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The increasing efficiency of tornado days in the United States

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Abstract The authors analyze the historical record of tornado reports in the United States and find evidence for changes in tornado climatology possibly related to global warming. They do this by examining the annual number of days with many tornadoes and the ratio of these days to days with at least one tornado and by examining the annual proportion of tornadoes occurring on days with many tornadoes. Additional evidence of a changing tornado climate is presented by considering tornadoes in geographic clusters and by analyzing the density of tornadoes within the clusters. There is a consistent decrease in the number of days with at least one tornado at the same time as an increase in the number of days with many tornadoes. These changes are interpreted as an increasing proportion of tornadoes occurring on days with many tornadoes. Coincident with these temporal changes are increases in tornado density as defined by the number of tornadoes per area. Trends are insensitive to the begin year of the analysis. The bottom line is that the risk of big tornado days featuring densely concentrated tornado outbreaks is on the rise. The results are broadly consistent with numerical modeling studies that project increases in convective energy within the tornado environment.

Keywords Tornado · Trends · Cluster · Outbreak · Efficiency

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1 Introduction

The United States experiences more tornadoes than any country on earth (Grazulis 1990). Advances in technology help to continuously improve forecasts and warnings; nevertheless the active 2011 season (with over 1700 tornadoes) took the lives of more than 550 people (Simmons and Sutter 2012). As the climate continues to warm it is important to understand whether tornado devastation (Brooks and Doswell 2001) might get collectively worse.

There exists large year-to-year variation in tornado frequency, but a consensus report on extreme storms and climate change (Kunkel 2013) found little evidence of trends in occurrence rates for the subset of tornadoes that are most reliable. Frequency is only one component of the tornado climate however. In particular the number of days with many tornadoes and the spatial density of tornadoes provide additional analytics for understanding how tornadoes might be changing collectively.

Here we study the historical record of tornado reports from a climatological perspective. In particular, we examine the annual number of days with many tornadoes and the ratio of these days to days with at least one tornado. Further we examine the annual proportion of tornadoes occurring on days with many tornadoes. We also examine tornadoes occurring in spatial clusters and consider the number of tornadoes by cluster and by cluster area.

Over the last 60 years (1954–2013), as well as more recent periods of shorter duration, we find a consistent decrease in the number of days with at least one tornado but at the same time we find an increase in the number of days with many tornadoes. This results in an increasing proportion of tornadoes occurring on big tornado days. Coincident with these changes we find the spatial and temporal concentration of tornadoes has increased. It appears that

the risk of big tornado days featuring clusters of densely packed tornadoes is on the rise. We suggest these trends could be related to concomitant increases in both convective available potential energy (CAPE) and convective inhibition (CIN) within the near-tornado environment.

The paper is organized as follows. In section two we describe the tornado database used in this study and mention the rationale behind our focus on tornadoes with an (E) F scale rating of one or higher. In section three we examine the temporal frequency of tornadoes and tornado days on an annual basis. We show that although the annual mean number of tornadoes is stable the number of days with tornadoes is decreasing. This decreasing trend is compensated by an increasing number of days with many tornadoes. In section four we examine the spatial characteristics of tornado clusters. We use an objective algorithm to group touchdown locations and examine the annual average number of tornadoes per cluster and the annual average number density of the cluster. In section five we provide a summary of our analyzes and suggest what environmental factors might be involved in these changes.

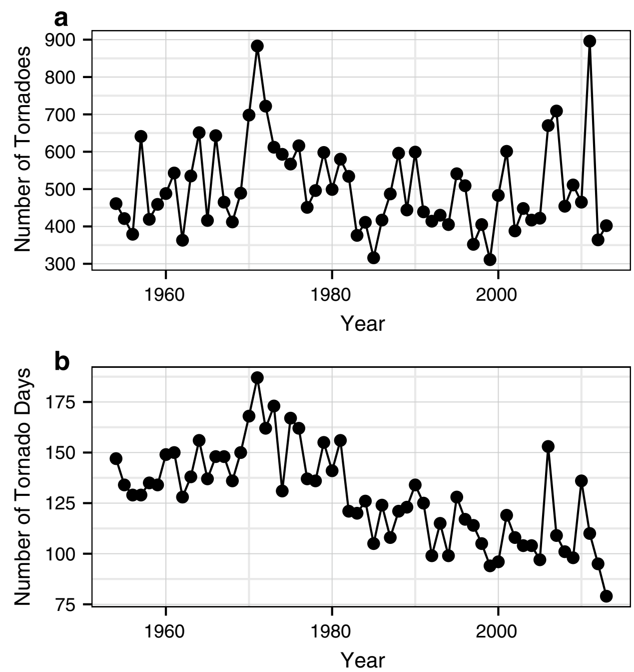

Fig. 1 (E)F1+ tornado frequency (1954–2013). **a** Annual number of tornadoes and **b** annual number of days with at least one tornado

2 Tornado data used in this study

The US Storm Prediction Center (SPC) maintains the most readily available record of tornadoes in the United States compiled from National Weather Service (NWS) *Storm Data* publications and reviewed by the US National Climate Data Center (Verbout et al. 2006). We obtain the dataset containing all reported tornadoes over the period 1950–2013 from www.spc.noaa.gov/gis/svrgis/zipped/tornado.zip. According to a report by the Pacific Northwest National Laboratory for the US Nuclear Regulatory Commission the SPC database is in reasonably good condition and acceptable for use in this type of climatology (Ramsdell and Rishel 2007).

