ELSEVIER

Atmospheric Research 1109 (2003) xxx–xxx

ATMOSPHERIC RESEARCH

www.elsevier.com/locate/atmos

The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data

Harold E. Brooks[a,*], James W. Lee[b,1], Jeffrey P. Craven[c,2]

[a] NOAA/National Severe Storms Laboratory, 1313 Halley Circle, Norman, OK 73069, USA
[b] University of Oklahoma, Norman, OK, USA
[c] NOAA/National Weather Service/Storm Prediction Center, Norman, OK, USA

Abstract

Proximity sounding analysis has long been a tool to determine environmental conditions associated with different kinds of weather events and to discriminate between them. It has been limited, necessarily, by the spatial and temporal distribution of soundings. The recent development of reanalysis datasets that cover the globe with spatial grid spacing on the order of 200 km and temporal spacing every 6 h allows for the possibility of increasing the number of proximity soundings by creating "pseudo-soundings." We have used the National Center for Atmospheric Research (NCAR)/United States National Centers for Environmental Prediction (NCEP) reanalysis system to create soundings and find environmental conditions associated with significant severe thunderstorms (hail at least 5 cm in diameter, wind gusts at least 120 km h^{-1}, or a tornado of at least F2 damage) and to discriminate between significant tornadic and non-tornadic thunderstorm environments in the eastern United States for the period 1997–1999. Applying the relationships from that region to Europe and the rest of the globe, we have made estimates of the frequency of favorable conditions for significant severe thunderstorms. Southern Europe has the greatest frequency of significant severe thunderstorm environments, particularly over the Spanish plateau and the region east of the Adriatic Sea. Favorable significant tornadic environments are found in France and east of the Adriatic. Worldwide, favorable significant thunderstorm environments are concentrated in equatorial Africa, the central United States, southern Brazil and northern Argentina, and near the Himalayas. Tornadic environments are by far the most common in the central United States, with lesser areas in southern Brazil and northern Argentina.

Keywords: Spatial distribution; Severe thunderstorm; Tornado

* Corresponding author.
E-mail address: Harold.Brooks@noaa.gov (H.E. Brooks).
[1] Current affiliation: NOAA/National Weather Service, Key West, FL, USA.
[2] Current affiliation: NOAA/National Weather Service, Jackson, MS, USA.

0169-8095/03/$ - see front matter © 2003 Published by Elsevier Science B.V.
doi:10.1016/S0169-8095(03)00045-0

1. Introduction

Severe thunderstorms pose a significant challenge for development of reasonably accurate climatologies. They are rare events at any particular location and, in general, their reporting depends upon the presence of a system designed to collect data and an observer at the location of the event. Brooks and Doswell (2001) discussed some of the problems with particular regard to the tornado-reporting problem. A lack of uniformity in standards for data collection between different countries and changes through time in the way data are collected makes comparisons across space and time very difficult.

A possible solution to some of the problems is to use meteorological covariates (Brown and Murphy, 1996) to estimate the occurrence of events. Covariates are variables that are measured consistently in space and time and have some relationship to the event of interest. In effect, the challenge of estimating occurrence of the weather event of interest is transformed from solving the poor quality of observations to developing a reasonable relationship between a well-observed variable and the event we are actually interested in.

In the severe weather community, there is a long tradition of studies of so-called ‘‘proximity soundings’’, rawinsonde launches taken near to severe weather events in space and time, to try to determine the relationship between large-scale environmental variables and severe weather occurrence (e.g., Fawbush and Miller, 1952, 1954; Beebe, 1955, 1958, 1963; Darkow, 1969; Turcotte and Vigneux, 1987; Johns et al., 1993; Brooks et al., 1994; Rasmussen and Blanchard, 1998; Craven, 2001; Craven et al., 2002a; Brooks and Craven, 2002). A goal on many of these studies was to find a small set of parameters that could discriminate between different kinds of weather of interest, say between severe and non-severe thunderstorm environments or tornadic and non-tornadic environments.

Proximity sounding analyses are naturally related to the concept of meteorological covariates. If a relationship can be established between variables associated with the soundings and severe weather occurrence in regions where the reporting of severe weather is reasonably good, it might be possible to apply those relationships to soundings taken in other locations where the severe weather reporting is not as good and estimate the likely occurrence of severe weather. For instance, if a particular combination of convective available potential energy (CAPE) and vertical shear of the tropospheric horizontal winds is associated with severe thunderstorms more often than another combination, then the frequent occurrence of the former combination at some other location would imply that severe thunderstorms are likely to be frequent at the second location.

Here, we focus on detection of environments associated with ‘‘significant severe thunderstorms’’, those producing hail of 5 cm or greater in diameter, wind gusts of 120 km h^{-1} or greater, or a tornado of F2 intensity or greater, and those producing significant tornadoes (F2 or greater). In one sense, this is for practical considerations. Rasmussen and Blanchard (1998) and Craven et al. (2002a) have shown that discriminating between those events and less-severe events is easier than discriminating between less-severe storms and non-severe thunderstorms in the United States. Thus, the task should be easier than for trying to identify all severe thunderstorms. In addition, these storms will almost always produce significant threats to life and property no matter where they occur. This is not meant to imply that other storms are not of importance, but just that they may be more difficult to detect in the large-scale environmental conditions.

Our primary goal in this paper is to determine if relationships between sounding-derived parameters and severe weather occurrence, determined in the United States, where the severe weather reporting system is relatively good, can be applied to other parts of the globe. Lee (2002) took proximity sounding analysis in a new direction that is especially useful. He used the reanalysis data producing by the United States National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) (Kalnay et al., 1996) to produce artificial soundings for the environmental conditions side of covariate relationship using the region of the United States east of the Rocky Mountains from 1997 to 1999. The higher horizontal resolution of the reanalysis compared to the observed sounding network (roughly 200 km spacing vs. 400 km spacing) is attractive for proximity studies, since it increases the likelihood that any event will be associated with a sounding. We have chosen a definition of proximity in keeping with Craven (2001) and Craven et al. (2002a,b) with events required to occur within 3 h of the sounding time and within 100 nautical miles (185 km) in space. With the reanalysis spacing, all events meet the spatial criterion, so that the only soundings that would be lost will be because of the temporal constraint. Since the temporal spacing of the reanalysis is 6 h, it would be possible to have all events as proximity, if all sounding times were used. In this preliminary study, we have only looked at the reanalysis time closest to late afternoon and early evening (local time) since many locations show an apparent peak in significant severe weather occurrence during that time of day. For the area of the globe between 45°W and 45°E longitude (including the European region), the 1800 UTC time was used. For 135°W to 45°W (including the United States), 0000 UTC was used, on so forth around the globe.

2. The NCAR/NCEP reanalysis dataset

The reanalysis dataset was created through the cooperative efforts of the United States National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) (Kalnay et al., 1996) to produce relatively high-resolution global analyses of atmospheric fields over a long time period. The reanalysis data record has since been extended to include January 1948 through July 2002. The basic concept of the reanalysis was to:

1. Recover all available observations from each time index and synthesize them with a static data assimilation system.
2. Use the observational fields to initialize a model for a 6-h forecast. The model used (hereafter referred to as the reanalysis model) was identical to the NCEP global operational model, except for the horizontal resolution. The reanalysis model is T62 (equivalent to a horizontal resolution of approximately 210 km), while the operational model is T126 (approximately 105 km).

3. Use the forecast as a first-guess, in conjunction with concurrent observational fields, to construct the reanalysis output. Reanalysis fields were generated with an optimal interpolation technique.
4. Repeat the process every 6 h.

Thus, the reanalysis used model forecasts and observations to transport information from regions of high observational density to those with fewer observations. The state of the atmosphere could thus be estimated in areas that are relatively devoid of data. The result of the reanalysis process was a dataset consisting of a global, three-dimensional picture of the atmosphere at 6-h intervals during a period of more than 50 years.

