Annual Cycles of Thermodynamic Parameters from Global Reanalysis Data

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Abstract

Annual cycles of sounding-derived parameters have been limited in their use, because of the lack of data from around the world. The purpose of this study was to identify annual cycles and the variability of four thermodynamic parameters: Convective Available Potential Energy (CAPE), the magnitude of vector wind difference between surface and 6-km above ground level (hereafter Deep Shear), the mean mixing ratio in the lowest 100-hPa (hereafter mixing ratio), and 700-hPa—500-hPa lapse rate. The artificial soundings were created by using a global reanalysis dataset. Years analyzed were 1975, 1987, and 1995-1999. Locations chosen included locations in the United States, east of the Rocky Mountains, and in Europe. Relationships between CAPE and Deep Shear were identified as well as relationships between lapse rates and mixing ratios. Mean threshold mixing ratios were identified for the use of determining the cycle of moisture throughout the year for the United States and Europe. These were compared to the storm activity in the locations analyzed. A part of Europe was identified as having similar cycles as the upper Great Plains of the United States. By knowing the annual cycles and storm activity in the United States, we were able to apply the same concepts to Europe in areas that lacked good storm activity reporting.

1. Introduction

While severe weather occurrences are documented in some parts of the world, the climatological annual cycles of the thermodynamic parameters that make the severe weather possible are not documented. Climatologies of the annual cycles and the variability of thermodynamic parameters are important for different people, such as weather forecasters, the public, safety personnel, and insurance companies. Knowing the annual cycle and variability helps to distinguish what time of year is best for severe weather. Places over the globe have similar and dissimilar cycles. Knowing the cycles at locations with good weather reporting would enable us to extrapolate to places where weather reporting is not as good. We are able to compare a location's known storm activity to another location's unknown storm activity by using both locations' annual cycles of convective parameters. These climatologies establish a better understanding of what to expect during the year, which could help in developing seasonal forecasts.

Previously, problems with completing accurate climatologies of thermodynamic sounding parameters include the lack of data collection from around the world. Few locations release rawinsondes, which makes a problem with the amount of data available for use. One way to solve this is to use artificial soundings. Artificial soundings are produced using a global reanalysis data set (discussed in section 2).

Brooks et al. (2003b) takes analyses of artificial sounding from the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996) to determine if relationships between sounding parameters and severe weather occurrence in areas with good severe weather reporting and apply that to areas where severe weather reporting is not as good. Brooks et al.'s (2003b) findings included relationships between Convective Available Potential Energy (CAPE) and the magnitude of vector wind difference between the surface and 6-km above ground level (hereafter as Deep Shear), as well as, surface – 1-km lapse rates and Lifting Condensation Level (LCL) heights. This study shows significant severe weather (at least 2-in diameter hail, 65-kt wind gusts, or F2 tornado) is associated with high CAPE and Deep Shear. Likewise, high surface – 1-km lapse rates and low LCL heights are associated with environments where significant tornados are likely. Brooks et al. (2003a) studies the climatology of tornado days and the annual cycle of tornado days at a given location. None of these papers considers the annual cycles or the variability of the thermodynamic sounding parameters.

The primary goal of this study is to determine the annual cycles and the variability of sounding-derived parameters from locations in the United States and in Europe. We also want to compare locations in the United States to locations in Europe in order to evaluate their storm activity by using their thermodynamic parameters. In Section 2, the dataset and methodology are discussed. In Section 3, the results are presented, followed by a discussion of the results in Section 4. In Section 5, the study is concluded.

2. Dataset and Methodology

Data for this study comes from the NCEP/NCAR Reanalysis data (Kalnay et al. 1996). The reanalysis dataset is made by recovering available observations and building a 6-h forecast model from these observations. Brooks et al. (2003b) discusses problems with the reanalysis data. They state the reanalysis data has estimation problems with vertical gradients, which effect the surface-based parameters and the parameters that are used to measure strong inversions. Artificial soundings are produced using the techniques in Brooks et al. (2003). A version of the Skew-t/Hodograph Analysis and Research Program (SHARP) (Hart and Korotky, 1991) is used to analyze the artificial soundings. The artificial soundings had a spatial resolution of 1.875° in longitude and 1.915° in latitude (about 200-km) and a temporal resolution of 6-h. The sounding-derived parameters in the current study include CAPE (J/kg), Deep Shear (m/s), 700-hPa – 500-hPa lapse rate (K/km) (hereafter lapse rate), and the mean mixing ratio in the lowest 100-hPa (g/kg) (hereafter mixing ratio). Data came from years 1973, 1987, and 1995-1999. The year 1973 was chosen for its above average tornado reports in the U.S., while 1987 was chosen for its below average tornado reports. The years 1995-1999 were chosen in order to obtain a time series dataset. For every analysis, all years are included unless otherwise stated. All data from the artificial soundings are considered "good." We obtained all stations east of the Rocky Mountains in the United States and all stations in Europe for the mixing ratio analyses to get a large-scale map of the distribution of the mixing ratio cycles. We used nine stations, four in the United States and five in Europe (Fig 1), for the analysis of CAPE and Deep Shear. Focusing on the day when CAPE is largest, which we assume to be associated with the potential for strongest convection, narrows the dataset. For the United States, this time is 0000Z for all locations. Every analysis for the U.S. is based on 0000Z. Europe varies from 0600Z to 1800Z. Each European location kept its designated time throughout all analyses.

