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Relationship between sounding derived parameters and the strength of tornadoes in Europe and the USA from reanalysis data

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ABSTRACT

Proximity soundings from reanalysis data for tornado events in Europe for the years 1958 to 1999 and in the US for the years 1991 to 1999 have been used for generating distributions of parameter combinations important for severe convection. They include parcel updraft velocity (WMAX) and deep-layer shear (DLS), lifting condensation level (LCL) and deep-layer shear (DLS), and LCL and shallow-layer shear (LLS) for weak and significant tornadoes. We investigate how well they discriminate between weak and significant tornadoes. For Europe, these distributions have been generated for unrated, F0 and F1 tornadoes as well to discover if the unrated tornadoes can be associated with the weak tornadoes.

The pattern of parameter combination distributions for unrated tornadoes in Europe strongly resembles the pattern of F0 tornadoes. Thus, the unrated tornadoes are likely to consist of mostly F0 tornadoes. Consequently, the unrated tornadoes have been included into the weak tornadoes and distributions of parameter combinations have been generated for these.

In Europe, none of the three combinations can discriminate well between weak and significant tornadoes, but all can discriminate if the unrated tornadoes are included with the weak tornadoes (unrated/weak). In the US, the combinations of LCL and either of the shear parameters discriminate well between weak and significant tornadoes, with significant tornadoes occurring at lower LCL and higher shear values than the weak ones. In Europe, the shear shows the same behavior, but the LCL behaves differently, with significant tornadoes occurring at higher LCL than the unrated/weak ones. The combination of WMAX and DLS is a good discriminator between unrated/weak and significant tornadoes in Europe, but not in the US, with significant tornadoes occurring at a higher WMAX and DLS than the unrated/weak tornadoes.

1. Introduction

There have been many studies that have focused on the environments in which tornadoes form. Good discriminators between significant severe and less severe thunderstorms and tornadic and non-tornadic thunderstorms have been found to include Convective Available Potential Energy (CAPE), wind shear (e.g. Brooks et al., 2003b; Rasmussen and Blanchard, 1998; Craven et al., 2002a,b) and the height of the Lifting Condensation Level (LCL) (Brooks et al., 2003b; Rasmussen and Blanchard, 1998). Rasmussen and Wilhelmson (1983) found that tornadic storms appear to form in high CAPE, high shear environments, whereas non-rotating thunderstorms usually form in low CAPE, low shear environments. Brooks et al. (2003b) stated that significant severe thunderstorms[1] are usually formed in high CAPE, high shear

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[1] The term "significant severe thunderstorm" comes from US usage and includes storms that produce hail with a diameter of at least 5 cm, wind gusts of 120 km/h or more and/or a significant tornado (F2 or greater) (Hales, 1988).

environments. Rasmussen and Blanchard (1998) found that thunderstorm environments with lower (higher) LCL heights were more likely to be associated with significant (weak or no) tornadoes. Thompson et al. (2003) found the parameters CAPE, wind shear and LCL also discriminate between significantly tornadic and non-tornadic supercells. CAPE and wind shear were found to be higher for the significantly tornadic supercells, whereas the LCL was found to be lower for that category.

For Europe, studies concerning the relationship between the parameters CAPE, wind shear and the LCL have been carried out by Kaltenböck et al. (2009) and by Groenemeijer and van Delden (2007) for the Netherlands. Kaltenböck et al. (2009) found that F2 and F3 tornadoes are usually associated with higher shear than the weaker tornadoes. Significant tornadoes are also more likely the lower the LCL height is. In the Netherlands, LCL and CAPE are not useful parameters in distinguishing between tornadic and thunderstorm environments. The shear can distinguish between the strength of tornadoes with stronger tornadoes associated with higher shear (Groenemeijer and van Delden, 2007).

In this study, we will examine the relationship of the strength of tornadoes in association with the parameters CAPE, shear and LCL. Therefore, the effect of combinations of the parameters CAPE (in terms of parcel updraft velocity WMAX), DLS (deep-layer shear, the magnitude of the vector wind difference between the surface and 6 km), LLS (low-level shear, surface to 1 km) and the LCL height are analyzed for weak (F0, F1) and significant (F2 and greater) tornadoes in Europe as well as in the US. Differences between Europe and the US will be discussed.

We are also interested in the tornadoes in the European Severe Weather Database (ESWD) (Dotzek et al., 2009) that have not been assigned damage ratings. Unlike the US dataset, for which all tornadoes are rated, some of the ESWD tornadoes have no ratings assigned. We will examine the hypothesis that the unrated tornadoes are likely to be weak. This is of importance because the dataset for the weak tornadoes is small with an apparent underreporting of F0 tornadoes (Dotzek et al., 2009). If the unrated tornadoes do, indeed, resemble the weak tornadoes, we can add those to the dataset of weak tornadoes with some confidence. Thereafter, distributions of all three parameter combinations of the weak tornadoes including the unrated tornadoes in Europe will be compared to the distributions of the significant tornadoes in Europe. In the following, Section 2 deals with the data that were used. The results are presented in Section 3 and Section 4 provides a summary and a discussion of the results.

2. Data and methodology

The data that were used for this study are from the ESWD for the years 1958 to 1999 and the Storm Prediction Center (SPC) for the years 1991 to 1999 for the US. The US dataset consisted of 4510 (3957 weak and 553 significant) tornado events, whereas the European dataset consisted of only 303 (66 weak, 122 significant and 115 unrated) tornado events. No data have been used after 1999, since the analyzed soundings were only created through then. In addition, Doswell et al. (2009) showed that significant changes in the US tornado rating practices took place after that date. The European dataset is geographically biased towards central European countries (Romero et al., 2007) since only some of the European countries have already converted their data to ESWD format (Dotzek et al., 2009). Also there has been an underreporting in the years prior to 2004 in the eastern and south-western parts of Europe (Dotzek et al., 2009). The ESWD data have different verification levels assigned to them. These are QC0: "as received", QC0+: "plausibility checked", QC1:" report confirmed" and QC2: "event fully verified" (Dotzek et al., 2009). For this study, we have used data from all verification levels.

The environmental parameters that will be analyzed here have been derived from the National Center for Atmospheric Research (NCAR)/United States National Center for Environmental Prediction (NCEP) reanalysis (Kalney et al., 1996) for the closest location to the tornado in time and space. In order to represent proximity soundings, so-called "pseudo soundings" (Brooks et al., 2003b) were created from the reanalysis data to create the environmental information.

