J4.2 A GLOBAL VIEW OF SEVERE THUNDERSTORMS: ESTIMATING THE CURRENT DISTRIBUTION AND POSSIBLE FUTURE CHANGES

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1. WHAT IS THE CURRENT STATE?

Severe thunderstorms are a hazard in many parts of the world. Our understanding of their distribution in space and time is limited by problems in our physical understanding of the processes, and in limitations of the observational databases. Given those limitations, the question of how, if at all, severe thunderstorms will change under climate change scenarios is difficult to answer. In this paper, I will discuss the challenges and offer a plan in order to attack the problems.

Reports of severe thunderstorms (in the United States, a thunderstorm is severe if it produces hail of at least ¾ in. diameter, or wind gusts of 50 kts, or a tornado; most other countries that define severe thunderstorms include some criterion involving heavy precipitation) depend upon the presence of an observer and a system to collect the observation. In most countries, the data collection is not a part of the national weather service and, in many, depends upon someone doing it outside of their normal job.

As part of forecasting severe thunderstorms, the US NWS has collected reports in near-real time since the early 1950s. This represents the longest and most complete record recorded anywhere. Records from before then exist from local NWS office archives, newspaper accounts and other sources. Grazulis (1993) has discussed the challenges of using those sources in attempting to determine the record of tornadoes in the US.

Given the official nature of the relatively long record collected by the NWS, the US severe weather database represents something of a gold standard for severe weather databases in other countries. Brooks and Doswell (2001) pointed out similarities in the distribution of tornadoes by intensity in tornado databases around the world, although pointing out evidence for substantially more underreporting in other countries. Dotzek et al. (2003) and Feuerstein et al. (2005) extended that work, showing that the distributions could be modelled statistically, strengthening the case that underreporting is a bigger issue in other countries and that the US is substantially closer to reporting the true distribution.

Brooks (2000) and Doswell et al. (2005) considered the distribution of non-tornadic severe thunderstorm reports, which have increased by an order of magnitude since the 1950s. Brooks (2000) showed that the relative distribution by intensity, nationally, hasn't changed much for the more intense events (with an overall doubling or trebling), but that least intense severe events have dramatically increased in number. Doswell et al. (2005) highlighted the regional differences in reports, with local or regional office policy decisions making it extremely difficult to get more than a broad, general sense of non-tornadic severe thunderstorms.

By far, the best severe thunderstorm-related dataset is that for US tornadoes. That said, it has serious limits, even beyond basic problems associated with uncertainties in measurement and estimation. Brooks (2004) showed that large, in some cases highly statistically significant, changes have occurred in the distribution of path length and width over the years, some of which don't correspond to expected changes associated with policy revisions. As an example the width of tornadoes rated F2 (on the Fujita scale that goes from F0 to F5) are now similar to the widths of F3 tornadoes 30 years ago. The width increase began *before* a policy change to report maximum width instead of mean width was enacted and, in fact, the widths stop increasing at the time of the policy change.

Verbout et al. (2006) found circumstantial evidence that tornadoes prior to the mid-1970s were overrated, based on the distribution of tornado occurrence on the biggest days of each year. This is consistent with the environmental evidence discussed by Brooks and Craven (2002), and the general discussion of Grazulis (1993). The overrating is likely associated with the retrospective rating process applied to tornadoes from 1950-1975 after the adoption of the NWS of the Fujita scale for rating tornadoes. As a result, the limit to the useful length of the dataset for some important variables is much shorter than the full record. Still, estimates of the distribution can be developed by smoothing the data and using tornado "days" rather than tornado reports (Brooks et al. 2003a).

Clearly, the observed record of reports is insufficient to estimate the true occurrence of severe thunderstorms, even in the US, where the database is relatively good. Elsewhere, the records are completely inadequate except for the coarsest kinds of information.

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2. THE USE OF ENVIRONMENTAL INFORMATION

Given the lack of consistent observations of events, another possibility is to use large-scale environmental observations as a proxy. If reliable relationships between environmental conditions and events can be developed, then the distribution of those favorable environmental conditions can be studied. Such an approach was recommended by the IPCC (2002). Fortunately, studies of the environmental conditions associated with severe thunderstorms and tornadoes have been carried out for many years for the purpose of improving forecasts (e.g., Rasmussen and Blanchard 1998.)

