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Climatological aspects of convective parameters from the NCAR/NCEP reanalysis

Harold E. Brooks [a,*], Aaron R. Anderson [b,1], Kathrin Riemann [c],
Irina Ebbers [c], Heather Flachs [d]

[a] *NOAA/National Severe Storms Laboratory, Norman, Oklahoma, USA*
[b] *University of Oklahoma, Norman, Oklahoma, USA*
[c] *University of Hamburg, Hamburg, Germany*
[d] *Northern Illinois University, DeKalb, Illinois, USA*

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Abstract

Annual cycles of convectively important atmospheric parameters have been computed for a variety of from the National Center for Atmospheric Research (NCAR)/National Centers for Environmental Prediction (NCEP) global reanalysis, using 7 years of reanalysis data. Regions in the central United States show stronger seasonality in combinations of thermodynamic parameters than found elsewhere in North America or Europe. As a result, there is a period of time in spring and early summer when climatological mean conditions are supportive of severe thunderstorms.

The annual cycles help in understanding the large-scale processes that lead to the combination of atmospheric ingredients necessary for strong convection. This, in turn, lays groundwork for possible changes in distribution of the environments associated with possible global climate change.

Keywords: Thunderstorms; Tornadoes; Forecasting; Climate

1. Introduction

An important tenet of forecasting any weather phenomenon is that the environmental conditions are critical in determining what will occur. An understanding of the “ingredients” for a particular weather event allows forecasters to focus their attention during the course of a forecast (Doswell et al., 1996). An understanding of the climatological distribution of those ingredients provides an estimate of where and when the corresponding events are most likely. The climatological distribution may not be useful in making a forecast on a particular day, but it can help in understanding the differences between what happens at different locations and times of day.

Brooks et al. (2003b) used data from a global reanalysis dataset (Kalnay et al., 1996) to develop relationships between environmental variables and severe thunderstorms in the United States, and then applied those relationships to make estimates of the distribution of severe thunderstorms and tornadoes

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[*] Corresponding author. NSSL/FRDD, National Weather Center, 120 David L. Boren Boulevard, Norman, OK 73072, USA.

E-mail address: Harold.Brooks@noaa.gov (H.E. Brooks).

[1] Current affiliation: Weathernews, Inc., Norman, Oklahoma, USA.

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around the world. They made no effort to consider the temporal variability of the phenomena or the associated ingredients. In this paper, we will look at the mean annual cycle of some of the important ingredients with the hope that it will improve our understanding of the temporal and spatial distribution of the phenomena. In particular, we want to consider how important variables change in conjunction with each other. Clearly, if a change in one ingredient makes thunderstorms more likely, a change in another ingredient could make them less likely and the question of whether thunderstorms were more likely would depend on which term dominates.

This discussion lays the groundwork for consideration of possible effects of global climate change on the distribution of severe thunderstorms. A workshop on extreme weather and climate change put on by the Intergovernmental Panel on Climate Change (IPCC, 2002) noted that observations of severe thunderstorms are not collected uniformly and there are long, consistent records in few locations. As a result, an emphasis on consideration of the environmental conditions was recommended. Here, we wish to begin to address the question of what the current distribution of environmental conditions is.

After considering how the mean annual cycles are constructed, we will show the annual cycle of thermodynamic parameters at a variety of points in North America and Europe. Then, shear will be added for a subset of points. A discussion of the implications of the results will close the paper.

2. Methodology

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. Here, we will use the data from 7 years, 1973, 1987 and 1995–1999.[2] Given this amount of data, we will look at the mean in this paper and not consider variability at this time.

The basic concept of the reanalysis was to produce a best guess of the state of the atmosphere at 6-h intervals. Output is available from the reanalysis on 27σ levels ($\sigma = p/p_o$, where p is pressure and p_o is surface pressure) in the vertical above the surface and in the form of spectral coefficients in the horizontal, with a horizontal spacing of 1.875° in longitude and 1.915° in latitude, equivalent to a grid spacing slightly finer than 200 km over most of the globe. Lee (2002) and Brooks et al. (2003a,b) discuss the process of taking the reanalysis data and converting it into vertical profiles that resemble radiosonde profiles. Those profiles 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. Additional details on the processing can be found in Lee (2002) and Brooks et al. (2003b). Sterl (2004) reported on inhomogeneities in the reanalysis in the Southern Hemisphere with a break point around 1980, when satellite data began to be incorporated into the reanalysis process. Observational density was good enough in the Northern Hemisphere to lessen that change there. Caution must be taken when looking at fields involving strong vertical gradients, which the reanalysis has difficulties with. Betts et al. (1996) found the reanalysis to be slightly moister and cooler in the boundary layer in the Great Plains of the US in summer in comparison with observations from a field project, although they found the overall performance of the reanalysis to be quite good. Zwiers and Kharin (1998) have pointed out that low-level winds in the reanalysis tend to be weaker than in observations. Depending on the nature of the virtual structure of the errors, this may not affect the qualitative interpretation of our results, but indicates that caution must be taken in applying the results to observed soundings quantitatively.

Our attention here is focused on four variables:

1. Mean mixing ratio over the lowest 100 hPa
2. Mean lapse rate from 700 to 500 hPa
3. Convective Available Potential Energy (CAPE) using a parcel with the mean properties of the lowest 100 hPa
4. “Deep shear”, the magnitude of the vector difference between the surface and 6 km above ground level winds.

In particular, we will consider the relationship between the mixing ratio and lapse rate and between the CAPE and shear terms.

