P1.15 **A GIS-Based Approach to Lightning Studies for West Texas and New Mexico**

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1. INTRODUCTION

Precipitation forecasting in the presence of synoptic-scale systems generally is reliable, especially when conducted by experienced forecasters using good guidance. However, in the absence of these large-scale systems, forecasting in mountainous areas becomes more difficult since small scale topographic features can produce spottier precipitation patterns.

This paper is an extension of previous works such as Lericos and Fuelberg (2002), Smith and Fuelberg (2005), and López et al. (1997). However, we emphasize regions of topographically induced thunderstorm genesis, as was done in Banta and Schaaf (1987) and Schaaf et al. (1988). A major difference with the latter two studies is our use of data from the National Lightning Detection Network (NLDN) instead of satellite imagery.

Our objective is to improve Probability of Precipitation (PoP) forecasts on days with little synoptic-scale activity, when orography and the large-scale flow interact to initiate a large portion of the thunderstorm and precipitation activity. The first step of this study involves creating a detailed lightning climatology of the study region, not only for all warm season days, but also for different wind flow regimes, with a special focus on thunderstorm genesis. That climatology is presented here.

Our study domain is New Mexico and West Texas, as illustrated by the red box in Fig. 1. The cities of Amarillo (AMA) and Albuquerque (ABQ) are marked, since they are used as references later. We will show that this region experiences a strong topographic influence on thunderstorm activity. Our ongoing research will integrate this influence into a useful forecasting tool.

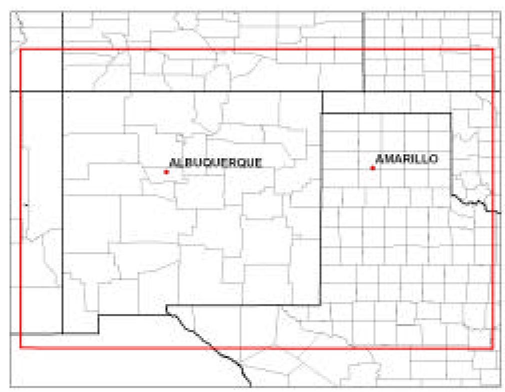

Fig. 1. Study area (outlined in red) with the reference cities marked.

2. TOPOGRAPHY

The topography of the study region varies significantly (Fig. 2). Important features include the relatively flat eastern part of the domain (West Texas), which contains caprock features near Amarillo. A major landmark in this region is Palo Duro Canyon, directly southeast of Amarillo. The western part of the domain contains greater topographic variation, including several large peaks in New Mexico that play a strong role in thunderstorm initiation. This will be discussed in more detail later.

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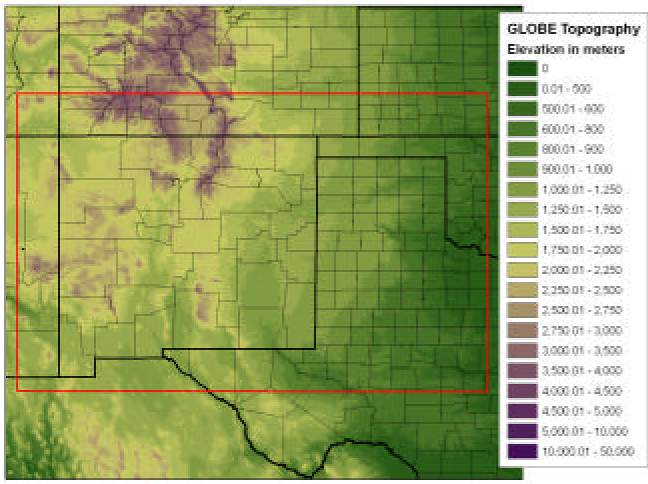

Fig. 2. USGS GLOBE topographic map of the region. Elevations are in meters.

3. DATA AND METHODOLOGY

For the initial lightning climatology, we chose a region extending from 99° W to 110° W and 31° N to 38° N. This area covers the entirety of New Mexico, as well as West Texas (Fig.1). Warm season (May – September) lightning data for 1989-2004 from the National Lightning Detection Network (NLDN) (operated by Vaisala Global Atmospherics, Inc.) first were quality controlled. These quality control processes included removing weak positive flashes (those less than 10 kA, considered indicative of cloud-to-cloud flashes), as well as checking for duplicate flashes. These procedures are consistent with those discussed in previous works (Cummins et al. 1998; Smith and Fuelberg 2005). Data from 2000, as well as June 1999 were not available for the study.

Once the data were quality controlled, the domain was divided into 2.5 km x 2.5 km gridboxes. Lightning flashes within each box then were counted and plotted using ArcGIS to produce a total lightning image consisting of all hours and days during the period. Images also were generated of the total counts for each hour of all days combined.

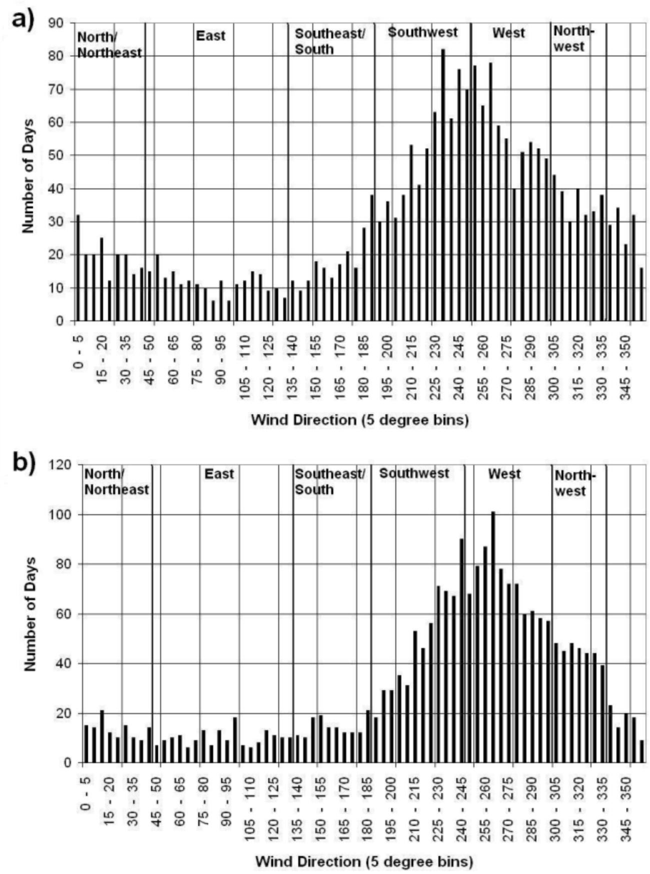

Fig. 3. Vector mean 500-700 hPa wind distributions in 5 degree bins for a) Amarillo (top) and b) Albuquerque (bottom).

