Evaluation of NEXRAD rainfall data for hydrologic modeling along Texas coast and inland watersheds

Final Project Report

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Evaluation of NEXRAD rainfall data for hydrologic modeling along Texas coast and inland watersheds

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Executive Summary

High resolution gridded precipitation estimates from NEXRAD Stage III product are widely used for hourly and daily severe weather warning and flood forecasting. However, its operational use in large scale hydrologic and water quality modeling has been slow due to bias/error in the radar rainfall estimates. In this study hourly accumulations of daily Stage III NEXRAD precipitation estimates from 2000 to 2004 were compared with an extensive network of First-Order and cooperative rain gages in two National Weather Service's (NWS) river forecast center regions covering Texas and Oklahoma. The accuracy of radar estimates was measured in terms of Modified Coefficient of Efficiency (Modified COE). In addition to the assessment of error in NEXRAD precipitation estimates, detailed assessment of spatial and temporal characteristics of daily rainfall events were made in three coastal and three inland watersheds. The spatial and temporal characterization will help understand the advantages in the usability of the NEXRAD data in modeling coastal and inland watersheds over the traditional rain gage network.

Background

Rainfall is a critical input for water resources assessment, drought monitoring and flood forecasting. It is also a highly variable component both in space and time. The limitations of raingage data in characterizing the space-time variability of rainfall could be effectively overcome by the use of radar data. During recent years considerable advances have been made in weather radar technology and radar rainfall data are becoming widely available for hydrologic modeling and flood forecasting. The United States NWS NEXt Generation RADar (NEXRAD) [formally known as the Weather Surveillance Radar – 1988 Doppler (WSR-88D)] is used for monitoring storm movement and as an early warning system about dangerous weather conditions with much better spatial (16km^2) and temporal (hourly) sampling. Although radar has been in use for over forty years, it was primarily used for weather predictions. Only during the past decade has its use in hydrologic applications been explored. The primary reason for slow adaptability of radar data by the hydrologic community is the bias in the radar rainfall estimates. The NEXRAD stage III precipitation data involves radar data correction using hourly data from rain gages under the umbrella of individual radars. In spite of this correction, studies have shown considerable difference between radar and rain gage data. Hence, the quality of radar precipitation data over the study area should be assessed before its use in hydrologic models.

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Objective

Texas Water Development Board (TWDB) uses hydrologic models to study runoff and groundwater recharge in several coastal and inland watershed. Precipitation data from rain gage network has been the major source of input for hydrologic models. Recently TWDB has started exploring the usefulness of NEXRAD derived precipitation estimates for modeling coastal and inland watersheds. The objectives of this study are:

1. Evaluation of radar data accuracy across all of Texas and
2. Spatial and Temporal Characterization of radar data in six watersheds (three inland and three coastal watersheds). Three coastal watersheds are Galveston Bay, Lavaca Bay, and Corpus Christi Bay. Three inland watersheds are Denton, Concho and San Antonio (Figure 1).

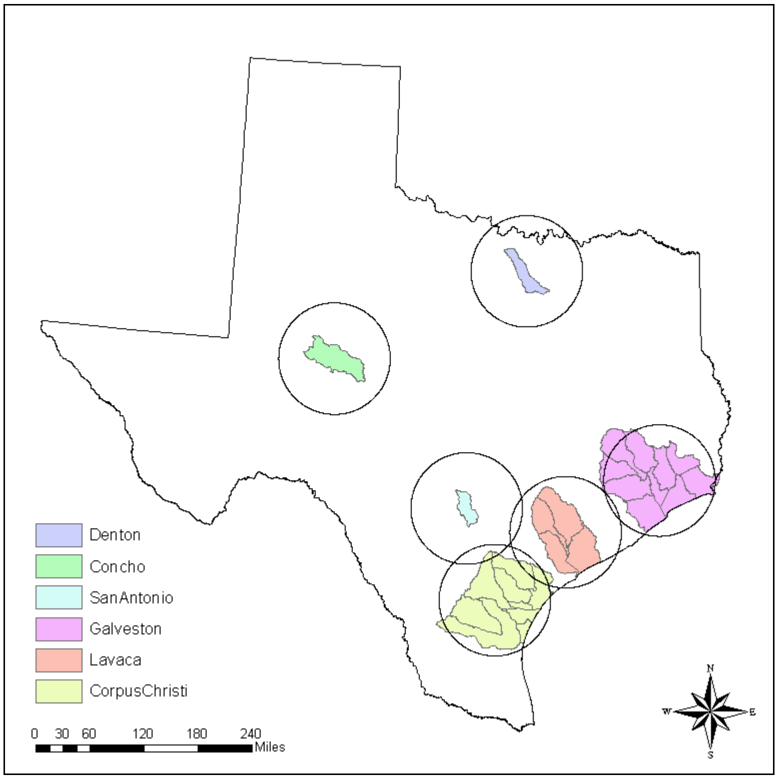


Figure 1. Costal and Inland Study Areas along with the 100km radius from the centroid of the watershed.

Objective 1: Evaluation of radar data accuracy across all of Texas

Texas falls under the umbrella of two National Weather Service (NWS) river forecasting center regions 1) West-Gulf River Forecast Center region (WGRFC) and 2) Arkansas-Red Basin River Forecast Center region (ABRFC). Hence the data for this study were obtained from these two RFC's for 5-years (2000-2004). Measured rainfall data from rain gage network were obtained from hundreds of cooperative weather stations scattered across the state along with First-Order weather stations operated by NWS and airports in the vicinity of major urban areas. **A detailed paper discussing the data and methodology used for objective 1 can be found in the <u>Appendix</u>**. Here are the major results and conclusion from that study:

1. Overall the radar error was the lowest at First-Order rain gages in measuring rainfall greater than zero millimeters with the modified COE between 0.8 and 0.9 in both ABRFC and WGRFC region. However, seasonal and threshold analysis showed that the radar error was high in measuring rainfall events between 12.71 and 25.4mm (median modified COE < 0.5). The error was more predominant during Autumn and Summer at the WGRFC region and Spring and Summer in the ABRFC region. The poor performance of the radar during summer and the transition seasons of Autumn and Spring indicate that better radar calibrations and improvements in radar algorithms are needed to capture the convective storm events especially in measuring medium rainfall range.

2. The radar error was more pronounced in the COOP rain gage network than the First-Order rain gages but followed a similar trend. Although the radar error appear to be random, a multiple regression analysis of modified COE at COOP rain gages showed a week dependence of radar error as a function of distance of the gage from radar center, distance of the gage from the coast and elevation difference between rain gage and radar. However, due to the small R^2 value of the regression it is difficult to identify the reasons for poor comparison between radar and COOP rain gage estimates.

3. Although COOP rain gages operate under less stringent guidelines than the First-Order rain gages, most of them operates under highest of standards maintained by conscientious observers and it is a true representative of the weather at where the people live. In addition, the poor performance of the radar in measuring medium range rainfall (12.71 to 25.4mm) even at the First-Order rain gages, which are operationally used for radar calibration and bias adjustments, indicate that better radar calibrations and improvements in radar algorithms are needed.

The overall radar accuracy at the COOP and the First-Order rain gages located within 100km radius of six watersheds are shown in figures 2 to 7. From these figures and the Box-plots in figure 8, the radar data compared well with all the handful of First-Order rain gages (Modified COE > 0.8) except at Corpus Christi Bay. At one of the First-Order rain gages in Corpus Christi Bay the modified COE was close to 0.7. At most of the COOP rain gages, the radar estimation efficiency was poor (modified COE of 0.4 to 0.8 at most of the rain gages). These results were consistent with the pattern observed from analysis with First-Order and COOP rain gages across a wider region of Texas and Oklahoma (See Appendix).

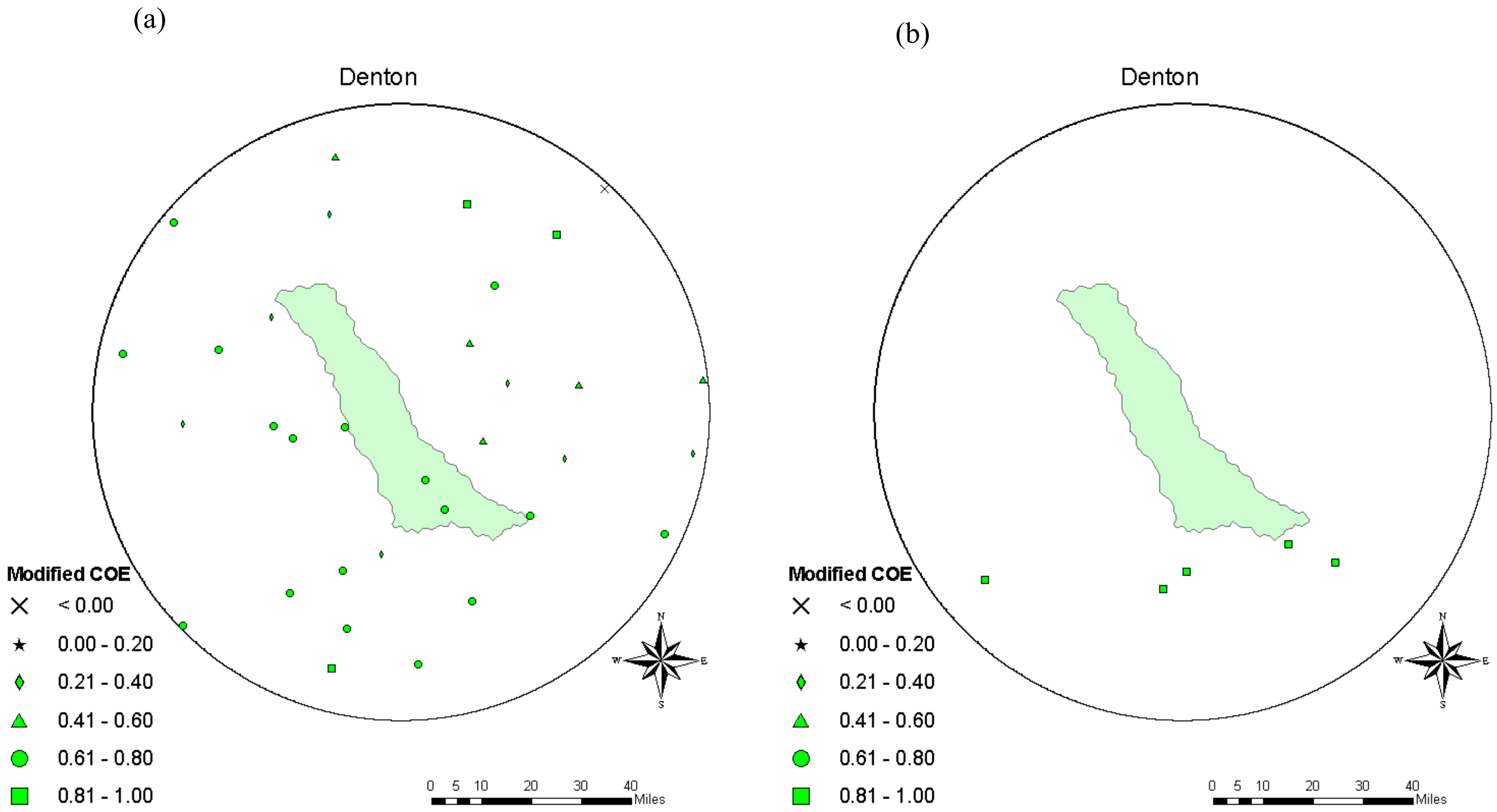


Figure 2. Spatial distribution of modified COE in Denton a) COOP rain gages b) First-Order rain gages.

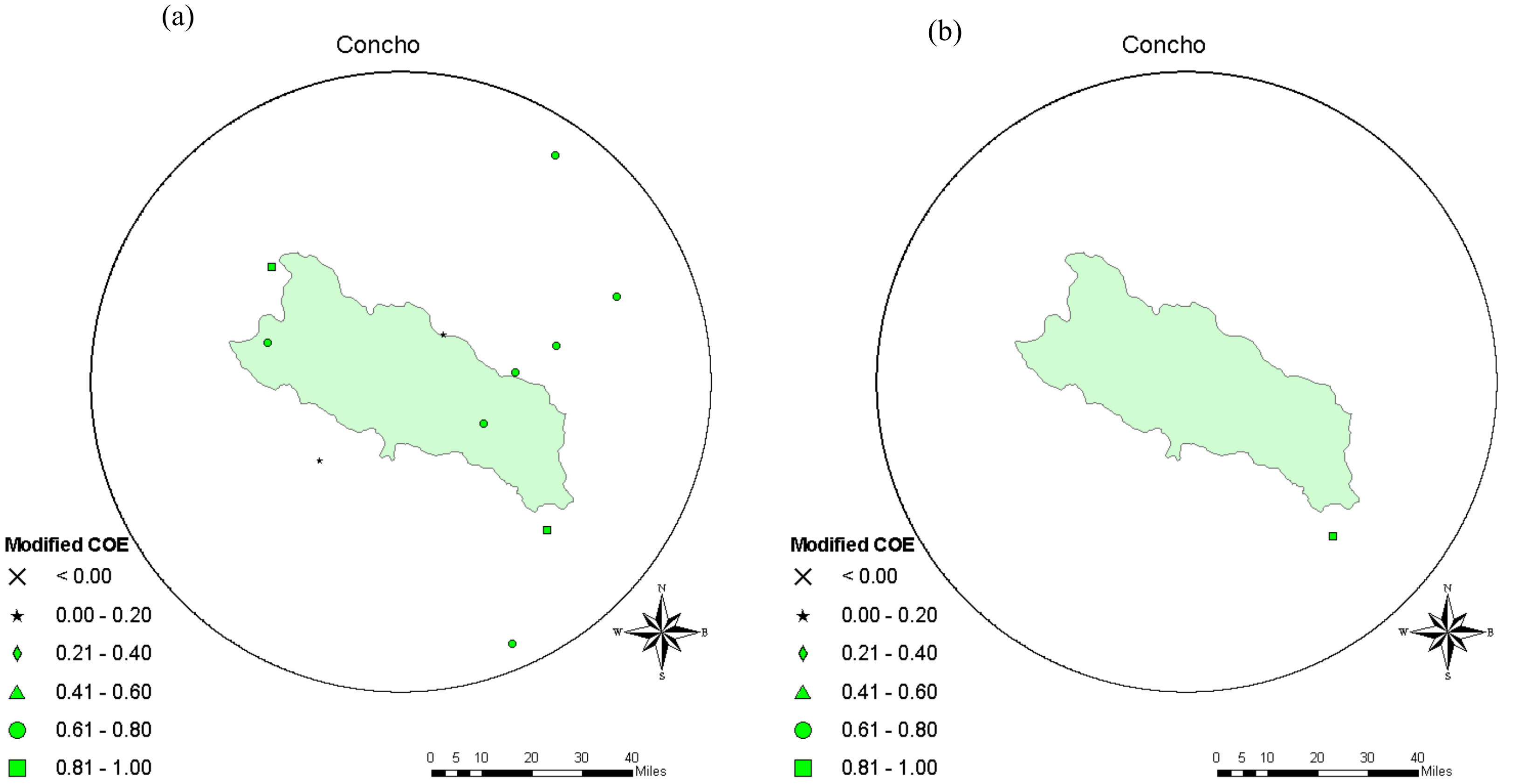


Figure 3. Spatial distribution of modified COE in Concho a) COOP rain gages b) First-Order rain gages.

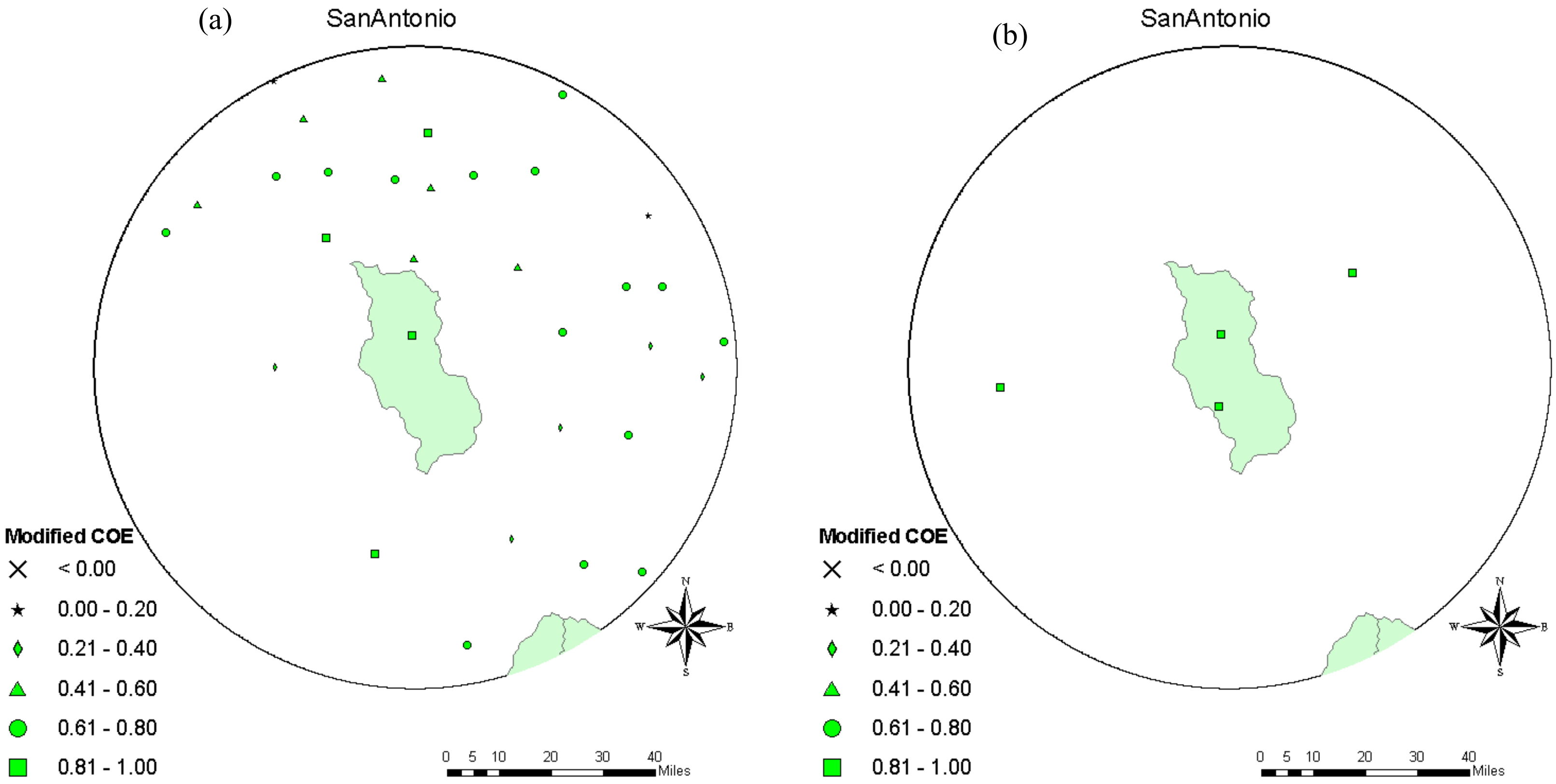


Figure 4. Spatial distribution of modified COE in San Antonio a) COOP rain gages b) First-Order rain gages.

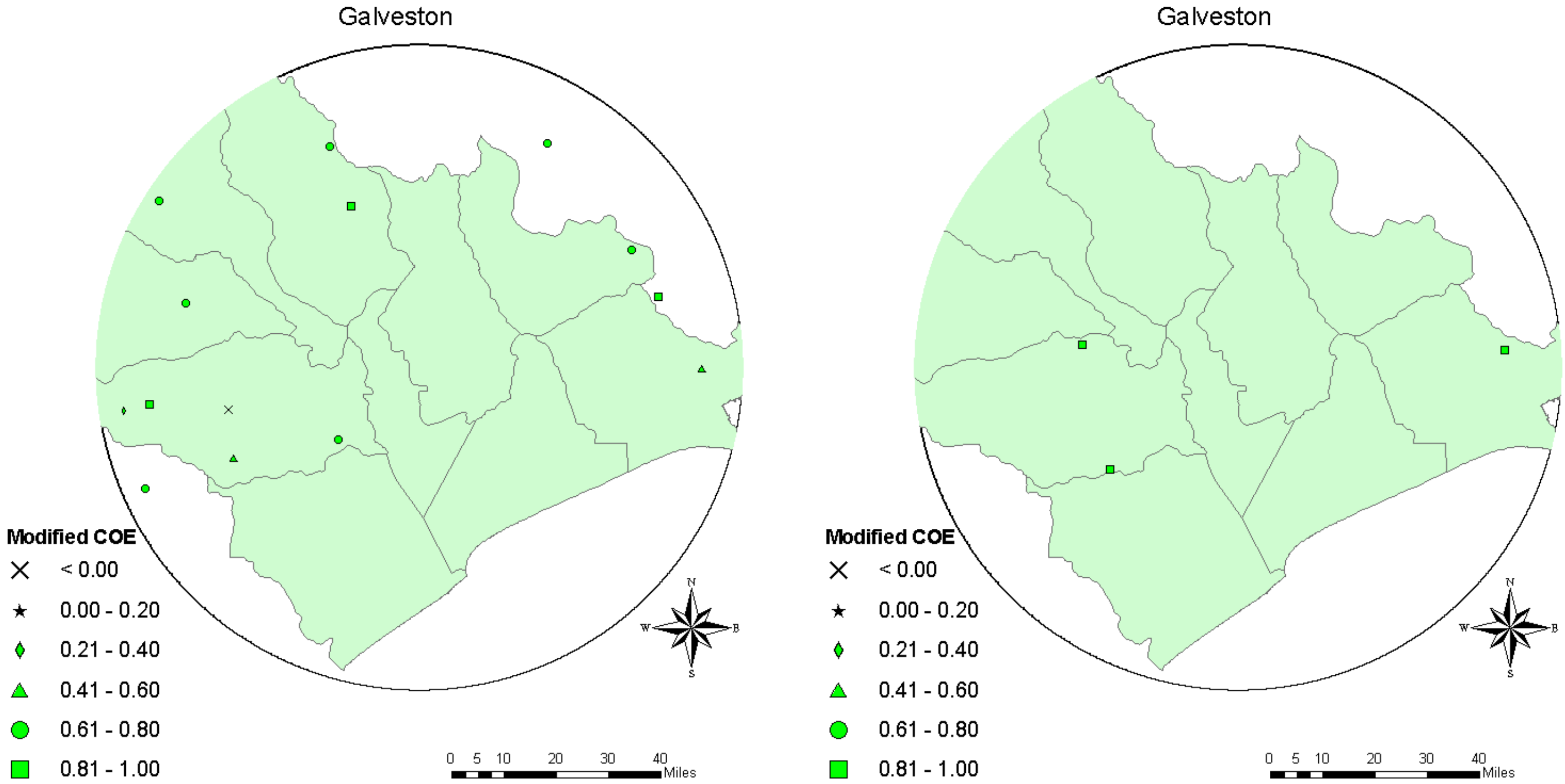


Figure 5. Spatial distribution of modified COE in Galveston Bay a) COOP rain gages b) First-Order rain gages.

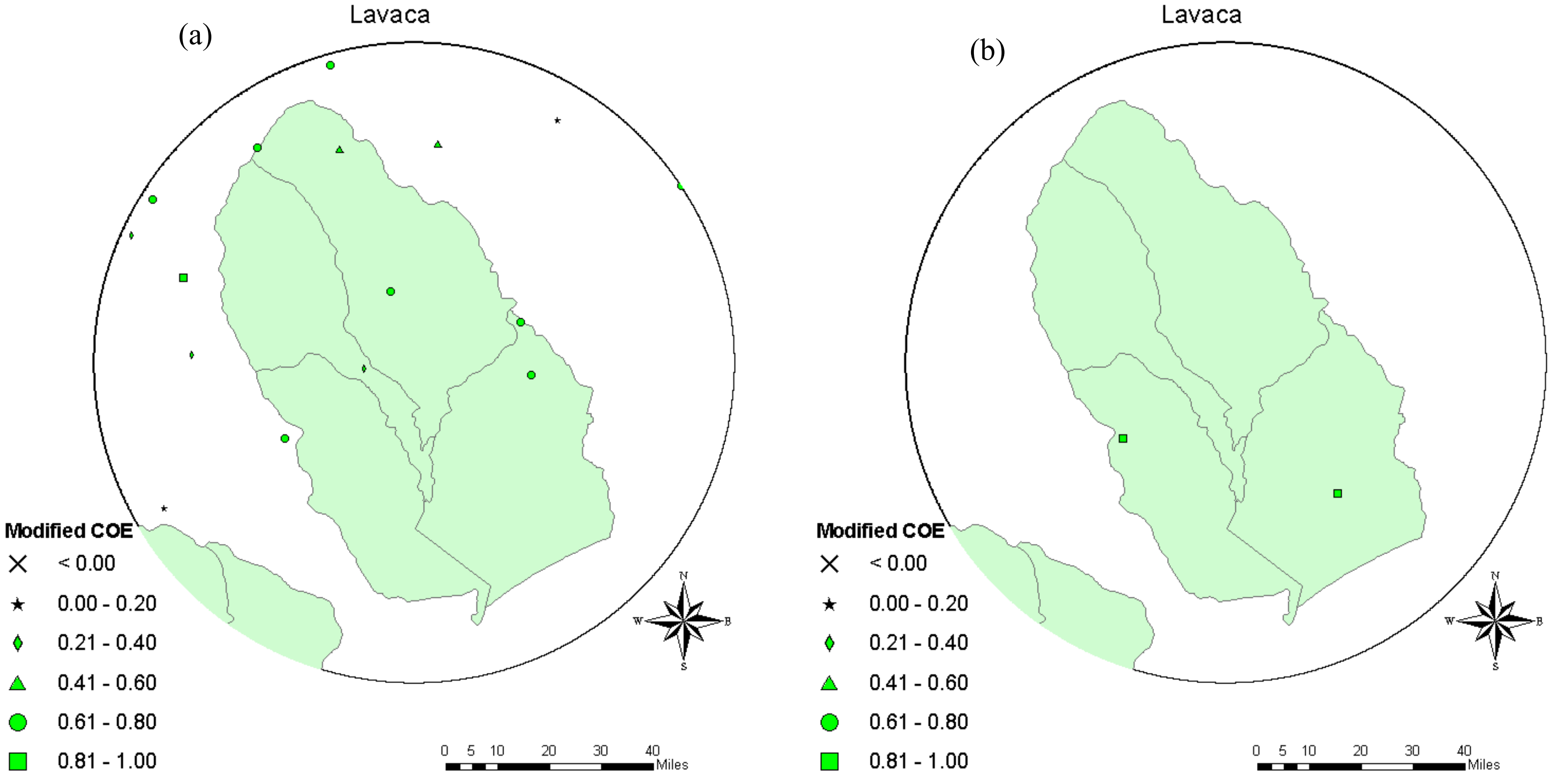


Figure 6. Spatial distribution of modified COE in Lavaca Bay a) COOP rain gages b) First-Order rain gages.

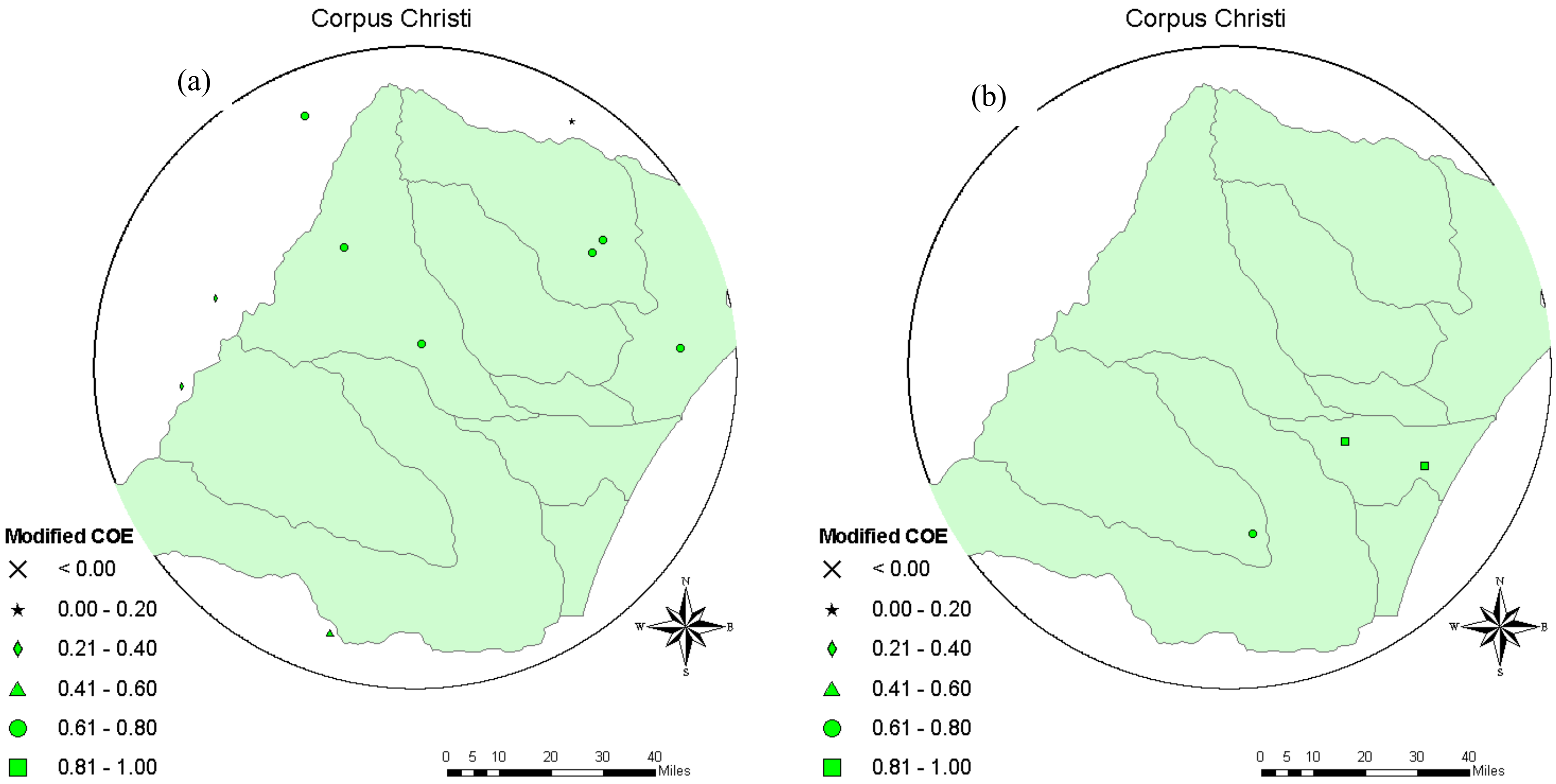


Figure 7. Spatial distribution of modified COE in Corpus Christi Bay a) COOP rain gages b) First-Order rain gages.

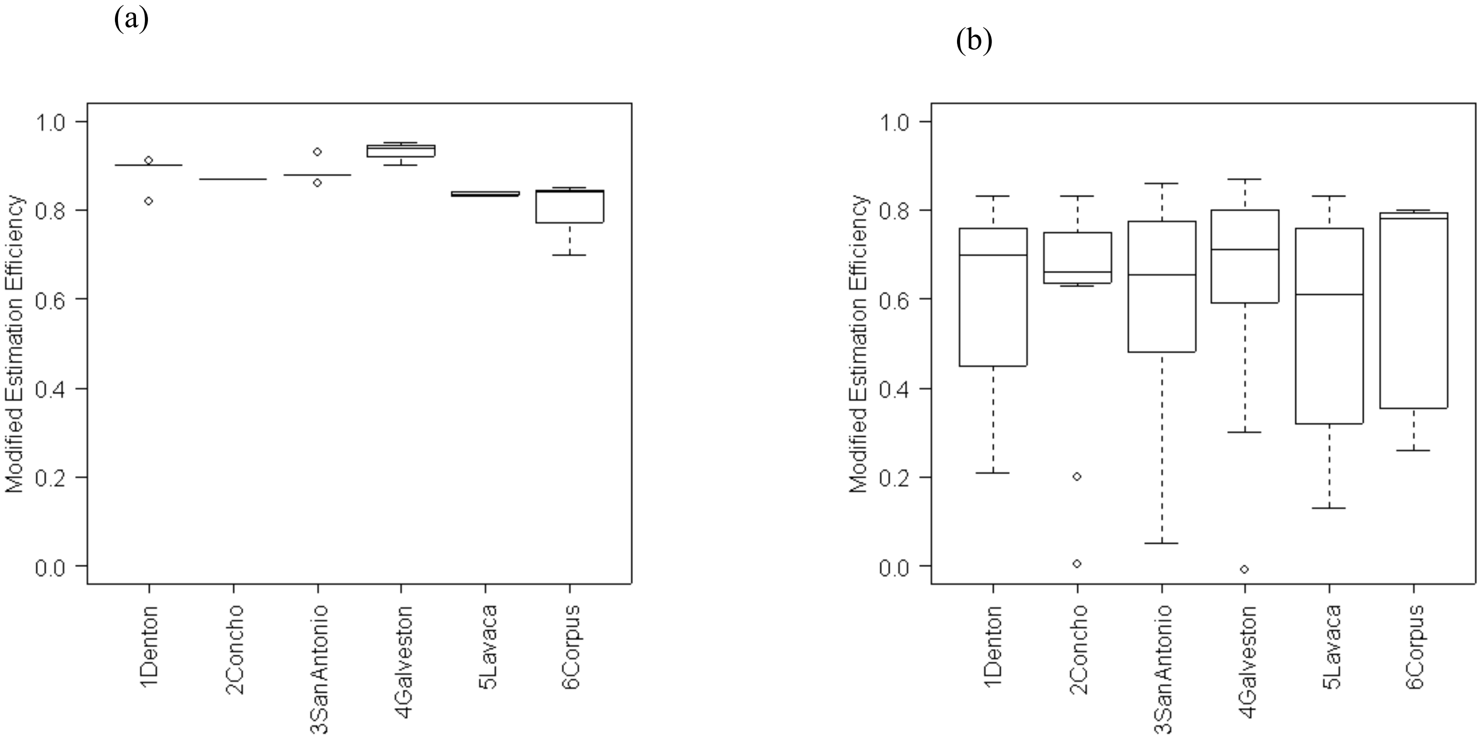


Figure 8. Box-Plots showing the distribution of Modified COE ; exclusive of days with zero rainfall using 9-Cell minimum difference comparison method. a) First-Order rain gages b) COOP rain gages.

Objective 2: Spatial and Temporal Characterization of radar data

Spatial Characterization

A statistical measure called spatial auto-correlation was used to assess the spatial variability of radar data. Spatial autocorrelation gives an estimate of how similar or different are the rainfall from center pixel with respect to the surrounding pixels. Spatial autocorrelation was computed at five different levels (spatial lags) from daily rainfall grids by offsetting the entire grid by one pixel (4km), two pixels (8km), three pixels (12km), four pixels (16km) and five pixels (20km) on all the four major directions and then comparing them with the original rainfall grid. The analysis was done by masking the rainfall grid based on a circle of 100km radius from the center of six watersheds (Figure 1). This will give an estimate of spatial variability of rainfall in these six watersheds during different seasons of the year.

Using five years of daily rainfall grids (2000-2004) spatial autocorrelation was calculated for the six watersheds on a daily time step. Based on the spatial correlation calculated for individual events for each month over the five year period, its monthly distribution is shown as a box-plot for each of the six watersheds for the five levels of spatial offsets (lags) (Figures 9 to 13). There is a strong temporal pattern in the spatial correlation especially in the three coastal watersheds than at the three inland watersheds. In the coastal watersheds, the spatial autocorrelation reduces during the summer months of July, August and September. The rainfall pattern during summer months is convectional in nature and not widespread, while the winter events tend to be frontal stratiform and spread across a wide region. The convection storm events seem to produce rainfall with high spatial variability especially at the coastal region. This temporal pattern in spatial autocorrelation is more pronounced as the spatial offset (lag) increases. This strongly suggests that the rainfall spatial variability is very high in the coastal region. Among the inland watersheds, a strong temporal pattern in the spatial autocorrelation was observed at the San Antonio watershed which is closest to the coast than Denton and Concho watersheds.

For the Coastal watersheds, even for a spatial lag of one cell (4km), the autocorrelation became as low as 0.8 which is equivalent to an r^2 of 0.64 suggest that the spatial variability of rainfall is quite high in the coastal regions especially during summer. The spatial autocorrelation reduced drastically for each incremental lag. A very high dense network of rain gages would be needed to capture this spatial variability of rainfall. Hence, radar rainfall data will be very useful to capture this high spatial variability in rainfall.