For the mixing ratio and lapse rate, values at all four times of day for each day were considered for each

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[2] Analysis of the data began with 1999 and worked backwards for five years. The two earlier years were chosen for an unrelated study dealing with tornado occurrence in the United States. Plans call for analysis of 42 years of data to be carried out in the near future.

location. The values at the time of day for a particular day when the mixing ratio was greatest were selected. Differences between allowing the time of day to vary and fixing it are slight, but detectible, for the mixing ratio, with half the dates being on the order of 0.6 g kg^{-1} or less. The diurnal cycle of lapse rate is relatively smaller. Given that difference, focusing on the mixing ratio puts greater emphasis on the most convectively unstable environments. With our interest in severe convection, this seems an appropriate choice.

Once the values for the mixing ratio and lapse rate are found for each day, the mean for each day of the year is calculated (ignoring 29 February). After that, a 31-day running mean is computed to smooth the data. This produces a final result that has the temporal smoothing of a monthly mean, but has daily resolution, so that, if large changes occur on the time scale of a month, but are not coincident with the arbitrary boundaries of months, they still can be seen in their full extent.

For the CAPE and deep shear, a similar procedure is followed, except that the time of day selected is that when CAPE is at its maximum. Also, only days with CAPE greater than zero are considered. Thus, the mean can be thought of as a conditional mean, given that CAPE is positive. This is done to focus attention on times when convection is likely. For instance, deep shear is likely to large during the middle of winter, but in the absence of CAPE, its organizing effects on thunderstorms are irrelevant. The focus on positive-CAPE days only does mean that sample size becomes a problem for some locations, particularly those in high latitudes in winter. Caution must be exercised in interpreting annual cycles there, if a small number of days during the period of record had positive CAPE, but it was a relatively large value on each day. It is conceptually possible that CAPE could appear to be large because of a single day. In practice, none of the locations studied have had this problem.

3. Results

3.1. Low-level moisture and lapse rates

Doswell et al. (1996) describe three basic “ingredients” for thunderstorms: lower tropospheric moisture, potential instability and some lifting mechanism, such as a convergent boundary. The lifting mechanisms will not be captured well by the reanalysis, but the other two have fields that relate to them. The mean mixing ratio in the lowest 100 hPa provides a direct measure of the lower tropospheric moisture. Lapse rates between 700 and 500 hPa can provide information on the potential instability. Because the lapse rate calculation is tied to specific levels, it is obviously not a complete representation of the potential instability. Inversion layers just below 500 hPa, for example, might mean that the lapse rate underestimates the potential. In addition, it might be possible for a region of steep lapse rates to exist that does not correspond to the 700–500-hPa layer. Other things being equal, the potential for strong convection increases with increasing low-level moisture and steeper mid-tropospheric lapse rates.

We wish to look at the annual cycle of moisture and lapse rates at a large number of points, but in order to make the picture clearer, we will be begin by focusing on one location, 35°N, 97.5°W (near Oklahoma City, Oklahoma, USA). As will become clear later, one reason for choosing this location as a starting point is that it has a clear, relatively easy-to-understand mean annual cycle. All of the points that go into the calculation of the mean conditions on 1 January and 1 July have been plotted (Fig. 1), in order to provide an indication of the degree of scatter. Summer points tend to have smaller variability in lapse rates than winter points (the absolute minimum standard deviation for the points going into the calculation of the mean is 0.6 K km^{-1} in August, with winter values of 1 K km^{-1}), although the degree of variability in mixing ratio is similar (the standard deviation is between 1.5 and 2.0 g kg^{-1} for all of January and July.) Variability in the mixing ratio is concentrated in the transition seasons, with the absolute maximum mixing ratio standard deviation of 3.5 g kg^{-1} in the middle of October and a spring maximum of 2.7 g kg^{-1} in the middle of April.

Given the large scatter, the mean pattern tells a suggestive story of the background thermodynamic characteristics in the Oklahoma City area. The primary source of moisture is the Gulf of Mexico, located approximately 800 km to the south. High values of mid-tropospheric lapse rates are associated with air that is heated and dried over the elevated terrain of the southwestern US (Doswell et al., 1996), approximately 800 km to the west. Starting with 1 January, the atmosphere is dry (3.7 g kg^{-1}) and relatively stable (6.3 K km^{-1}). In the first 3 months of the year, the mean values of both mixing ratio and lapse rates slowly increase to values of approximately 6 g kg^{-1} and 7 K km^{-1}, respectively. During the spring and early summer, the lapse rates stay relatively constant, while the mixing ratio increases to over 13 g kg^{-1} by 1 July. Other parts of the sounding structure being the same, during this time of year, the combination of low-level moisture and large mid-tropospheric lapse rates would lead to large values of CAPE. In July, the lapse rates