After the spatial distribution of lightning for all days was plotted, the data were separated into two regions (East and West) along the New Mexico/Texas border (approximately 103.05° W). This was done to allow the use of varying criteria (such as wind levels or speed) for each region as necessary.

For a preliminary assessment of topographic influences, USGS GLOBE (Global Land One-km Base Elevation Project) topographic data were used. These data allowed the identification of features that likely were initiators of lightning activity.

Radiosonde data for the study period were evaluated at Amarillo (AMA) for the East region and Albuquerque (ABQ) for the West region. A vector mean 500 hPa – 700 hPa wind was determined at each site each day from the 1200 UTC sounding. The number of days in each five degree wind interval was counted and plotted to aid in determining the major wind regimes that influence the area. These plots are shown in Fig. 3a (AMA) and Fig. 3b (ABQ). It is clear that southwesterly winds are most common in each area during the warm season, while easterly winds are least common.

Once the daily mean layer winds were determined, plots of lightning flashes versus wind direction were made. Each day with a specified wind direction (rounded to the nearest whole degree) and its corresponding number of flashes constituted a numbered pair. All numbered pairs then were plotted, as shown in Fig. 4a (AMA) and Fig. 4b (ABQ).

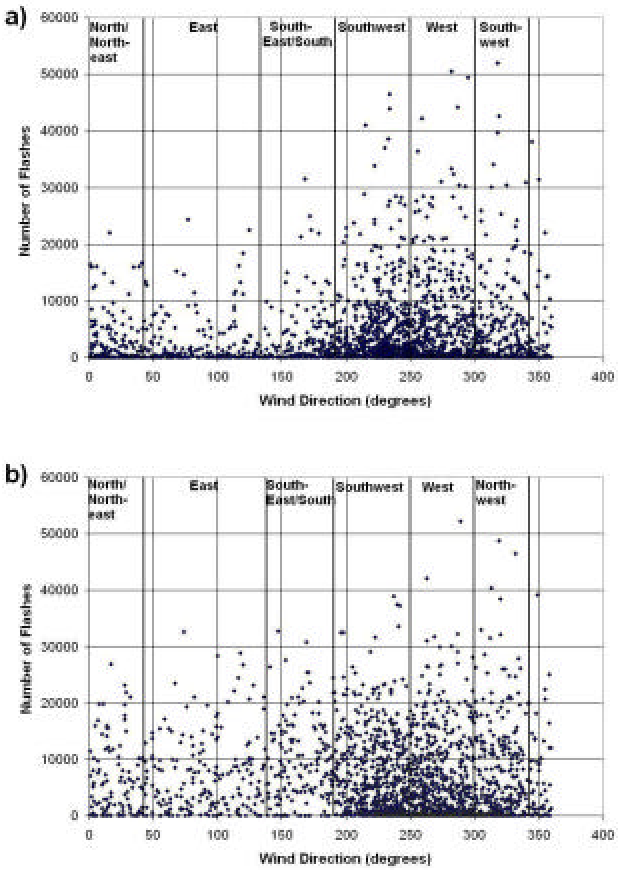

Fig. 4. Scatter plots of lightning vs. vector mean 500-700 hPa wind direction for a) Amarillo (top) and b) Albuquerque (bottom).

The plots in Figs. 3 - 4 aided in determining the major regimes affecting the domain. Seven major wind regimes were defined: Northerly/ Northeasterly (340° – 45°), Easterly (45° – 135°), Southeasterly/Southerly (135° – 190°), Southwesterly (190° – 250°), Westerly (250° – 300°), Northwesterly (300° – 340°), and Calm (Winds < 5 knots). As a preliminary step, these regimes were used for both the East and West regions.

To focus on the genesis areas of storms due to topography, only the first 10% of lightning flashes from topographically initiated storms were selected. Examination of hourly data (discussed later in Fig. 6) suggests that 1800 UTC was the primary time of thunderstorm initiation. Therefore, only the first 10% of each day's lightning flashes that occurred after 1800 UTC were used.

4. RESULTS

4.1. All Flow Regimes

The total lightning distribution (all hours under all wind directions) is shown in Fig. 5. The hotter colors represent greater flash densities (total number of flashes per 2.5 x 2.5 km gridbox), while the colder colors represent few or no flashes.

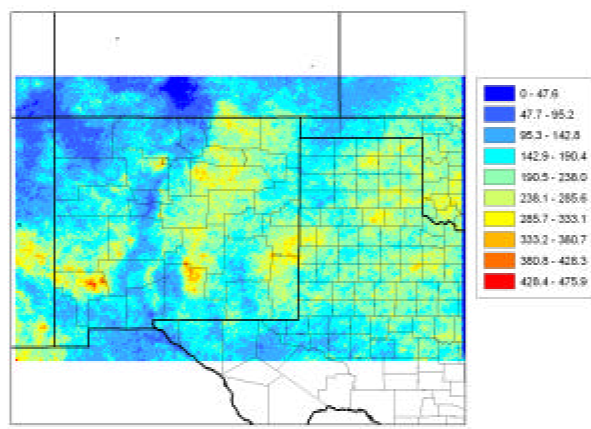

Fig. 5. Total flash counts per 2.5 x 2.5 km box for the entire region over all days and all hours. Units are flashes per gridbox.

Results show that while West Texas has more uniform lightning activity throughout, New Mexico contains the greatest flash densities. In other words, the number of lightning flashes in Texas varies much less than over New Mexico, which exhibits the greatest flash densities. Some of these densities exceed 450 flashes per gridbox. Later results will show that these areas of greatest flash densities are common initiation points for thunderstorm activity under all wind regimes. One should note that these apparent genesis regions correspond to significant topographic features, as seen in the USGS GLOBE data (with major features highlighted in red) (Fig. 7).

