2011 Atlantic Tropical Cyclone Outlook

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Summary of 2011 Forecast Results

The 2011 Atlantic hurricane season is forecast to be more active than the 1950-2000 average, but slightly less than the 2010 season. Specific predictions are:

1. Expected number of tropical cyclones (tropical storms and hurricanes) developing in the Atlantic basin: 13-16 (1950-2000 average: 9.6);
2. Expected number of hurricanes developing in the Atlantic basin: 7-9 (1950-2000 average: 6);
3. Expected number of major hurricanes in the Atlantic basin: 3-5 (1950-2000 average: 2.3);
4. Expected number of tropical cyclones in the Gulf of Mexico: 3-5;
5. Expected number of hurricanes in the Gulf of Mexico: 1-3;
6. Expected number of major hurricanes in the Gulf of Mexico: 0-1;
7. Number of tropical cyclones making landfall along the US Gulf coast: 2-4. There is a 97% chance at least one tropical cyclone will strike the US Gulf Coast, which reduces to 72% for a hurricane and 45% for a major hurricane;
8. There is a 70% chance at least one tropical cyclone will strike the US Southeast coast. This probability reduces to about 40% for a hurricane, and approximately 15% for a major hurricane;
9. There is a 30% chance at least one tropical cyclone will make landfall along the US Northeast coast. The chance reduces to about 12% for that storm to be a hurricane. The chance for a major hurricane to make landfall in the Northeast US coast is historically small, and is essentially unpredictable due to insufficient data sample.

Note: Atlantic hurricane season starts on June 1, and ends on November 30. Atlantic basin includes the Gulf of Mexico and the Caribbean Sea. Northeast coast extends from Virginia to Maine. Southeast coast covers the coastal region of the east coast of Florida to North Carolina.

1 Data

We forecast the number of storms that either form in a particular area of the Atlantic Basin or make landfall to a particular stretch of the US coastline. Information to obtain historical counts is available from the National Hurricane Center at http://www.nhc.noaa.gov/pastall.shtml#hurdat, or http://weather.unisys.com/hurricane/atlantic/index.html. The data lists tropical systems in the Atlantic since 1851. To train our model we use past storm counts from 1950 to 2010. We utilize various weather indices to assist in the prediction of the counts for an upcoming hurricane season. We obtain these monthly indices from http://www.cdc.noaa.gov/data/climateindices/ and include Atlantic Meridional Mode (AMM), Atlantic Multidecadal Oscillation (AMO), Atlantic Warm Pool (AWP), Dipole Mode (DM), Tropical Northern Atlantic (TNA), Tropical Southern Atlantic (TSA), Western Hemisphere Warm Pool (WHWP), and a representation of El Niño-Southern Oscillation (ENSO). AMM is calculated from sea surface temperature (SST) datasets over the region between 21S to 32N and 74W to 15E. AMO is a time series calculated from the Kaplan SST dataset that is an index on North Atlantic temperatures. This detrended time series is a weighted average of SSTs between latitudes 0 and 70N. The AWP is a weighted average of SSTs between latitudes 6 and 30N and longitudes 10 and 100W. DM is the difference in average SST over two locations in the Atlantic. Box 1 is the area within latitude 4 to 24N and longitude 16 to 60W. Box 2 is the area within latitude 4 to 24S and longitude 30W to 12E. TNA is the anomaly of the average of the monthly SST from 5.5N to 23.5N and 15W to 57.5W. TSA is the anomaly of the average of the monthly SST from Equator to 20S and 10E to 30W. The WHWP is the monthly anomaly of the ocean surface area warmer than 28.5C in the Atlantic and eastern North Pacific. To represent ENSO we use the anomalies for regions one and two, referenced NINO1.2. For estimating the upcoming number of storms we use the forecast NINO1.2 values for the upcoming hurricane season.

2 Methods

Our goal is to estimate the expected number of tropical cyclones (TC), hurricanes (H) and major hurricanes (MH) to form or make landfall in a particular area, represented by λ_i for i=1,…,18. Forecasts are made for TC, H, and MH counts and landfalls as listed in Table 1. TC includes tropical storms, hurricanes, and major hurricanes; H includes tropical storms and category 1-2 hurricanes; MH includes category 3-5 hurricanes.

Table 1: *2011 Forecast Regions*

Storm Counts	Landfalls
Gulf of Mexico basin	Gulf coast
Caribbean basin	Southeast coast[2]
Atlantic basin[1]	Northeast coast[3]

[1] The Atlantic, Gulf of Mexico and the Caribbean
[2] East coast of Florida to the North Carolina/Virginia border
[3] North Carolina/Virginia border through Maine

2.1 Statistical Model

We use the statistical model of log-linear regression, which assumes the $\log(\lambda_i)$ to be linearly related to the selected climate indices. We chose which months to include for the indices following research of Keith and Xie (2009). Once the months for each index are selected, the averages of the values are calculated to create a single representative value from each index. Before implementing the regression we examine the correlations between the climate indices. All values, except TSA and NINO1.2, showed strong correlation to each other. To alleviate this issue, we perform a principle component analysis (PCA) on the remaining indices. A PCA takes many correlated values and reduces them into fewer uncorrelated values. These values are organized by the amount of variability explained in the data. We incorporate the first principle component (PC1), TSA, and NINO12 into our regression statement and the log of our response is modeled as

$$\log(\lambda) = \beta_0 + \beta_1(PC1) + \beta_2\,(TSA) + \beta_3(NINO12) + \varepsilon,$$

where β_0 is the intercept; β_1, β_2, and β_3 are the regression coefficients; and ε is the random error. Using the data from previous years, the coefficients for PC1, TSA, and NINO12 are estimated using maximum likelihood methods. With these estimates, we then use the current climate index values (listed in table 2) to predict the values of $\log(\lambda_i)$. The forecast values for NINO12 are obtained from the National Centers for Environmental Protection (NCEP) coupled forecast system (CFS) model as seen in Figure 1 (a).

Table 2: *Values of climate indices used in forecast*

Index Name	Months Averaged Over	Index Value
AMM	January 2011, February 2011, March 2011	3.89
AMO	January 2011, February 2011	0.17
DM	January 2011, February 2011, March 2011	0.31
NAO	January 2011, February 2011, March 2011	0.14
NINO1.2*	July 2011, August 2011, September 2011	0.25
TNA	January 2011, February 2011	0.80
TSA	November 2010, December 2010, January 2011	0.43
WHWP	August 2010, September 2010, October 2010, November 2010	3.35

* Forecast

2.2 Ensemble Approach

To help account for uncertainty in the NINO1.2 forecast and sensitivity to certain climate indices we adopt an ensemble approach. We use four models and create 12 forecasts each. The models vary based on AMM and NAO and the 12 forecasts arise from varying the value for NINO1.2. Table 4 shows the models fit and gives the 2011 values. Model 1 is described in section 2.1.

In section 2.1 we reference the NCEP CFS model. This model has been updated with a second version (CFSv2). Figure 1 (a) and (b) show the ensemble forecasts for CFS and CFSv2, respectively. Due to the discrepancy between models and the variability of the ensembles from each model we create forecasts from each of the models for 12 NINO12 values. We choose 10 values equally spaced over the overall range of CFS and CFSv2 (-0.51, -0.25, 0.00, 0.26, 0.51,

0.77, 1.02, 1.28, 1.53, 1.79) and include additional values based on the ensemble mean of CFS and the ensemble mean of CFSv2 (0.19 and 0.50, respectively). We then average over our 48 ensemble members to make a single forecast.

Table 3: *Different models based on AMM and NAO and the 2011 values*

	AMM averaged over January, February, March	AMM averaged over January, February
NAO averaged over January, February, March	Model 1 AMM=3.89; NAO=0.14	Model 2 AMM=5.16; NAO=0.14
NAO March	Model 3 AMM=3.89; NAO=0.61	Model 4 AMM=5.16; NAO=0.61

3. Results

3.1 Single Forecast

Once the values of λ have been calculated using the methodology of section 2.1, we compare our forecasts with climatology as seen in Figured 2-10 (in gold). We use three climatology values: 1950-2010 (>50 year average), 1991-2010 (20 year average), and 1996-2010 (15 year average). Using the normal approximation, we also create 95% prediction intervals for the $\log(\lambda_i)$. We transform back to the scale of the data by exponentiating the estimates and bounds. This does result in non-symmetric prediction limits, but is still a 95% interval since the exponential function is monotone. The estimated number of storms (λ_i) and the lower and upper bounds are listed in Table 4. Significant differences between climatology and the forecast values are validated through the 95 percent prediction intervals. If a climatology value falls within this interval, we say that the forecast is not significantly different from the climatology. Estimates based on climatology are listed in Table 5.

Table 4: *Estimates and 95% prediction intervals for tropical cyclones in the Atlantic using the model of section 2.1*

Category		Lower Limit	Estimate	Upper Limit
Gulf Coast Landfalls	Tropical Cyclone	2.27	3.26	4.68
	Hurricane	0.71	1.25	2.19
	Major Hurricane	0.26	0.61	1.41
Southeast Landfalls	Tropical Cyclone	0.76	1.23	2.00
	Hurricane	0.30	0.58	1.12
	Major Hurricane	0.05	0.16	0.49
Northeast Landfalls	Tropical Cyclone	0.16	0.35	0.80
	Hurricane	0.03	0.11	0.44
	Major Hurricane	0.00	0.00	0.24
Atlantic Storms	Tropical Cyclone	12.18	14.48	17.22
	Hurricane	6.53	8.20	10.31
	Major Hurricane	3.05	4.26	5.95
Caribbean Storms	Tropical Cyclone	2.70	3.84	5.48
	Hurricane	1.71	2.68	4.22
	Major Hurricane	0.87	1.56	2.78
Gulf of Mexico Storms	Tropical Cyclone	3.29	4.49	6.13
	Hurricane	1.25	1.97	3.10
	Major Hurricane	0.47	0.95	1.90

Table 5: *Estimates and based on climatology*

Category		>50 year	20 year	15 year
Gulf Coast Landfalls	Tropical Cyclone	**2.16**	2.75	3.07
	Hurricane	0.95	1.05	1.20
	Major Hurricane	0.39	0.45	0.47
Southeast Landfalls	Tropical Cyclone	1.03	1.35	1.53
	Hurricane	0.62	0.75	0.80
	Major Hurricane	0.23	0.20	0.13
Northeast Landfalls	Tropical Cyclone	0.38	0.30	0.27
	Hurricane	0.15	0.05	0.00
	Major Hurricane	0.05	0.00	0.00
Atlantic Storms	Tropical Cyclone	**10.31**	12.70	13.73
	Hurricane	**6.18**	7.10	7.73
	Major Hurricane	**2.70**	3.25	3.73
Caribbean Storms	Tropical Cyclone	**2.39**	3.20	3.67
	Hurricane	**1.33**	1.90	2.40
	Major Hurricane	0.74	0.90	1.13
Gulf of Mexico Storms	Tropical Cyclone	**3.10**	3.80	4.27
	Hurricane	1.62	1.80	2.00
	Major Hurricane	0.67	0.70	0.80

*Estimates in boldface fall outside the 95% prediction intervals based on the single forecast in table 4.