Output is available from the reanalysis on 28σ levels ($\sigma = p/p_0$, where p is pressure and p_0 is surface pressure) in the vertical, and in the form of spectral coefficients in the horizontal. Approximately 10σ levels exist between the near-surface (the lowest having $\sigma = 0.995$) and 700 hPa. When the spectral coefficient data are translated onto an equally spaced (in latitude and longitude) grid, the result is 192×94 gridpoints. The spatial resolution is 1.875° in longitude and 1.915° in latitude, equivalent to a grid spacing slightly finer than 200 km over most of the globe.

The reanalysis data includes six atmospheric fields. Surface height (in terms of geopotential) is constant over time. The other five fields are available every 6 h. The

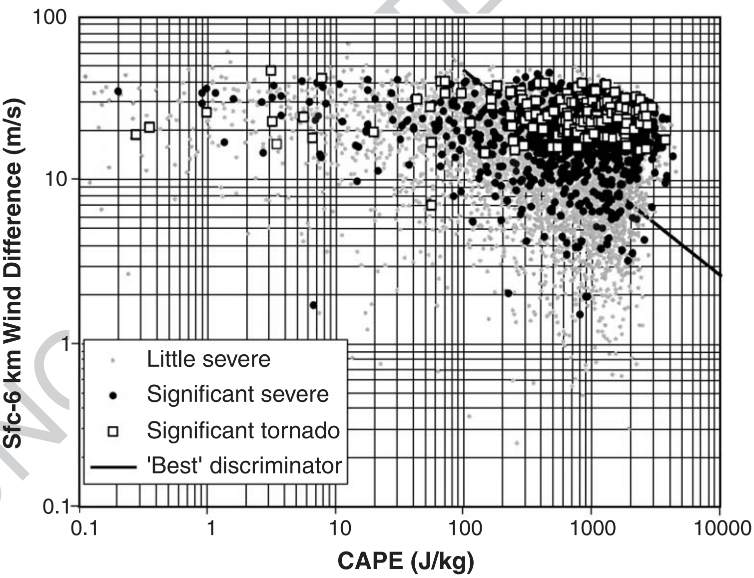

Fig. 1. Magnitude of the vector wind difference between the surface and 6 km (m s^{-1}) and CAPE (J kg^{-1}) for all reanalysis soundings associated with severe thunderstorms in US for 1997–1999, segregated by weather type: non-significant severe weather (small gray dots), significant, non-tornadic severe weather (large black dots), and significant tornadoes (open squares). Solid black line is best discriminator between soundings associated with significant severe thunderstorms of any kind and other soundings. Note that non-severe soundings are not included in the figure.

natural log of surface pressure is the only one of these five variables not available above the surface. The other four (virtual temperature, specific humidity, divergence, and vorticity) are available at 28 vertical levels. Atmospheric parameters necessary for the construction of a sounding (i.e., temperature, dewpoint, wind speed and direction, heights, and pressure) were derived from the six initial fields using the Spherepack software package (Adams and Swarztrauber, 1999).

The soundings were analyzed using a version of the Skew-t/Hodograph Analysis and Research Program (SHARP) (Hart and Korotky, 1991) to produce a large number of convectively important parameters. Lee (2002) demonstrated that for most parameters, the reanalysis produces values that resemble collocated observed soundings. The reanalysis has the most problems with things involving strong vertical gradients, so that surface-based parameters may not be reproduced as well, and parameters that attempt to measure a strong inversion may also not be estimated well.

Brooks et al. (1994) discussed problems with determining if a sounding is appropriate for use in proximity studies. Although the reanalysis data could have some of the problems discussed, such as a sounding being taken on the other side of a significant boundary from the event of interest, or a sounding not sampling important mesoscale variability, it should have fewer problems with things such as convective contamination of the sounding. For our purposes, we have carried out no quality control on the soundings. All soundings are considered 'good'. Lee (2002) associated all soundings with the most severe weather event that occurred within 3 h and 185 km of the location. Thus, if a significant tornado occurred

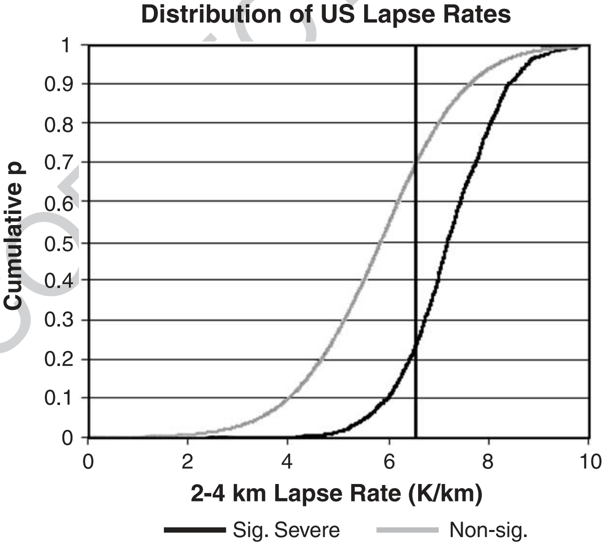

Fig. 2. Cumulative distribution functions of 2–4 km AGL lapse rates (K km^{-1}) for all significant severe thunderstorm soundings (black line), and other soundings (gray line) for all 1997–1999 US soundings. The lines show the fraction of the soundings (value on the ordinate) with lapse rates equal to or less than the value on the abscissa. Lapse rate of 6.5 K km^{-1} indicated by vertical line. 22% of significant severe thunderstorm soundings have a lapse rate less than that, while 70% of the less severe soundings do.

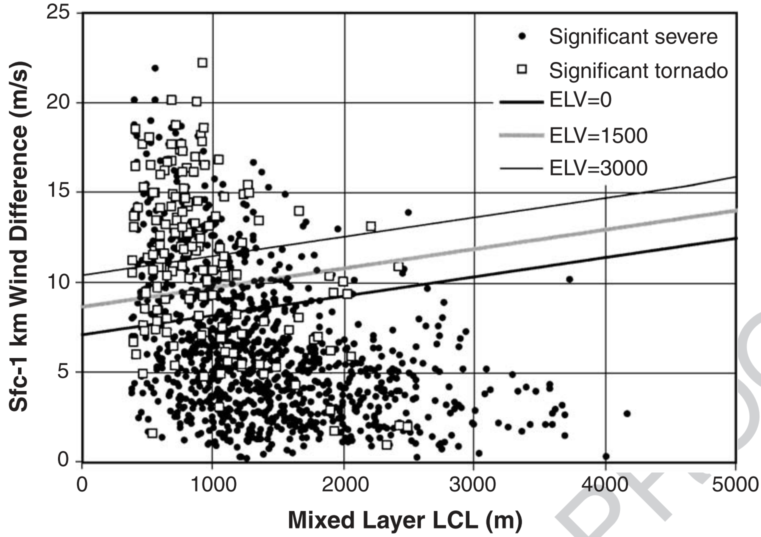

Fig. 3. Magnitude of the vector wind difference between the surface and 1 km (m s^{-1}) and height of mixed layer lifted condensation level (in m) for all US reanalysis soundings associated with significant severe thunderstorms, segregated by weather type: non-tornadic soundings (black dots), tornadic soundings (open squares). Thick black (gray, thin black) line is line from linear discriminant analysis associated with station elevation of 0 (1500, 3000) m.

within the space and time constraints, the sounding was considered tornadic. If no significant tornado occurred, but a significant non-tornadic event occurred, the sounding was considered significant tornadic. If severe weather occurred, but it was non-significant, the sounding was considered severe, and if no severe weather occurred, the sounding was non-severe.