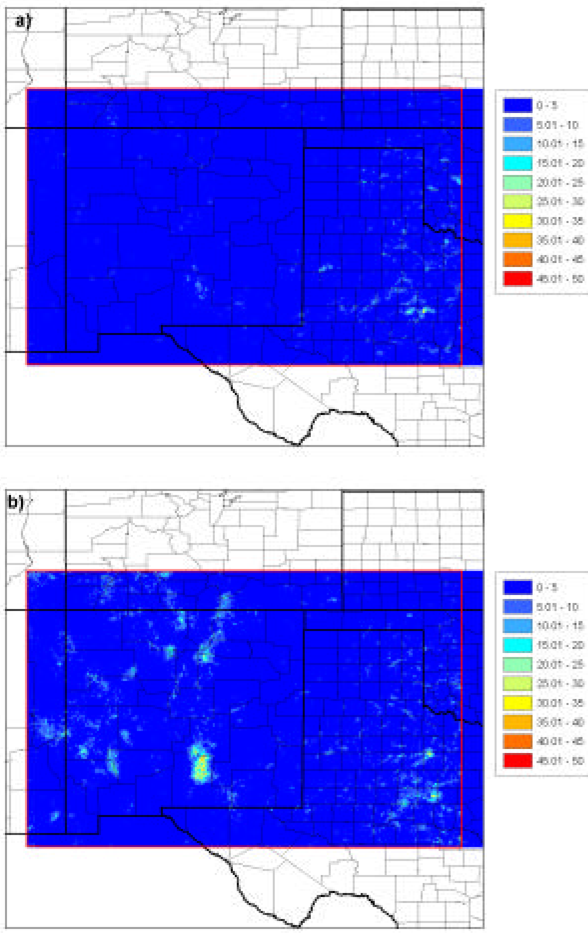

Fig. 6. Lightning initiation - flash counts for all days for a) 1700 UTC and b) 1800 UTC for the entire region. Units are total number of flashes per 2.5 x 2.5 km gridbox.

Lightning is most active from late morning through evening. The initiation period begins around 1800 UTC (Fig. 6). Fig. 6a, the 1700 UTC total lightning image, shows little activity; however, by 1800 UTC (Fig. 6b), greater density areas begin to develop. These initiation areas correspond with the highlighted topographic features in red in Fig. 7. The hourly distribution of total flashes (Fig. 8) confirms the initiation time, exhibiting a rapid increase in total flashes beginning at 1800 UTC.

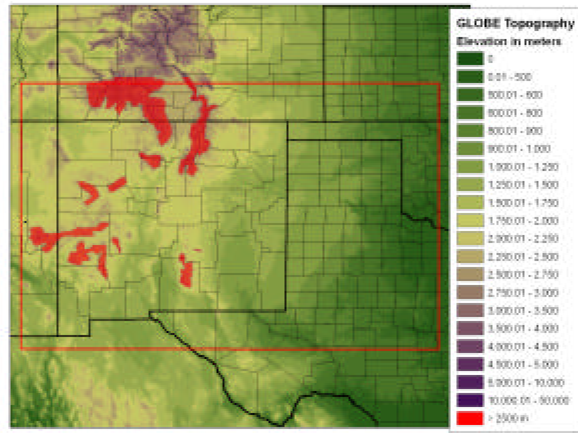

Fig. 7. Topographic map with specific initiating features (>2500 m) highlighted in red.

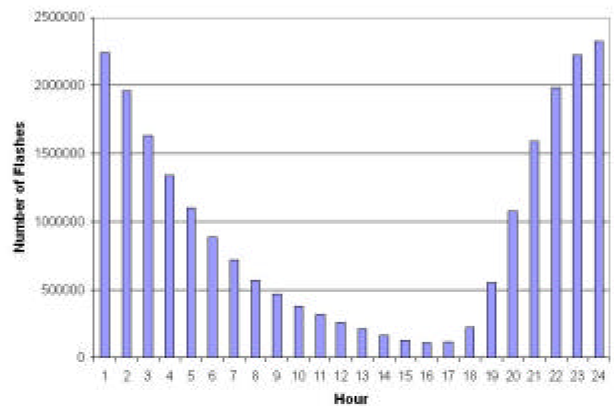

Fig. 8. Hourly distribution of total flashes. Note the rapi d increase beginning at 1800 UTC.

4.2. Results for Eastern Region

The East region consists primarily of West Texas (the panhandle, and a small portion of the Oklahoma panhandle). As previously described (Fig. 5), this region exhibits comparatively uniform lightning activity, with genesis in some locales likely governed by caprock features. However, hourly animations also show lightning initiation in the West region that advances into the East region.

The dominant flow regimes for the East region are southwesterly and westerly which comprise nearly half of the total days (Fig. 9). Conversely, relatively few days exhibit flow with an easterly component.

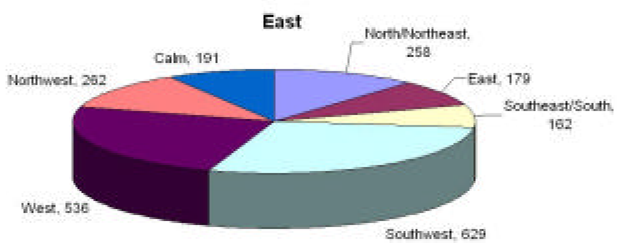

Fig. 9. Distribution of days within flow regimes of the East region.

Table 1 summarizes total lightning activity for all flashes under each flow regime for the East region. The most prolific producer of lightning is westerly flow, which contains the most flashes (2,845,534 flashes over the study period), the highest mean flashes per lightning day and regime day (6,268 and 5,309 flashes per day, respectively), and the highest median count for flashes during a lightning day (3,496 flashes). Least active in the East region is easterly flow, with fewer than 3,000 mean flashes per lightning day and per regime day.

4.2.1. Northerly/Northeasterly Flow

Fig. 10 shows the daily density of initial (first 10%) lightning flashes occurring after 1800 UTC (hereby denoted initiating flash densities) for the East region during northerly/northwesterly flow (340° – 45°). The units on initiating flash density maps are flashes degree^{-2} regime day^{-1}. The greatest density of activity occurs at the southeast corner of the region, where flash coverage also is greatest. The mid-section of the region exhibits only small densities of these initial flashes, and only spotty initiation occurs in the northern portion of the map. This flow produces the smallest percentage of lightning days for the region, with lightning occurring on only 76% of all regime days (Table 1).