3.2 Ensemble Forecast

Using the ensemble approach we run 48 separate forecasts for the 2011 hurricane season with the methods from section 2.1. We then create a single forecast by taking simple averages of the results (i.e. weighting each ensemble member equally). Figures 2 to 10 compare the ensemble (in black) forecast toe climatology. Table 6 provides the ensemble estimates obtained by averaging the 48 single estimates. The lower and upper bounds listed in Table 6 result from averaging the lower and upper bounds of the individual 95% prediction intervals. The ensemble forecast takes into account the variability in the NINO1.2 forecast. The spread of the 48 forecasts is displayed in Figures 11 to 28.

Table 6: *Estimates and 95% prediction intervals for tropical cyclones in the Atlantic using the model of section 2.1*

Category		Lower Limit	Estimate	Upper Limit
Gulf Coast Landfalls	Tropical Cyclone	2.27	3.44	5.23
	Hurricane	0.68	1.28	2.45
	Major Hurricane	0.23	0.60	1.62
Southeast Landfalls	Tropical Cyclone	0.70	1.23	2.19
	Hurricane	0.25	0.54	1.18
	Major Hurricane	0.04	0.15	0.54
Northeast Landfalls	Tropical Cyclone	0.14	0.35	0.91
	Hurricane	0.03	0.12	0.57
	Major Hurricane	0.00	0.00	0.31
Atlantic Storms	Tropical Cyclone	11.97	14.61	17.85
	Hurricane	6.25	8.13	10.59
	Major Hurricane	2.90	4.27	6.31
Caribbean Storms	Tropical Cyclone	2.56	3.86	5.85
	Hurricane	1.65	2.80	4.79
	Major Hurricane	0.79	1.56	3.12
Gulf of Mexico Storms	Tropical Cyclone	3.19	4.56	6.55
	Hurricane	1.14	1.92	3.24
	Major Hurricane	0.41	0.91	2.04

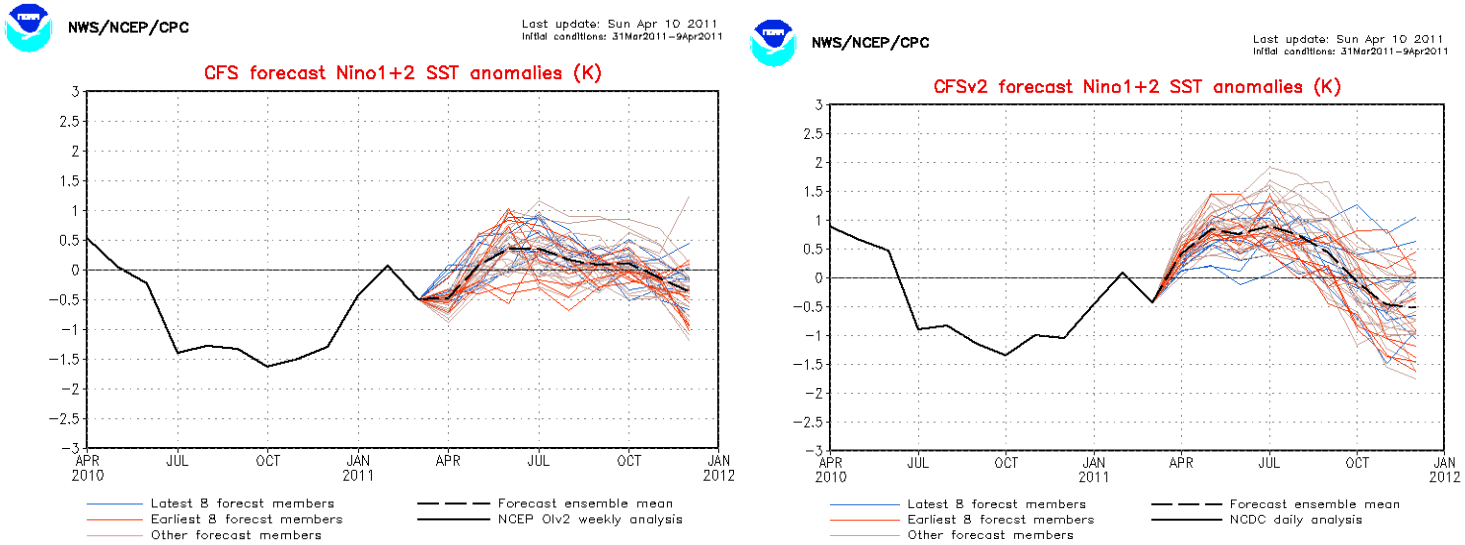

Figure 1: *Forecasted NINO12 from* (a) *NCEP CFS model*[1], (b) *NCEP CFSv2 model*[2]

[1] http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/ensoforecast.shtml

[2] http://www.cpc.ncep.noaa.gov/products/CFSv2/CFSv2seasonal.shtml

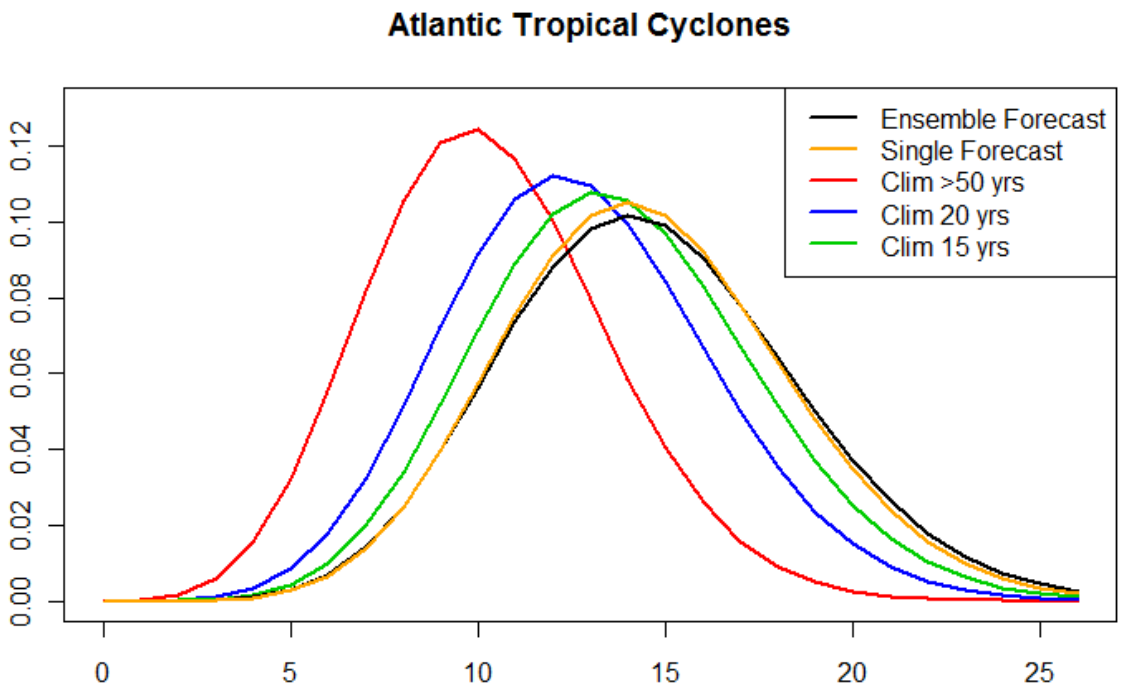

Figure 2: *Probabilities for the number of tropical cyclones in the Atlantic basin for 2011: single ensemble forecast (black), single forecast (gold), past 50 years climatology (red), past 20 years climatology (blue) and past 15 years climatology (green).*

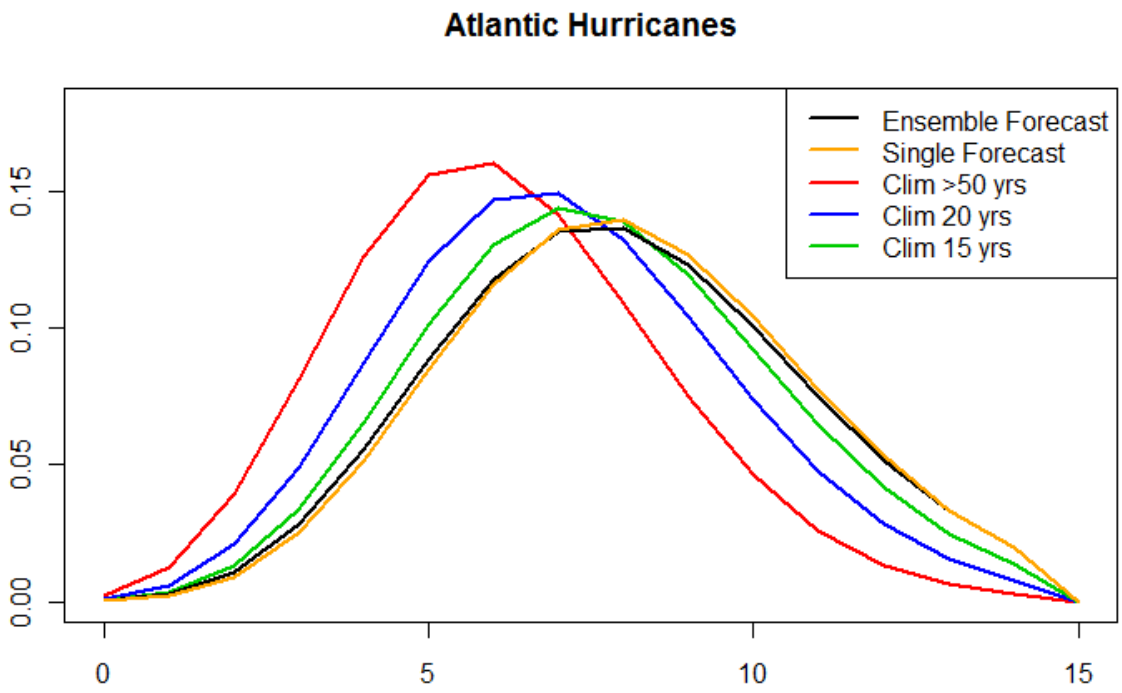

Figure 3: *Probabilities for the number of hurricanes in the Atlantic basin for 2011: single ensemble forecast (black), single forecast (gold), past 50 years climatology (red), past 20 years climatology (blue) and past 15 years climatology (green).*

