Mapping the Impact of Terrain on Lightning Incidence and Multiple Ground Contacts in Cloud-to-ground Flashes

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ABSTRACT: The climatological incidence of cloud-to-ground (CG) lightning is known to have large regional differences associated synoptic-scale variations in weather that impact the development and propagation of deep convection. At smaller spatial scales, terrain variations are known to play a significant role in the development of deep convection leading to thunderstorms. Convective clouds frequently build over the high terrain typically beginning in the late morning or early afternoon, driven by mountain-valley circulations. In addition to the enhancement of deep convection in complex terrain, there are flash-scale interactions between downward propagating leaders and terrain variations that can alter the nature and location of attachment to ground. This suggests that there may be terrain-related variations in not only the incidence (ground flash density) of CG lightning and the location of the first flash in a storm, but also in some of the physical parameters of CG lightning flashes. The work presented here focuses on demonstrating the impact of terrain on the nature of multiple ground contacts in CG flashes using data provided by the U.S. National Lightning Detection Network during the period of 2006 through 2011. A method for classifying a CG stroke as creating a new ground contact or occurring in a pre-existing channel is presented first. This method employs information that can be provided by modern lightning locating systems. This tool is then used to study the spatial distribution of the average number of ground contacts per flash and the dominant spatial separation distances, in 5x5 degree regions with differing terrain variations. These data are analyzed at sub-km spatial scales using the DTED digital elevation model dataset.

INTRODUCTION

The climatological incidence of cloud-to-ground (CG) lightning is known to have large regional differences associated synoptic-scale variations in weather that impact the development and propagation of deep convection. These regional variations have been noted by a number of researchers. A "smoothed" depiction of these variations for the U.S. National Lightning Detection Network™ (NLDN) is shown in Fig. 1, with ground flash density (GFD - flashes/km2/yr) ranging from over 14 fl/km2 in portions of Florida in the southeastern U.S. to fewer than 0.1 fl/km2 along the west coast of the U.S. At smaller spatial scales, terrain variations are known to play a significant role in the development of deep convection leading to thunderstorms.

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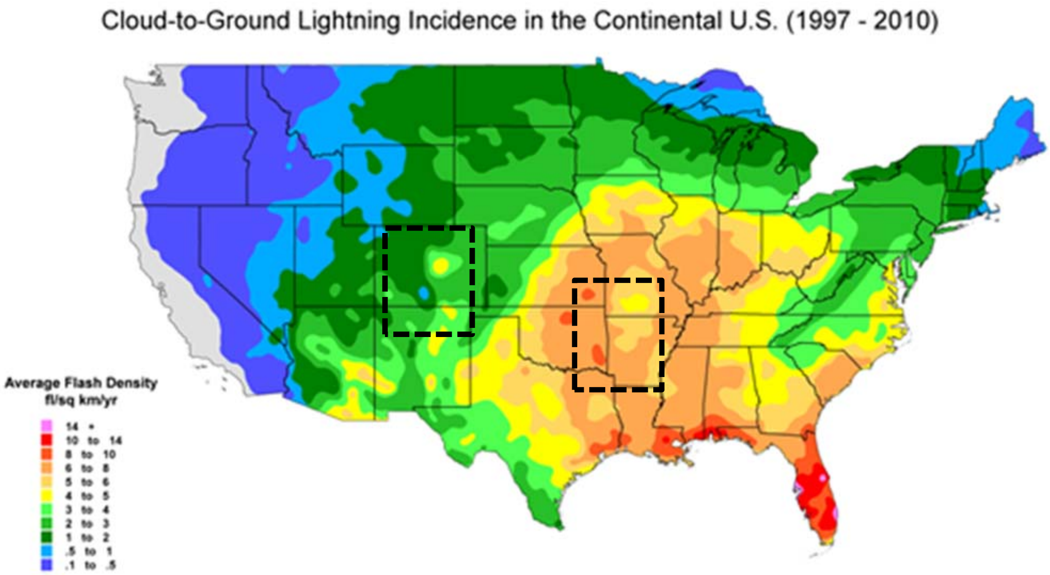

Figure 1. Cloud-to-ground lightning flash density (per square kilometer per year) for the U.S. from 1997 to 20010. Scale is on left side of map. The western and central analysis domains are indicated by the 5x5 degree boxes (dotted lines). Reproduced with permission from Vaisala, Inc.

Convective clouds frequently build over the high terrain, typically beginning in the late morning or early afternoon, driven by mountain-valley circulations (Orville 1975; Hagen et al., 2011; Kottmeier at al. 2008). A small number of studies have specifically related complex terrain and lightning incidence derived using Lightning Locating Systems (LLSs). See for example Lopez and Holle 1986; Kotroni and Lagouvardos 2008; Bourscheidt et al. 2009.

In addition to the enhancement of deep convection in complex terrain, there are flash-scale interactions between downward propagating leaders and terrain variations that can alter the nature and location of attachment to ground. More speculatively, it is even possible that extreme terrain variations or high terrain might alter the conditions under which preliminary breakdown occurs above the freezing level in clouds – the first step in the generation of a CG lightning flash.

These effects suggest that there may be terrain-related variations in not only the incidence of CG lightning, but also in some of the physical parameters of CG lightning such as flash multiplicity, first-stroke peak current, and the number of ground contacts per flash.

The work presented here focuses on the impact of terrain on lightning incidence and the number of ground contacts in negative CG flashes. A method for classifying a CG stroke as creating a new ground contact (NGC) or occurring in a pre-existing channel (PEC) is presented first. The method employs information that can be provided by modern LLSs. The method is then used to study the spatial distribution of the average number of ground contacts per flash (CPF) in two regions with differing terrain variations.

It should be noted that LLS-based estimates of new ground contacts can only be provided when the leader initiating a subsequent stroke takes a unique path to ground. LLS network have difficulty resolving the smaller fraction of cases when two or more branches of the same downward-propagating leader reach the ground at about the same time and initiate two or more nearly simultaneous (with ~100 μs) return strokes (Kong et al. 2009; Stolzenburg et al. 2012; Saraiva et al. 2014) Additionally, "root branching" (at the level of a few 10's of meters) cannot be resolved.

DATA AND METHODS

Data and Domain

Data used in this analysis were all detected strokes in negative CG flashes observed by the NLDN (Cummins and Murphy 2009) for the full years of 2006 through 2011. Four 5x5 degree domains were analysed, two or which are presented in detail. The western domain includes the south-eastern portion of the Rocky Mountains and associated lowlands to the south and east. This region was selected for two reasons – it contains extreme terrain variations (altitudes range from 1200m to over 4000m), and it also has the most extreme synoptic-level variation in GFD in the U.S., in the San Louis Valley region. The central domain includes the Ouachita Mountains in the south of the domain and a large portion of the Ozarks to the north. This region was selected because it contains the highlands of the central U.S, but with more moderate terrain variations than the Rockies, with elevations varying between 20m and 700m. These mountains are surrounded by large low-altitude flat regions with high soil electrical conductivity, making it unlikely that electromagnetic propagation effects will seriously distort the lightning waveforms and impact the quality of the lightning locations and related parameters.