Proximity soundings were used here because in several studies they have proven to be useful in describing the environmental conditions a severe weather event is associated with. (e.g. Brooks, 2009; Brooks et al., 2003b, 2007; Craven and Brooks, 2004; Rasmussen and Blanchard, 1998; Groenemeijer and van Delden, 2007). This is done by finding a group of parameters that could distinguish between different types of weather, for example tornadic and non-tornadic (Brooks et al., 2003b). The reanalysis produces a sounding every 6 h for each of the 192×94 grid points over the whole globe with a spatial resolution of 1.875° in longitude and 1.915° in latitude, which accounts for a grid spacing of approximately 200 km. As a result, the proximity criteria are that the sounding is taken within 3 h and 180 km of the tornado. The atmospheric fields each reanalysis sounding provides, including surface height (in terms of geopotential), surface pressure, virtual temperature, specific humidity, divergence and vorticity, are available at 28 levels in the vertical except surface height and surface pressure. For more details on the sounding development, see Brooks et al. (2003b).

By using the reanalysis data it is assured that every event will be associated with a sounding while keeping with the definition of proximity, whereas every event is always associated with the nearest sounding in space and time. The observational sounding network itself does not provide as complete coverage as the reanalysis (Brooks et al., 2003b). The inherent trade-off is with the representativeness of reanalysis-based soundings.

Proximity soundings, whether from observations or derived from reanalysis, contain errors that have to be taken into account. The errors and problems of the observational soundings include the temporal and spatial variability of the air mass within the environment of an event (Brooks et al., 1994; Doswell, 1982; Davies-Jones, 1993), which means that a proximity sounding might not necessarily represent the "real" environment in which the event took place (Brooks et al., 1994). It is possible that a sounding could be taken on the other side of a significant boundary from the event, for example a front or a dryline and thus does not sample the air mass an event is associated with (Brooks et al., 1994). More challenging, Brooks et al. (1994) showed that if there is strong mesoscale variability, it is possible that environments represented by soundings may not be representative for the environment in which the actual event happens, even if they are close in time and space. They (Brooks et al., 1994) also found that, for tornadic environments, the environment can change considerably between the sounding times and it is possible that CAPE values, for example, can change radically within only a few minutes in time and a few kilometers in space.

The limits for the proximity could be set smaller in order to have a sounding closer to where the real event took place, and thus minimize the problem with the variability of the air mass. However, that would mean that the dataset would be much smaller since not every event could be associated with a sounding. If the dataset is too small, no useful proximity studies could be achieved. That is why the proximity limits are chosen to be coarser, even though this might blur the results (Brooks et al., 1994).

The reanalysis also has issues that must be considered when interpreting results derived from those data. For example, the reanalysis does not represent all parameters that are important in the development of tornadoes (Brooks et al., 2003b). Capping inversions that could play a role in suppressing convection should not be expected to be represented by the reanalysis. It also does not contain information on the initiation of convection or interactions with boundaries (Markowski et al., 1998). Mesoscale effects cannot be represented by global model data. This may be especially important in interpreting the results for Europe, since in Europe the synoptic forcing is believed to be stronger and the presence of boundaries (for example due to topography) to be more frequent than in the US (Brooks, 2009). The synoptic forcing as well as local influences, such as orography are the most common factors in the initiation of a thunderstorm in Europe (Kaltenböck et al., 2009).

In order to get parameters that are important for convection out of the reanalysis data, the Skew-t/Hodograph Analysis and Research Program (SHARP) (Hart and Korotky, 1991) was used, which produces these parameters out of the reanalysis data. For both, Europe and the US the CAPE = 0 soundings were removed, because these might not represent the air mass in which the event took place, as well as the challenges they add to any analysis. The values for the parcel updraft velocity (hereafter referred to as WMAX) were calculated directly from the CAPE values, with WMAX equaling the square root of 2× CAPE (Holton, 1992). The WMAX is a velocity based on parcel theory. It represents the maximum velocity a statically unstable parcel can have when it rises, assuming it does not mix with the environment and it adjusts instantaneously to the local environmental pressure while rising (Holton, 1992). In this study the WMAX instead of CAPE was interpreted. Typically, CAPE has been used (e.g., Brooks et al., 2003b), but we are using WMAX here for a couple of reasons. Usually, the large range of values for CAPE has forced discrimination techniques to use something like the logarithm of CAPE in order to make the analysis less sensitive to extreme values of CAPE. WMAX represents another approach to reducing the dynamic range. It also has an intuitive appeal in that the units are the same as that frequently used to describe shear, if the shear is calculated over a constant layer, as in this study and in many operational applications. The CAPE that has been used here for calculating the WMAX was based on a parcel that is mixed over the lowest 100 hPa and then lifted using a virtual temperature correction. More information about the virtual temperature correction can be obtained in Doswell and Rasmussen (1994). The LCL height was also calculated based on a parcel that is mixed over the lowest 100 hPa.

In order to analyze the effects of the parameters on the strength of tornadoes, density distributions for combinations of two parameters have been generated for the various tornado classes of interest. The combinations include WMAX/DLS, LCL/DLS and LCL/LLS. Besides the density distribution, the Wilcoxon–Mann–Whitney significance test (Wilks, 2006) has been applied to combinations of weak/significant tornadoes in the US and Europe and to combinations of unrated/rated, unrated/weak, unrated/F0, unrated/F1 and unrated + weak/significant tornadoes just for Europe. This has been done for each of the four parameters (WMAX, DLS, LLS, LCL). The Wilcoxon–Mann–Whitney test has been carried out in order to show the significance of the results that are derived from the density distributions.

The distributions are estimated using a non-parametric density estimation technique (Silverman, 1986). No assumptions are made about the nature of the distribution and a Gaussian kernel was applied to the data (e.g. Brooks et al., 2003a). The density estimate technique can be thought of as the application of a smoother. This has been done, because the values of the parameters that come out of SHARP are based on reanalysis data and represent isolated observations only. By applying the smoother you get a distribution that is consistent to the underlying hypothetical "true" distribution of these isolated observations, which is the distribution of environmental conditions (but here just shown for the three mentioned parameter combinations) that support a tornado event. The sigma parameter for the Gaussian was 5 m s^{-1} for WMAX, DLS, and LLS, and 500 m for the LCL. These are relatively heavy smoothing intervals, but the tornado datasets are not very large and thus these heavier smoothing intervals were used in order to get a reasonable picture of the distributions from the datasets. This means that the overall distribution should be representative of the true distribution, but details have been smoothed out. This is a consequence of the trade-off between the desire for a large sample size in order to see details and the practical limitations of the length of time to collect such a sample.