For the inland watersheds, the spatial correlation started reducing below 0.8 after a spatial lag of two cells (8 km). Although this suggest a spatial variability slightly lesser than that off coastal watersheds it is by no means uniformly distributed. The spatial variability is quite high in the inland watersheds as well and radar rainfall data will be very useful to capture this high spatial variability in rainfall.

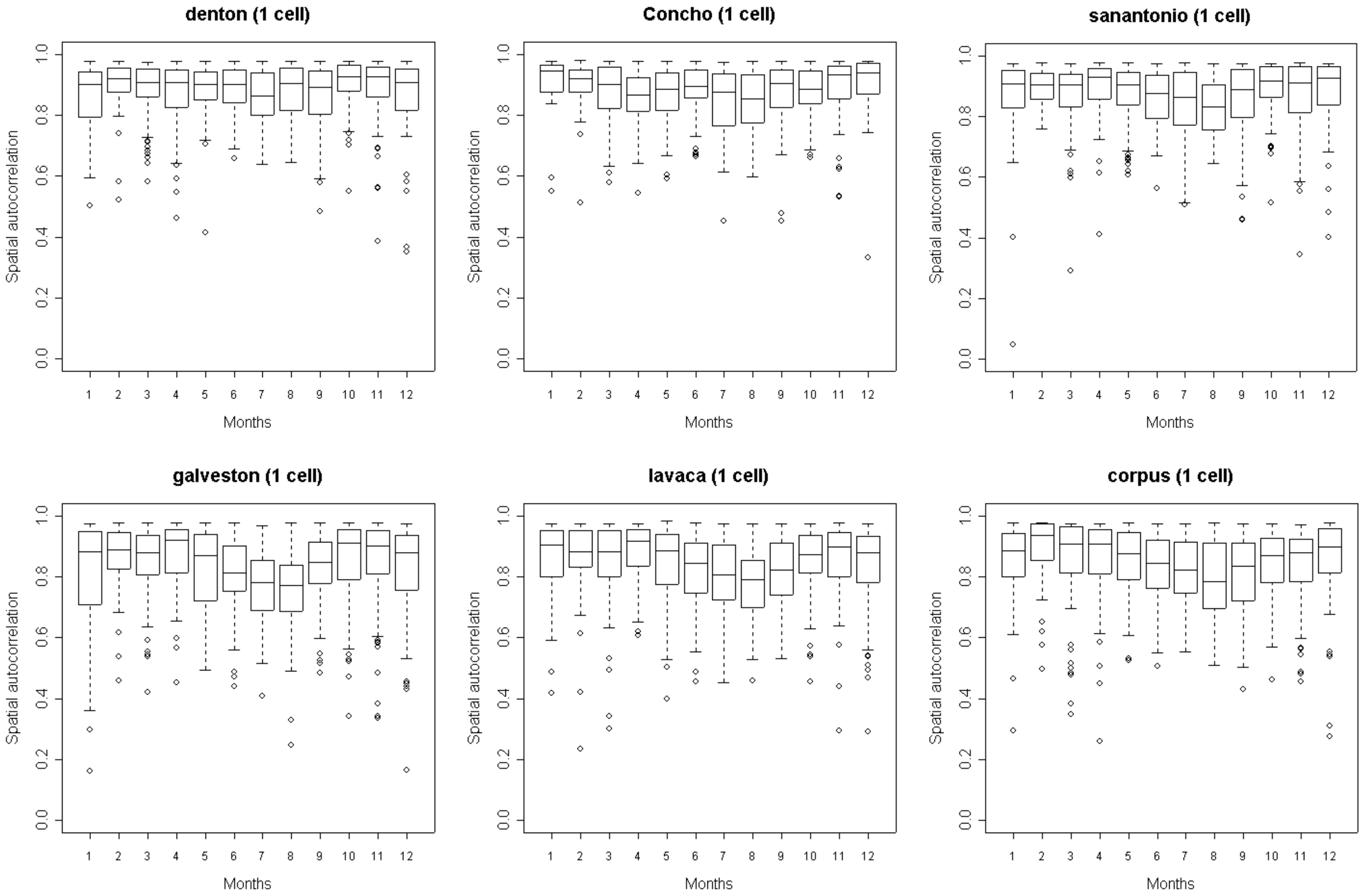


Figure 9. Monthly distribution of spatial autocorrelation of daily rainfall grids based on five years of radar data: one cell lag (4km).

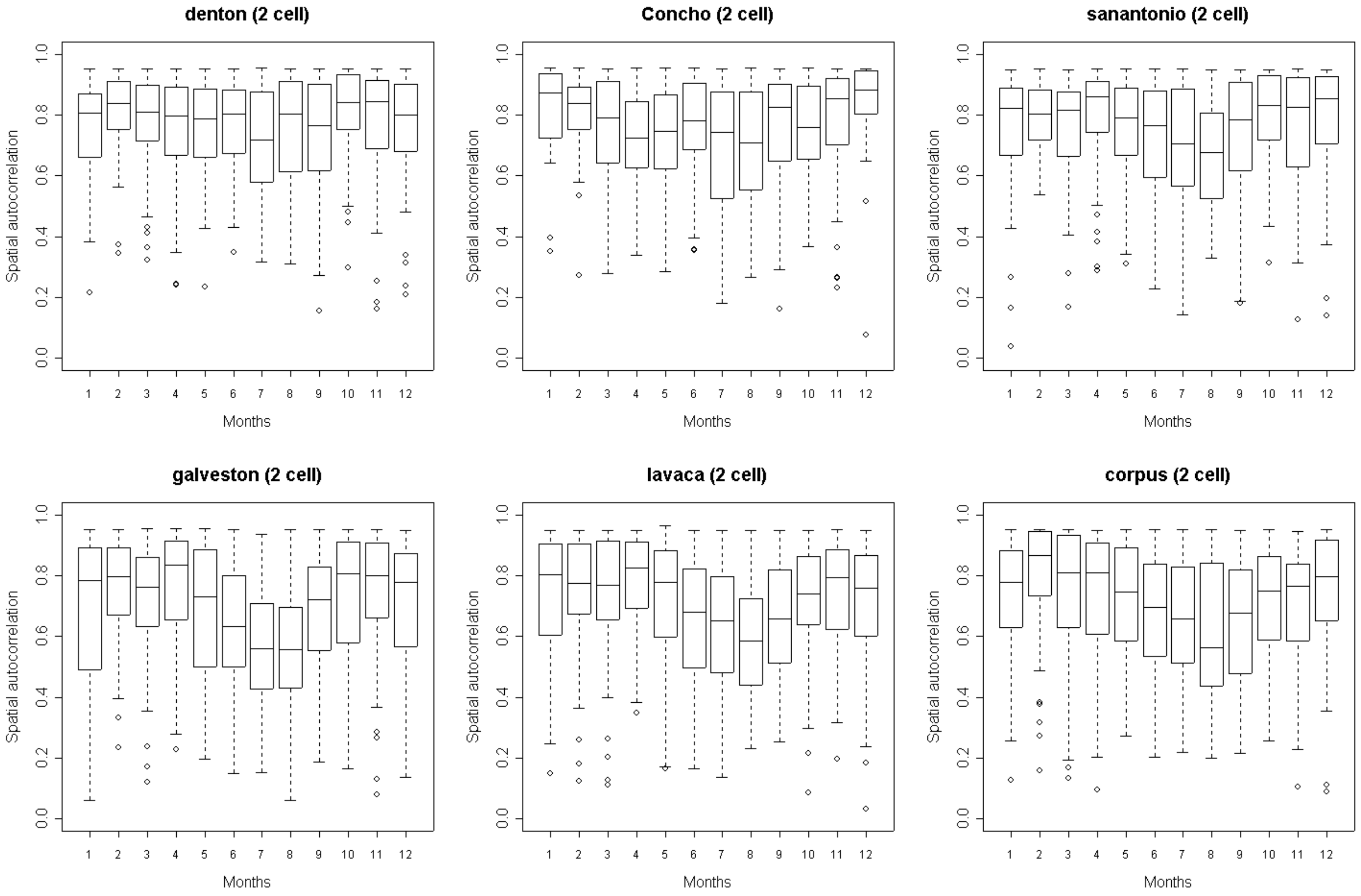
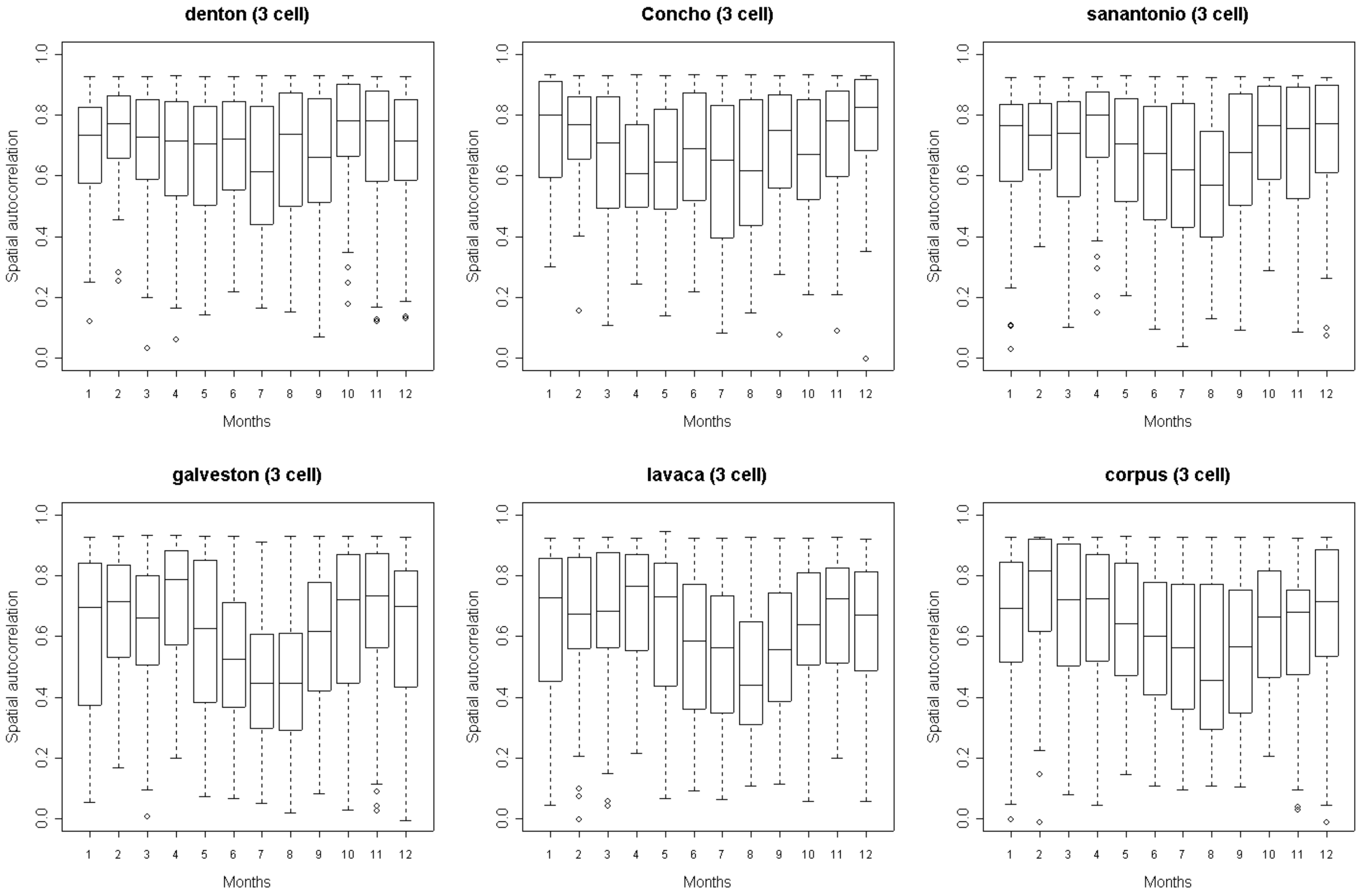


Figure 10. Monthly distribution of spatial autocorrelation of daily rainfall grids based on five years of radar data: two cell lag (8km).


denton (3 cell)

Concho (3 cell)

sanantonio (3 cell)

galveston (3 cell)

lavaca (3 cell)

corpus (3 cell)

Figure 11. Monthly distribution of spatial autocorrelation of daily rainfall grids based on five years of radar data: three cell lag (12km).

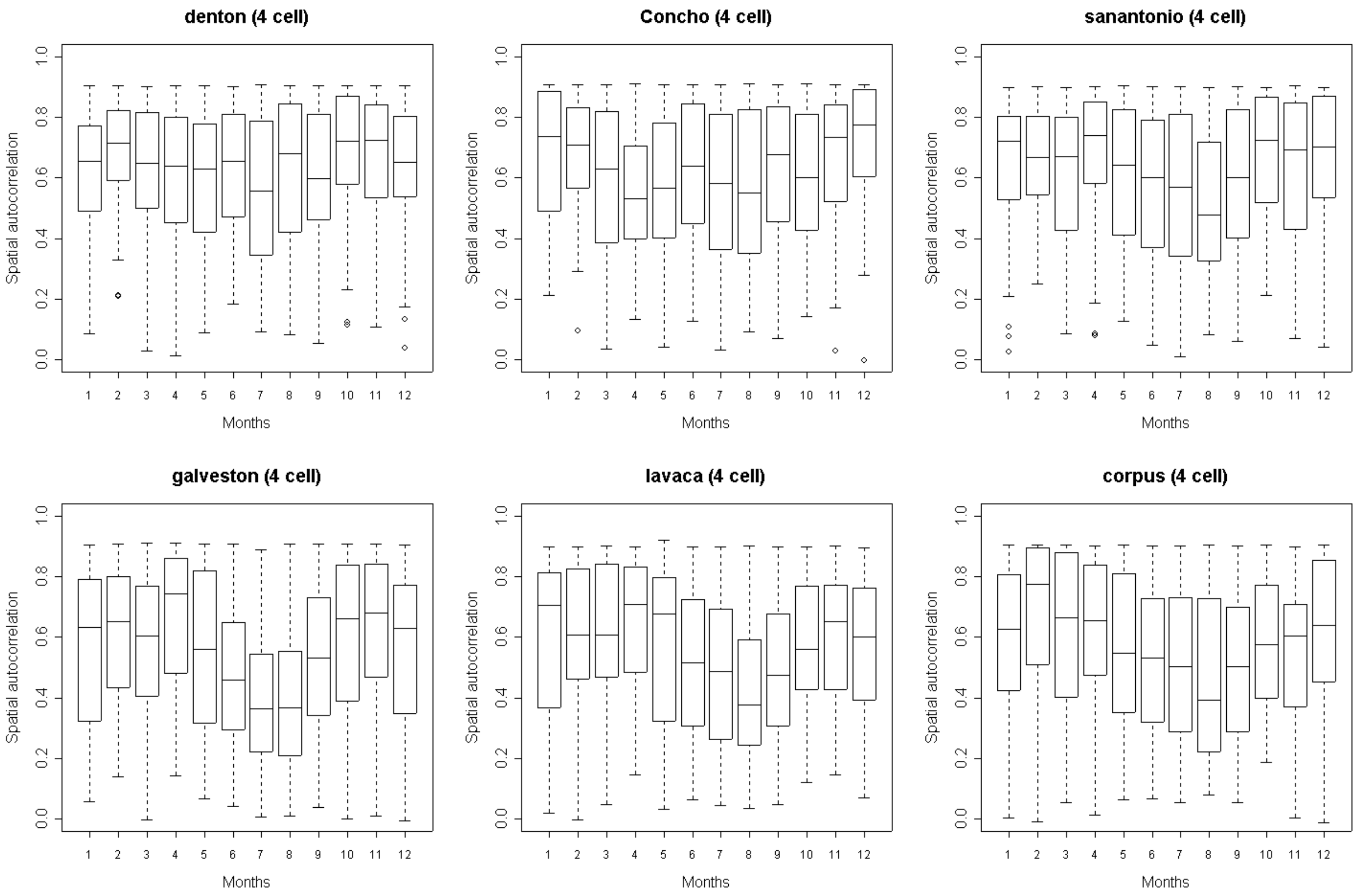


Figure 12. Monthly distribution of spatial autocorrelation of daily rainfall grids based on five years of radar data: four cell lag (16km).

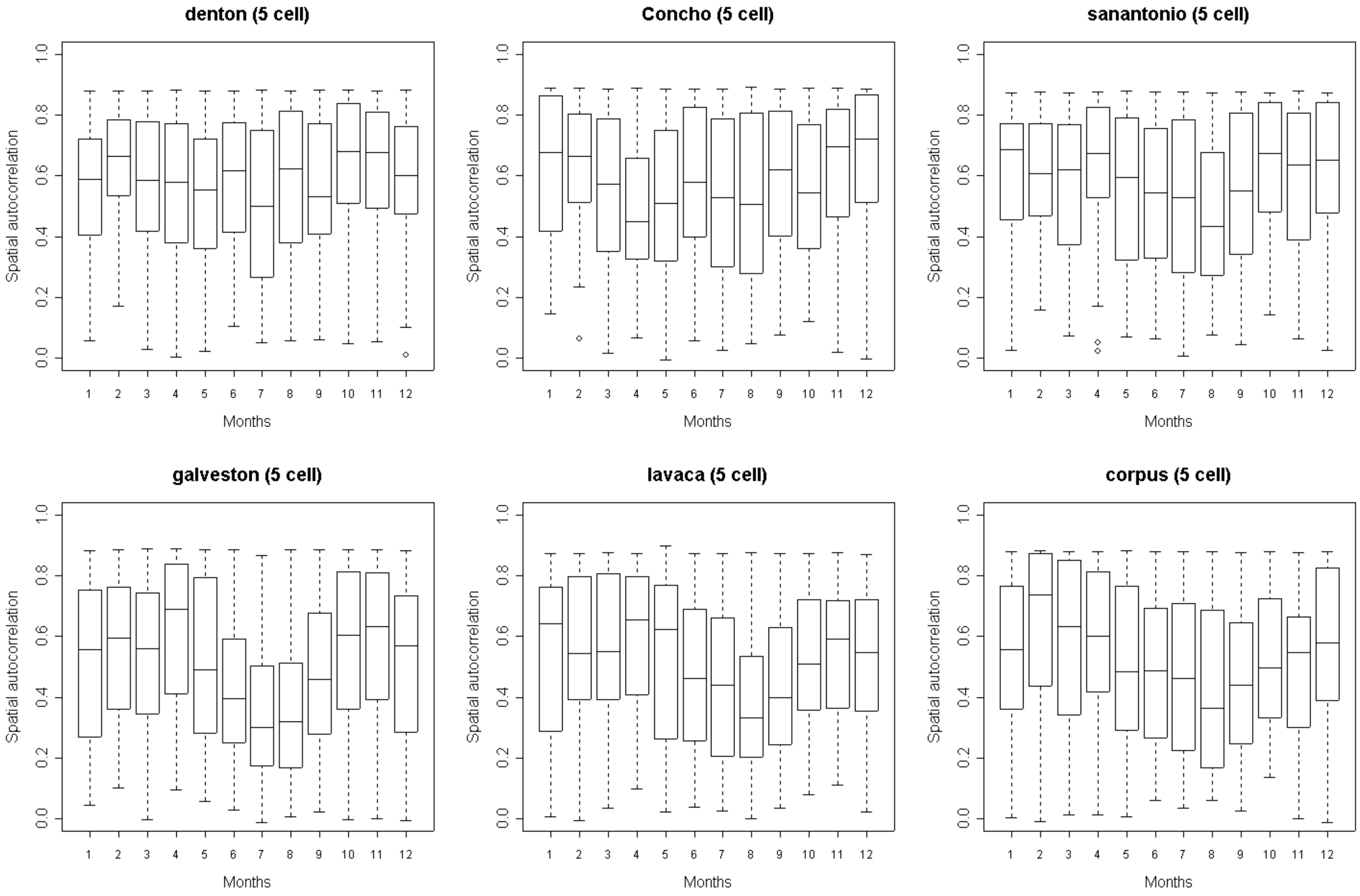


Figure 13. Monthly distribution of spatial autocorrelation of daily rainfall grids based on five years of radar data: five cell lag (20km).

Spatio-Temporal Characterization

The analysis described above measured the spatial variability of daily rainfall grids. In order to analyze how the time series of individual NEXRAD cells compare with adjacent cells, the daily rainfall grids from 2004 were used. The well know correlation coefficient was used as a statistical measure to evaluate the spatio-temporal characteristic of the rainfall data over entire Texas based on NEXRAD data from WGRFC. Results from this analysis (Figures 14 to 18) show that temporal correlation between adjacent grids decrease with increase in distance between grids. The correlation is low especially in mountainous regions of west Texas and Pan-handle even for NEXRAD grids displaced only by 4km (Figure 14). However, comparing NEXRAD grids that are further apart, temporal correlation begins to reduce at the coastal regions as well as the central and pan-handle regions of Texas which are also characterized by low rainfall. The temporal correlation coefficient was quite high for the high rainfall regions of north-east Texas even for NEXRAD grids displaced by 20 km (Figure 18). This analysis again confirms the assessment that NEXRAD data will be very useful to capture the spatial and temporal variability of rainfall across most of Texas and is a valuable data source for hydrologic modeling.

Temporal Characterization

Using five years of NEXRAD data (2000-2004) several maps were created to depict the statewide distribution of rainfall. The maps are:

1. Average Monthly and annual precipitation
2. Average Monthly and annual maximum daily precipitation
3. Average standard deviation of rainfall events (Monthly and Annual)
4. Average Monthly and annual number of rainy days
5. Driest month of the year
6. Wettest month of the year
7. Month with highest number of rainy days
8. Month with lowest number of rainy days.

Conclusion

As can be seen from these maps and other analysis conducted in this study, the spatial and temporal pattern of rainfall in Texas is highly variable across Texas at both inland and coastal watersheds. In spite of the errors in NEXRAD data, it is a valuable data source for hydrologic modeling at a high spatial resolution. Due to the inherent errors in the radar estimation, it can never replace the traditional rain gage network. By combining the dense network of Cooperative rain gages across Texas with radar data through a bias adjustment framework the accuracy of radar rainfall estimates could be improved. Nevertheless, the study concludes that NEXRAD rainfall data will be very useful for TWDB in its coastal and inland modeling programs.

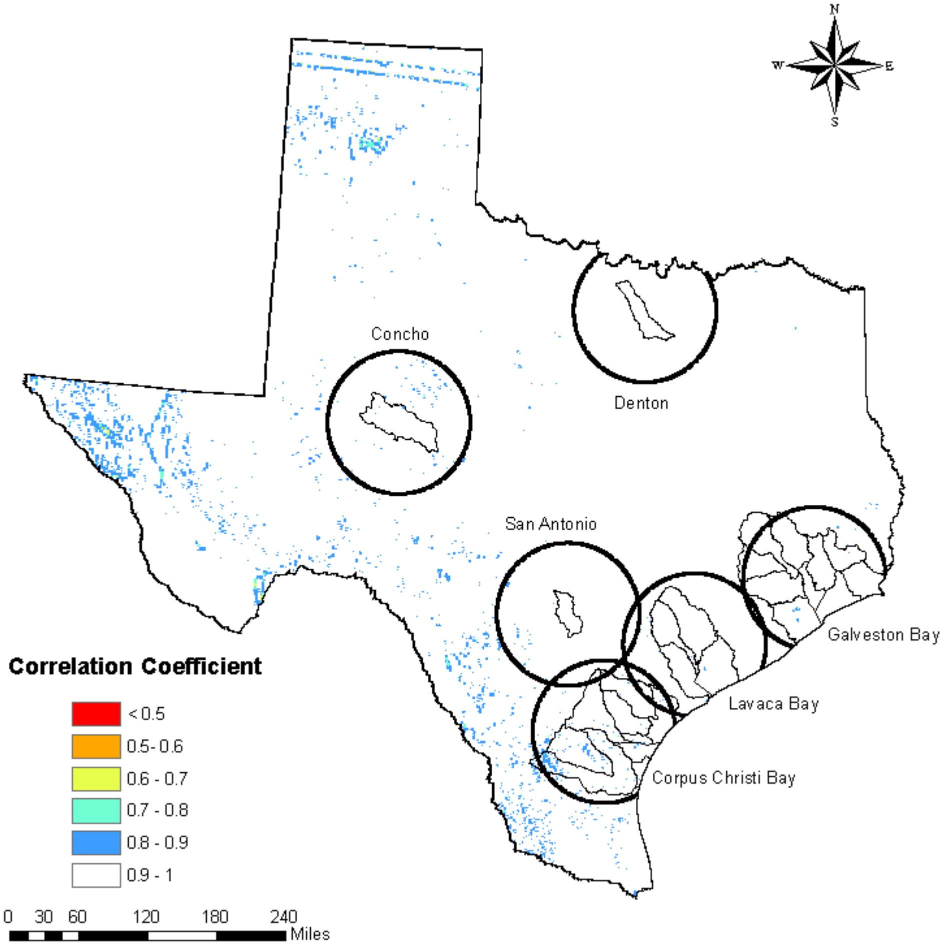


Figure 14. Correlation coefficient between time-series of data (2004) of NEXRAD grids displaced by 4km.

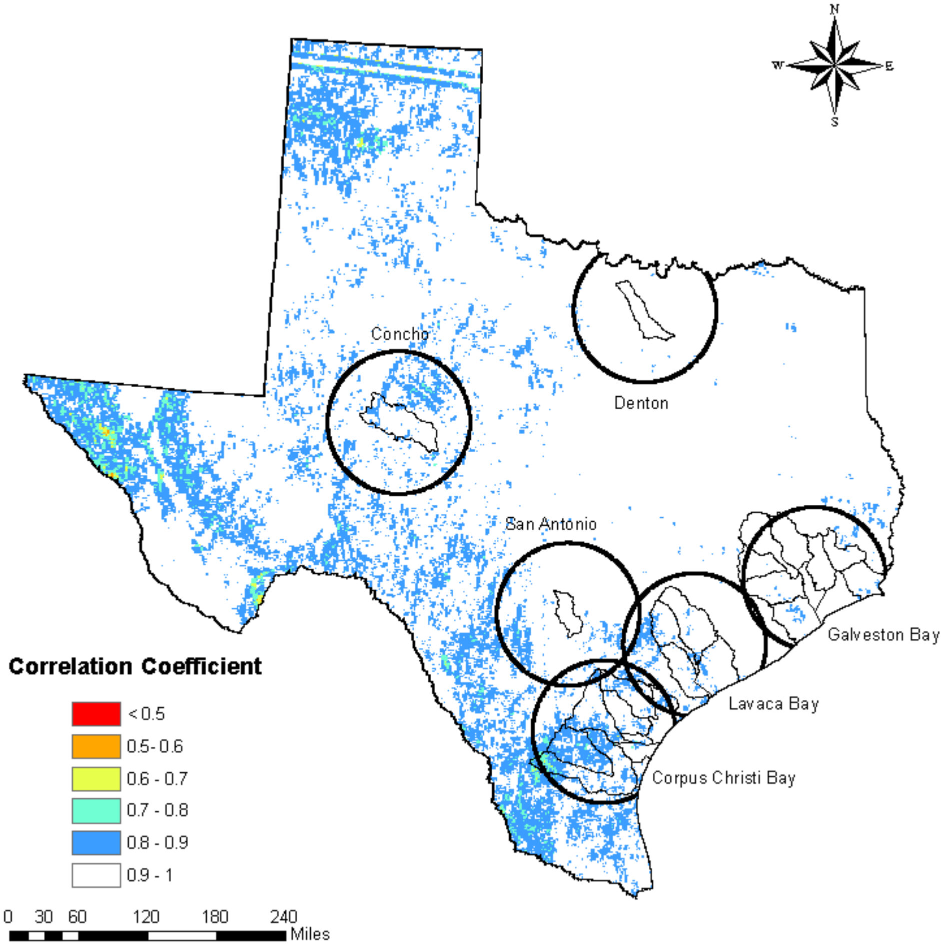


Figure 15. Correlation coefficient between time-series of data (2004) of NEXRAD grids displaced by 8km.

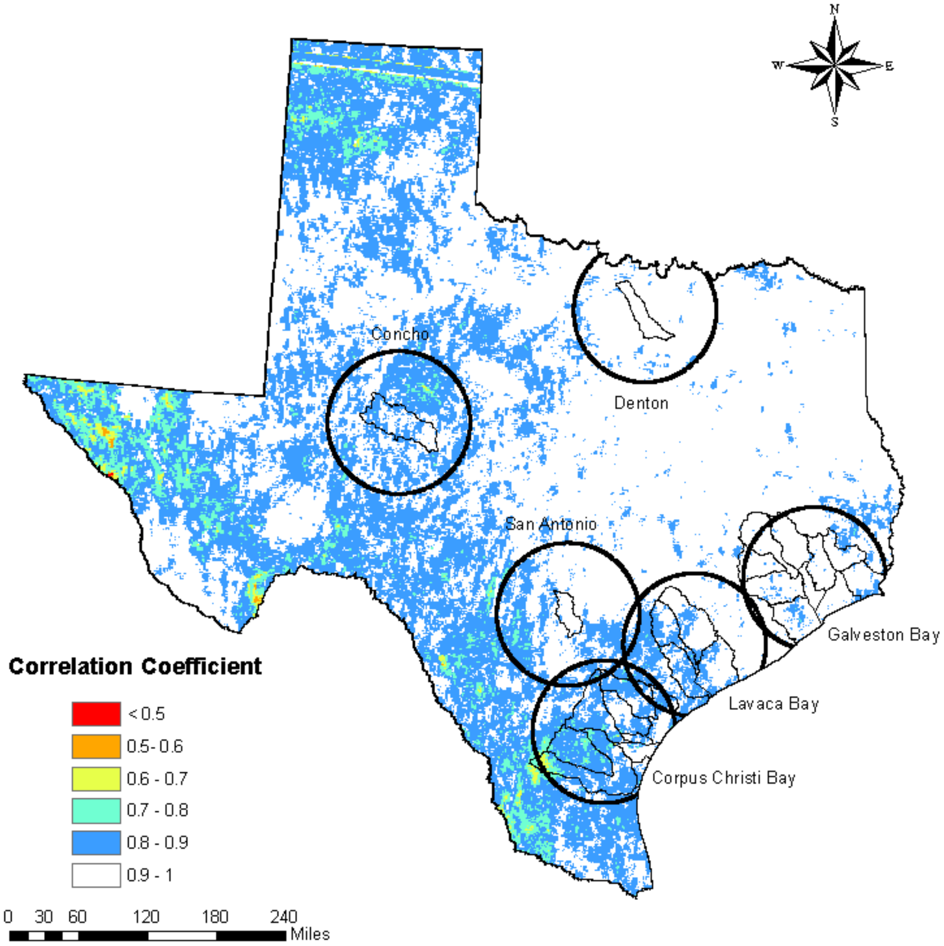


Figure 16. Correlation coefficient between time-series of data (2004) of NEXRAD grids displaced by 12km.

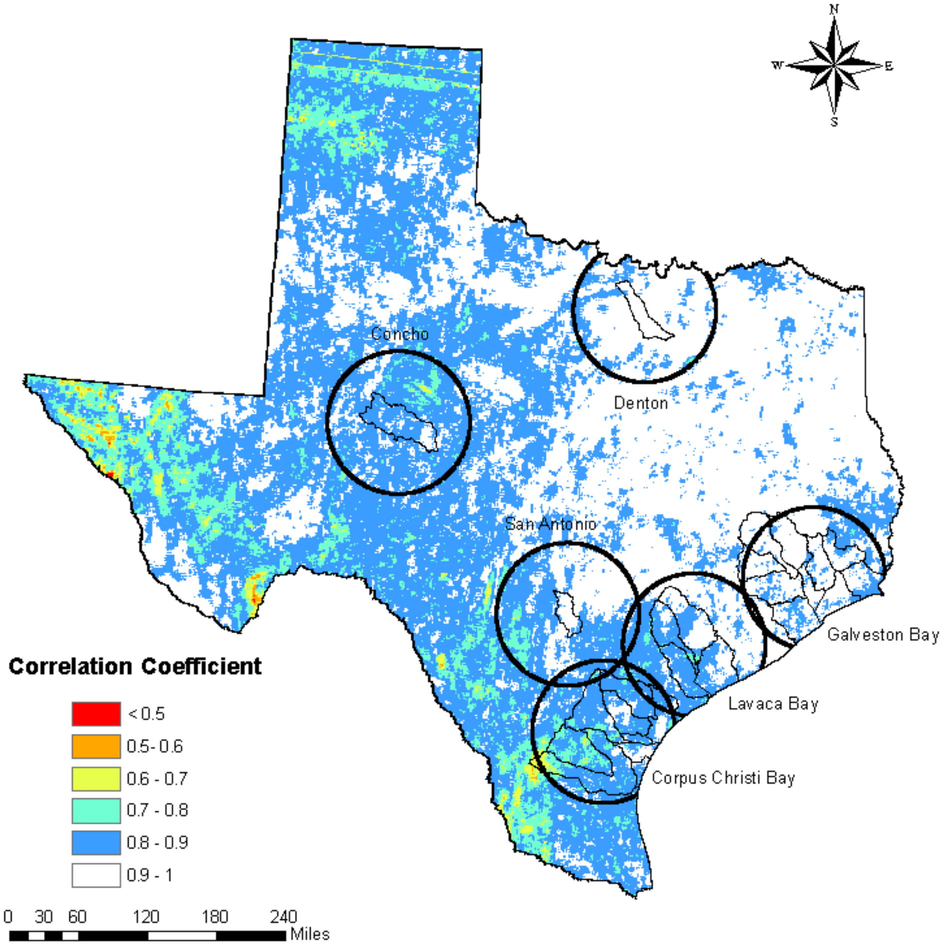


Figure 17. Correlation coefficient between time-series of data (2004) of NEXRAD grids displaced by 16km.