3. Results

3.1. Identification of parameters for discrimination

Previous studies indicated that CAPE and shear over a deep level of the atmosphere are good parameters to use in combination to discriminate between significant severe

Table 1
Five environments into which all soundings are divided, listed in expected order of increasing severity

Environment	Description
1	CAPE = 0
2	0 < CAPE < 100 J kg^{-1}
3	CAPE ≥ 100, but below line on Fig. 1 or 2–4 km AGL lapse rate < 6.5 K km^{-1}
4 (Severe)	CAPE ≥ 100 and 2–4 km AGL lapse rate >6.5 K km^{-1}, above line on Fig. 1, but non-tornadic
5 (Tornadic)	Same as 4, but meeting tornadic discriminant analysis threshold

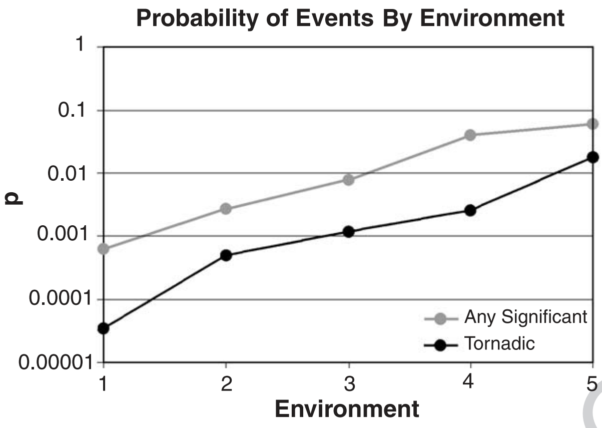

Fig. 4. Probability of tornadic (black) and any significant severe thunderstorm (gray) given identification of environment as in Table 1.

thunderstorms and less severe events (Rasmussen and Blanchard, 1998; Craven et al., 2002a) The question of which parcel to use in calculating CAPE does not have an obvious answer. Based on Craven et al. (2002b), we have chosen to use a parcel with thermodynamic properties mixed over the lowest 100 hPa. For the shear, we have chosen to use the magnitude of the vector difference between the winds at the surface and 6 km above ground level. (Since the only time we will compare shear values of different soundings will be for shear over a constant depth of the atmosphere, we will occasionally

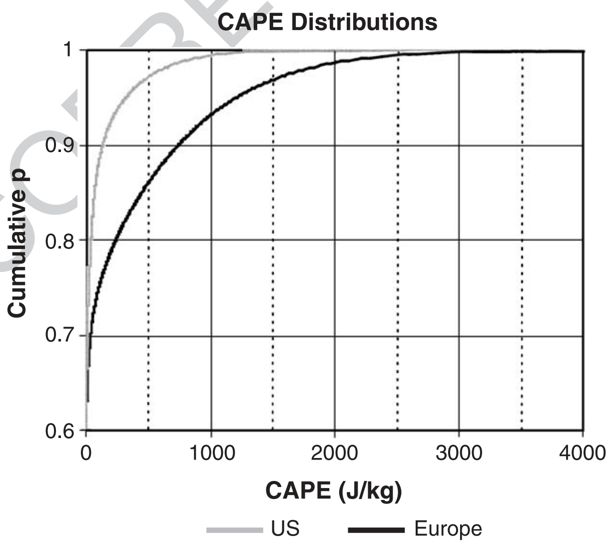

Fig. 5. Cumulative distribution function of CAPE (J kg^{-1}) for soundings from 1997 to 1999 for region of US east of the Rocky Mountains (black line) and Europe south of 60°N (gray line). Note that scale starts at $p = 0.60$.

refer to the wind difference as "shear" for simplicity.) A scatterplot of the 0–6 km shear and CAPE for all soundings with non-zero CAPE associated with severe thunderstorms from the reanalysis in the United States for 1997 to 1999 illustrates the discrimination based on the reanalysis (Fig. 1). In general, significant severe thunderstorms are associated with high CAPE and high shear. (The non-severe soundings are not included in the figure, but would predominantly be found in the low CAPE region.)

A "best" discriminator line has been included in Fig. 1. It was computed by using linear discriminant analysis (Wilks, 1995) for all soundings associated with severe weather with at least 100 J kg^{-1} of CAPE, using logarithms of the CAPE and the 0–6 km shear as the input parameters. Logarithmic relationships between CAPE and shear have previously been shown to discriminate between severe and non-severe thunderstorm environments (Turcotte and Vigneux, 1987). The discrimination line from the analysis is

$$2.86\log(S6) + 1.79\log(CAPE) = 8.36 \quad (1)$$

where S6 is the 0–6 km shear (in m s^{-1}). Above that line, soundings are more likely to be associated with significant severe thunderstorms.

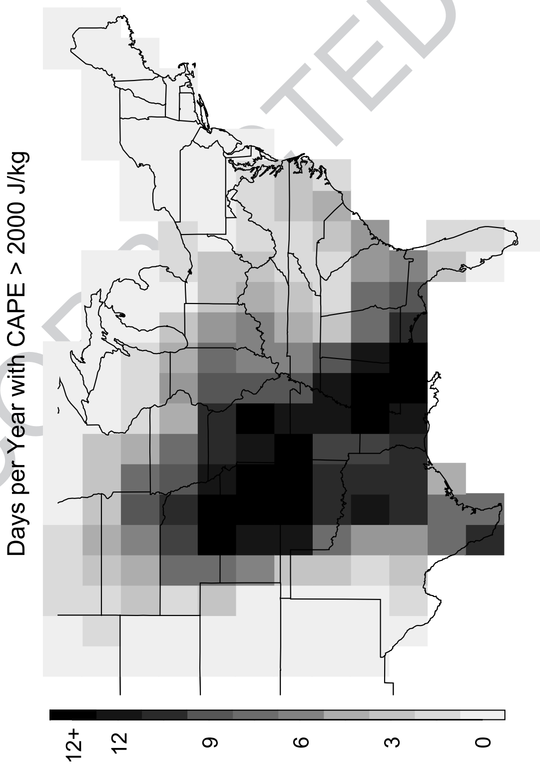

Fig. 6. Days per year with at least CAPE of at least 2000 J kg^{-1} from reanalysis soundings in US, based on 1997–1999 period.

After looking at the spatial distribution of soundings above the line in Fig. 1 (which will be discussed later), a second important discriminatory parameter was identified: the lapse rate of temperature from 2 to 4 km above ground level. This parameter has not been studied in the observational studies, but shows a strong discriminatory capability between significant severe thunderstorm environments and less-severe environments (Fig. 2). Almost 78% of the significant severe soundings have a lapse rate of at least 6.5 K km^{-1}, while only 30% of the less severe soundings are that unstable.

Craven (2001) and Craven et al. (2002a,b) found that shear over the lowest 1 km of the atmosphere and the height of the lifted condensation level provide the best discrimination between significant tornadic environments and significant non-tornadic environments. Combining the two with the reanalysis data (Fig. 3) illustrates that the two parameters work well in the reanalysis also. In comparison with the observational studies (Craven et al., 2002a,b), the 0–1 km shear is typically lower in the reanalysis. This is consistent with the notion that strong vertical gradients are not reproduced well by the reanalysis. Nevertheless, the two parameters show signs of discriminating well between the environments associated with the two kinds of events. From analysis of the spatial distribution of the two parameters in the United States, however, it is clear that there are significant differences in the performance of the discrimination in the Plains region, compared to the

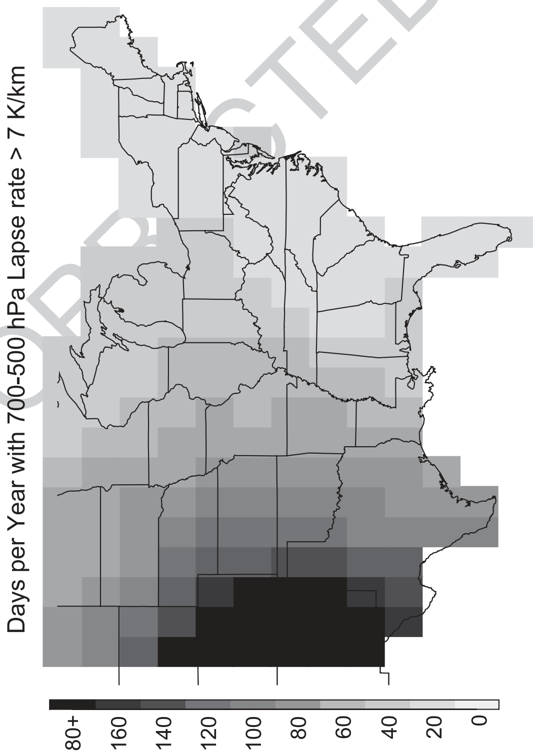

Fig. 7. Same as Fig. 6, except for 700–500 hPa lapse rates exceeding 7 K km^{-1}.