While applying the smoother on each parameter combination, an analysis grid was created. For the combination WMAX/DLS the analysis grid consisted of 100 × 100 grid points, for the combination LCL/DLS of 40 × 100 and for the combination LCL/LLS of 40 × 40 grid points. The grid size was 1 m s^{-1} for DLS, LLS and WMAX and 100 m for the LCL. Each analysis grid point contains a value of how likely it is for the combination of parameter values that it represents (for example WMAX = 20 m s^{-1} and DLS = 15 m s^{-1}) to appear in a tornado sounding. The more often a tornado occurs near a certain grid point, the higher the value of that grid point. The value of each grid point was calculated by using the Gaussian smoother, which assumes that a certain combination of parameter values (for example WMAX = 20 m s^{-1} and DLS = 15 m s^{-1}) provides information about another combination of parameter values close to it (for example WMAX = 20 m s^{-1} and DLS = 18 m s^{-1}), but provides little information on combinations of parameter values further away from it (for example WMAX = 40 m s^{-1} and DLS = 35 m s^{-1}).

The smoother was applied on the different combinations of parameters, but for each of these parameter combinations the different F-scales were separated, resulting in an analysis field for each different F-scale for each parameter combination. This was done in order to know the probability of the different combinations of parameter values for every different type (F-scale) of tornado to occur. For Europe, a field for the unrated tornadoes was also created for each parameter combination.

The density distributions are based on the values of the analysis fields. For the distributions of the weak tornadoes, the values for each same grid point of the F0 and F1 analysis grids have been summed up before generating the distribution. This has been done separately for Europe and the US and for each different parameter combination. For the significant tornadoes the values of the same grid points for the F2 and stronger tornadoes have been summed up. The unrated + weak field was created in a similar way.

To see the differences between the unsmoothed and the smoothed data distribution, example scatter plots of the significant tornadoes for the combination LCL/LLS have been generated and overlaid by the corresponding density distribution (Fig. 1). The impact of the smoother can be seen well here. Both scatter plots for the US and Europe do not show any data points for LCL heights lower than about 400 m. However, both density distributions show density lines for LCL heights until 0 m as a result of the heavy smoother. If the interval had been smaller, for example 100 m, density lines would probably not be shown for the low LCL values, but there might be details implied in the middle of the field, such as at about LCL = 1000 m and LLS = 12 m s^{-1} for the US (Fig. 1a).

The plotted density distributions do not contain explicit information about the maximum ranges of the data because of choices in the contouring, which represents the number of soundings in the dataset at each parameter combination in the field. We have chosen to display a limited number of lines on each figure. Given the greater number of events in the US database, using the same contour interval on both US and European data would lead to many more lines on the US plots. The impact can be seen especially in Fig. 1a since there are data points located at higher LCL values than the density line which is associated with the lowest plotted density. Comparing both plots for the US and Europe, the density line with the lowest density for Europe reaches a higher LCL value (about 2200 m) than the one for the US (about 1900 m), even though the scatter plot for the US has more data points located at higher LCL values than the scatter plot for Europe. This is due to the contour interval choice as a result of the different sample sizes of the two datasets. The highest contour value for Europe is equal to the lowest plotted contour in the US plot. The density plots are useful for getting quantitative information on the relationships between parameter combinations across the field, and, to a lesser extent, qualitative information to compare different fields.

3. Results

3.1. Combination of updraft velocity and deep-layer shear

The density distribution for the weak and significant tornadoes in the US (Fig. 2a) for WMAX/DLS shows that significant tornadoes occur with higher DLS values than weak

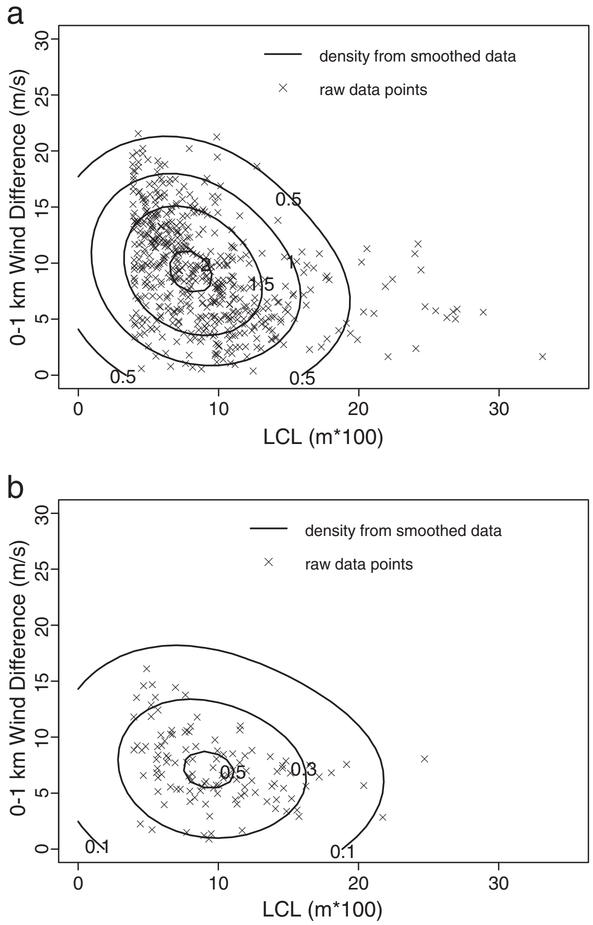

Fig. 1. Distribution of smoothed and unsmoothed data for significant tornadoes in a) the US and b) Europe for the combination LCL/low-level shear. Sample size: a) n = 553, b) n = 122. Values of contour lines, from inside to outside, are: a) 2, 1.5, 1 and 0.5, b) 0.5, 0.3, 0.1. The contours are occurrences per grid point over the database. For example, the 0.5 contour line of the significant tornadoes in the US shows for which grid points (combinations of parameter values) 0.5 events occur at that grid point for the significant tornadoes in the US.

tornadoes. The WMAX values for significant tornadoes, however, are about the same as for the weak ones, except that they are also spread out more to higher as well as lower WMAX values. The WMAX distributions for weak and significant tornadoes in the US are not statistically significantly different (95% significance level), according to the Wilcoxon–Mann–Whitney test (Table 1). The DLS values of the two datasets on the other hand are statistically significant at the 99% confidence level.

