Clustering US Tornadoes

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Examining the Environmental Characteristics of Tornado Outbreaks in the United States with Spatial Clustering.

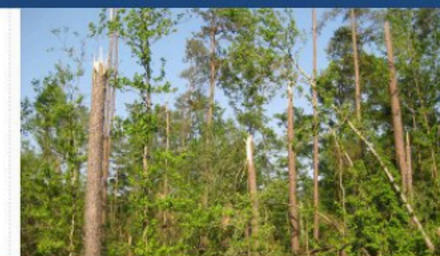
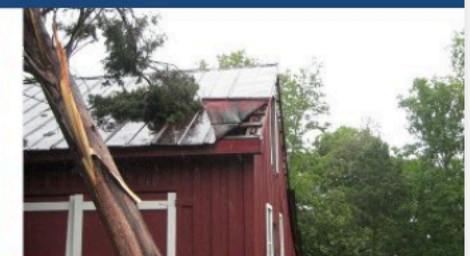
Integrating *R-INLA* with **R** Spatial Packages and the *fpc*, flexible procedures for clustering package.

Joint work with James B. Elsner . Generated using R-Studio on Sun Jun 28 10:41:28 2015 .

What is a tornado outbreak?

- Tornadoes are common in the United States particularly in the Midwest and South.
  - Violent circulation attached to a parent cloud with rotational winds in excess 30 m/s.
  - Causes fatalities and complete destruction of buildings.
- Many tornadoes often occur in a single day known as an outbreak.
  - Define an outbreak as a single day with more than N tornadoes.
  - N=16
- Outbreak may be split geographically into separate regions.
  - Reflect local nature of outbreak.
  - Tornado characteristics and environment vary from region to region.

Enhanced Fujita Scale

EF Rating	Wind Speeds	Expected Damage		
EF-0	65-85 mph	'Minor' damage: shingles blown off or parts of a roof peeled off, damage to gutters/siding, branches broken off trees, shallow rooted trees toppled.		
EF-1	86-110 mph	'Moderate' damage: more significant roof damage, windows broken, exterior doors damaged or lost, mobile homes overturned or badly damaged.		
EF-2	111-135 mph	'Considerable' damage: roofs torn off well constructed homes, homes shifted off their foundation, mobile homes completely destroyed, large trees snapped or uprooted, cars can be tossed.		
EF-3	136-165 mph	'Severe' damage: entire stories of well constructed homes destroyed, significant damage done to large buildings, homes with weak foundations can be blown away, trees begin to lose their bark.		
EF-4	166-200 mph	'Extreme' damage: Well constructed homes are leveled, cars are thrown significant distances, top story exterior walls of masonry buildings would likely collapse.		
EF-5	> 200 mph	'Massive/incredible' damage: Well constructed homes are swept away, steel-reinforced concrete structures are critically damaged, high-rise buildings sustain severe structural damage, trees are usually completely debarked, stripped of branches and snapped.		

Research Interests

- How does spatial clustering help us define the notion of a tornado outbreak?
- How do tornado outbreaks differ from each other?
- What mesoscale environmental conditions effect the frequency and energy of each tornado in an outbreak?
- What environment characteristics are common between tornado outbreaks?
- Could this method be used to identify conditions that lead to outbreaks?