Selected results from two other domains will be presented – southern Arizona in the southwest U.S., and Florida in the southeast U.S. Results from these regions will be used to drive-home key points that are brought to light in the western and central domains.

Spatial Analysis

For this study, CG lightning parameters were computed in 600x600 grids over the two 5x5 degree domains, resulting in grid sizes of 0.7 km^2. All gridded data were spatially smoothed using a 2-dimensional Gaussian filter with a standard deviation of 2 grids. Primary parameters in this study include the Ground Stroke Density (GSD in strokes/km2/yr) and the average number of ground contacts per flash (CPF). Additional data-quality parameters are used to address concerns about the possible impact of detection technology on observed results.

The resulting gridded data were mapped onto a digital elevation model (DEM) for visualization, employing the Digital Terrain Elevation Data (DTED) developed by the National Imagery and Mapping Agency (NIMA). For DTED, the elevation is given in meters above mean sea level (MSL). Its accuracy is +/- 50 meters in the horizontal and +/- 30 meters in the vertical. The horizontal latitude-longitude resolution of the dataset is 30 arc-seconds (~500m). Specific visualization methods include plan-view representations with elevation isoclines to identify terrain gradients, and 3D renderings using elevated viewing points and solar illumination to provide clearer perception of terrain gradient direction and complexity.

Classification of Ground Contacts

Ground contacts were classified as "existing" (PEC - established by an earlier stroke in the flash) or new (NGC). A recent study by Stall et al. (2009) carried out in southern Arizona identified the

LLS-derived return stroke and flash parameters that strongly correlate with the establishment of a NGC. These included the threshold-to-peak rise-time of the closest-reporting sensor, stroke order within the flash, and peak current. The authors used GPS-synchronized video observations to classify the PEC and NGC strokes. In the study presented here, 51 PEC and 55 NGC strokes out of those used by Stall et al. (a refined subset of the original data) were employed to train a Linear Discriminant function. In the most general form explored in this work, the three parameters identified by Stall et al. were combined with both the smallest separation distance from earlier strokes in the flash and the ratio of this distance to the estimated median location error (ellipse semi-major axis - see Cummins et al. 1998) resulting in a discriminant function with 6 parameters. In order to make the method "transportable" to regions with different ground electrical conductivity (and therefore different average rise-times to the nearest sensors (Scheftic et al. 2008), the rise-time values within a flash were divided by the rise-time for the first stroke in that flash. The classification error for this 6-parameter configuration was compared to errors obtained for various subsets of parameters. It was found that equivalent classification accuracy was obtained by excluding peak current, resulting in the following discriminant function:

$$\boldsymbol{DISC} = 0.255 - 3.92\,\boldsymbol{RT} + 1.11\,\boldsymbol{Order} - 0.17(\boldsymbol{D}/\boldsymbol{SMA}) - 1.11\,\boldsymbol{D} \qquad (1)$$

where ***RT*** is rise-time (threshold-to-peak) relative to the 1st stroke rise-time, **Order** is the stroke index within the flash (1 through M, where M is the flash multiplicity), ***D*** is the separation distance (km) from the closest earlier strokes in the flash, ***D/SMA*** is the ratio of this distance to the ellipse SMA for the current stroke, and the value 0.255 is the scaling constant required to place the classification threshold at zero. Negative values of DISC are associated with NGC strokes.

The training dataset had over 93% correct classification, with similar classification errors for both PEC and NGC strokes. This is somewhat better than was found by Cummins (2012) due to small corrections in the training dataset, and to the use of first-stroke referenced rise-times. However, the classification scores for a training dataset will typically be better than what can be achieved in actual use of a classifier. Unfortunately our available dataset was too small to have an independent "test" dataset to evaluate performance, so a "jackknife" procedure was used in the evaluation. More specifically, individual observations were excluded, and discriminant coefficients were obtained from the reduced set of observations (missing one event). These coefficients were then used to classify excluded events, resulting in 106 sets of parameters. The classification results for this jackknife analysis are shown in Table 1. Performance using the jackknife procedure decreased only slightly, with better than 92% classification for both PEC and NGC strokes.

Table 1. Classification Table for training dataset (jackknife test), using 5 classification parameters.

		True Classification	
		NGC	PEC
DISC Classification	NGC	92.7	7.3
	PEC	7.8	92.2

The discriminant coefficients derived using the jackknife procedure had some sensitivity to the exclusion of individual events. This is illustrated in histograms in Fig. 2, showing the distributions of the discriminant coefficients. The "*" in each histogram indicates the coefficient value obtained using the complete dataset.

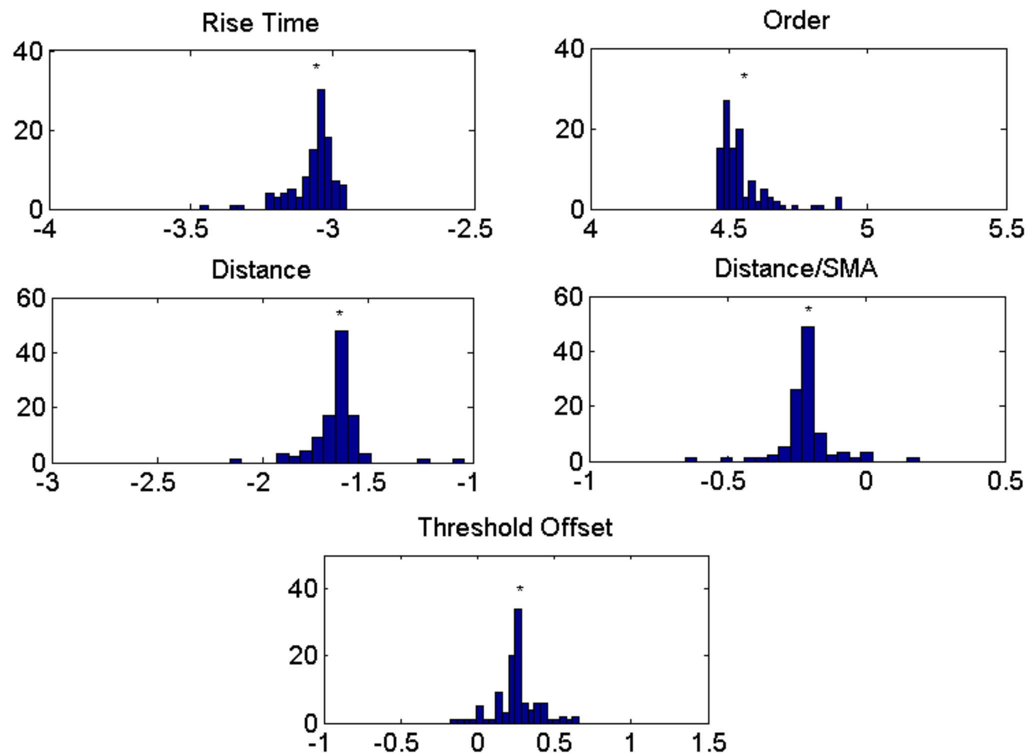

Figure 2. Histograms of classification parameters obtained using jackknife procedure. The "*" represents the values obtained using all 106 training observations.

