days in the late 1970s.

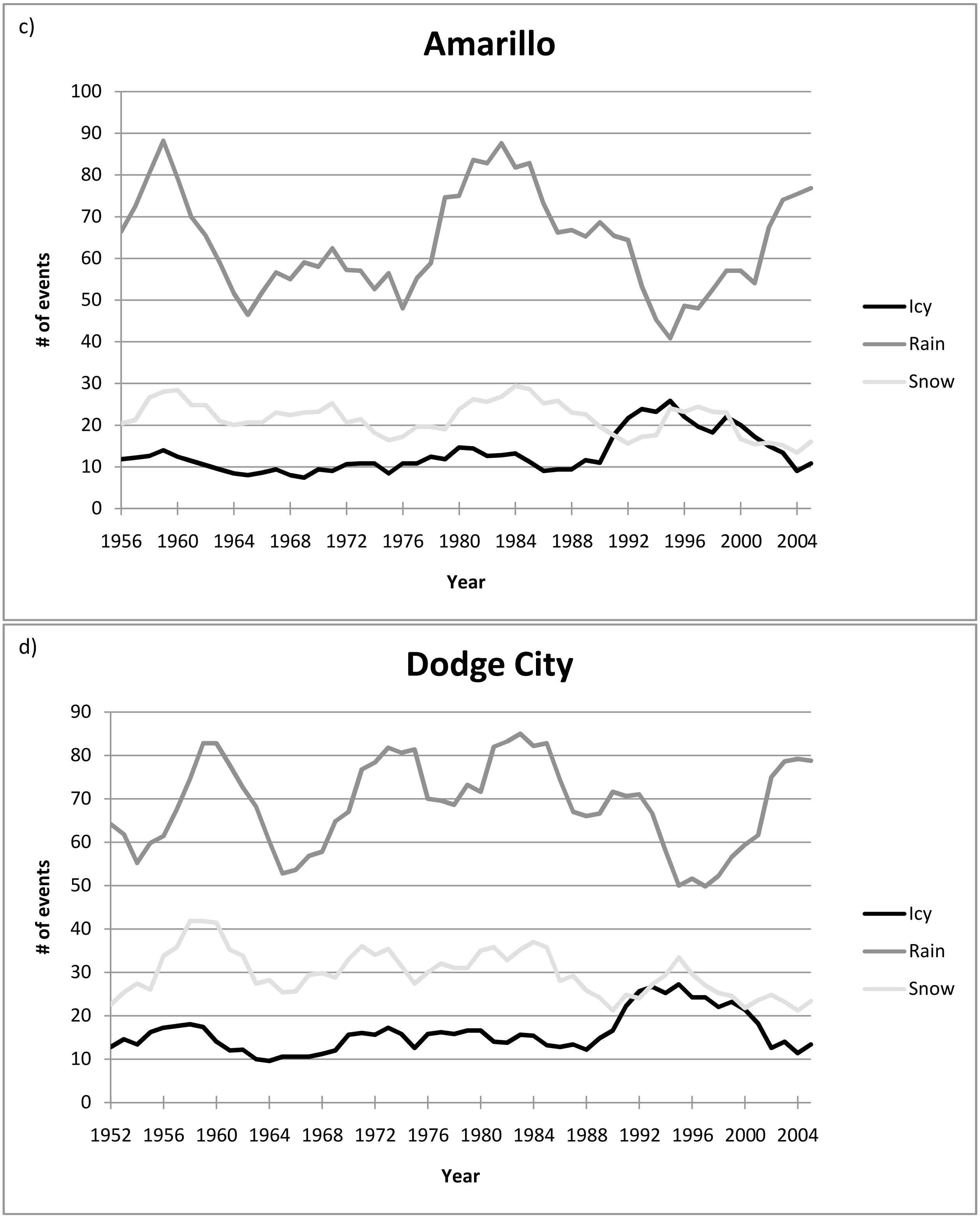