2.1 Statistical Treatment of Dataset

Smoothing techniques are employed to the dataset. To do this, running means, yearly means, and monthly means are applied to the dataset. Running means are used to obtain a smooth curve for a comparison between mixing ratios and lapse rates. Yearly and monthly means are applied to all sounding-derived parameters for a smooth time series. For all CAPE analyses, the zero CAPE values are omitted since those days are assumed to have low probability of convection, and their inclusion might show the interpretation of other parameters.

3. Results

3.1 Oklahoma City, Oklahoma

The Southern Plains is near the maximum in severe weather occurrence in the U.S. (Brooks et al. 2003b). Oklahoma City is chosen as a representative location. Logarithmic relationships between nonzero CAPE and Deep Shear are shown to be a good tool for discriminating between environments associated with severe thunderstorms and those that are not (Turcotte and Vigneux, 1987 and Brooks et al. 2003). Generally, severe thunderstorms are associated with high CAPE and high Deep Shear. Utilizing this for Oklahoma City (Fig 2) shows that Oklahoma City has a large amount of days in the large Deep Shear and large CAPE regions, which is consistent with a high frequency of severe storm activity per year. When comparing the above average severe year 1973 with the below average 1987 for months April, May, and June, shows that the distinguishing factor between these two years is not the value of CAPE, but it is the Deep Shear value. Year 1987 shows at least 14 days out of 172 days with below 10-m/s Deep

Shear, while 1973 has only 6 days out of 177 days with below 10-m/s Deep Shear. An above average year for tornados does not necessarily mean that the year also has high average CAPE values.

It is found that there is a relationship between lapse rates and mixing ratios. High mixing ratios and steep lapse rates correspond to large amounts of CAPE for convection. When both or one is not present, the environment appears more stable. One way to show the variability and annual cycle of mixing ratio and lapse rates is to plot them. To create the plot, the lapse rate and mixing ratio data went through a 7-day running mean (e.g. all 1 Jan were averaged together for all 7 years) and then a 31-day running mean, which smoothed the data. Oklahoma City showed a wide variability between seasons (Fig 3a). Their cycle starts in January with low mixing ratios and low lapse rates. As the year progresses, lapse rates and mixing ratios start to decrease by spring. In late spring/early summer is when lapse rates start to reach their highest points of 7.1-K/km, with mixing ratios of 10-g/kg. As July approaches, lapse rates start to decrease, while mixing ratios continue to increase. Late July is when lapse rates decrease dramatically and mixing ratios hold steady at 13-g/kg. In fall and winter, lapse rates are held constant, as mixing ratios start to retreat back to dry winter levels. Oklahoma City's mixing ratio values varied from 3-g/kg to 13-g/kg, while lapse rates varied from 6.1-K/km to 7.1-K/km. Oklahoma City's highest peak of lapse rate and mixing ratio occurs around 18 May. Oklahoma City's environment drops in stability around July, because that is when the lapse rates start to decrease dramatically.

3.2 Other US Cities

In order to explore spatial variability within the U.S., similar analyses are carried out at other locations: Nashville, Tennessee, Cadillac, Michigan, and Pierre, South Dakota, which approximates a rectangle in the central part of the country. This gives us an estimate of change as we move east and north.

3.2a CAPE / Deep Shear Distribution

Nashville demonstrates a greater number of days with nonzero CAPE than Oklahoma City. Over the seven years, Nashville has 1,339 days or 52% of the dataset (approximately 191 days per year) with nonzero CAPE, while Oklahoma City has only 1,152 days or 45% of the dataset (approximately 165 days per year) with nonzero CAPE. Given nonzero CAPE, Oklahoma City has a better probability of having a day with greater than 2,000 J/kg CAPE. The probability of Oklahoma City having greater than 2,000 J/kg CAPE is 3.5% (approximately 12 days per year), while Nashville's probability is only 1% (approximately 4 days per year). The distribution of CAPE shows that Nashville has a greater number of days with low CAPE with high Deep Shear than Oklahoma City does.

Cadillac, Michigan has 902 days or 35% of the dataset (approximately 129 days per year) with nonzero CAPE, which is less than both Oklahoma City and Nashville. Cadillac's probability of experiencing a day with above 2,000-J/kg CAPE is 0.12% (approximately 0.5 days per year). Overall, Cadillac, Michigan exhibits few days with large CAPE, but does have more days with 10 – 100-J/kg CAPE with high Deep Shear.

Pierre, South Dakota experiences 909 days or 36% of the dataset (approximately 130 days per year) with nonzero CAPE, which is similar to Cadillac's days with nonzero

CAPE. Pierre's probability of having a day with above 2,000-J/kg CAPE is 1.25% (approximately 5 days per year), which is greater than Cadillac and Nashville. Pierre's distribution of CAPE is comparable to Nashville's, except Pierre has 3 days with a below 1-m/s Deep Shear.

The annual cycle of mean monthly CAPE (Fig 4a) shows Oklahoma City has the largest CAPE throughout an average year, while Michigan has the lowest CAPE throughout an average year. Every city, except Nashville, has the same cycle with one peak in late spring. Nashville has two peaks with one in late spring and another in late fall/early winter. Through these average monthly cycles, the interseasonal variability of these locations is determined. Oklahoma City has the greatest interseasonal variability with a 1,172-J/kg difference between May and January, followed by Nashville at 690-J/kg, and South Dakota at 572-J/kg, and finally Michigan with 330-J/kg.