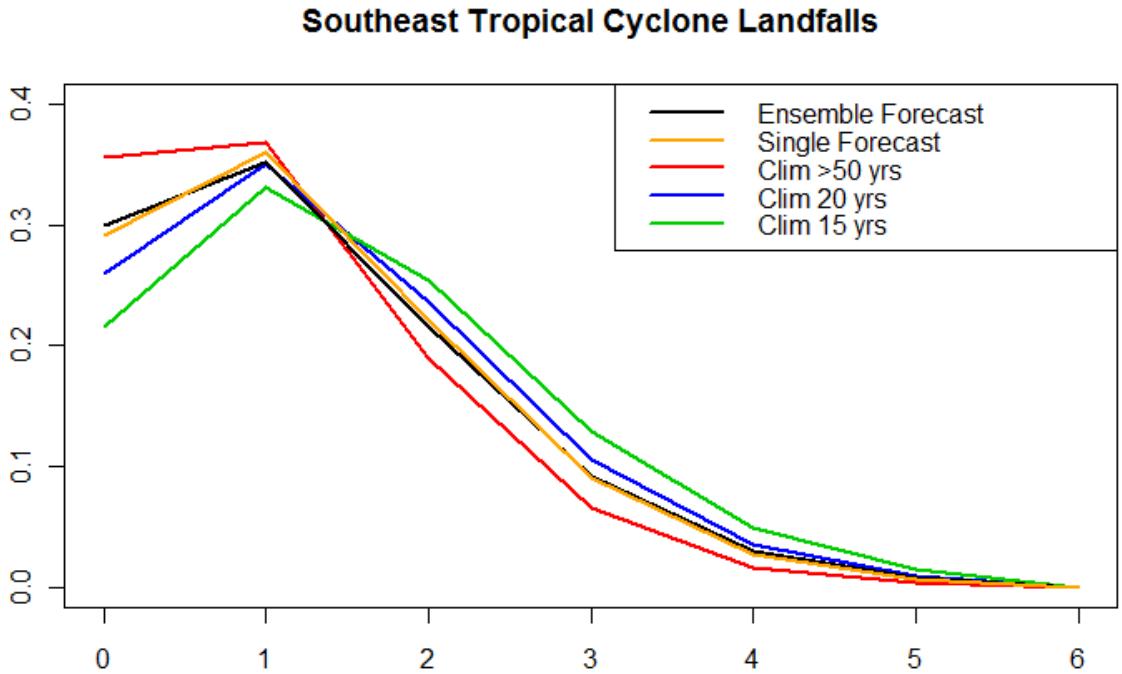

Figure 4: *Probabilities for the number of tropical cyclones landfalls on the southeast coast for 2011: ensemble forecast (black), single forecast (gold), past 50 years climatology (red), past 20 years climatology (blue) and past 15 years climatology (green).*

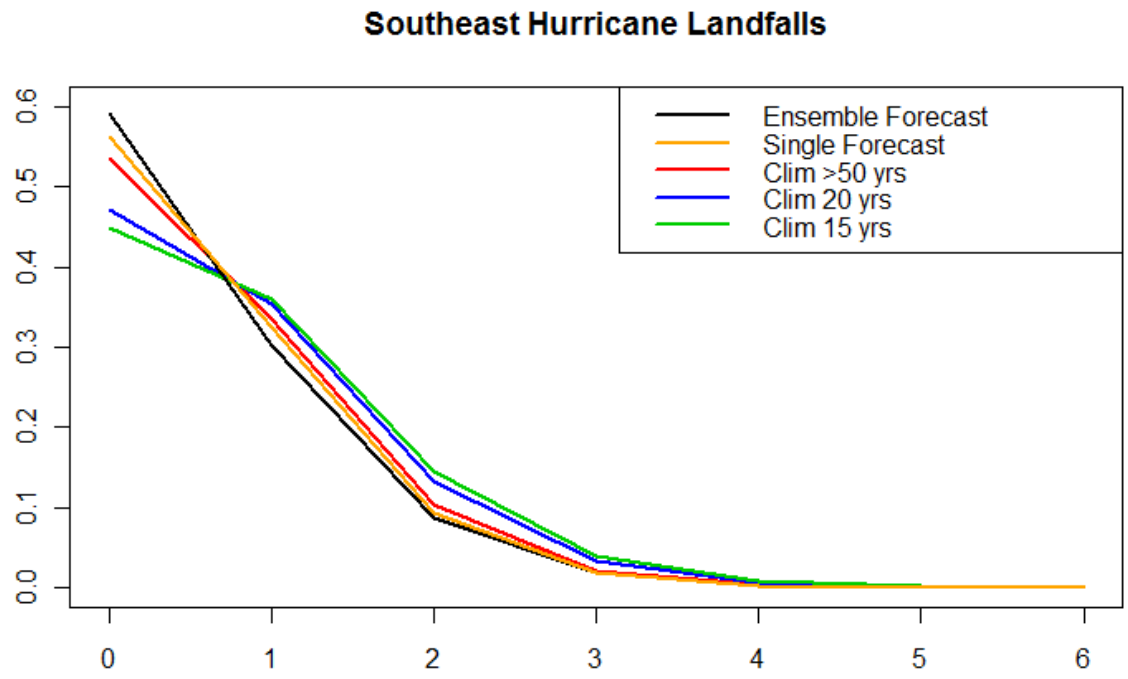

Figure 5: *Probabilities for the number of hurricane landfalls on the southeast coast for 2011: ensemble forecast (black), single forecast (gold), past 50 years climatology (red), past 20 years climatology (blue) and past 15 years climatology (green).*

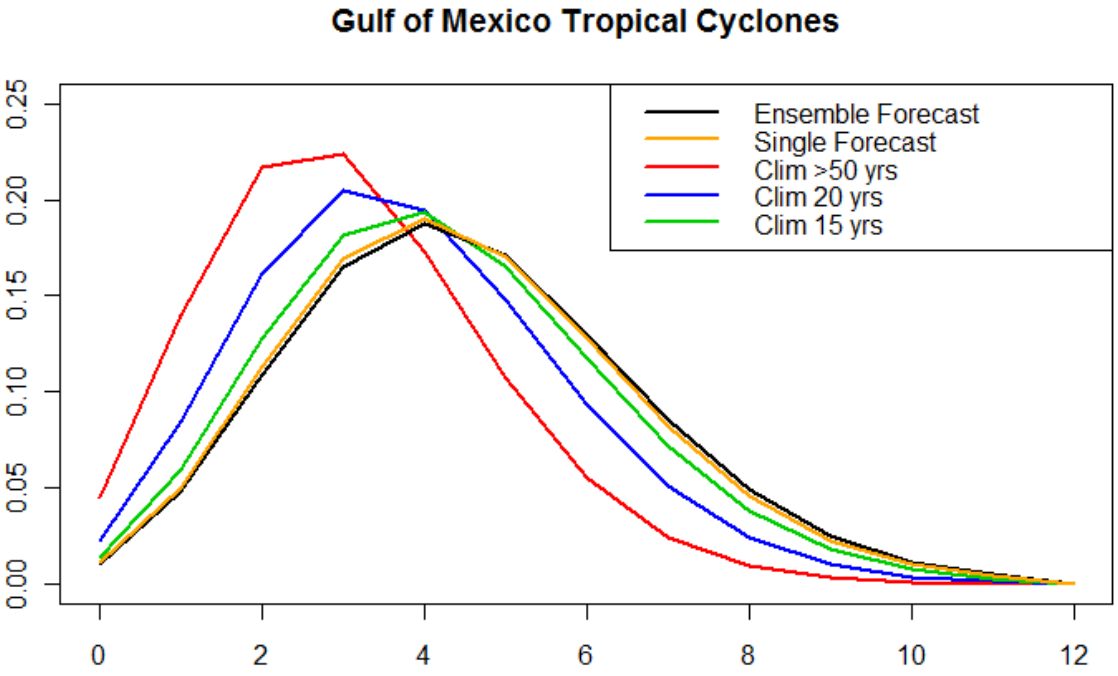

Figure 6: *Probabilities for the number of tropical cyclones in the Gulf Mexico for 2011: single ensemble forecast (black), single forecast (gold), past 50 years climatology (red), past 20 years climatology (blue) and past 15 years climatology (green).*

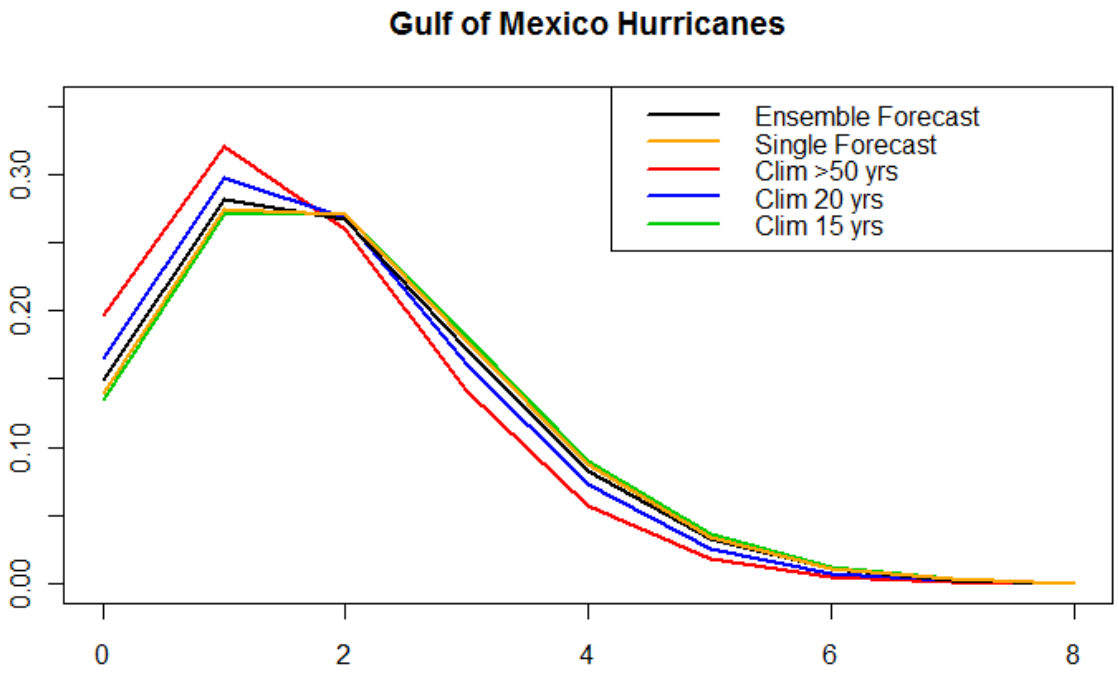

Figure 7: *Probabilities for the number of hurricanes in the Gulf Mexico for 2011: ensemble forecast (black), single forecast (gold), past 50 years climatology (red), past 20 years climatology (blue) and past 15 years climatology (green).*