Strategy for analysis

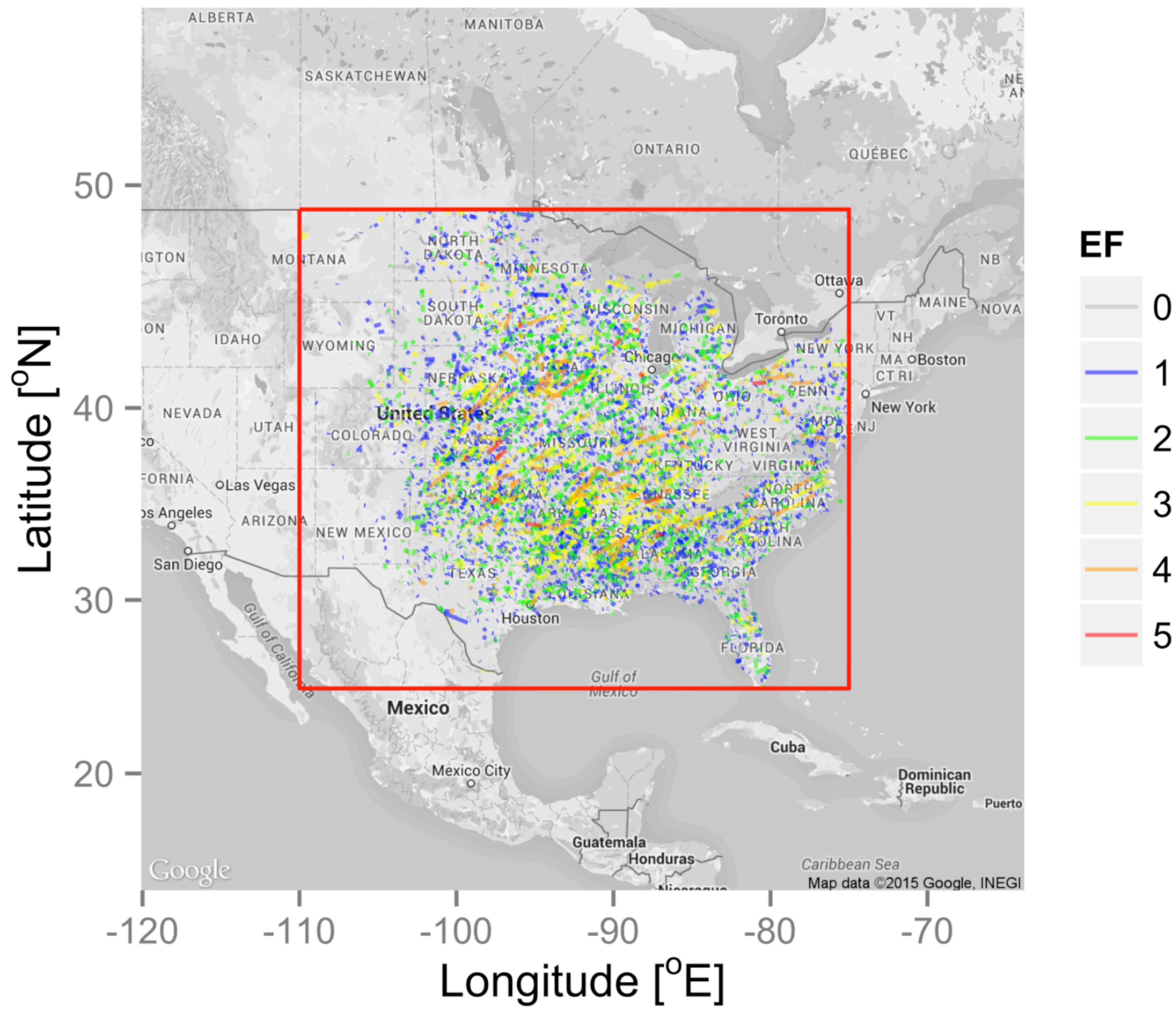
- Reduce to outbreak days and split the data set by days.
- For each day cluster tornadoes into groups.
- For each group find the convex hull of tornado start locations.
- Generate summary statistics of
  - tornadoes within each group.
  - environmental conditions within each convex hull.
- Model the relationship between the tornado statistics and environmental conditions.

Tornado Data Set

We use a modified tornado data set keeping tornado paths in the Midwest and South from from 1979 to 2010 of at least EF0 (F0) strength. The data set is put into **R** **SpatialLinesDataFrame** objects or arrays. We use the **R** **ggplot2** package for plotting data sets.

- Tornado data set is a spatial line data set with attributes from the SPC.
  - Use staring location and storm strength in our study.
- Reanalysis (Environmental) data from Climate Forecast System Reanalysis from NCAR
  - Initially we examine the CAPE and HLCY.
  - $1/2^\circ$ by $1/2^\circ$ resolution spatially
  - 4 times per day at 0000Z, 0600Z, 1200Z, 1800Z

Study Area


EF
0
1
2
3
4
5
Latitude [^{o}N]
Longitude [^{o}E]
50
40
30
20
-120
-110
-100
-90
-80
-70
ALBERTA
MANITOBA
SASKATCHEWAN
ONTARIO
QUÉBEC
MONTANA
NORTH DAKOTA
MINNESOTA
SOUTH DAKOTA
WISCONSIN
MICHIGAN
IDAHO
WYOMING
NEBRASKA
NEVADA
UTAH
COLORADO
United States
MISSOURI
ILLINOIS
INDIANA
OHIO
PENN
NEW YORK
WEST VIRGINIA
VIRGINIA
KENTUCKY
TENNESSEE
NORTH CAROLINA
SOUTH CAROLINA
GEORGIA
ARKANSAS
OKLAHOMA
TEXAS
LOUISIANA
FLORIDA
ARIZONA
NEW MEXICO
Las Vegas
San Diego
Houston
Chicago
Toronto
Ottawa
Boston
New York
MAINE
VT
NH
MA
CT RI
NJ
NB
Gulf of Mexico
Mexico
Mexico City
Cuba
Dominican Republic
Puerto
Guatemala
Honduras
Caribbean Sea
Google
Map data ©2015 Google, INEGI

Clustering

- why? separate tornadoes into groups for analysis
  - Each group may have different characteristics
- what? The staring spatial locations for each tornado.
  - x and y values in the Lambert Conformal Conic projection
    - centered at $33^{\circ} N$
  - could use storm strength, EF magnitude, alone or as another clustering variable.
- Why use partitioning around medoid type of clustering?
  - Provide a sample observation representative of the whole.
  - Cluster around an actual tornado, not just an empty center.
  - The mediod tornado is not unique, just representative sample from cluster.