4.2.2. Easterly Flow

Initiating flash densities during easterly flow (45° - 135°) for the East region are shown in Fig. 11. Once again, much of the activity occurs in the southeast portion of the domain; however, the area of maximum densities is further north than under northerly/northeasterly flow. In addition, there is a strong pocket of activity southeast of Amarillo in the vicinity of Palo Duro Canyon. This maximum likely is due to the forcing of air up the canyon wall, which will only occur during certain wind directions. Despite the high density of initial flashes, easterly flow exhibits the smallest amount of mean flashes per lightning day (2,496 flashes per lightning day) and regime day (2,077 flashes per regime day), as well as the lowest median flash count (692 flashes) (Table 1).

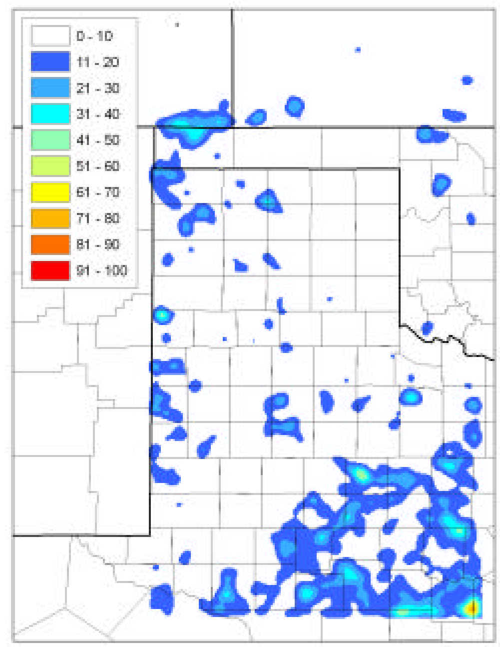

Fig. 10. Initiating flash densities for the East region under northerly/northeasterly flow. Units are flashes degree^{-2} regime day^{-1}.

4.2.3. Southeasterly/Southerly Flow

Despite being the least common flow regime for the East region (Fig. 9), southerly/ southeasterly (135° - 190°) flow produces the second highest percentage of lightning days (Table 1). Initial flash densities for this regime are shown in Fig. 12. While the southeast corner of the domain exhibits significantly less lightning under this regime, the Palo Duro Canyon area shows a large increase in activity, both in the density of flashes and in the size of the area over which these flashes occur. There also is significant activity west of Amarillo, in the south- and northwest corners of the domain, and a broad area of moderate densities in the southeast part of the domain. This latter area is noteworthy since it seems to be the one exception in a regime that is dominated by activity in the western part of the domain. A possible explanation to the activity in this zone is its proximity to the city of Abilene, suggesting lightning enhancement by urban influences.

TABLE 1. Total flash characteristics for each flow type in the East region.

Regime	No. flashes	No. flow days	No. lightning days	Percent lightning days	Mean flashes per lightning day	Mean flashes per regime day	Median flashes per lightning day
North/Northeast	714056	258	196	76	3643	2768	1108
East	371854	179	149	83	2496	2077	682
Southeast/South	468292	162	140	86	3345	2891	1255
Southwest	2814114	629	567	90	4963	4474	2348
West	2845534	536	454	85	6268	5309	3496
Northwest	1181205	262	216	82	5469	4508	2394
Calm	510549	191	164	86	3113	2673	1466

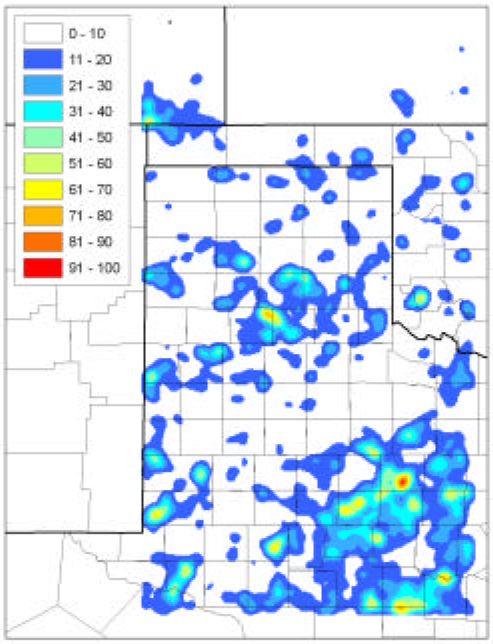

Fig. 11. Initiating flash densities for the East region under easterly flow. Units are flashes degree^{-2} regime day^{-1}.

4.2.4. Southwesterly Flow

Southwesterly flow (190° – 250°) produces a broad expanse of small to moderate initiating flash densities across the East region (Fig. 13). This regime is the most common and produces the highest percentage (90%) of lightning days, and ranks 3rd in the region for mean flashes per lightning day and regime day (4,963 and 4,474 flashes per day, respectively) (Table 1). This high percentage of lightning days is a possible byproduct of southwest flow being typical of prefrontal or dryline conditions. Even though the warm season months of May through September were chosen to remove as much frontal influence as possible, this regime may experience some effects. These facets currently are being investigated. Spatially, no location in the region exhibits exceptionally large flash densities, although several noteworthy regions do exist, namely a location southwest of Amarillo on the west edge of the map, and the most active location in the southwest corner of the region. The latter is unique because this portion of the domain generally exhibits very small initiating flash densities. However, activity is relatively uniform throughout the entire domain, except for the north and southeast-most portions.

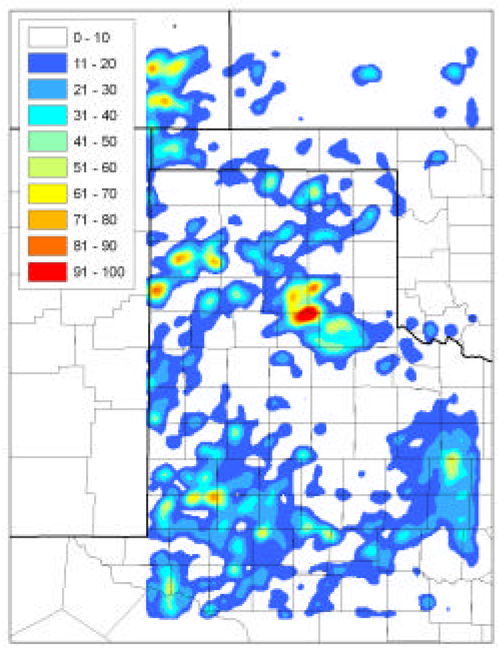

Fig. 12. Initiating flash densities for the East region under southeasterly/southerly flow. Units are flashes degree^{-2} regime day^{-1}.