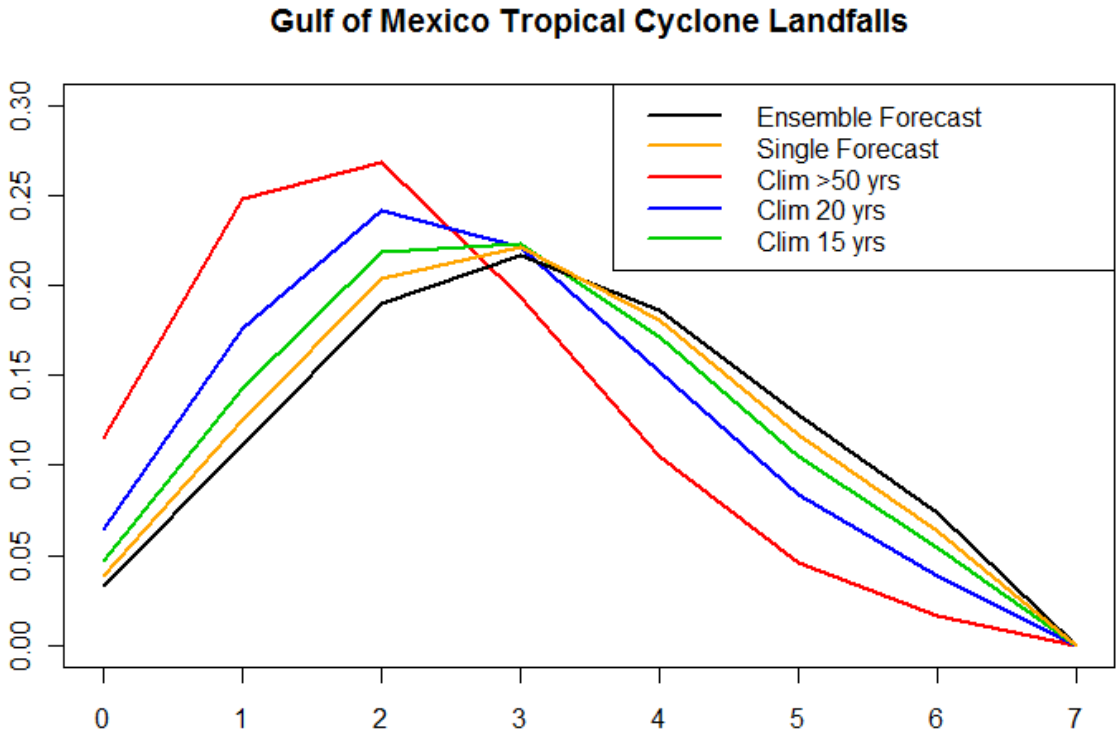

Figure 8: *Probabilities for the number tropical cyclone landfalls on the Gulf coast for 2011: ensemble forecast (black), single forecast (gold), past 50 years climatology (red), past 20 years climatology (blue) and past 15 years climatology (green).*

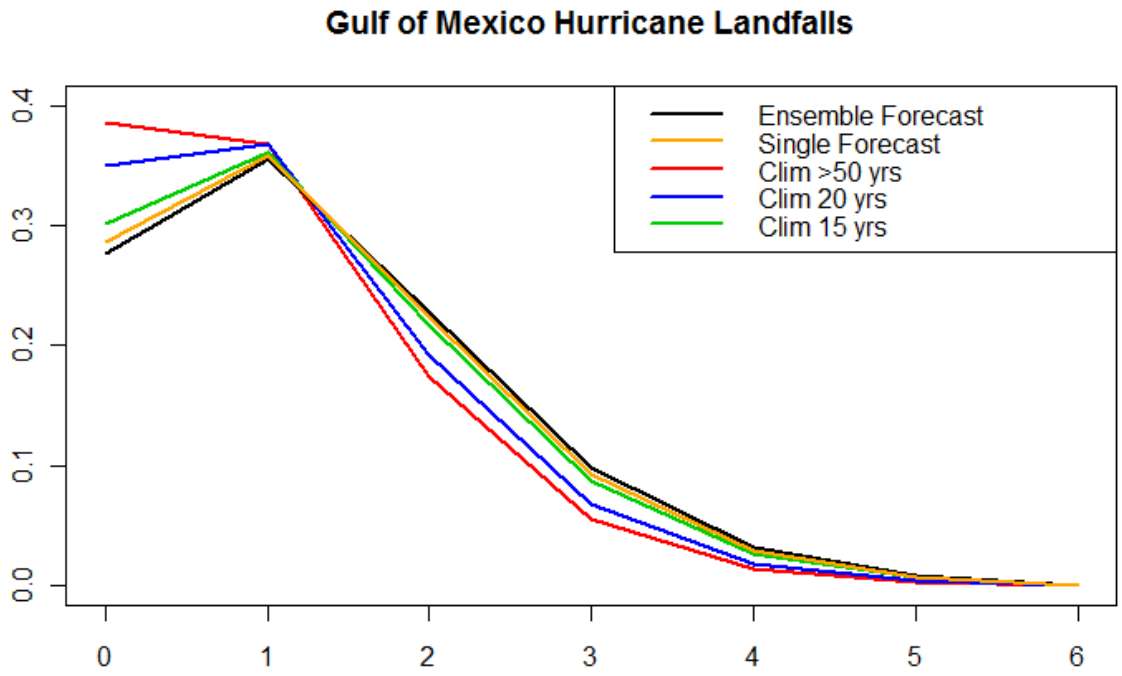

Figure 9: *Probabilities for the number hurricane landfalls on the Gulf coast for 2011: single ensemble forecast (black), single forecast (gold), past 50 years climatology (red), past 20 years climatology (blue) and past 15 years climatology (green).*

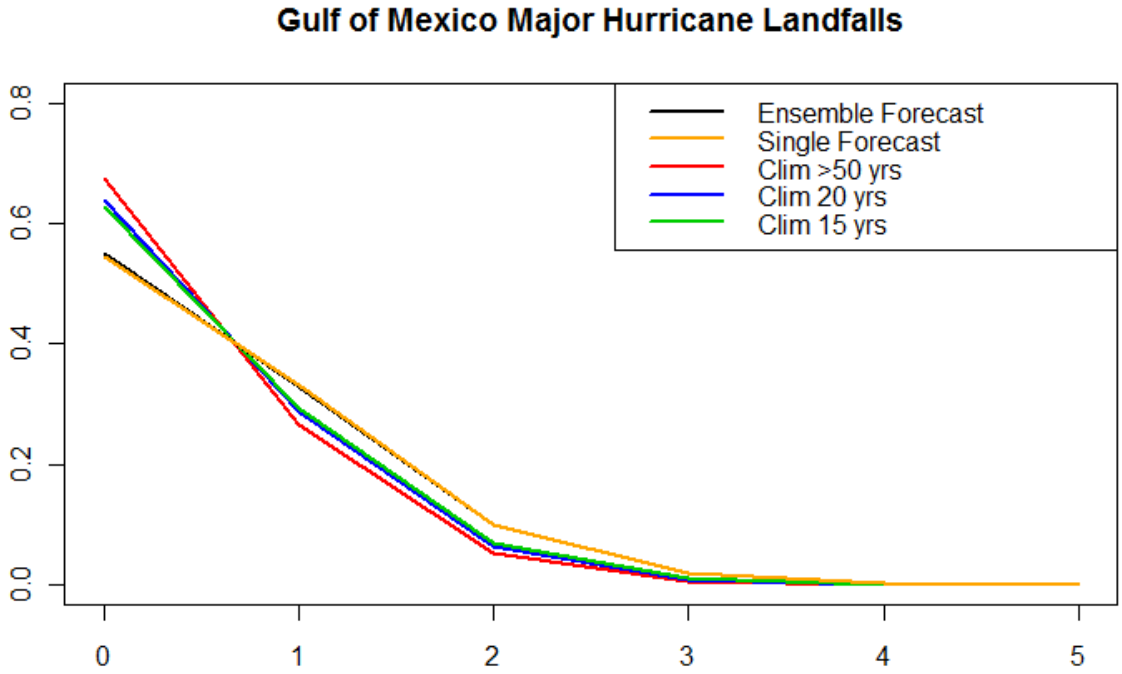

Figure 10: *Probabilities for the number major hurricane landfalls on the Gulf coast for 2011: ensemble forecast (black), single forecast (gold), past 50 years climatology (red), past 20 years climatology (blue) and past 15 years climatology (green).*

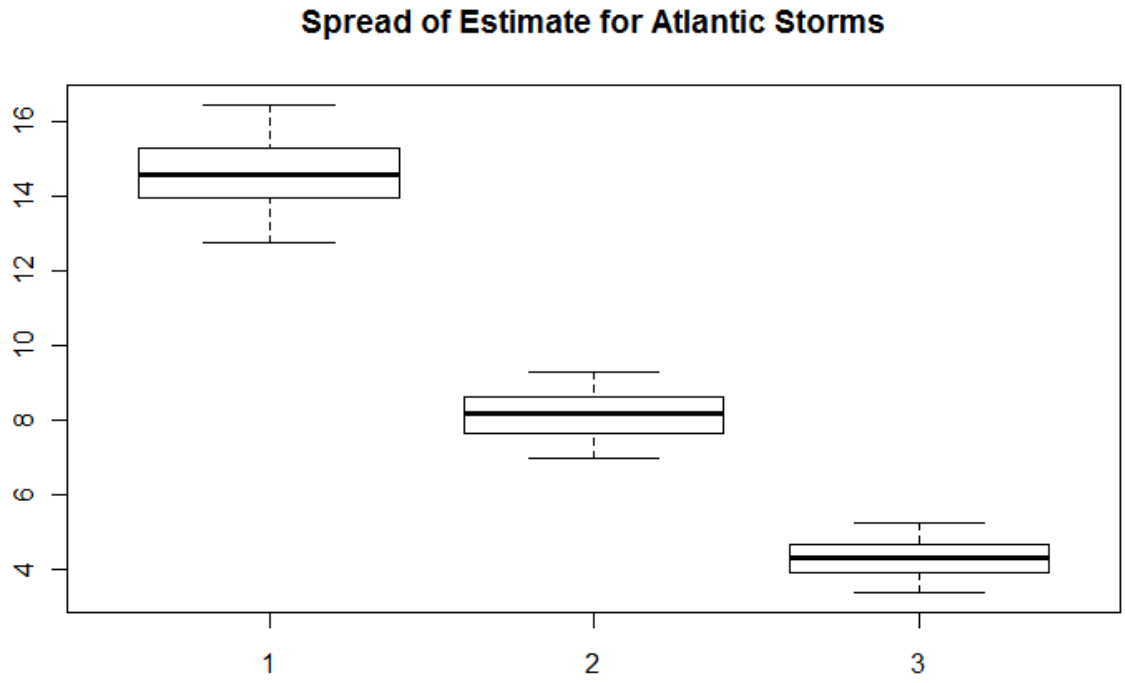

Figure 11: *Spread of ensemble estimates for Atlantic storms;* (1) *tropical cyclones,* (2) *hurricanes,* (3) *major hurricanes.*