Clustering Example

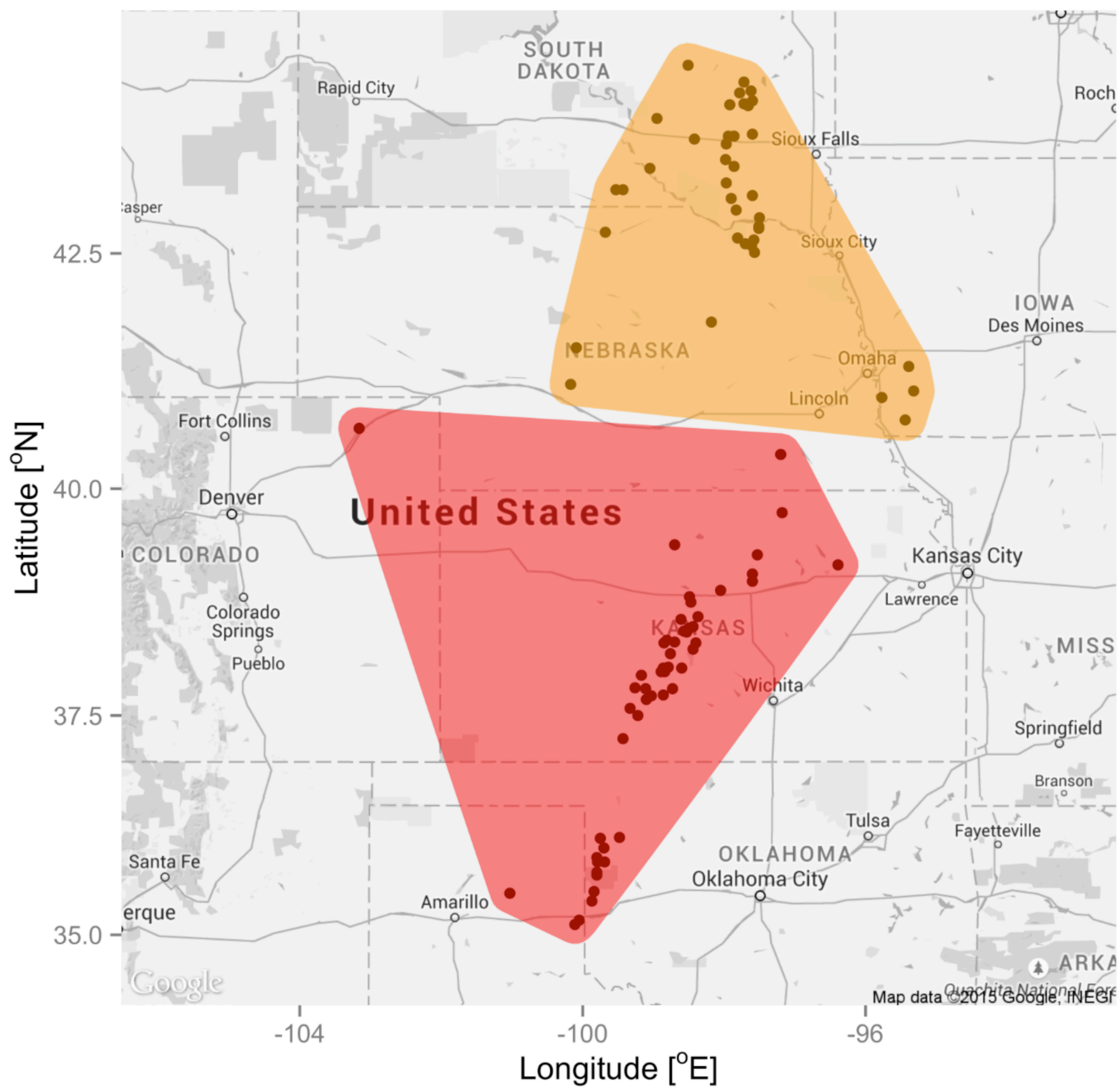
- Subset tornado database to fit within our bounding box, and remove tornadoes without EF classification.
- Remove all days with less than 16 tornadoes.
- Split data by day and run medoid clustering algorithm.
- Create a convex hull around each cluster, enlarge it by 25km and convert to lon lat projection.

```
xx = subset(TornC.spdf, Date == "2007-05-05")
cc = coordinates(xx)
best = pamk(cc, krange = 1:(N-1), alpha = .01)
cluster = best$pamobject$clustering
clustloc = split(1:length(xx),cluster)
Hulls = lapply(clustloc,function(i)

spTransform(gBuffer(gConvexHull(xx[i,]),id=cluster[i[1]],width=25000),longlat))

Hulls.df = do.call("rbind",lapply(Hulls, fortify))
Map = get_map(location = c(lon=-99.5,lat=39.8), source = "google",
              maptype = "roadmap", zoom = 6, color = "bw")
ggmap(Map, extent = "panel") + geom_point(aes(x = slon, y = slat),
      data = TornC.df[TornC.df$Date == dd, ],color = "black") +
geom_polygon(aes(x = long, y = lat, fill=id ,alpha=.5),
      data = Hulls.df
,show_guide=FALSE)+scale_fill_manual(values=c("red","orange"))
```