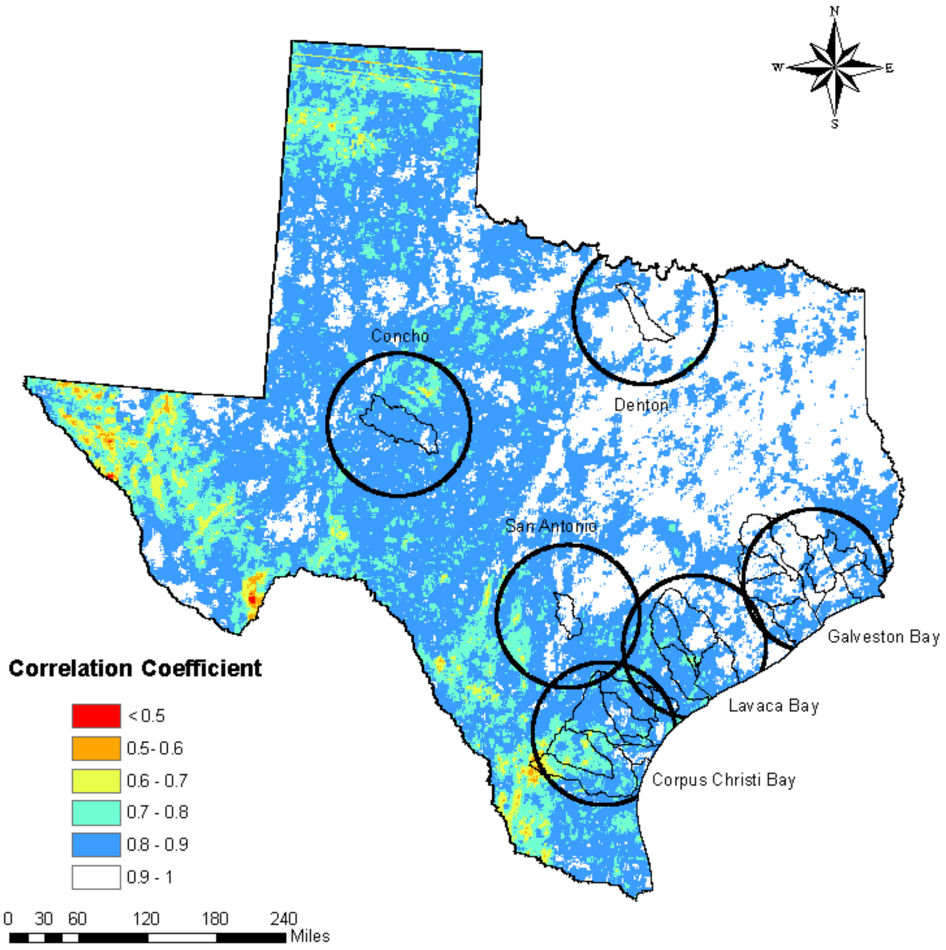
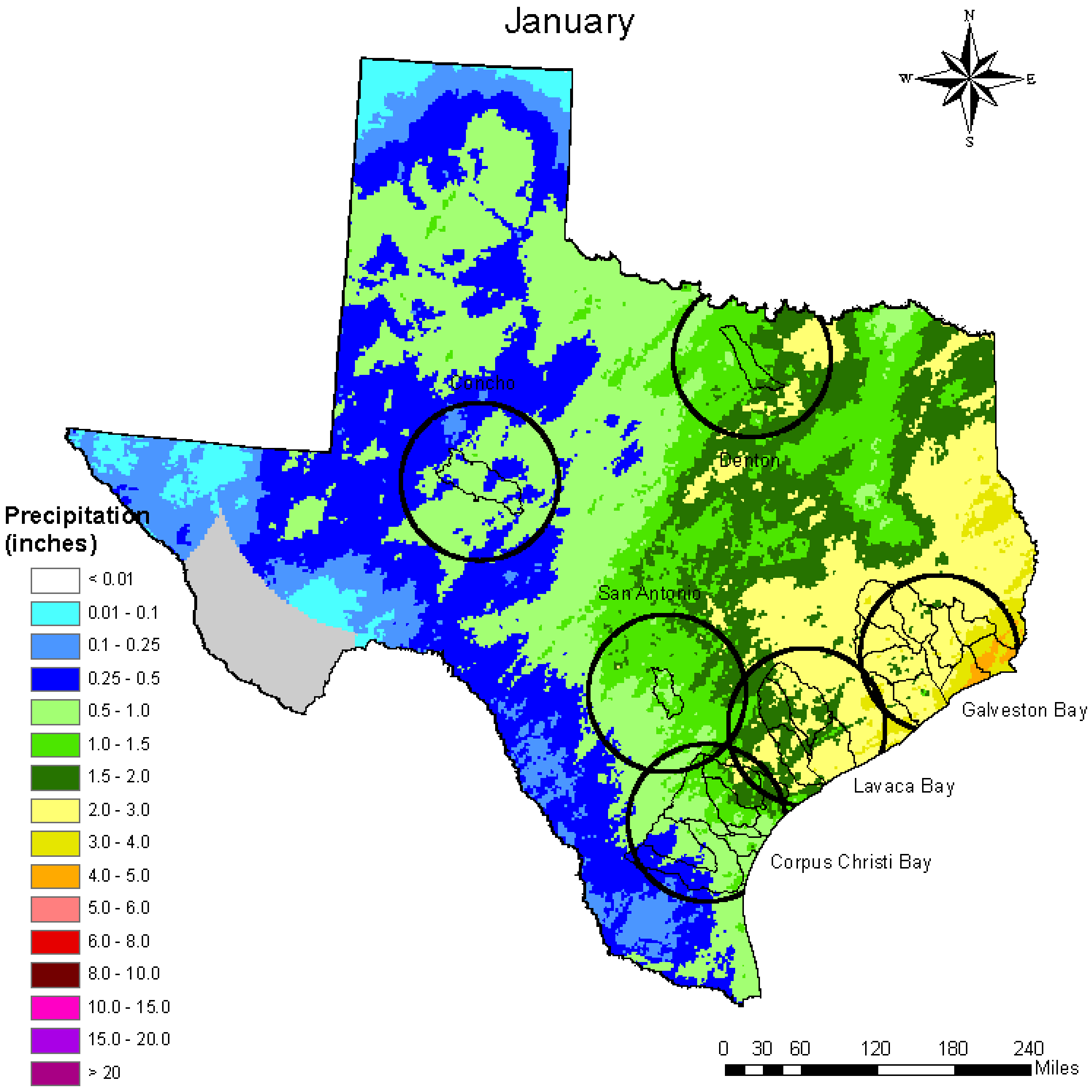


Figure 18. Correlation coefficient between time-series of data (2004) of NEXRAD grids displaced by 20km.

Average Monthly and annual precipitation


January
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Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Precipitation (inches)
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0.25 - 0.5
0.5 - 1.0
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3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
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8.0 - 10.0
10.0 - 15.0
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> 20
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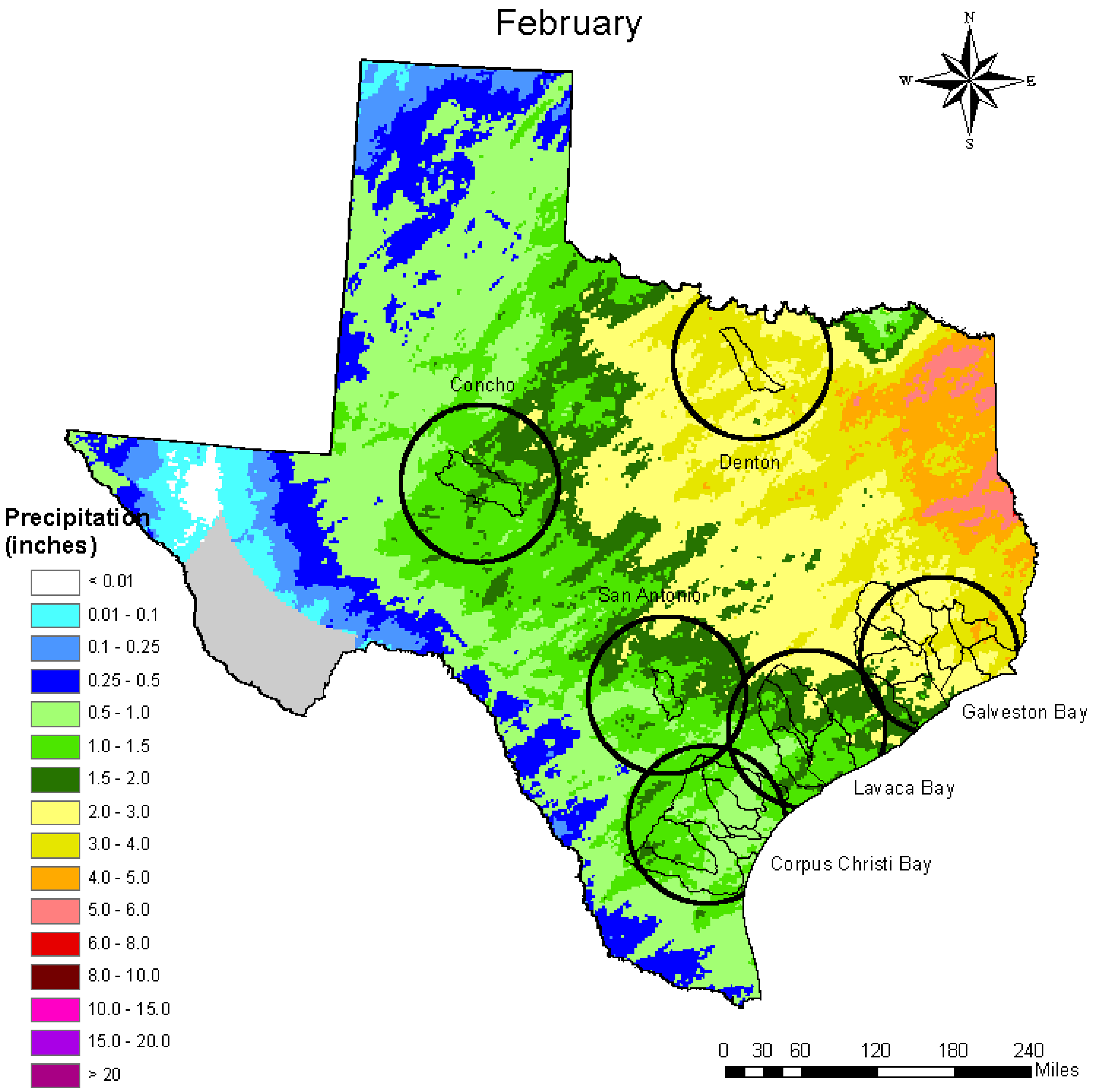
February
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Galveston Bay
Lavaca Bay
Corpus Christi Bay
Precipitation (inches)
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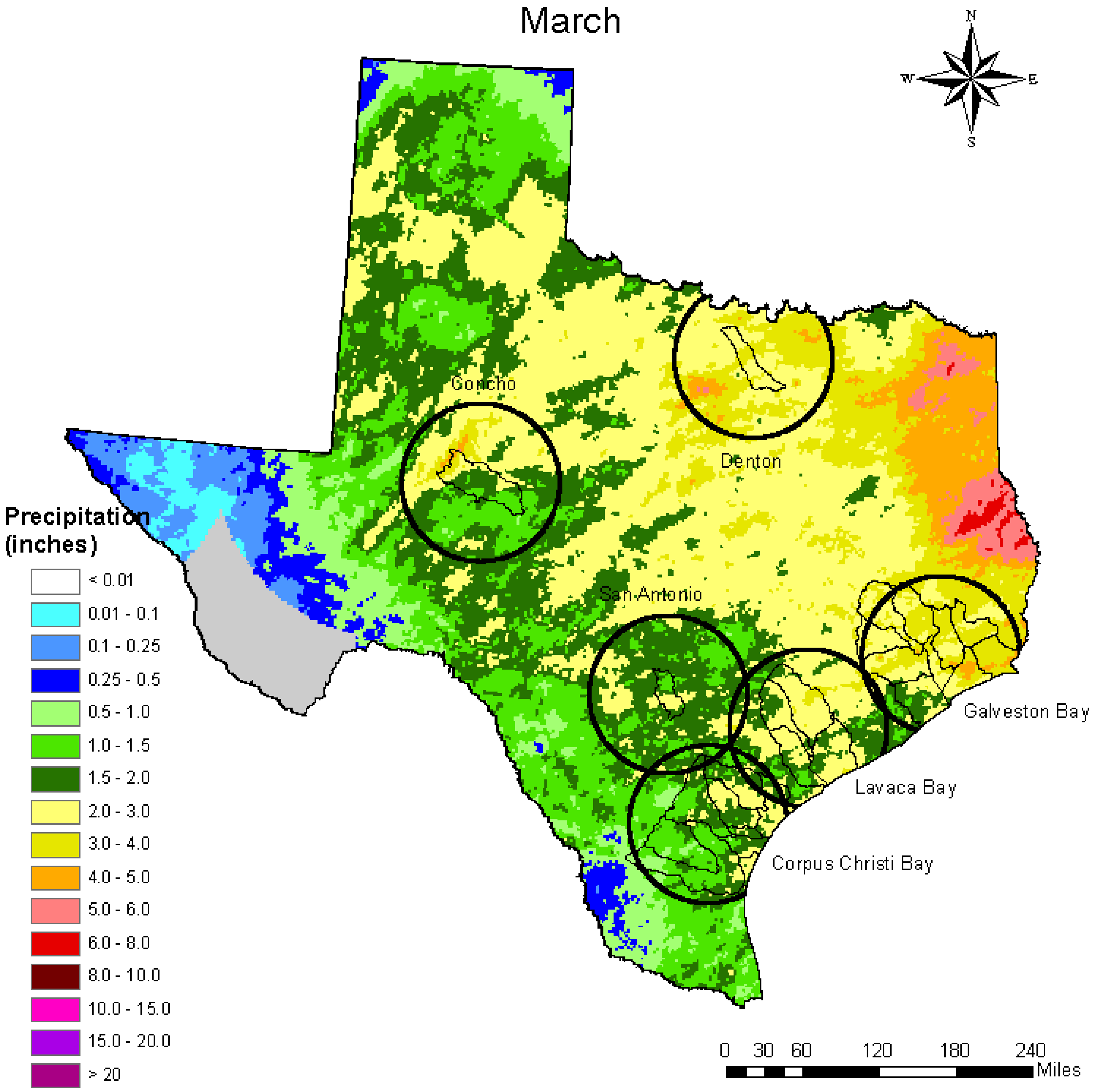
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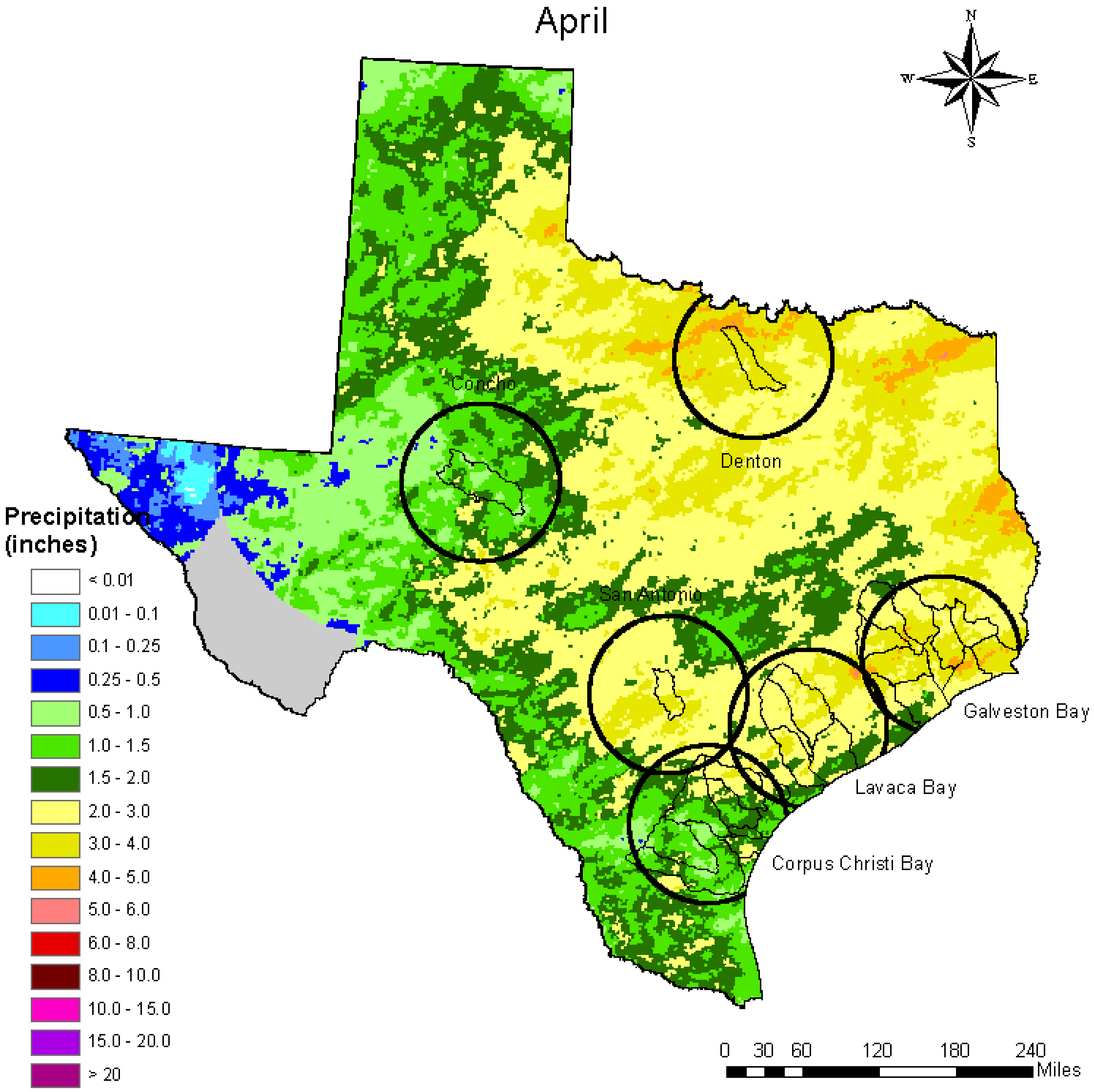
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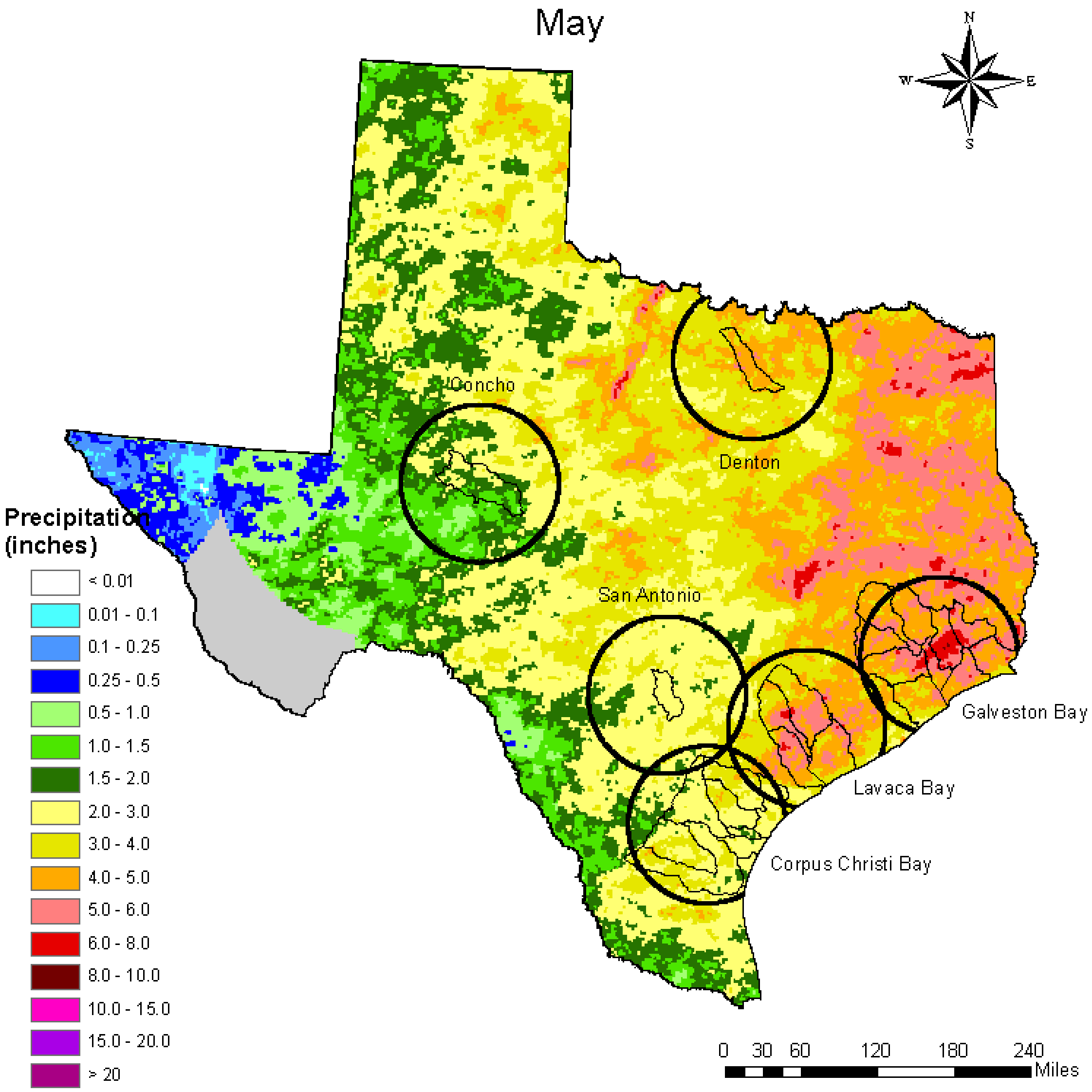
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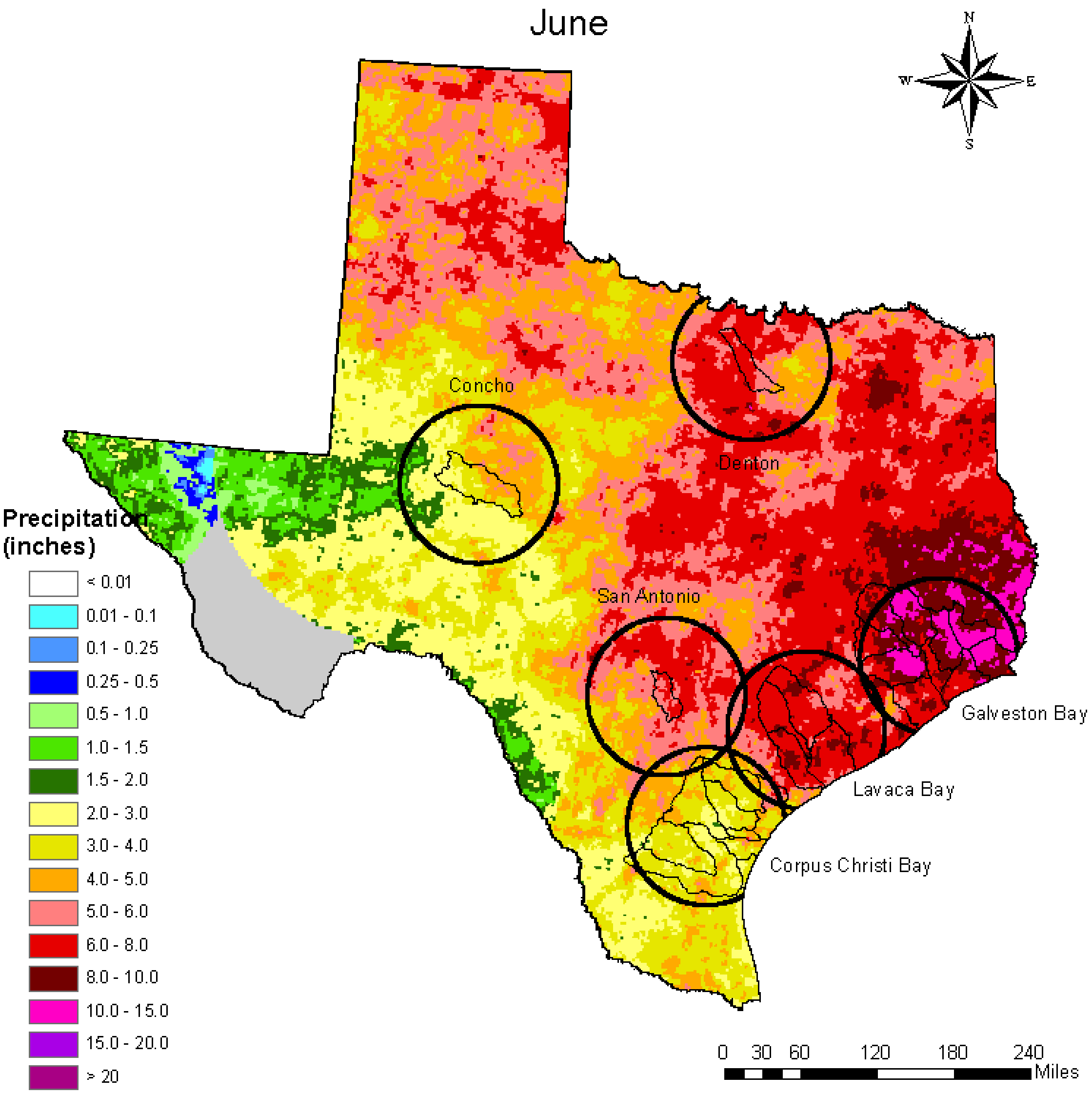
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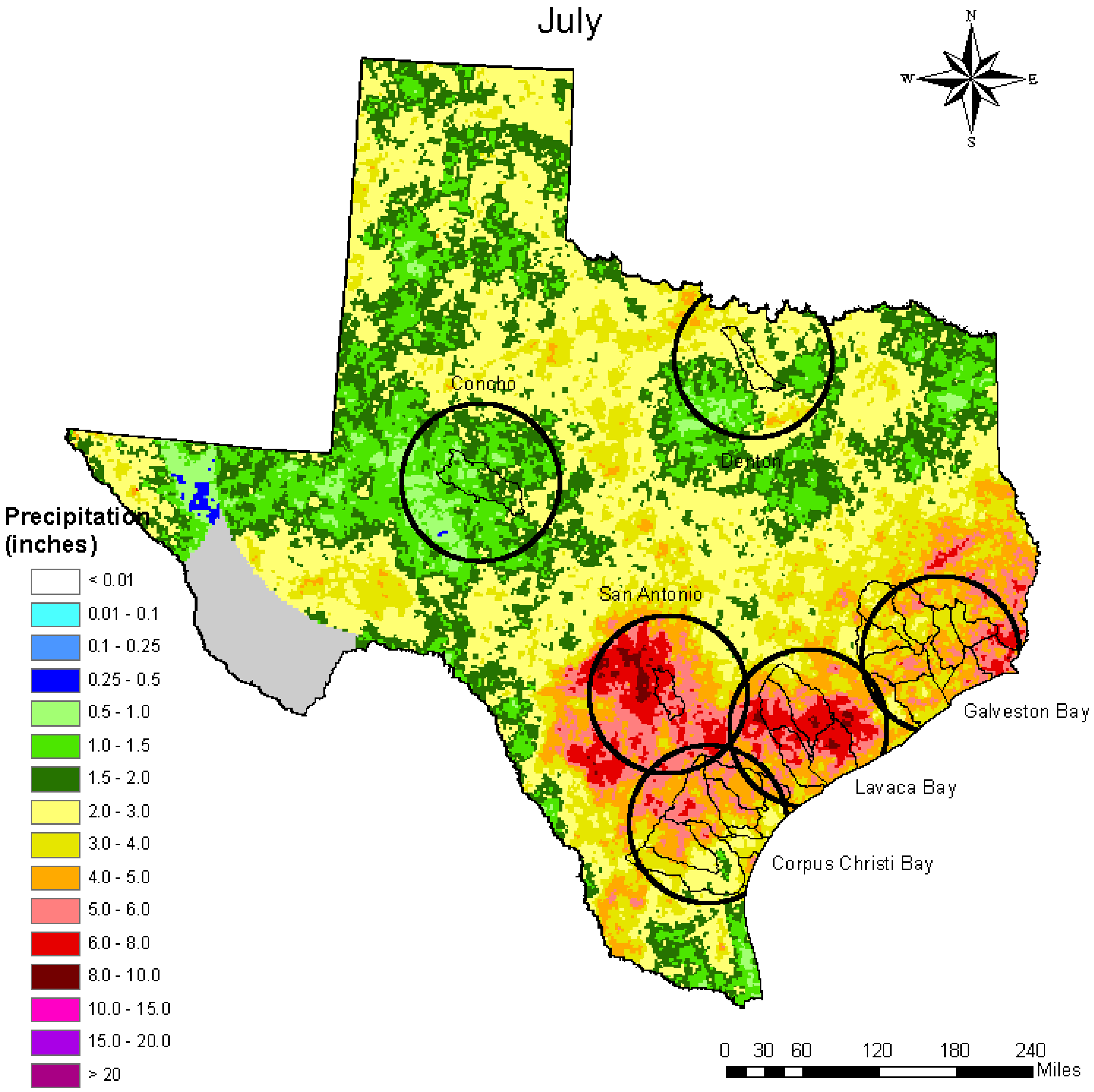
July
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San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
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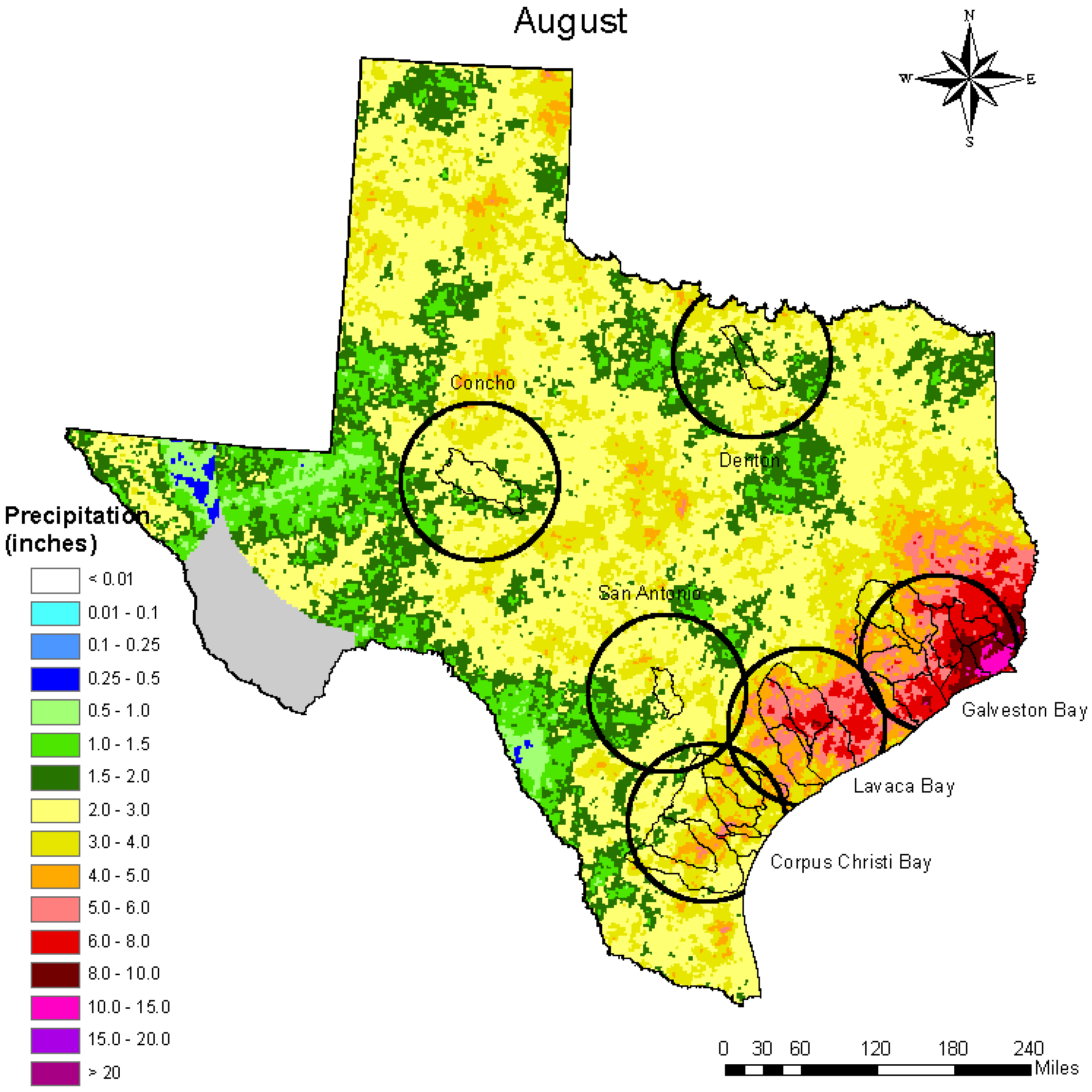
August
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Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Precipitation (inches)
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0.1 - 0.25
0.25 - 0.5
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1.5 - 2.0
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10.0 - 15.0
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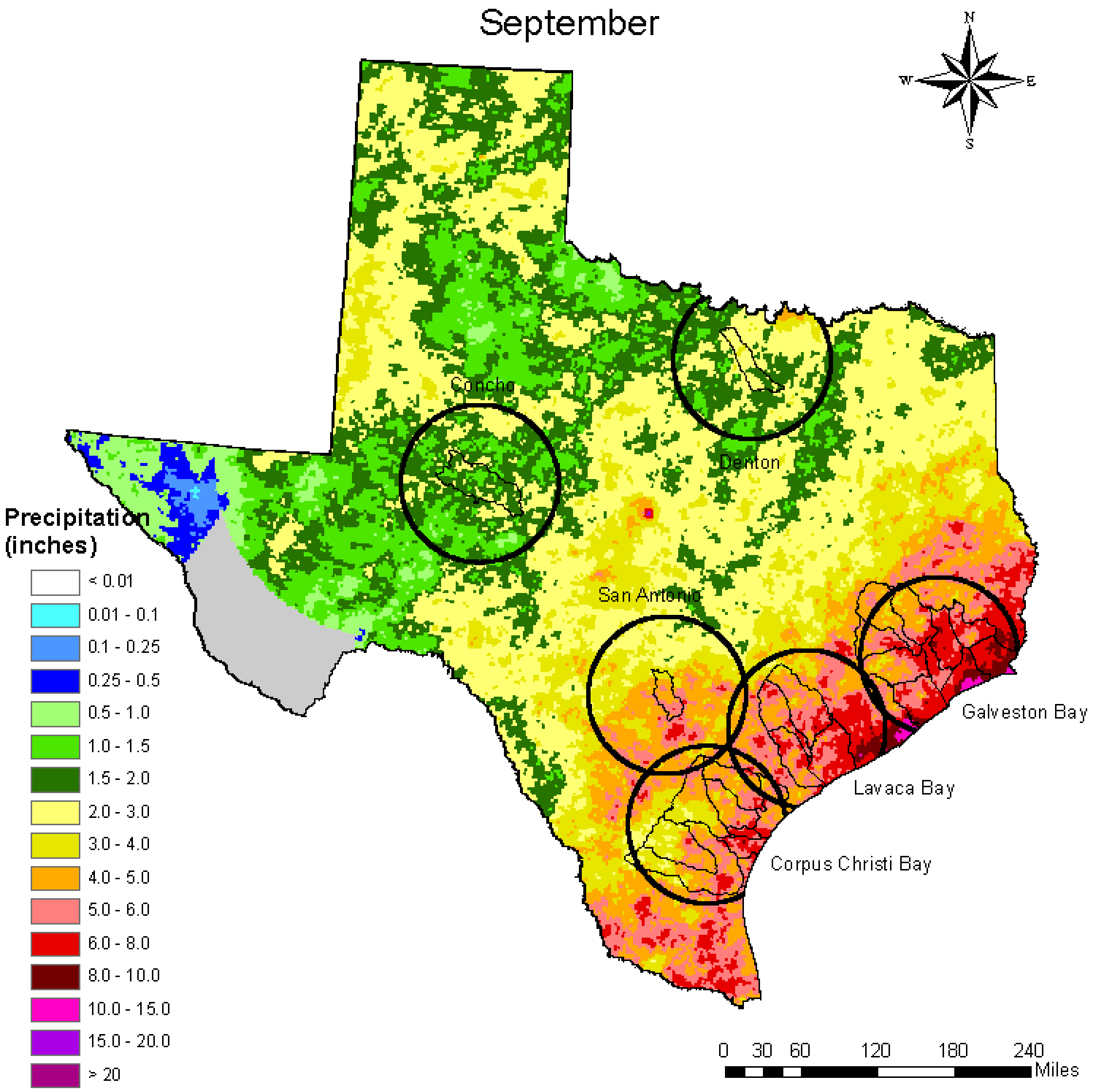
September
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Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Precipitation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
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1.0 - 1.5
1.5 - 2.0
2.0 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
10.0 - 15.0
15.0 - 20.0
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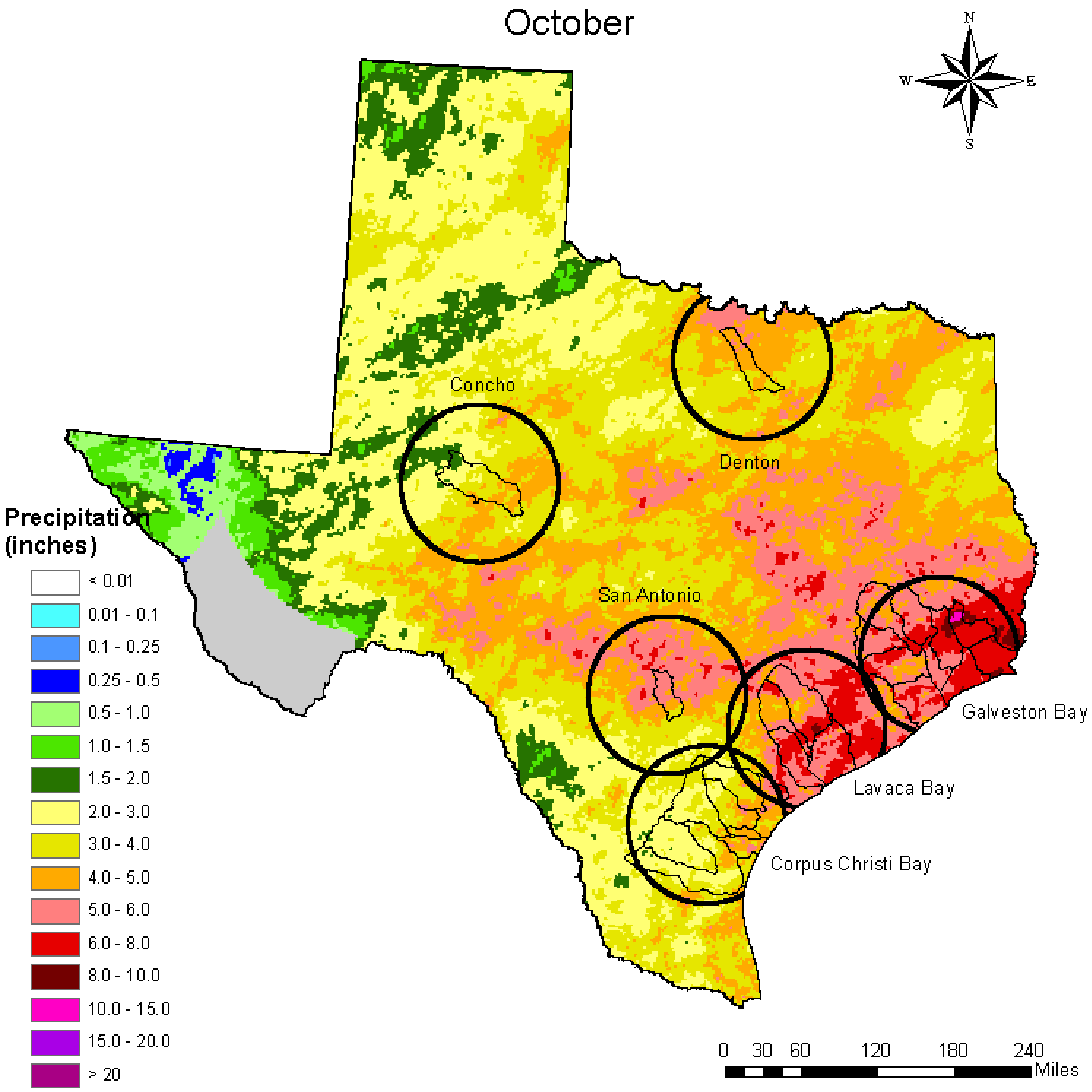
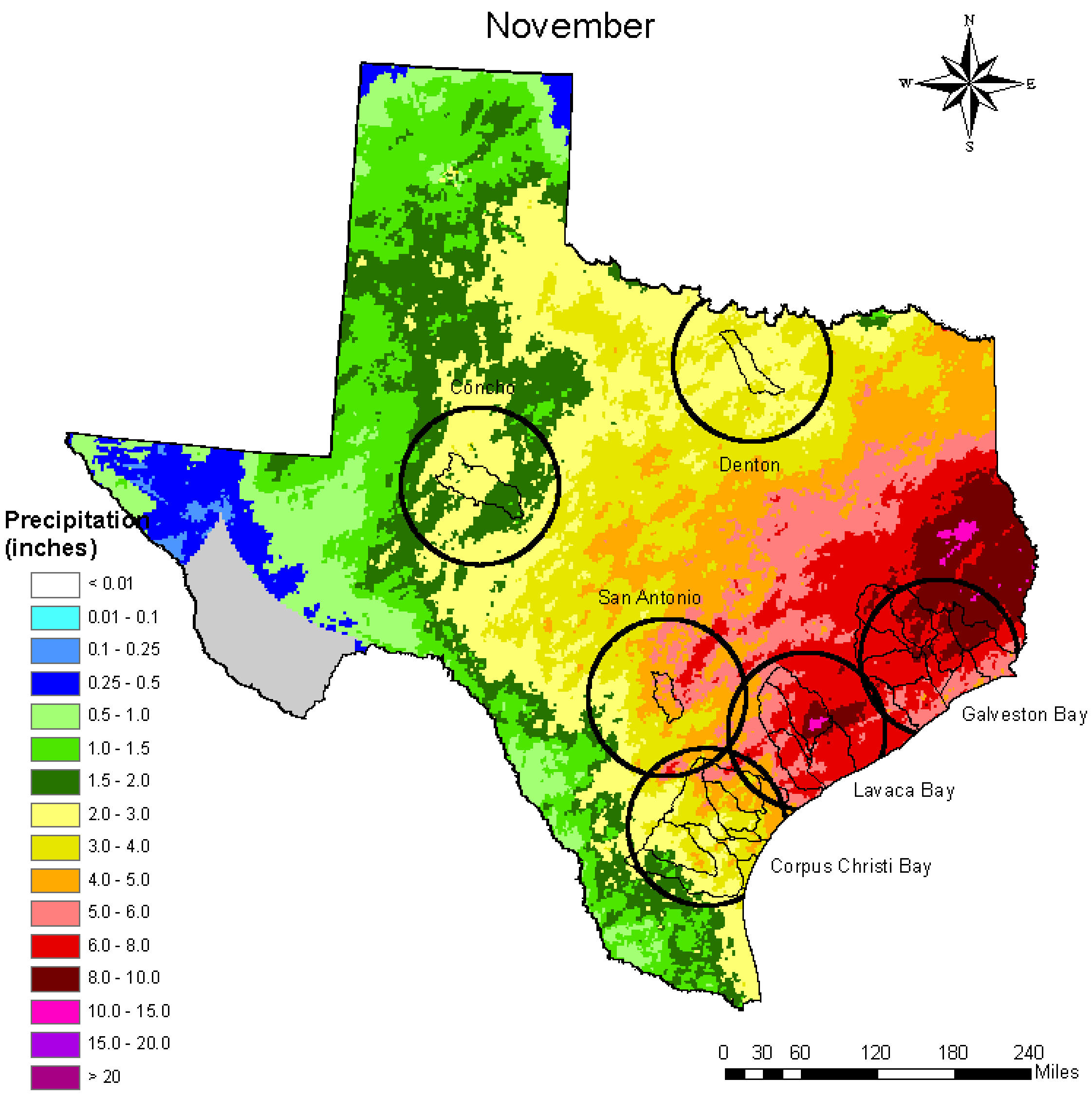
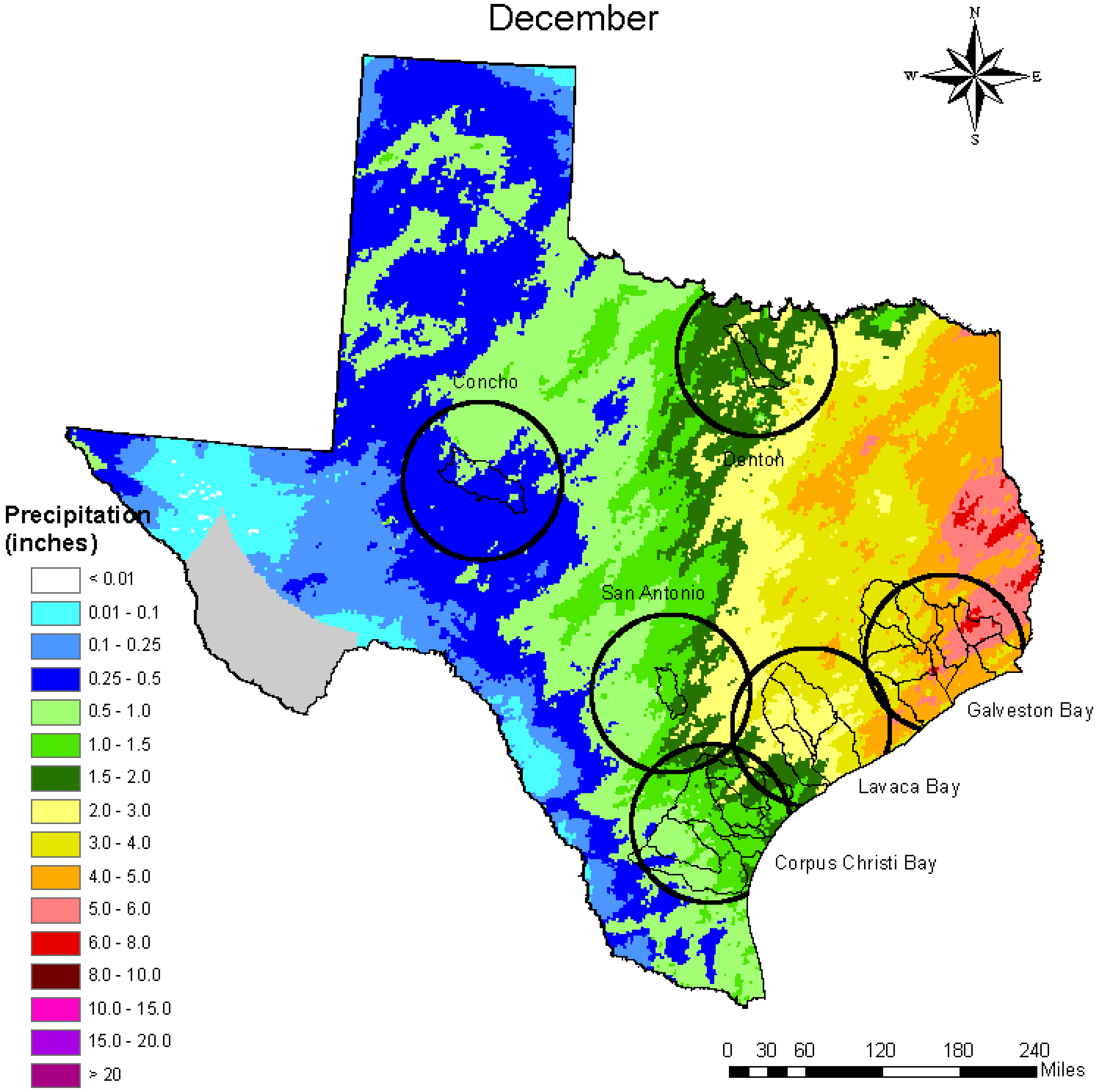
180
240
Miles