Brooks and Craven (2002) produced a large dataset of radiosonde observations in the vicinity of significant severe thunderstorms (hail of diameter 2 in. or more, wind gusts of 65 kts or more, and/or an F2 or greater tornado) in the US. Based on other work, it was clear that it was difficult to discriminate between “non-significant” severe thunderstorms and non-severe thunderstorms, but that significant severe thunderstorm environments could be discriminated from other environments by using the convective available potential energy (CAPE) and the magnitude of the vector wind difference between the surface and 6 km above ground level (so-called “deep shear”) (Fig. 1 top). Significant tornadic environments could be discriminated from significant non-tornadic environments with the height of the lifted condensation level and the magnitude of the vector wind difference between the surface and 1 km above ground level (so-called “shallow shear”) (Fig. 2 top).

Given the paucity of radiosonde observations, Brooks et al. (2003b) repeated the work of Brooks and Craven (2002), but using pseudo-soundings derived from the NCAR/NCEP reanalysis. The discrimination for significant severe thunderstorms compared to non-significant events is remarkably similar to that from the observed radiosondes (Fig. 1 bottom). The discrimination is not as good for tornadic versus non-tornadic soundings (Fig. 2 bottom), probably because of difficulties in the reanalysis resolving sharp gradients and the boundary layer. Brooks et al. (2003b) went on to use those relationships to estimate the distribution of favorable environments in terms of number of days per year in which at least one of the four reanalysis times on a day falls in the appropriate region. Their analysis is updated with slightly changed predictors and for the period 1980-1999 in Fig. 3. Primary regions of favorable environments are downstream of major mountain ranges, in particular the meridionally-aligned ranges in the Americas. The significant tornado threat in the central US is noticeable, a result of the frequency of occurrence of strong low-level jets.

It’s important to note that the reanalysis results have problems. A 1-2 gridpoint wide, several gridpoint long north-south region just east of the Andes seems to be overdone, given the conditions around it, based on consideration of the annual cycle. Nevertheless, the large-scale distribution is likely to be a reasonable first guess.

3. QUALITATIVE SPECULATION ON CLIMATE CHANGE EFFECTS

A useful starting point for discussing the possible effects of a greenhouse-enhanced climate on severe thunderstorms is to consider the expected large-scale mean changes. The CAPE-shear diagram in Fig. 1 is instructive. The likelihood of an environment being severe (or tornadic) is higher for high CAPE-shear combinations. In order to quantify this, the results of a simple kernel density estimation of the probability of significant severe thunderstorms (including significant tornado) or significant tornadic storms, given a combination of CAPE and shear is given in Fig. 4. (A grid in log(CAPE)-log(shear) space was constructed with grid spacing 0.1 in each direction. Sounding parameters from a particular sounding were associated with a grid point if the distance between the sounding values and grid point was less than 0.2 in log-log space. The fraction of associated soundings that were severe or tornadic, given the total number of soundings, was then computed for all points with at least 30 associated soundings.) The strong gradient in probability going to high CAPE-shear is clear in the figure.

A naïve expectation for the mean conditions for CAPE in a greenhouse-enhanced climate is for it to increase with the increasing temperature and low-level moisture. Obviously, changes in the lapse rates aloft will have a significant effect on the magnitude and, if temperatures aloft warm sufficiently, could overwhelm the low-level changes. Nevertheless, it is reasonable to assume to first order that CAPE will increase. The CAPE effect, therefore, would be to increase the probability of severe thunderstorms and tornadoes.

Deep tropospheric shear, on the other hand, might reasonably be expected to decrease with a decreasing equator-to-pole temperature gradient. The primary effect of that would be to decrease the probability of severe thunderstorms and tornadoes. The net effect of changes in shear and CAPE is difficult to tell. The gradient in probability is roughly parallel to constant CAPE X shear values. As such, the question of which would dominate is very difficult to answer.

Of course, in reality, the mean conditions are not what we're particularly interested in. Of greater important is how the changes on individual days occur. It's possible for small changes in the mean to occur with large changes on every day. If, for instance, shear ended up being large on a small number of days, while decreased on a large number of days, the overall mean value might go down, while the number of days with favorable conditions might increase.

In order to look at how things have changed, annual counts of favorable days at every point in the reanalysis have been calculated. The sounding parameters for each of the four soundings on a day were computed and, if at least one sounding on the day fell in the favorable regions in diagrams in Fig. 2, the sounding was deemed tornadic, severe, or non-severe. Note that the decision is done in two parts. First, the CAPE-deep shear space is examined to see if the sounding is severe. If and only if it is, the lifted condensation level-shallow shear space is considered to see it is tornadic. Thus, all tornadic soundings are also severe.