3.2b Lapse Rate / Mixing Ratio Distribution

The lapse rate and mixing ratio annual cycles of the other United States cities that are analyzed, (Fig 3a) shows that Nashville is the only city that has as large a seasonal difference between spring and fall as Oklahoma City does. All locations show a big winter and summer difference. The lapse rate and mixing ratio annual cycles gave an idea of the general cycles of mixing ratios and lapse rates elsewhere in the United States. The farther north from the Gulf of Mexico, the lower the mixing ratio a location experiences. The mixing ratios decrease as one goes north in the United States. Lapse Rates decrease the farther away the location is from the Rocky Mountains. Nashville, Tennessee and Cadillac, Michigan have lower lapse rates than Pierre, South Dakota and

Oklahoma City because Nashville and Cadillac are further away from the Rocky Mountains.

3.3 European Cities

Europe has fewer reports of severe weather occurrences, which might have been a factor of the quality of severe weather reporting. We analyzed Europe to get an idea of the severe weather that occurred there. To analyze Europe's thermodynamic parameters, five European cities are analyzed: Léon, Spain, Oxford, England, Shostka, Ukraine, Udine, Italy, and Helsinki, Finland. Léon, Spain at 42° latitude is influenced by the Bay of Biscay and a mountain range to its north. Oxford, England at 51° latitude is influenced by the English Channel to its south and the Cambrian Mountains to its west. Shostka, Ukraine at 52° latitude is influenced by the Black Sea to its south and by relatively high terrain to the west. Udine, Italy at 46° latitude is influenced by the Adriatic Sea to its south and the Alps to its north. Helsinki, Finland at 61° latitude is influenced by the Gulf of Finland to its south and by flat terrain surrounding it.

3.3a CAPE / Deep Shear Distribution

Europe is known for having less CAPE than the United States. The European location analyzed for severe storms, following the notion that severe thunderstorms occur with high Deep Shear and high CAPE, would be in Shostka, Ukraine. The determining factor in whether a location will have good CAPE and Deep Shear that is conducive for severe storms is the proximity to topography. A mountain range has to be in close proximity to the location for the atmosphere not to lose its severe potential by the time the air made it to the location. The mountain range also has to be upwind from the location in order for the air over the mountain to make it to the location.

The annual cycle of mean monthly CAPE for the European locations (Fig 4b) shows that Shostka, Ukraine has the highest CAPE, while Oxford, England has the lowest CAPE. Shostka, Ukraine has the most variability between months with July being the month with the greatest CAPE. The other European cities follow the same cycle, except for Leon, Spain that reached its highest CAPE in a month later in August. When comparing Figure a to Figure b, there is a contrast between the United States and Europe's monthly CAPE values, but both the US and Europe follow the same cycle with low CAPE in winter months and high CAPE in summer months.

3.3b Lapse Rate / Mixing Ratio Distribution

The lapse rate and mixing ratio analysis for Europe (Fig 3b) is not as easily to interpret as the analysis for the United States. Shostka, Ukraine has the greatest seasonal difference between its spring and fall seasons, and most resembles the graph of Oklahoma City's lapse rate and mixing ratio cycle, but with lower lapse rates and less moisture. All of the European locations cover the same range of lapse rates, which is influenced by the lack of large north-south mountain ranges such as the Rocky Mountains. The farther north in Europe, the lower the mixing ratio values become. Another factor that influenced mixing ratio was whether the location was land-locked. If the location was, it tended to have lower mixing ratios than if it was next to a body of water. European locations, except Shostka, Ukraine, tend to have their highest lapse rates near the beginning of the cycle when moisture is at its lowest. Shostka has its highest lapse rates during their spring season, which resembles the United States.

3.4 Similarity between Ukraine and northern U.S.

Shostka, Ukraine is similar to the United States more than any other location in Europe. When comparing Shostka to locations in the United States, Pierre, South Dakota resembles Shostka the most. Shostka and Pierre have the same monthly average mixing ratio cycles with the exception of 0.5-g/kg (Fig 6). They also have similar CAPE cycles, except Shostka has an extra peak of CAPE when South Dakota is still decreasing from its peak in July (Fig 5). Shostka, Ukraine has lower lapse rates than Pierre, South Dakota does. The factor that affects the lapse rates is that Pierre is located closer to a large north-south mountain range than Shostka, Ukraine. Shostka is closer in its lapse rate and mixing ratio cycle to the United States, because of its well-defined loop that showed that Shostka had variability between their spring and fall season. Since Pierre, South Dakota and Shostka, Ukraine have similar thermodynamic parameters throughout the year, we assume from those parameters that the severe weather in these two locations is similar as well.

3.5 Threshold Mixing Ratio Cycles

Brooks et al. (2003a) presents a figure of the date of maximum tornado threat for locations with at least 0.25 tornado days per year. We want to reproduce a figure for the United States, that is similar to Brooks et al.'s figure, but instead take a threshold mixing ratio value and plot when a location reaches that threshold (Fig 7). When comparing Brooks et al.'s figure to our threshold mixing ratio figure, we find that the mixing ratios follow a similar cycle as the date of maximum tornado threat did. Therefore, we conclude that the date of when a threshold mixing ratio is met is related to a location's storm activity throughout a year. Since we apply this theory to the United States, we also apply it to Europe (Fig 8). The thresholds chosen for the United States include 6-g/kg, 7-g/kg, and 8 g/kg. For Europe, the thresholds chosen are lower since most places did not experience 8-g/kg mixing ratio, therefore, Europe's thresholds were 5-g/kg, 6-g/kg, and 7-g/kg. According to a Skew-t/log p diagram, 5-g/kg, 6-g/kg, 7-g/kg, and 8-g/kg are approximately be 45° F, 50° F, 54° F, and 58° F, respectively. Therefore, when a location reaches one of these thresholds, it signifies that storm activity is capable of taking place. From Figure 7, one can tell that moisture starts near the Gulf of Mexico and, as the months progress, it moves into the eastern Great Plains. The moisture then continued to grow outward from the Great Plains. From Figure 8, one can see that moisture starts in the Pacific and over the Black Sea and then slowly starts to make its way onshore and then inland.