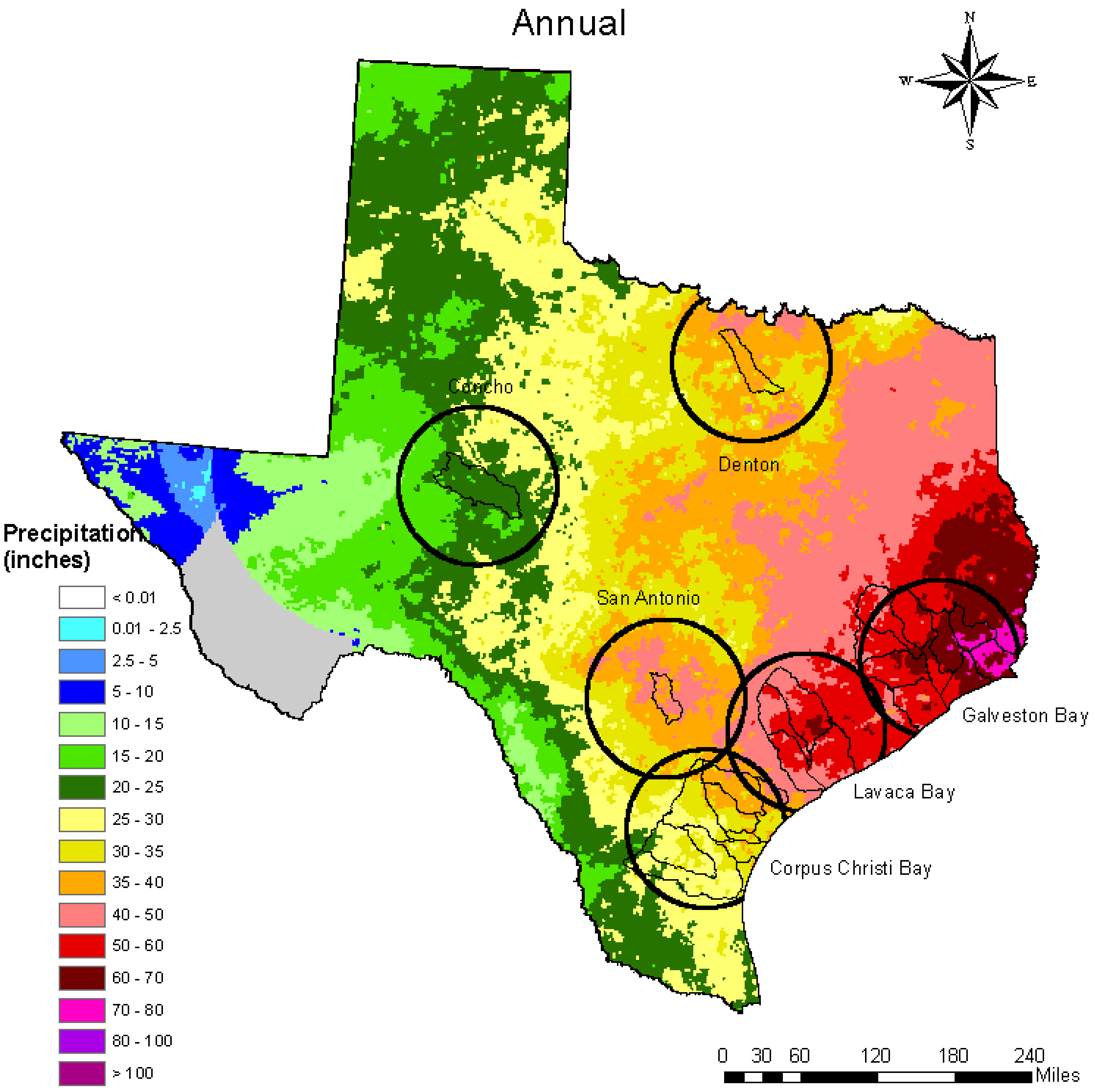

October
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Precipitation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
10.0 - 15.0
15.0 - 20.0
> 20
0 30 60 120 180 240
Miles


November
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Precipitation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
10.0 - 15.0
15.0 - 20.0
> 20
0
30
60
120
180
240
Miles

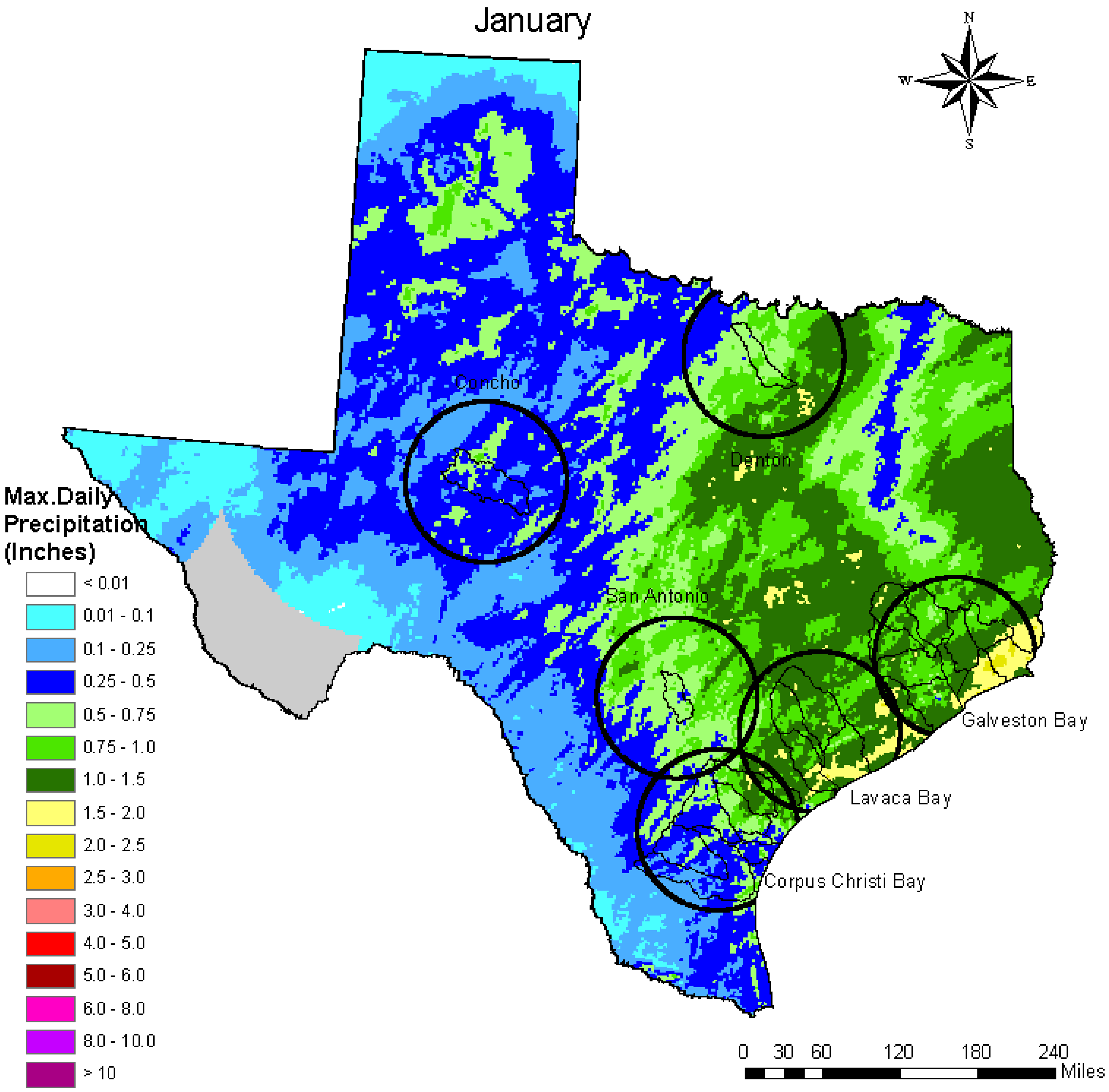


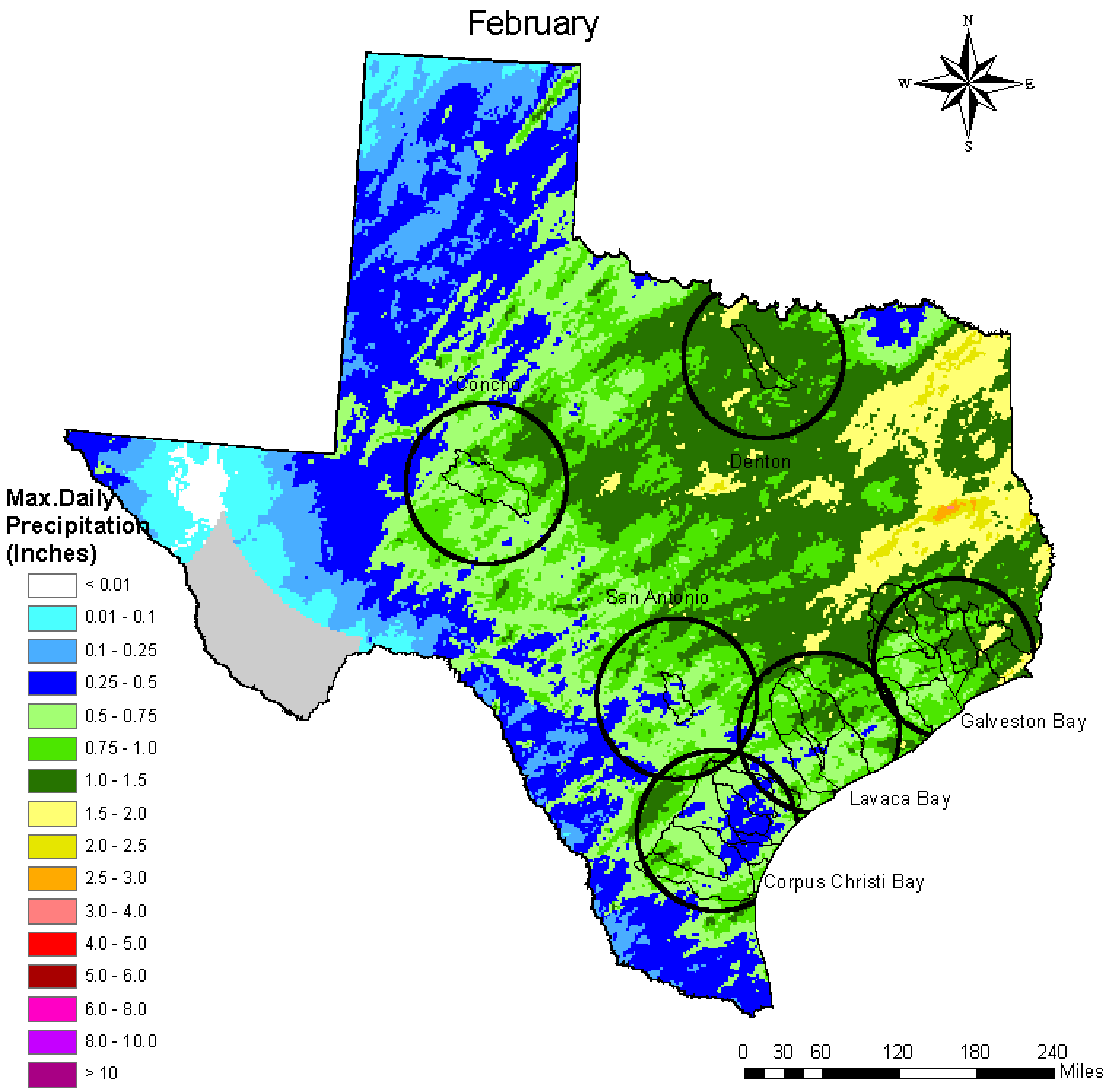
December

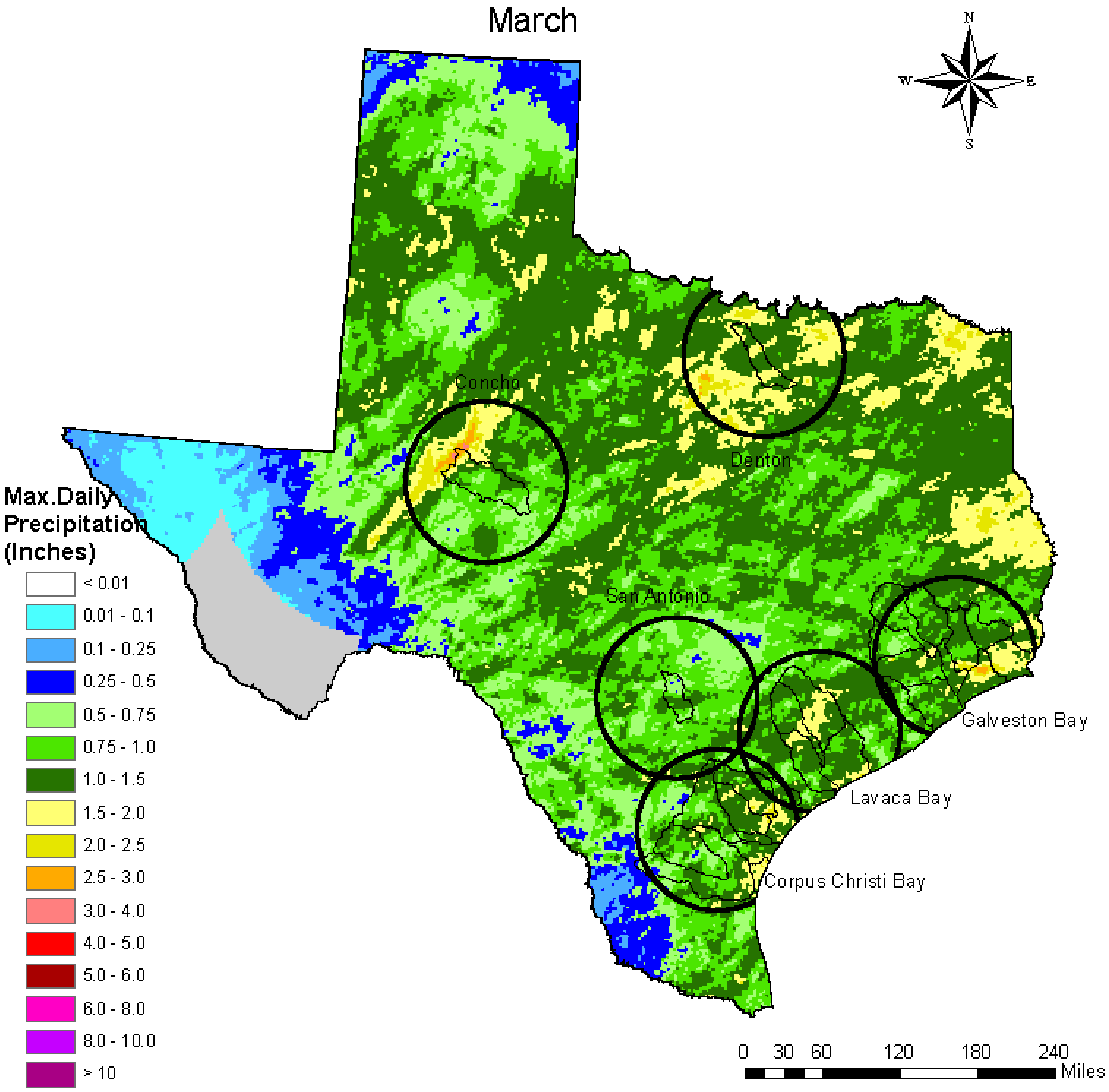
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Precipitation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
10.0 - 15.0
15.0 - 20.0
> 20
0 30 60 120 180 240
Miles

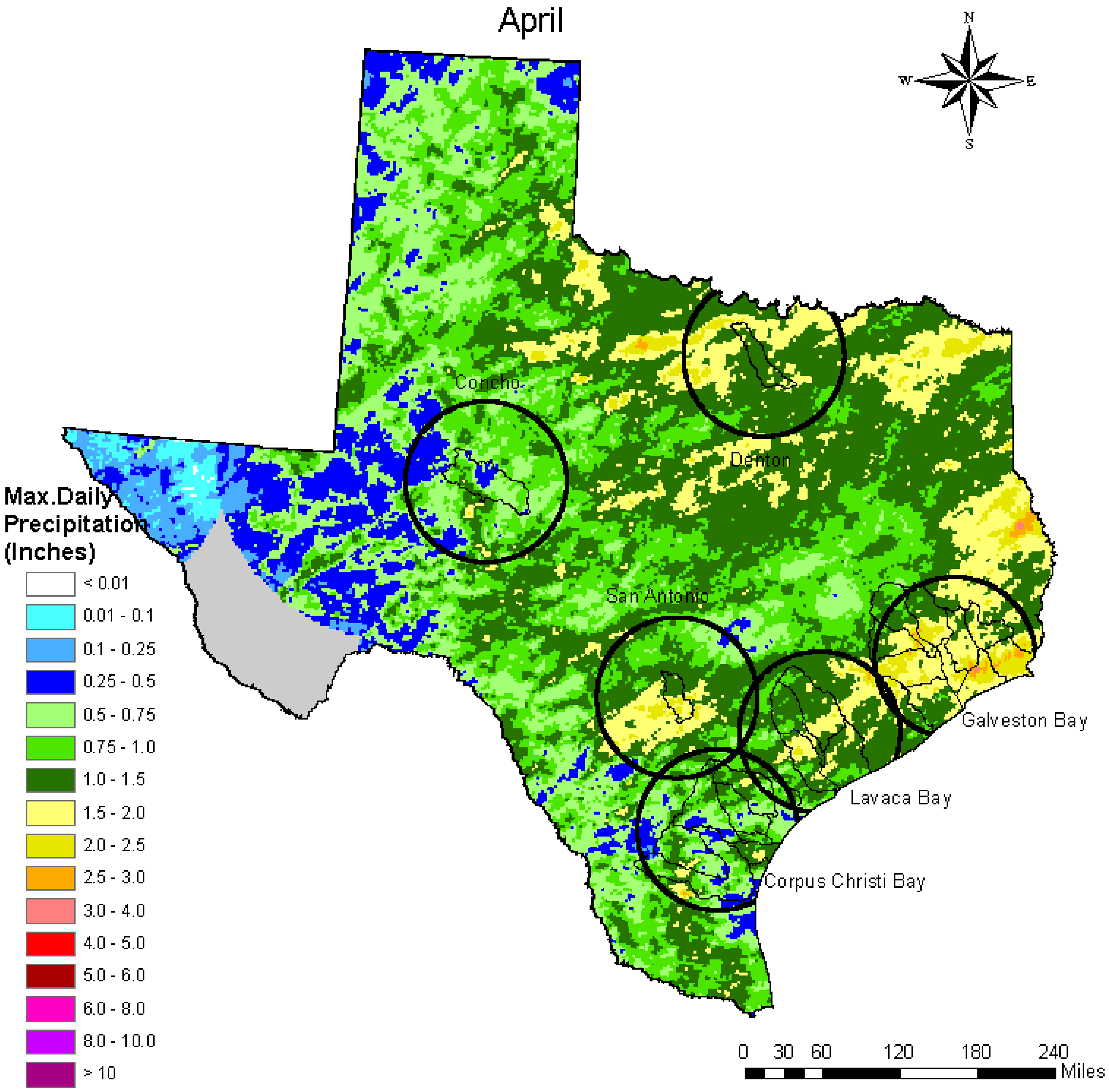

Annual
N
W
E
S
Precipitation (inches)
< 0.01
0.01 - 2.5
2.5 - 5
5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 100
> 100
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
0 30 60 120 180 240
Miles

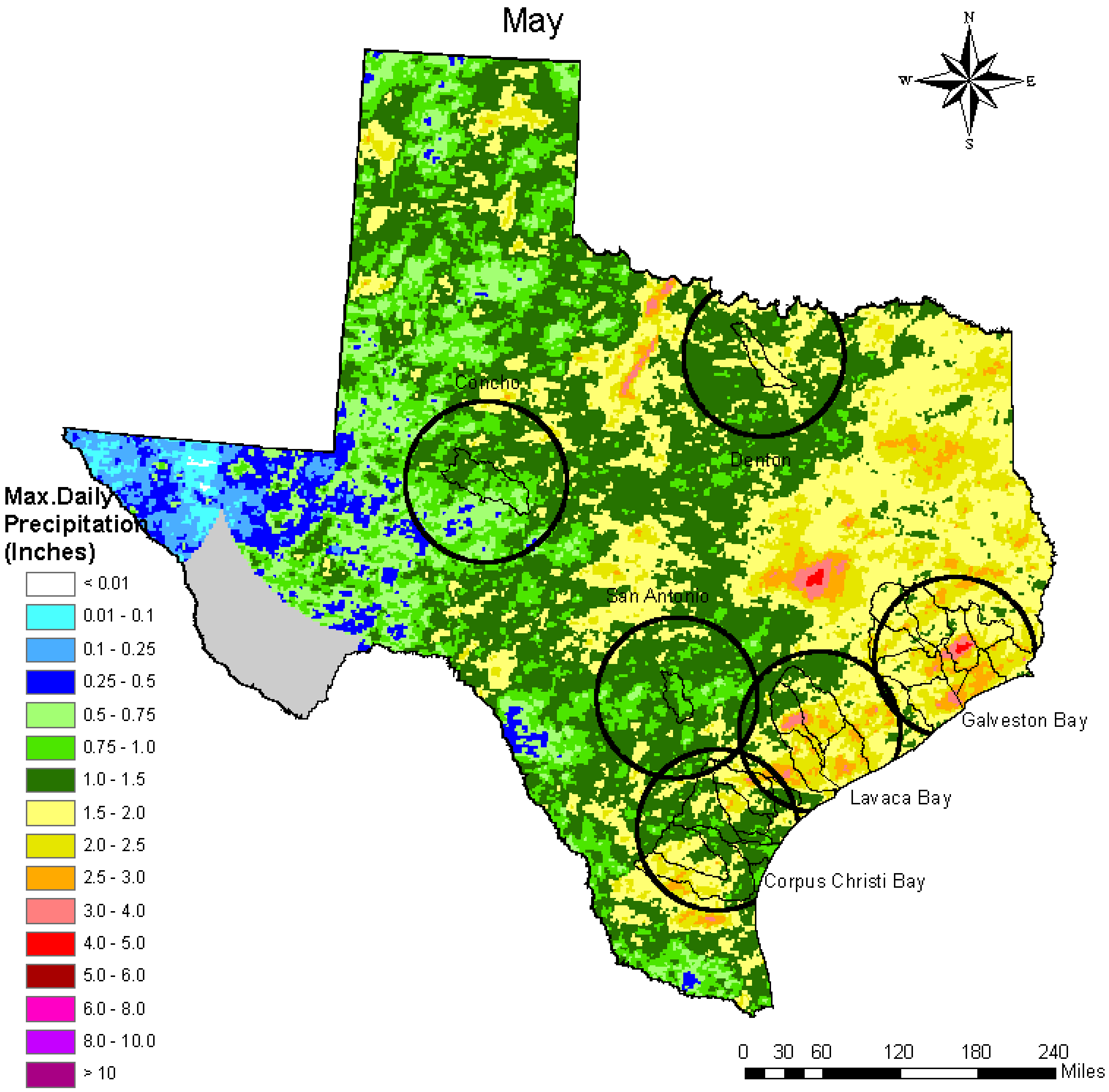
Average Monthly and annual maximum daily precipitation

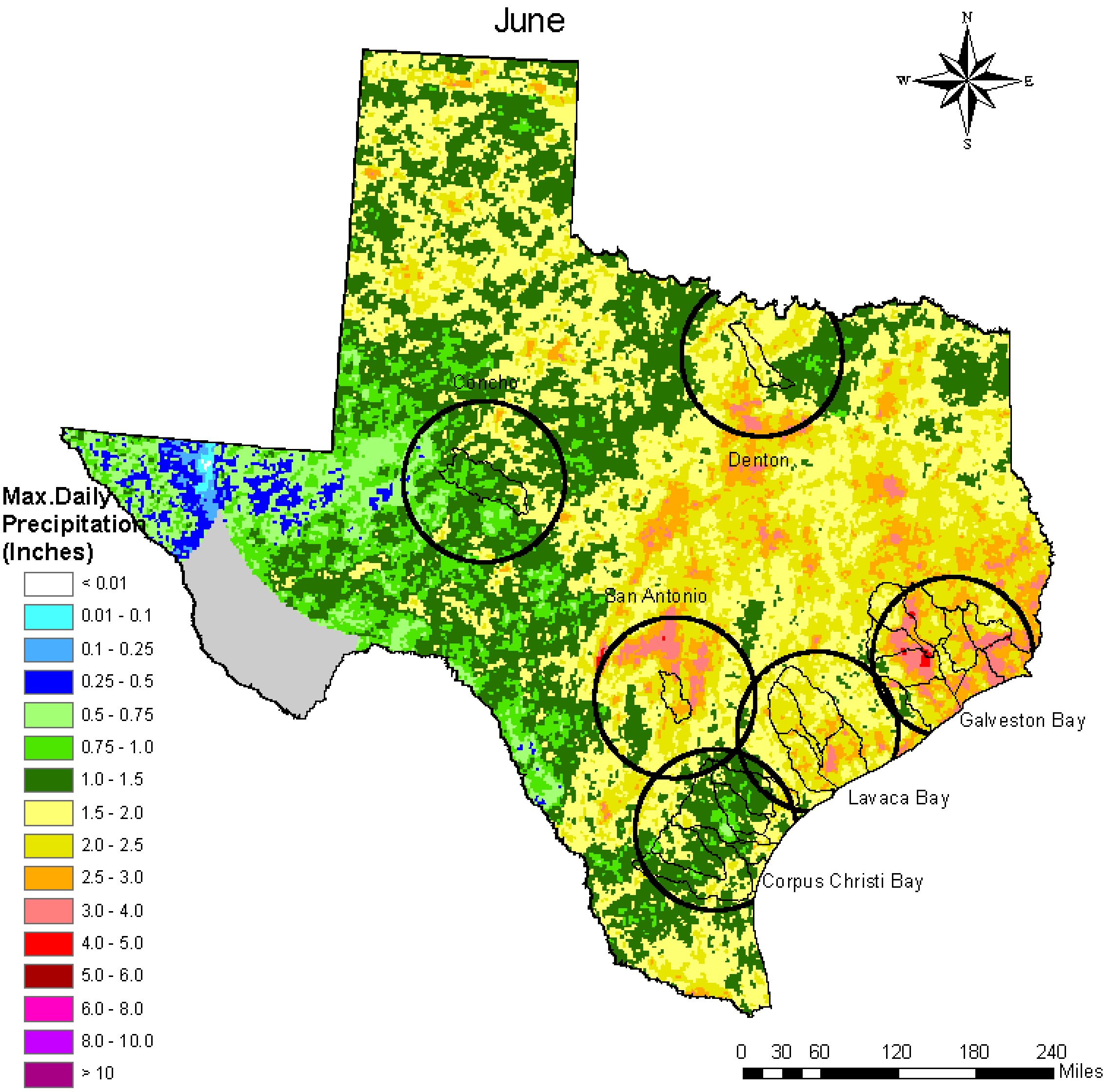

January
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
0
30
60
120
180
240
Miles