Three of the five LLS parameters (excluding the offset and Distance/SMA) showed about 10% variation, with clearly dominant modal values and 2-3 "outliers." The most variable parameter (in terms of percentage change) was the ""offset", which serves to "center" the discriminant function about zero. The outliers are sufficiently large to suggest that there may be a few misclassified events in the training dataset. It would be likely to misclassify some NGC strokes as a PEC, due to (1) the fact that only one camera was used, and (2) because of the difficulty in resolving near-ground channel splitting for distant lightning. Both of these issues would allow some NGC events to appear to be in the same channel.

The classification histograms in Fig. 3 show that all but one event that was (potentially) misclassified by the discriminant analysis had small discriminant values, indicating fairly robust classification for this rather small training dataset. As an independent assessment of the discriminant classification, the method was applied to a 6-year NLDN dataset in a small region of southern Arizona. This region is the area used in both the original Stall et al. study and in a study of Valine and Krider (2012). The percentage of strokes in this area that were estimated to create a NGC, as a function of stroke order, is shown in Fig. 4. The percentage of second strokes creating an NGC (63%) is significantly higher than the 43% found by Valine and Krider. . It is possible that the true percentage is higher than was found in those single-camera studies, but the magnitude of this difference suggests that the absolute magnitude of the estimates to be provided in the following section should be interpreted with some caution.

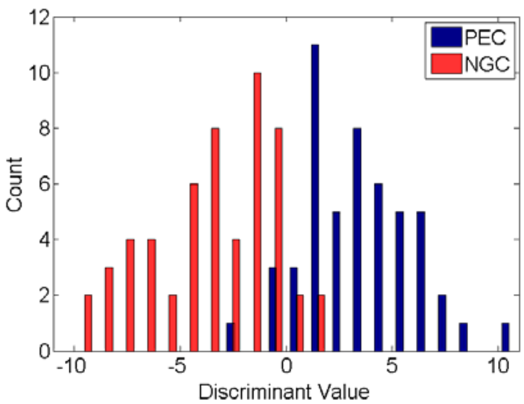

Figure 3. Classification histograms showing the count of video-classified events as a function of the discriminant value. Negative values are classified as new ground contacts (NGC).

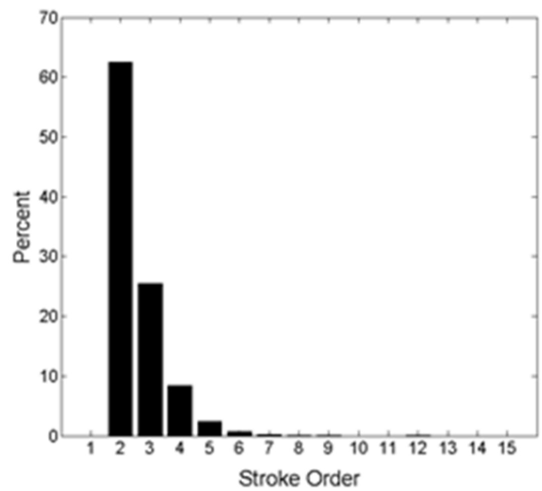

Figure 4. Estimated percentage of strokes establishing a NGC, as a function of stroke order, for southern Arizona (2006-2011).

RESULTS

In this section, complete analyses are presented for both the central and western domains. Negative ground stroke density (GSD) and the average number of ground contacts per flash (CPF) are the primary observations. The spatial pattern of terrain elevation and spatial rate-of-change of terrain are also presented, and compared to the CPF spatial patterns. In addition, selected results from southern Arizona and Florida will be used to reinforce interpretation of results in the western and central domains.

Central Domain

The GSD and CPF for the central domain are shown in Figs. 5 and 6, respectively. The left-hand panels show the 2-D projection of these data overlaid by 100m elevation isoclines (black lines). The right-hand panels show the same data overlaid on the DEM data as 3-D renderings using elevated viewing points and solar illumination.

The highest GSD values (12-15 per km^2/yr) generally occurred in regions of highest terrain gradient, depicted by the closest spacing of the 100m isoclines in the left panel of Fig. 5. Additional insight into the specific locations of the GSD maxima is provided in the right panel, showing high density in large areas of uniform slope and increasing altitude. Some of the large-gradient regions appear to be “protected” from high lightning incidence, while a few of the lower-gradient regions to the west and northwest exhibit some of the highest incidence. This GSD is consistent with orographically-driven thunderstorm development and propagation, with low level moisture and winds preferentially arriving from the south and south-east.

The estimated CPF values in Fig. 6 vary between 1.4 and 2.0, with higher values generally occurring in areas of high terrain and high terrain gradient, although the CPF and GSD values in this domain show very different behaviors with respect to local terrain. Interestingly, one of the regions of highest slope and highest GSD (34.4N, 95W) has moderate CPF values. Additionally, the area around (33.4N, 92.8W) has high CPF and a very low GSD. These behaviors are best seen by comparing the 2-D panels in Figs. 5 and 6. The lower CPF values in the range of 1.4-1.7, found in the low-lying areas, are consistent with the values reported in the literature in various parts of the world (Stall et al. 2009; Valine and Krider 2002; Saba et al. 2006; Thottappillil et al. 1992; Ishii et al. 1998).

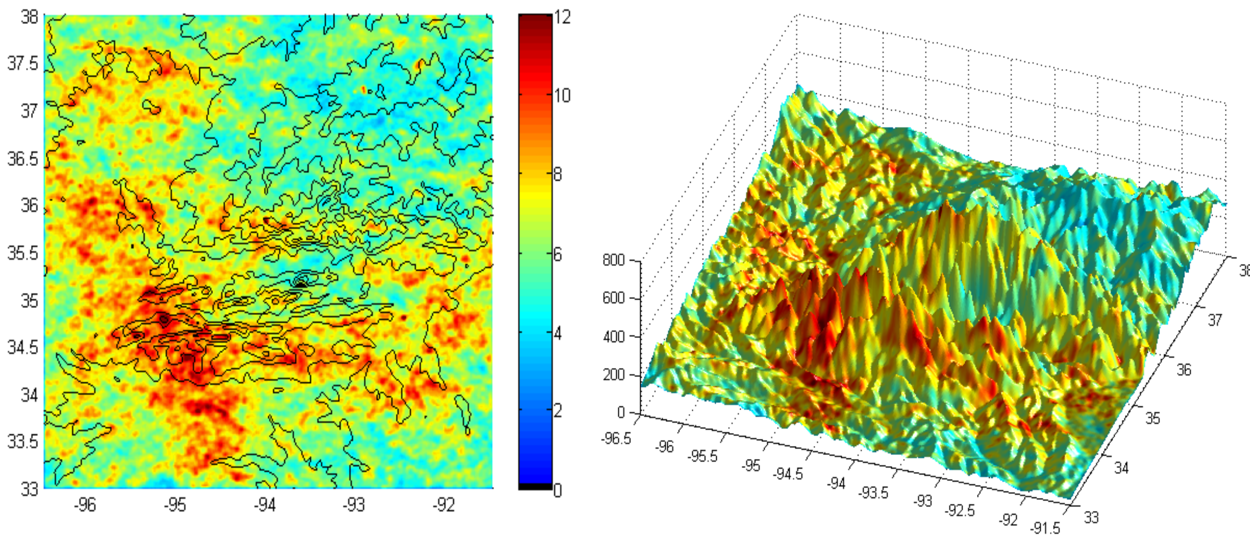

Figure 5. 6-year ground stroke density (GSD) for negative flashes near the Ozark Mountains. (Left) Data overlaid by 100m isoclines. (Right) viewed from an elevated viewing and, with solar illumination at that same angle.