4. Discussion

This study focuses on the climatologies of annual cycles. One way to improve these climatologies is use more years in the dataset. This allows us to assess variability better as we look for long-term trends.

Seasonal differences affects every location analyzed. In the United States, the farther north the location was, the less seasonal difference between fall and spring the location has. Unlike the United States, Europe, all locations have small interseasonal variabilities. Ukraine has the largest variability between spring and fall than the other European locations.

There are theoretical implications for this research. By using the reanalysis data to make artificial soundings, we are able to see around the globe when otherwise it is impossible because of the lack of data. The only way to get a global perspective is to use a global dataset. This research can be used in a global forecast model to help predict what might happen in future years by studying what the past trends have been. These annual cycles can help forecast for a season at a time. People would know what the average of a season would be like and what the extreme of a season is like. They would know what to expect during the year, helps them be prepared.

5. Conclusion

In this study, we have identified the annual cycles of CAPE, 0—6-km Deep Shear, 100-mb mixing ratio, and 700-mb—500-mb lapse rate. When CAPE and Deep Shear are analyzed together, their logarithmic relationship shows to be a good discriminator between storm environments. When 100-mb mixing ratio and 700-mb—500-mb lapse rate are analyzed together, it is found that a clear cycle of mixing ratio and lapse rates exists. Through this analysis, we are able to generalize about the storm activity in a location by comparing mean threshold mixing ratios to the figures in Brooks et al. (2003). Mixing ratios are found to have a clear growth cycle as the year progressed through the United States and Europe. We find that parts of Ukraine are similar in their cycles to parts of the upper Great Plains, by analyzing monthly averages of CAPE and mixing ratio.

There is more reanalysis data to look at and more of the world that needs to be analyzed. We hope that in the future the global reanalysis would help to strengthen the global modeling systems.

6. Acknowledgments

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8. List of Figures

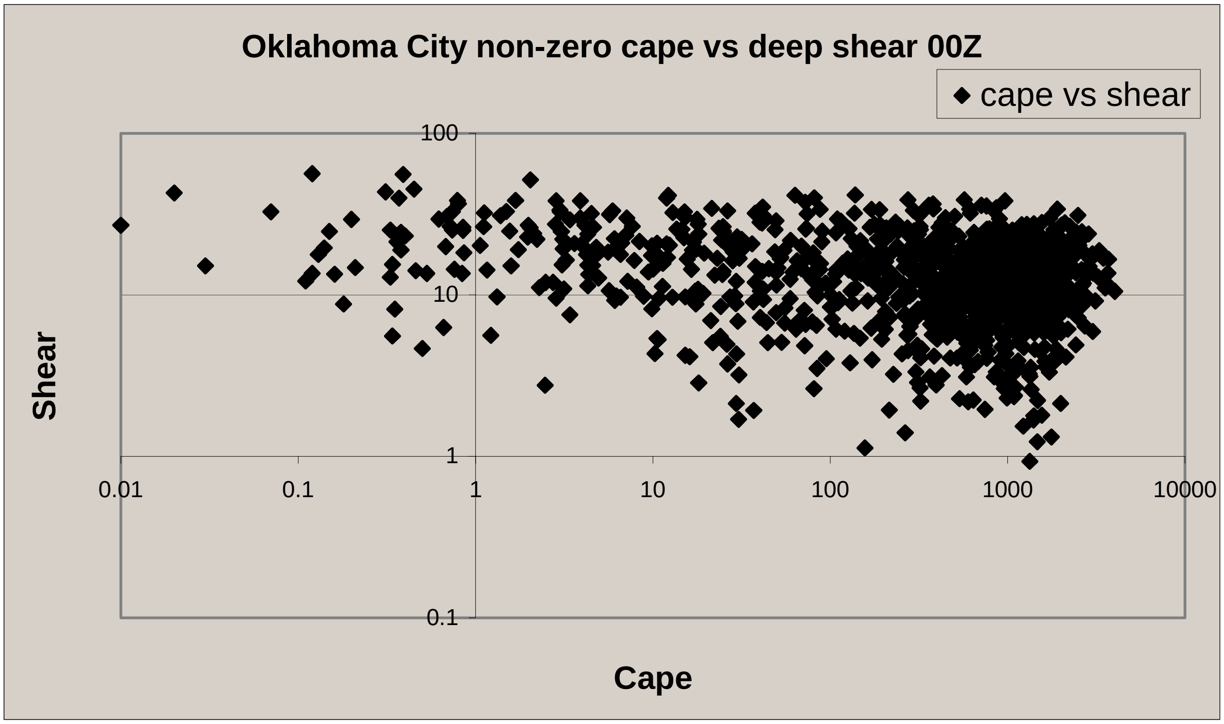
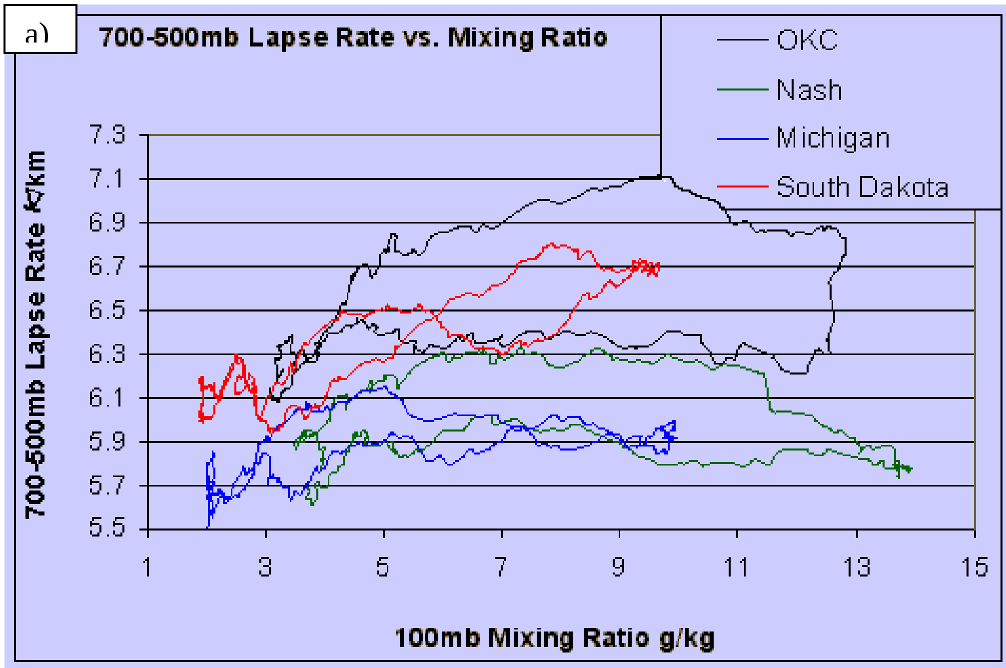