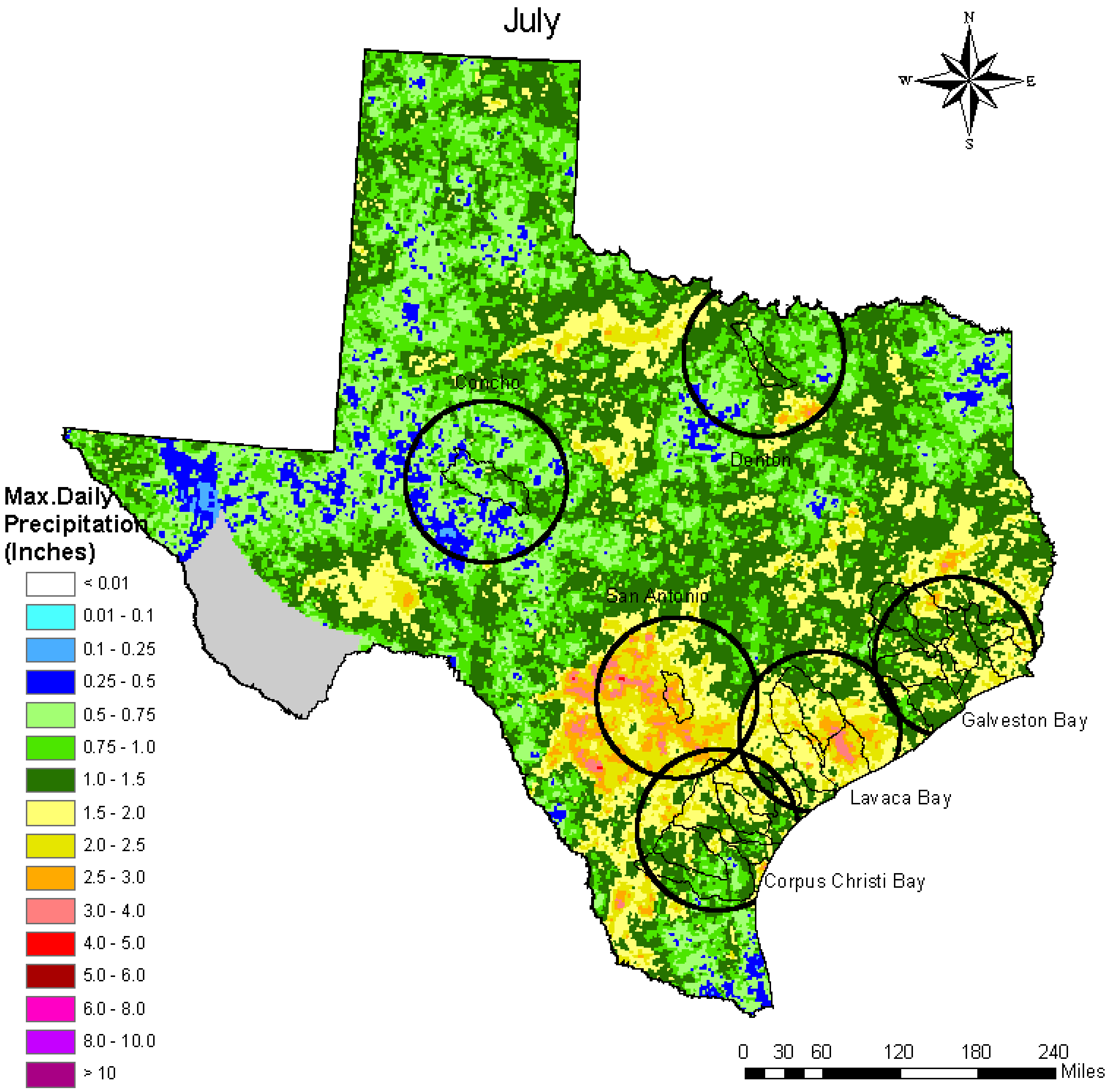

February
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
0 30 60 120 180 240
Miles

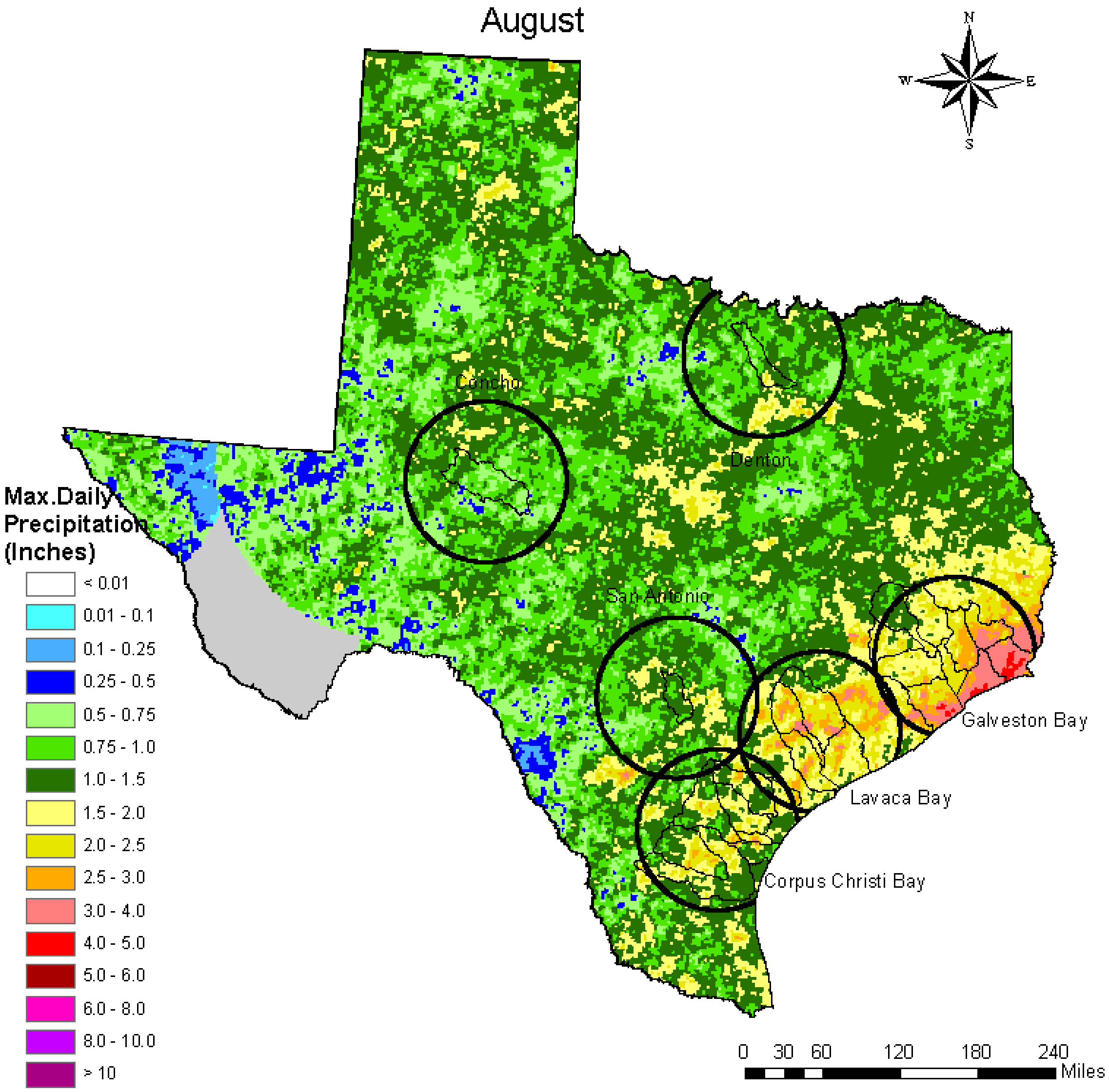

March
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
0
30
60
120
180
240
Miles

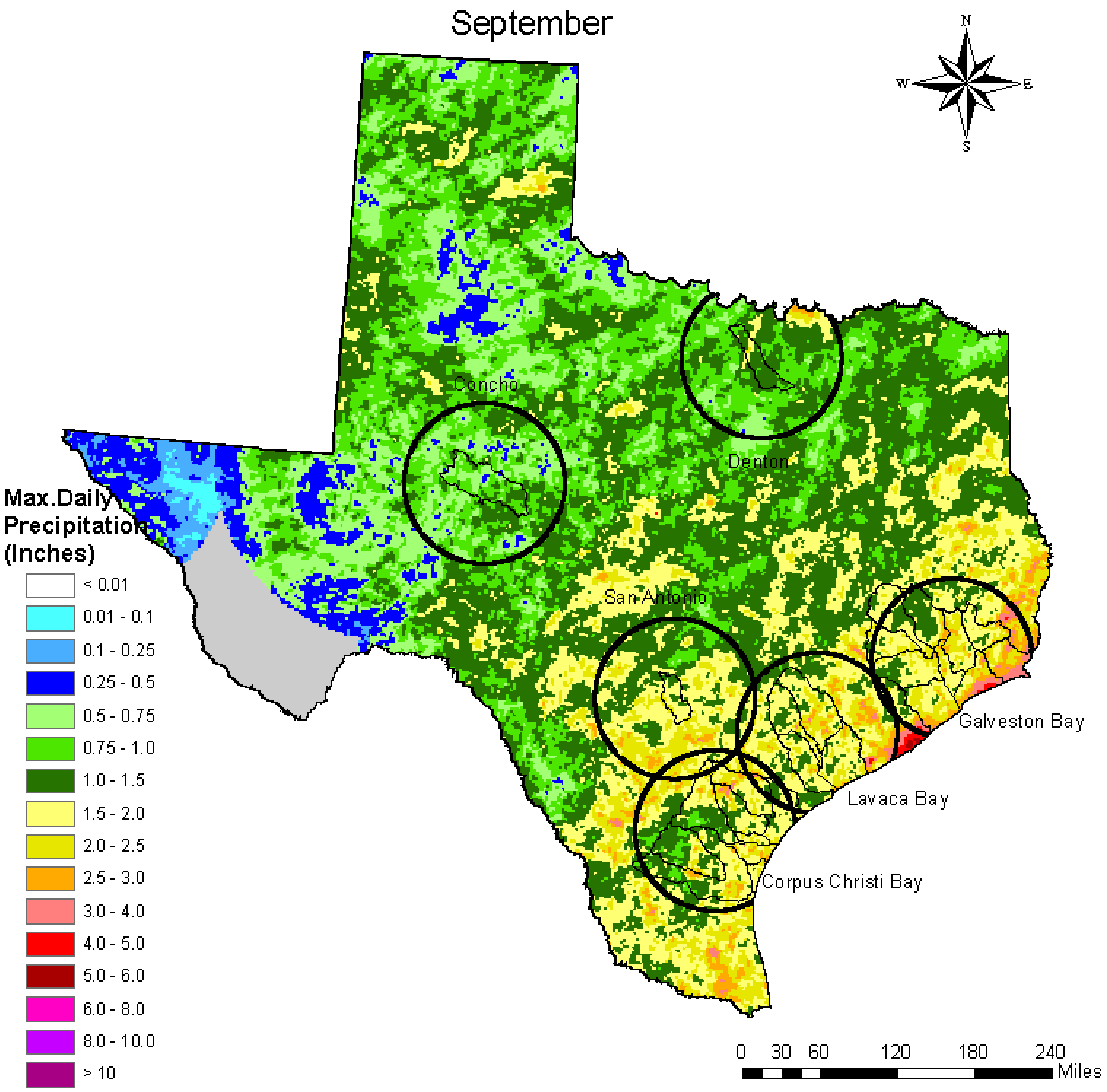

April
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
0
30
60
120
180
240
Miles


May
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
0
30
60
120
180
240
Miles

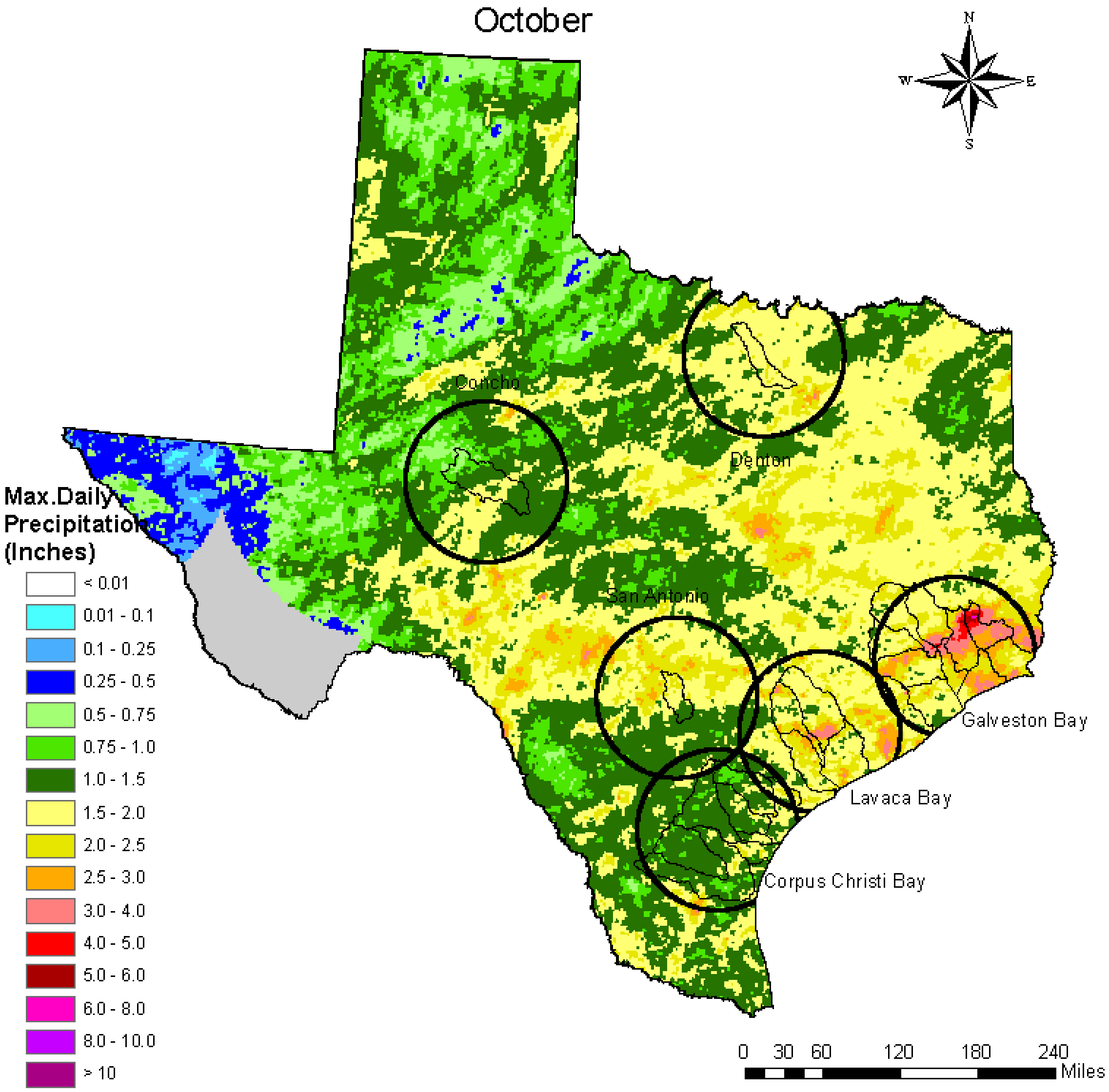

June
N
W
E
S
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
0
30
60
120
180
240
Miles

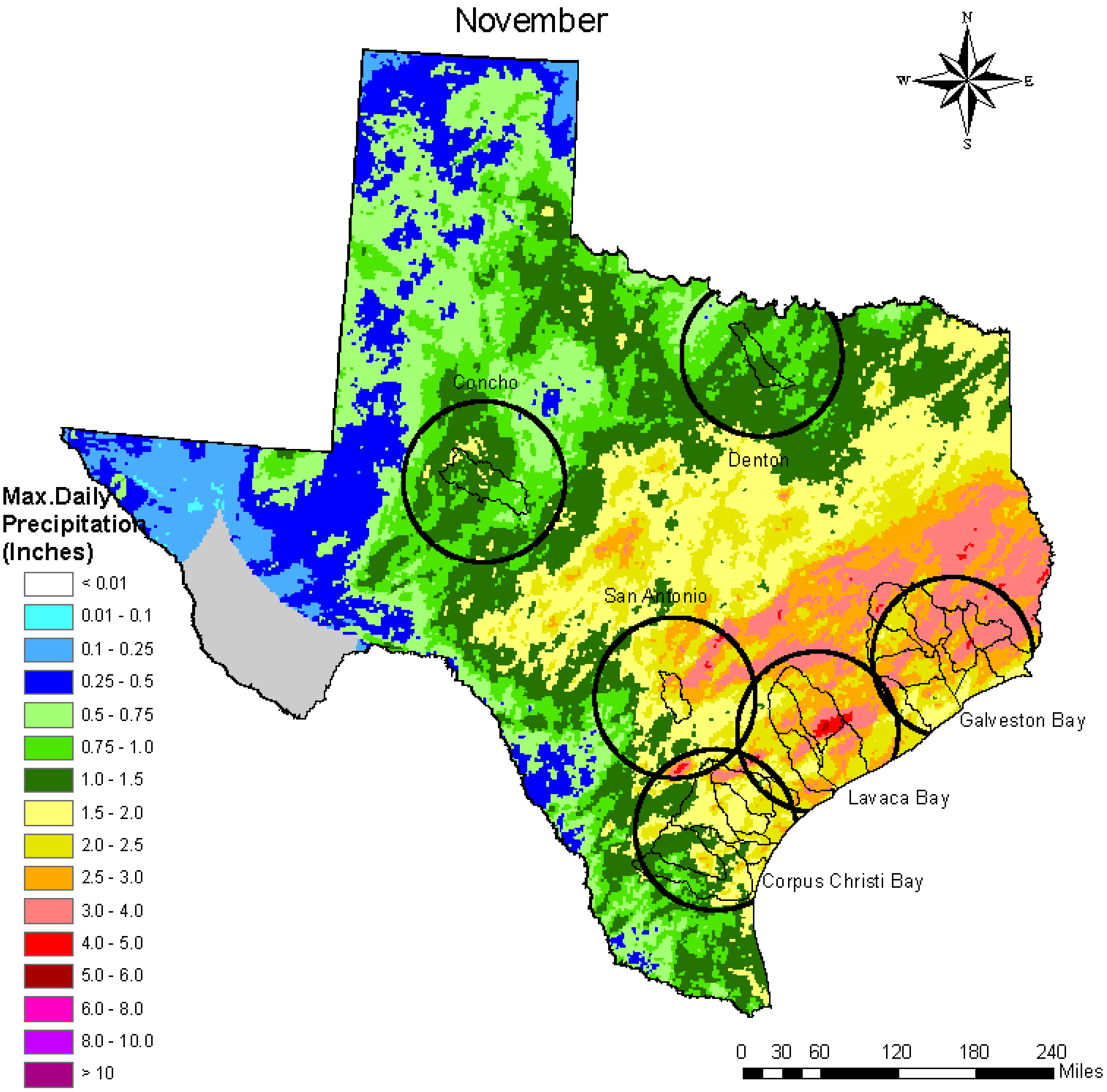

July
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
0
30
60
120
180
240
Miles

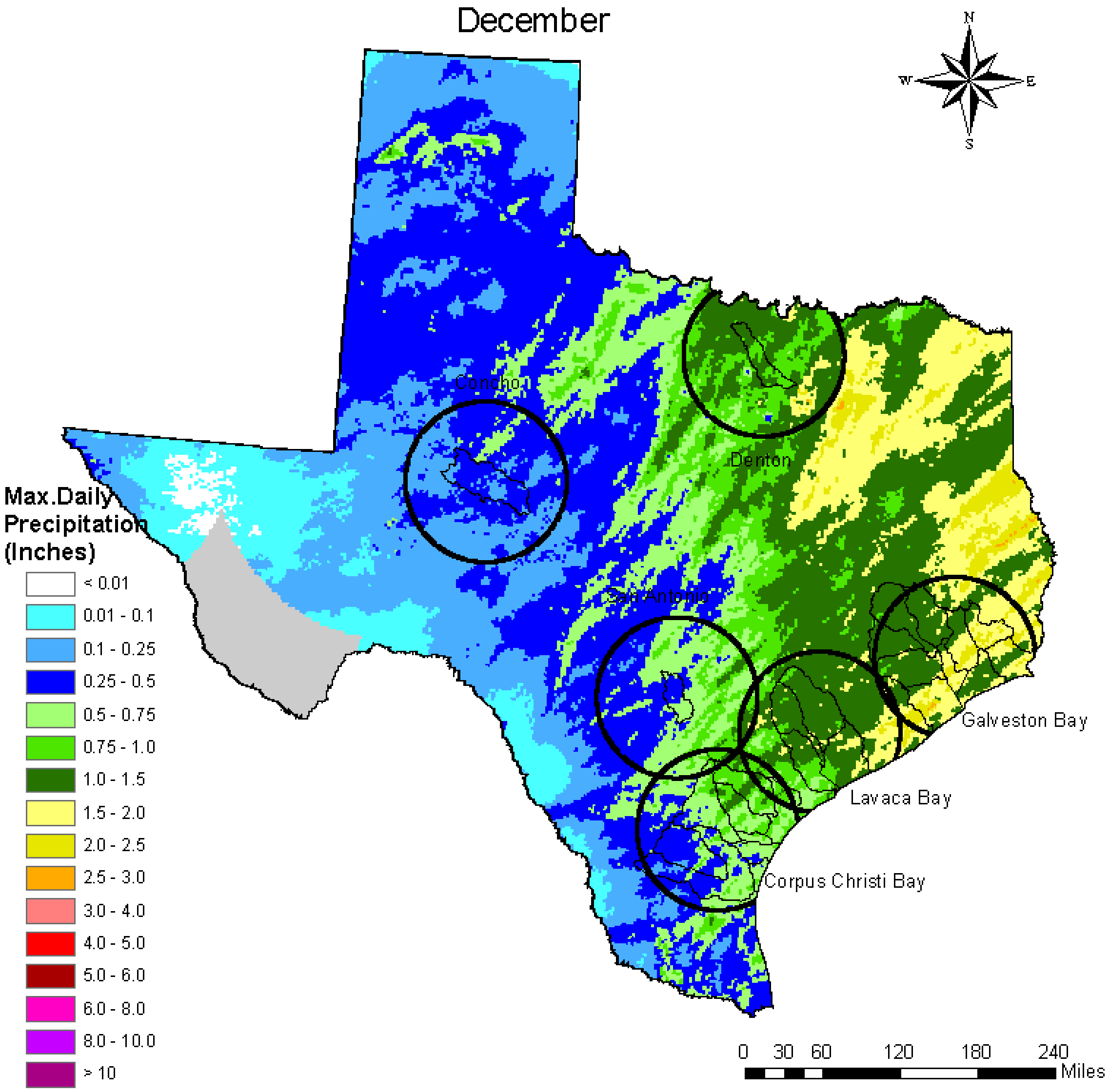

August
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
0 30 60 120 180 240
Miles

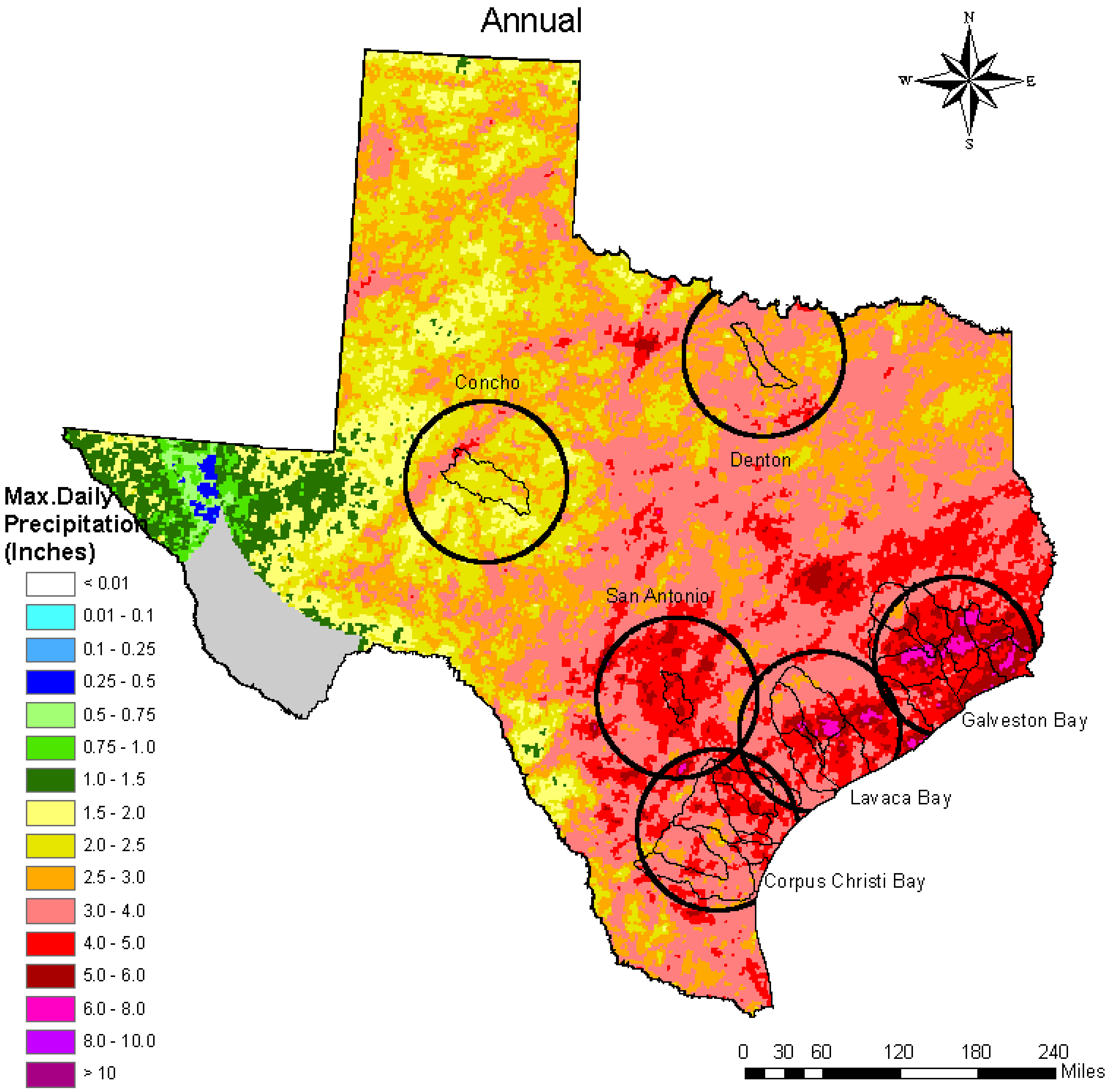


September
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
0
30
60
120
180
240
Miles

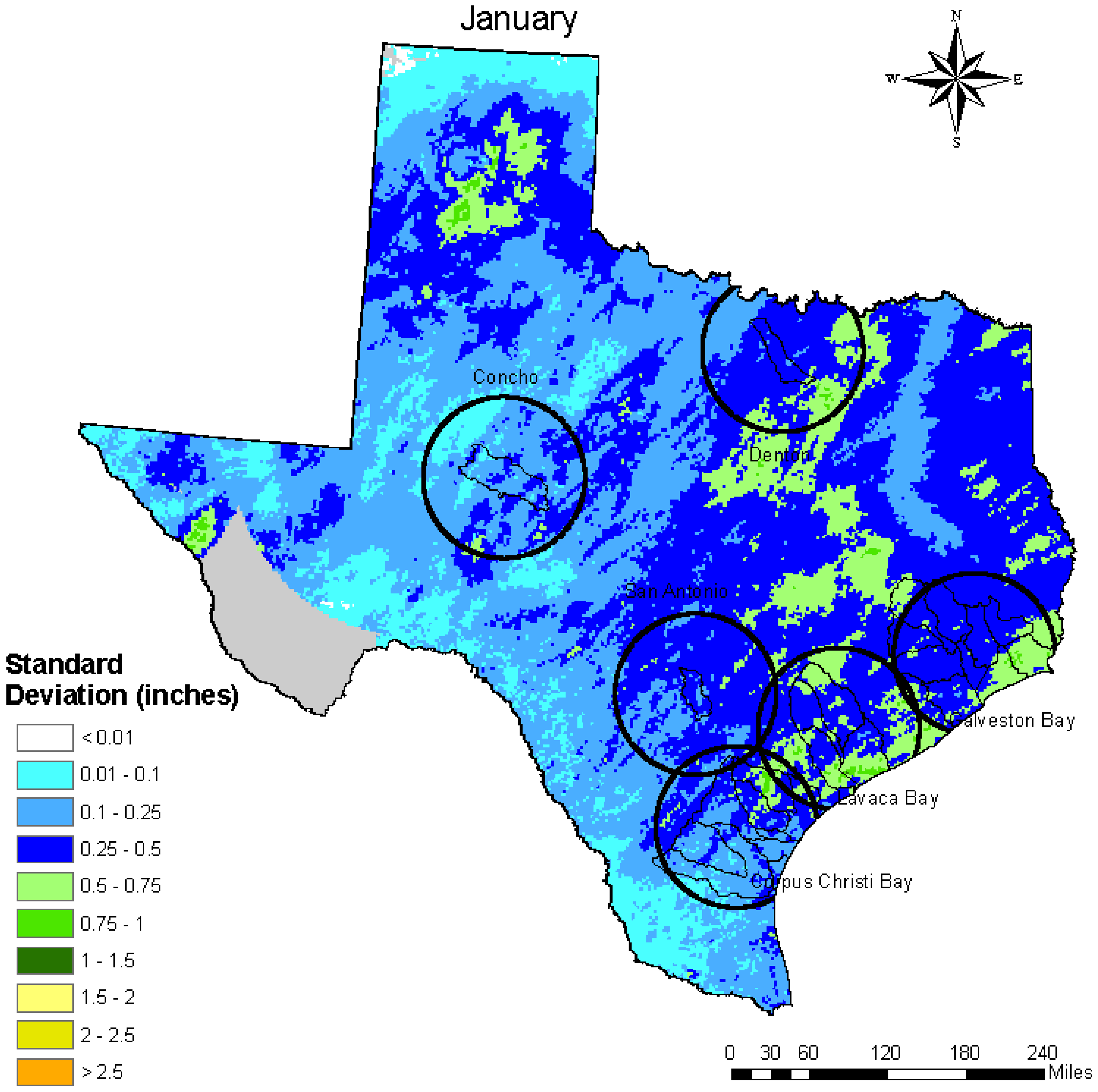

October
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Max.Daily
Precipitation
(Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
0
30
60
120
180
240
Miles

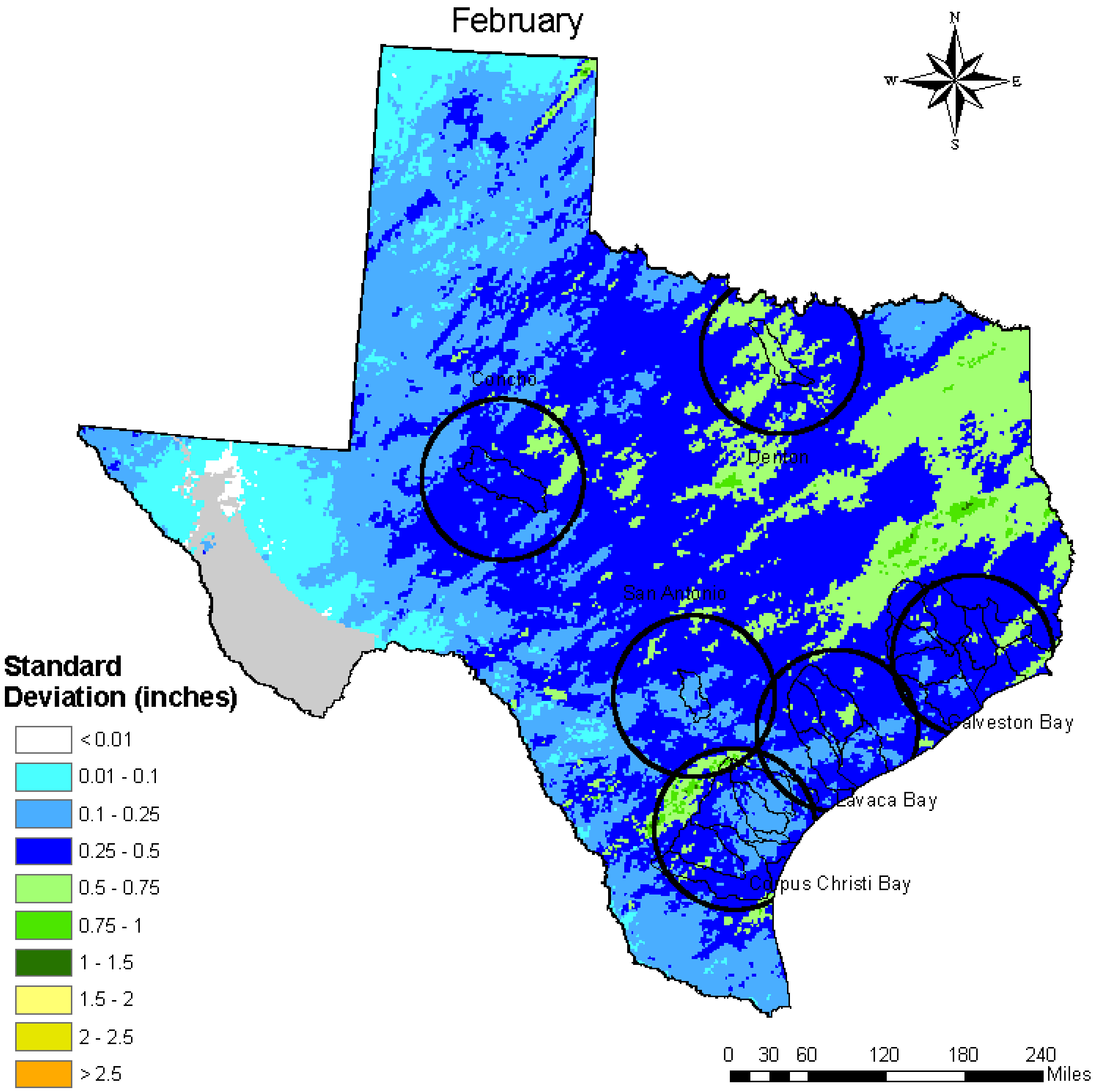

November
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
0 30 60 120 180 240
Miles

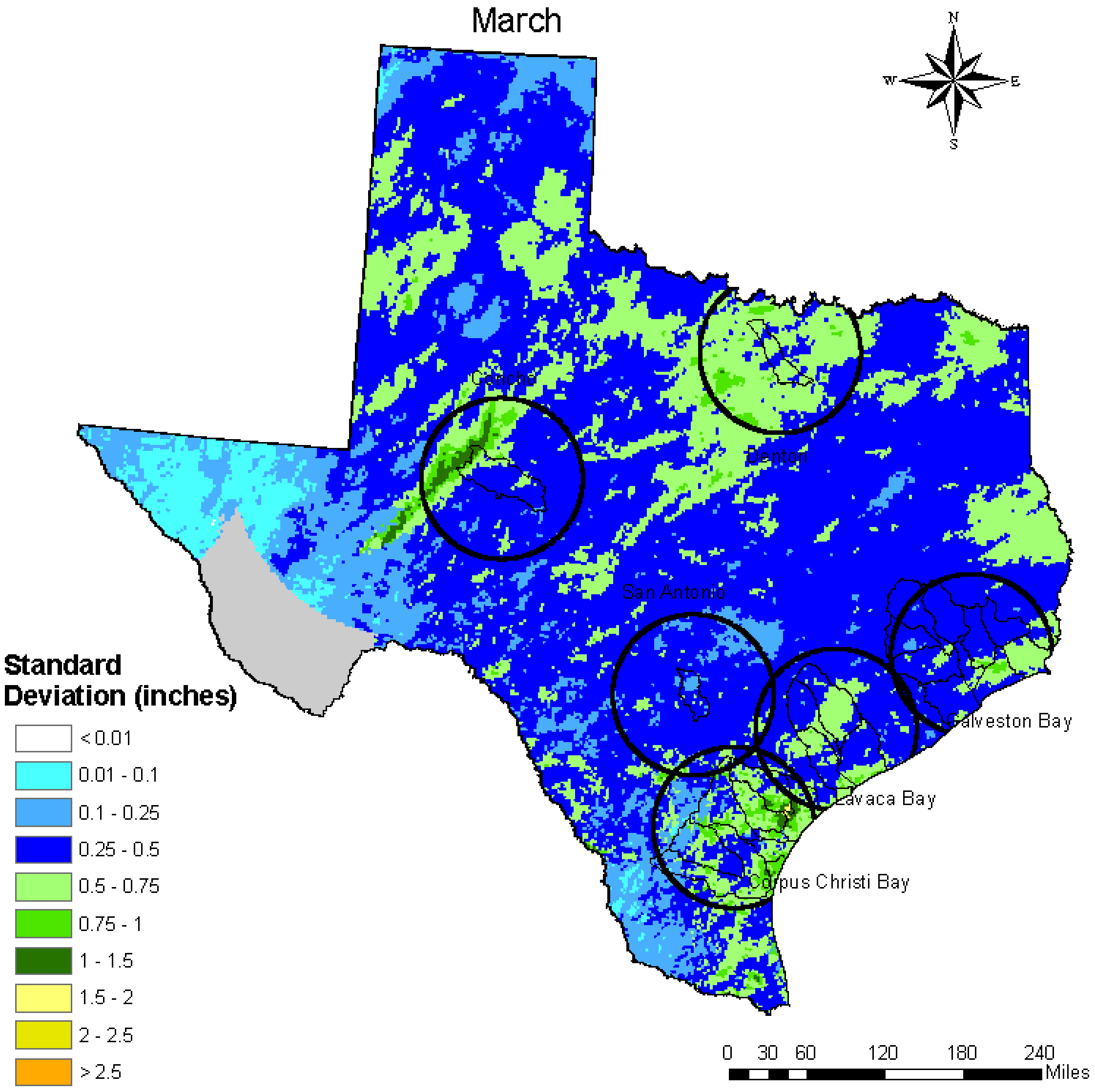

December
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
0 30 60 120 180 240
Miles