area further to the east. Given that the Plains locations are at higher elevation, a third parameter, station elevation, was added to the linear discriminant analysis. The resulting discrimination plane was defined by

$$2.74\mathrm{S1} - 2.99 \times 10^{-4}\mathrm{LCL} - 3.06 \times 10^{-4}\mathrm{ELV} = 1.93 \quad (2)$$

where S1 is the 0–1 km shear (in m s^{-1}), LCL is the mean layer lifted condensation level (in m), and ELV is the station elevation (in m). Lines in the shear/LCL space associated with various station elevations are shown in Fig. 3, but, in general, low LCL heights and high shear are associated with tornadic events. The lines move towards higher shear with increasing station elevation. This implies that at very high elevations, significant tornadoes should be very rare, an implication supported by lack of observed events at high elevation.

In all, there are five different environments into which the soundings fall, based on the discrimination lines shown in Figs. 1 and 3, and the CAPE value (Table 1). The first is those soundings with 0 CAPE, which make up 112,620 of the 197,100 soundings in the dataset (57.1%). The second is all soundings with positive CAPE, but less than 100 J kg^{-1}, which number 35,111 (17.8%). The third is made up of those soundings with at least 100 J kg^{-1}, but either are below the discrimination line in Fig. 1 or have 2–4 km AGL

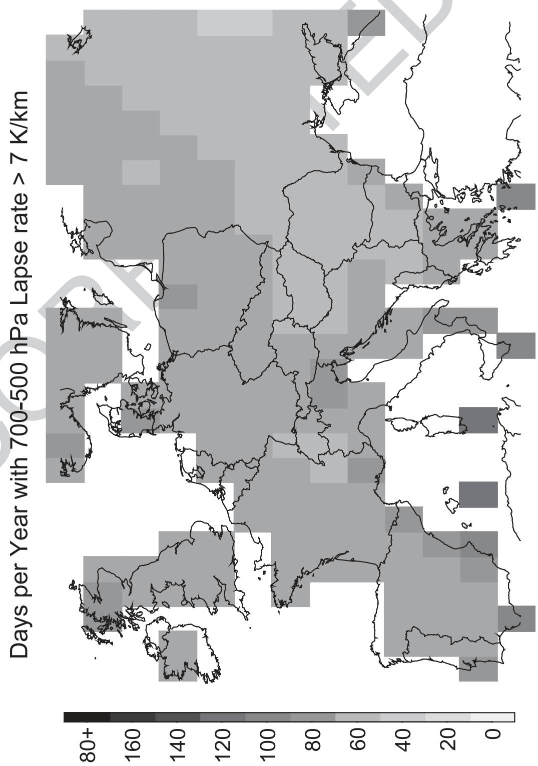

Fig. 8. Same as Fig. 7, except for European region.

lapse rates < 6.5 K km^{-1}, with a total of 31,489 soundings (16.0%). The fourth category represents soundings expected to associated with non-tornadic significant severe thunderstorms, namely those soundings meeting the discriminant analysis criterion for deep atmospheric variables (i.e, above the line in Fig. 1), but not the discriminant analysis criterion for shallow atmospheric variables (i.e., below the line in Fig. 3, adjusted for station elevation), with CAPE ≥ 100 J kg^{-1} and 2–4 km AGL lapse rates ≥ 6.5 K km^{-1}, a total of 13,928 soundings (7.1%). For convenience, we will refer to these as "severe" soundings hereafter. The final category contains those soundings that are meet both of the discrimination criteria with CAPE ≥ 100 J kg^{-1} and 2–4 km AGL lapse rates ≥ 6.5 K km^{-1}, a total of 3641 soundings (1.8%). These will be referred to as "tornadic" soundings hereafter.

As the identified environmental conditions become more severe, the probability that the soundings will be associated with reported significant severe thunderstorms or significant tornadoes increases monotonically (Fig. 4). Going from the CAPE = 0 environments to the tornadic environments, the probabilities of severe and tornadic storms increases by two orders of magnitude or more. The probabilities of significant severe weather of any kind goes from 0.06% to 6%, while the probability of a significant tornado increases from

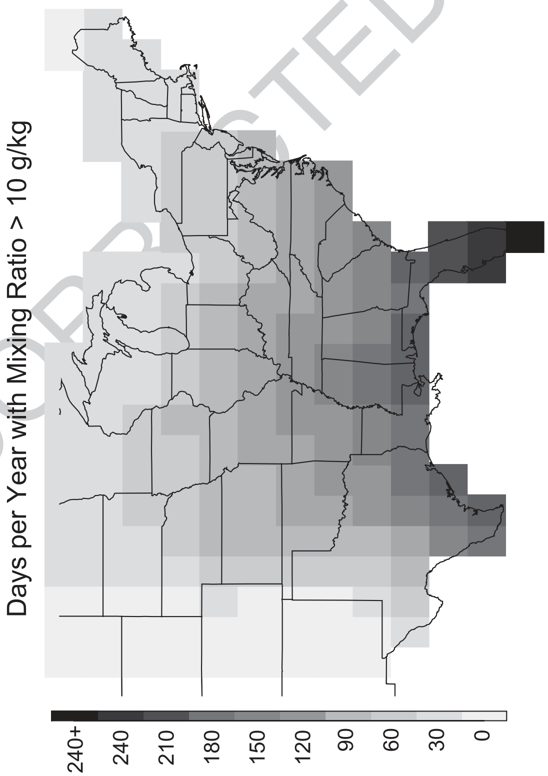

Fig. 9. Same as Fig. 6, except for mean lowest 100 hPa mixing ratio exceeding 10 g kg^{-1}.

0.004% to 2%. This provides some confidence that the discrimination lines defined here have some physical relevance. After discussing some of the differences in the distribution of parameters in the United States and Europe, we will return to these probabilities to make an estimate of the frequency of significant severe thunderstorm and tornadic events in Europe.

3.2. Distribution of environmental instability in the United States and Europe

One of the biggest differences in the environmental conditions in the United States east of the Rocky Mountains and Europe is that European environments tend to have lower CAPE, as illustrated by a comparison of the cumulative distribution function of CAPE in the two areas (Fig. 5). The region of Europe under consideration is the land area south of 60°N and has the same number of grid points in the reanalysis as the eastern United States region for ease of comparison. The years 1997–1999 are considered, as was the case with the United States, but the sounding time is1800 UTC, in an effort to capture the late afternoon/early evening environments. While 1000 J kg^{-1} of CAPE is not common in the United States (~ 7% of all soundings), it occurs much less often in Europe (~ 1%) and 2000 J kg^{-1} is almost unknown in Europe. There are only 32 soundings

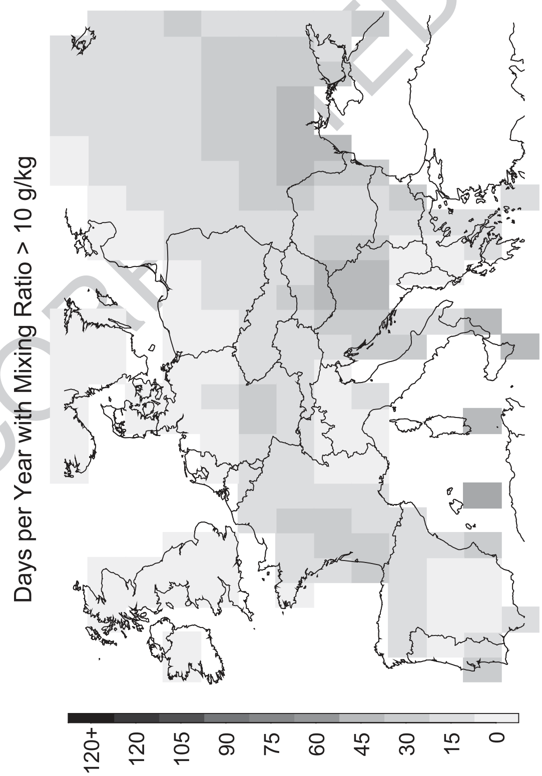

Fig. 10. Same as Fig. 9, except for European region. Note that scale of days is different than in Fig. 9.