Improved observational practices lead to an increase in the number of reported weaker tornadoes (Doswell et al. 2005; Verbout et al. 2006). Some small tornadoes can go undocumented even today in places with few people or limited communication infrastructure but the probability of this happening appears to be decreasing (Elsner et al. 2013). A further complicating factor is the damage scale used to rate tornadoes. The Fujita damage scale was first published in 1971 (Fujita and Pearson 1973) and adopted in 1973 for rating tornadoes in the near aftermath (Edwards et al. 2013). Tornadoes in the SPC dataset before this time were rated retroactively using information gathered from newspaper accounts and photographs (Coleman and Dixon 2014); a procedure that might have led to an over-rating of some earlier tornadoes (Schaefer and Edwards 1999; Anderson et al. 2007).

Thus, in this study, we restrict our analysis to tornadoes rated (E)F1 and higher on the damage scale consistent with advice given by the SPC (Verbout et al. 2006). Hereafter the word 'tornado' in this paper will be understood to refer only to tornadoes that received a damage rating of at least (E)F1.

3 Increasing probability of big tornado days

We begin by plotting the number of tornadoes and the number of days with at least one tornado by year (Fig. 1). The frequency of tornadoes fluctuates widely from year to year. The fewest (311) occurred in 1999 and the most (896) occurred in 2011. Keep in mind these statistics refer to tornadoes receiving a damage rating of at least (E)F1. The mean annual rate is 505 tornadoes per year and the median rate is 474 tornadoes per year. The year-to-year variation is larger than expected under the assumption of a homogeneous Poisson process (Elsner and Widen 2014). Despite this large inter-annual variation in the annual number of tornadoes there is no long term trend.

We also plot the number of days with least one tornado. A day with at least one tornado is called a 'tornado day' (more specifically a 'one-tornado' day). The number of tornado days also varies considerably from year to year with a low of 79 days in 2013 to a high of 187 in 1971. The mean (and median) number of tornado days is 128. In contrast to

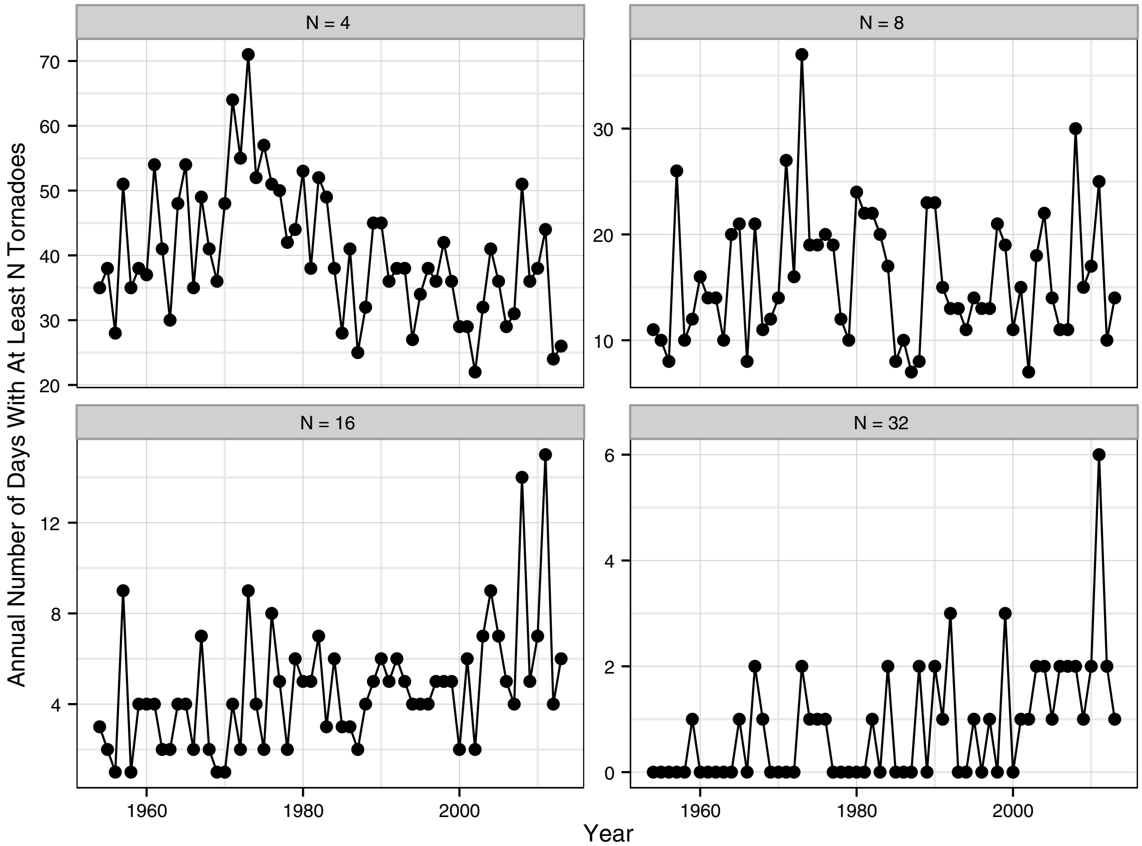

Fig. 2 Tornado days (1954–2013). The annual number of days with at least four, eight, 16, and 32 tornadoes