4.2.5. Westerly Flow

Westerly flow (250° – 300°) is the second most common regime in the East region (Fig. 9), occurring on 536 study days. Also, as previously mentioned, it produces the greatest total flash count, the highest mean number of flashes per lightning day and regime day, and the greatest median flash count for a lightning day (Table 1). Fig. 14 is the initiating flash density map for this regime. Once again, there are no especially active regions, only several moderately active spots. The focus of activity is shifted toward the southeast quarter of the map, with the only larger area of moderate activity outside that quarter occurring near Palo Duro Canyon. Within this southeastern corner, initiating flash densities are as great as 50 to 60 flashes degree^{-2}day^{-1}.

4.2.6. Northwesterly Flow

Fig. 15 shows initiating flash densities for the East region during northwesterly flow (300° – 340°). This is not a particularly active regime for the East region, as seen from the large area of zero or small densities. Northwesterly flow is most likely the driest flow for this region, and the reduction in initiating flash densities likely is a result. The only moderately active portion of the domain is found on the southern edge, with densities up to 61 to 70 flashes degree^{-2}day^{-1}.

4.2.7. Calm Flow

In terms of the maximum densities of initial flashes, the calm (mean wind of less than 5 kt) regime (Fig. 16) is by far the most active. During this flow regime, four small areas of 91 to 100 flashes degree^{-2}day^{-1}, as well as several other areas near this amount, are located throughout the map. Several of these areas are located in a broad area in the middle of the domain, with one focus collocated with Palo Duro Canyon. A majority of the areas of greatest density are slightly shifted from the preferred areas of other regimes (such as the maximum area in the northern panhandle that occurs west of a similar maximum in westerly flow (Fig. 14), and does not appear in other regimes). This suggests that the direction of wind flow over topography strongly influences favorable formation regions.

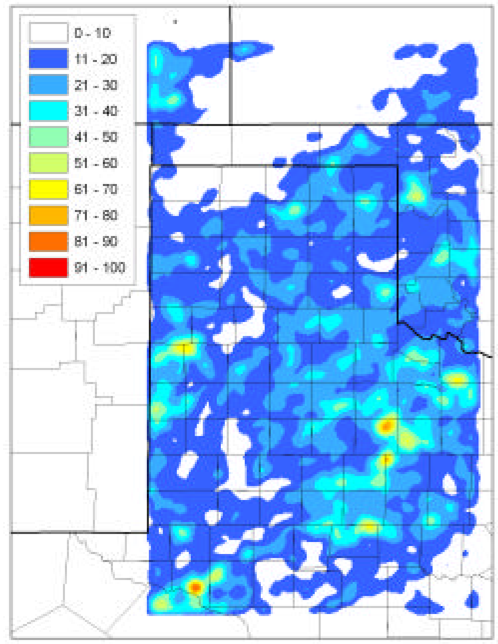

Fig. 13. Initiating flash densities for the East region under southwesterly flow. Units are flashes degree^{-2} regime day^{-1}.

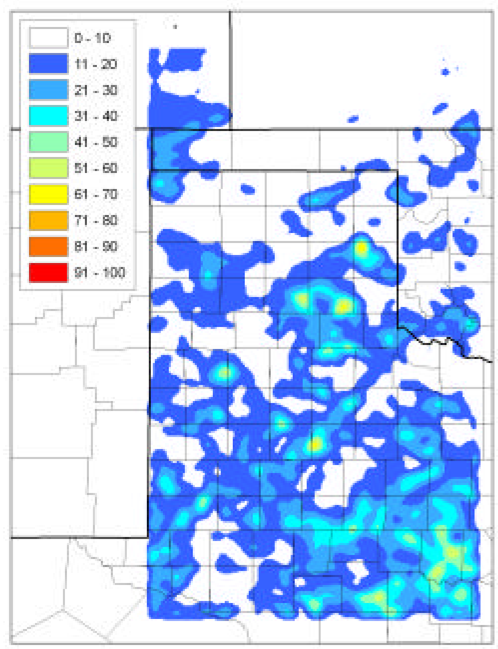

Fig. 14. Initiating flash densities for the East region under westerly flow. Units are flashes degree^{-2} regime day^{-1}.

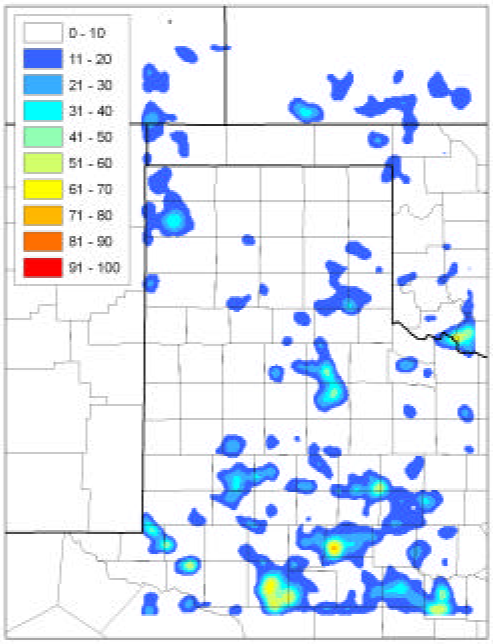

Fig. 15. Initiating flash densities for the East region under northwesterly flow. Units are flashes degree^{-2} regime day^{-1}.