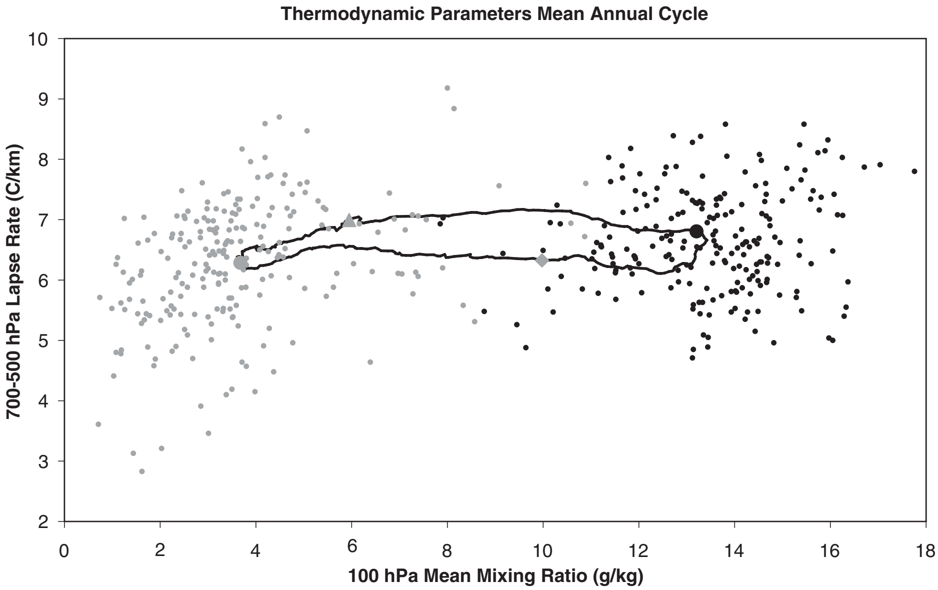

Fig. 1. Mean annual cycle of lowest 100-hPa mean mixing ratio and 700–500-hPa lapse rate for 35°N, 97.5°W. Small gray (black) circles indicate raw values that went into compute mean values for 1 January (1 July). Large gray (black) circle indicates mean value of 1 January (1 July). Gray triangle (diamond) indicates mean value for 1 April (1 October). First day of January, April, June and October also indicated by 1, 4, 7 and 10.

abruptly decrease while the mixing ratio stays high. The abrupt decrease is due to a decrease in the lapse rates over the southwestern US and the weakening (and occasional reversal) of the westerly upper level flow as subtropical air masses move northward, leading to less advection of high lapse rate mid-tropospheric air. From mid-August through the rest of the calendar year, the mixing ratio decreases at a relatively constant value of the mid-tropospheric lapse rate, approximately 0.5 K km^{-1} lower than the spring value.

In order to assess geographic variability, the mean annual cycles along north–south and east–west cross sections through Oklahoma City are presented. The locations of the cross sections can be seen in Fig. 2. In the southwestern part of the US, the annual cycle tends to be dominated by changes in lapse rate, with low mixing ratio values throughout the year (Fig. 3). The peak value of lapse rate occurs in July and increases in mixing ratio occur after that. Note that this is a very different annual cycle than seen at Oklahoma City, where the mixing ratio increases in the spring and early summer. Moving eastward, the changes in mixing ratio become greater until, in the eastern US (the points at 91.9°W and eastward), the annual cycle is almost entirely dominated by changes in mixing ratio at relatively low values of lapse rate. The central part of the cross section is unique in having a significant period of time in which both the lapse rates and mixing ratio values are high. This corresponds to the region where severe and tornadic thunderstorms are most likely in the US (Brooks et al., 2003a; Doswell et al., 2005).

The north–south cross section shows a slight increase in the annual mean lapse rates as we move southward along the cross section, but the "gap" between the spring and fall seasons is much larger as in that direction (Fig. 4). As in the case of the Oklahoma City profile, this is a result of the changes in the winds aloft and corresponding change in the source and advection of lapse rates through the summer. Moisture tends to increase in the southward direction, particularly in the cold season. As a result, the lapse rates play a more important role in describing the annual cycle of thermodynamics in the southern end of the cross section.

The situation in Europe is very different, as illustrated by the cross sections located as in Fig. 5. In the east–west direction at 48°N, the cycles are compressed compared to North America (Fig. 6). The lapse rates are lower, reflective of the absence of a source of high lapse rate air comparable to the Rocky Mountains, but there is also very little difference between the values in the spring and fall. The annual cycle of moisture is also smaller in comparison with North America, with the high values of eastern North America never being reached. The most striking feature, however, is the lack of geographic variability. While the lowest values of moisture at the westernmost point on the cross section (in Normandy) are higher than elsewhere, because of the proximity to the Atlantic Ocean, and the

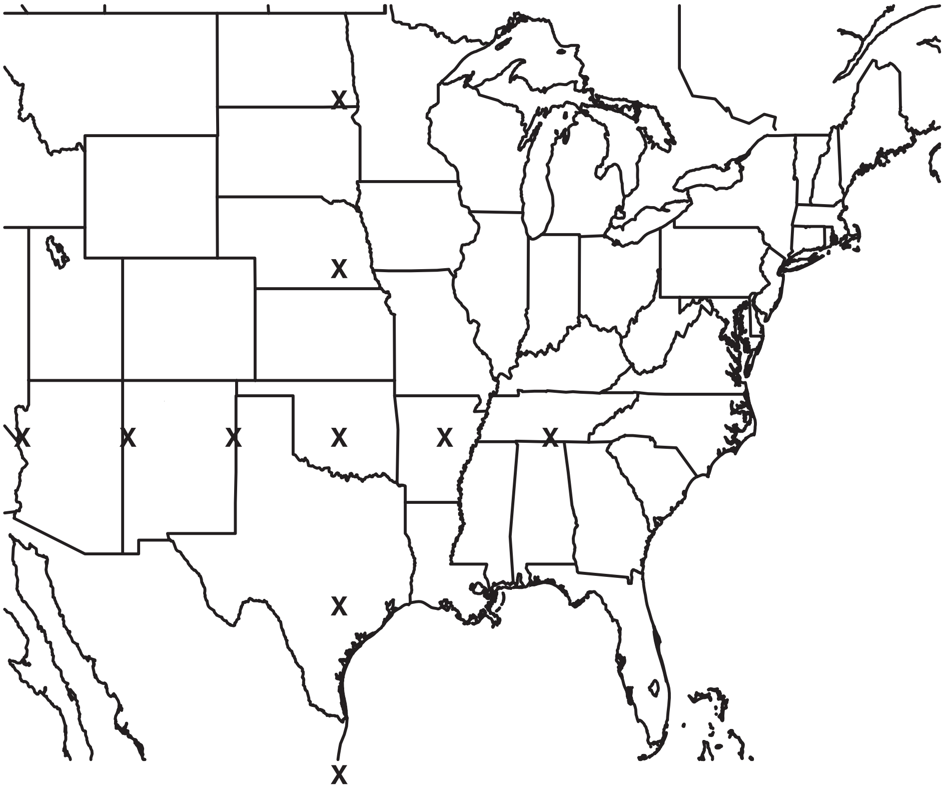

Fig. 2. Map of locations for cross sections in North America.