annual tornado frequency the number of tornado days has been declining since the 1970's. The total number of tornadoes is not trending so the atmosphere must be producing more tornadoes on tornado days (Fig. 2). Here we define four thresholds for tornado days starting with $N = 4$ tornadoes and continuing in powers of two. The starting threshold is based on the fact that a four-tornado day is just above the long term daily mean as indicated by dividing the mean annual tornado count (505) by the mean number of tornado days (128).

There is a downward trend in the number of tornado days when a tornado day is defined by at least four tornadoes but upward trends in the number of tornado days when a tornado day is defined by at least eight, 16, and 32 tornadoes. In particular before 1980 the number of days per year with at least 16 tornadoes averaged between three and four. Since 2000 the average has doubled to seven. The change in the number of days per year with at least 32 tornadoes is even more dramatic. Most years prior to 1990 had no days with 32 tornadoes. However, since 2001 there has been no year without a tornado day with at least 32 tornadoes and in 2011 there were six such days (see Fig. 2d).

The ratio of the number of days with many tornadoes to the total number of one-tornado days is the conditional probability of a big day. Said another way, given a day with at least one tornado the ratio is the probability that the day's tornado count will exceed N tornadoes (Fig. 3). A big is defined for at least four, eight, 16, and 32 tornadoes. Upward trends are noted in all cases (blue lines) with the largest trend occurring when a big day is defined as having at least 32 tornadoes. The trends are a constant percentage increase per year and result in curved lines on the plots with the curvature most pronounced for the biggest tornado days.

Trends are estimated using a maximum likelihood procedure with a generalized linear model having a logarithmic link function and assuming the counts are described by a negative binomial distribution. According to Elsner and Widen (2014) the negative binomial distribution describes annual tornado counts better than a Poisson distribution. Trend values are given in percent per year and range from $.31 \pm .15\,\%/\text{yr}$ (s.e.) for days with at least four tornadoes, $.99 \pm .21\,\%/\text{yr}$ (s.e.) for days with at least eight tornadoes, $2.5 \pm .37\,\%/\text{yr}$ (s.e.) for days with at least 16 tornadoes, and $5.4 \pm .96\,\%/\text{yr}$ (s.e.) for days with at least 32 tornadoes.

A somewhat different perspective is obtained by computing the proportion of tornadoes occurring on big days.