Table 2
Estimating the number of significant severe thunderstorms and tornadoes in Europe

Environment	*p* (Severe US)	*p* (Tornadic US)	*N* (US)	*N* (Europe)	Severe (Europe)	Tornadic (Europe)
1	0.000630	0.000036	112,620	114,624	72.3	4.1
2	0.002734	0.000513	35,111	59,350	162.3	30.4
3	0.007964	0.001177	33,149	19,038	151.6	22.4
4	0.038771	0.002513	13,928	6449	250.0	16.2
5	0.060148	0.017303	3641	639	38.4	11.1
Total	1190 (Obs.)	159 (Obs.)			674.6	84.2

Second and third columns give probability of any significant severe thunderstorms and significant tornadoes associated with the environments as defined in Table 1, with the total number of observed proximity soundings in the last row. Fourth and fifth columns are number of soundings in each classification for each region. Last two columns give estimated number of severe and tornadic proximity soundings that would be expected in 3 years in Europe on the reanalysis grid if probabilities in US apply directly.

out of the almost 200,000 total with that high of a CAPE. Approximately 1% of the United States soundings have that much CAPE. Most of the United States east of the Rocky Mountains, with the exception of the Appalachian Mountains, has a CAPE of at

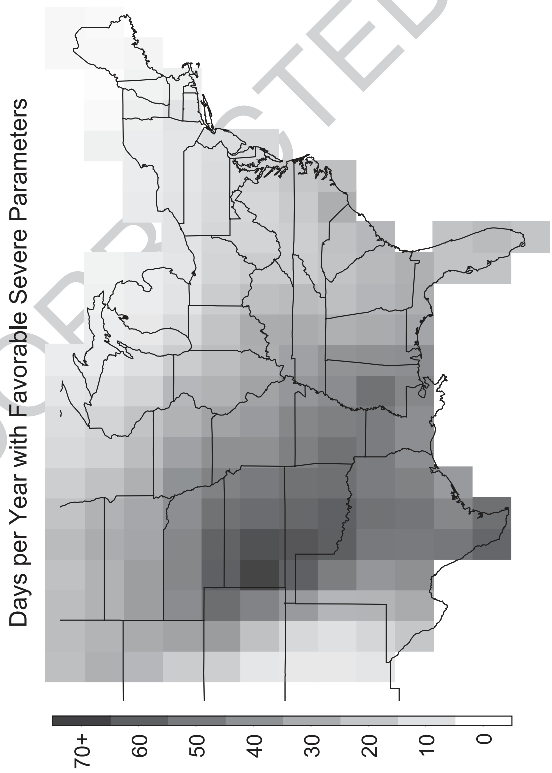

Fig. 11. Same as Fig. 6, except for soundings identified as being favorable for significant severe thunderstorms.

2000 J kg^{-1} five days of more per year (Fig. 6). No location in Europe averages as much as 1 day per year.

In a simplistic way, CAPE can be thought of as being a combination of steep lapse rates in the mid-troposphere and abundant boundary-layer moisture. The spatial distribution of the number of days per year with the 700–500 hPa lapse rate at least 7 K kg^{-1} shows the importance of the high terrain of the Rocky Mountains for generating steep lapse rates in the Plains of the United States, east of the mountains (Fig. 7). The peak in lapse rate occurrence is over the Rockies, with about 250 days per year, but the region of 50 days per year extends to roughly the Mississippi River. That is about the maximum frequency over the continental part of Europe (Fig. 8).

Even though there are substantial differences in lapse rates, the low-level moisture differences are even larger. Taking 10 g kg^{-1} of mean mixing ratio in the lowest 100 hPa above ground as a threshold for abundant low-level moisture, most of the central and southeastern United States has at least 90 days of abundant moisture per year, with values peaking at over 300 days per year in southern Florida (Fig. 9). In contrast, nowhere over continental Europe has abundant moisture even 60 days per year (Fig. 10). Some of this difference is due to the latitudinal difference, but the Gulf of Mexico provides a source of

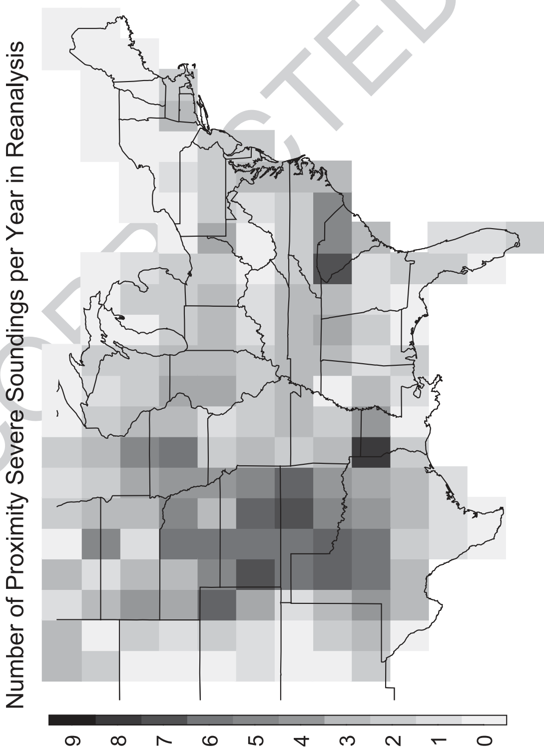

Fig. 12. Same as Fig. 6, except for number of reanalysis soundings associated with significant severe thunderstorms.

warm water and a long fetch to modify air masses headed towards North America. In contrast, the Mediterranean is not as warm most of the year and is relatively small. In particular, surface winds out of the south, that provide a rich moisture source for the United States, would mean that trajectories approaching Europe would have started over the Sahara Desert and substantial modification by the Mediterranean would be difficult.

3.3. Distribution of significant severe thunderstorm and tornado environments

We can use the probabilities shown in Fig. 4 and Table 2 to estimate the frequency of environments supportive of severe convection in Europe, assuming that the environments that produce severe convection in the United States would produce severe convection in Europe as well (Table 2). There are less than half the numbers of severe environments identified in Europe and only about 20% of the tornadic environments during the 3-year period. Applying the probabilities from the US to each class of environment in Europe, we estimate that about 675 significant severe thunderstorm proximity soundings at 1800 UTC would be taken in Europe on the reanalysis grid in a 3-year period, for an average of 225 per year, with a similar report collection efficiency as in the United States. This compares to the United States number of 1190 soundings (397 per year). For significant tornadoes,

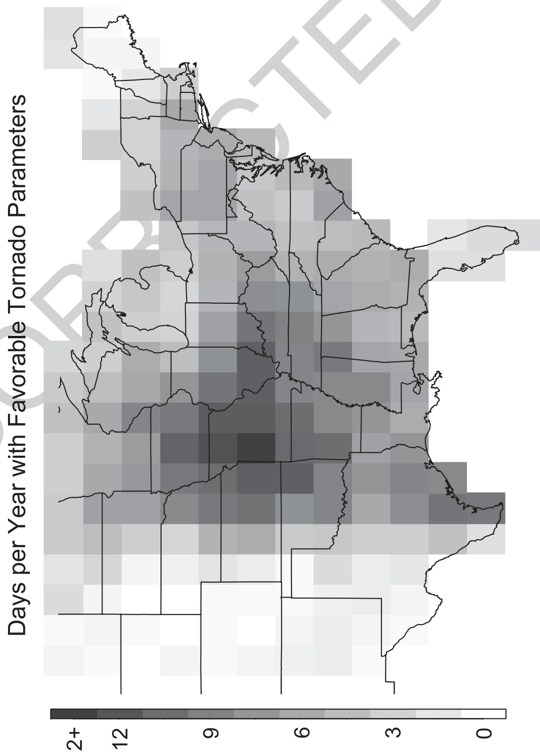

Fig. 13. Same as Fig. 11, except for soundings associated with significant tornadoes.