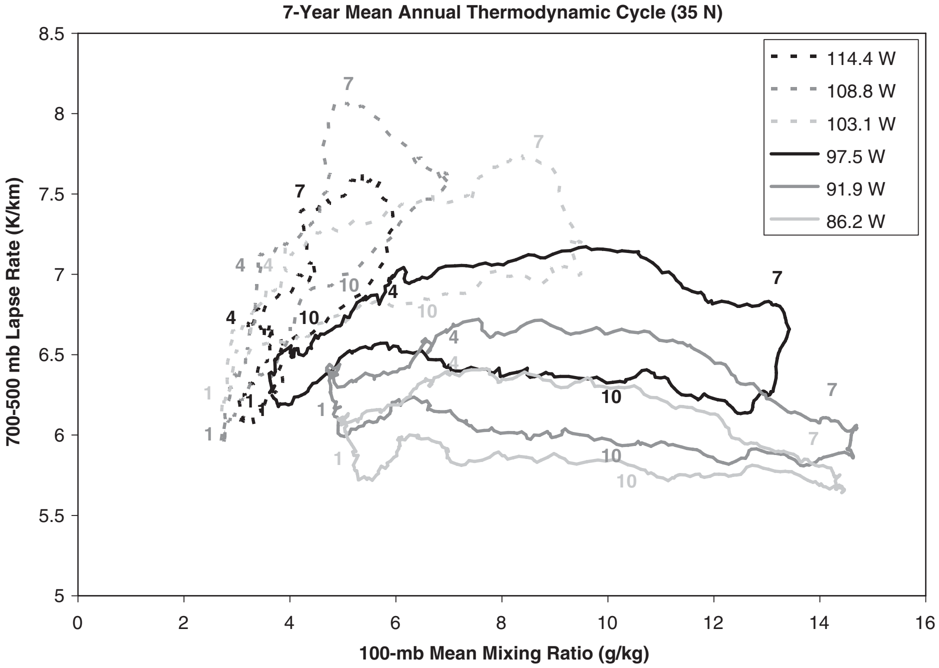

Fig. 3. Mean annual cycles of lowest 100-hPa mean mixing ratio and 700–500-hPa lapse rate at 35°N. Numbers indicate first day of month (1 January, 4 April, 7 July and 10 October). For locations, see Fig. 2.

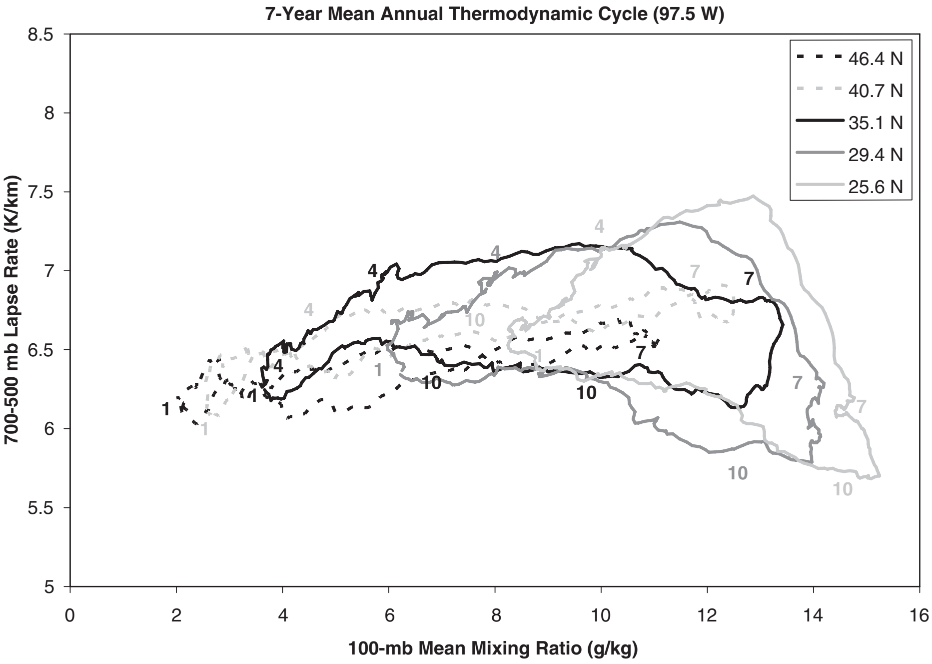

Fig. 4. Same as Fig. 3, except along 97.5°W.

summer values of moisture are higher at 28.1°E than elsewhere, as a result of the warm waters of the Black Sea, the differences in the various cycles are much smaller than in North America. The lack of source regions for extreme values of mid-tropospheric lapse rates and low-level moisture in Europe comparable to the

Fig. 5. Map of locations for cross sections in Europe.