Video-based observations of multi-contact flashes are just now being carried out in mountainous regions (Saraiva et al., 2014), thus we cannot currently validate the higher estimates in the higher, complex terrain (1.7 to 2.0).

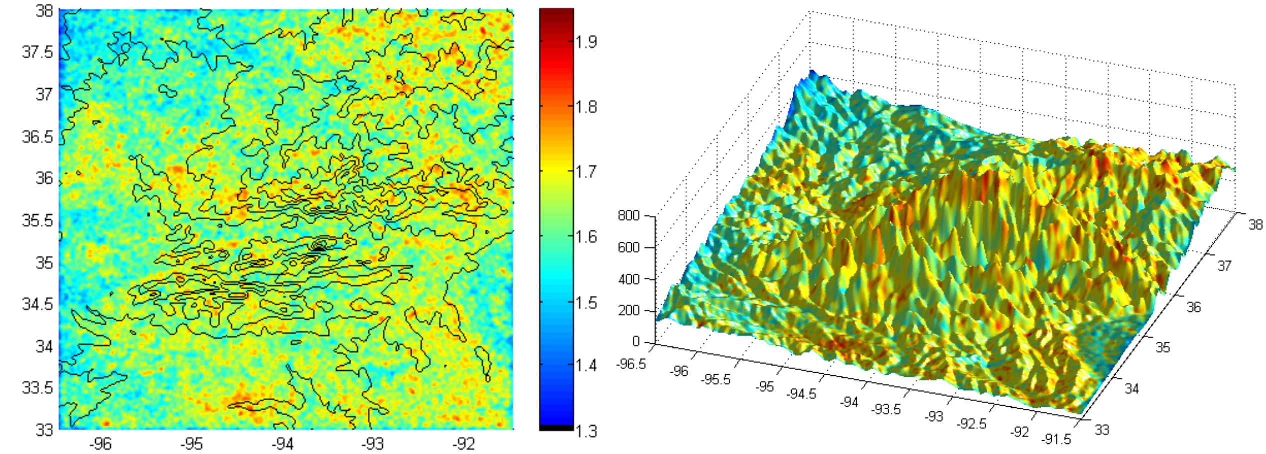

Figure 6. 6-year average number of ground contacts per negative flash (CPF) for negative flashes near the Ozark Mountains, (a) overlaid by 100m isoclines, (b) viewed from an elevated viewing and, with solar illumination at that same angle.

Exploratory assessment of terrain elevation, gradient, and local spatial frequency suggested that high spatial-frequency variations in terrain might play an important role in modulating the number of ground contacts per flash (CPF). Fig. 7 illustrates this fact. The left panel repeats the left panel of Fig. 6, with some highlighted regions. The right panel shows the high spatial-frequency variations, depicted as the signed (+/-) peak amplitude of the terrain variations for spatial wavelengths less than ~2 km. When comparing these data with the CPF pattern on the left, higher CPF values appear to be generally consistent with peak variations greater than 10-15 m.

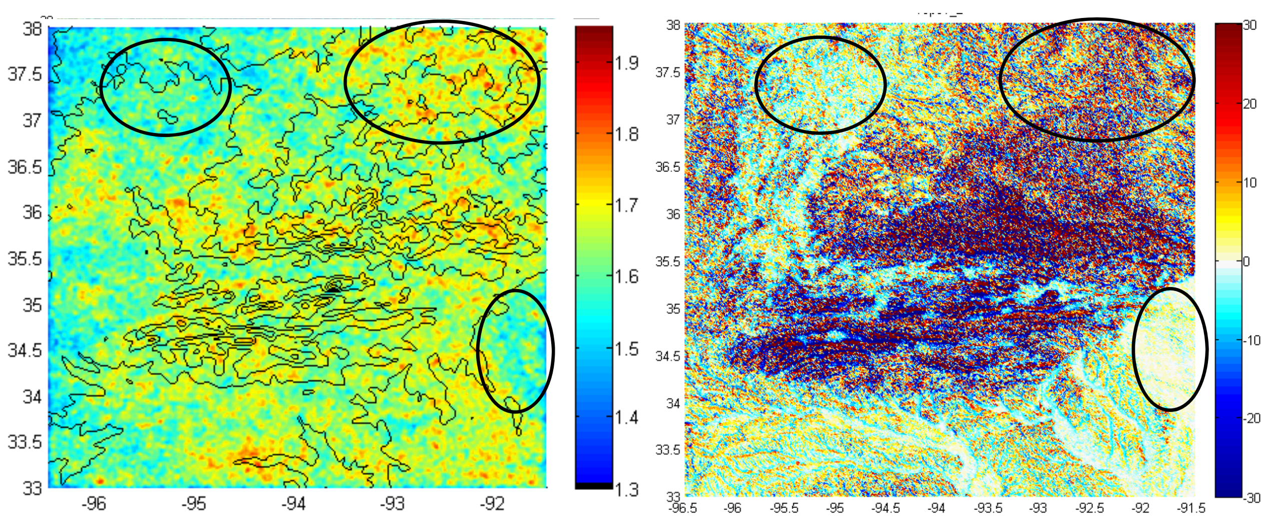

Figure 7. Same CPF data as in Fig. 6 (left panel) and 1-2 km spatial variations of terrain (right panel) near the Ozark Mountains. Elevation is in meters. The terrain variations are signed (+/-) peak amplitude values(in meters).

The three regions identified by black ovals were selected to illustrate the range of relationships between average CPF and terrain. The upper-left and lower-right ovals show regions with low CPF values. Viewing Fig. 5, It is clear that lightning stroke density is high in these regions, and the terrain is either flat (lower-right) or has a gentle slope (upper-left). The right panel of Fig. 7 shows that both of these regions have very low-amplitude terrain variations in the 1-2 km spatial frequency range. The upper-right region exhibits some of the largest CPF values (left Panel), along with frequent large-amplitude terrain variations (> 30m) n the 1-2 km spatial frequency range. Interestingly, this region has the uniformly-lowest stroke density on this domain (see Fig. 5). In summary, we see clear evidence that the number of ground contact per flash is associated with high spatial-frequency terrain variations (~1-2 km), and that it is poorly correlated with stroke density and terrain elevation.