Clusters on May 5, 2007



Summary Statistics and Analysis

- We calculate summary statistics within each cluster using the
  - tornado data set, for each group of tornadoes.
  - environmental data within each convex hull at 1200Z and 1800Z.
- We combine these into a single dataframe for analysis.
- We use R-INLA to analyze the relationship of
  - total kinetic energy and tornado counts to
    - Convective Available Potential Energy (CAPE),
    - Storm relative helicity (HLCY).

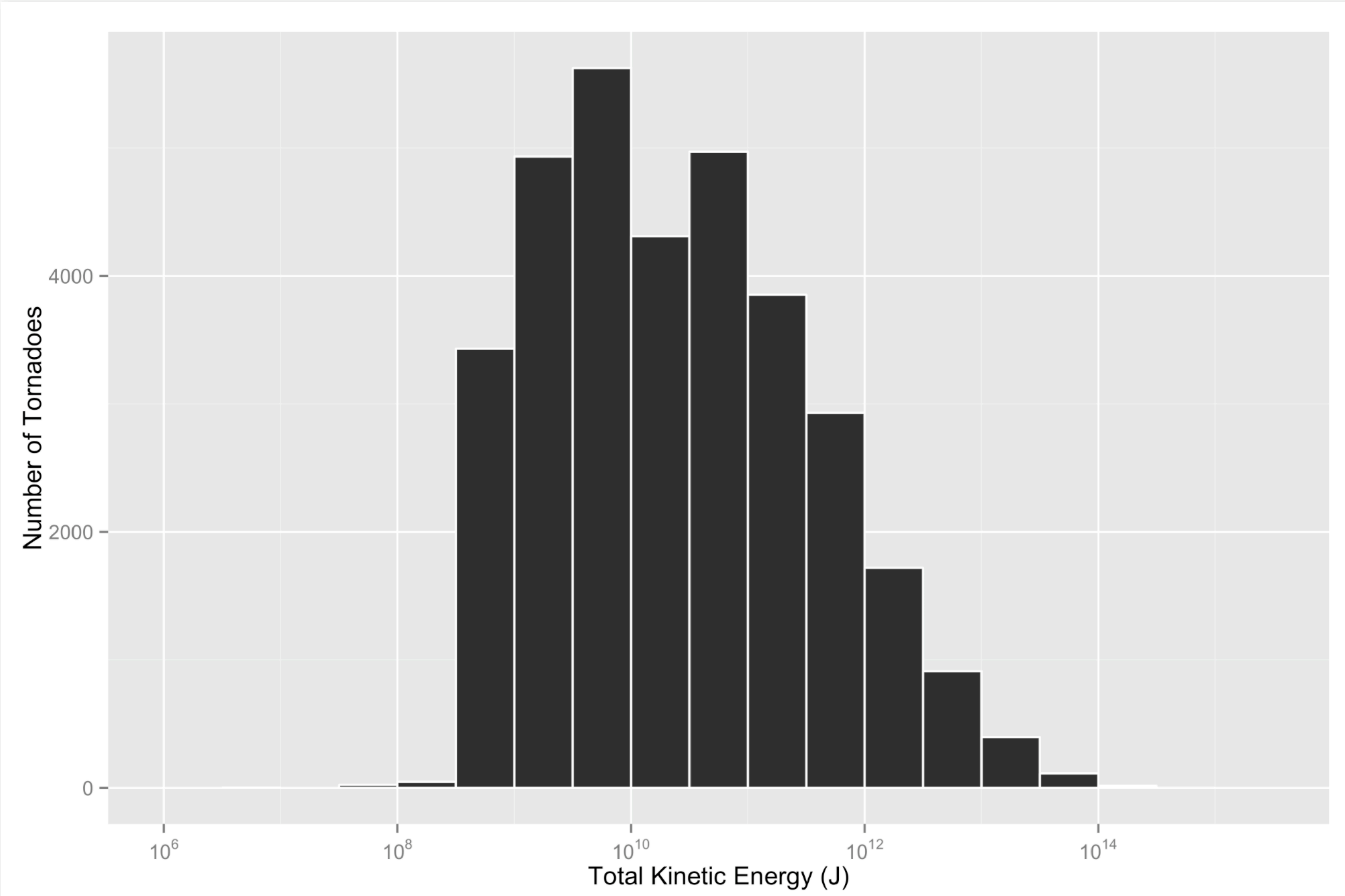
Summary Statistics for Tornadoes

- Total count of:
  - **nT** Tornadoes, at least EF0.
  - **nST** Strong Tornadoes, at least EF3.
- **T**otal **K**inetic **E**nergy for all tornadoes.
  - TKE = Height * Area * TKE per m^3.
    - Height approximated as 1km
    - Area approximated by ellipsoid.
    - Fixed proprtion of areas assigned to each EF strength.
    - Uses midpoint of EF scale $E = 1/2 \rho V^2$
    - $\rho \sim 10^3 \mathrm{kg/m^3}$

Total kinetic energy in megajoules per m^3 based on the tornado's strength is:

EF0	EF1	EF2	EF3	EF4	EF5
0.570	0.661	0.786	0.919	0.974	1.054

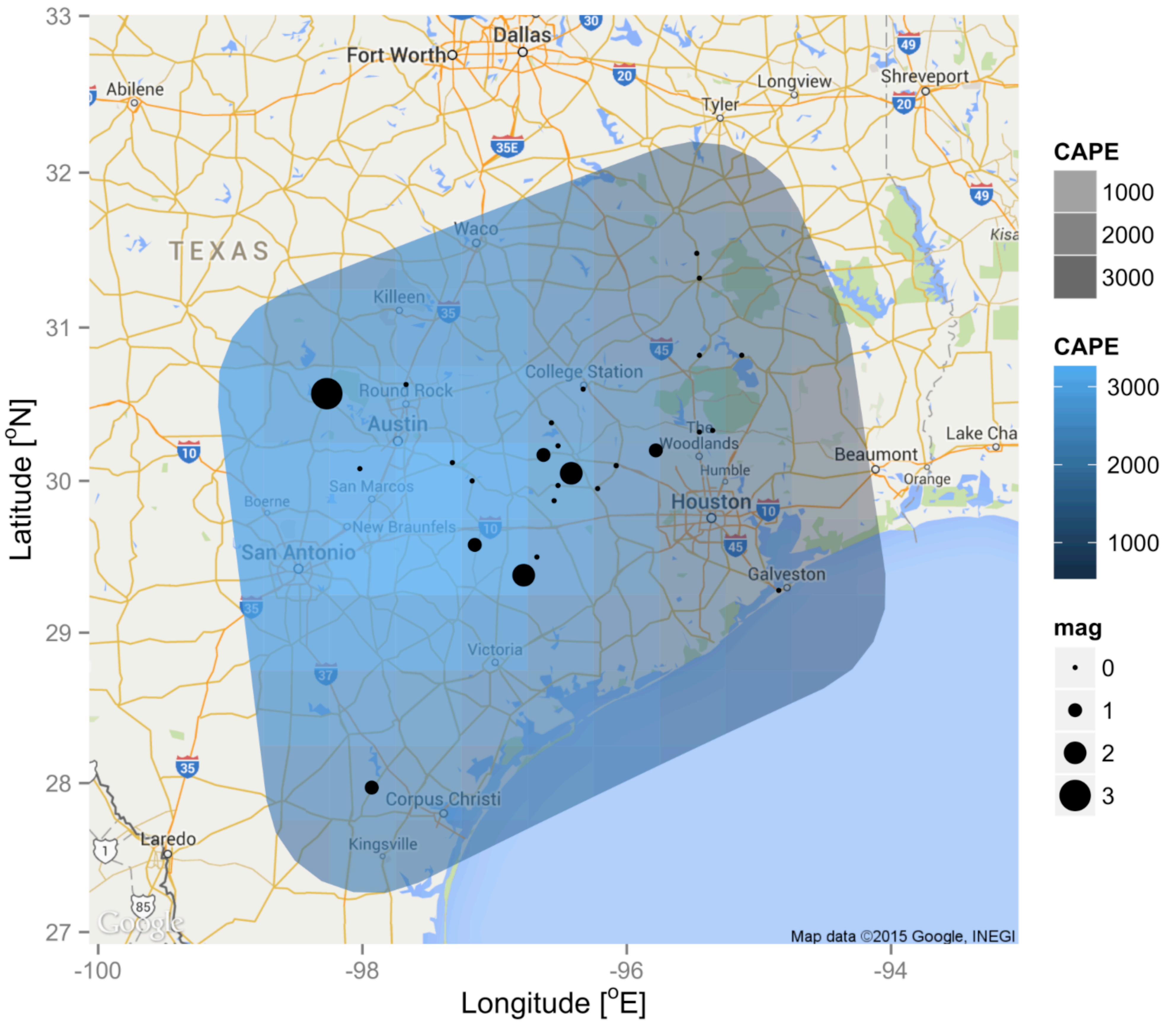
Distribution of log10(TKE)