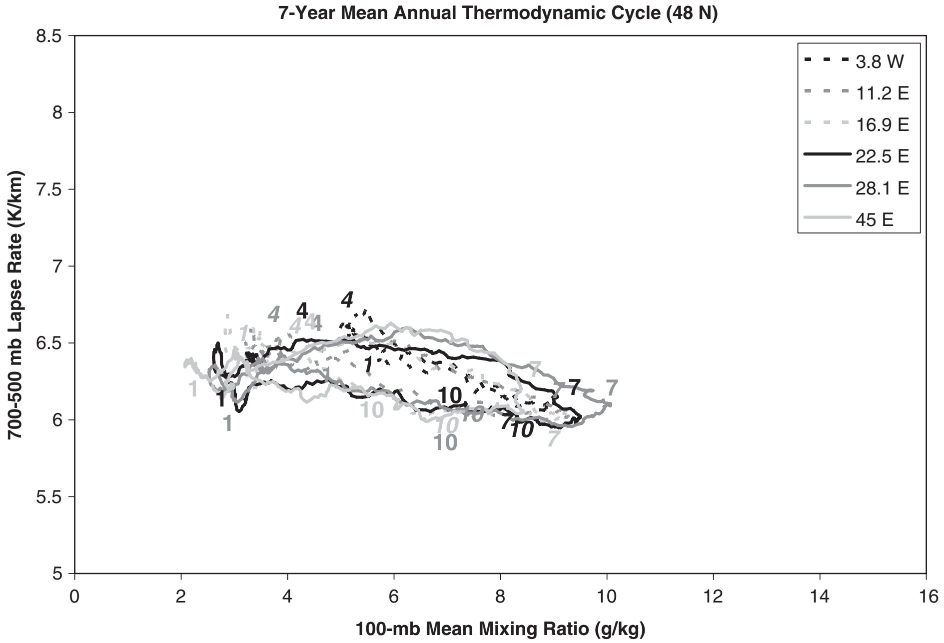

Fig. 6. Same as Fig. 3, except along 48.3°N. See Fig. 5 for locations. Western three points have months highlighted in italics.

Rocky Mountains and Gulf of Mexico lessens the extremes of the annual cycle.

The European north–south cross section shows more variability than the east–west cross section, mostly in the increase in moisture from north to south (Fig. 7). The cycles in this cross section illustrate another difference in the European and North American environments. In North America, there are times of the year when lapse rates and moisture are both relatively near their maximum values at the same time. In Europe, high values of lapse rate tend to be associated with low values of moisture. As a result, in the mean, high values of

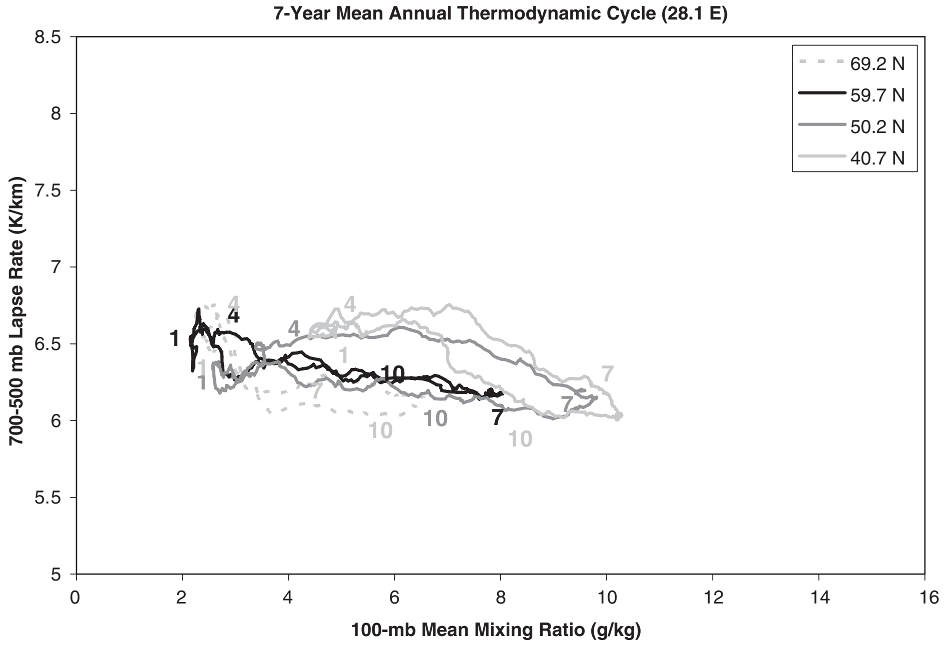

Fig. 7. Same as Fig. 6, except along 28.1°E.

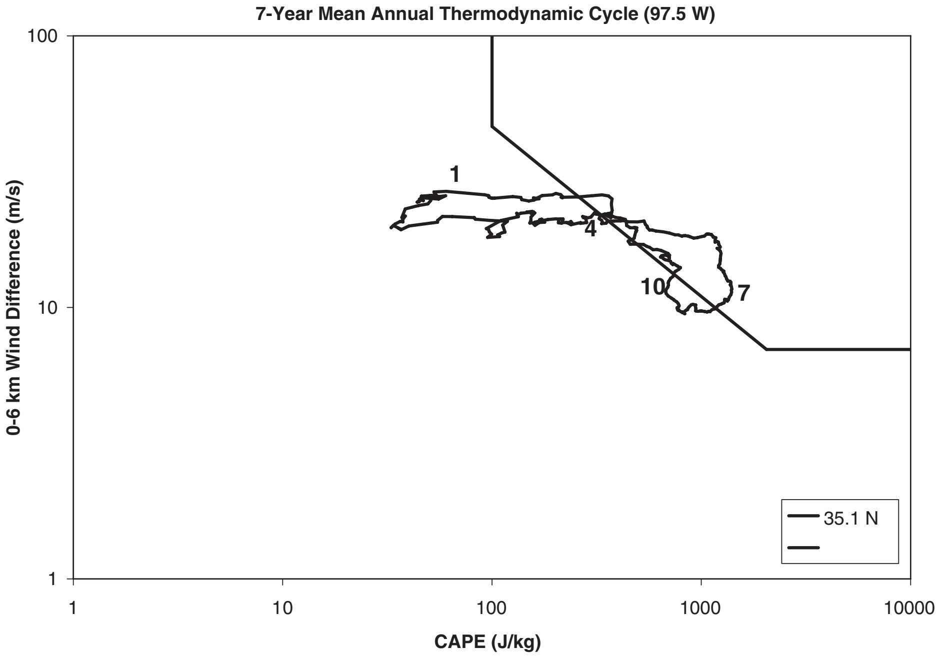

Fig. 8. Mean annual cycle of CAPE and "deep shear" for 35°N, 97.5°W (Oklahoma City) with logarithmic scale. Heavy straight line indicates best discrimination line adapted from Brooks et al. (2003b).