Western Domain

The plan-view GSD and CPF for the western domain are shown in Figs. 8 and 9, respectively. The left-hand panels show the 2-D projection of these data overlaid by 300m elevation isoclines (black lines). The right-hand panels show the same data overlaid on the DEM data, shown as 3-D renderings using elevated viewing points and solar illumination.

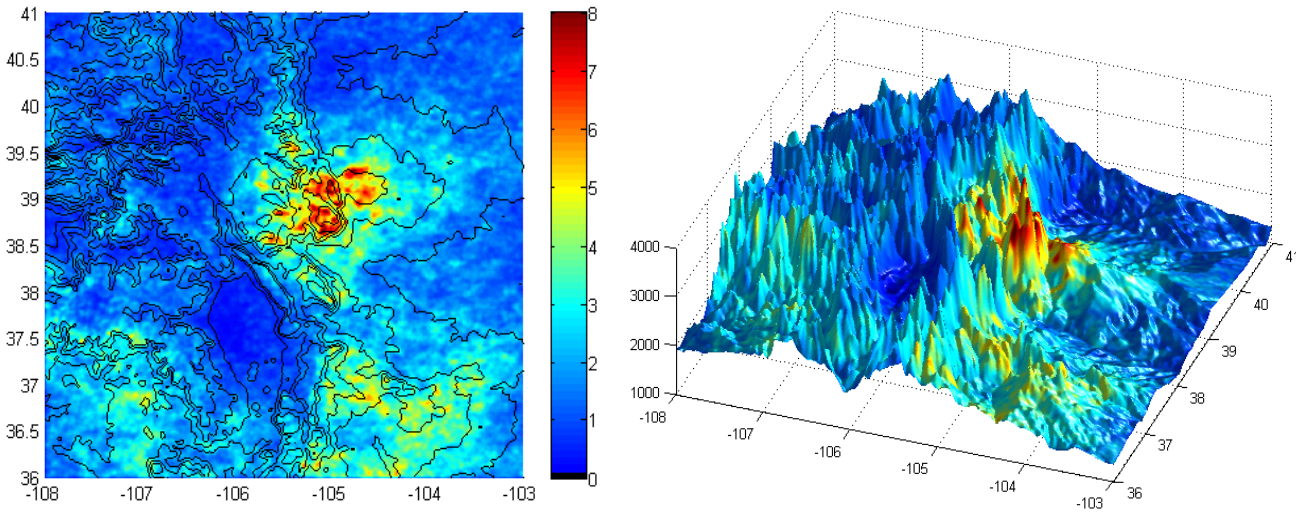

Figure 8. 6-year ground stroke density (GSD) for negative flashes near the Rocky Mountains. (a) Data overlaid by 100m isoclines. (b) viewed from an elevated viewing and, with solar illumination at that same angle.

The highest GSD values (6-8 per km2/yr) again occurred in regions of highest terrain gradient, depicted by the closest spacing of the 300m isoclines in left panel of Fig. 8. The right panel illustrates that the highest densities generally occurred more than halfway up the mountain slopes. As in the central domain, some of the large-gradient regions appear to be “protected” from high lightning incidence, while a few of the lower-gradient regions to the southeast exhibit high lightning incidence. This GSD is also consistent with orographically-driven thunderstorm development and propagation with low level moisture and winds preferentially arriving from the south-southwest (Gulf of California) and the south-east (Gulf of Mexico).

The estimated CPF values, shown in Fig, 9, vary between 1.3 and 1.9, with higher values generally occurring in the areas of high terrain gradient. As was found for the central domain, there are areas with high CPF values that do not coincide with high terrain gradient. Particularly clear areas are the far eastern region between north latitudes 37 and 38, and a small region centered on 106W longitude in the north latitude range of 36 to 36.5. The low elevation and elevation gradient in these areas can be best seen on the left panel of Fig. 10, showing a top-down view of elevation in this western domain.

The high spatial-frequency terrain variations for this region are provided in the right-hand panel of Fig. 10. Note that the two small areas with high CPF discussed above exhibit local peak roughness values exceeding 30m. The elevation map in the left-hand panel clearly shows the low elevation in these areas.

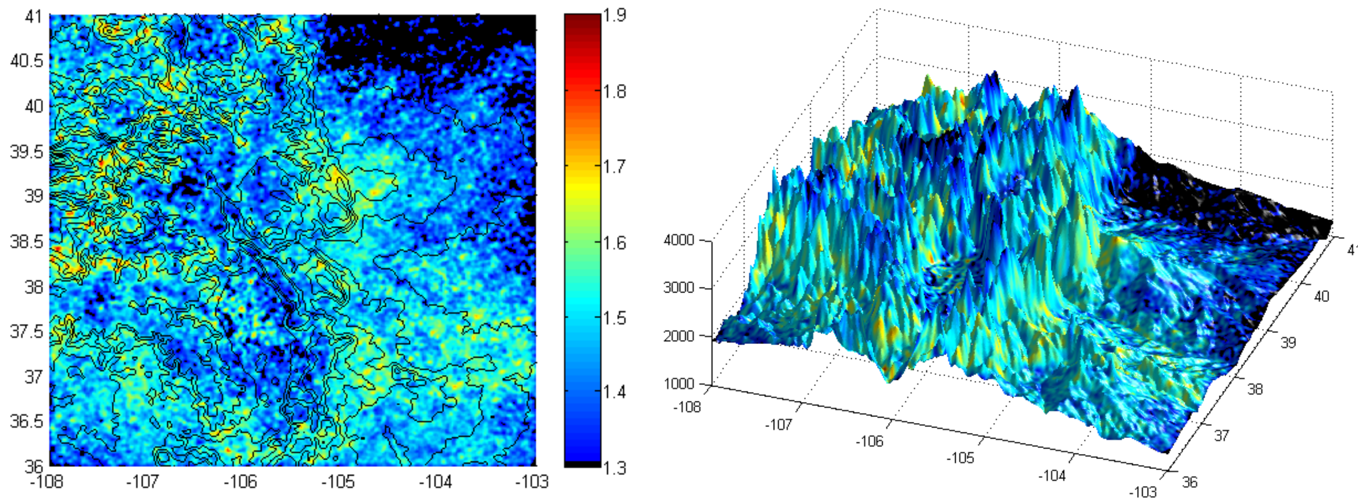

Figure 9. 6-year average number of ground contacts per negative flash (CPF) for negative flashes near the Rocky Mountains, (a) overlaid by 100m isoclines, (b) viewed from an elevated viewing and, with solar illumination at that same angle.