As an example, regional counts were computed for areas 15 by 15 points (roughly 28° latitude by longitude) for regions east of the Rockies and Andes. These squares included the primary high-frequency locations seen in Fig. 3. The fraction of the total number of soundings (15X15X365=82,125) meeting favorable severe criteria for the North American and South American regions is shown in Fig. 4 (top). On average, about 40% more favorable environments are identified in North America. Linear regression gives a positive slope for North America of about 0.5% per year of the overall mean value, but the slope is not significant and it is important to note that 1980 is one of the highest years and 1999 is one of the smallest. In the South American region, the linear regression fit is negative, but again it is not statistically significant.

The fraction of severe storm environments that are tornadic is approximately twice as high in North America than in South America (Fig. 5 bottom). This is a result of larger values of the shallow shear being present in the central US than in South America. Slopes of a linear regression fit are near zero for both regions.

Regional interannual variability can be assessed by considering averages over a few year period. As an example, the difference in the mean number of days per year identified as supportive of severe storms in the late 1990s and 1980s for the US shows that there were many more days in the late 1990s identified as severe than in the late 1980s in the southern Plains and southeastern US and fewer days in the northern Plains (Fig. 6). Given that the average number of favorable environment days is on the order of 30 per year, differences of 10, as seen in the southern portion of the domain, are very large. The pattern shift is consistent with changes in the distribution of tornadoes between those two periods. Given that a similar figure of differences between different five year periods show no long-term consistent, we cannot identify those changes as being associated with a long-term trend. Instead, they are more likely reflections of the true differences in a relatively constant climate. Given interannual variability on the order of 1/3 of the mean value, changes in the long-term mean will have to be large before they become of great practical importance.

4. FUTURE WORK

Several efforts to examine climate model simulations in the same way as the reanalysis has been studied are beginning. As a first step, the ability of climate models to reproduce the gross features of the convective environments in current climate simulations will be assessed. Changes from the model climate in climate change scenarios can then be evaluated. It isn't necessary that the current observed distribution be exactly replicated for value to come from the study. Of greater interest is the change in the location, shape, and spread of the "cloud" of points similar to that seen in Figs. 1 and 2. If the cloud in a climate change scenario moves "up and to the right" in CAPE-shear space, then the model is clearly forecasting more environments supportive of severe thunderstorms. At present, however, no reasonable expectations of what will occur can be made. From relatively simple principles, one could predict almost any effect.

Models and consideration of environmental conditions seem to be the only hopes for providing any useful answers about possible changes in severe thunderstorm and tornado distributions. The records of observed reports are inadequate to give any answer. Given the large changes in the reporting databases that appear completely unphysical, any rather large changes in physical events (say 50%) might be completely masked. At present, any statements about changes in severe thunderstorms and tornadoes are nothing more than idle speculation.

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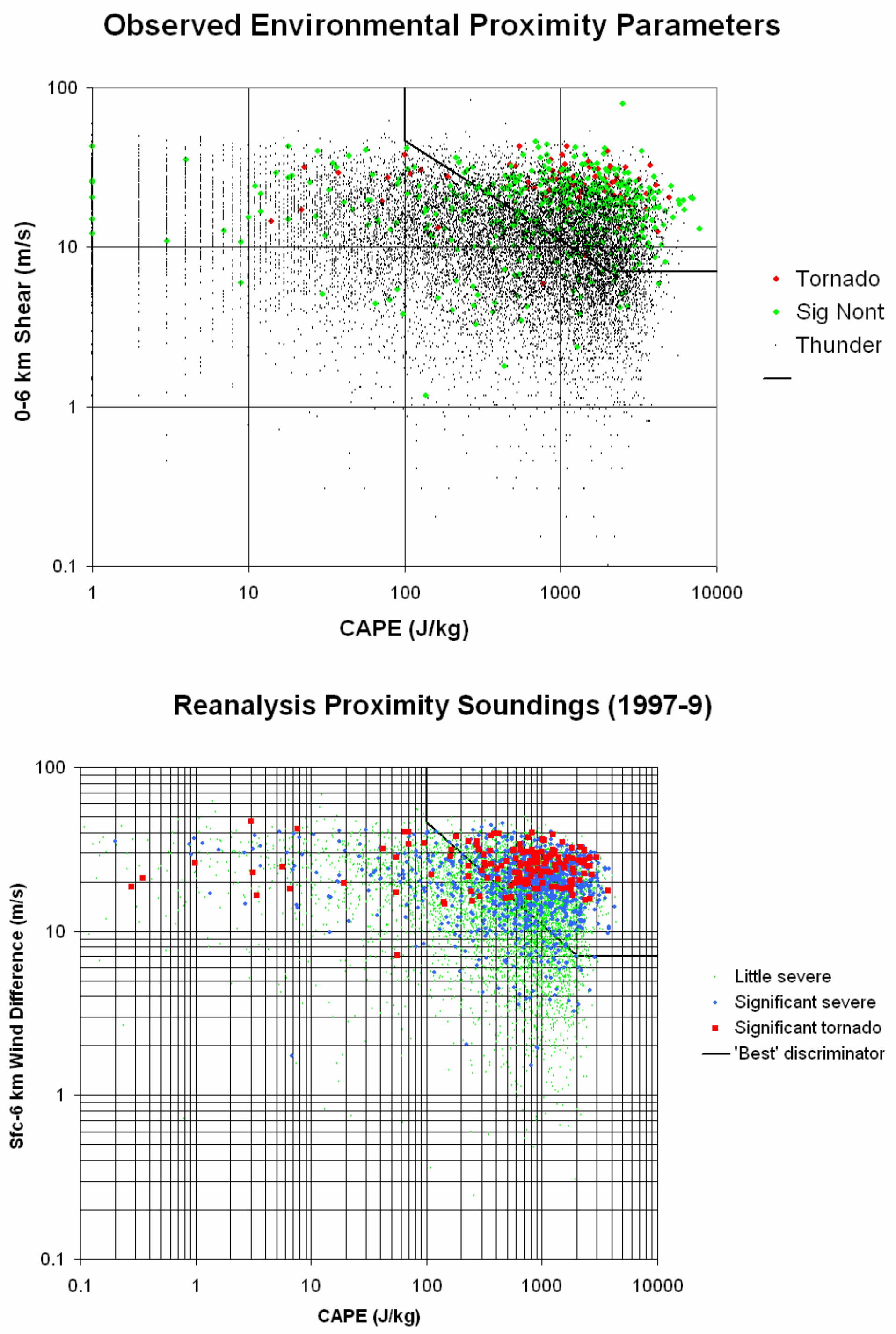