Environmental Conditions

- Thunderstorms may form if there is the potential for covection with lots of CAPE and little CIN.
  - **C**onvective **A**vailable **P**otential **E**nergy
  - **C**onvective **IN**hibition
  - CIN is required to get lots of CAPE.
- Thunderstorms may become super cell thunderstorms.
  - Updraft sustained by wind shear.
  - Storm rotates with directional wind shear.
- Super Cell thunderstorms may produce tornadoes.
  - Surface inflow wind contains rotation that upscales.
  - 0 - 3000m, total column storm relative helicity (HLCY)
- CAPE and HLCY measured in Joules/Kg or m^2 / s^2.

Sample Cape and Resulting Tornadoes



Summary Environmental Statistics

- Calculated the mean, maximum, median and standard deviation.
  - Within the convex hulls generated for each cluster
  - CAPE and HLCY at 1200Z and 1800Z
- Used only the 1800Z weighted mean values.
  - Values within each CAPE/HLCY grid box assumed to be the same value.
  - Grid intersection areas used as weights.
  - Use **rgeos** functions.
    - **gIntersects** to find which grids are in each cluster.
    - **gIntersection** to find the spatial intersection of each grid to the cluster.
    - **gArea** to find the are of the intersection.
    - **gConvexHull** to create convex hull for each cluster.
    - **gBuffer** to expand each hull by 80km.
- Need to explore wind shear
  - Reanalysis data exists (u,v) for many levels from surface to stratosphere.

Analysis using R-INLA

- See http://www.r-inla.org, Bayesian modelling using integrated nested Laplace approximation.
- Previous work using INLA: Rpubs Tornado Climatology
- All covariates and response require scaling.
- Negative binomial distribution for counts.
- Gamma distribution for mean TKE per tornado in Terajoules, **mTKET**.
- Model covariates for **mTKET** are
  - **LnT** Logarithm for Number of Tornadoes,
  - **CAPEK** CAPE in K Joules,
  - **HLCYH** Storm relative helicity in H Joules.
- Model covariates for **nT** and **nST** are
  - **CAPEK** and **HLCYH**.
- $\log(\mu) = \beta_0 + \beta_1 \text{LnT} + \beta_2 \text{CAPEK} + \beta_3 \text{HLCYH}$