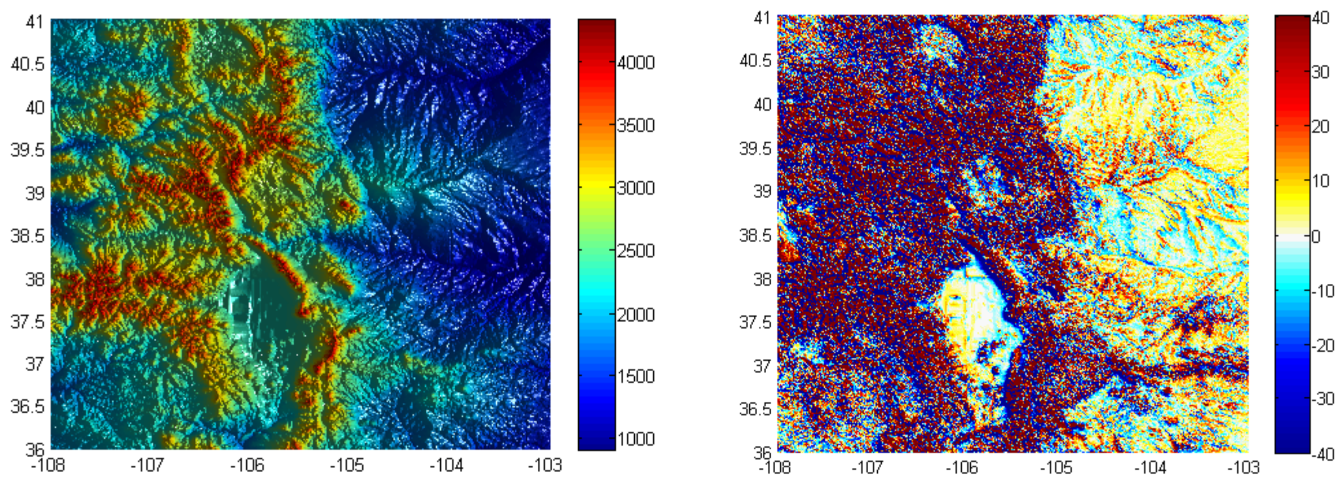

Figure 10. Terrain elevation (left panel) and local roughness (right panel) near the Ozark Mountains. Elevation is in meters. Roughness is the signed (+/-) peak amplitude (meters) of the terrain variations in the spatial wavelengths less than ~2 km.

Sensitivity and Data Quality

There are a number of reasons to be concerned about the sensitivity of the NGC/PEC classifier to regional variations of LLS parameters and to the small training dataset. Regarding the training dataset, it should be noted that the classification method (to date) does not produce a large distinction (in the discriminant parameter space) between some PEC and NGC strokes. The histogram in Fig. 11 illustrate this problem, showing the classification results in Fig. 3 re-plotted without using the a-priori knowledge of the "true" classification. Note that this distribution has some of its most-probable values occurring near the classification threshold (zero). This indicates that small errors in the discriminant coefficients can produce a significant shift in the percentages of NGC and PEC strokes. It is unclear (1) if this is an inherent problem with classification using these parameters, (2) if a different classification approach might work better, or (3) if the training dataset is flawed. It is likely that the threshold for classification could be off (from zero) by no more than 1 discrimination units (see Figs. 2 and 3), thus it reasonable to expect that the spatial patterns of the number of ground-contacts-per-flash are potentially more robust than the absolute CPF values. Future work is needed to both refine the classification method and better quantify the uncertainty.

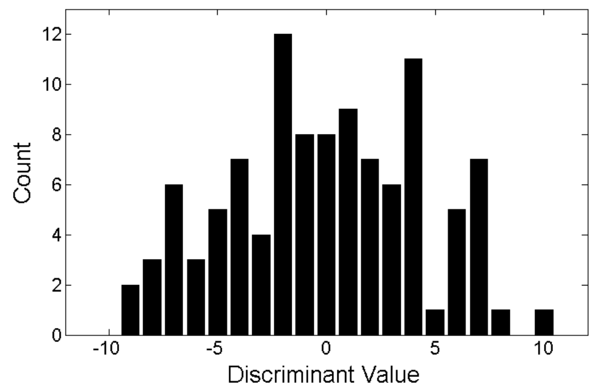

Figure 11. Classification histogram from Fig. 3, ignoring the classification type.

Regional variations of LLS-derived lightning parameters are associated with physical properties of lightning, the measurement environment, and the topology of the LLS network. The effect of large regional variation of rise-time (i.e. due to ground electrical conductivity) has been somewhat mitigated by normalizing the subsequent stroke rise-times by the rise-time of the first stroke. Since the classification parameters are dependent on both rise-time and LLS location accuracy, it is important to look for spatial variations in these aspects of the datasets that might correlate strongly with the spatial distribution of the CPF parameter. Figs. 12 and 13 show the spatial variation of these and other parameters, for the Central and Western domains, respectively. The six panels in Figs. 12 and 13 show mean values for three critical LLS parameters, two separation-distance measurements (PEC and NGC), and the CPF map (top center - included for visual reference). All maps include terrain isoclines in black (height separation is dependent on total height variation), to provide a terrain "context". The chi^2 value (upper-left panel) is a measure of "agreement" among the sensors used to geo-locate a stroke [9]. For properly calibrated LLSs, the mean value should be close to 1; values below 3 are good, and values below ~10 are considered acceptable. Large chi2 values generally occur from large arrival-time errors (due to propagation effects), or long rise-times (either inherent in the event itself or a result of propagation effects). The mean rise-time for all 1st strokes is shown in the upper-right panels, in units of µs. The lower middle map (SMA) is the mean value of the semi-major axis of the location confidence ellipse (50th percentile – see Cummins et al., 1998) for all reported strokes. The mean separation distance between a stroke and its spatially-closest neighbor in a flash are mapped separately for NGC strokes (lower left map) and PEC strokes (lower right map).

Results for the central domain (Fig. 12) are rather easy to interpret. The mean rise-time, chi^2, and SMA maps show little spatial variation, and indicate uniform LLS performance. The mean NGC distance is small (< ~400m), and the mean PEC distance varies between 1.5 and 2 km. This value is generally consistent with findings in the literature. These results provide some confidence that there are real terrain-related variations in the number of ground contacts per flash, and that these variations are likely dependent on terrain gradient and/or local roughness.