Fig. 1: Scatterplot of environmental conditions associated with weather types with convective available potential energy (CAPE) on abscissa and magnitude of vector difference between surface and 6 km above ground level on ordinate for years 1997-9. Top from observed soundings with red points for significant tornadoes, green for significant non-tornadic storms, and black dots for other severe or non-severe thunder. Bottom from reanalysis soundings with non-tornadic significant in blue and other severe in green. Black line represents linear discriminant (computed in log-log space) with minimum of 100 J kg^{-1} and 7 m s^{-1}. Note change in horizontal axis between figures.

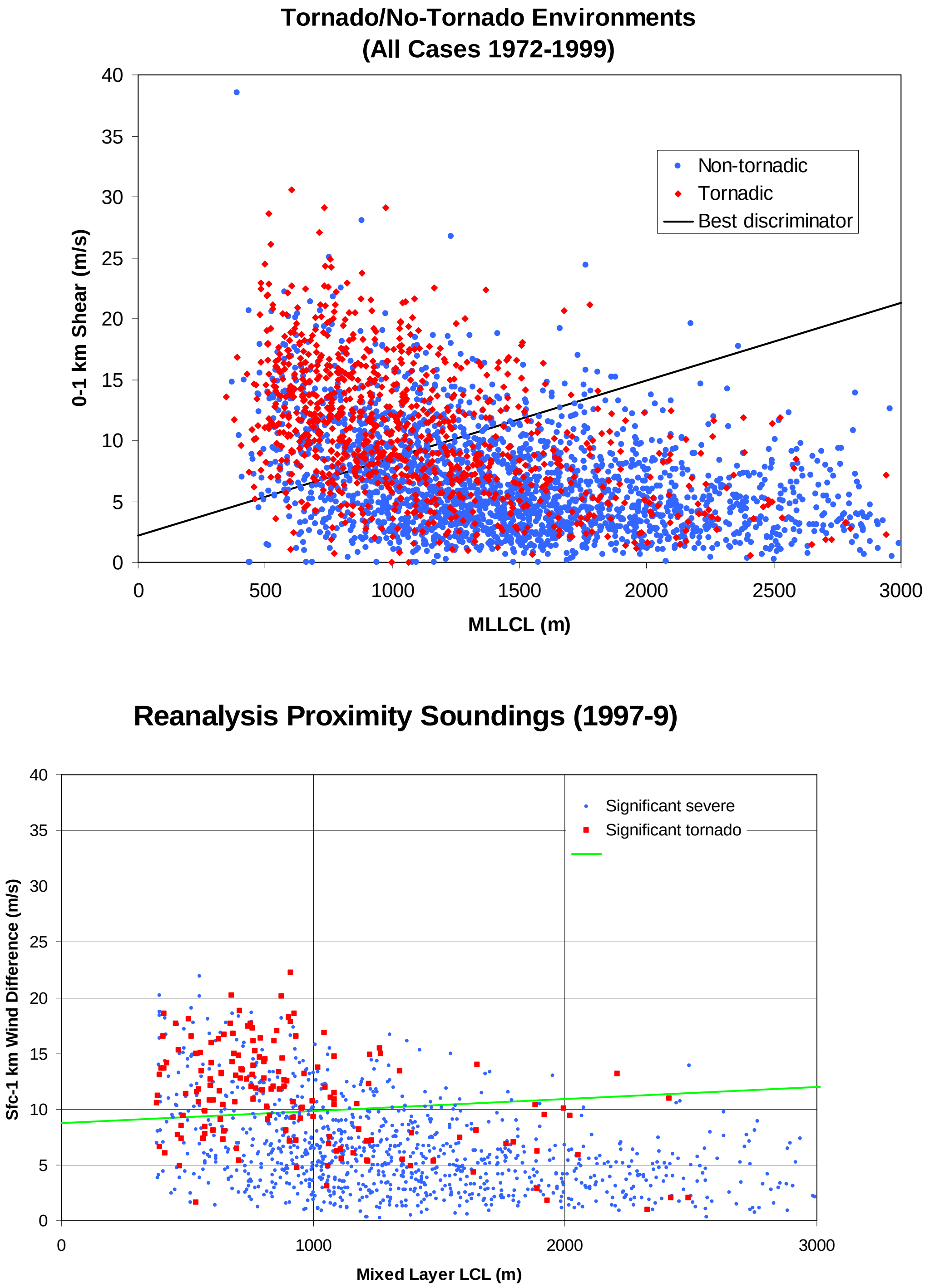
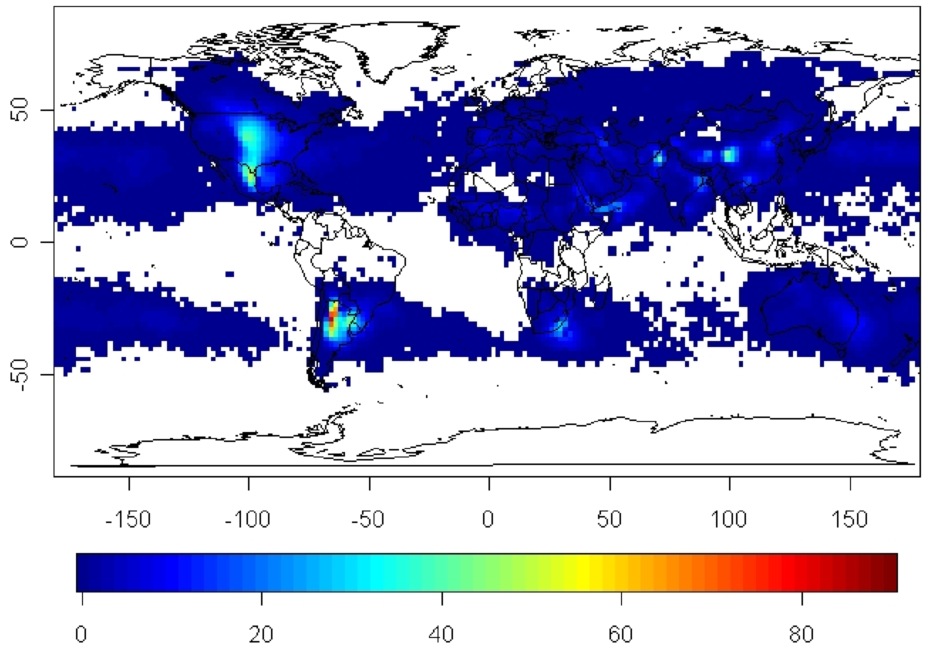


Fig. 2: Discrimination between significant tornadic (red) and significant non-tornadic (blue) soundings using height of lifted condensation level using a parcel mixed over the lowest 100 hPa of the atmosphere magnitude of vector difference between surface and 1 km above ground level. Linear discriminant line included. Top from observed soundings (1972-1999) and bottom from reanalysis soundings (1997-1999).