Model Output for mTKET

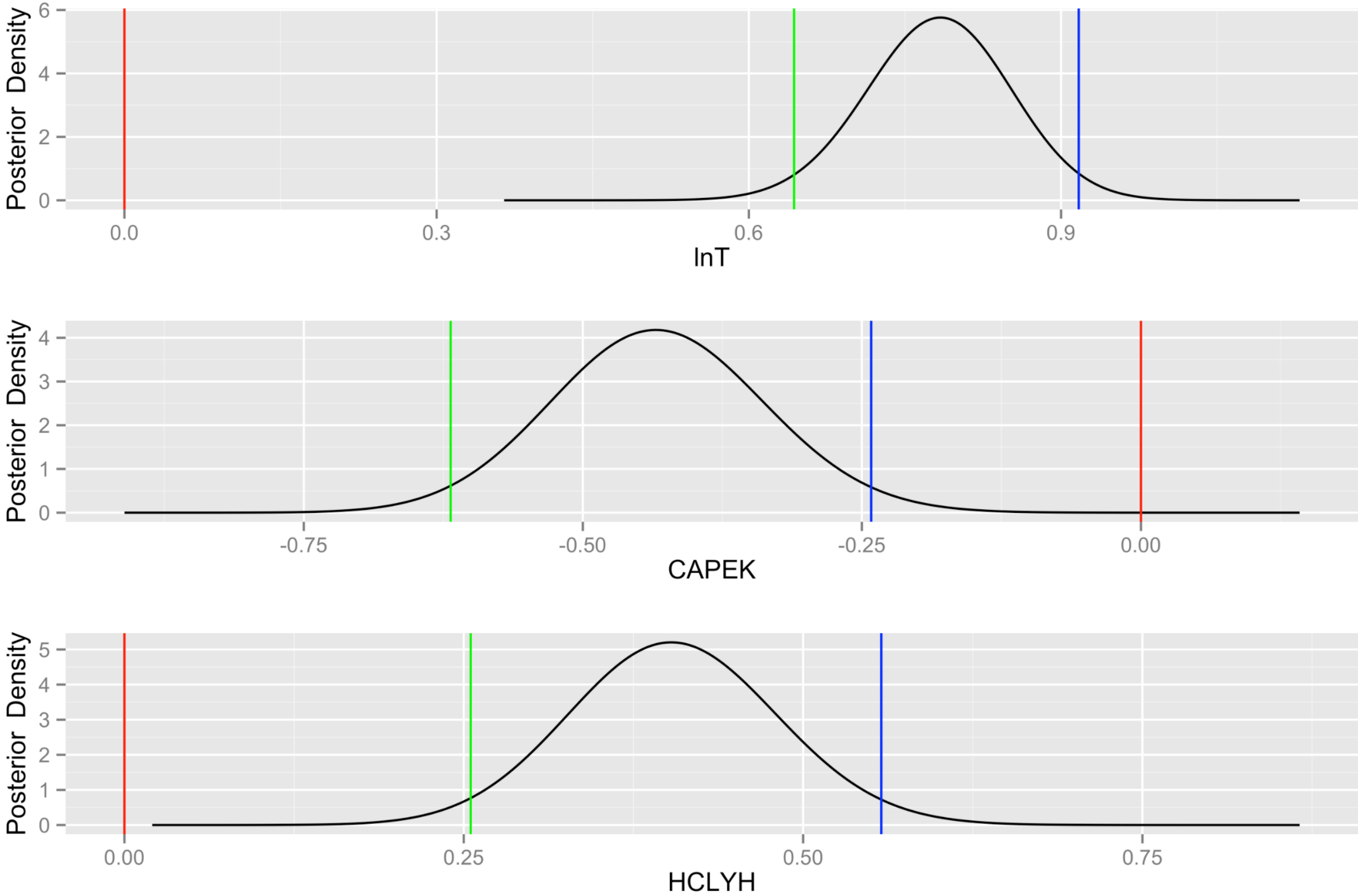
```
Fixed effects:
              mean    sd 0.025quant 0.5quant 0.975quant   mode kld
(Intercept) -2.690 0.234     -3.143   -2.693     -2.223 -2.697   0
lnT          0.782 0.069      0.643    0.783      0.916  0.784   0
CAPEK       -0.432 0.096     -0.618   -0.433     -0.242 -0.435   0
HLCYH        0.405 0.077      0.256    0.404      0.557  0.403   0

The model has no random effects

Model hyperparameters:
                                                 mean    sd 0.025quant 0.5quant
Precision parameter for the Gamma observations 0.563 0.026      0.513    0.563
                                               0.975quant  mode
Precision parameter for the Gamma observations      0.617 0.562

Expected number of effective parameters(std dev): 4.01(0.00)
Number of equivalent replicates : 158.27

Deviance Information Criterion: 825.34
Effective number of parameters: 4.65
```



Posterior Density
0
2
4
6
0.0
0.3
0.6
0.9
lnT
Posterior Density
0
1
2
3
4
-0.75
-0.50
-0.25
0.00
CAPEK
Posterior Density
0
1
2
3
4
5
0.00
0.25
0.50
0.75
HCLYH