The density plots for the weak and the significant tornadoes in Europe (Fig. 2b) show that more significant tornadoes are occurring at higher DLS and WMAX values than the weak ones. That is, stronger tornadoes are usually associated with higher DLS and WMAX values. The maximum for the significant tornadoes is spread out more to higher WMAX values than the one for the weak tornadoes. Thus, for the significant tornadoes, there is more variability in the WMAX than for the weak tornadoes. The combination WMAX/DLS seems to discriminate between weak and

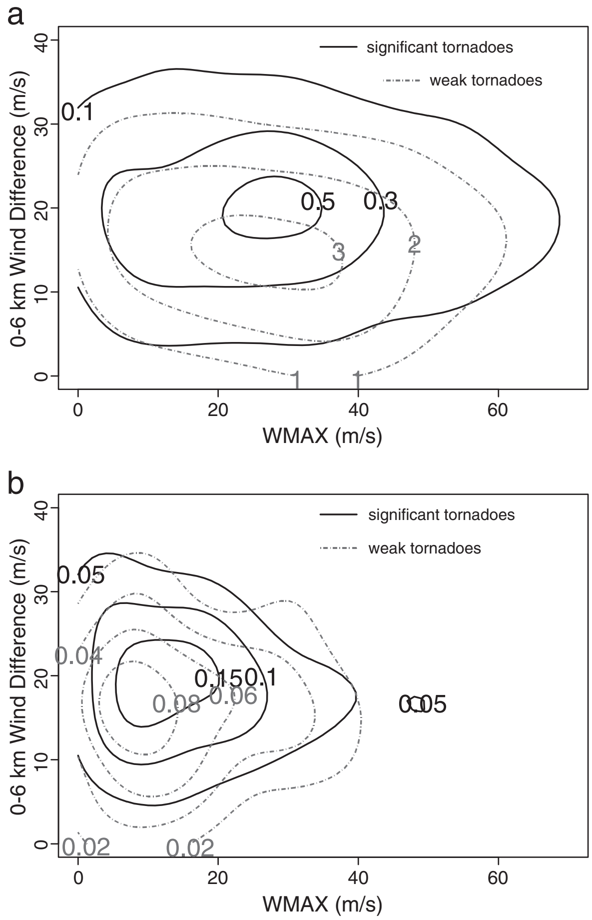

Fig. 2. Density distributions of weak (F0, F1) and significant (F2+) tornadoes for the parameter combination WMAX/deep-layer shear for a) the US and b) Europe. Values of contour lines, from inside to outside, are: a) 0.5, 0.3 and 0.1 for significant and 3, 2 and 1 for weak tornadoes, b) 0.15, 0.1 and 0.05 for significant and 0.08, 0.06, 0.04 and 0.02 for weak tornadoes. The contour value of the small area in Fig. 2b at approximately WMAX = 50 m/s is 0.05 for significant tornadoes. Sample size: a) n = 3957 for weak, n = 553 for significant tornadoes, b) n = 66 for weak, n = 122 for significant tornadoes.

significant tornadoes in Europe. As with the US, the WMAX distributions are not statistically significantly different, but the DLS distributions are different (99% confidence level) (Table 1).

Comparing the density distributions for weak and significant tornadoes in Europe and the US (Fig 2a and b), the distribution of weak tornadoes in the US is spread out more for WMAX than in Europe. This implies that in the US there is a greater variability in the WMAX for weak tornadoes than in Europe. Another difference between Europe and the US is that in the US the outer contour lines for weak as well as for significant tornadoes reach higher WMAX values than the ones in Europe. Thus, in Europe tornadoes do not usually occur for very high WMAX values, whereas in the US this is more likely. This is a result of the generally lower values of CAPE in Europe (Brooks et al., 2003b). This is because the generators for high CAPE, which are high lapse rates in the mid-troposphere and high values of boundary-layer moisture, usually do not occur in Europe as often as in the US. The reason for this is the presence of the Rocky Mountains which high terrain accounts for the creation of high lapse rates and the presence of the Gulf of Mexico which is big and warm enough to provide abundant moisture on many days of the year.

3.2. Combination of LCL and deep-layer shear

The plot for the density distributions of the combination LCL/DLS for the weak and significant tornadoes in the US (Fig. 3a) points out the differences between the occurrence of weak and significant tornadoes. Significant tornadoes tend to occur at higher DLS and lower LCL values than weak tornadoes. Also, the maximum for the weak tornadoes is spread out more than the one for the significant tornadoes which means there is more variability in the values of DLS and LCL height for the weak tornadoes. Another thing that is evident from the density plot is that there are weak tornadoes occurring for much higher LCL heights and lower DLS values than the significant tornadoes do, since the outer contour intervals of the weak tornadoes reach lower values for the DLS and higher values for the LCL. On the other hand, weak and significant tornadoes both occur at low LCL and high DLS values. This suggests that for the significant tornadoes there is a lower threshold for the DLS and an upper threshold for the LCL height in the US. The results of comparing weak and significant tornadoes for the US for the individual parameters LCL and DLS are statistically significant at the 99% confidence level (Table 1). Consequently, this supports the result that the combination of DLS and LCL can be considered as a good discriminator between weak and significant tornadoes in the

Table 1
P-values derived from the Wilcoxon–Mann–Whitney Test for different combinations of datasets, for the different parameters. The compared datasets are statistically significant at the 99% confidence level, if p < 0.005, statistically significant at the 98% confidence level, if p < 0.01, statistically significant at the 96% confidence level if p < 0.02 and statistically significant at the 95% confidence level if p < 0.025.