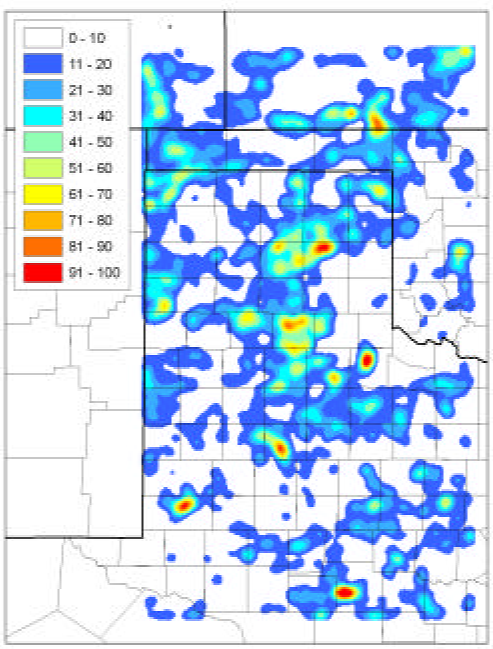

Fig. 16. Initiating flash densities for the East region under calm flow. Units are flashes degree^{-2} regime day^{-1}.

4.3. Results for Western Region

Results for the second half of the domain now will be examined. The West region, consisting primarily of New Mexico, is considerably more active than the East. While the scale for flashes per degree squared per day was kept constant for each of the maps for the East region, the scale has been adjusted for the West region maps to account for the strong increase in densities. The red shades on the East region scale now correspond to the third lowest grouping on the West region scale. This new scale is kept constant for each regime within the West region. The primary activity in the West region appears as variations in specific location and size of areas generated by the primary topographic features highlighted in Fig. 7.

Fig. 17 shows the distribution of days within each regime. As with the East region, westerly and southwesterly flow dominate, accounting for over half of the total days for the West region.

Lightning is much more common over the West region; all regimes experience lightning on 85% or more of days during the study period (Table 2). The very active southeasterly/ southerly flow regime over New Mexico likely is a result of monsoonal flow which occurs during the warm season.

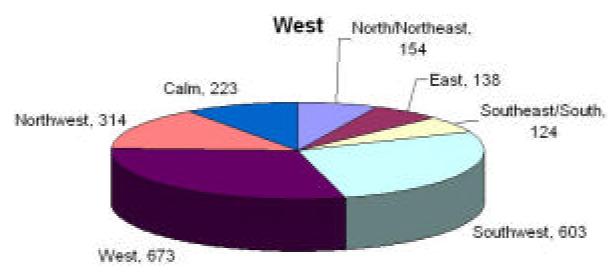

Fig. 17. Distribution of days within flow regimes the West region.

4.3.1. Northerly/Northeasterly Flow

The first regime for the West region is northerly/northeasterly flow (340° - 45°) (Fig. 18). This regime is moderately active (with respect to the other regimes in the region), with four distinctive peaks of 151 to 175 flashes degree^{-2}day^{-1}. Each corresponds with the highlighted areas of enhanced topography in Fig. 7.

TABLE 2. Total flash characteristics for each flow type in the West region.

Regime	No. flashes	No. flow days	No. Lightning days	Percent lightning days	Mean flashes per lightning day	Mean flashes per regime day	Median flashes per lightning day
North/Northeast	965200	154	131	85	7368	6268	5685
East	900613	138	125	91	7205	6526	4869
Southeast/South	1203110	124	113	91	10647	9703	9160
Southwest	3555911	603	553	92	6430	5897	4050
West	3129316	673	591	88	5295	4650	2086
Northwest	1902825	314	272	87	6996	6060	3394
Calm	1755952	223	199	89	8824	7874	7943

4.3.2. Easterly Flow

Fig. 19 shows initial flash densities for the West region under easterly flow (45° - 135°). Easterly flow accounts for the second lowest number of both regime days and lightning days, and produces the fewest total flashes during the study period (Table 2). This regime is not particularly active over New Mexico, with mainly small areas and densities of only 126 – 150 flashes degree^{-2}day^{-1} (which is fairly small for this region). While each of the genesis areas seems at least somewhat active, the westernmost area is the strongest. The location west of New Mexico has a density exceeding 200 flashes degree^{-2}day^{-1}.

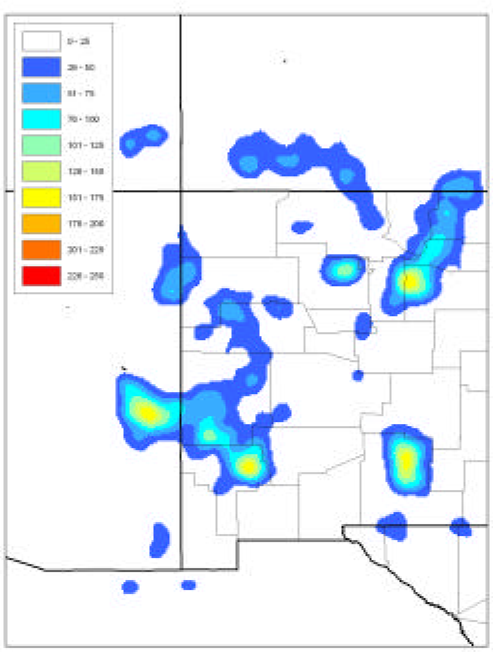

Fig. 18. Initiating flash densities for the West region under northerly/northeasterly flow. Units are flashes degree^{-2} regime day^{-1}.

4.3.3. Southeasterly/Southerly Flow

Fig. 20 is the initial flash density map for southerly/southeasterly flow (135° - 190°). Despite accounting for just over 5% of all days for the region, this regime exhibits much activity over New Mexico, producing the greatest mean number of flashes per lightning day (10,647 flashes per day) and regime day (9,703 flashes per day), as well as the greatest median flash count for a lightning day (9,160 flashes). In terms of the spatial distribution of densities, a strong maximum of over 200 flashes degree^{-2} day^{-1} is located in the southeastern part of the state. One should also note that the northeastern corner of the state is more active as well, with a peak exceeding 150 flashes degree^{-2}day^{-1}. Once again, thunderstorm genesis is a probable result of the predominant topographic features, with each producing a widespread area of lightning.

4.3.4. Southwesterly Flow

Southwesterly flow (90° – 250°) (Fig. 21) brings dry air from the Mexican plateau over New Mexico, and as a result, the West region experiences markedly less lightning activity than during southerly/southeasterly flow. While each of the main topographic features contributes to some degree of lightning activity, all densities are less than 100 flashes degree^{-2}day^{-1}. The most widespread area of large densities (which also is the greatest density on the map) once again is in southeastern New Mexico. Note that the preferred zone in central northern New Mexico is confined to only a small bullseye.