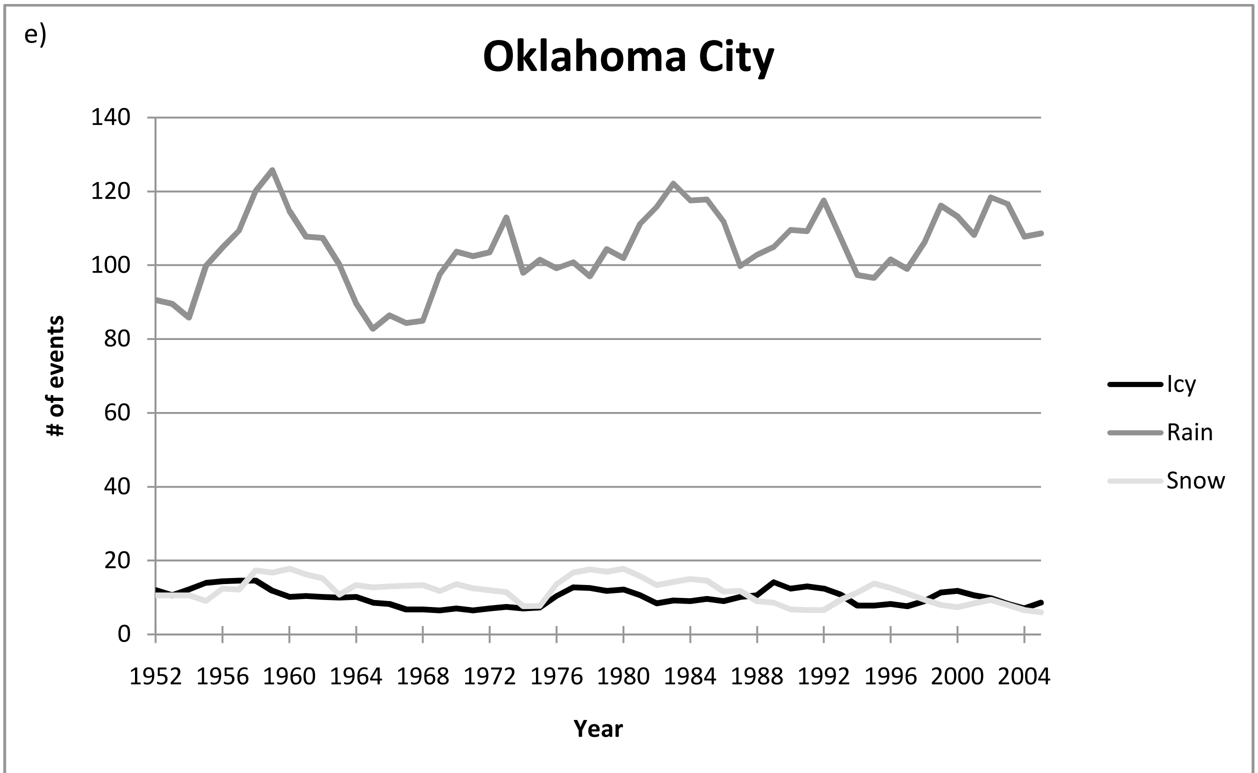