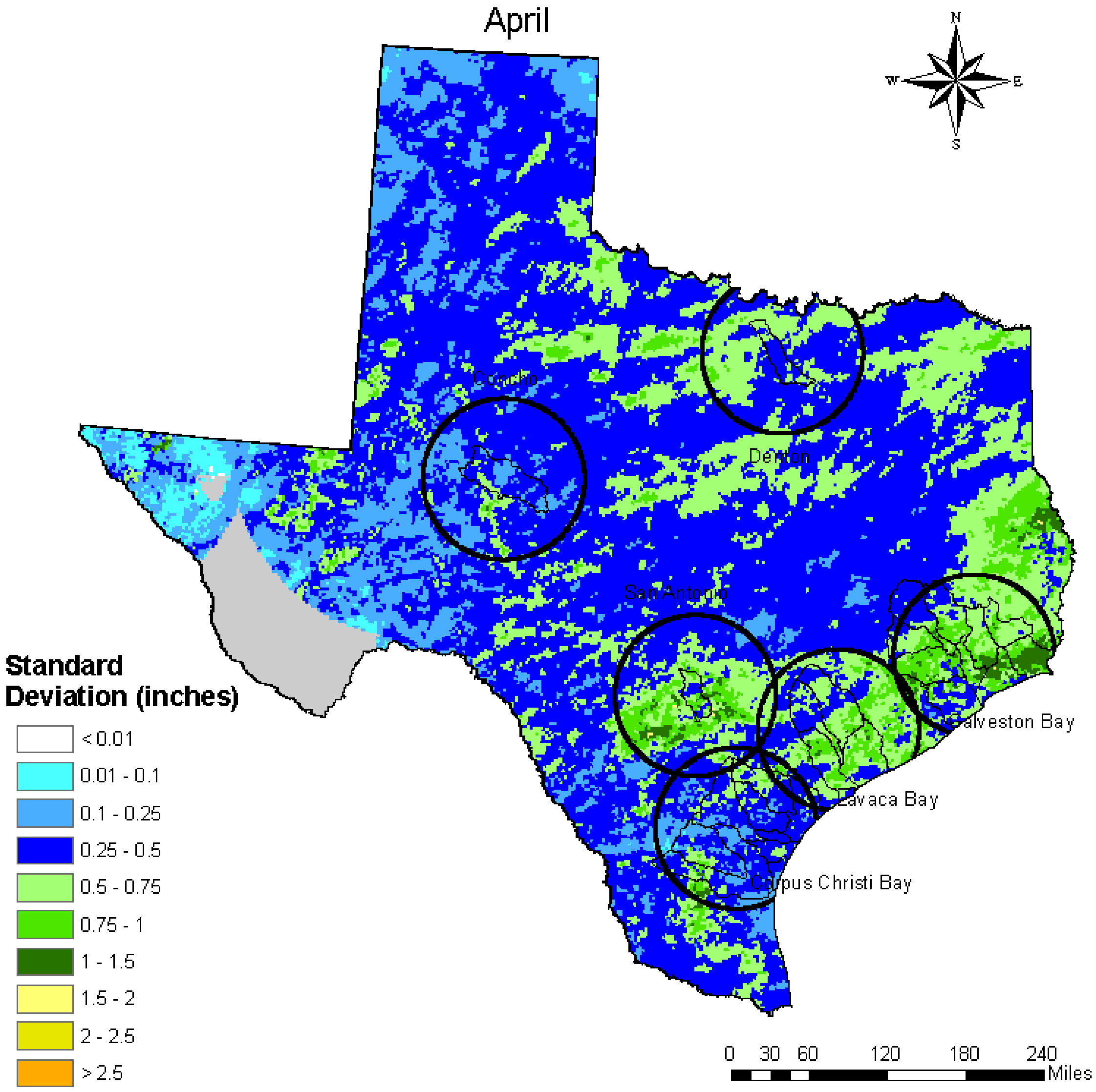

Annual
N
W
E
S
Max.Daily Precipitation (Inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 8.0
8.0 - 10.0
> 10
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
0
30
60
120
180
240
Miles

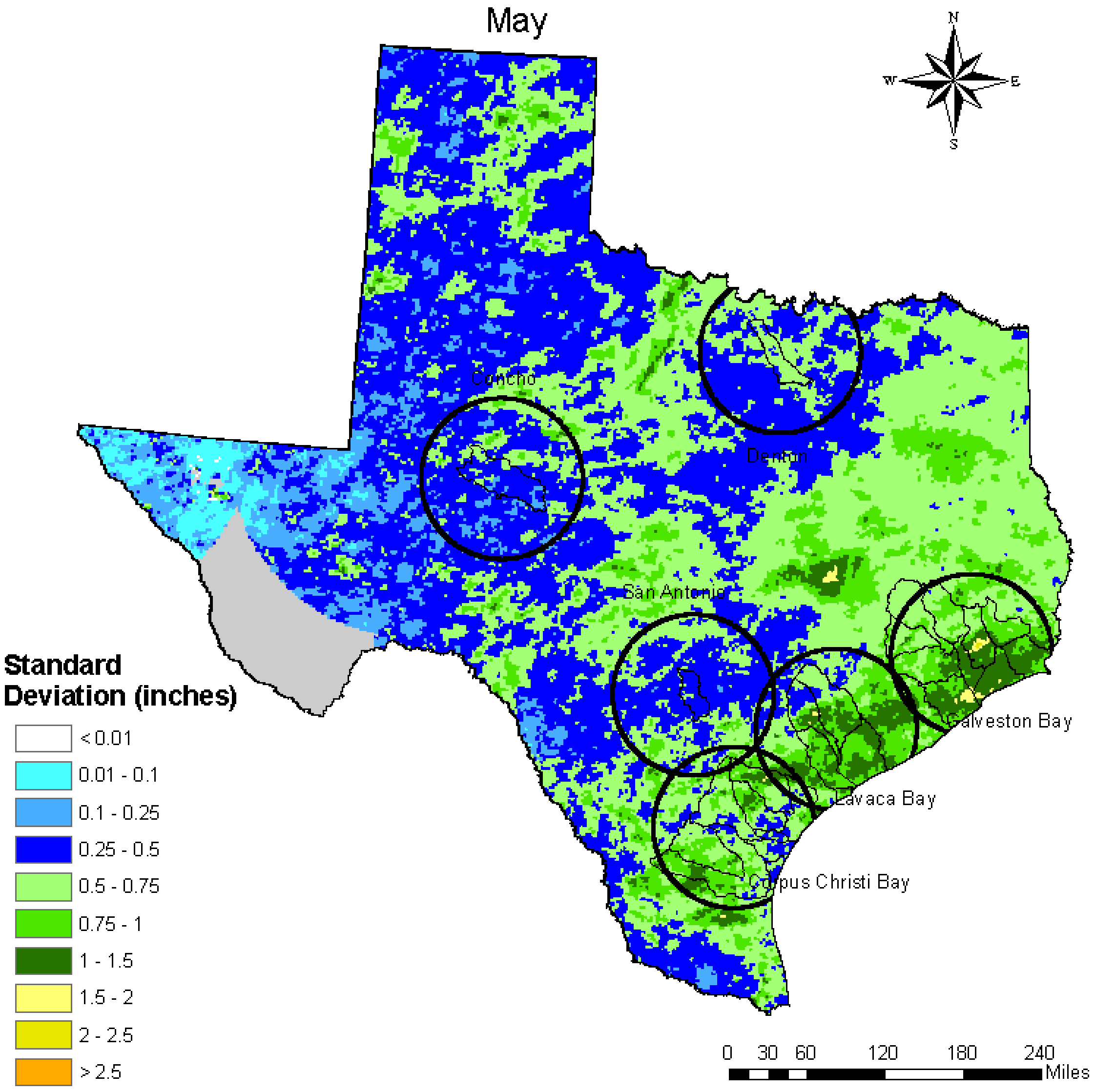
Average standard deviation of rainfall events (Monthly and Annual)


January
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0 30 60 120 180 240
Miles


February
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0 30 60 120 180 240
Miles

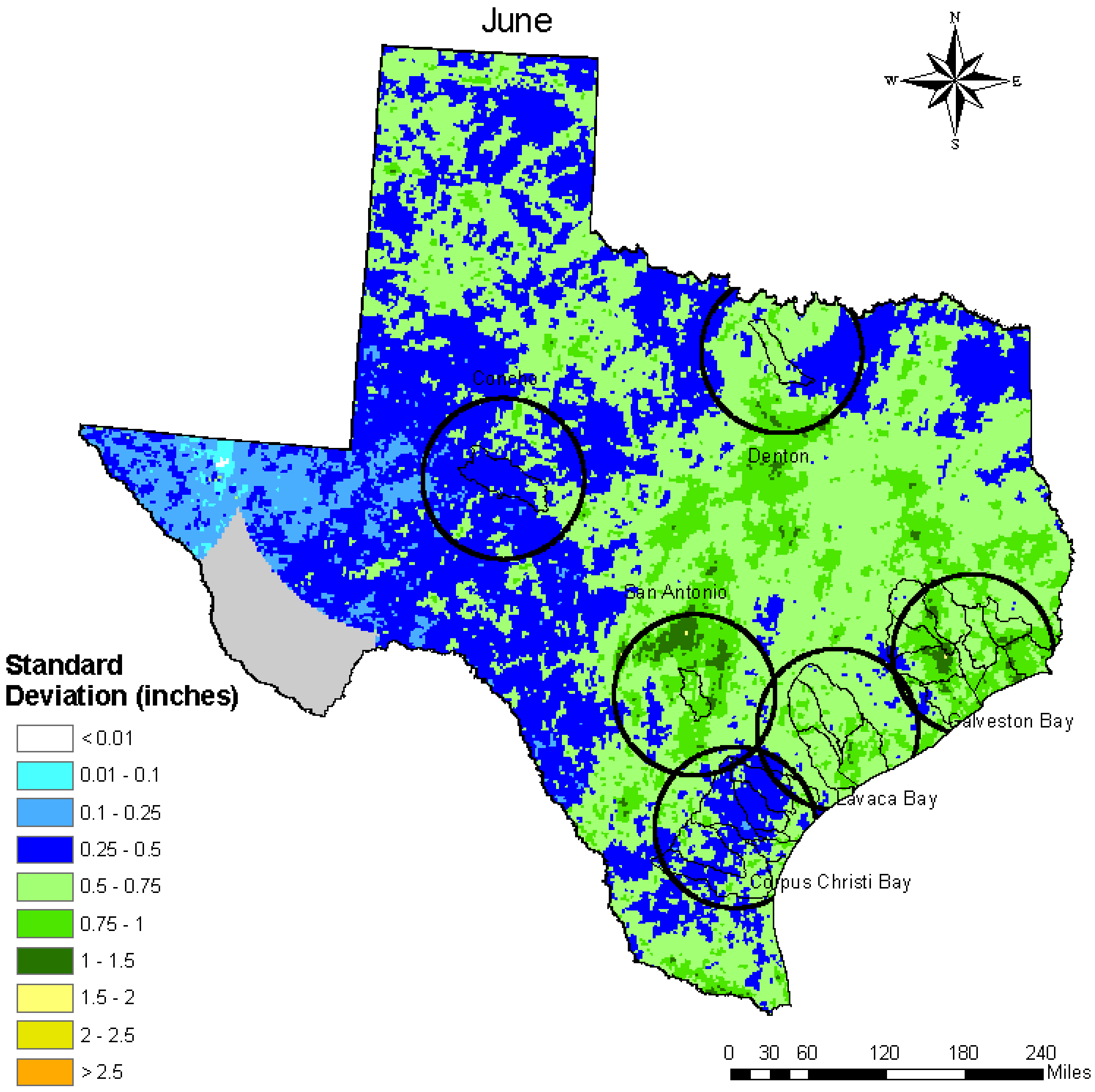

March
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0
30
60
120
180
240
Miles

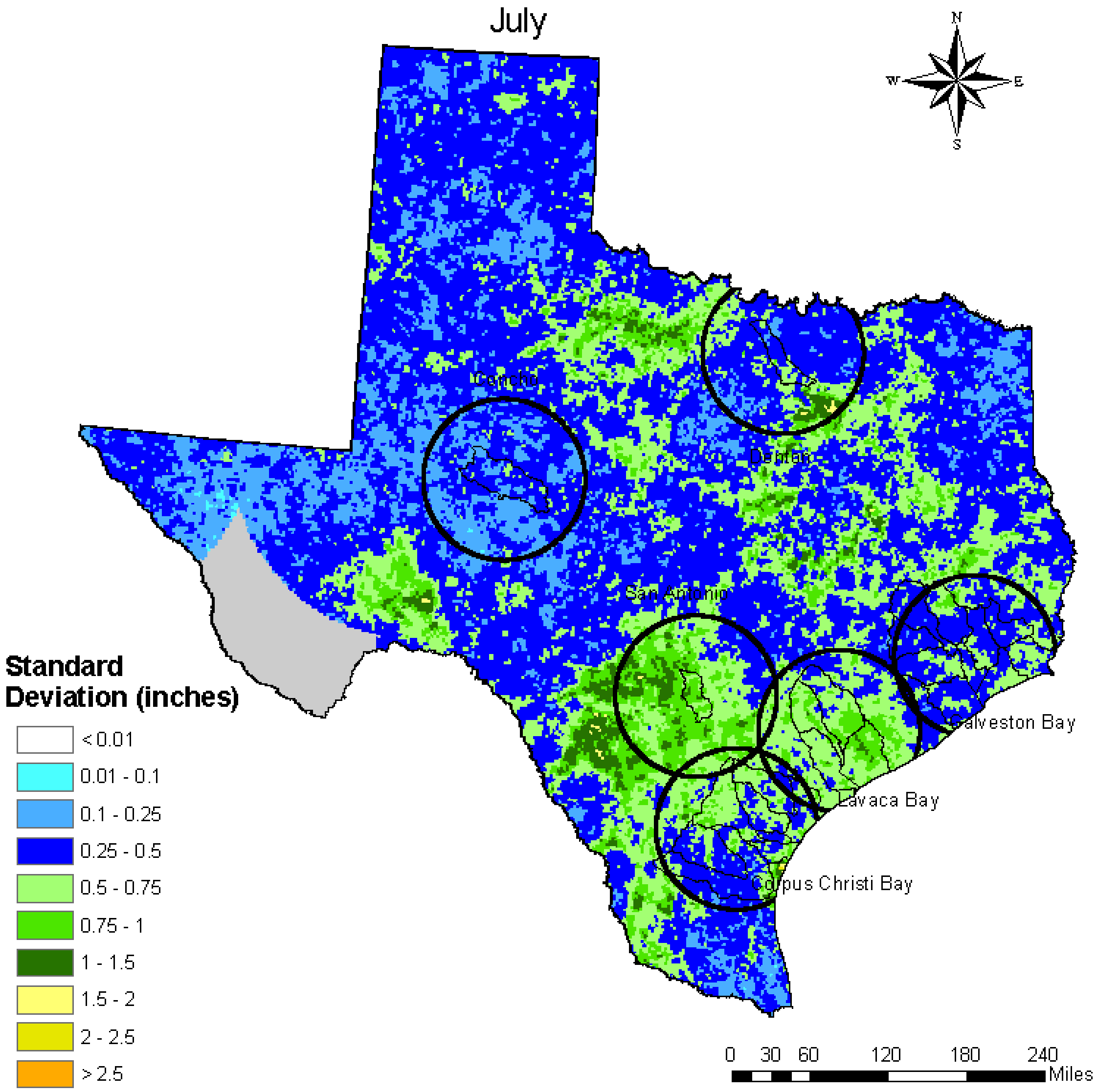

April
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0 30 60 120 180 240
Miles

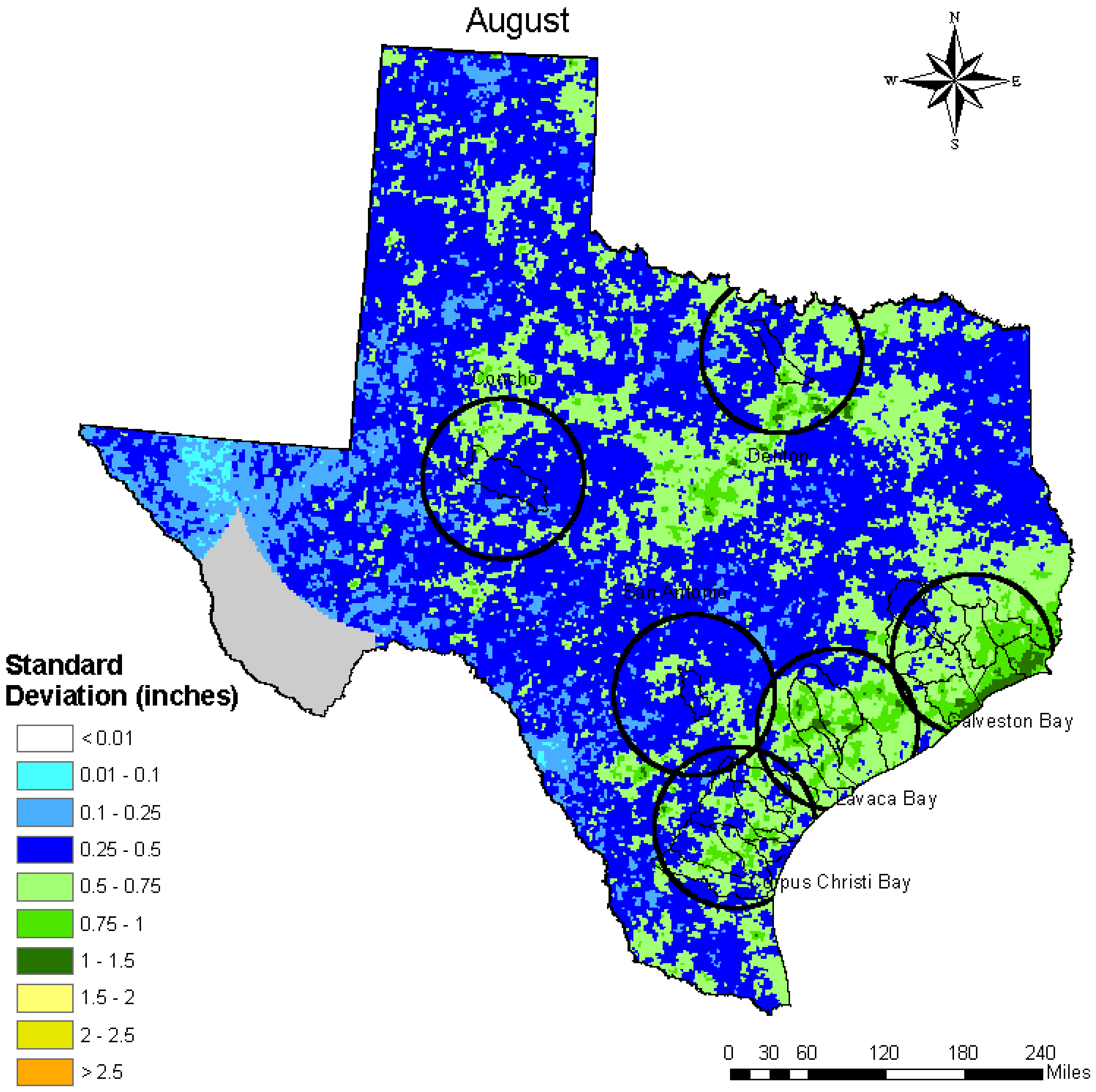


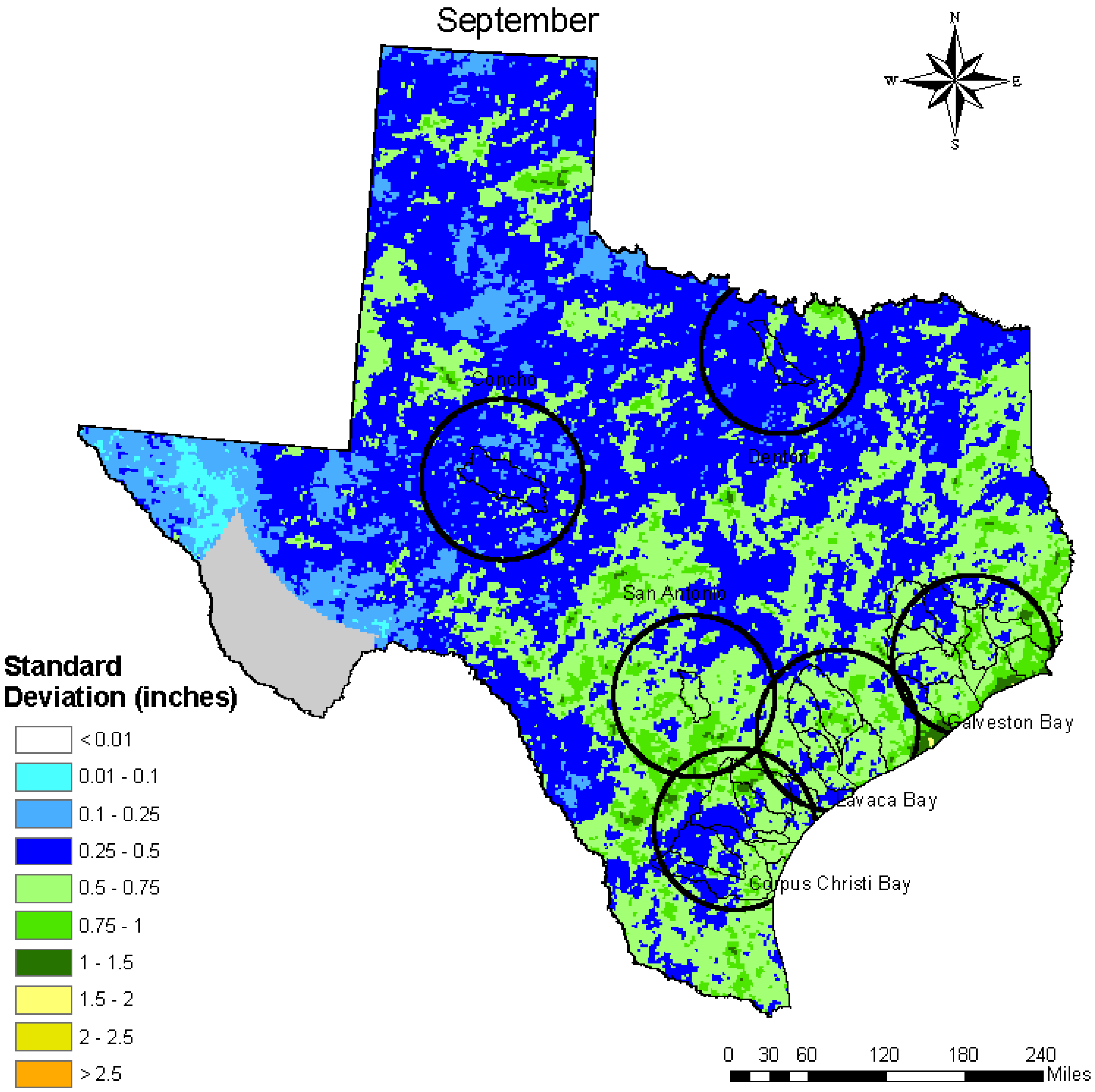
May

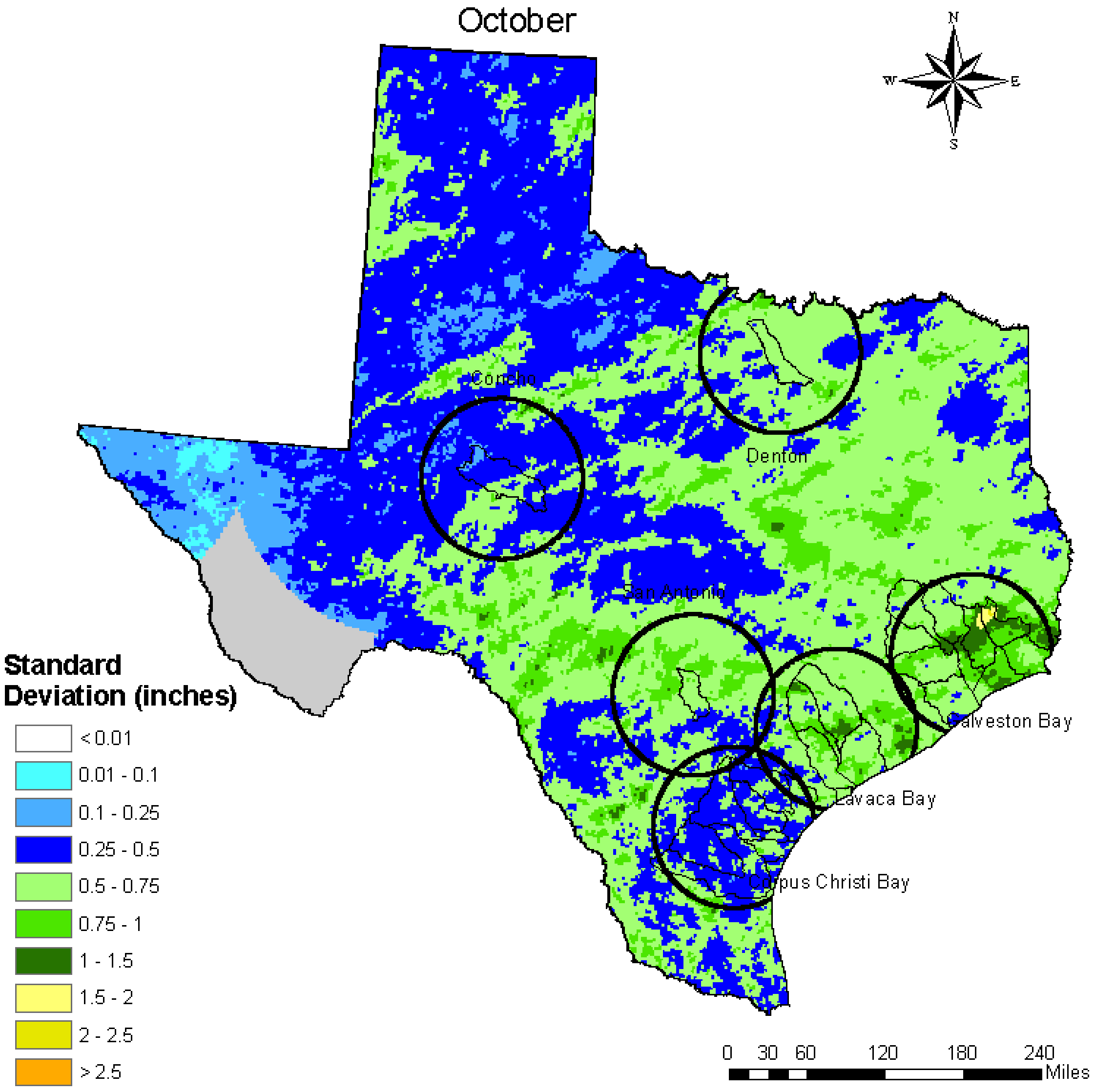
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0
30
60
120
180
240
Miles

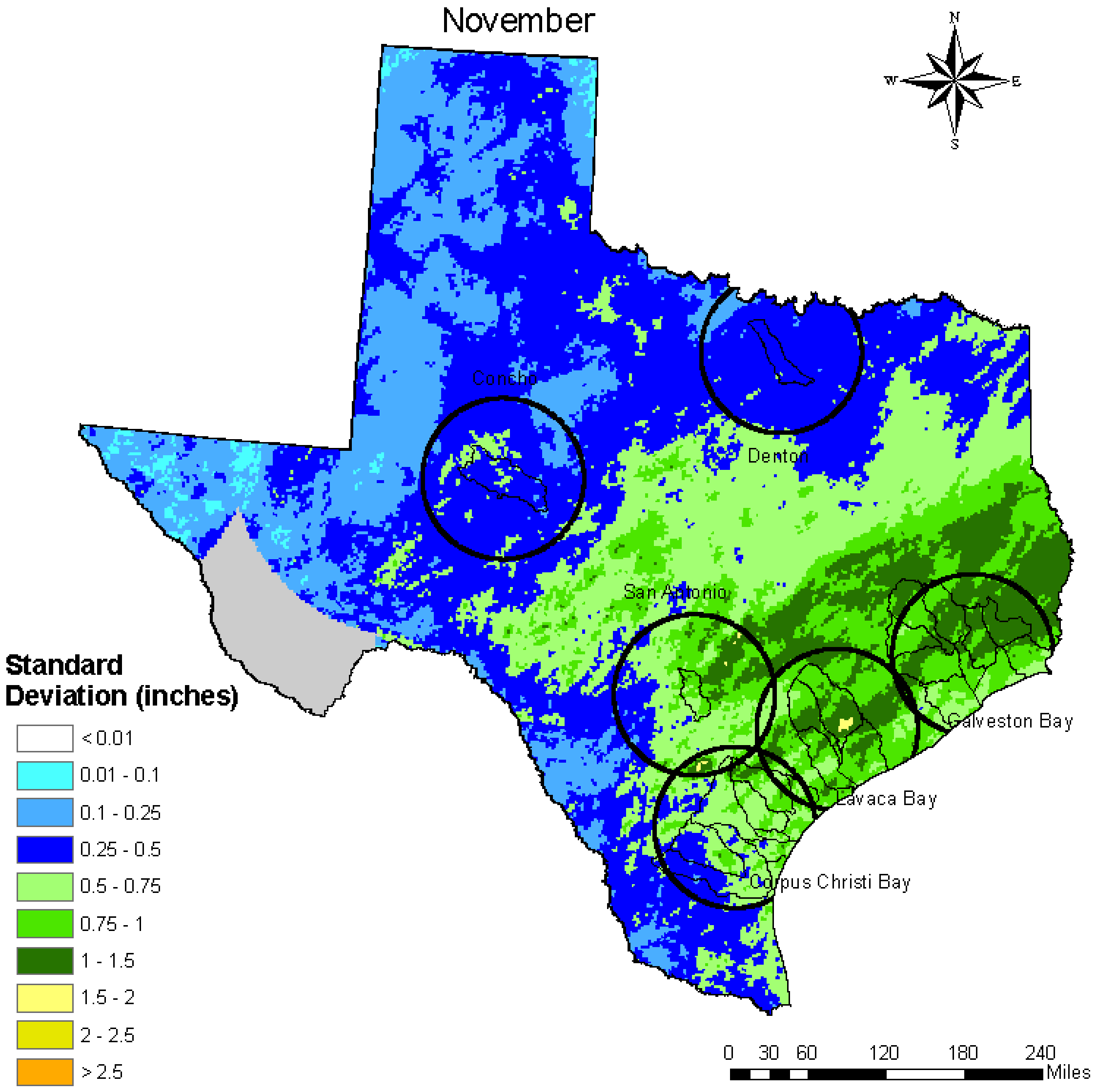

June
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0
30
60
120
180
240
Miles

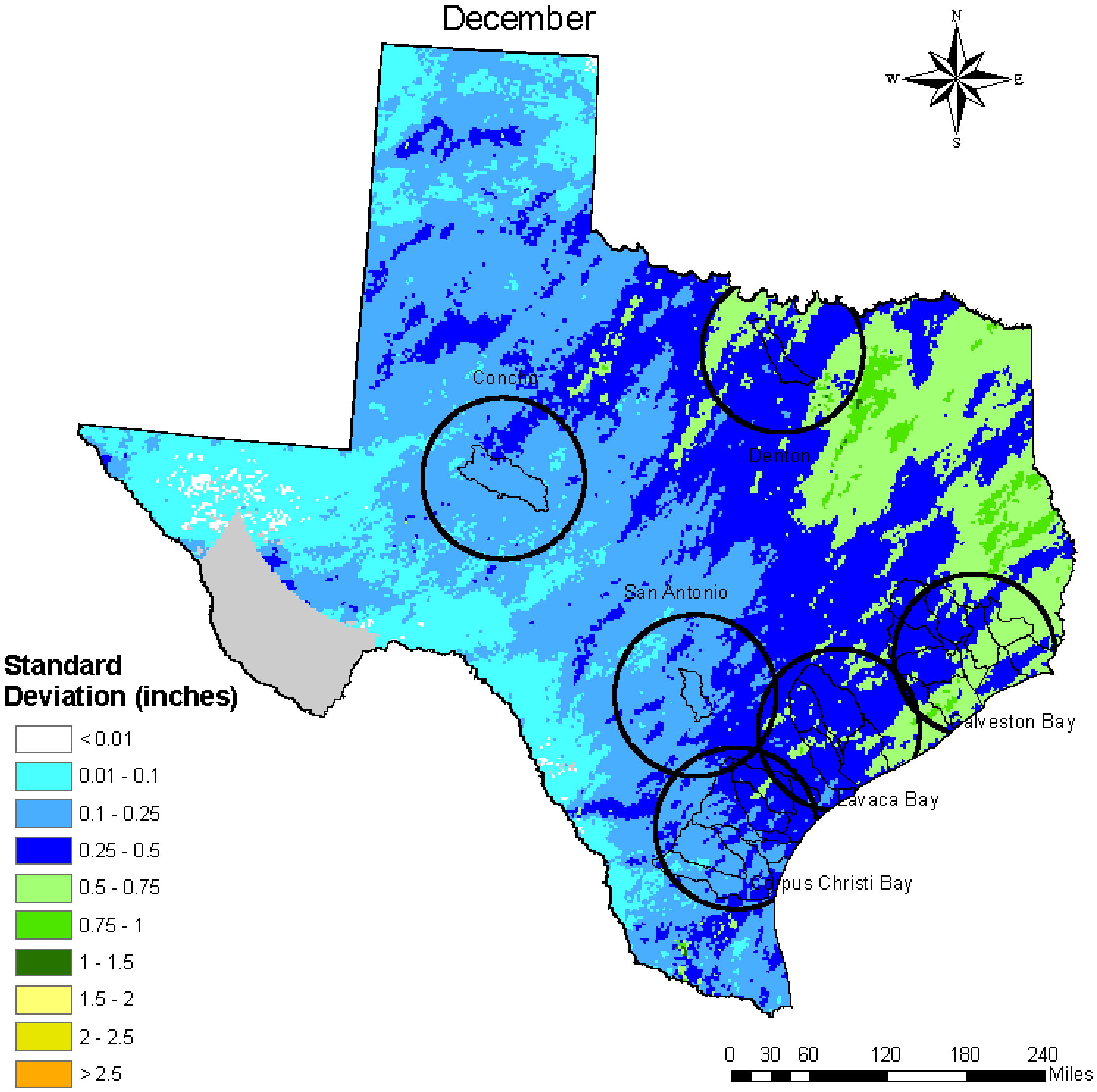

July
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0
30
60
120
180
240
Miles


August
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0
30
60
120
180
240
Miles