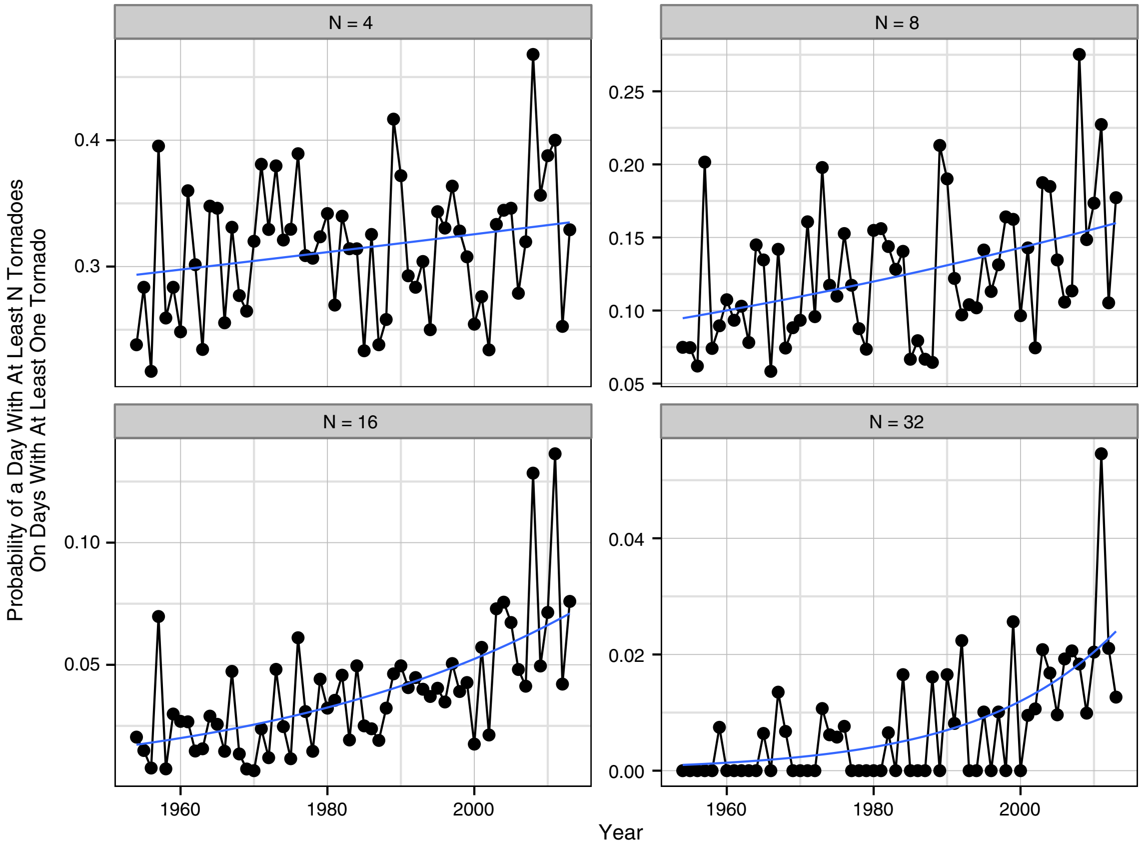

Fig. 3 Annual probability of a big tornado day on a day with at least one tornado. Probabilities are computed for days having at least 4, 8, 16, and 32 tornadoes

That is we determine the percentage of all tornadoes during a given year that occur on big days (Fig. 4). Upward trends are noted in all cases (blue lines) with the largest trends occurring when a big day is defined as having at least 32 tornadoes. Trend values are given in percent per year and range from $1.2 \pm .14\,\%/\mathrm{yr}$ (s.e.) for days with at least four tornadoes, $1.9 \pm .16\,\%/\mathrm{yr}$ (s.e.) for days with at least eight tornadoes, $3.3 \pm .26\,\%/\mathrm{yr}$ (s.e.) for days with at least 16 tornadoes, and $5.6 \pm .67\,\%/\mathrm{yr}$ (s.e.) for days with at least 32 tornadoes.

Trends are computed on four subsets of the data since 1954, 1974, 1984, and 1994 (Fig. 5). Trends range between a few percent per year up to nearly 10 % per year depending on the data subset and the definition of a big tornado day. In most cases there is a significant upward trend. In general the largest trend magnitude occurs on days with the most tornadoes. The trends are insensitive to what year the analysis begins.

These trends represent observational evidence of changes in severe deep moist convection possibly related to our changing climate. If we define efficiency as the atmosphere's ability to generate the same number of tornadoes on fewer days, then these upward trends indicate increasing efficiency of severe convection. A portion of the trend could be the result of changes in data collection procedures. However, increasing data collection efforts would likely result in more tornado days and thus a decrease in the conditional probability of a big day.

4 The increasing spatial density of tornadoes

An explanation for the increasing efficiency (more big tornado days) is simply larger areas favorable for tornadoes. We call this the large-scale hypothesis because it hints at the involvement of larger scale dynamical factors like vertical wind shear as the cause rather than smaller scale local thermodynamics. To examine evidence for this hypothesis, here we consider changes to the spatial dimensions of tornado occurrences. We begin by defining tornado clusters.

4.1 Tornado clusters

On a day with more than a few tornadoes the geographic area encompassing the touchdown locations varies over several orders of magnitude (e.g., 10–10^6 km^2) so we group