Figure 2: 0—6km Deep Shear (m/s) plotted against nonzero CAPE (J/kg) on a logarithmic scale. High density occurs in the upper right corner of the graph, which are days with high CAPE and high Deep Shear values.



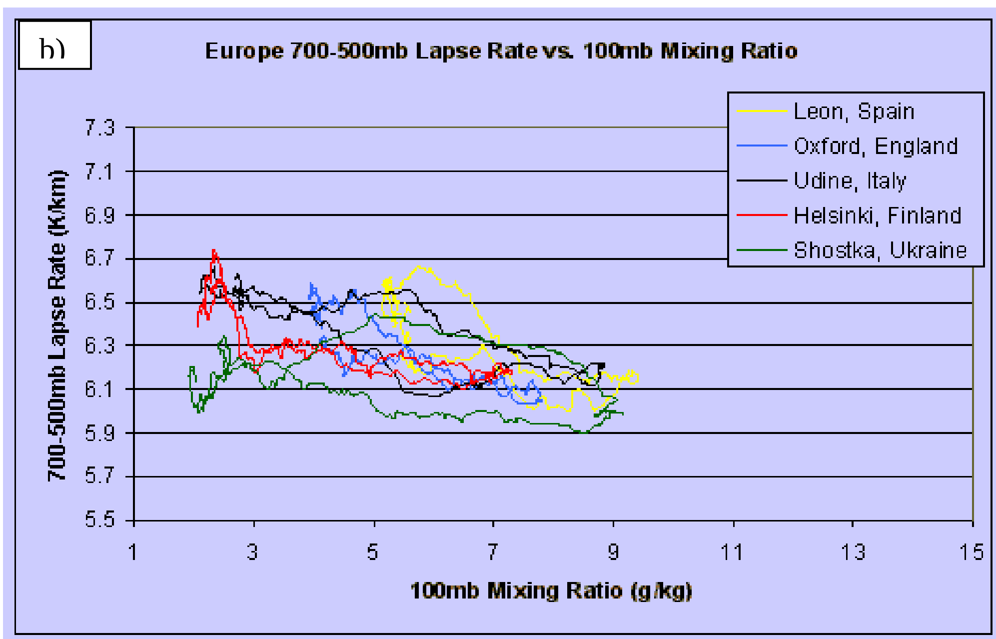
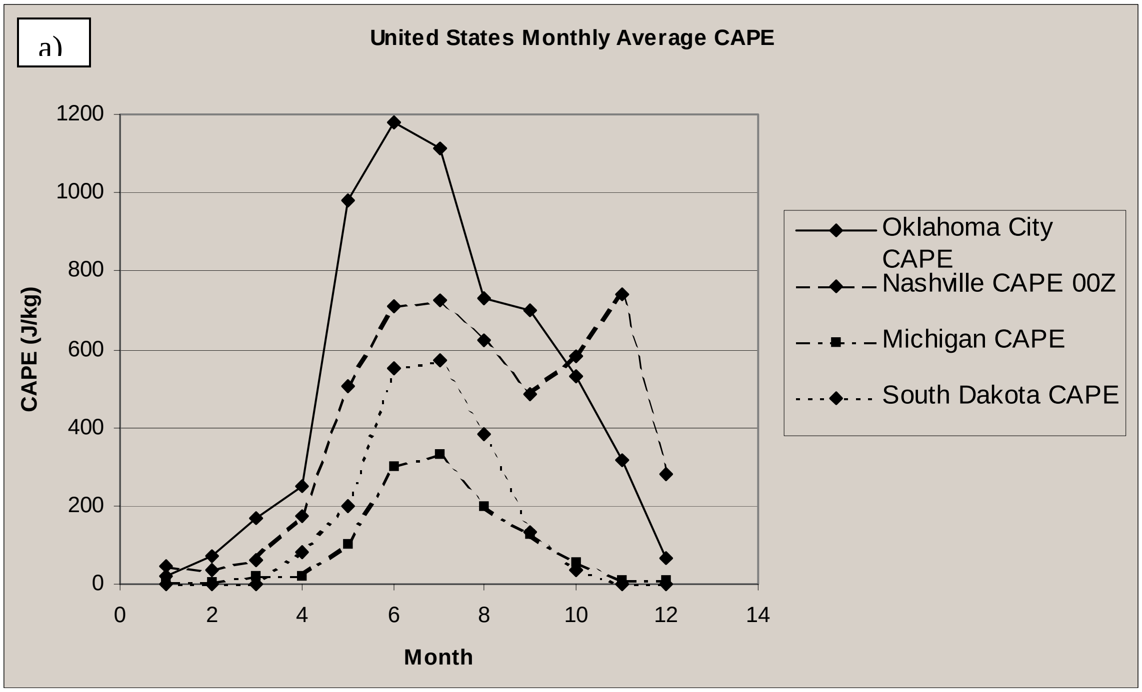