the results imply 84 soundings (28 per year) in Europe compared to 159 (53 per year) in the United States. Dotzek (2001) estimates, based on surveys at the 2002 European Conference on Severe Storms, that a little over 300 tornadoes per year occur in Europe using the United States definition that excludes waterspouts. In the United States, an average of approximately 1200 tornadoes per year occur in current reporting conditions (Bruening et al., 2002), so that the ratio of significant tornado soundings to total tornadoes is about 1:23. The European values imply a ratio of 1:11. Caution must be used in interpreting the data, given the uncertainties in the reporting and the fact that the relationships between environments and events are not perfect. In particular, 63 (40%) of the United States tornadic soundings come from the environments associated with tornadoes by the discriminant analysis, but only 11 (13%) of the implied European tornadoes do so. The largest contribution to the tornadic sounding estimate in Europe comes from the CAPE < 100 J kg environments, with 30 (36%) of the soundings. Thus, the estimate depends on knowing the values for the low probability events. Nevertheless, it seems likely to be on the right order.

Just as we constructed maps of the spatial distribution of parameters for the different regions, we can map the frequency of the environments in the different regions. The pattern of the distribution of identified significant severe thunderstorm environments (Fig.

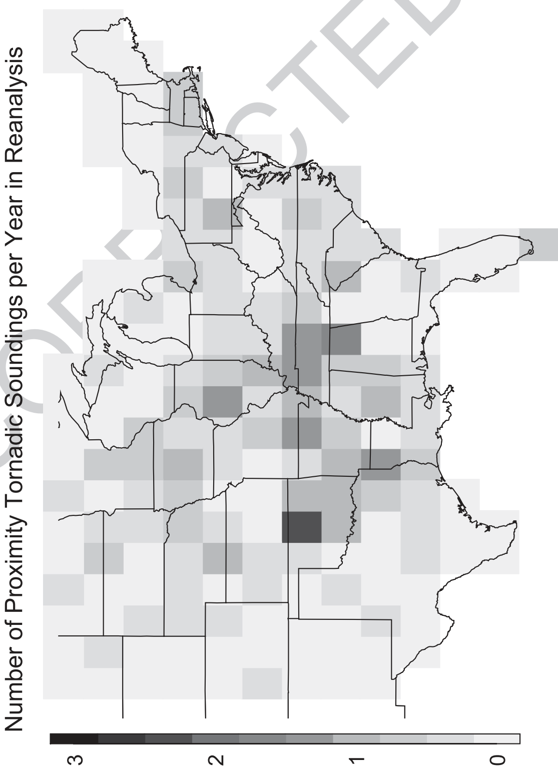

Fig. 14. Same as Fig. 12, except for significant tornadoes.

11) in the United States bears a strong resemblance to the observed distribution of significant severe weather reports (Fig. 12). Both show maxima in the Plains dropping off rapidly towards the northeast. Note that the environmental identifications only imply that severe convection is favored, not that it necessarily will occur. Nothing in the reanalysis provides information on the initiation of convection, for example. Nevertheless, the similarity of the pattern is encouraging.

The similarity between the identified and observed environments for significant tornadoes is not quite as good (Figs. 13 and 14). The pattern in the identification is shifted slightly to the east, by a grid point or so on the western side and two grid points or so on the eastern side of the maximum region in the central United States. The smaller sample size of the tornadic events makes it harder to evaluate the quality of the relationship between identification and observation. The poorer agreement is also likely to result from our poorer understanding of tornadic processes. It is almost certainly true that the relationship is not as simple as can be explained by a few environmental parameters. Also, those parameters that have been suggested as important for distinguishing tornadic from non-tornadic environments, such as low-level shear and LCL height, involve shallow layers of the atmosphere. The cautions about the ability of the reanalysis to capture strong vertical gradients may be very important here. In addition, in at least

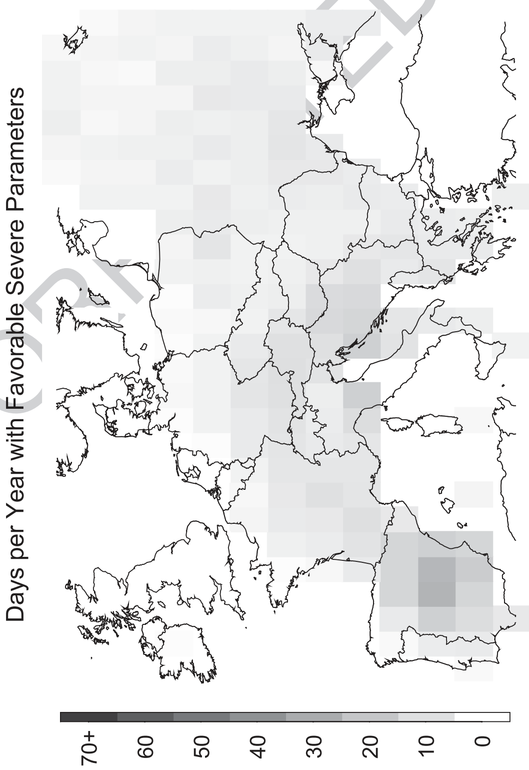

Fig. 15. Same as Fig. 11, except for European region.

some cases, interactions with boundaries that cannot be sampled by the reanalysis are important in tornadogenesis (Markowski et al., 1998, Rasmussen et al., 2000).

With those cautions in mind, application of the relationships derived from the severe weather reports in the United States to European soundings shows the greatest frequency of favorable environments for significant severe thunderstorms to be in the south (Fig. 15). A large area from Spain northeastward through Germany and then southeastward through the Balkans and along the north shore of the Black Sea is highlighted. Within that area, the Spanish plateau and the area from northern Italy to Bosnia stand out as the most frequent locations, although the rates are half of the peaks in the United States. Long-term, detailed climatologies of severe thunderstorms for these regions do not exist, but there are suggestions that significant amounts of strong to severe thunderstorms occur there (e.g., Costa et al., 2001, Morel and Senesi, 2002).

The distribution of favorable significant tornado environments is somewhat different (Fig. 16). The region near Bosnia has the highest frequency on the continent, but France (Paul, 2001), western Germany (Dotzek, 2001) and the Ukraine also have relatively high numbers of a few days per year with significant tornado potential. These values are comparable to those in the northern United States (Fig. 13), a region at a similar latitude.

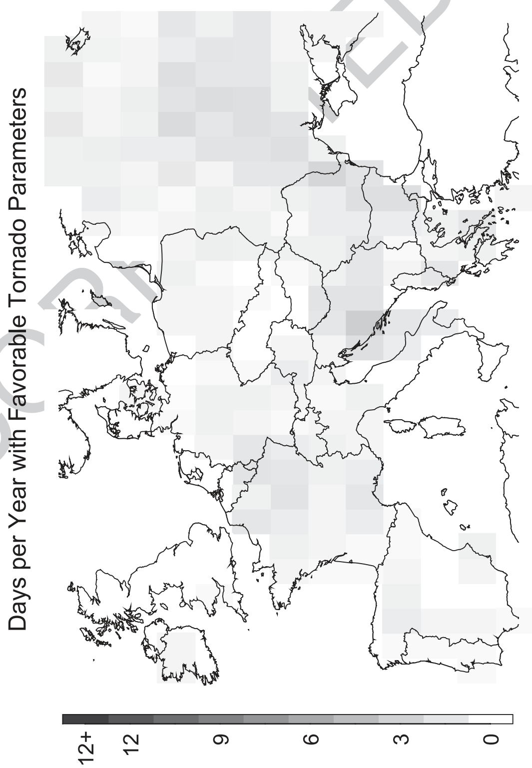

Fig. 16. Same as Fig. 12, except for European region.