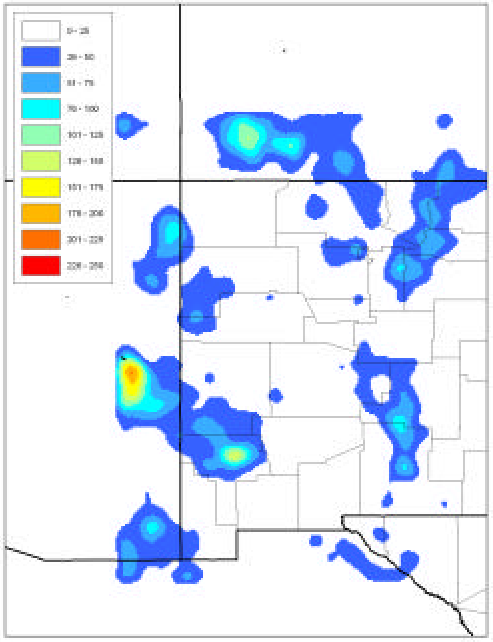

Fig. 19. Initiating flash densities for the West region under easterly flow. Units are flashes degree^{-2} regime day^{-1}.

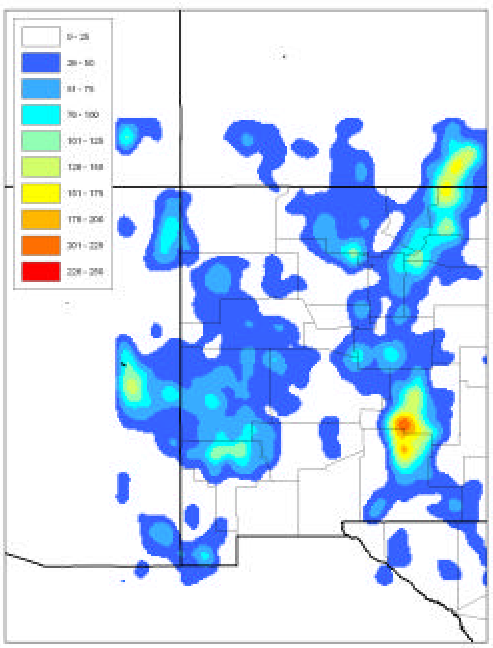

Fig. 20. Initiating flash densities for the West region under southeasterly/southerly flow. Units are flashes degree^{-2} regime day^{-1}.

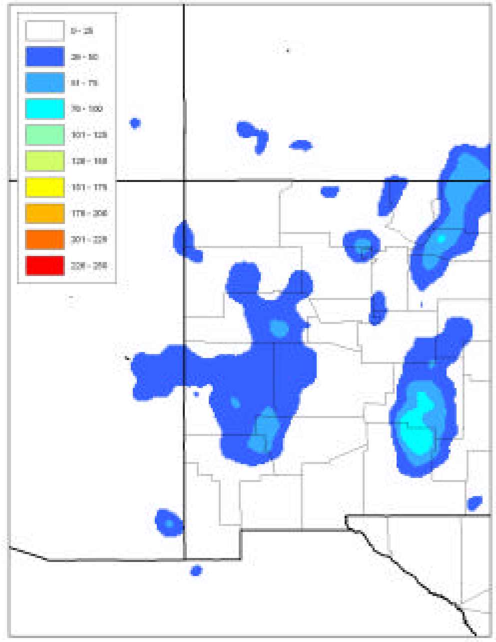

Fig. 21. Initiating flash densities for the West region under southwesterly flow. Units are flashes degree^{-2} regime day^{-1}.

4.3.5. <u>Westerly Flow</u>

Easily the least active regime for the West region is westerly flow (250° – 300°), shown in Fig. 22. While this regime has the second greatest number of flashes (Table 2), this is strictly a function of the large number of days in this regime. Once normalized by regime days, this apparent activity is greatly reduced (actually the smallest mean and median flashes per lightning day, as well as the smallest mean flashes per regime day). As with southwesterly flow, the greatest densities are less than 100 flashes degree^{-2}day^{-1}, and the areas in this regime are smaller than those of southwesterly flow. The primary topographic features still seem to have a visible effect, however the extent and magnitude of the preferred zones are much less than in any other regime.

4.3.6. <u>Northwesterly Flow</u>

Initiating flash densities during northwesterly flow (300° – 340°) for the West region are shown in Fig. 23. This regime is moderately active, with the third greatest total flash count (Table 2), and densities nearing 175 flashes degree^{-2}day^{-1} in southern New Mexico. Note that both the magnitude and spatial extent of the flash hotspots in northern New Mexico are only slightly increased compared to westerly flow, whereas the southern points are much stronger.

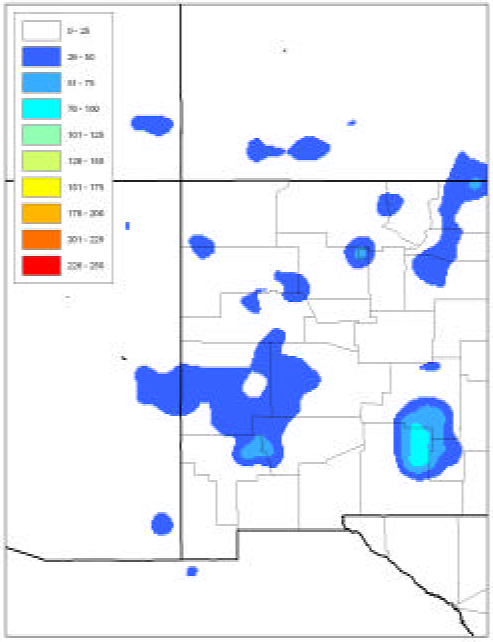

Fig. 22. Initiating flash densities for the West region under westerly flow. Units are flashes degree^{-2} regime day^{-1}.

4.3.7. Calm Flow

The calm flow regime (daily mean wind speed less than 5 kt) (Fig. 24) has the second greatest overall coverage in the region. In addition, calm flow exhibits the second greatest mean values for flashes per lightning day and regime day (8,824 and 7,874 flashes, respectively), as well as the second greatest median flash count. There are several areas nearing 200 flashes degree^{-2}day^{-1}. The two northern topographic features, as well as the westernmost of the two southern features, exhibit densities of this magnitude, while the southeastern zone shows only slightly lesser densities. The spatial extent of the regions of increased flash density also has increased. One should note that the zone west of New Mexico (as seen in Fig. 18 for northerly/northeasterly flow) also exhibits a greater density.