Mean Annual Severe Environment Days (1980-1999)



Mean Annual Tornadic Environment Days (1980-1999)

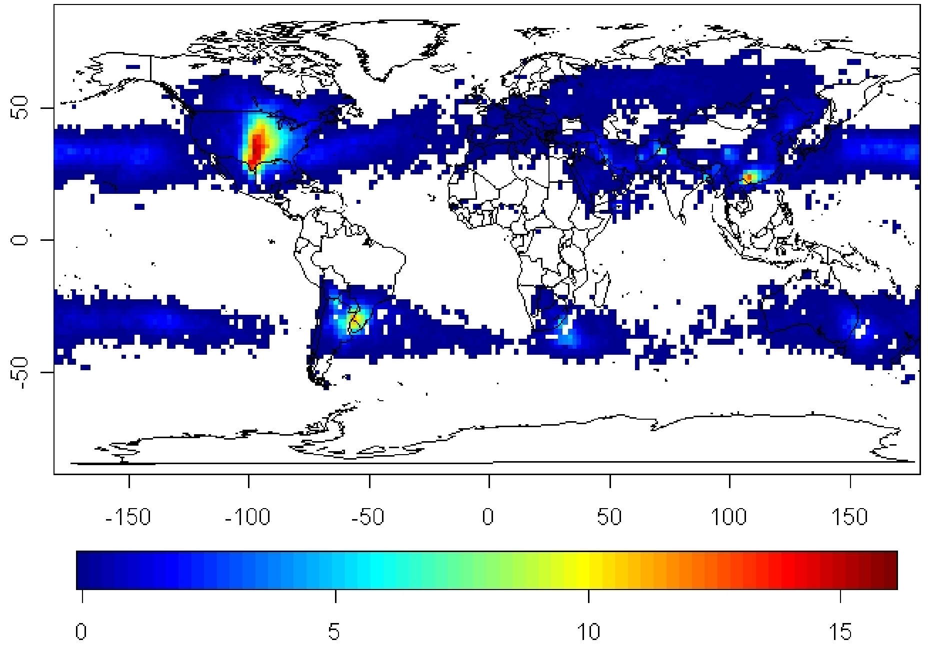


Fig. 3: Estimated mean annual days with favorable conditions for significant severe (including tornadic) storms (top) and significant tornadic storms (bottom) from reanalysis soundings from 1980-1999. White represents locations with identically zero days.