Figure 3: The mean 700-mb—500-mb Lapse Rates are plotted against mean 100-mb Mixing Ratios. a) represents the United States cities that were analyzed and b) represents the European cities that were analyzed



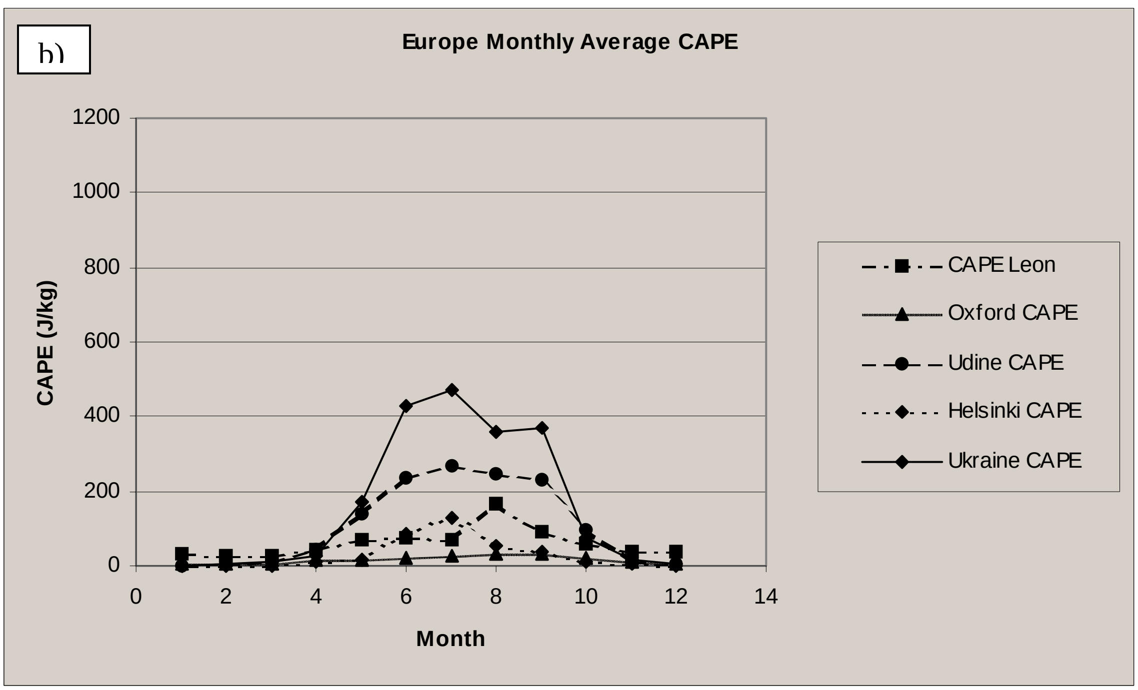


Figure 4: A) is the United States's locations monthly averaged CAPE separated by the individual months. B) is the European's locations monthly averaged CAPE separated by the individual months.