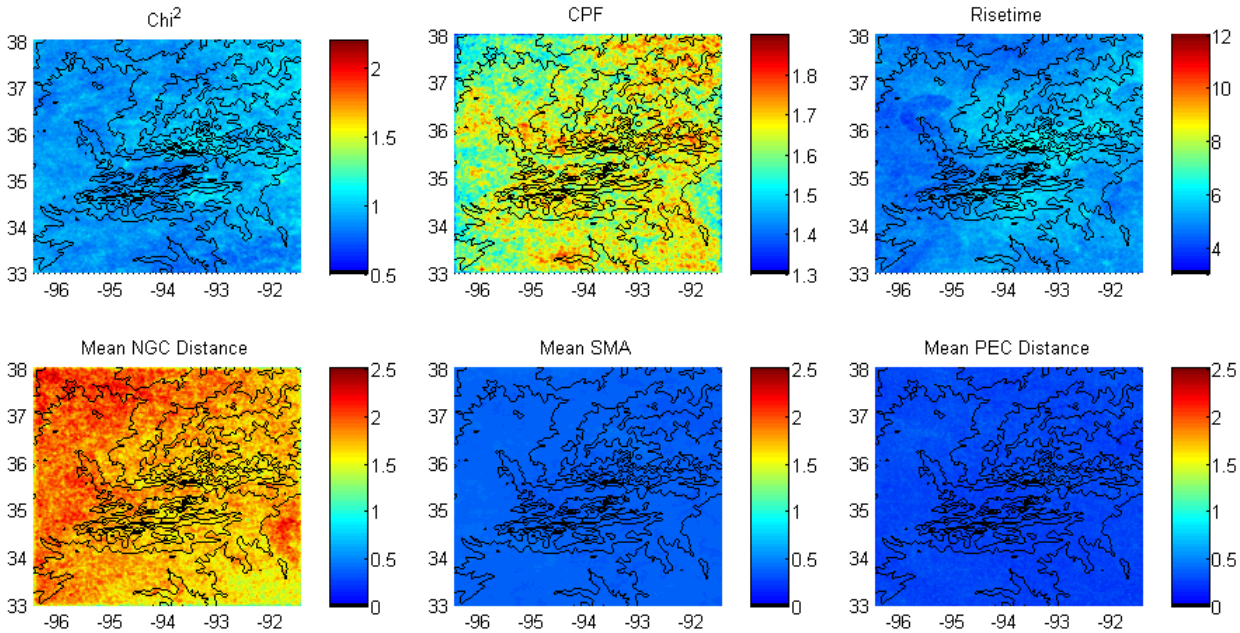

Figure 12. Spatial maps of mean LLS parameters near the Ozark Mountains (Central Domain). Rise-time is in μs, and all distance-related parameters are in km. See text for details.

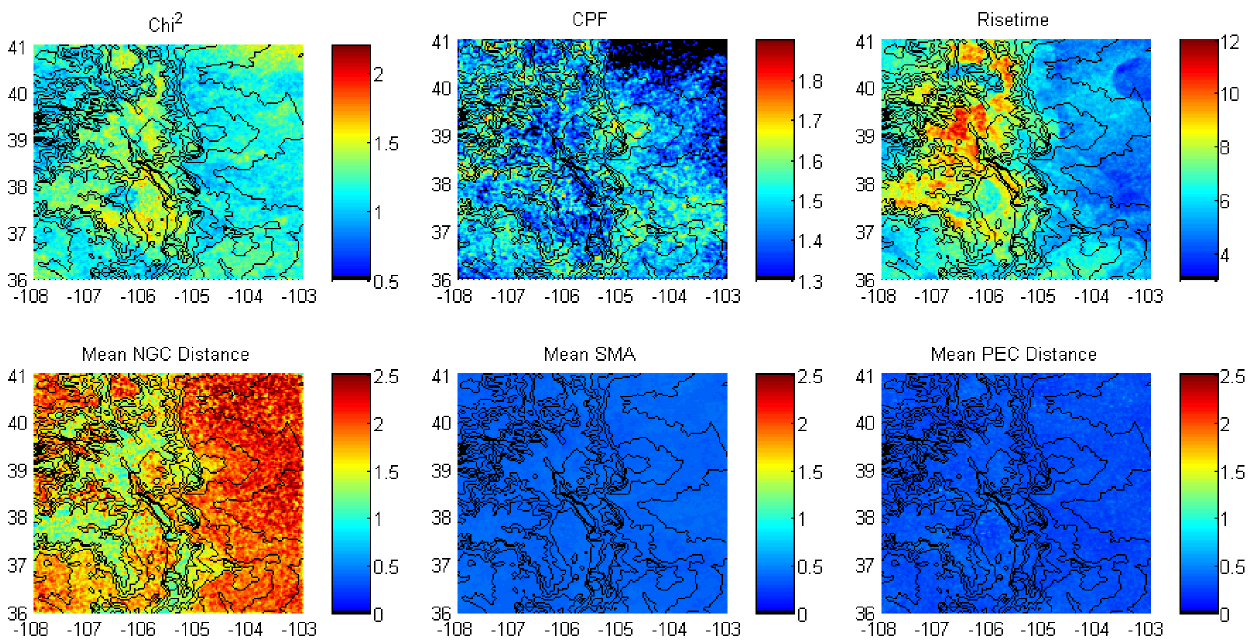

Figure 13. Spatial maps of mean LLS parameters in the Rocky Mountains (Western Domain). Rise-time is in μs, and all distance-related parameters are in km. See text for details.

The story is more complex for the western domain, shown in Fig. 13. The mean SMA and PEC distances are small and the maps show no regional variation, similar to the findings for the central domain. However, the chi^2 values do show terrain-related variations that broadly reflect the rather significant variations in mean rise-time. The rise-time variations in this area were first reported by Bardo et al., 2004, and were shown to correlate well with electrical conductivity, ranging from 15 mS/m for the plains in the western portion of this domain, down to 2 mS/m in the area of largest mean rise-time (~12 μs). Given that the largest mean chi^2 values are below 2, one would expect an increased timing error of roughly √2, resulting in an equal additional location uncertainty. This finding leads to the expectation that there might be an increase in the CPF values and the mean NGC distance in this high-chi^2 region. However, the opposite is true – both of these values decrease throughout most of the high-chi^2 region. At this point, there is no satisfactory explanation for this finding. There is no obvious spatial relationship between the mean NGC distance and the mean value of the normalized rise-time parameter (not shown). The clearest spatial relationship seems to be with absolute terrain elevation (see left-hand panel of Fig. 10). The regions with mean NGC distance below ~1.4 km are also regions that have the highest uniform elevation of about 4000m.

Recent work by Pedeboy and Schulz (2014) using a k-means approach to identify new ground contacts has shown that LLS networks with location errors in the range of a few hundred meters can produce valid identification of more than 90% of the NGC strokes using only the computed location and the stroke order. This approach might be a more robust in the face of low and/or variable electrical conductivity.