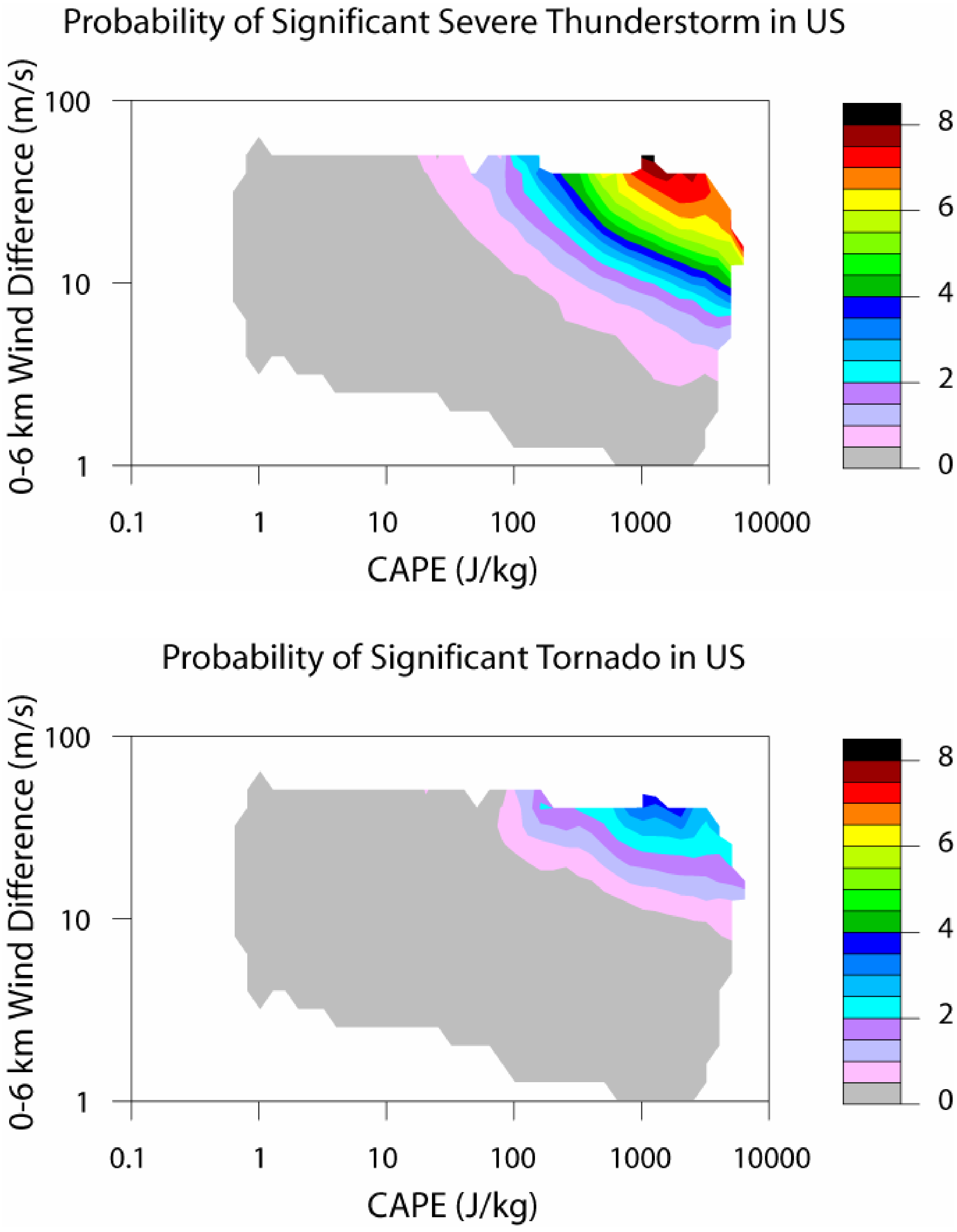


Fig. 4: Estimated probability (in %) of any significant severe storm (top) and significant tornadic storm (bottom) given combination of CAPE and magnitude of vector difference between surface and 6 km above ground level. Calculations carried out by gridding cases in log-log space and then associating soundings "near" gridpoint (within a distance of 0.2 in log-log space) with that point and then computing fraction of cases with appropriate number of events occurring. White areas indicate conditions do not occur frequently enough to estimate frequency (fewer than 30 cases).