CAPE are much more unlikely than in North America, as seen in Brooks et al. (2003b).

3.2. CAPE and shear

The lapse rate and moisture profiles shown before can be thought of as the building blocks of CAPE. Although CAPE may be important for thunderstorms to have strong updrafts, shear acts to organize the storms, increasing their chances of being severe (Doswell et al., 1996). Brooks et al. (2003b) showed that a combination of CAPE and the deep shear discriminate between the environments associated with thunderstorms producing "significant" severe weather[3] and those that do not. As a result, we want to show annual cycles for selected locations for these parameters as well. We begin, as before, with the Oklahoma City cycle (Fig. 8). In winter, the shear is high and CAPE is low (note that these are mean values calculated only for days when CAPE is positive). Approaching spring, the CAPE increases with the shear remaining high, so that the mean conditions are supportive of severe thunderstorms, according to the discrimination line of Brooks et al. (2003b). It is important to note that the discrimination line should not be thought of as an absolute. Rather, the probability of a sounding being severe increases as the conditions move up and to the right on the figure. Nevertheless, for the entire spring, the Oklahoma City mean conditions are above the discrimination line. This implies that the primary convective forecasting problem is frequently whether thunderstorms will initiate. Given that conditions are favorable often enough to result in the mean conditions being favorable, it is not surprising that a large number of severe thunderstorms occur. As the spring progresses, the environments change from being high-shear, low-CAPE to being high-CAPE, low-shear. In summer, the shear is insufficient to support severe thunderstorms in the mean. In fall, the shear increases as the CAPE decreases and, for a brief period, the mean environment is again supportive of severe thunderstorms. Later in the year, the CAPE decreases again as winter begins.

Along the east–west cross section in the US, the westernmost points have little CAPE, even at the most unstable times (Fig. 9). Values of CAPE increase moving eastward to 95°W and then slowly decrease continuing eastward, so that the 86°W point has similar maximum values to 103°W. The least unstable location east of the Rocky Mountains is at 80°W. Looking at the deep shear, the variability from west to east is less than for CAPE. The shear is slightly less at 114°W, but the rest of the cross section shows similar ranges of shear for

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[3] Significant severe thunderstorms are those that produce hail of at least 5 cm in diameter, wind gusts of at least 120 km h^{-1} or a tornado rated at least F2 on the Fujita scale.

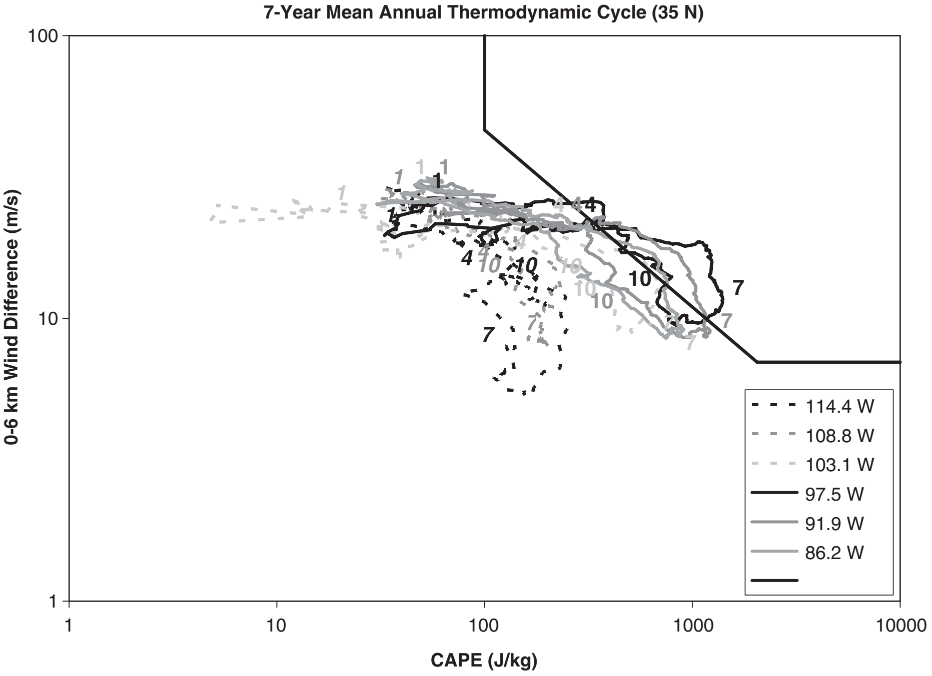

Fig. 9. Same as Fig. 3 except for CAPE and deep shear.

all locations. Qualitatively, looking at the combination suggests that the mean environmental conditions are most favorable in a region in the central part of the US, consistent with the observations of severe thunderstorms (Brooks et al., 2003a; Doswell et al., 2005).

The north–south cross section provides more insight (Fig. 10). Not surprisingly, CAPE is less at the points north of 40°N. At those same locations, shear is always high, with the mean values never less than 10 m s^{-1}. Going south of the Oklahoma City point, the CAPE is always high, but the shear values are less than 10 m s^{-1} during much of the summer and fall. From an ingredients-based approach, CAPE is likely to be the missing ingredient in the northern part of the cross section and shear is likely to the missing ingredient in the southern part. It is important to remember that this is an incomplete description of the environmental conditions. As Brooks et al. (2003b) noted, the reanalysis should not be expected to represent capping inversions that might suppress convection, particularly in the southern US and northeastern Mexico.