FIG. 3. c,d. c) Same description as for a), for Amarillo, TX. d) Same description as for a), for Dodge City, KS. Note the peak in icy precipitation in the 1990s and the overall downward trend in the frequency of snow events at both locations.



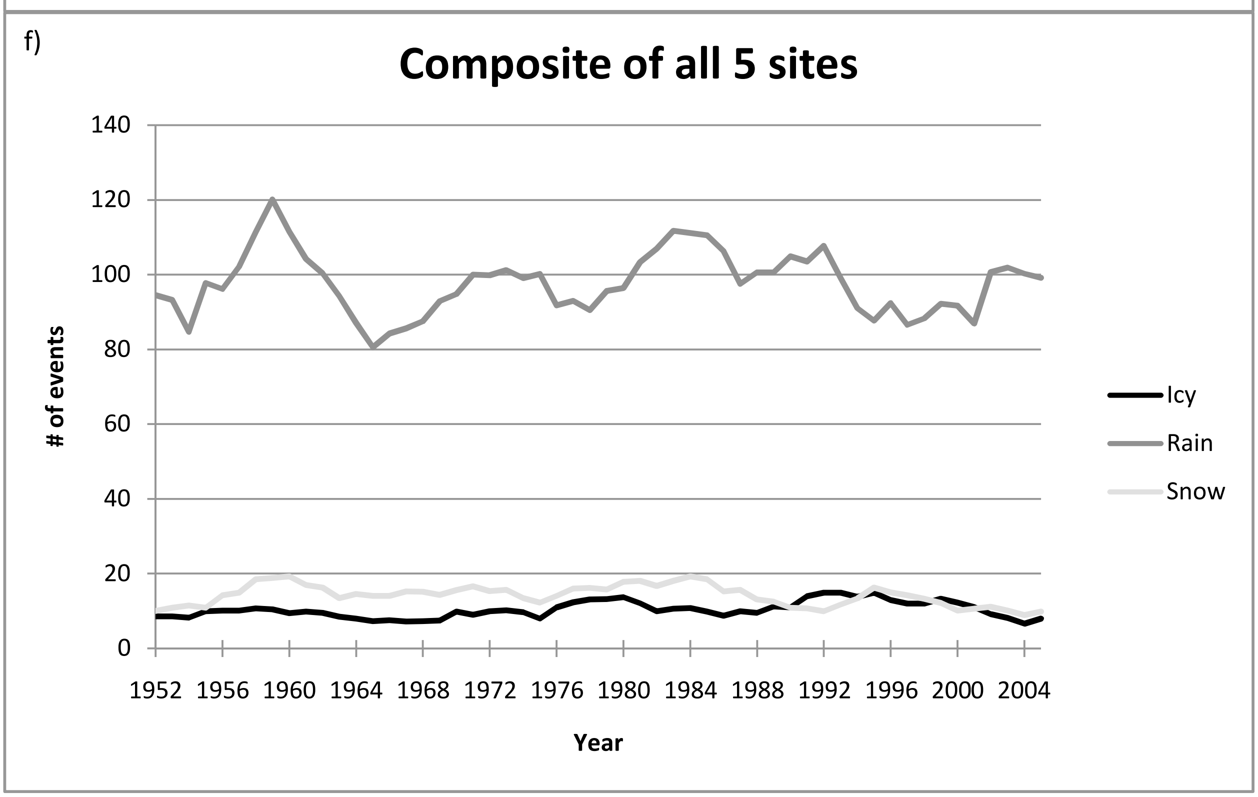


FIG. 3. e,f. e) Same description as for a), except for Oklahoma City, OK. f) Same description as for a), except for the composite of all 5 stations. Notice the decrease in the number of snow events in the composite, particularly evident starting in the middle 1980s. There is also a slight increase in the number of icy precipitation events in the composite.

vapor, making any precipitation event that would occur be more likely to produce heavier accumulations of ice. These reasons are why a temperature of 4℃ is a good dividing line to differentiate a ZR event from an icy precipitation event that likely not going to cause as much damage.

The results from this section of the study are actually quite a bit different than those from the first segment. For Little Rock, AR, the maximum annual number of ZR events occurred around 1970 (Fig 4a). From then on, there has been a steady decline in the frequency of ZR events. On the other hand, the number of annual ZR events in Ft. Worth did not peak until the early 1990s (Fig 4a). Since that time, the frequency of ZR events in Ft. Worth has decreased dramatically.

While there was a stark contrast between the trends in the number of icy precipitation and ZR events in Little Rock and Ft. Worth, Dodge City and Amarillo both had similar trends in icy precipitation and ZR events. In both Amarillo and Dodge City, the highest frequency of ZR events occurred in the same timeframe as the highest frequency of icy precipitation events, in the middle 1990s (Fig 4b). It is not clear why the maxima of icy precipitation and ZR events match up in the western locations but does not match up in at any other station.

Oklahoma City again has its own unique pattern. From the Oklahoma City data, the highest annual number of ZR events occurred around 1990 (Fig 4c). Looking at the long-term trends, there seems to be an upward trend in the average number of ZR events in Oklahoma City, especially from circa 1980 to the present. There was also an era of elevated ZR event frequency in the 1950s in Oklahoma City. The pattern in Oklahoma City closely resembles the overall pattern in the South Central United States, as shown by the composite (Fig 4c). In the entire region, there appears to be an increase in the number of ZR events for the entire time period.

c. LINK TO TELECONNECTIONS

The connection between various teleconnection indices and wintry precipitation was also investigated briefly in this study. If any teleconnection index is strongly associated with icy precipitation events or ZR events, it would be important to understand so that more seasonal prediction and preparation for such events could take place. Consequently, it is important to at least briefly investigate the connection of teleconnection indices with wintry precipitation events.