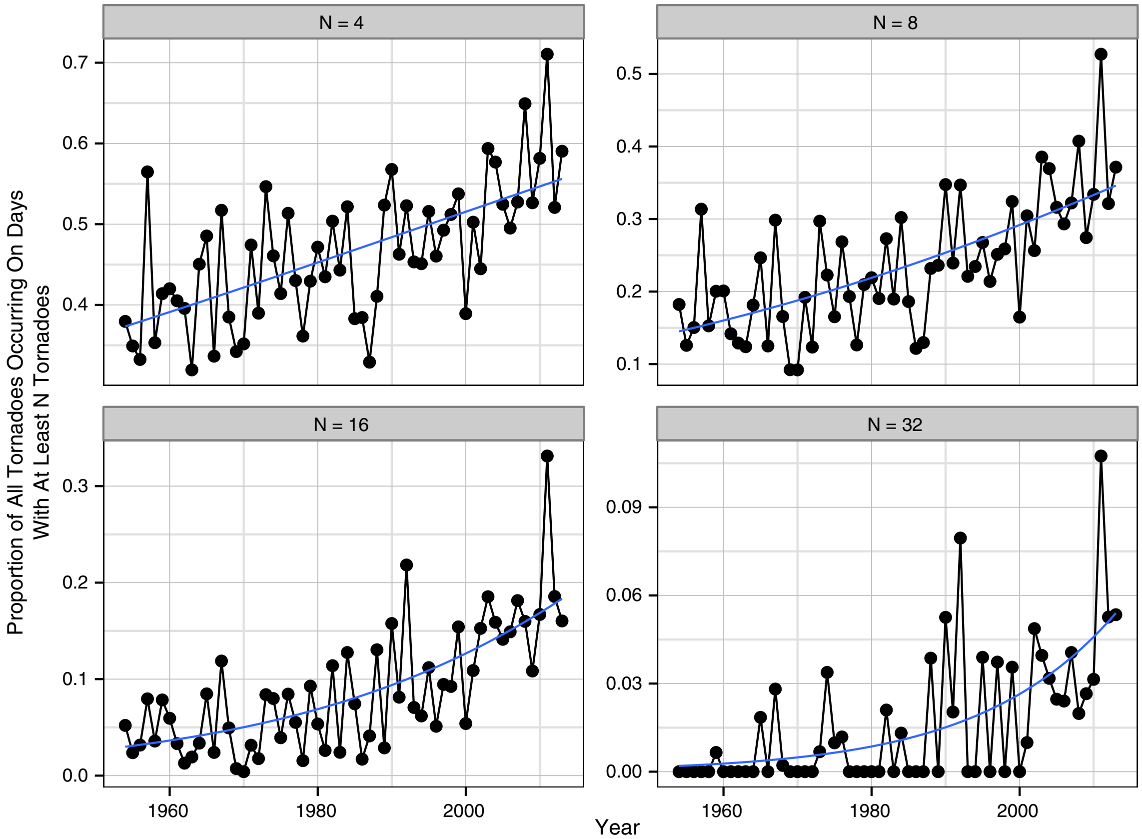

Fig. 4 Annual proportion of all tornadoes each year that occurs on big days. Proportions are computed for days having at least four, eight, 16, and 32 tornadoes

the tornadoes into clusters. A tornado cluster is defined as a set of touchdown locations. A day with more than one cluster has more than one distinct tornado area with the areas separated by a distance greater than the average within-cluster tornado distance.

On each tornado day we determine the number of clusters using a method that groups touchdown locations based on a partitioning around the medoids (Reynolds et al. 1992). The medoid is a representative touchdown location for the cluster whose average distance to all other tornado locations in the cluster is minimal. It is similar to a centroid, but the medoid is an actual tornado location (think mean versus median). The algorithm is coded in R using the *pamk* function from the fpc package (Hennig 2014) and determines whether there is more than one cluster using the Duda-Hart test (Duda and Hart 1973). Distances are computed using a Lambert conformal conic projection.

Figure 6 shows the results from the cluster procedure. The left panel is an example from May 8, 2008 showing the touchdown locations with black dots, the medoids with red circles, and the area of the two clusters with gray shading. The area is delineated by computing the convex hull around the clustered touchdown locations and adding a 40 km buffer around the hull. The convex hull is the minimum area encompassing the locations that retains a convex shape. The buffer distance corresponds to SPC's forecast probabilities defined as the chance of a tornado occurring within 25 miles of any point.

The two clusters represent distinct regions of elevated tornado risk. In this case the clusters roughly match the two 5 % forecast probability contours on the tornado outlook issued at 1630 UTC on May 8, 2008 by the SPC. The day featured a shortwave trough lifting northeastward from Arkansas. A round of late morning and early afternoon severe convection occurred across northern Alabama and adjoining states followed by a round of late evening severe convection across North Carolina and Virginia.

The right panel shows the locations and size of all medoids on days with at least 16 tornadoes over the period 1954–2013. The distribution is fairly homogeneous over a large part of the Midwest and South. Fewer clusters are noted in the High Plains and over the Appalachian Mountains. There is some evidence of somewhat larger clusters over the Ohio and Tennessee Valleys.

Other cluster methods have been applied to tornado data including merging areal buffers around tornado tracks