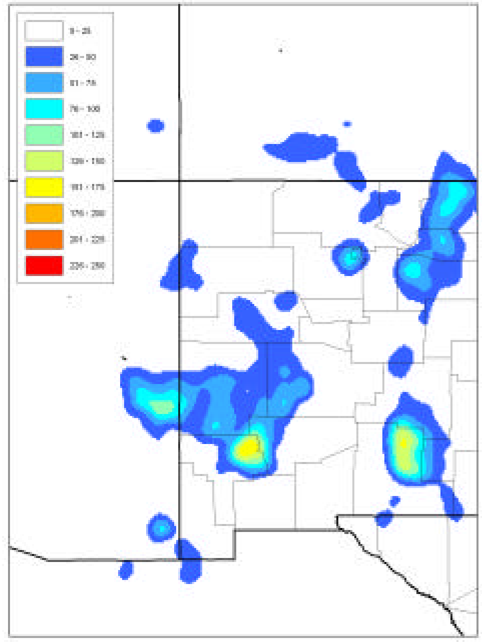

Fig. 23. Initiating flash densities for the West region under northwesterly flow. Units are flashes degree^{-2} regime day^{-1}.

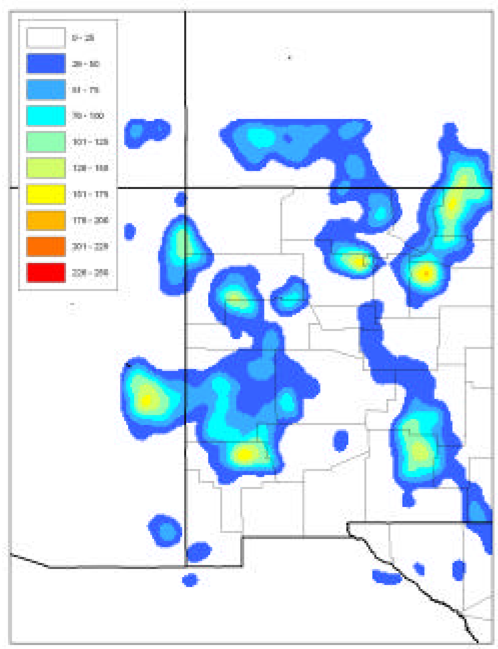

Fig. 24. Initiating flash densities for the West region under calm flow. Units are flashes degree^{-2} regime day^{-1}.

5. CONCLUSIONS

Flash density analyses (Fig. 5) and the topographic map of the study domain (Fig. 2) make it clear that topography exerts a strong influence on the favored zones for thunderstorm genesis in New Mexico and West Texas during the warm season. In addition, our examination of the evolution of lightning activity (Fig. 6) indicates that the approximate time of topographic initiation is 1800 UTC. Subdividing the lightning data by flow regimes reveals that the wind direction, in combination with the topography, influences the exact size and location of the zones of favored lightning.

In summary, topography governs the lightning formation in the study domain, and will be a useful tool in forecasting the location of thunderstorm genesis during the warm season days with little synoptic activity.

6. FUTURE WORK

We plan to experiment with a mean wind at lower levels (likely surface to 700 hPa) for the East region. Having split the domain into East and West regions makes this easy to implement.

Our future work will emphasize the creation of a convenient, relatively easy to use tool to prepare a forecast map of thunderstorm initiation based on input fields of moisture, stability, wind speed and direction, and topography.

Using the Raster Calculator function within ArcGIS, in conjunction with an equation (to be determined through statistical regression similar to that in Reap (1994)), wind speed, direction, moisture (possibly RH), and instability (most likely CAPE, suggested by Solomon and Baker (1994)) will be combined to determine locations where favorable combinations of moisture, instability, and topographic forcing exist for thunderstorm genesis. Since ArcGIS can interpolate a smooth field from point data (most commonly using inverse-distance-weighted interpolation), a variety of data can be used: surface, RAOB, MOS, or even reanalysis data of past cases.

Once the appropriate equation for each region is determined and high resolution topographic layers are obtained, smooth fields can be quickly generated, and a forecast map of thunderstorm initiation can be created.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Banta, R. M., and C. B. Schaaf, 1987: Thunderstorm genesis zones in the Colorado Rocky Mountains as determined by traceback of geosynchronous satellite images. *Mon. Wea. Rev.*, **115**,463-476

Cummins, K. L., M. J. Murphy, W. L. Hiscox, E. A. Bardo, R. B. Pyle, and A. E. Pifer, 1998: A Combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network. *J. Geophys. Res.*, **103**, 9035-9044.

Lericos, T. P., H. E. Fuelberg, A. I. Watson, and R. L. Holle. 2002: Warm season lightning distributions over the Florida peninsula as related to synoptic patterns. *Weather and Forecasting*, **17**, 83-98.

López, R. E., R. L. Holle, and A. I. Watson. 1997: Spatial and temporal distributions of lightning over Arizona from a power utility perspective. *J. Applied Met.*, **36**, 825-831.

NGDC, 2004: *USGS GLOBE Elevation Data*. Internet Dataset. [Available from NOAA/NGDC/MGG-GLOBE Project, http://www.ngdc.noaa.gov/mgg/topo/globeget.html.]

Reap, R.. 1994: Analysis and prediction of lightning strike distributions associated with synoptic map types over Florida. *Mon. Wea. Rev.*, **122**, 1698-1715.

Schaaf, C. B., Wurman, J., and R. M. Banta, 1988: Thunderstorm-producing terrain features. *Bull. Am. Met. Soc.*, **69, No. 3**, 272-277

Smith, J. R., H. E. Fuelberg, A. I. Watson. 2005: Warm season lightning distributions over the Northern Gulf of Mexico Coast and Their relation to synoptic-scale and mesoscale environments. *Weather and Forecasting*, **20**, 415-438.

Solomon, R. and M. Baker. 1994: Electrification of New Mexico thunderstorms. *Mon. Wea. Rev.*, **122,** 1878-1886.