As with the moisture and lapse rate plots, the east–west cross section in Europe shows little variability and is not shown here. Looking at the north–south cross section (Fig. 11), CAPE increases from northern Finland to the south, although the highest values are substantially less than those seen in the US. Similarly to the northern US points, shear is always high in the mean. The nature of the annual cycle is somewhat different than in the US. In the central part of the US, the CAPE becomes large, while the shear is still large. In the European cycles, the CAPE increases, while the shear is decreasing. Thus, in the mean, one ingredient is always lacking. Note that, even though the mean values may be associated with environments associated with significant severe thunderstorms, individual days may well be. The implications of this result will be discussed later.

As mentioned before, low-level mixing ratio and mid-tropospheric lapse rates can be thought of as ingredients for CAPE. Thus, we can use the annual cycle of those two parameters, with the points on the cycle coded by the deep shear, in order to try to understand the multi-parameter nature of the ingredients for severe convection. To highlight the differences in conditions in the US and Europe, consider the cycles at Kiev, Ukraine and Oklahoma City (Fig. 12). Both show that shear is greatest in the cold season and least in the summer. The Oklahoma City curve shows the strong climatological support for severe thunderstorms, with mean deep shear greater than 16 m s^{-1} during May, when the lapse rates are approximately 7 K km^{-1} or greater and the mixing ratio is greater than 8 g kg^{-1}. In the fall, when the shears become large again, the lapse rates and moisture values are supportive of weaker CAPE than in the spring. As seen in Fig. 8, the mean

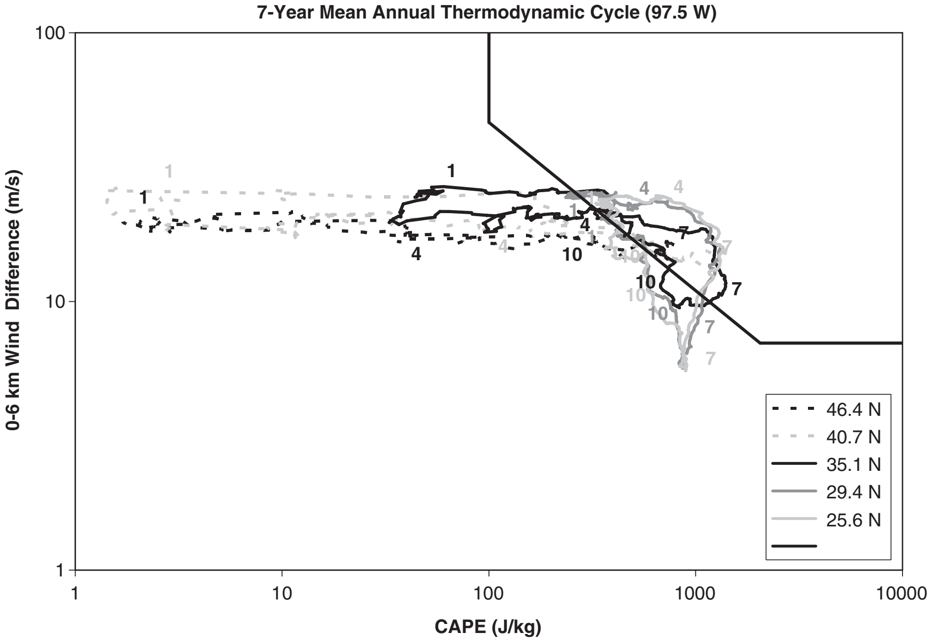

Fig. 10. Same as Fig. 4 except for CAPE and deep shear.

conditions are still supportive of severe convection, but with lesser CAPE than in the spring. Interestingly, the lapse rate and moisture values at Kiev in springtime are similar to the Oklahoma City values in the fall. At that time, though, the shear values are about 4 m s^{-1} less at Kiev and become even weaker in the summer. Thus, the Kiev spring and early summer thermodynamic conditions resemble the fall in Oklahoma City, the peak of the secondary severe convective threat, with lesser shear values, making severe convection less likely at the time

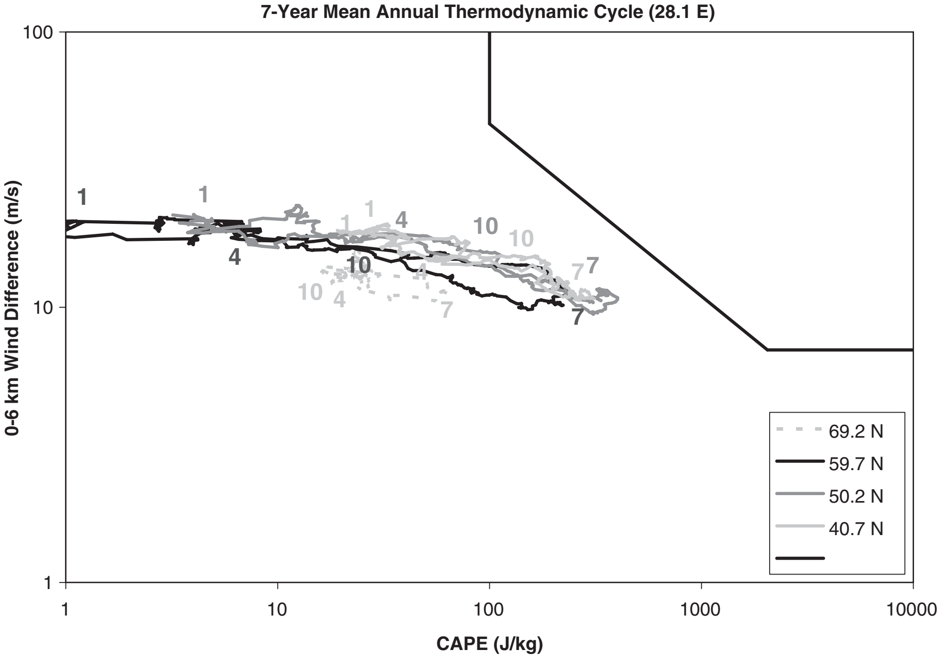

Fig. 11. Same as Fig. 7 except for CAPE and deep shear.