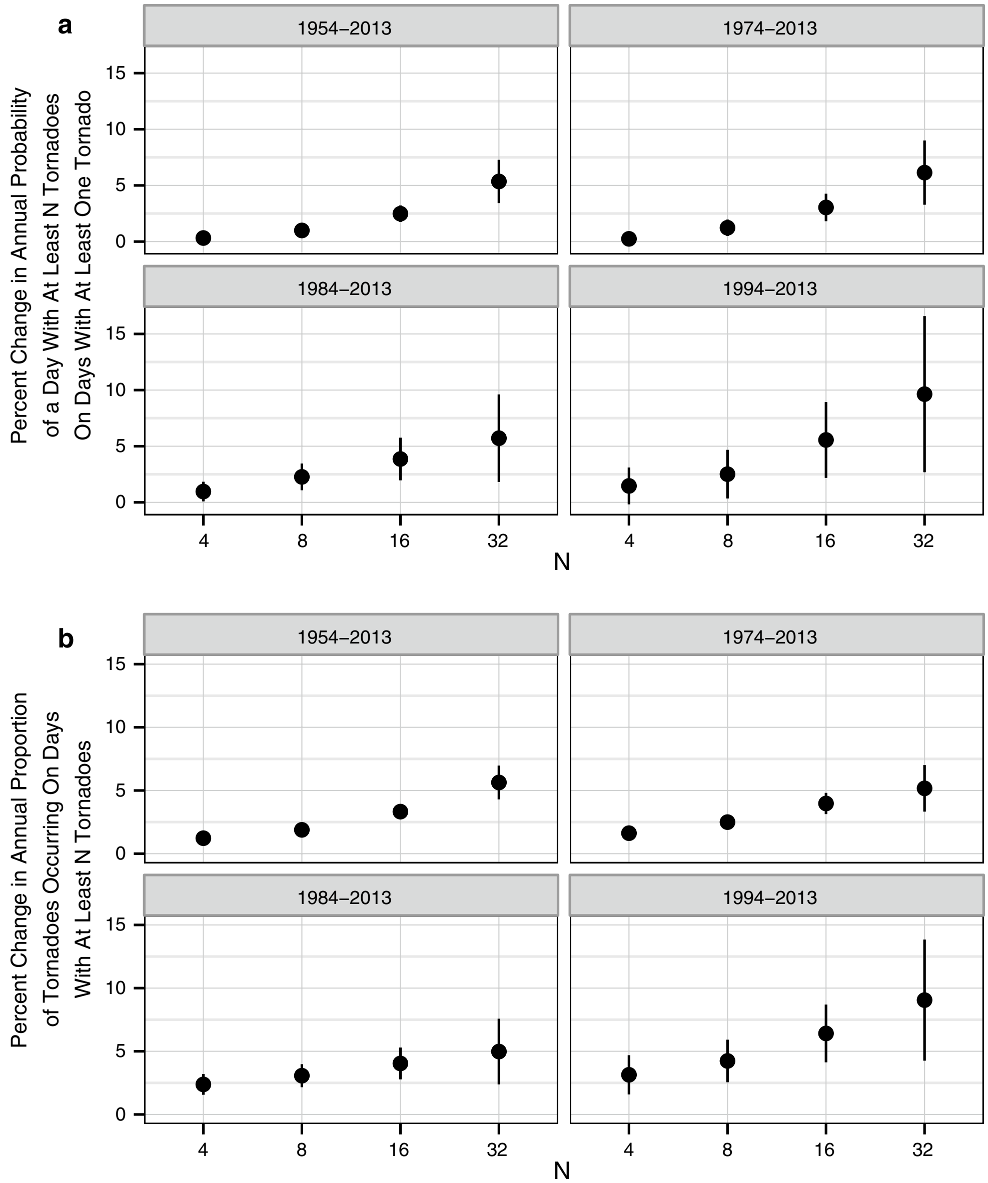

Fig. 5 Trends in big tornado days. **a** Percent change in the annual probability of at least N tornadoes for $N = 4, 8, 16$, and 32 on days with at least one tornado. **b** Percent change in the annual proportion of tornadoes occurring on days with at least $N = 4, 8, 16$, and 32 tornadoes. The estimated trend is given as a *dot* and the 95 % uncertainty level is given as a *vertical line*. Trends are estimated using four subsets of the data including 1954–2013, 1974–2013, 1984–2013, and 1994–2013

(Dean 2010) and kernel density estimation (Shafer and Doswell 2011). For our purpose the medoid approach has the advantage that it includes all tornadoes on a given day and the results are easier to interpret since the procedure does not require a bandwidth distance. The method is objective allowing for a quick delineation of tornado clusters on any day. The single parameter is the significance level (here kept at .05) for the Duda-Hart test, which determines if there is more than one cluster. No parameter is needed to determine the number of clusters beyond one.

4.2 Changes in cluster statistics

Over the study period there is an annual average of about two clusters per day on tornado days with at least 16 tornadoes (Fig. 7). On an annual basis the total area of the clusters is about 1.5 million square km. The number of clusters is trending slightly upward and the total cluster area is trending slightly downward, but neither change is statistically significant. Thus, the upward trend in the proportion of tornadoes occurring on big days discussed in the