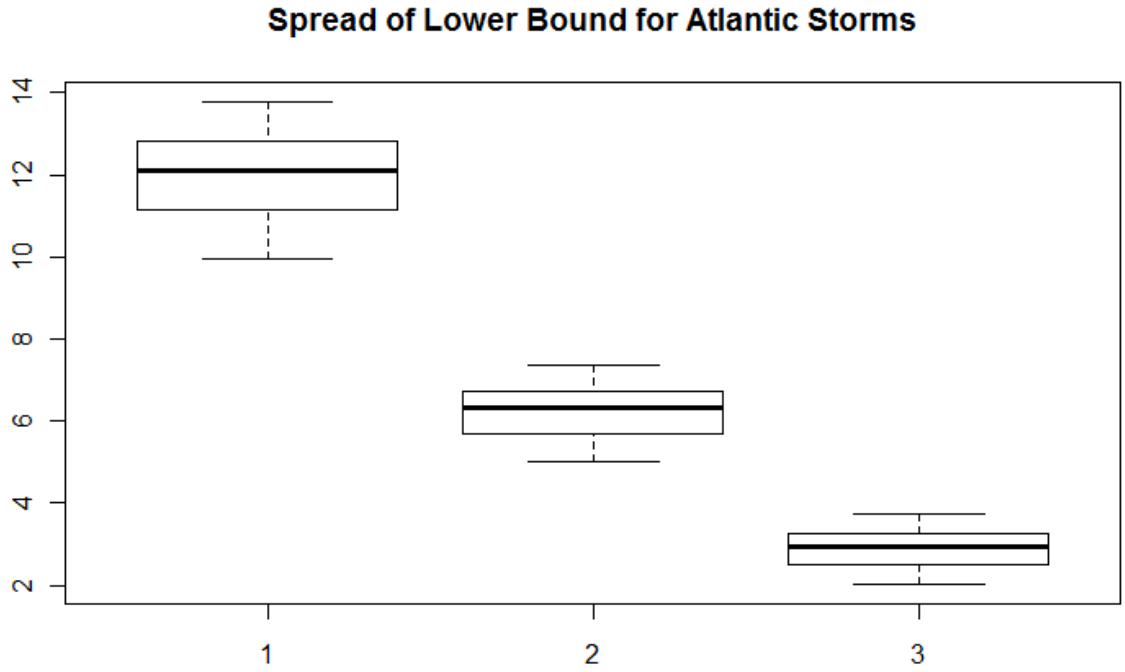

Figure 12: *Spread of ensemble lower bounds for Atlantic storms;* (1) *tropical cyclones,* (2) *hurricanes,* (3) *major hurricanes.*

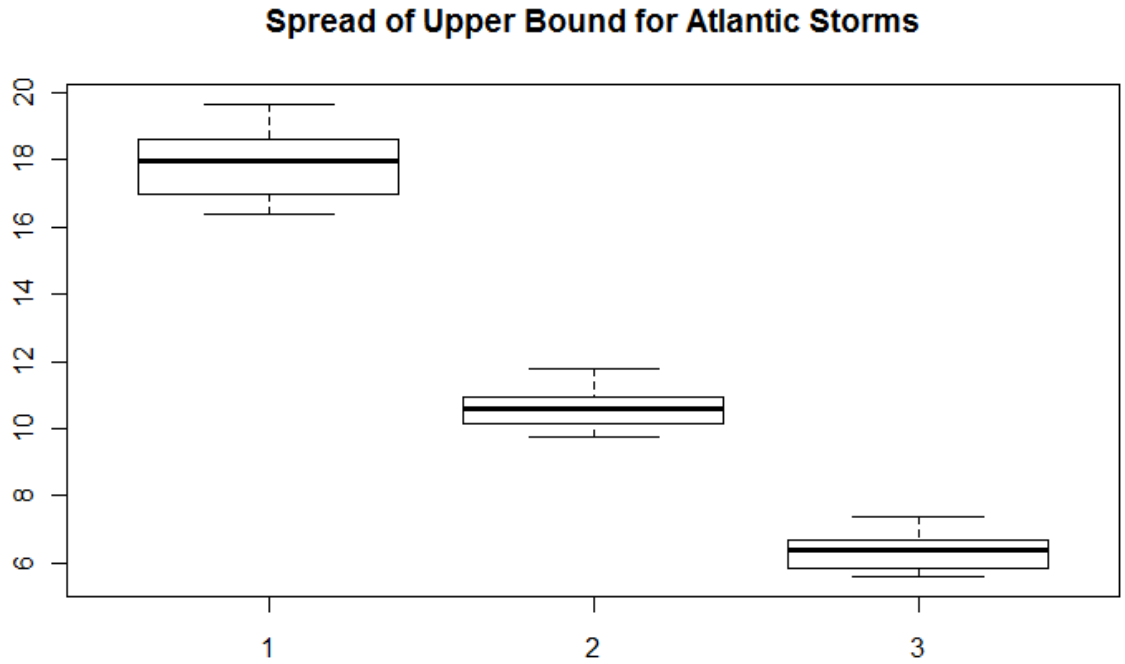

Figure 13: *Spread of ensemble upper bounds for Atlantic storms;* (1) *tropical cyclones,* (2) *hurricanes,* (3) *major hurricanes.*

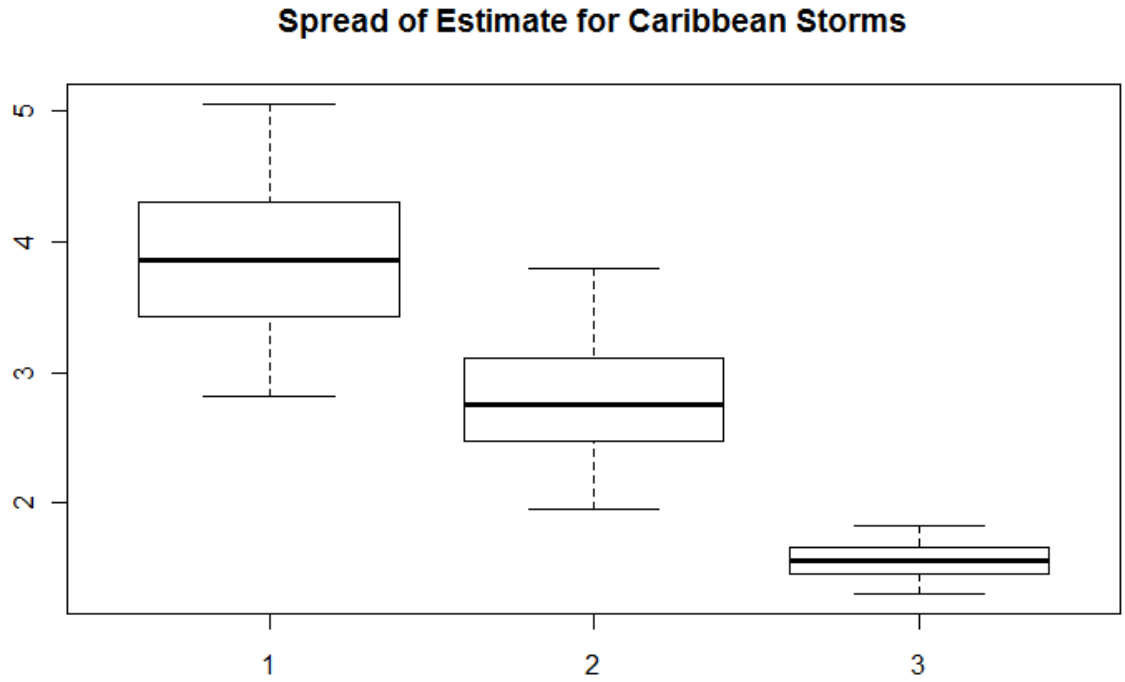

Figure 14: *Spread of ensemble estimates for Caribbean storms;* (1) *tropical cyclones,* (2) *hurricanes,* (3) *major hurricanes.*

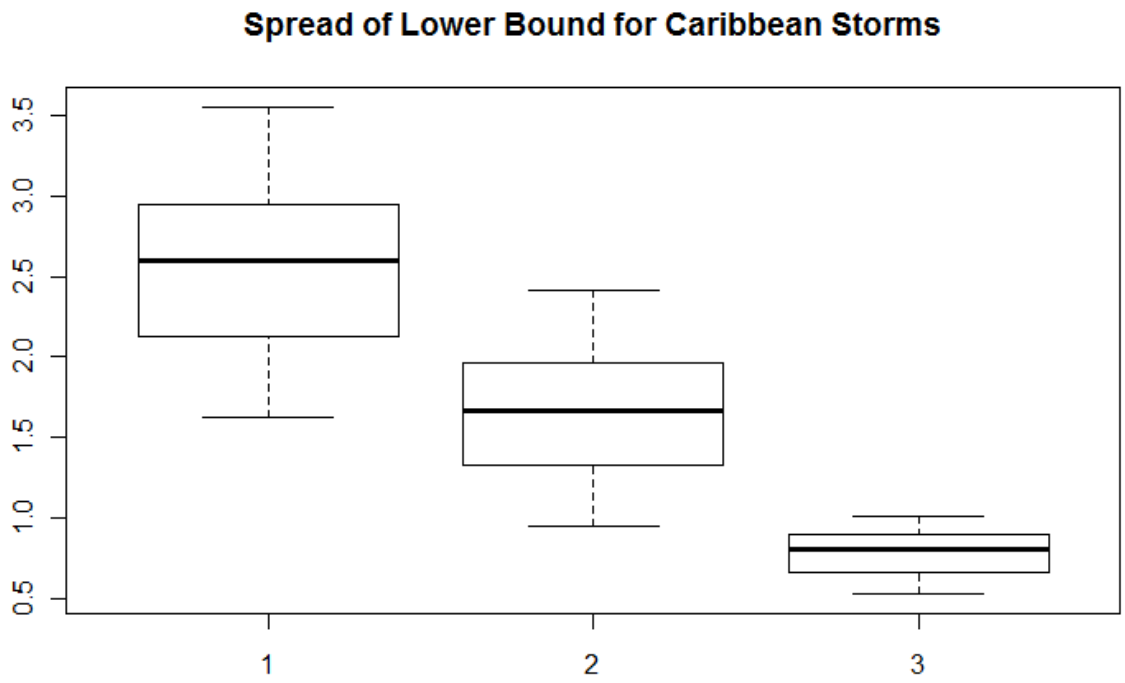

Figure 15: *Spread of ensemble lower bounds for Caribbean storms;* (1) *tropical cyclones,* (2) *hurricanes,* (3) *major hurricanes.*