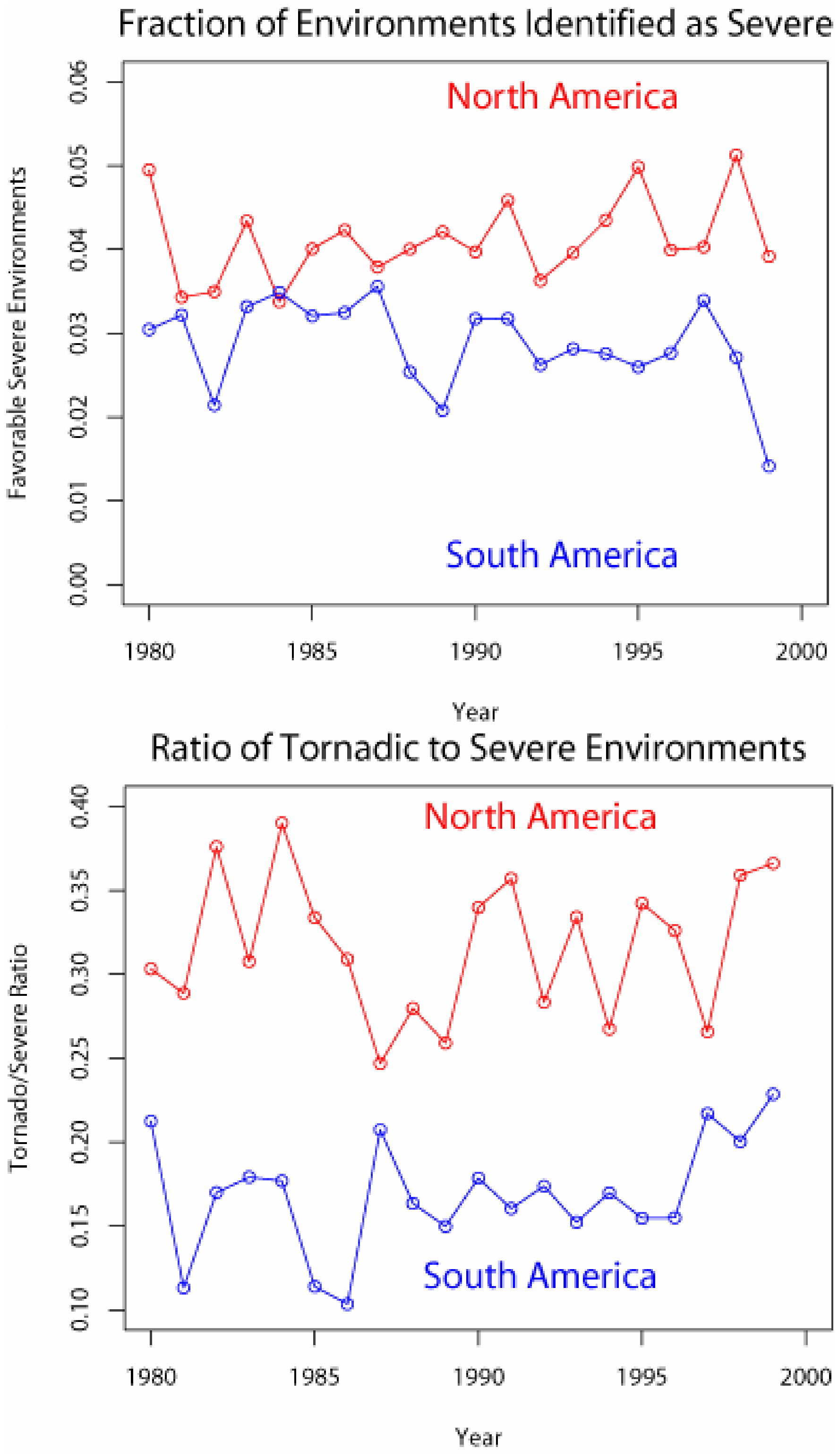


Fig. 5: (Top) Fraction of total reanalysis gridpoint-days associated with significant severe thunderstorm environments for 15x15 grid point boxes east of Rocky Mountains in North America and east of Andes in South America containing highest concentration of favorable environments from Fig. 4 for each year from 1980-1999. (Bottom) Ratio of environments associated