As with the United States, great caution must be taken in interpretation. The period of study is relatively short and we are hampered by a lack of observational reports of events.

The process of producing large number of soundings from the reanalysis takes considerable time and computer storage space. As a result, we have been somewhat limited in what we could consider elsewhere. We created soundings for the 3 years for points with vegetation (DeFries and Townshend, 1994) around the world using every other gridpoint in longitude and latitude in the reanalysis data. The DeFries and Townshend dataset contains land-cover characteristics on a $1 \times 1^\circ$ latitude–longitude grid. Data were interpolated to the reanalysis grid and, if the point on the reanalysis had vegetation, that point had soundings created. Soundings were created for the reanalysis time closest to the late afternoon/early evening time period. Thus, the region from 45°W to 135°W had soundings at 0000 UTC, the region from 45°E to 45°W had soundings at 1800 UTC, the region from 135°E to 45°E had soundings from 1200 UTC, and the region from 135°W to 135°E had soundings from 0600 UTC.

Again, it was assumed that the relationships derived from the United States data would apply. Regions with the greatest frequency of favorable significant severe thunderstorm conditions are equatorial Africa and the central United States (Fig. 17). Less frequent

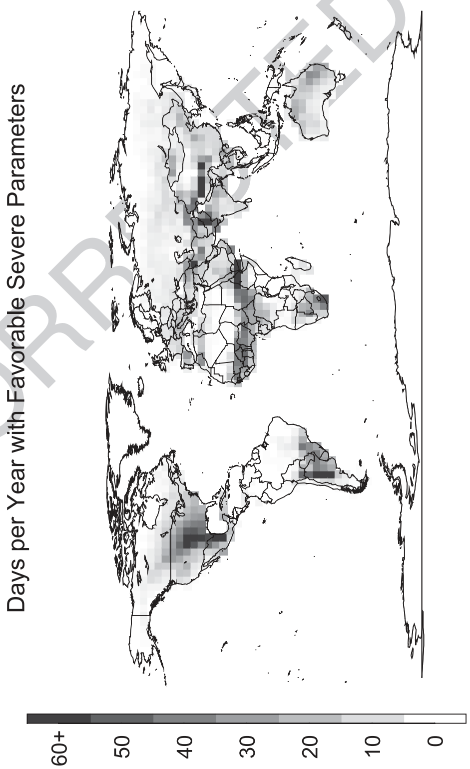

Fig. 17. Same as Fig. 11, except for world and different scale. Every other reanalysis grid point over land considered.

regions include the area near the Himalayas and southern Brazil and northern Argentina. In general, regions downstream of large mountain chains and equatorial Africa are highlighted. It is not clear why there is no corresponding maximum over equatorial South America. The problems with reporting become even more acute outside of North American and Europe, but Sommeria and Testud (1984) described a field project to study African squall lines and Altinger de Schwarzkopf and Rosso (1982) showed evidence for significant tornado activity in northern Argentina.

The regions of significant tornado environments are more limited (Fig. 18). The central United States, southern Brazil and northern Argentina, and a limited area around the Himalayas are the most noticeable areas of coverage. Scattered areas exist across the northern and central parts of Eurasian, but not with as high of peak frequencies. Perhaps most interesting, in comparison to the significant thunderstorm map, is the almost complete absence of favorable tornadic environments in equatorial Africa. This is a result of the near absence of high 0–1 km shear. Of the 2738 soundings identified as favorable for significant severe thunderstorms in equatorial Africa, only 11 (0.4%) have a 0–1 km wind difference of at least 10 m s^{-1}. In contrast, for North America, 208 (12.4%) of the 1678 significant severe thunderstorm soundings have that much shear. The peak African shear is 11.6 m s^{-1}, a value exceeded by 7.0% of the North American soundings.

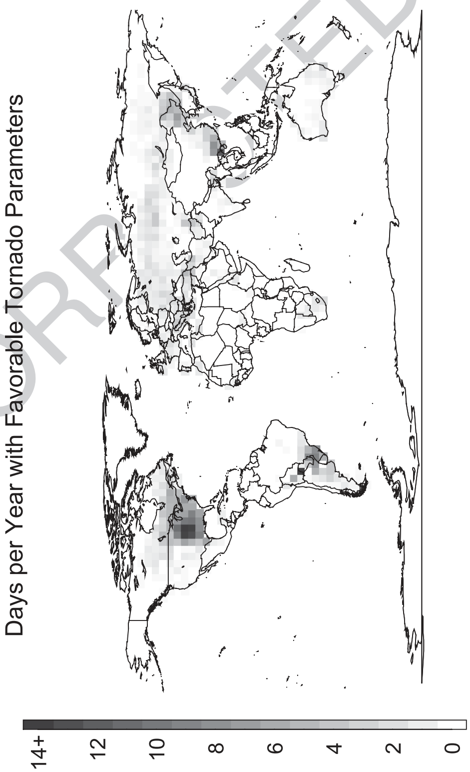

Fig. 18. Same as Fig. 17, except for tornadic parameters.

4. Discussion

The reanalysis system has shown a great deal of promise as a source of environmental information. Much of what is seen in the results makes intuitive physical sense. From an ingredients-based approach (Doswell et al., 1996) to severe thunderstorms, abundant lower-tropospheric moisture, steep mid-tropospheric lapse rates, and strong tropospheric wind shear are important. The central United States is in an ideal location for the juxtaposition of those ingredients with the high terrain of the Rocky Mountains providing a source for high lapse rate air and the Gulf of Mexico providing the moisture. Winds from the surface from over the Gulf (southerly) and from over the Rockies in the mid-troposphere results in strong shear at the same time it brings the thermodynamic ingredients together. Other regions near high terrain with moisture sources on their equatorward side (east of the Andes and south and east of the Himalayas) show up as well.

Given that our understanding of tornadic processes is not as good as for severe thunderstorms, more caution must be taken in interpreting the details. On the coarse scale, the distribution appears reasonable with the central United States being the most frequent location for favorable conditions. At the detail level, the United States distribution is too far east. This implies that we do not understand everything that is going on. At the simplest level, it is unlikely that the small number of parameters used here can capture the full physical processes of importance. It is also likely that processes that are important are not even captured in soundings (e.g., boundaries). In addition, it is plausible that more than one combination of processes is capable of producing significant tornadoes. As such, even if our list of ingredients describes the environments well for one of those processes, it might not describe the environments of other processes.

While the spatial distribution of environments may (or may not) be correct, the magnitude of occurrence of events is open to question. The probability that a favorable environment will actually be associated with an event is unknown. The number of observed proximity soundings associated with significant severe thunderstorms in the region studied in the United States is approximately 7% of the environments identified as "severe" or "tornadic." The efficiency of the atmosphere in producing severe thunderstorms in conditions that the sounding analysis identifies as favorable is unknown, and the strong possibility that it is spatially variable and involves environmental conditions not included in the reanalysis makes coming up with quantitative estimates of the global frequency of events challenging, if not impossible.

This work has been the first step in using reanalysis data to look at environments of hazardous weather. We have looked globally at only one analysis time for 3 years for a quarter of the land area outside of Antarctica and Greenland, and for one analysis time for 3 years over a small part of the planet. As a result, we can say nothing at all about the diurnal cycle and nothing of significance about interannual variability. While it is plausible that many severe thunderstorms occur in the late afternoon and early evening and we carried out our analysis at the nearest time to that part of the day, severe thunderstorms clearly occur throughout the day. As a result, we hope to look at the entire reanalysis data back through 1957 in order to consider the spatial and temporal variability.