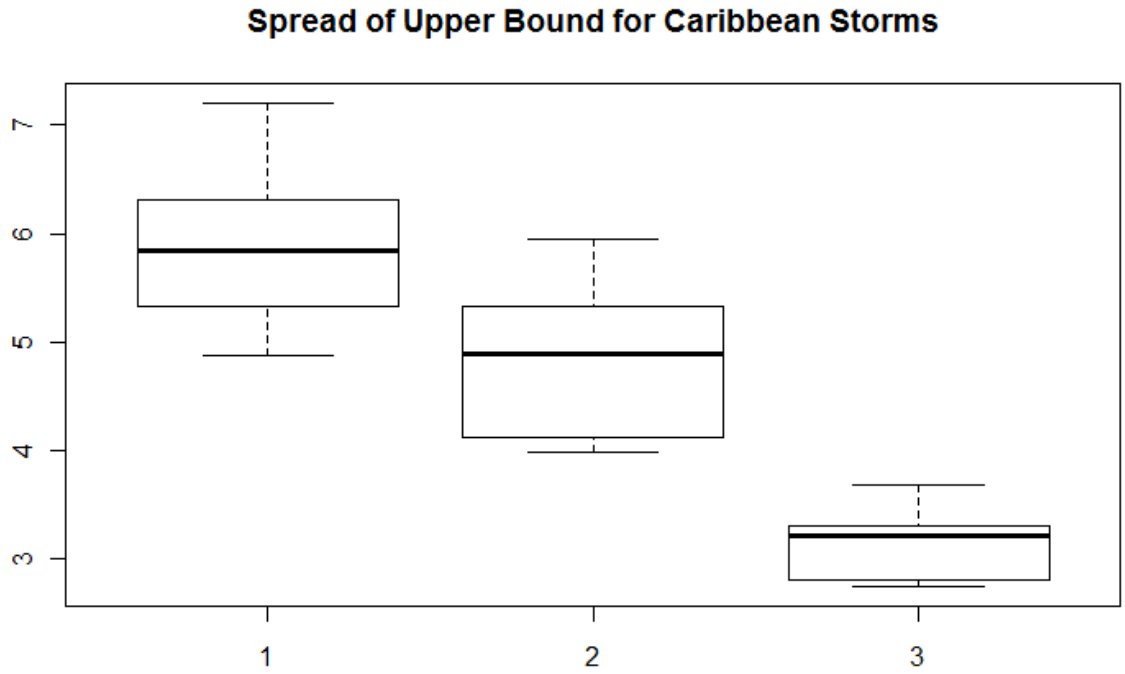

Figure 16: *Spread of ensemble upper bounds for Caribbean storms;* (1) *tropical cyclones,* (2) *hurricanes,* (3) *major hurricanes.*

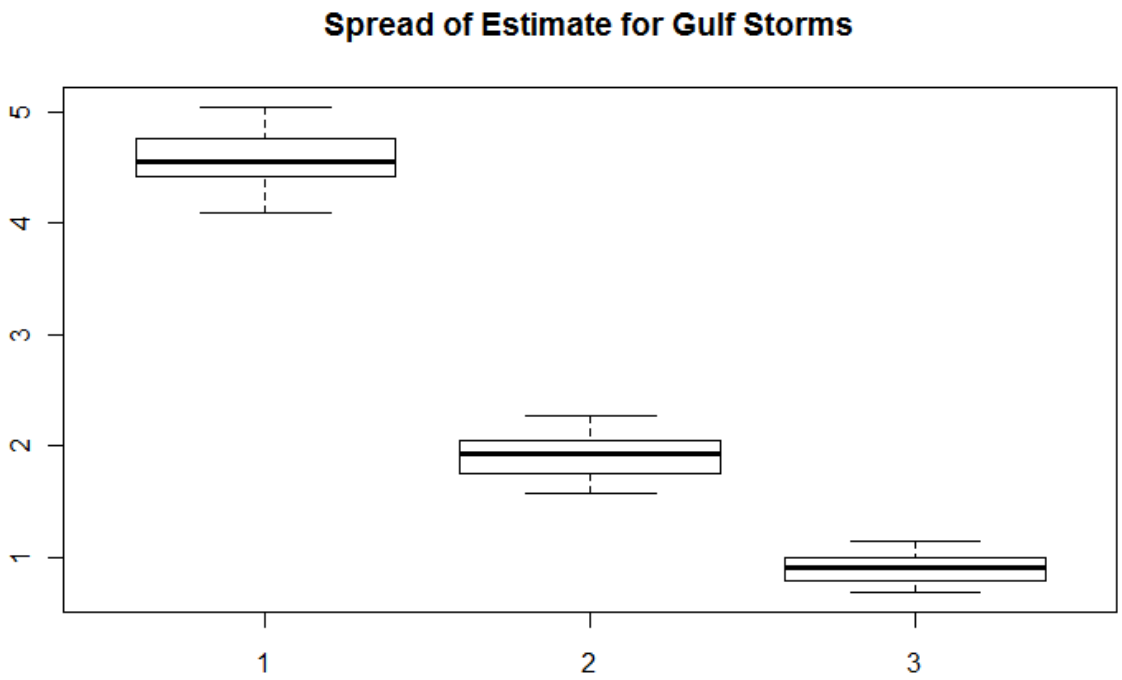

Figure 17: *Spread of ensemble estimates for Gulf of Mexico storms;* (1) *tropical cyclones,* (2) *hurricanes,* (3) *major hurricanes.*

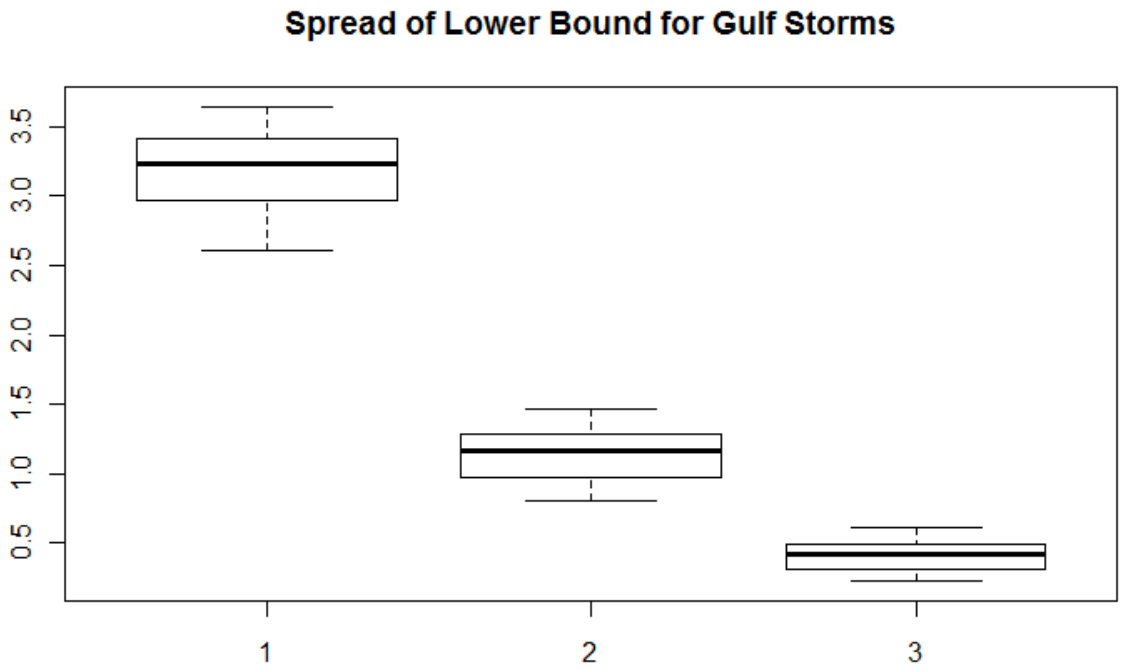

Figure 18: *Spread of lower bounds for Gulf of Mexico storms;* (1) *tropical cyclones,* (2) *hurricanes,* (3) *major hurricanes.*

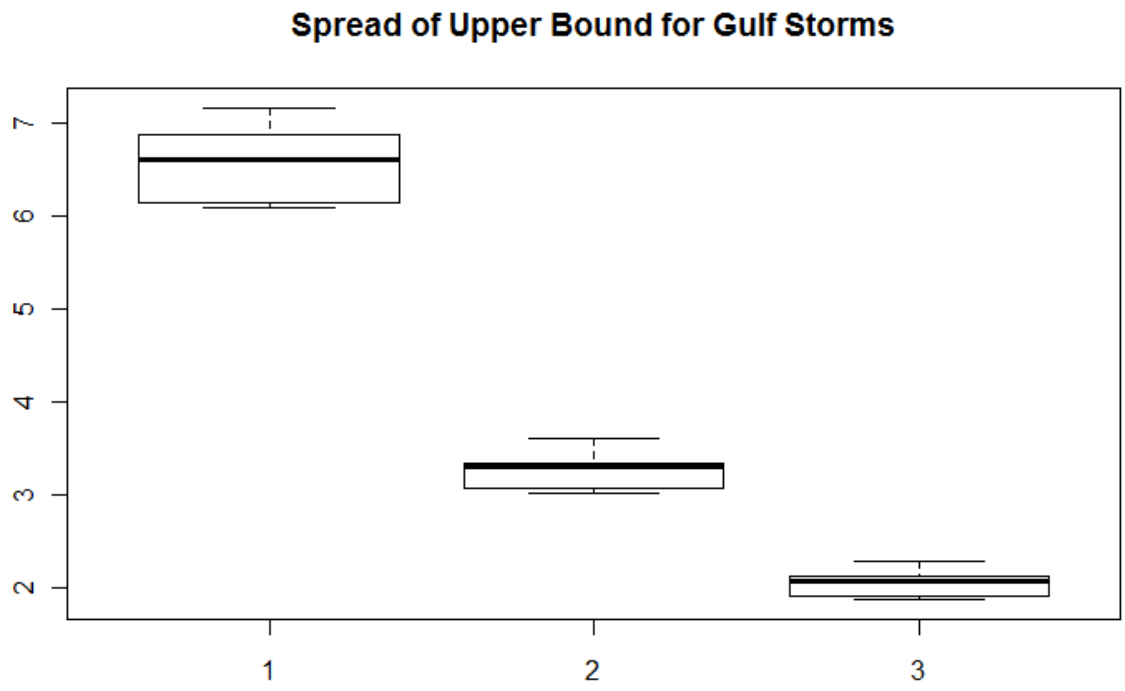

Figure 19: *Spread of upper bounds for Gulf of Mexico storms;* (1) *tropical cyclones,* (2) *hurricanes,* (3) *major hurricanes.*

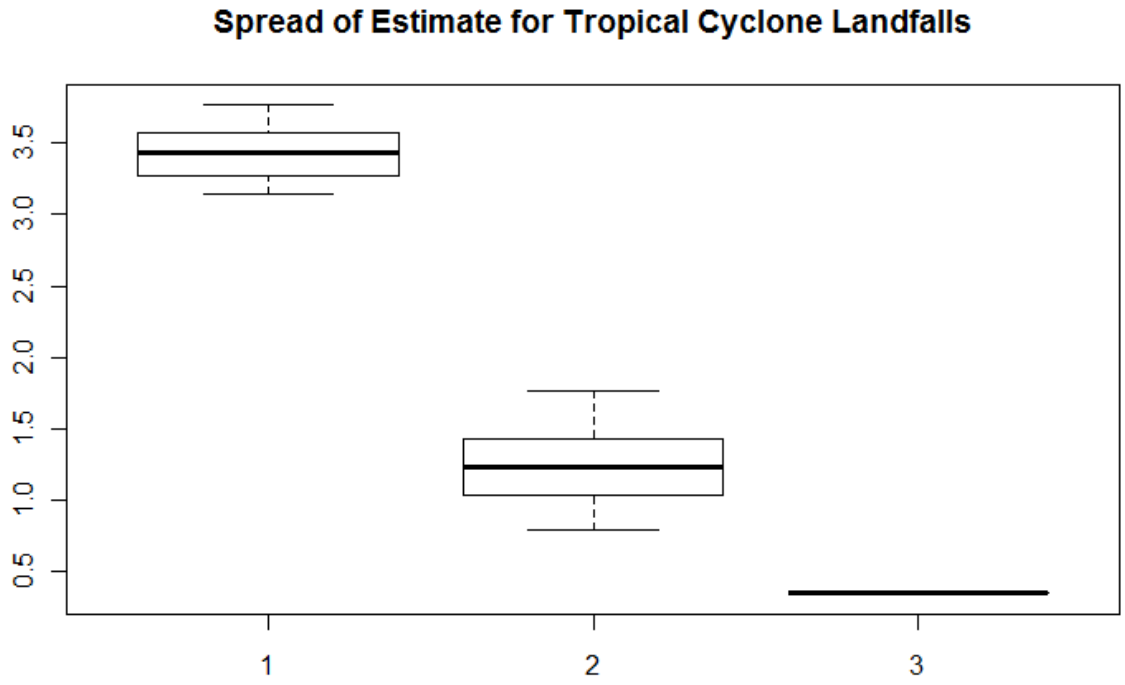

Figure 20: *Spread of estimates for tropical storm landfalls;* (1) *Gulf Coast,* (2) *Southeast Coast,* (3) *Northeast Coast.*