with tornadic conditions to those associated with significant severe thunderstorms for each year in same region.

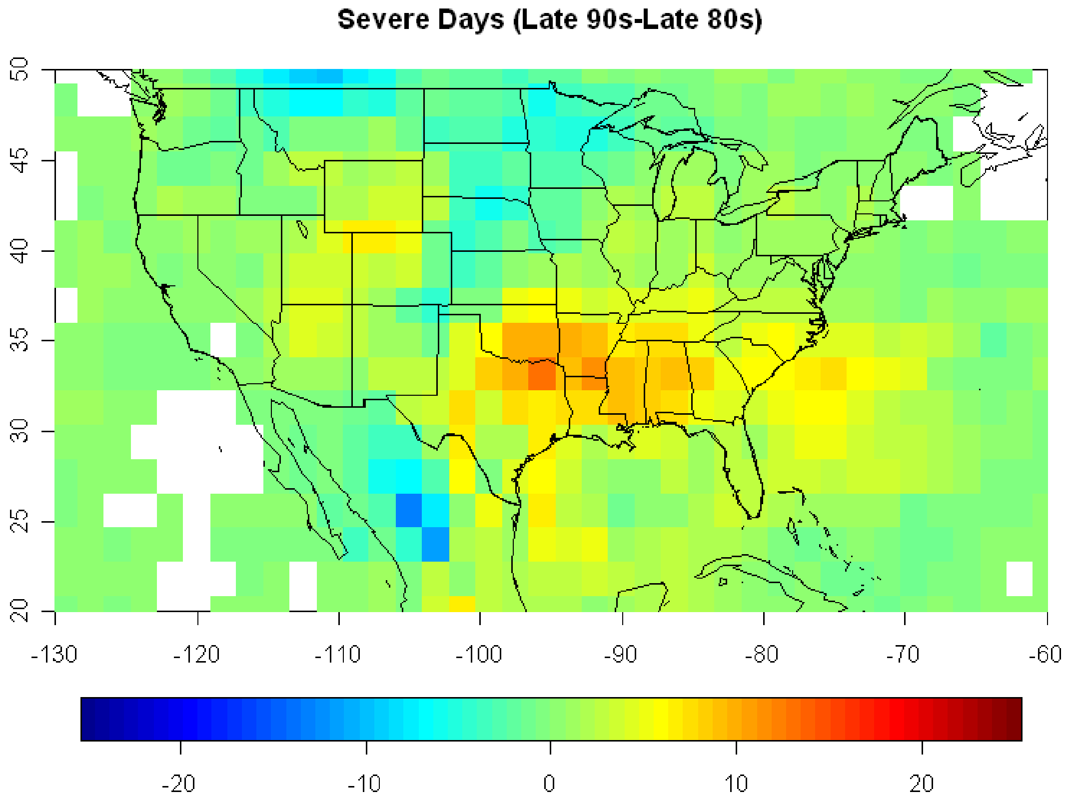


Fig. 6: Difference in mean number of days associated with significant severe thunderstorm environments between periods 1985-1989 and 1995-1999. Positive (negative) values indicate more frequent severe thunderstorm environments in late 1990s (1980s).