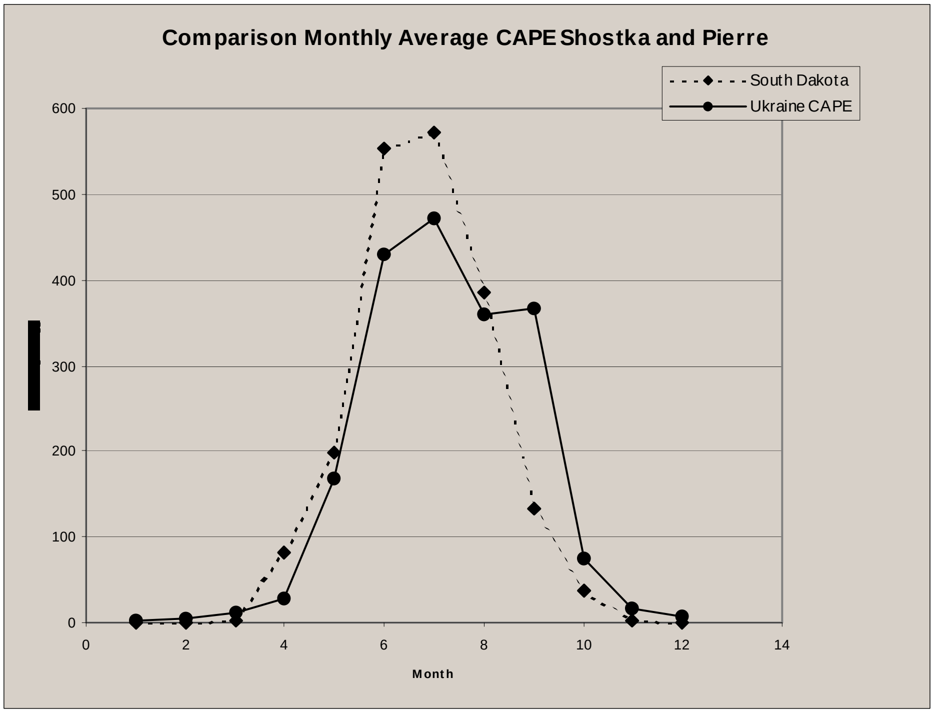


Figure 5: A comparison between Pierre, South Dakota and Shostka, Ukraine. Monthly averaged CAPE (J/kg) is plotted against the month that CAPE occurred in.

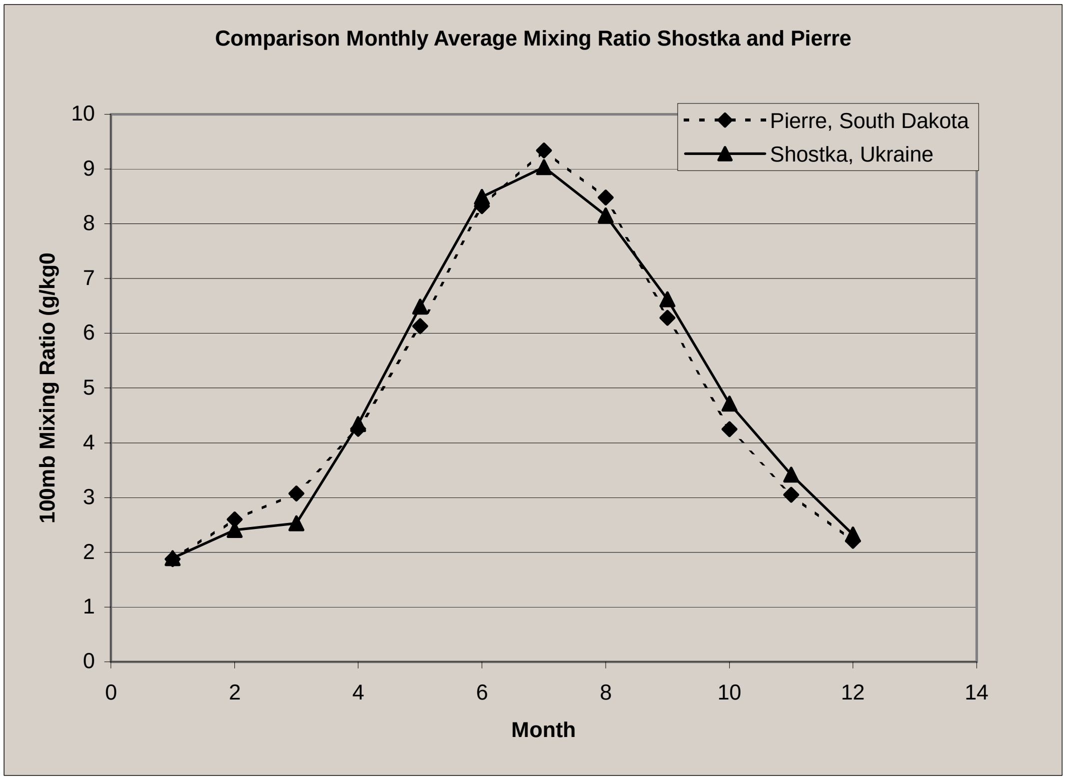
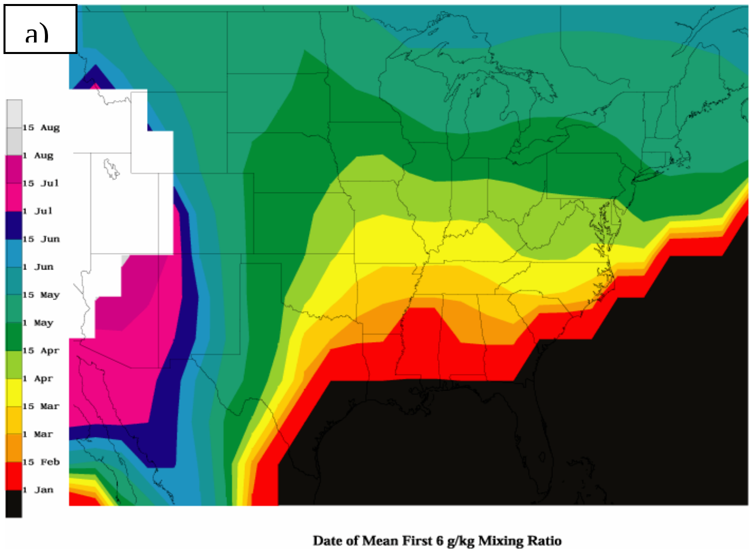


Figure 6: A comparison of the Monthly Average 100-mb mixing ratios for Shostka, Ukraine and Pierre, South Dakota.