		WMAX	DLS	LLS	LCL
US	weak/sig	0.06547066	5.6828E−23	5.1349E−31	2.272E−23
Europe	weak/sig	0.23350515	0.00370489	0.00571282	0.23033537
	unrated/rated	0.00026392	3.9683E−07	3.9747E−12	0.00789965
	unrated/weak	0.01456876	0.0184068	2.8334E−05	0.10240248
	unrated/F1	0.00755077	0.00621795	8.2477E−07	0.09531394
	unrated/F0	0.4933485	0.31435801	0.18842865	0.38416226
	weak + unrated/sig	0.00275786	9.1117E−08	4.0193E−10	0.01552645

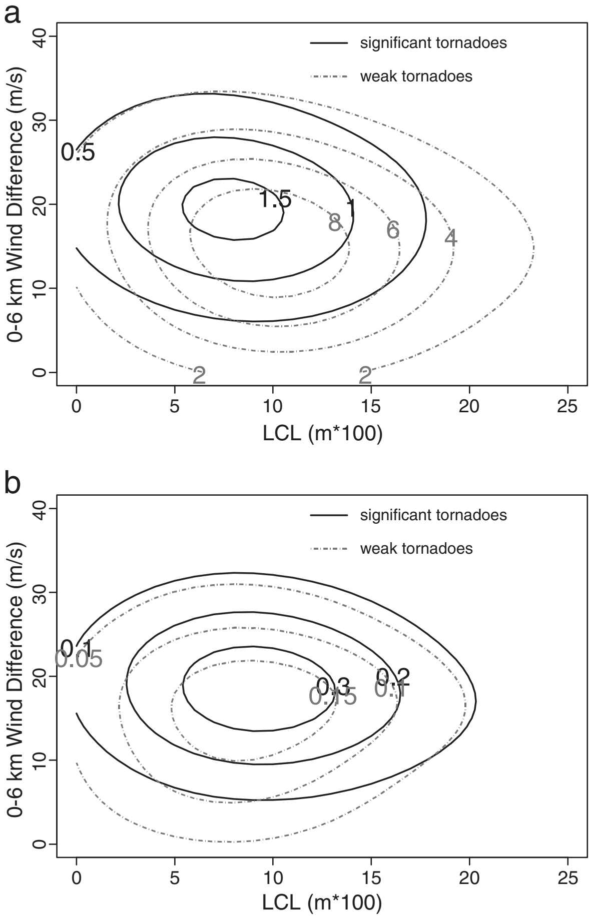

Fig. 3. As Fig. 2, but for the combination LCL/deep-layer shear. Values of contour lines, from inside to outside, are: a) 1.5, 1 and 0.5 for significant and 8, 6, 4 and 2 for weak tornadoes, b) 0.3, 0.2 and 0.1 for significant and 0.15, 0.1 and 0.05 for weak tornadoes. Sample size: As Fig. 2.

US (e.g., Rasmussen and Blanchard, 1998; Craven and Brooks, 2004).

For Europe, the situation is different. The maximum for weak tornadoes is shifted to slightly lower DLS values and is also enlarged somewhat to lower LCL heights (Fig. 3b). The outer contour line for the significant tornadoes also reaches slightly higher LCL heights and DLS values than the one for the weak tornadoes does. Thus, the density distributions for the weak and significant tornadoes in Europe show that the significant tornadoes occur with slightly higher DLS and slightly larger LCL height than the weak ones. This is different from the US, where the significant tornadoes occur on average at lower LCL heights than the weak tornadoes. However, the differences between weak and significant tornadoes for the LCL in Europe are not statistically significant (Table 1). Thus, even if the distributions of weak and significant tornadoes in Europe (Fig. 3b) show differences in the behavior of the LCL compared to the US, these differences may be a result of sampling issues. The results of the DLS, on the other hand, are statistically significant at the 99% confidence level (Table 1). The end result is the DLS/LCL, as a combination, and, in particular, LCL individually, is not as good of a discriminator between weak and strong tornadoes in Europe as in the US.

3.3. Combination of LCL and low-level shear

Most significant tornadoes in the US occur at higher LLS and lower LCL height than most of the weak tornadoes (Fig. 4a). Comparing LCL and LLS between weak and significant tornadoes for the US shows that both are statistically significant at the 99% confidence level (Table 1). As a result, the combination LCL/LLS can be considered as a good discriminator between weak and significant tornadoes in the US. The differences in the distributions for weak and significant tornadoes in the US are bigger for the combination LCL/LLS than for LCL/DLS. The importance of low-level shear in discriminating between significant tornadic and non-significant tornadic environments was noted by Craven and Brooks (2004). Weak and significant tornadoes occur for similarly high LLS values, with the significant tornadoes reaching only slightly higher values. For the LCL height, the highest values associated with weak tornadoes are much larger than for significant tornadoes. Thus, the significant tornadoes show about the same variability in LLS but a

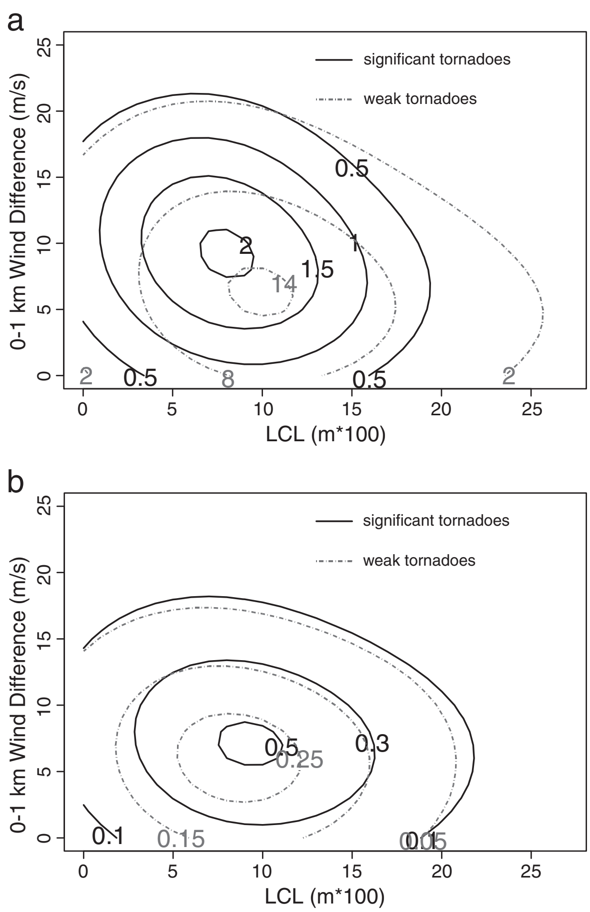

Fig. 4. As Fig. 2, but for the combination LCL/low-level shear. Values of contour lines, from inside to outside, are: a) 2, 1.5 and 0.5 for significant and 14, 8 and 2 for weak tornadoes, b) 0.5, 0.3 and 0.1 for significant and 0.25, 0.15 and 0.05 for weak tornadoes. Sample size: As Fig. 2.

smaller variability in the LCL height compared to the weak tornadoes.