Much of the data used in this section came from the Climate Prediction Center (CPC). The dataset for the North Atlantic Oscillation (NAO), East Atlantic (EA), West Pacific (WP), East Pacific/North Pacific (EP/NP), Pacific-North America (PNA), East Atlantic/West Russian (EA/WR), Scandinavian (SCA), and the Polar/Eurasian (POL) patterns came from CPC (available online at ftp://ftp.cpc.ncep.noaa.gov/ wd52dg/data/indices/tele_index.nh). The data for the Multivariate ENSO Index (MEI) comes from the Earth Systems Research Laboratory (ESRL; available online at http://www.cdc.noaa ,gov/people/klaus.wolter/MEI/table.html). The Joint Institute for the Study of the Atmosphere and Ocean (JISAO) at the University of Washington provided the dataset for the Pacific Decadal Oscillation (PDO) that was used in this study (available online at http://jisao.washington .edu/pdo/PDO.latest).

Since the number of icy precipitation events and number of ZR events has been summed annually, the teleconnection indices have been averaged for each year during the six months of the year that are included in this study. Subsequently, the correlation coefficients were calculated between each teleconnection and each station, as well as between each teleconnection and a composite of all the stations. This was done for both icy precipitation events and ZR events.

The results for the correlations between icy precipitation and the teleconnections are shown in table 1. Overall, there are not any strong correlations between the teleconnections and the icy precipitation. However, there is correlation coefficient of 0.27 and 0.26 between the composite and the NAO and EA, respectively. However, the correlation does not exist at all stations. At Oklahoma City, the