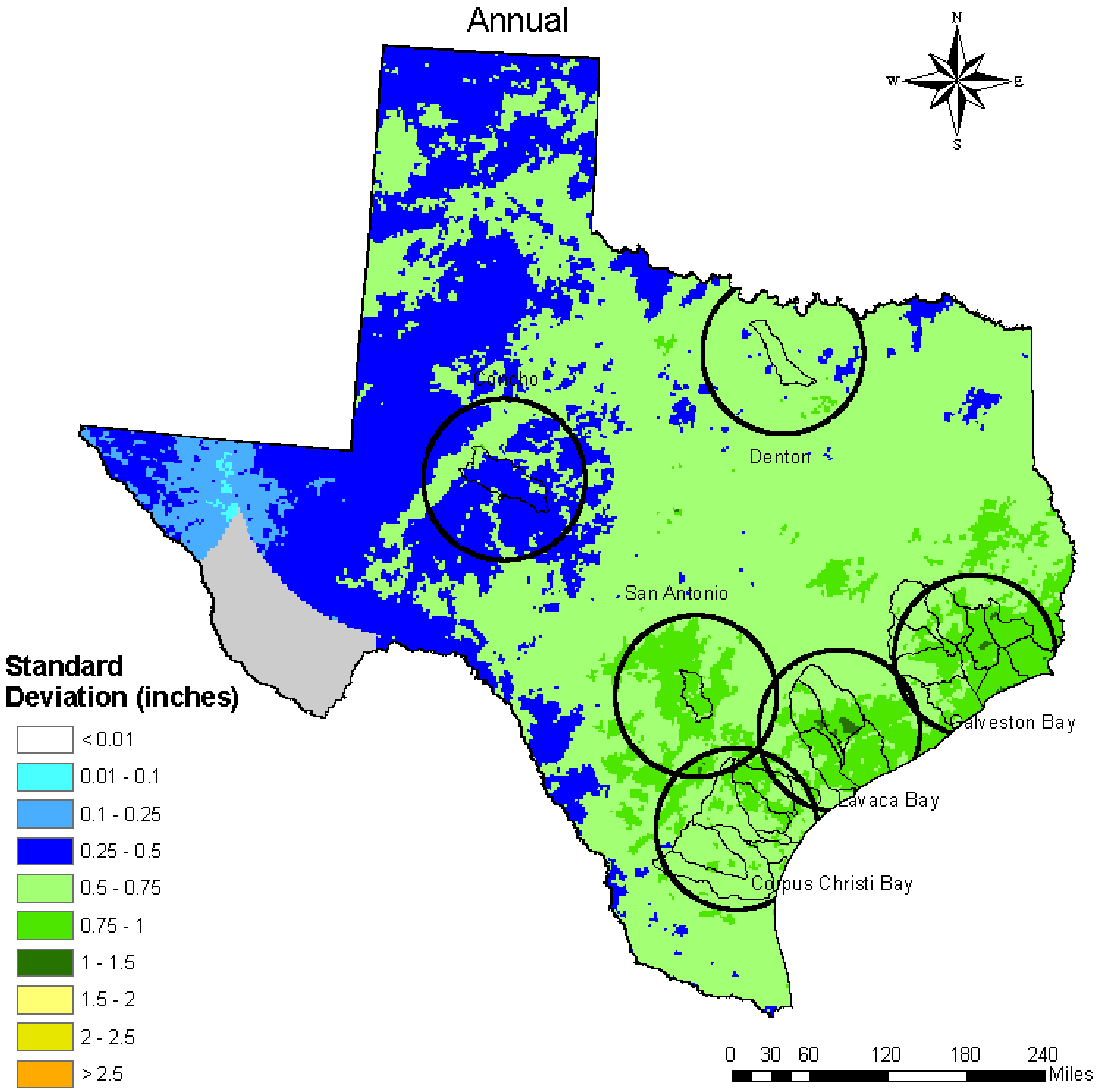

September
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0
30
60
120
180
240
Miles


October
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0
30
60
120
180
240
Miles

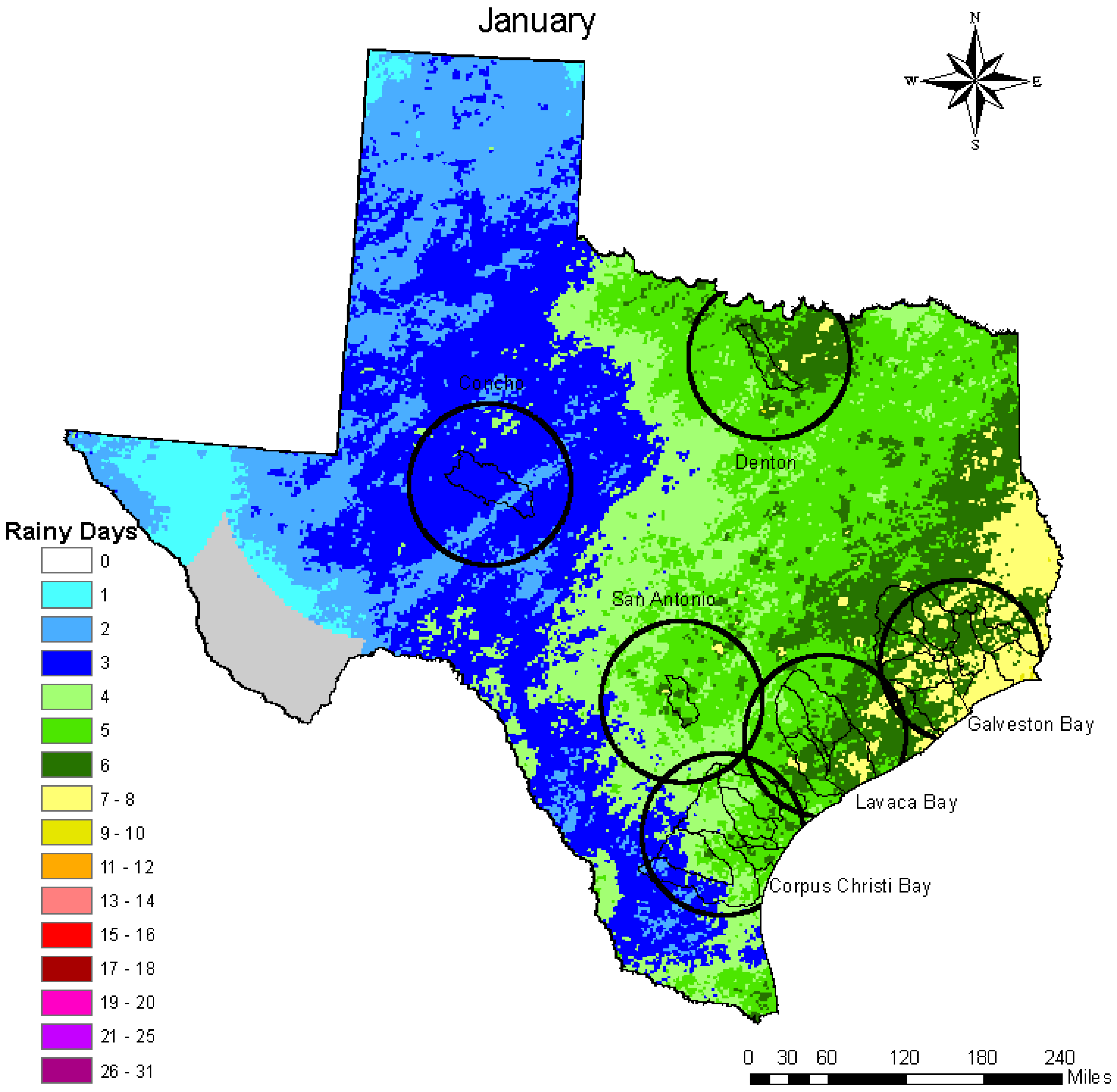

November
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0 30 60 120 180 240
Miles

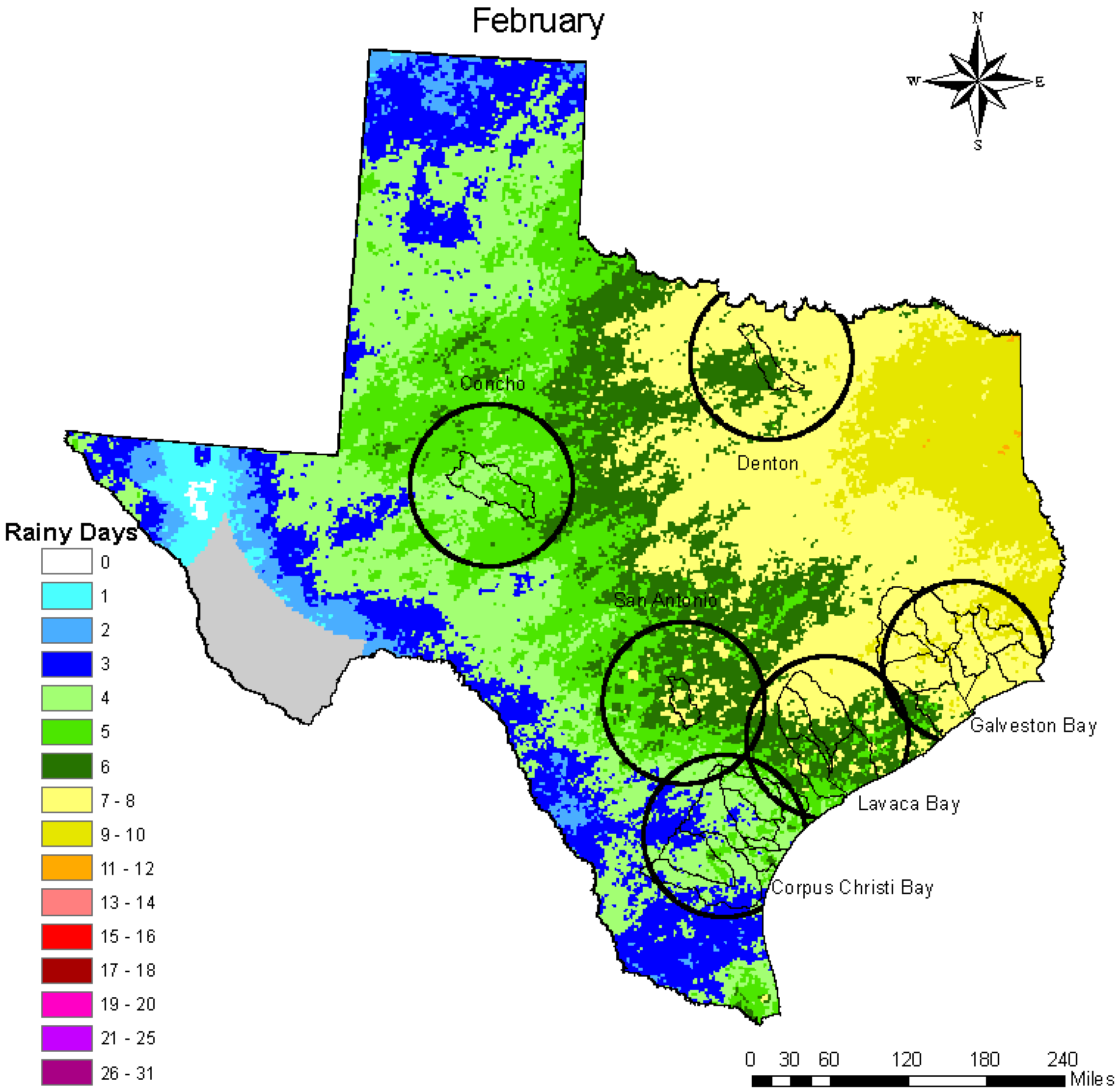

December

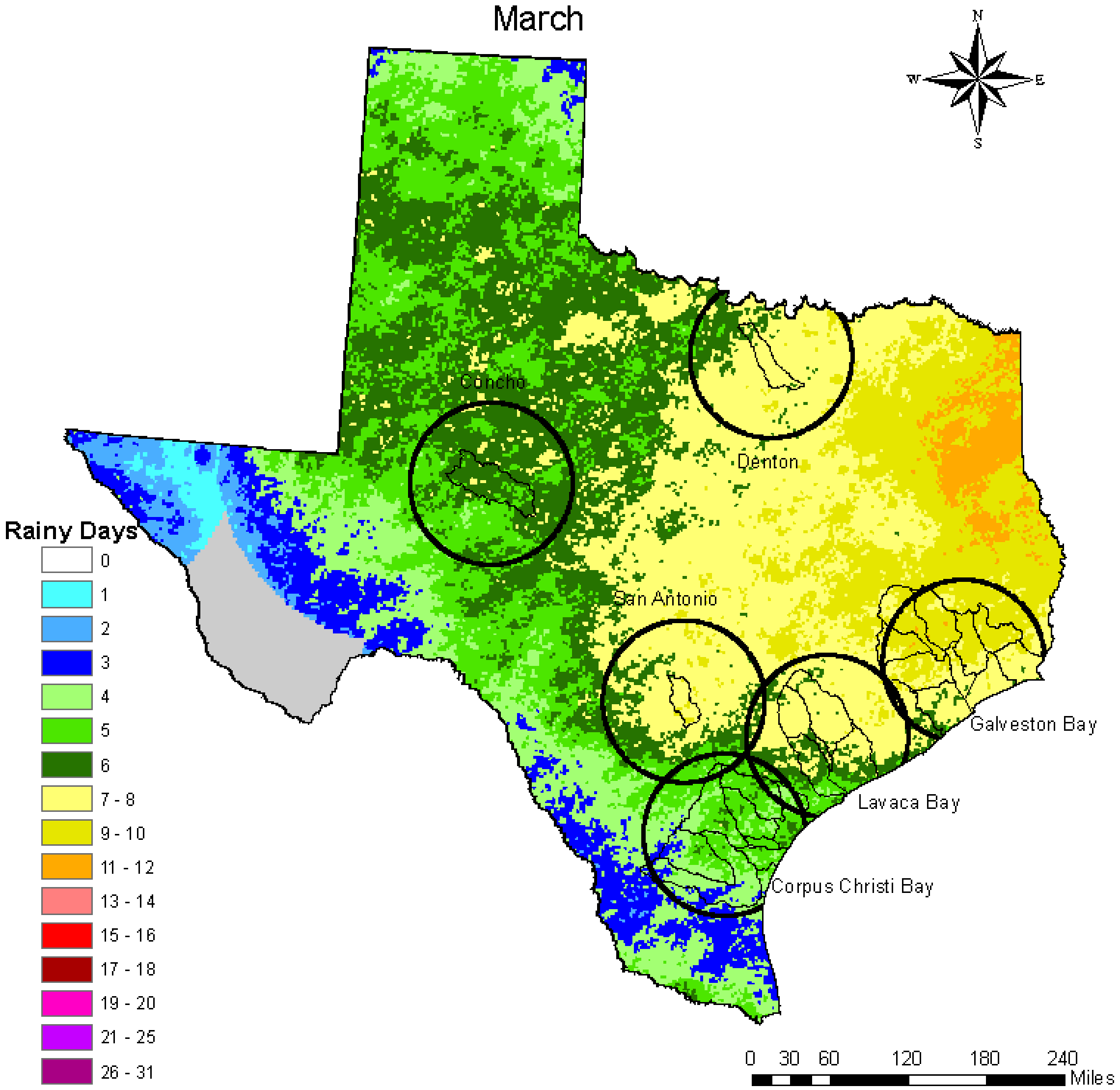
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0 30 60 120 180 240
Miles


Annual
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Standard Deviation (inches)
< 0.01
0.01 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.5
1.5 - 2
2 - 2.5
> 2.5
0
30
60
120
180
240
Miles

Average Monthly and annual number of rainy days

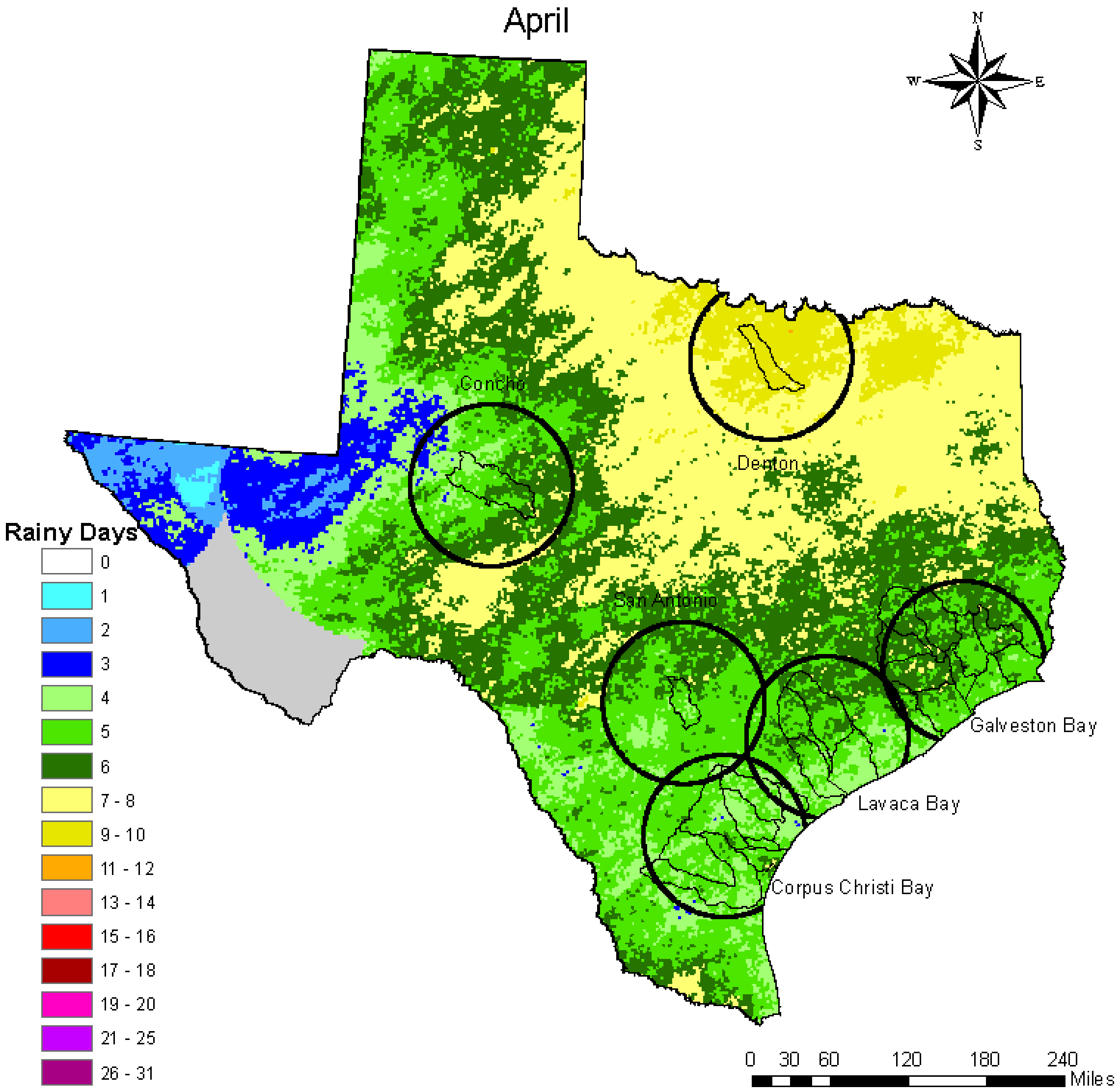

January
N
W
E
S
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
0
30
60
120
180
240
Miles

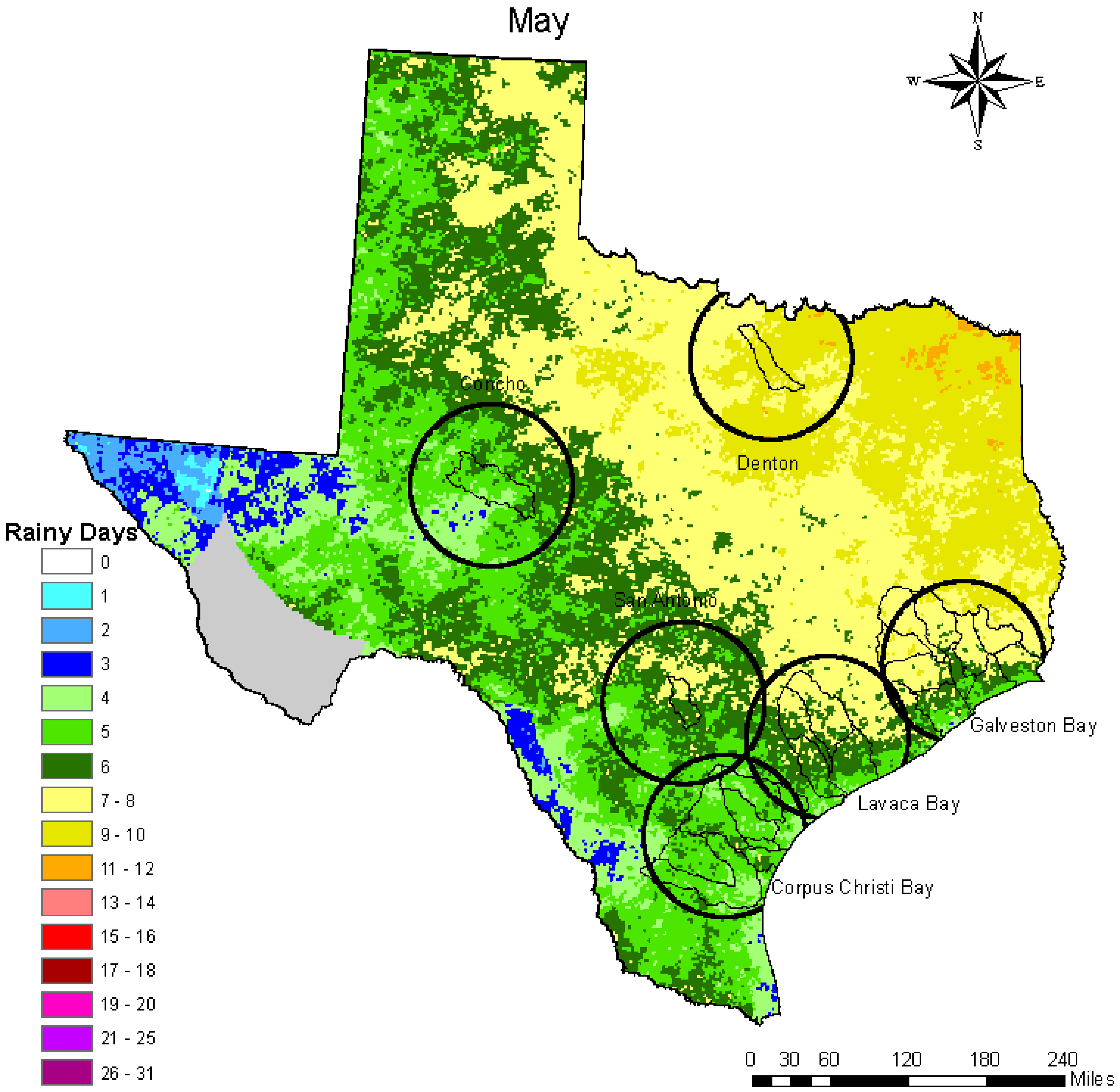

February
N
W
E
S
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
0 30 60 120 180 240
Miles

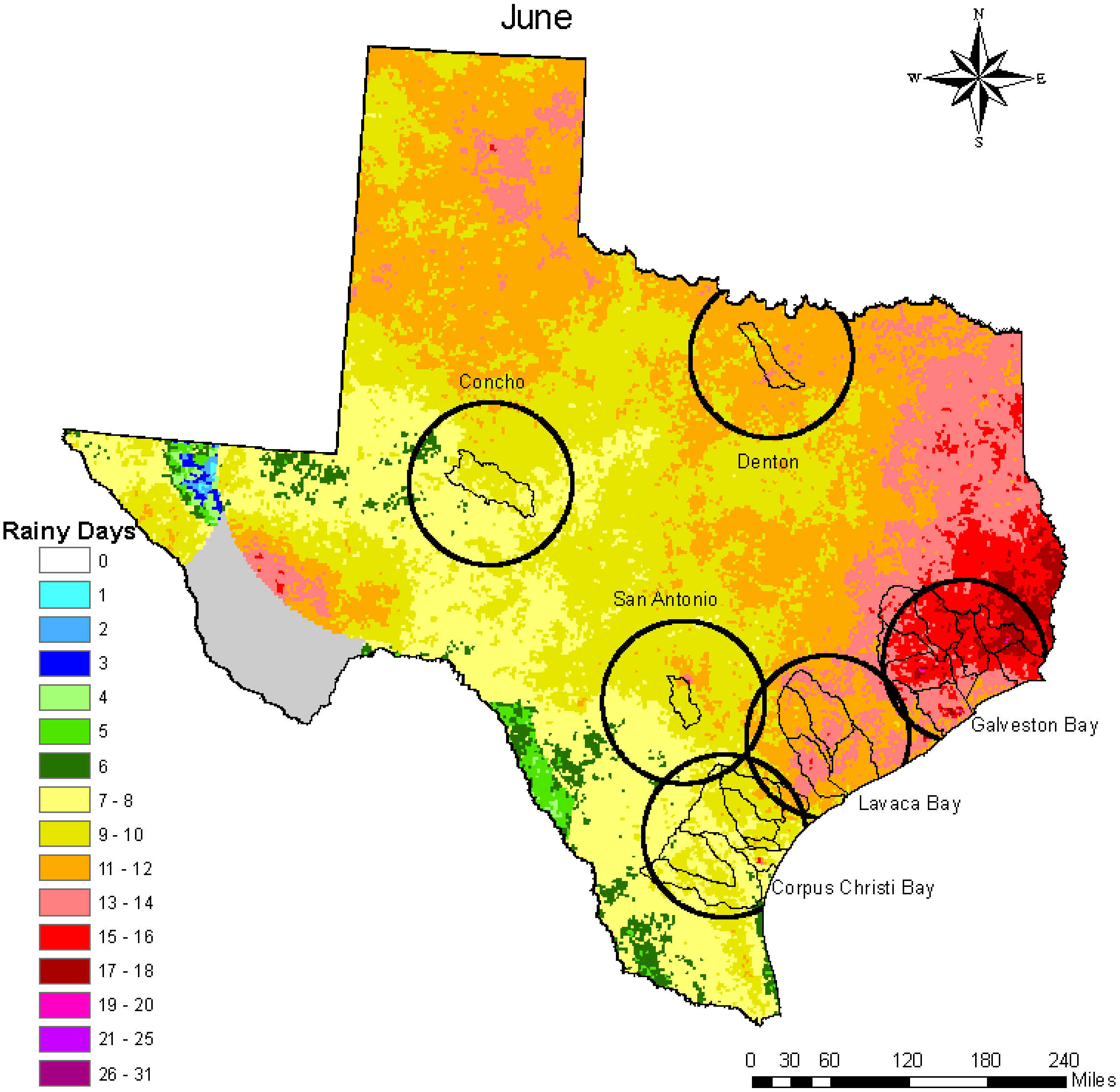


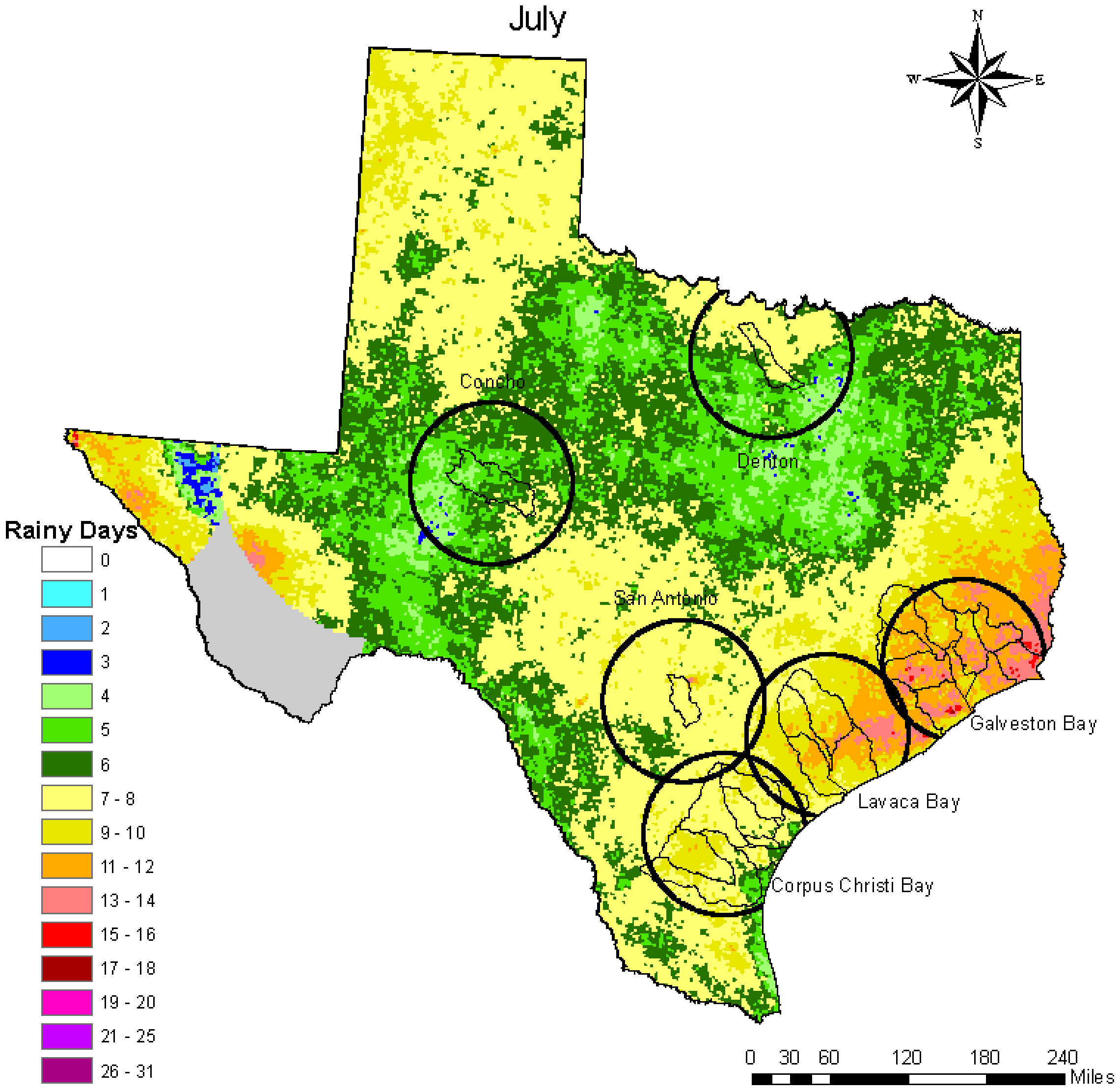
March

N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
0 30 60 120 180 240
Miles

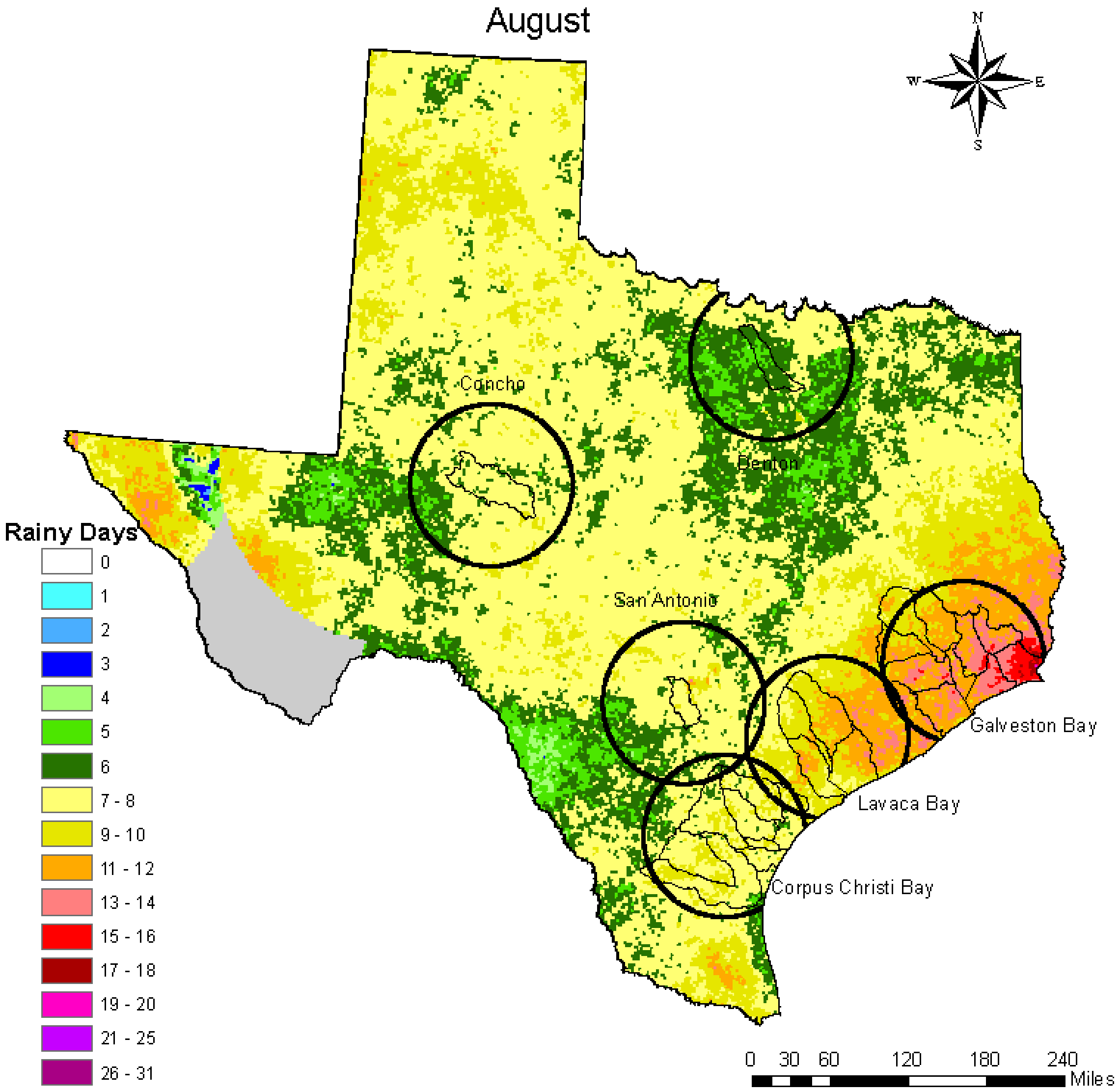

April
N
W
E
S
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
0
30
60
120
180
240
Miles

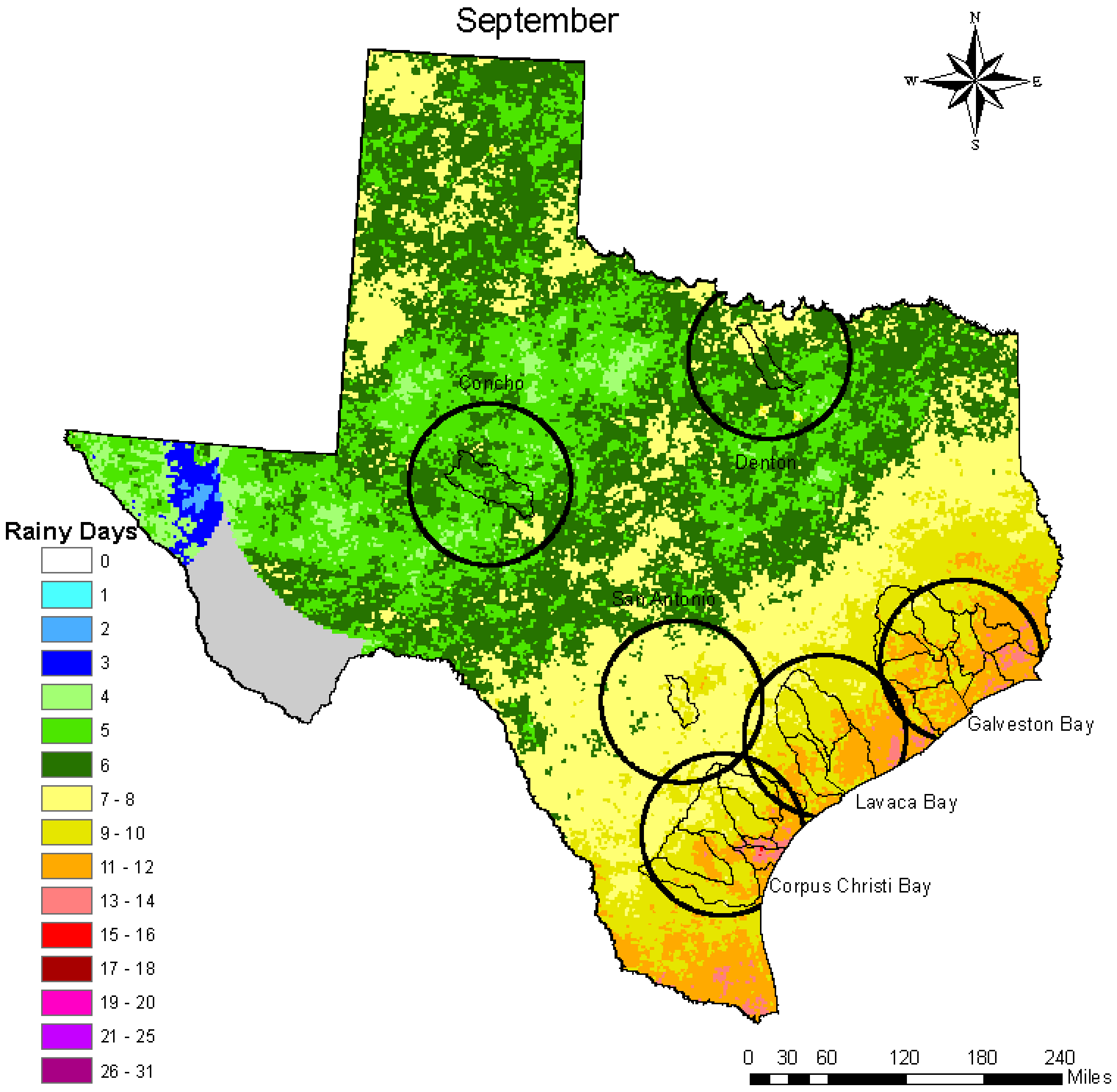

May
N
W
E
S
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
0
30
60
120
180
240
Miles