The density distribution for significant tornadoes in Europe is shifted to higher LLS values (statistically significant at a 98% confidence interval) and slightly higher LCL heights than weak tornadoes (Fig. 4b). The greater spread of the distribution for weak tornadoes is indicative of greater variability. Overall, the distributions imply that, in Europe, weak tornadoes occur at slightly lower LLS and slightly lower LCL than significant ones.

In summary, the shear patterns in the two areas are similar (significant tornadoes are shifted to stronger shear environments), but the LCL differences are not consistent. LCL appears to be a good discriminator in the US distributions, but not in Europe. Whether this is a physically important distinction is not clear at this time. Differences in the sample size make it difficult to interpret the LCL results with confidence. It is possible that the differences result from the lack of variability in LCL heights in Europe in general (Brooks, 2009).

3.4. Unrated tornadoes in Europe

An important question that we wanted to address relates to the parameter distributions for the unrated tornadoes in Europe. Fundamentally, the question is whether the unrated tornadoes should be considered as more closely approximating random draws from the overall distribution of tornadoes, or if they are preferentially weaker. If the latter is correct, we would expect to see the distributions for unrated tornadoes look much like that for weak tornadoes.

Most unrated tornadoes occur at lower DLS and slightly lower WMAX than most F1 tornadoes in Europe (Fig. 5a). These results are statistically significant for both parameters DLS and WMAX at the 98% confidence interval (Table 1). Given the previous result that tornadoes tend to be stronger for higher values of DLS, this implies that the unrated tornadoes should be weaker than the F1 tornadoes. A comparison of the distributions indicates that the unrated tornadoes correspond well to the F0 tornadoes, with perhaps slightly higher values of DLS and slightly higher values of WMAX (Fig. 5b). Since the unrated tornadoes appear to be weaker than F1 tornadoes, it is suggested that the unrated tornadoes are probably mostly F0 tornadoes and, almost certainly, few, if any are significant tornadoes. However, none of the parameters show statistically significant differences for the F0 and unrated tornadoes (Table 1).

3.5. Inclusion of unrated tornadoes into weak tornadoes in Europe

The unrated tornadoes in Europe have been suggested to contain mostly F0 tornadoes. Therefore including these unrated tornadoes into the weak tornadoes would increase the sample size for weak tornadoes. Therefore, distributions of weak + unrated tornadoes (hereafter referred to as unrated/weak tornadoes) in comparison with significant tornadoes have been generated for the three parameter combinations (Fig. 6).

Significant tornadoes are occurring at higher WMAX and higher DLS than the unrated/weak tornadoes (Fig. 6a). The results for comparing unrated/weak versus significant tornadoes are statistically significant at the 99% confidence level for both parameters (Table 1). Since the differences in the distributions are relatively big and the results are statistically significant, the combination WMAX/DLS can discriminate well between unrated/weak and significant tornadoes.

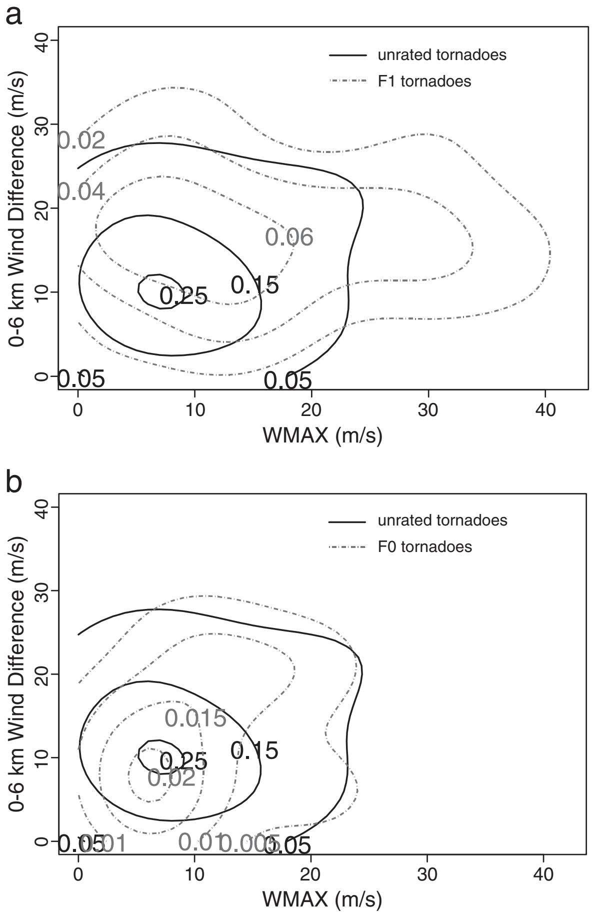

Fig. 5. Density distributions of a) unrated and F1 and b) unrated and F0 tornadoes in Europe for the parameter combination WMAX/deep-layer shear. Values of contour lines, from inside to outside, are: a) 0.25, 0.15 and 0.05 for unrated and 0.06, 0.04 and 0.02 for F1 tornadoes, b) 0.25, 0.15 and 0.05 for unrated and 0.02, 0.015, 0.01 and 0.005 for F0 tornadoes. Sample size: n = 115 for unrated, n = 57 for F1 and n = 9 for F0 tornadoes.

The maximum in distribution for the unrated/weak tornadoes is located at lower DLS values than for the significant tornadoes and is also located in the lower LCL part of the maximum for the significant tornadoes (Fig. 6b). Also, the outer contour line for the significant tornadoes reaches slightly higher DLS and LCL values than the one for the unrated/weak tornadoes. Thus, the significant tornadoes occur at higher DLS and higher LCL than the unrated/weak tornadoes. The results shown here are statistically significant, since results derived from both parameters are statistically significant, the LCL at the 96% confidence level and the DLS at the 99% confidence level (Table 1). The combination LCL/DLS appears to be a good discriminator between unrated/weak and significant tornadoes in Europe.