It may be possible to use the reanalysis to address issues of possible changes in distribution of severe thunderstorm environments through time and to use it to lay the groundwork for investigating possible effects of climate change scenarios on severe thunderstorms (Intergovernmental Panel on Climate Change, 2002). In one sense, the reanalysis can be thought of as a series of short forecasts and analyses from a global model. Our results suggest that the reanalysis is capable of providing useful information on the distribution of severe thunderstorm environments. A reasonable test of global climate models is whether they are able to reproduce the current observed distributions of environments. From our results, there is no reason to doubt that models are *capable* of reproducing the distribution. Whether they *do* is another question. If, however, they do, running the models under different climate change scenarios might prove instructive in providing an estimate of what could happen. The observed record of events is not long enough and events are rare enough that it is difficult to use the observed record in detecting climate change, but it might be possible to use the observations of environments (Brooks and Doswell, 2001).

At a basic level, our interpretation is limited by the paucity of high-quality observational records of severe thunderstorm events. Major improvements and testing of the hypothetical distributions shown here require improvements in our records of when, where, and what kind of events actually occur. These records will take years to develop and we urge the international meteorological community to begin the process now.

Acknowledgements

This work was sponsored, in part, by the NOAA Office of Global Programs (Grant #GC00-139). We want to thank Kim Elmore of NSSL and the Cooperative Institute for Mesoscale Meteorological Studies and Matt Wandishin of NSSL and the University of Arizona for invaluable assistance in creating the maps. Conversations with Chuck Doswell helped in forming the basic ideas behind the work.

References

Adams, J.C., Swarztrauber, P.N., 1999. SPHEREPACK 3.0: a model development facility. Mon. Weather Rev. 127, 1872–1878.

Altinger de Schwarzkopf, M.L., Rosso, L.C., 1982. Severe storms and tornadoes in Argentina. Preprints, 12th Conf. Severe Local Storms, San Antonio, Texas, USA, Amer. Meteorol., pp. 59–62.

Beebe, R.G., 1955. Types of airmasses in which tornadoes occur. Bull. Am. Meteorol. Soc. 36, 349–350.

Beebe, R.G., 1958. Tornado proximity soundings. Bull. Am. Meteorol. Soc. 39, 195–201.

Beebe, R.G., 1963. Tornado proximity soundings. Proc. 3rd Conf. on Severe Local Storms, Urbana, Illinois, USA, Amer. Meteorol., pp. 1–6.

Brooks, H.E., Craven, J.P., 2002. A database of proximity soundings for significant severe thunderstorms, 1957–1993. Preprints, 21st Conference on Severe Local Storms, San Antonio, Texas, Amer. Meteorol. Soc., pp. 639–642.

Brooks, H.E., Doswell III, C.A., 2001. Some aspects of the international climatology of tornadoes by damage classification. Atmos. Res. 56, 191–201.

Brooks, H.E., Doswell III, C.A., Cooper, J., 1994. On the environments of tornadic and nontornadic mesocyclones. Weather Forecast. 9, 606–618.

Brown, B.G., Murphy, A.H., 1996. Verification of aircraft icing forecasts: the use of standard measures and meteorological covariates. Preprints, 13th Conf. Probability and Statistics in the Atmospheric Sciences, San Francisco, California, USA, Amer. Meteorol. Soc., pp. 251–252.

Bruening, S.L., Kay, M.P., Brooks, H.E., 2002. A new perspective on the climatology of tornadoes in the United States. Preprints, 16th Conference on Probability and Statistics, Orlando, Florida, USA, Amer. Meteorol. Soc., pp. J96–J103.

Costa, S., Mezzasalma, P., Levizzani, V., Alberoni, P.P., Nanni, S., 2001. Deep convection over Northern Italy: synoptic and thermodynamic analysis. Atmos. Res. 56, 73–88.

Craven, J.P., 2001. A baseline climatology of sounding derived parameters associated with deep, moist convection. Unpublished manuscript. 56 pp. [Available from Storm Prediction Center, 1313 Halley Circle Norman, OK 73069 U.S.A.].

Craven, J.P., Brooks, H.E., Hart, J.A., 2002a. Baseline climatology of sounding derived parameters associated with deep, moist convection. Preprints, 21st Conference on Severe Local Storms, San Antonio, Texas, USA, Amer. Meteorol. Soc., pp. 643–646.

Craven, J.P., Jewell, R.E., Brooks, H.E., 2002b. Comparison between observed convective cloud-base heights and lifting condensation level for two different lifted parcels. Weather Forecast. 17, 885–890.

Darkow, G.L., 1969. An analysis of over sixty tornado proximity soundings. Preprints, 6th Conf. on Severe Local Storms, Chicago, Illinois, USA, Amer. Meteorol., pp. 218–221.

DeFries, R.S., Townshend, J.R.G., 1994. NDVI-derived land cover classification at a global scale. Int. J. Remote Sens. 15, 3567–3586.

Doswell III, C.A., Brooks, H.E., Maddox, R.A., 1996. Flash-flood forecasting: an ingredients-based methodology. Weather Forecast. 11, 360–381.

Dotzek, N., 2001. Tornadoes in Germany. Atmos. Res. 56, 233–252.

Fawbush, E.J., Miller, R.C., 1952. A mean sounding representative of the tornadic airmass environment. Bull. Am. Meteorol. Soc. 33, 303–307.

Fawbush, E.J., Miller, R.C., 1954. The types of airmasses in which North American tornadoes form. Bull. Am. Meteorol. Soc. 35, 154–165.

Hart, J.A., Korotky, W.D., 1991. The SHARP workstation—v1.50. A skew-t/hodograph analysis and research program for the IBM and compatible PC. User's manual. 62 pp. [Available from NOAA/NWS Forecast Office Charleston, WV].

Intergovernmental Panel on Climate Change, 2002: Workshop Report, IPCC Workshop on Changes in Extreme Weather and Climate Events, Beijing, China. 107 pp.

Johns, R.H., Davies, J.M., Leftwich, P.W., 1993. Some wind and instability parameters associated with strong and violent tornadoes: 2. Variations in the combinations of wind and instability parameters. The Tornado: Its Structure, Dynamics, Prediction and Hazards. Geophys. Monogr., vol. 79. Amer. Geophys. Union, pp. 583–590.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, B., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77, 437–472.

Lee, J.W., 2002. Tornado proximity soundings from the NCEP/NCAR reanalysis data. MS Thesis, University of Oklahoma. 61 pp.

Markowski, P.M., Rasmussen, E.N., Straka, J.M., 1998. The occurrence of tornadoes in supercells interacting with boundaries during VORTEX-95. Weather Forecast. 13, 852–859.

Morel, C., Senesi, S., 2002. A climatology of mesoscale convective systems over Europe using satellite infrared imagery: II. Characteristics of European mesoscale convective complexes. Q. J. R. Meteorol. Soc. 128, 1973–1995.

Paul, F., 2001. A developing inventory of tornadoes in France. Atmos. Res. 56, 269–280.

Rasmussen, E.N., Blanchard, D.O., 1998. A baseline climatology of sounding-derived supercell and tornado forecast parameters. Weather Forecast. 13, 1148–1164.

Rasmussen, E.N., Richardson, S., Straka, J.M., Markowski, P.M., Blanchard, D.O., 2000. The association of significant tornadoes with a baroclinic boundary on 2 June 1995. Mon. Weather Rev. 128, 174–191.

Sommeria, G., Testud, J., 1984. COPT 81: a field experiment designed for the study of dynamics and electrical activity of deep convection in continental tropical regions. Bull. Am. Meteorol. Soc. 65, 4–10.

Turcotte, V., Vigneux, D., 1987. Severe thunderstorms and hail forecasting using derived parameters from standard RAOBS data. Preprints, Second Workshop on operational meteorology. Halifax, Nova Scotia, Canada, Atmos. Environ. Service/Canadian Meteorol. and Oceanogr., pp. 142–153.

Wilks, D.S., 1995. Statistical Methods in the Atmospheric Sciences, Academic Press. 467 pp.