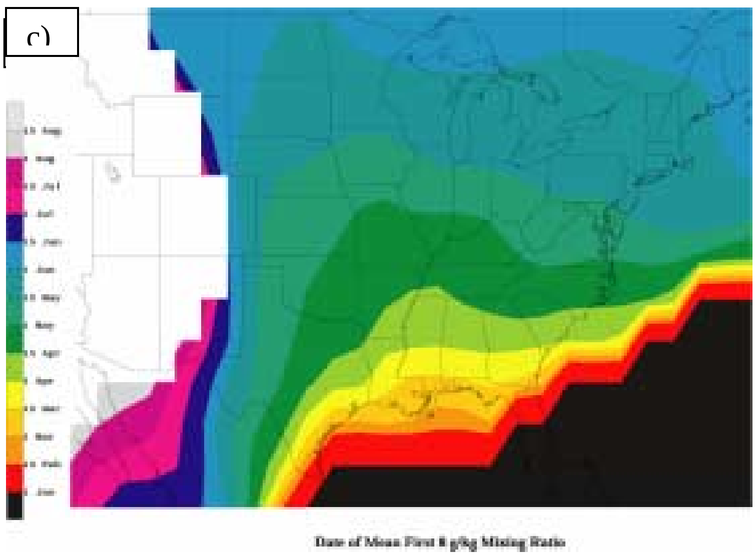
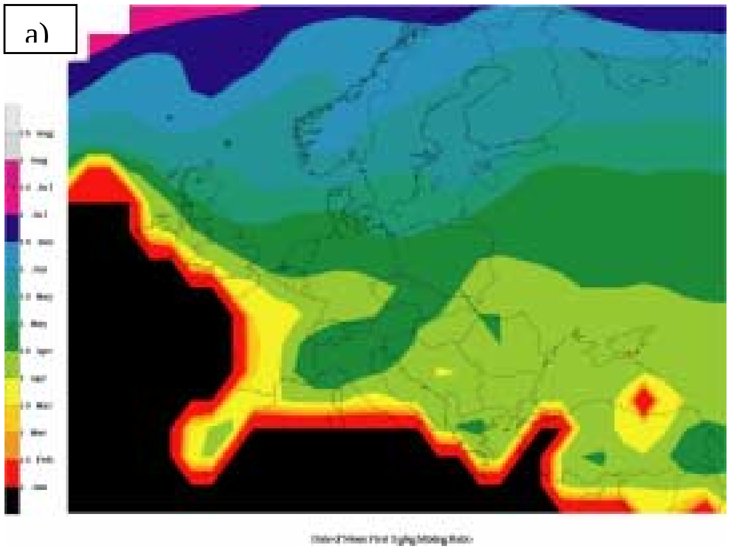
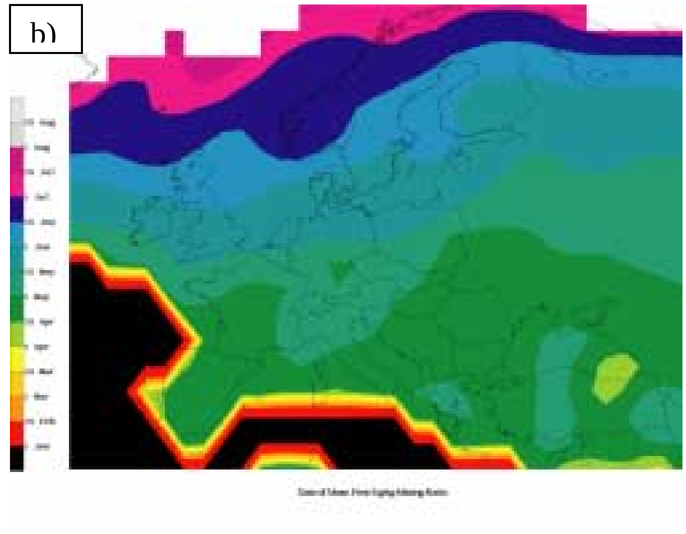


Figure 7: Date of mean first threshold value for a) 6-g/kg b) 7-G/kg c) 8-g/kg for the United States.





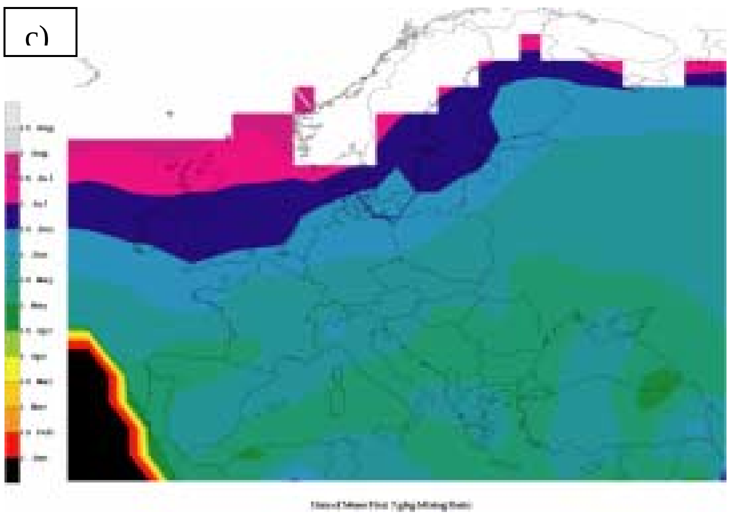


Figure 8: Same as Figure 7 except for Europe and with thresholds of a) 5-g/kg b) 6-g/kg and c)7-g/kg.