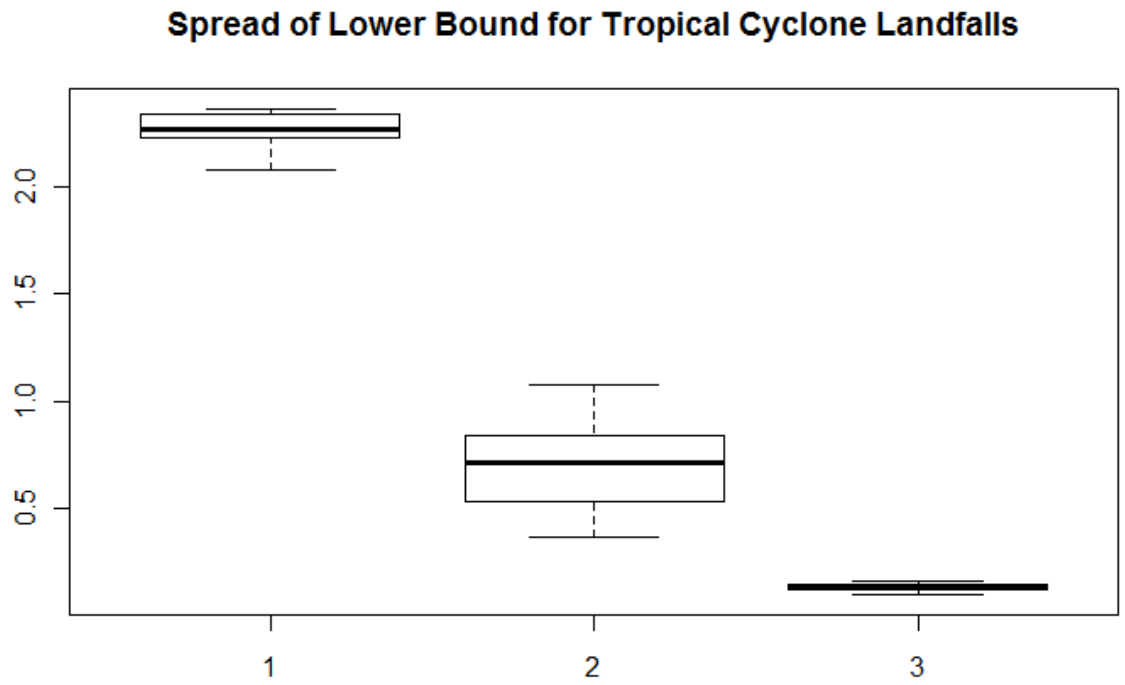

Figure 21: *Spread of lower bounds for tropical storm landfalls;* (1) *Gulf Coast,* (2) *Southeast Coast,* (3) *Northeast Coast.*

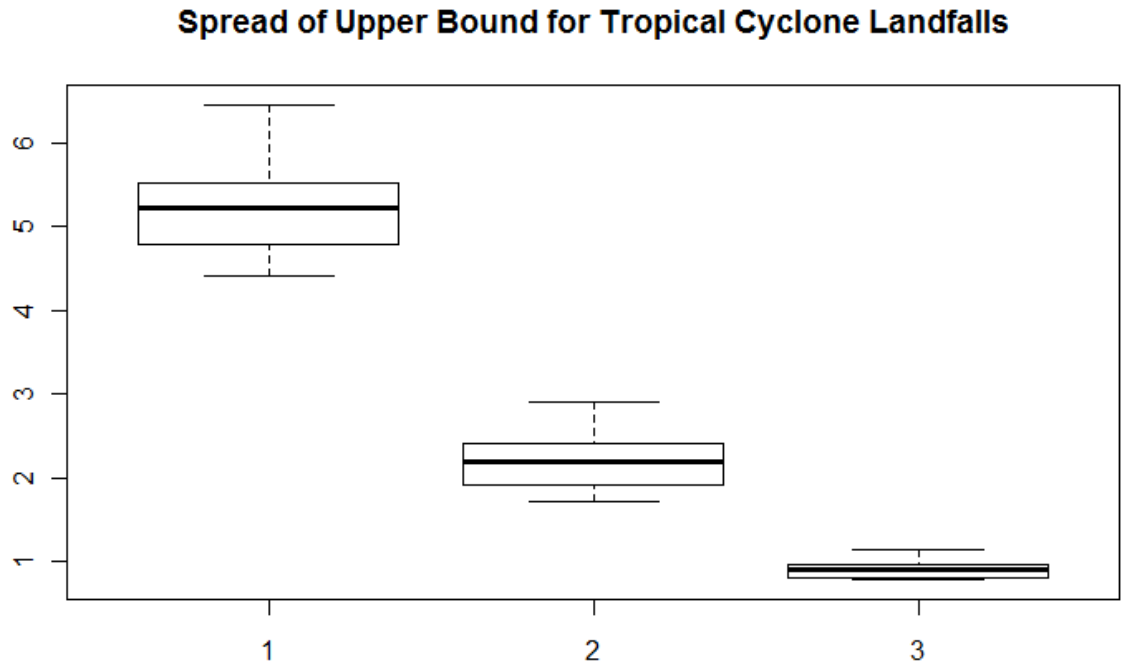

Figure 22: *Spread of upper bounds for tropical storm landfalls;* (1) *Gulf Coast,* (2) *Southeast Coast,* (3) *Northeast Coast.*

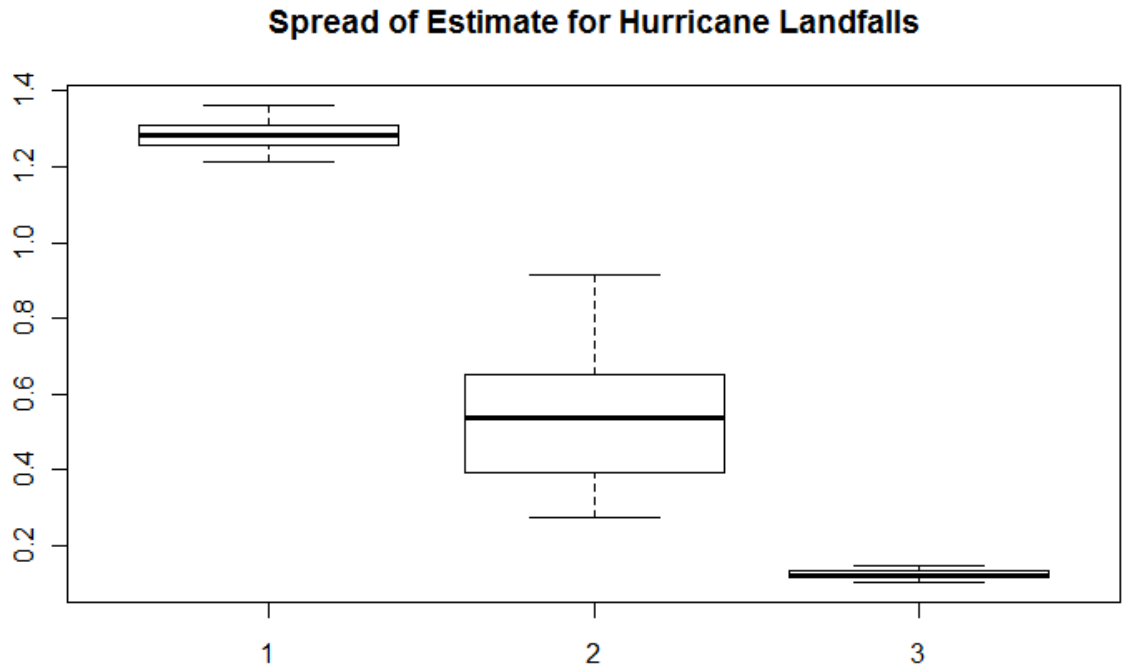

Figure 23: *Spread of estimates hurricane landfalls;* (1) *Gulf Coast,* (2) *Southeast Coast,* (3) *Northeast Coast.*

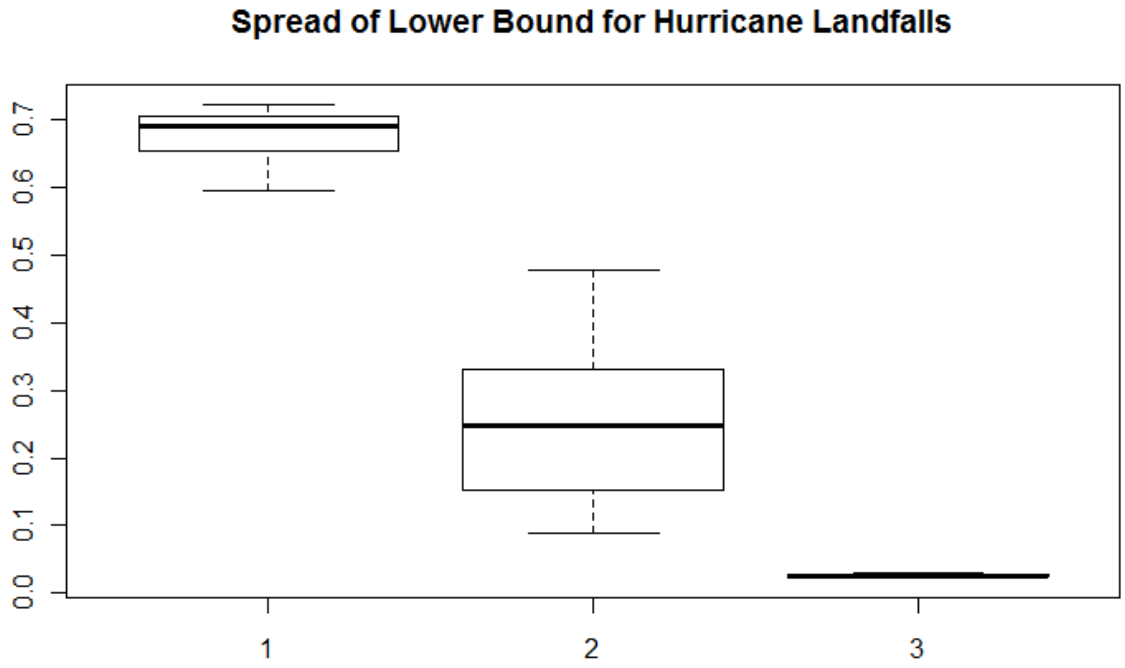

Figure 24: *Spread of lower bounds for hurricane landfalls;* (1) *Gulf Coast,* (2) *Southeast Coast,* (3) *Northeast Coast.*