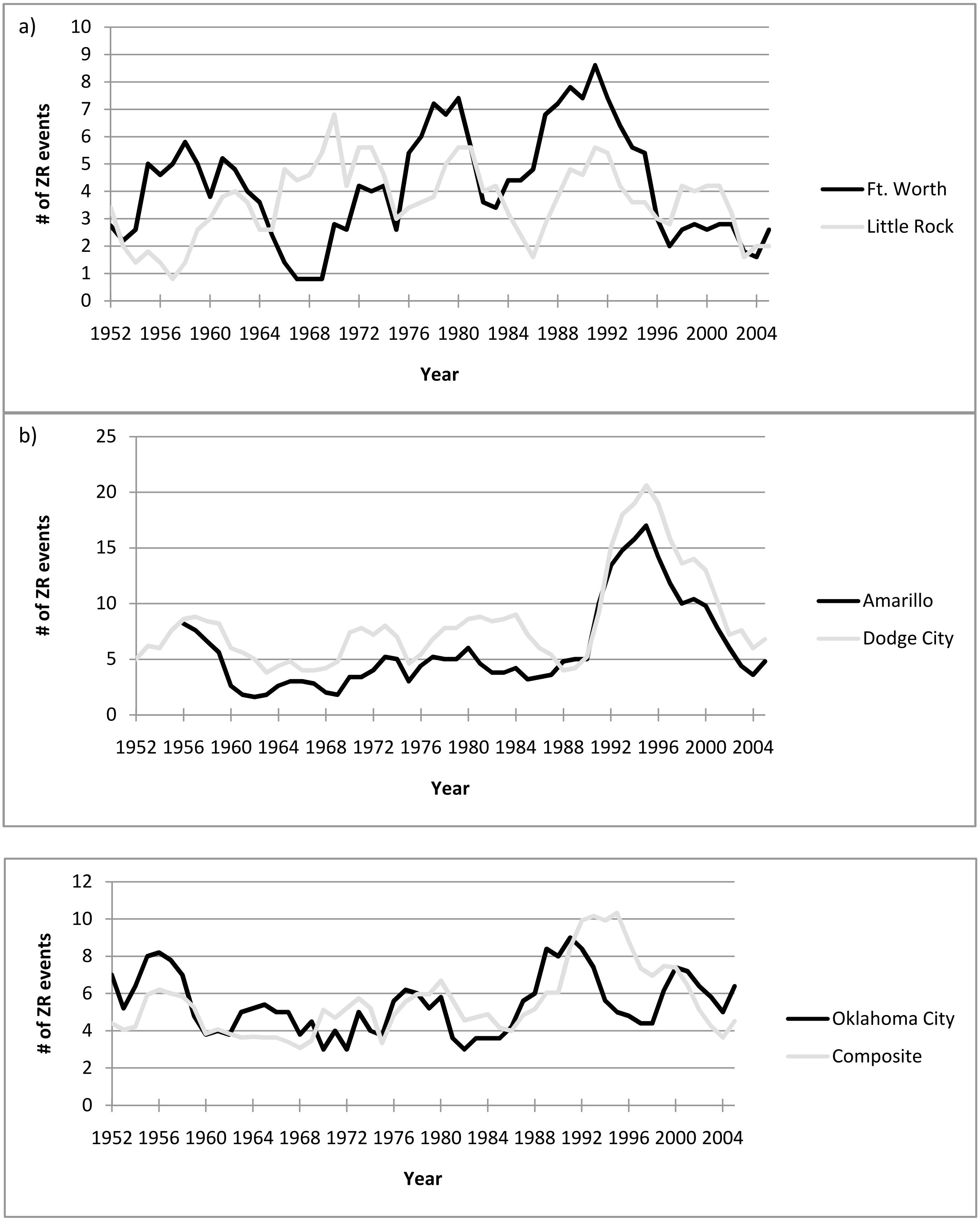


FIG. 4. a-c. The number of radiosonde indicated "potentially significant freezing rain events" (ZR events) for each year for each station, and the composite, is shown. The lines plotted are 5-year running means to factor out white noise.

	NAO	EA	WP	EP/NP	PNA	EA/WR	SCA	POL	MEI	PDO
COMPOSITE	0.27	0.26	0.05	0.20	0.00	0.15	-0.10	-0.03	0.18	0.01
AMARILLO	0.33	0.27	0.08	0.26	0.19	0.26	-0.11	-0.21	0.27	0.13
DODGE CITY	0.33	0.16	0.05	0.07	-0.01	0.14	-0.10	-0.13	0.09	-0.04
FT. WORTH	0.13	0.24	-0.24	0.28	0.04	0.14	0.05	0.25	0.15	0.14
LITTLE ROCK	0.01	0.20	-0.20	0.14	-0.18	0.00	-0.05	0.14	0.01	-0.04
OKLAHOMA CITY	0.02	0.07	0.04	0.02	-0.10	-0.02	-0.11	-0.03	0.03	-0.28

TABLE 1. Correlation coefficients between teleconnection indices and icy precipitation events for the five stations and composite.

correlation coefficient is much smaller between those two teleconnection indices and the number of icy precipitation events.

At all the stations and in the composite, the correlations between the NAO and the ZR events are much stronger than the correlations between the icy events and the NAO (Table 2). In fact, the correlation coefficient between the NAO and the composite of all five stations is 0.45. This correlation is stronger than the correlation between any individual station and the NAO. This is probably due to the fact that the composite helps to factor out some of the white noise that is experienced by each individual station, by looking at the region of the South Central United States as a whole. In addition, every station has a positive correlation between the NAO and the number of ZR events at that station. This indicates that the South Central United States is more likely to experience ZR events when the NAO is in a positive phase.

No other teleconnection exhibited a very strong correlation with ZR events. Also, any correlation that existed in the composite was not consistent in all five stations. It is unlikely that any of the other teleconnections is correlated with ZR events. In the future, it is important to look at each winter individually instead of the months of January, February, March, April, November, and December of a given year. A better signal may exist between the wintry precipitation and the teleconnections within one winter.

5. DISCUSSION

Overall, there has been a slight increase in the amount of annual icy precipitation events in the South Central United States over the last 58 years. During this same time period, there also has been an increase in the number of ZR events. The frequencies of ZR and icy precipitation events have peaked in the early 1990s and have decreased significantly since then. In just the last few years of the study, the frequency of ZR events has seemed to increase once again. It is possible that there may be some multi-decadal variability within the larger ZR trends, with the lower frequencies of ZR events occurring in the middle 1960s, middle 1980s, and early 2000s. The ZR trends will need to be looked at in the future to see if the frequency continues to increase, as it has in the past several years.