Inferences from Other Regions

In this section, selected results from Arizona and Florida are used to refine key points that were brought to light in the analysis of the western and central domains. The first topic relates to the apparent "protection" of some high-terrain regions from lightning, in that they seem to fall onto an "orographic shadow" of nearby mountain ranges that lay between the "protected" regions and approaching low-level moisture (see Figs. 5 and 8). This behavior is analogous to the well-known convective "rain shadow." Both of these domains (central and western) can be characterized as having multiple spatially-contiguous mountain ranges that interact differently with both low-level winds and mid-morning solar radiation. Further support for this kind of terrain interaction can be provided by studying regions where there are spatially-isolated mountains with significant terrain gradients, with the expectation of little or no shadowing. This condition exists to some degree in southern Arizona surrounding the Tucson Basin. The behavior in this region is illustrated in the 3D rendering of 16-year ground stroke

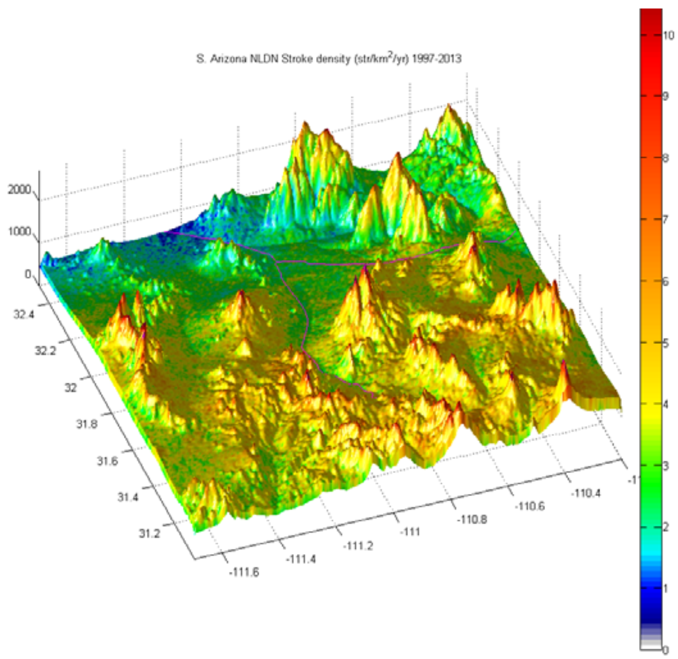

Figure 14. 16-year ground stroke density (GSD) for negative flashes in northern Mexico and southern, viewed from an elevated viewpoint in northwestern Mexico, with solar illumination at that same angle.

density shown in Fig. 14. The view-point for this image is in north-western Mexico. The magenta lines in this map represent Interstate highways 10 and 19, which join together and flow northward within the Tucson Basin. The basin is surrounded by a combination of mountain ranges and isolated peaks. Note that nearly every peak surrounding the Tucson Basin, irrespective of absolute height, exhibits a stroke density in excess of 9 strokes/km^2/year. The only peaks with lower stroke densities are in close proximity to horizontally-extensive mountainous regions.

The second topic in this section relates to the magnitude of the terrain variations required to "modulate" the average number of ground contacts per flash. In order to address this question, the behavior in the Florida peninsula and surrounding ocean was evaluated. Fig. 15 shows the terrain elevation (left), mean CPF (center), and high spatial-frequency (~1-2 km) terrain variations (right) for this area. Most of Florida has an elevation of less than 90 m, with some well-inland elevations below 10 m. The map of CPF shows a well-defined gradient along the coast on the very-low elevation regions, particularly for the northern portion of the domain with the largest variations for high spatial-frequency terrain (see right panel). These results extend the observations for the central and western domains by also demonstrating that for the ocean near a coastal boundary, which is functionally "flat" (even relative to Florida), there is precipitous drop-off of the mean CPF. There is a clear but modest enhancement of the number of ground-contacts-per-flash (CPF) over fairly flat land at sea-level, relative to over the coastal ocean. Possible interpretations of these findings are discussed in the following section.

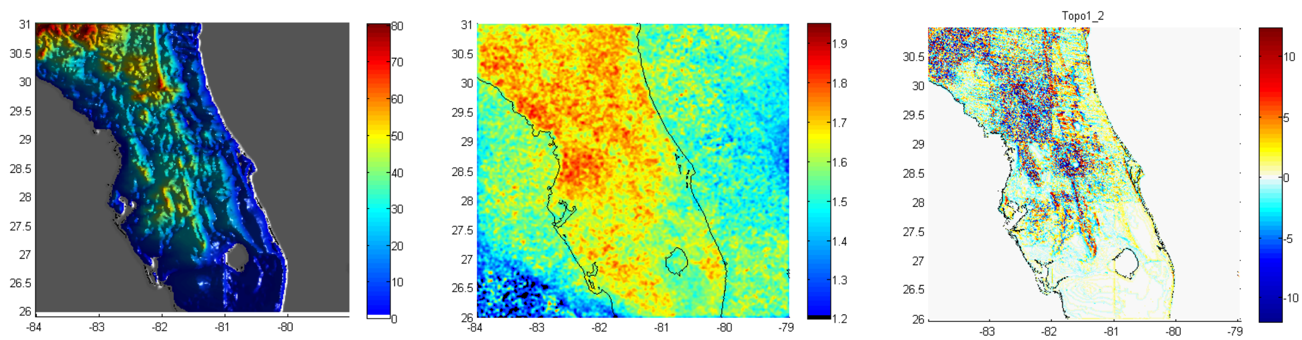

Figure 15. 6-year average number of ground contacts per negative flash (CPF) for negative flashes in the central Florida peninsula and surround ocean areas (left) terrain elevation map (color scale in meters); (center) mean contact-per-flash (CPF); (right) 1-2 km spatial variations of terrain. The terrain variations are signed (+/-) peak amplitude values in meters.

DISCUSSION AND CONCLUSIONS

The impact of large-area (100's of km^2) terrain gradient on lightning flash density is expected from the well-known orographic effect on the development of deep convection. It is interesting to see how well the high-density portions of the long-term ground stroke density maps, when overlaid on a smoothed 3D rendering of terrain, essentially "face" the preferred direction-of-arrival of warm moist air into regions with multiple spatially-contiguous mountain ranges. As noted for southern Arizona, spatially-separated mountains do not seem to exhibit the "shadowing" influence on each other, at least to the degree seen in areas with extensive "layers" of mountains and valleys. Future work in this area should include some quantification of the relationship of terrain geometry on the ingress and re-direction of low level moisture.

The results related to the average number of ground contacts-per-flash (CPF) are clearly thought provoking. There are several possible reasons for high spatial-frequency terrain variations to affect lightning attachment to ground. A likely factor is surface-driven turbulence, produced by variations in aerodynamic drag that disturbs space charge homogeneity underneath an electrified cloud, both within the planetary boundary layer and well above it. Work by Chauzy and Soula (1999) and other have clearly shown that surface space charge beneath thunderstorms can be vertically transported well beyond the boundary layer. There may also be an effect associated with spatial variations in the near-surface electric field brought about by height and slope variations of the surface electrical boundary condition (ground). These effects would produce competing areas of higher and lower electric field near the surface during leader propagation towards ground. Finally, sloping ground (related to terrain gradient and not to local roughness), when spatially interacting with the end-points of the leader "tree" approaching ground, can produce many more "equally likely" high-field ground attachment options, which may increase the likelihood of multiple ground attachments within a flash. All of these possible mechanisms will have reduced effects over large bodies of water, including oceans.

Currently, work is underway to directly evaluate the nature and variability of ground contacts in selected regions in the U.S. and Brazil using video and broadband electric field observations. This work with be coupled with analytical work that focusses on the nature of channel cutoff in negative leaders near ground, a necessary element for the formation of multiple ground contact in negative CG flashes.

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