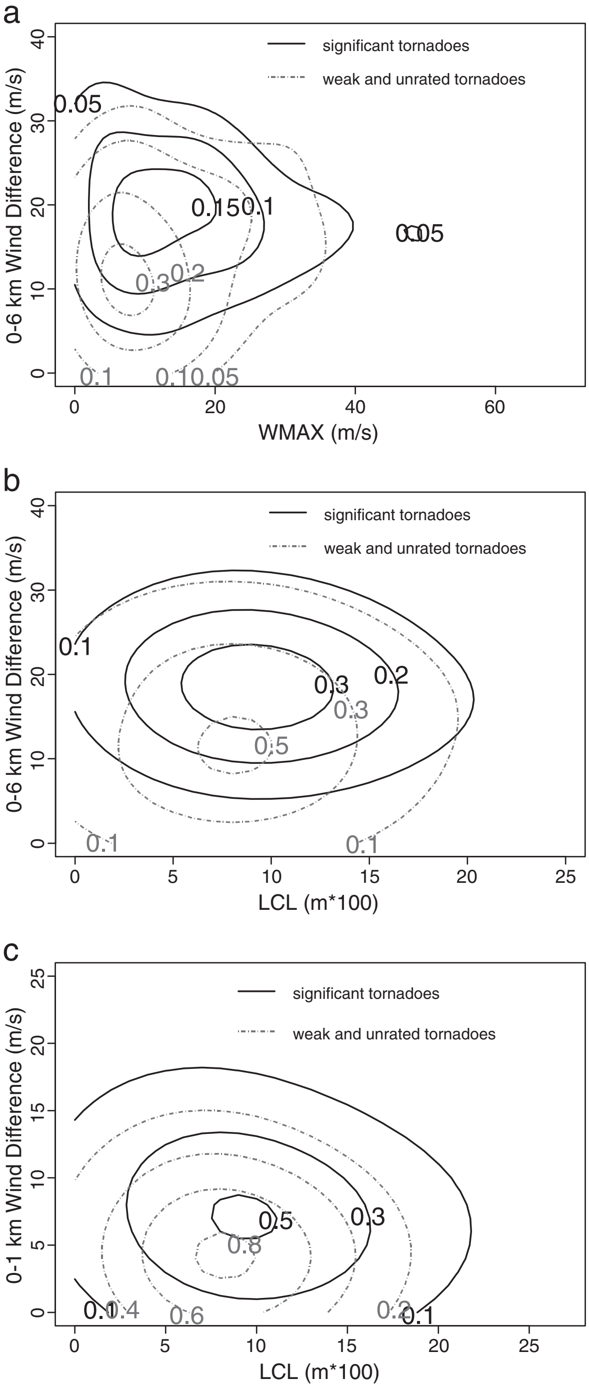

Fig. 6. Density distributions of unrated/weak (unrated, F0, F1) and significant (F2+) tornadoes for Europe for the parameter combinations a) WMAX/deep-layer shear, b) LCL/deep-layer shear and c) LCL/low-level shear. Values of contour lines, from inside to outside, are: a) 0.15, 0.1 and 0.05 for significant and 0.3, 0.2, 0.1 and 0.05 and for unrated/weak tornadoes, b) 0.3, 0.2 and 0.1 for significant and 0.5, 0.3 and 0.1 for unrated/weak tornadoes, c) 0.5, 0.3 and 0.1 for significant and 0.8, 0.6, 0.4 and 0.2 for unrated/weak tornadoes. The contour value of the small area in Fig. 6a at approximately WMAX = 50 m/s is 0.05 for significant tornadoes. Sample size: n = 122 for significant and n = 181 for unrated/weak tornadoes.

Significant tornadoes occur at higher LCL and higher LLS values than the unrated/weak tornadoes (Fig. 6c). The differences between unrated/weak and significant tornadoes are statistically significant since results derived from LCL are statistically significant at the 96% confidence level and results from LLS at the 99% confidence level (Table 1). Like the other two parameter combinations, also the combination LCL/LLS can discriminate well between unrated/weak and significant tornadoes in Europe.

The primary impact of including the unrated tornadoes as weak is to increase the significance of the single-parameter significance tests. As a result, climatological studies can include the unrated tornadoes with weak tornadoes with some confidence that they are part of the same distribution.

The distributions of unrated/weak and significant tornadoes for the combinations LCL/DLS and LCL/LLS show the same differences in the behavior of the LCL compared to the US as the distributions of weak and significant tornadoes in Europe. The LCL is higher for significant tornadoes than for unrated/weak tornadoes in Europe, whereas in the US the LCL is lower for significant tornadoes than weak tornadoes. Since in Europe the comparison of unrated/weak and significant tornadoes should represent the truth better than comparison of weak and significant tornadoes, the different behavior of the LCL height concerning weak and significant tornadoes in Europe and the US might be a representation of the truth and provides an interesting question for future studies.

4. Discussion

Perhaps our most important result is that the unrated tornadoes in the ESWD can be treated as weak tornadoes for many purposes. Including them with the weak tornadoes increased the sample size of the weak tornadoes and, from a statistical significance standpoint, improved the apparent discrimination between weak and significant tornadoes. It is not surprising that the unrated tornadoes are likely to be weak. Typically, the unrated tornadoes were short-lived and, as a result, did not cause enough damage to get rated. Brooks (2004) showed that, for the US, short path-length tornadoes tend to be weaker.

Significant tornadoes in Europe are associated with higher WMAX (and thus with higher CAPE) and DLS than the weak tornadoes. This is consistent with the findings of Thompson et al. (2003) for the US that significantly tornadic supercells are usually associated with higher CAPE and wind shear than non-tornadic supercells. Kaltenböck et al. (2009) found that significant tornadoes in Europe are associated with higher DLS than weak tornadoes. In the US, WMAX does not really vary with the strength of tornadoes and, as a result, is not a useful discriminator of intensity. This is different from Europe and in contrast with the impact of CAPE on other categories of thunderstorms in the US. Brooks et al. (2003b), for example, found that CAPE and shear have a strong influence on the discrimination between non-severe, severe, and significant severe thunderstorms, with higher CAPE and DLS increasing the probability for a more severe thunderstorm. Accordingly, in the US CAPE (and thus WMAX) is an important factor for providing information about the severity of thunderstorms, but not such an important factor in differentiating between the different strengths of tornadoes. A possible reason for why this is true in the US, but not in Europe, is that, in the US, tornadoes form in higher CAPE environments overall compared to Europe. Thus, the CAPE in US tornado environments is perhaps sufficient to support a significant tornado, but if other factors are not sufficient, then the tornado is weak. In Europe the CAPE is usually smaller in tornado environments than in the US and thus perhaps not always high enough to support the formation of a significant tornado. However, the significant tornadoes in Europe still form at lower WMAX (and thus CAPE) values than most tornadoes in the US. Kaltenböck et al. (2009) found that, for significant tornadoes in Europe, high values of CAPE are not needed.