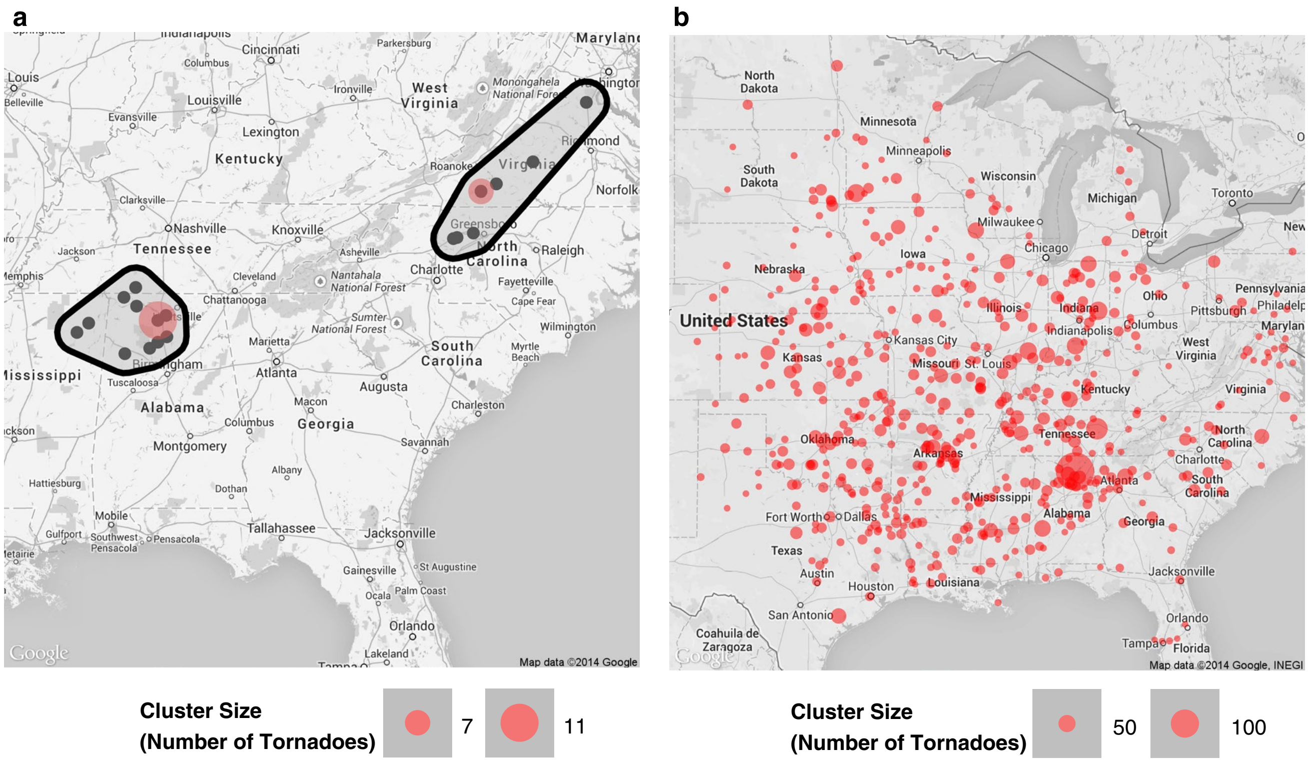

Fig. 6 Tornado clusters. **a** An example from May 8, 2008 showing the touchdown locations (*black dots*), the medoids (*red circles*), and the cluster area (*gray shading*). The cluster area is a 40 km around the convex hull. **b** Medoids of all clusters over all days with at least 16 tornadoes (1954–2013). The size of the *circle* is proportional to the number of tornadoes in the cluster

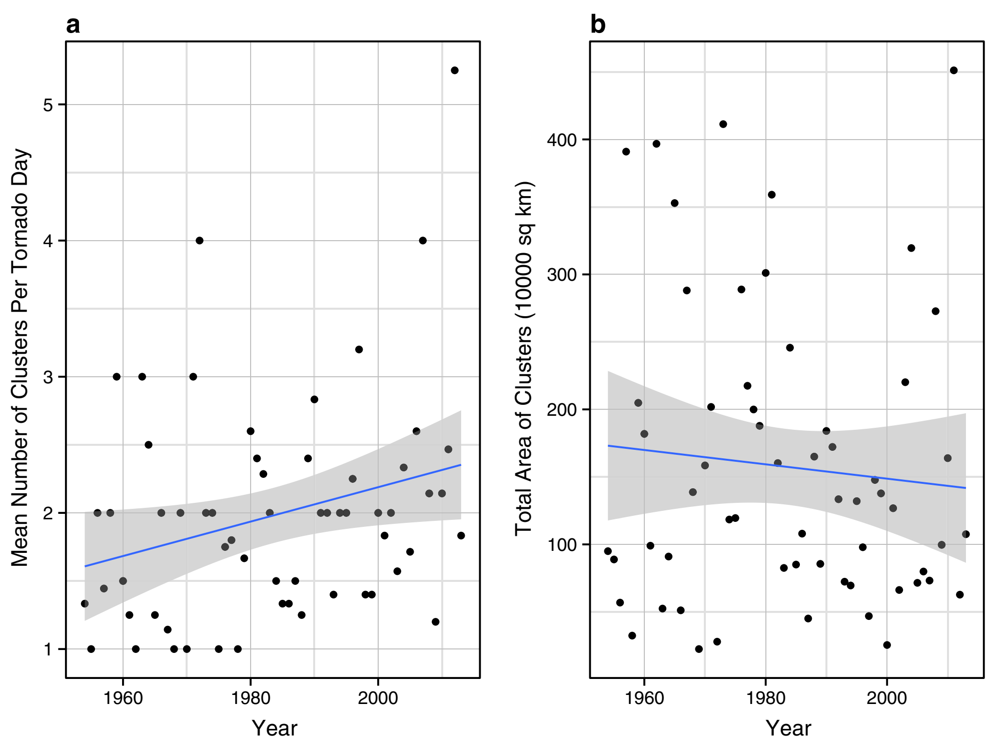

Fig. 7 Annual frequency and area of tornado clusters on days with at least 16 tornadoes. **a** Number of clusters per tornado day and **b** Total area of clusters. The trend line (*blue*) is a linear regression onto year with the *gray band* indicating the 95 % uncertainty around the trend value