Model Outputs for nT

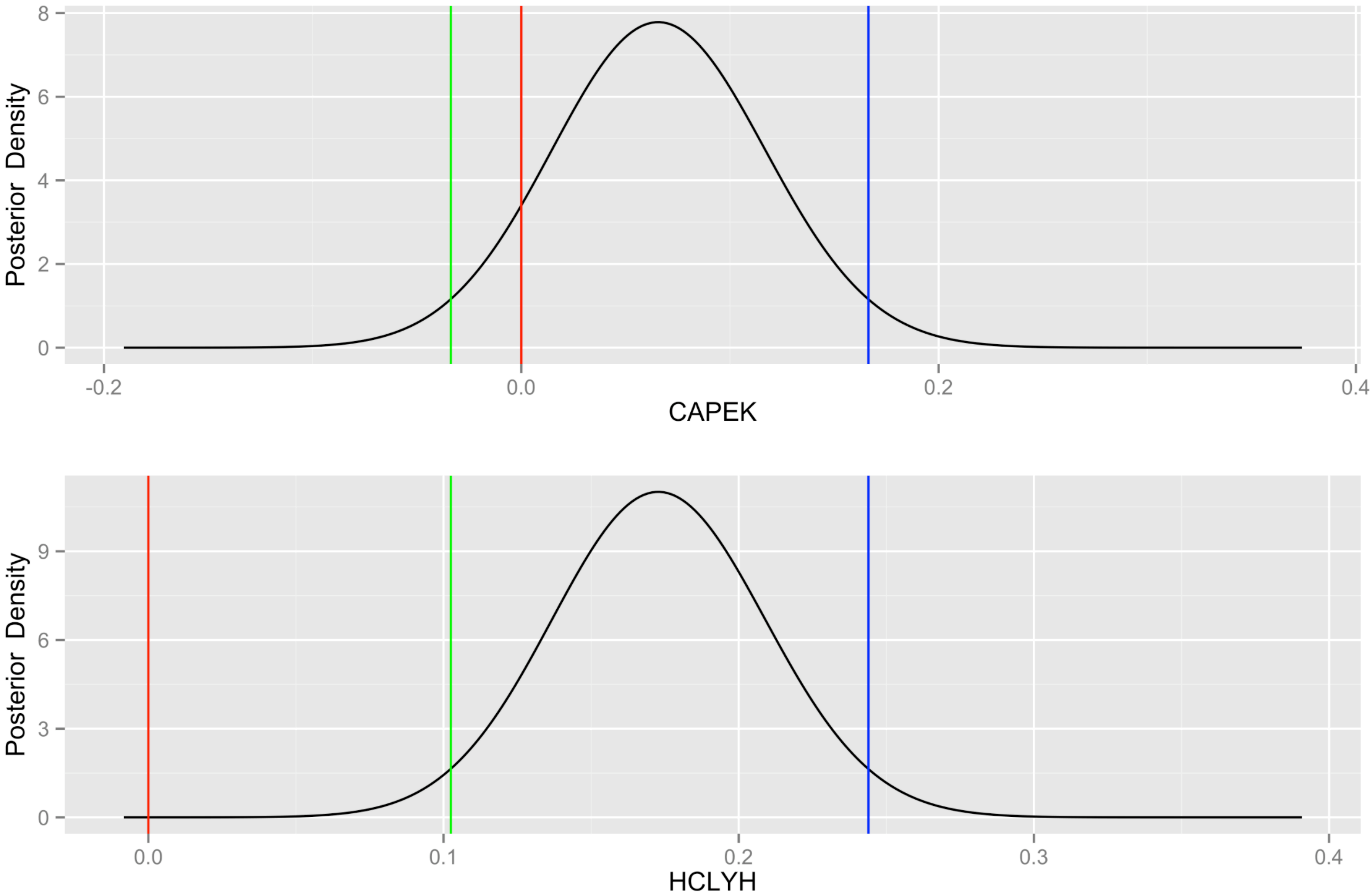
```
Fixed effects:
             mean    sd 0.025quant 0.5quant 0.975quant  mode kld
(Intercept) 2.760 0.084      2.595    2.760      2.926 2.760   0
HLCYH       0.173 0.036      0.102    0.173      0.245 0.173   0
CAPEK       0.066 0.051     -0.034    0.066      0.167 0.066   0

The model has no random effects

Model hyperparameters:
                                                        mean    sd 0.025quant
size for the nbinomial observations (overdispersion) 2.63 0.166       2.32
                                                     0.5quant 0.975quant mode
size for the nbinomial observations (overdispersion)     2.63       2.98 2.62

Expected number of effective parameters(std dev): 3.02(0.001)
Number of equivalent replicates : 209.61

Deviance Information Criterion: 4999.01
Effective number of parameters: 3.67
```



Posterior Density
8
6
4
2
0
-0.2
0.0
0.2
0.4
CAPEK
Posterior Density
9
6
3
0
0.0
0.1
0.2
0.3
0.4
HCLYH

Discussion

- 1800Z mean cape and mean helicity significantly related to mean TKE, controlling for the number of tornadoes.
  - leads to -35% and 50% in posterior mean TKE for each 1000 J/Kg increase in CAPE and 100 J/Kg helicity.
  - Using the logarithm of nT, negates needing to model both mean TKE and total TKE.
- Helicity is strongly related to number of storms and strong storms per cluster.
  - Cape is marginally related.
  - leads to 7% and 19% in posterior mean nT and 16% and 83% in posterior mean nST respectively with each 1000 Joule increase in cape and 100 J helicity, controlling for the other covariate.

Summary

- Using cluster methods we can separate groups for further study.
  - The **fpc** package with the **pamk()** function was used for medoid clustering.
  - The clustering algorithm runs quickly, so is suitable for data sets in which you may want to perform many clusters.
    - We had over 500 cluster days with 634 clusters.
    - We had (400,84,7,5,3,1,1) days with (1,2,3,4,5,7,8) clusters respectively.
- Interesting findings within relationships inside clusters:
  - While CAPE is required for storms to form, the observed cape within clusters seems to be negatively related to TKE.
  - Increasing HLCY seems to increase both the number of tornadoes, and the mean TKE a measure of efficiency of tornado production.

Future Reseach

- Better identification of tornadoes and tornado clusters.
  - Outlier detection and removal.
- Better selection of geographical areas associated with each region of an outbreak.
  - Non convex regions possibly defined by level sets of tornado density estimates.
- Addition of other variables.
  - Storm shear in the environment.
  - Storm size in clustering algorithm.

Thank you for your time.

Analysis and Talk on http://rpubs.com/thjagger/

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