Combining LCL with either of the shear parameters produced good discrimination in the US between weak and significant tornadoes, with lower LCL heights and higher shear associated with stronger tornadoes. The importance of LCL height in the US is consistent with Rasmussen and Blanchard (1998), as well as with the work of Thompson et al. (2003) on discriminating between significantly tornadic supercells and non-tornadic supercells. We find that the LLS (in combination with LCL) is a slightly better discriminator between weak and significant tornadoes than the DLS. Again, this is consistent with previous studies of the role of shear by itself (e.g., Craven and Brooks, 2004).

In Europe the LCL and shear can also discriminate between weak and significant tornadoes (when the unrated tornadoes are included with the weak). The DLS and the LLS show about the same behavior as in the US, which is that higher DLS and LLS are usually associated with stronger tornadoes. This has also been found by Groenemeijer and van Delden (2007) for LLS for tornadoes in the Netherlands and by Kaltenböck et al. (2009) for DLS associated with European tornadoes. The LCL, on the other hand, shows the opposite behavior in Europe than in the US, with higher LCL heights associated with stronger tornadoes in Europe. The behavior of the LCL in Europe concerning the strength of tornadoes is in contrast to what has been found by Kaltenböck et al. (2009). Groenemeijer and van Delden (2007) found that in the Netherland the LCL is not a useful parameter in discriminating tornadic environments from non-tornadic thunderstorm environments.

Since the findings for the LCL height in Europe in this study are in contrast to other studies in Europe (Kaltenböck et al., 2009; Groenemeijer and van Delden, 2007), it is open to question if the differences in the LCL height between weak and significant tornadoes in Europe which were shown in this study are meteorologically important. For one thing, the variability of the LCL height is not as large in Europe as in the US (e.g., Brooks et al., 2007). Our study used NCAR/NCEP reanalysis data so that reanalysis errors could be a source of problems as well, particularly in areas near complex terrain. Another reason why the LCL in Europe might not be represented well by the NCAR/NCEP reanalysis is the vertical resolution of the reanalysis. The reanalysis has problems representing strong vertical gradients (Brooks et al., 2003b). This means that surface based parameters might not be reproduced well. Thus, the LCL might not be reproduced well. Since the terrain in Europe is more variable on a small scale than in the plains of the US, gradients should be stronger there. Therefore it is possible that the LCL in Europe is represented more poorly than in the US.

To find out if the different terrain in Europe and the vertical resolution of the reanalysis data are the reasons for the differences in the behavior of the LCL height between Europe and the US, this study should be carried out with a different reanalysis, such as the higher resolution ECMWF (European Centre for Medium-range Weather Forecasts) analysis used by Kaltenböck et al. (2009). This has a grid spacing of about 25 km and 91 levels in the vertical (Kaltenböck et al., 2009), compared to the NCAR/NCEP reanalysis, with a grid spacing of about 200 km and only 28 levels in the vertical (Brooks et al., 2003b). Differences in the results for the LCL height in Europe between this study and the study of Kaltenböck et al. (2009) could be due to model resolution and/or model orography.

Other issues in the quality of the analysis are parameters that are not included in the reanalysis. Information about the initiation of a storm is unlikely to be provided by the reanalysis data (Doswell, 1987) since the spatial scale of initiation processes is smaller than the spatial scale of the reanalysis. Mesoscale processes, which are important for the formation of thunderstorms and tornadoes in Europe, have been described in several case studies (Schmid et al., 2000; Hannesen et al., 1998, 2000; Dotzek, 2001). For the initiation of some thunderstorms the formation of a convergence line ahead of a cold front of a synoptic system is important (Schmid et al., 2000; Hannesen et al., 2000). Lifting at a cold front and orographically induced convergence lines on a small scale are important in other cases (Hannesen et al., 1998). The orographically induced convergence lines develop if certain orographic features, like for example valleys, channel the airmasses. A good example is the Upper Rhine Valley in Southern Germany (Hannesen et al., 1998, 2000). Other orographic effects which are favourable for the development of thunderstorms and tornadoes are veering winds in the lowest kilometers, low-level heat, moisture content and forced lifting (Dotzek, 2001). An example for low-level heat and high moisture content is a situation that has been observed in the Upper Rhine Valley: Moist air is advected into the valley and ages there. Then, due to strong solar radiation and evapotranspiration the temperature and moisture content increase. However, this can only happen if a low-level inversion is present (Hannesen et al., 1998). Another mesoscale factor which enhances the formation of tornadoes is the horizontal low-level vorticity, which might be transformed into vertical vorticity in the updraft of a thunderstorm (Dotzek, 2001). Horizontal low-level vorticity is usually more apparent in regions with increasing terrain height and surface roughness (Dotzek, 2001). This shows again that the small-scale orography influences the formation of tornadoes. Also, Hannesen et al. (2000) showed in their study that some tornadoes are generated by small-scale terrain forcing effects.

Some factors not included in the reanalysis have been listed here. These might be more important for the formation of tornadoes in Europe than they are in the US and could therefore maybe explain the differences in the behavior of the LCL height between tornadoes in Europe and the US. Brooks (2009) also stated that it is plausible that the synoptic forcing and the presence of boundaries induced by the topography are stronger and more frequent in Europe than in the US.

It is also possible that the reanalysis is reasonably accurate and that the difference in the importance of the LCL in the US and Europe is real. We can only speculate about its origins.

High LCL heights in the presence of CAPE are rare in Europe (Brooks et al., 2007), but are common in the Plains of the US. High LCL heights are associated with low boundary-layer relative humidity. Markowski et al. (2002) showed that cold downdrafts (associated with evaporation in the boundary layer) are limiting factors in tornadogenesis. The absence of such boundary-layer structures in Europe could be a reason for the LCL height to be unimportant there.

To find out what the true reason is for the different behavior in LCL heights between Europe and the US, this study could be repeated with a higher resolution model, as well as with larger datasets. Answering this question is of importance because it addresses our fundamental understanding of tornadogenesis and how much of our apparent understanding of the large-scale influence is simply a result of the limited datasets that have been available for study previously.

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