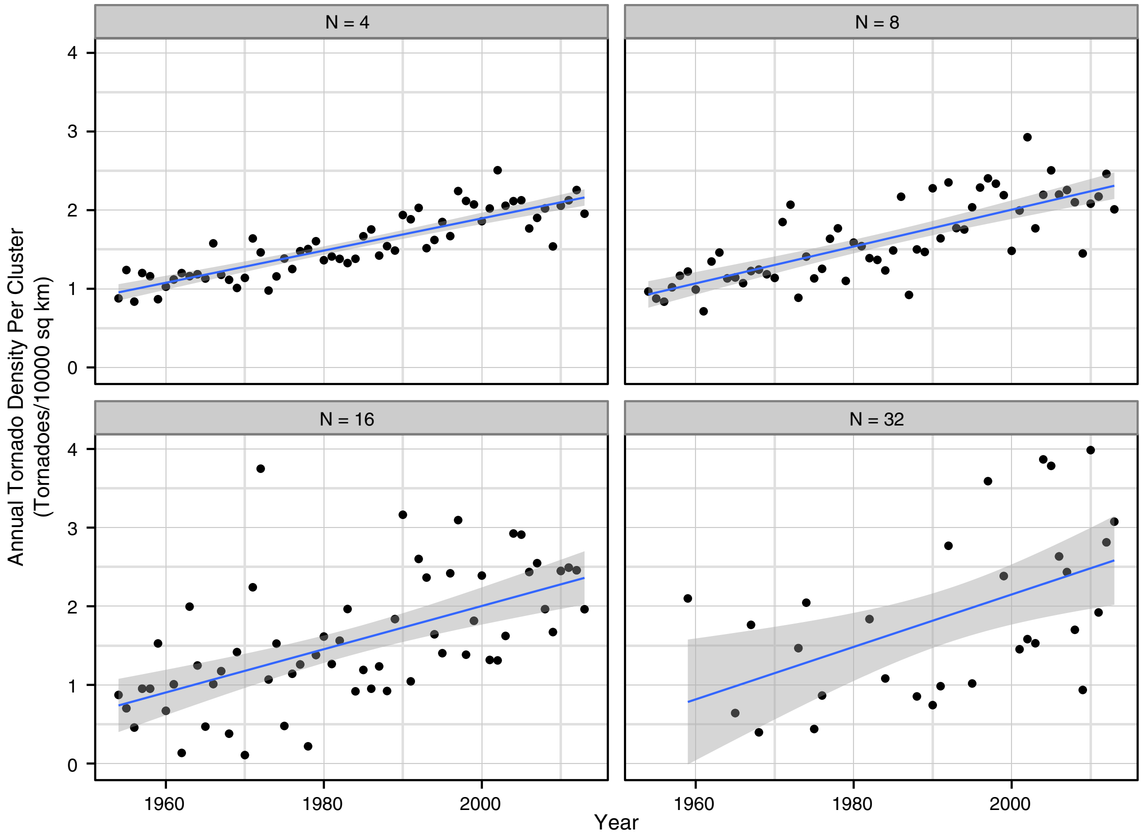

Fig. 8 Annual cluster number density at the four threshold levels defining a tornado day. The trend line (*blue*) is a linear regression onto year with the *gray band* indicating the 95 % uncertainty around the trend value

previous section is not a direct result of larger areas favorable for tornadoes.

There is a significant upward trend in the annual number of tornadoes per cluster area (cluster number density) (Fig. 8). The percent changes over the 60-year period range from a low of 123 % for tornado days defined by at least four tornadoes to 200 % for tornado days defined by at least 32 tornadoes. Thus, the upward trend in the proportion of tornadoes occurring on big days appears to be related to an increasing concentration of tornadoes rather than to larger areas favorable for deep convection. These results are similar to increases in heavy precipitation days during the 20th century over the United States (Groisman et al. 2004).

5 Summary and discussion

We present empirical evidence of changes in tornado climatology possibly related to a changing climate. We do this by examining the annual number of days with many tornadoes and the ratio of these days to days with at least one tornado as well as by checking the annual proportion of tornadoes occurring on days with many tornadoes. We also do this by exploring characteristics of spatial tornado clusters.

We find a consistent decrease in the number of days with at least one tornado but at the same time an increase in the number of days with many tornadoes. This results in an increasing proportion of tornadoes occurring on big tornado days, which we define as an increasing efficiency of the atmosphere to produce tornadoes. Coincident with these changes we find increases in tornado density as defined by the number of tornadoes per cluster area. It appears that the risk of big tornado days with densely concentrated clusters of tornadoes is increasing.

The increasing density of tornado occurrences within clusters suggests that the explanation for an increasing proportion of tornadoes occurring on big days might involve local-scale thermodynamics. In particular we hypothesize that increases in both CAPE driven by increases in low-level moisture and CIN driven by warming aloft could lead to fewer days with tornadoes and to smaller, but more active, areas of severe convection on days with tornadoes. These findings and speculations are broadly consistent with numerical modeling studies (Genio et al. 2007; Trapp et al. 2007; Diffenbaugh et al. 2013) of future

tornado environments especially those indicating that when deep convection occurs it may more likely become severe (Klooster and Roebber 2009).

Interpretation of the results rely on a consistent set of tornado data. As noted by an anonymous reviewer of an earlier draft, recent reporting practices with greater skill at interpreting damage might have changed some events to wind reports that would have been reported as tornadoes in the past [see Speheger et al. (2002) for a discussion]. This potential report bias might have some impact on the decline in the number of tornado days.

This research can be extended by investigating environmental conditions at the scale of the tornado clusters. We suggest an approach similar to that used by Dean (2010) but with a continuous variable space involving cluster size, shape (e.g., cluster roundness, etc) to characterize cluster environments of CAPE, CIN, and bulk shear. Further, the correspondence between tornado clusters and tornado outbreaks needs to be considered. A similar analysis can be performed on hail events. Another avenue of research involves the estimation of total energy within a cluster. This could be done by adding per tornado energy estimates over all tornadoes in the cluster.

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