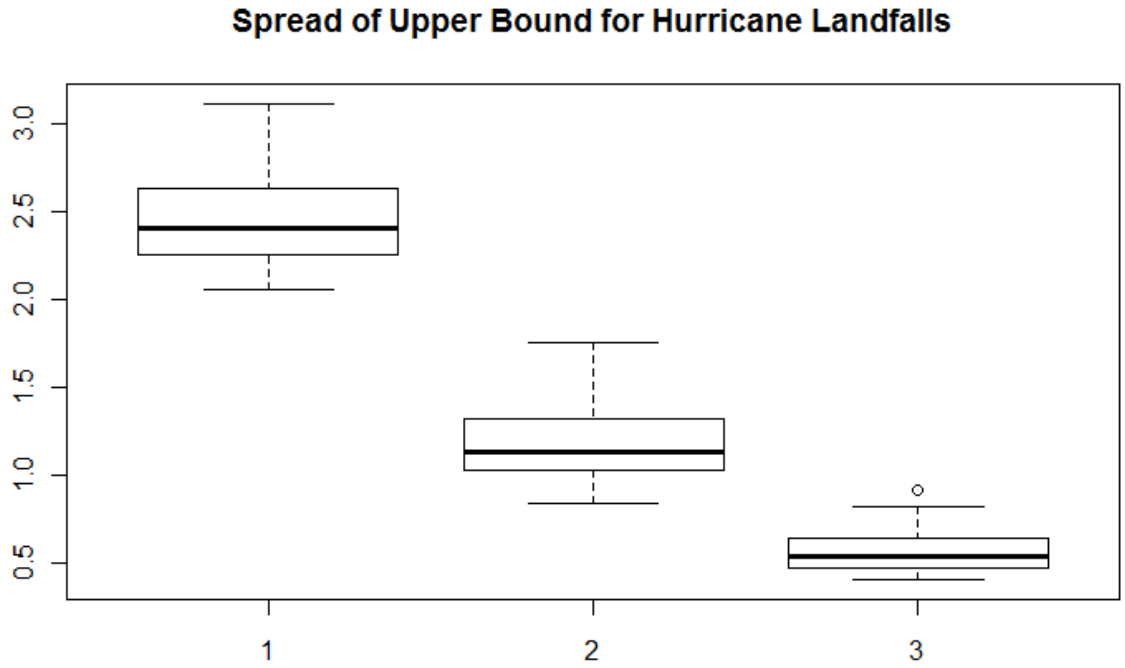

Figure 25: *Spread of upper bounds for hurricane landfalls;* (1) *Gulf Coast,* (2) *Southeast Coast,* (3) *Northeast Coast.*

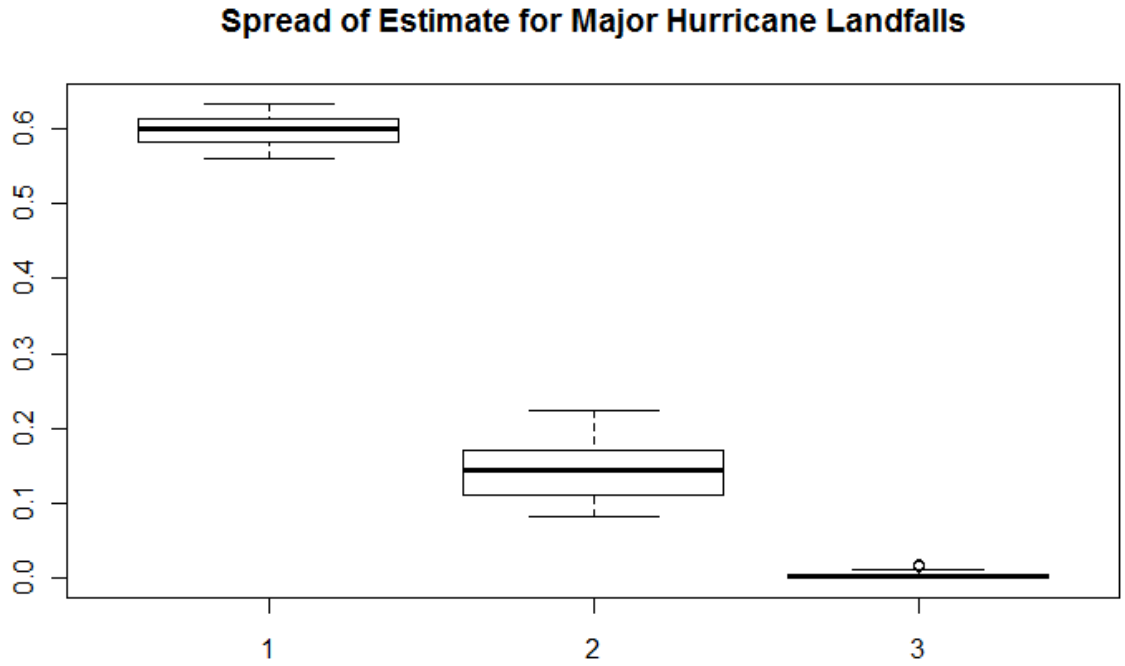

Figure 26: *Spread of estimates for major hurricane landfalls;* (1) *Gulf Coast,* (2) *Southeast Coast,* (3) *Northeast Coast.*

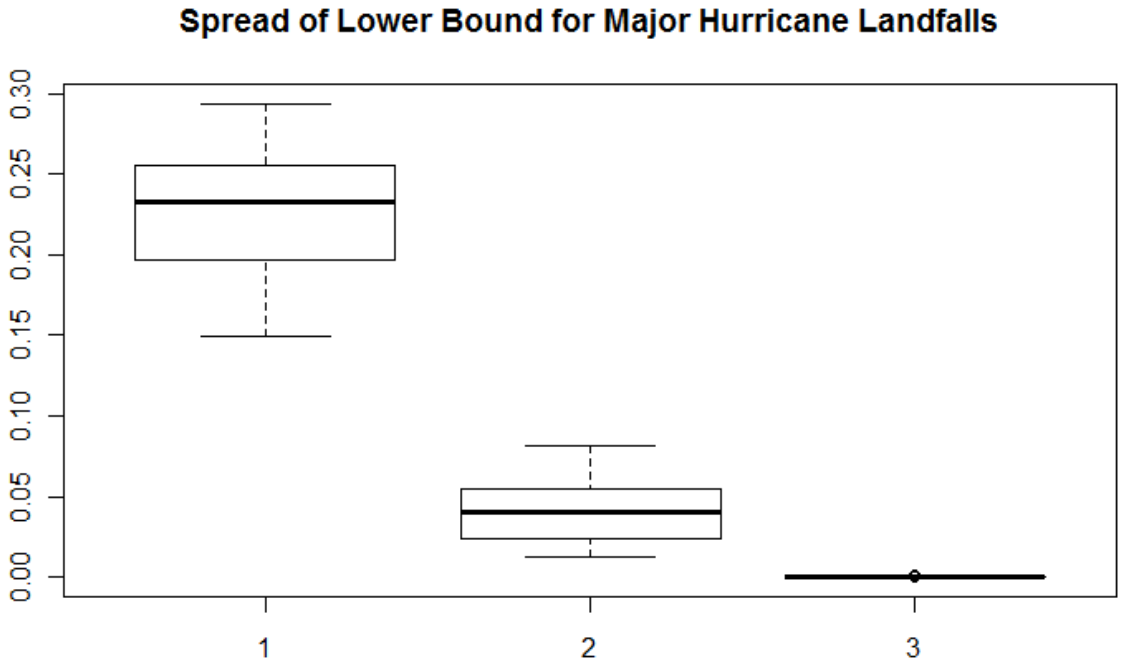

Figure 27: *Spread of lower bounds for major hurricane landfalls;* (1) *Gulf Coast,* (2) *Southeast Coast,* (3) *Northeast Coast.*

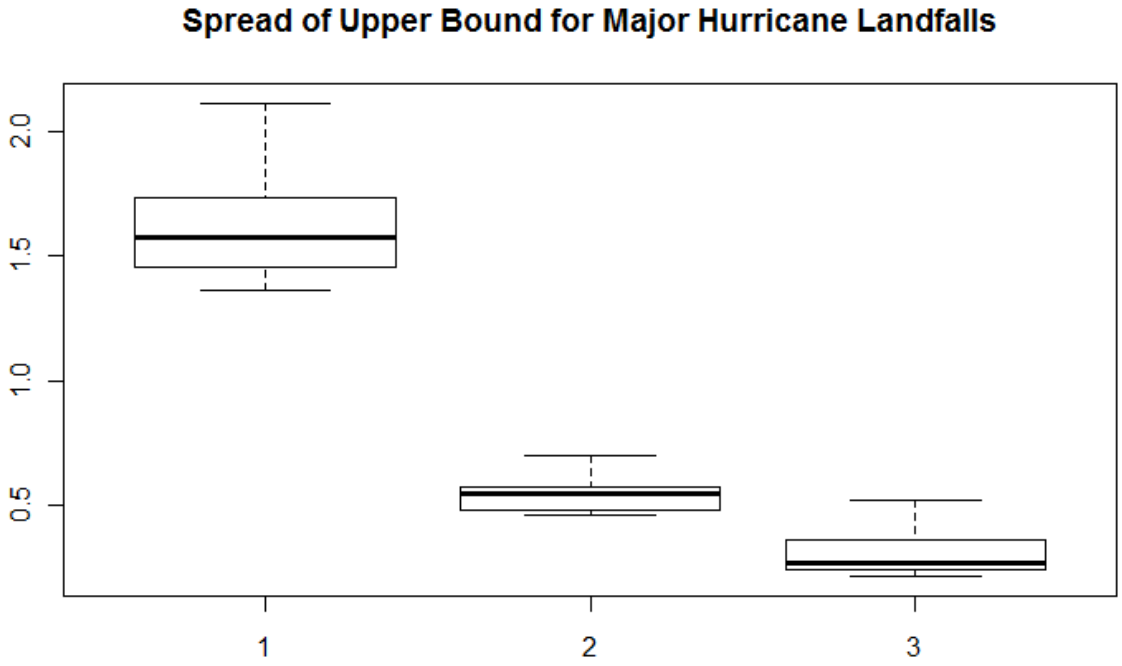

Figure 28: *Spread of upper bounds for major hurricane landfalls;* (1) *Gulf Coast,* (2) *Southeast Coast,* (3) *Northeast Coast.*