There appears to be an "ice belt" where icy precipitation, such as graupel, sleet, and freezing rain, is more likely. This ice belt has showed up at four of the five locations in the study, with Oklahoma City being the only station that did not indicate an ice belt. Oklahoma City may not have showed signs of the ice belt due to the fact that the ice belt itself has multi-decadal variability, and it was in a period of lower intensity than normal while the ice belt was over Oklahoma City in the 1980s.

The ice belt has shifted northwest with time. In the late 1970s, the ice belt was located over an area extending from the southwest to the northeast including Little Rock, AR, and Ft. Worth, TX. In the middle 1990s, the ice belt had retreated farther northwest and was located over a region including the cities of Dodge City and Amarillo.

It is difficult to truly determine if this ice belt is a real feature. A dataset that covers a wider area and possibly a longer period of time needs to be evaluated to verify if this ice belt really exists. However, given the results from this study, it appears as though this ice belt exists

	NAO	EA	WP	EP/NP	PNA	EA/WR	SCA	POL	MEI	PDO
COMPOSITE	0.45	0.20	-0.07	0.20	-0.14	0.12	-0.05	-0.07	0.07	-0.09
AMARILLO	0.42	0.13	0.06	0.18	-0.01	0.12	-0.11	-0.13	0.14	0.01
DODGE CITY	0.33	0.21	0.01	0.15	0.04	0.11	-0.07	-0.23	0.16	0.08
FT. WORTH	0.32	0.18	-0.18	0.28	-0.03	0.16	0.08	0.16	0.13	0.04
LITTLE ROCK	0.16	0.12	-0.26	-0.10	-0.28	0.02	-0.03	0.09	-0.16	-0.24
OKLAHOMA CITY	0.29	0.00	0.11	0.12	-0.32	-0.03	-0.05	0.06	-0.12	-0.36

TABLE 2. Correlation coefficients between teleconnection indices and ZR events for the five stations and composite.

and is shifting northwest with time. This would be concurrent with the fact that the climate has warmed in the South Central United States.

6. FUTURE RESEARCH

Datasets of GSOD and radiosondes will be collected for additional stations outside of the region studied. Analysis of these datasets will provide a bigger picture of what kind of changes are happening in wintertime precipitation patterns, particularly changes in freezing rain patterns. Doing this research will help determine the characteristics of the ice belt and better clarify whether or not ZR events are becoming a more frequent, widespread problem.

Also, it will be important to look at the change in moisture in the atmosphere during the ZR events. For this study, due to limitations in the dataset in some locations, the dew point depression was not examined to ascertain if the atmosphere was capable of producing precipitation at the time of the radiosonde launch. Examining changes in precipital water during ZR events is also important to determine if significant freezing rain events are becoming more likely. If the amount of precipital water is increasing, then it is likely that the ice accumulations during freezing rain events will likely increase and the frequency of significant ice storms will probably become more common.

7. CONCLUSIONS

Daily surface data, in conjunction with radiosonde data, was analyzed for five stations in the South Central United States. During the analysis, the number of snow, rain, and icy precipitation events was determined for each year. Icy precipitation can be graupel, sleet, or freezing rain. From examining the results and trends in these three types of precipitation, there seems to be a decrease in yearly snow events and a slight increase in the annual number of icy precipitation events; however, the frequencies of both snow and icy precipitation have decreased since about the year 2000.

An ice belt, in which the troposphere is more often favorable to produce icy precipitation, was also determined to exist. This ice belt was located over a region stretching from the southwest to the northeast, including the locations of Ft. Worth, TX, and Little Rock, AR, in the late 1970s. By the mid 1990s, the ice belt had shifted northwestward, over a region that encompasses Dodge City, KS, and Amarillo, TX.

At only two out of the five stations, the maximum frequency of “potentially significant freezing rain events” (ZR events) matched up with the peak in the frequency of icy precipitation events. There was no apparent ice belt in the ZR event data. However, up until very recently, there has been a clear increase in the frequency of ZR events in the South Central United States. The trends in ZR events will have to be reanalyzed again in several years to see if the frequency of ZR events continues to increase once again.

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