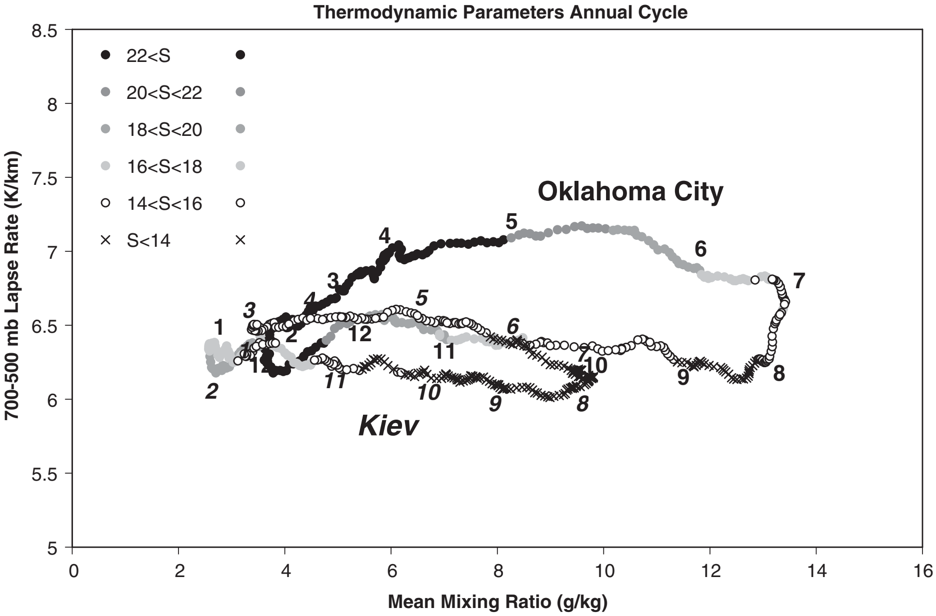

Fig. 12. Mean annual cycle of lowest 100-hPa mean mixing ratio and 700–500-hPa lapse rates for Oklahoma City (top curve) and Kiev, Ukraine (bottom curve). Points on curve are coded by value of deep shear, with black greater than 22 m s^{-1}, down to white (14–16 m s^{-1}) and “x” (shear less than 14 m s^{-1}). Numbers along curve indicate first day of numbered month during the year. Oklahoma City curve labeled in plain text, Kiev in italics.

of best conditions in Kiev than it is at the secondary peak in Oklahoma City.

4. Discussion

Consideration of the annual cycles of convective parameters provides insight into the convective season that might be expected in different locations. The central part of the US is characterized by a spring and early summer season in which the ingredients associated with severe convection come together in the climatological mean. Variability between conditions seen in different seasons is much larger in the US than in Europe.

There are significant implications of these results for weather forecasters. In a crude sense, the conditions observed at any location on a particular day can be thought of as a combination of the climatological conditions, synoptically driven departures from the climatological conditions and mesoscale perturbations on top of that. The existence of a large period of time during the year when climatological conditions support severe thunderstorms in the US makes the forecasting task there easier, in some sense, than in Europe. Challenges still exist in identifying if, where, and when storms will initiate, but the presence of large areas where conditions are favorable provides a strong starting point for the forecast process. In Europe, on the other hand, our results suggest that synoptic and mesoscale conditions are necessary to get environmental conditions supportive of the most severe convection. As a result, forecasters are unlikely to find widespread regions associated with severe convective environments and they will have an additional challenge in the forecast process.

Finally, the presence of severe thunderstorms is intimately associated with the environmental conditions. Challenges for future research include identification of the interannual variability with longer time series and the application of global climate models to look at climate change scenarios. If the models are capable of reproducing the gross features of the current convective environments, such as the mean conditions described here, whether they can get individual days “right” or not, they could be used to see in what ways, if any, the mean conditions change. It is insufficient to look at a single parameter to attempt to answer that question and, as shown here, there are challenges in interpreting the combinations of parameters.

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References

Betts, A.K., Hong, S.-Y., Pan, H.-L., 1996. Comparison of NCEP–NCAR reanalysis with 1987 FIFE data. Mon. Weather Rev. 124, 1480–1498.

Brooks, H.E., Craven, J.P., Kay, M.P., 2003a. Climatological estimates of local daily tornado probability. Weather Forecast. 18, 26–640.

Brooks, H.E., Lee, J.W., Craven, J.P., 2003b. The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. Atmos. Res. 67–68, 73–94.

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

Doswell III, C.A., Brooks, H.E., Kay, M.P., 2005. Climatological estimates of daily local nontornadic severe thunderstorm probability for the United States. Weather Forecast. 20, 577–595.

Hart, J.A., and W.D. Korotky, 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.].

IPCC, 2002. IPCC Workshop on Changes in Extreme Weather and Climate Events Workshop Report, Beijing, China, 11–13 June 2002, 107 pp. (Available at http://www.ipcc.ch/pub/extremes.pdf.)

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.

Sterl, A., 2004. On the (in)homogeneity of reanalysis products. J. Clim. 17, 3866–3873.

Zwiers, F.W., Kharin, V.V., 1998. Changes in the extremes of the climate simulated by CCC GCM2 under CO_2 doubling. J. Clim. 11, 2200–2222.