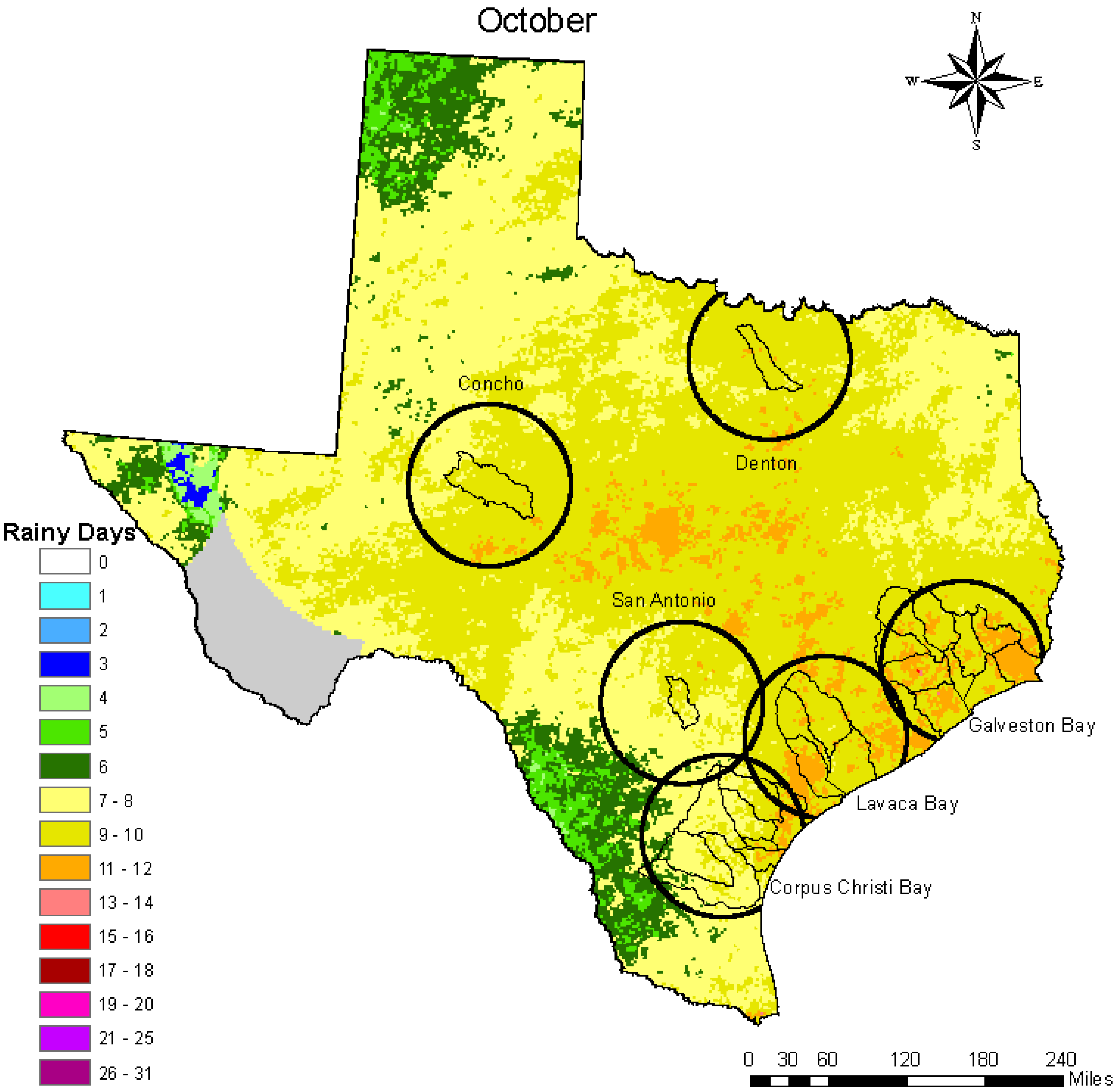

June
N
W
E
S
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
0
30
60
120
180
240
Miles


July

N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
0 30 60 120 180 240
Miles

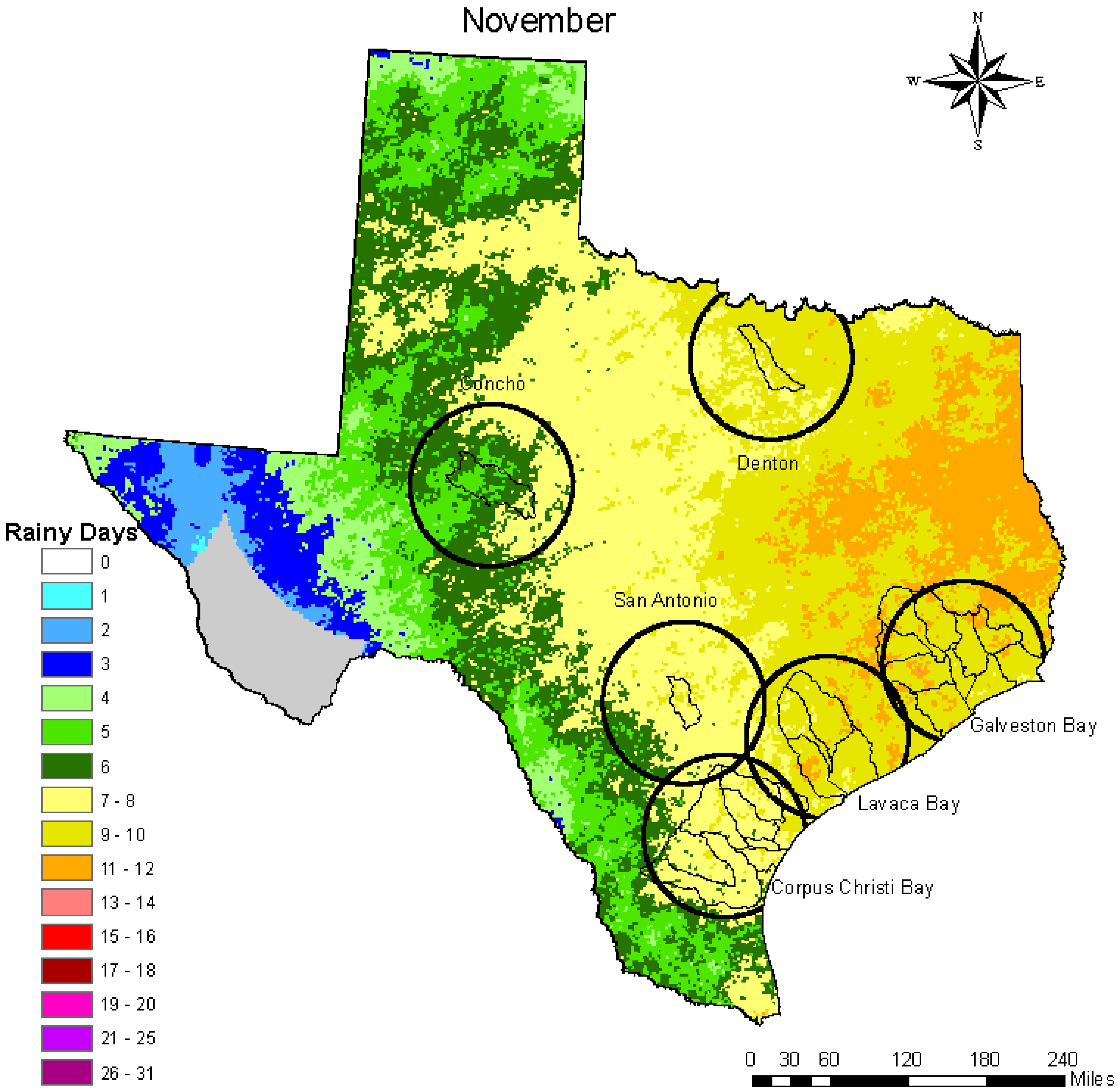

August
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
0
30
60
120
180
240
Miles

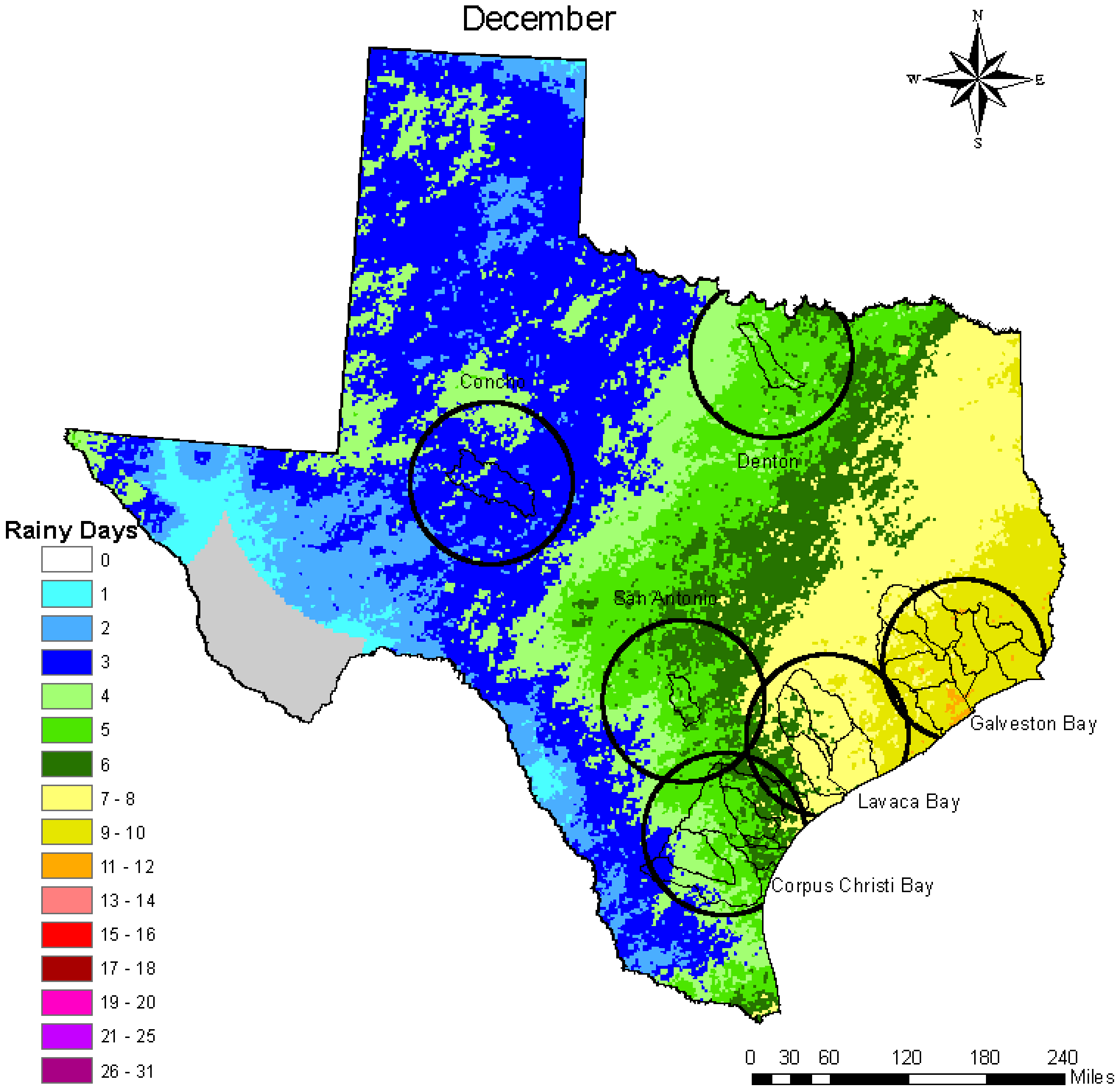

September
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
0 30 60 120 180 240
Miles



October

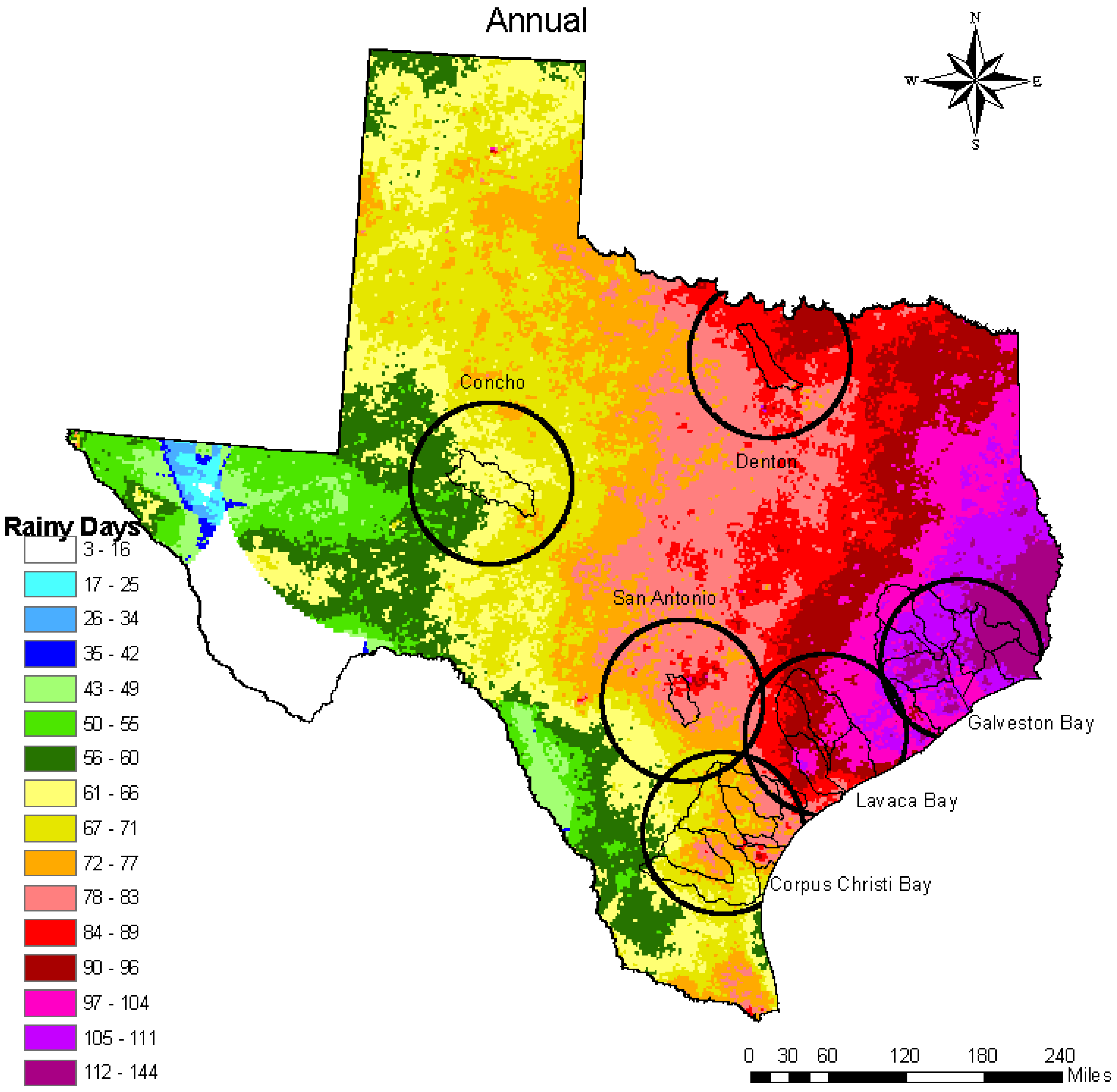
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
0 30 60 120 180 240
Miles


November
N
W
E
S
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
0
30
60
120
180
240
Miles



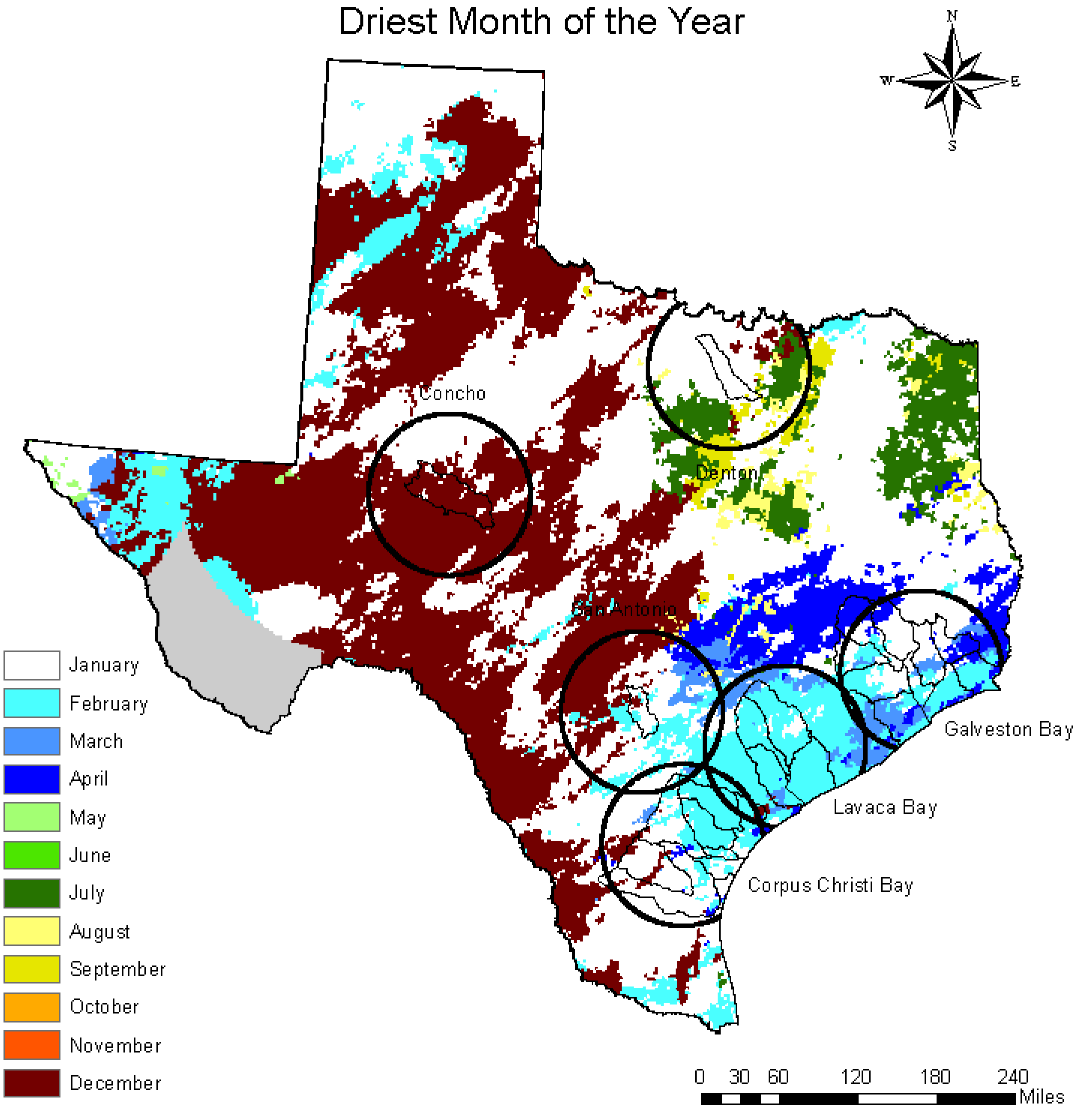
December

N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
Rainy Days
0
1
2
3
4
5
6
7 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 25
26 - 31
0 30 60 120 180 240
Miles

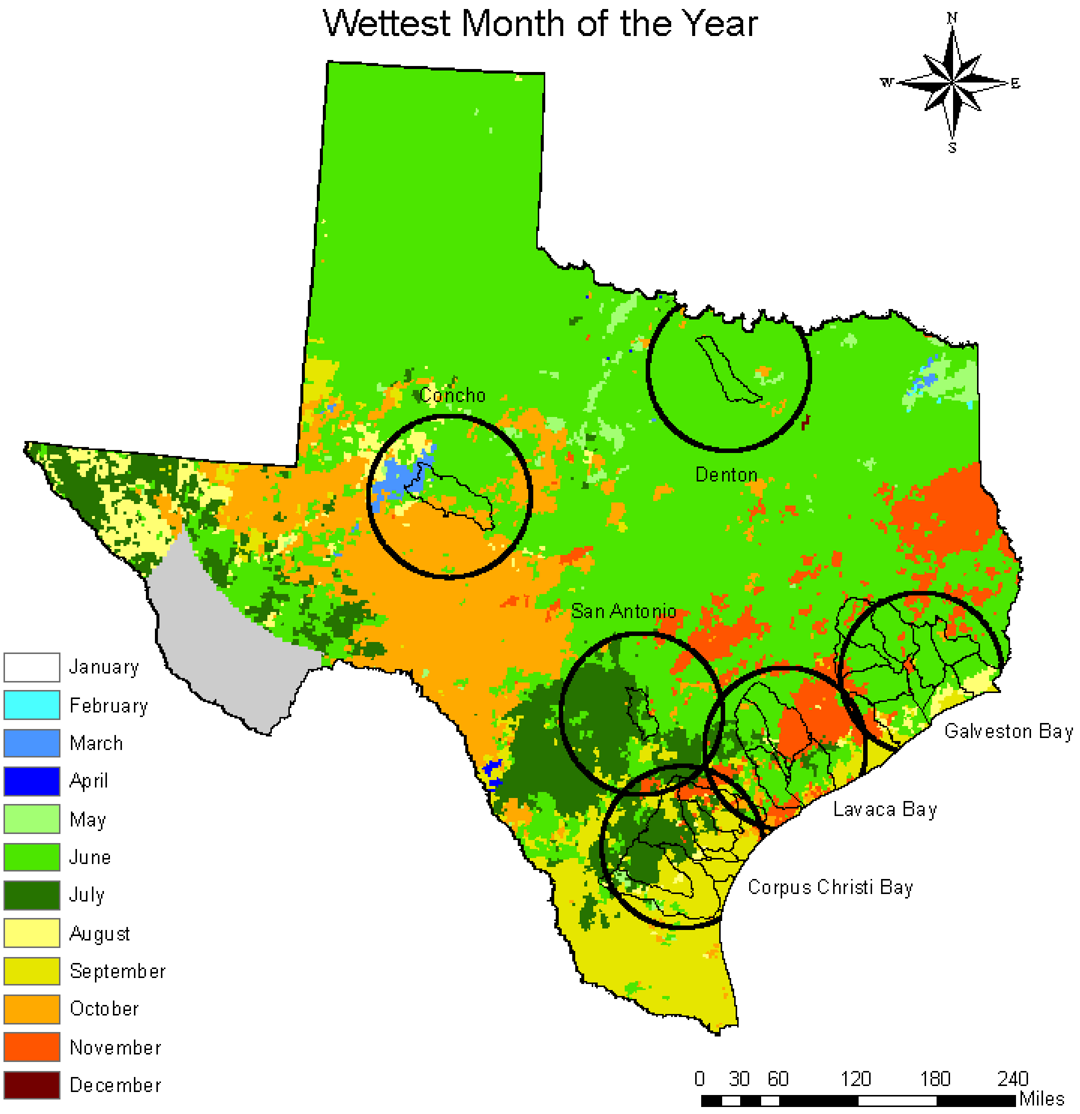


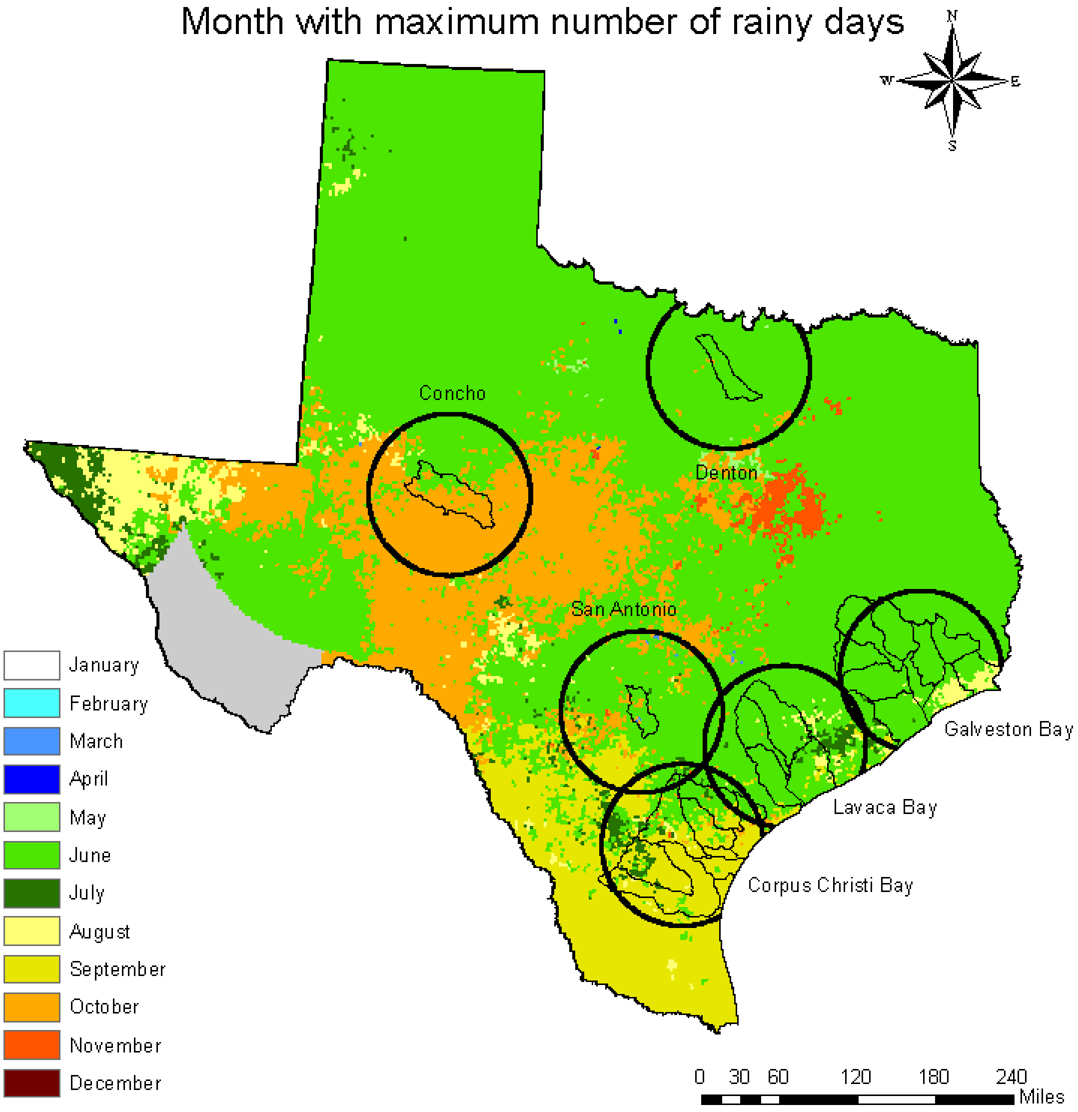
Annual

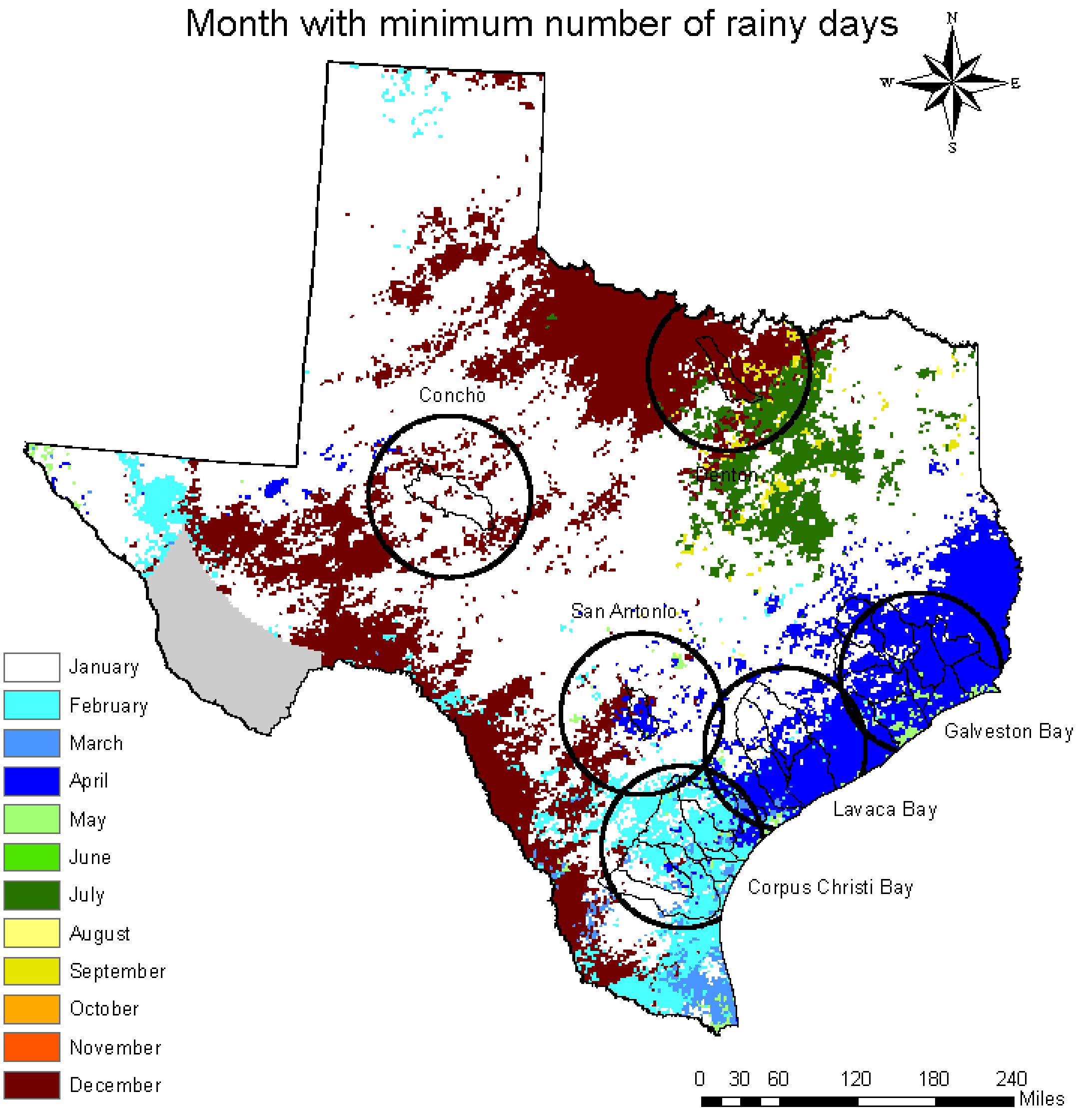
N
W
E
S
Rainy Days
3 - 16
17 - 25
26 - 34
35 - 42
43 - 49
50 - 55
56 - 60
61 - 66
67 - 71
72 - 77
78 - 83
84 - 89
90 - 96
97 - 104
105 - 111
112 - 144
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
0 30 60 120 180 240
Miles



Driest Month of the Year


Wettest Month of the Year
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
January
February
March
April
May
June
July
August
September
October
November
December
0
30
60
120
180
240
Miles


Month with maximum number of rainy days
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
January
February
March
April
May
June
July
August
September
October
November
December
0 30 60 120 180 240
Miles


Month with minimum number of rainy days
N
W
E
S
Concho
Denton
San Antonio
Galveston Bay
Lavaca Bay
Corpus Christi Bay
January
February
March
April
May
June
July
August
September
October
November
December
0
30
60
120
180
240
Miles

Appendix

Performance Evaluation of RADAR Rainfall Estimates with Rain gage Measurements

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Abstract

High resolution gridded precipitation estimates from NEXRAD Stage III product are widely used for hourly and daily severe weather warning and flood forecasting. However, its operational use in large scale hydrologic and water quality modeling has been slow due to bias/error in the radar rainfall estimates. In this study hourly accumulations of daily Stage III NEXRAD precipitation estimates from 2000 to 2004 were compared with an extensive network of First-Order and cooperative rain gages in two national weather service river forecast center regions covering Texas and Oklahoma. The accuracy of radar estimates was measured in terms of Modified Coefficient of Efficiency. Three methods of comparing point rain gage estimates with an area estimate of rainfall from radar, center cell method, 9-cell average method, and 9-cell minimum difference method, were evaluated. The 9-cell minimum difference method of radar and rain gage data comparison consistently gave better results than the other two methods. Using this method of radar and rain gage data comparison, the radar accuracy was evaluated for all days when both radar and rain gage measured rainfall. Further, the radar accuracy was evaluated for different seasons of the year and for different rainfall thresholds and for all combinations of seasons and thresholds. The analysis showed that overall the radar accuracy was low at both First-Order and Cooperative rain gage network in measuring daily rainfall thresholds between 12.7 and 25.4mm (0.5 to 1.0 inches) especially during Summer when convective storm events are predominant. However, comparatively the radar error was less for measuring daily rainfall lesser than 12.7mm or greater than 25.4mm. Overall the radar accuracy was poor at the cooperative rain gages than at the First-Order rain gages. Extensive analysis with rain gage data confirm the need for improvement in radar algorithm, technology and bias correction procedures are needed for wide range of applications in the area of hydrologic and water quality modeling.

Keywords: NEXRAD, radar, rain gage, bias, estimation, First-Order, Cooperative

Introduction

Rainfall is a critical input for water resources assessment, drought monitoring and flood forecasting. It is a highly variable component both in space and time. The limitations of rain gage data in characterizing the space-time variability of rainfall could be effectively overcome by the use of radar data. During recent years considerable advances have been made in weather radar technology and radar rainfall estimates. Due to its availability, several hydrological models have been developed with rainfall values obtained from the radar (Seo and Breindenbach 2002; Gibson 2000; Harrison et al. 2000) and provide operational rainstorm and river forecasts (Upton 2002 and Johnson 1999). The United States National Weather Service's (NWS) NEXt Generation RADar, formally knows as Weather Surveillance Radar - 1988 Doppler (WSR-88D), is used for monitoring storm movement and as an early warning system about dangerous weather conditions with much better spatial (16km^2) and temporal (hourly) sampling (Schaake, 1989). Although radar has been in use for over forty years, it was primarily used for weather predictions. Only during the past decade has its use in hydrologic applications and drought monitoring have been explored (Krajewski and Smith 2002; Narasimhan 2004). The primary reason for slow adaptability of radar data by the hydrologic community is the bias/error in the radar rainfall estimates (Smith et al. 1996). Numerous studies have assessed radar derived rainfall estimates with rain gage measurements (Smith et al. 1996; Young et al. 1999; Jayakrishnan et al. 2004; Johnson et al. 1999; Stellman et al. 2001).

Stellman et al. (2001) compared Mean Aerial Precipitation (MAP) from radar rainfall estimates with MAP from rain gage measurements for the headwaters of the Flint River basin, specifically Culloden basin in Georgia. The study found that the radar MAP underestimated rain gage MAP by 38% at the end of 2yr with the underestimation more pronounced during winter season (~ 50%); but compared well during summer season. Further, for high rainfall events (greater than 0.75in.) during summer season, minimum difference was observed between the radar and rain gage MAPs'; whereas, winter season MAP from rain gage exceeded radar MAP by as much as 150%. Another study by Johnson et al. (1999), compared radar MAP and rain gage MAP for southern plains region of the United States also showed that radar MAP underestimated rain gage MAP by 5-10%.

Smith et al. (1996) compared hourly rain gage and radar data under Tulsa radar umbrella and found that radar underestimated rainfall especially during cold season. Further, their analysis also showed that the radar underestimation tend to increase with distance from the radar. Young et al. (1999) also conducted a similar study for radar data from northern Appalachian Mountains in New York State and found that the radar estimates tend to be lower than the gage measurements, especially in cold season at longer ranges from the radar.

Jayakrishnan et al. (2004) compared the radar rainfall estimates with rain gages across the Texas-Gulf Basin from 1995 to 1999. The study compared radar data with the rain gages of First-Order (FO) weather stations and the Cooperative rain gages (COOP). First-Order stations are equipped with better instrument and trained professionals and maintained by the NWS or the Federal Aviation Administration (FAA); whereas the COOP stations are operated by voluntary observers from state/federal agencies, local governments, radio stations, businesses or private citizens, trained by NWS to take precipitation and temperature measurements. The study showed that the majority of First-Order stations had a Coefficient of Efficiency (COE) greater than 0.5 whereas only 35% of COOP had COE greater than 0.5. The study also found that the radar performance increased considerably over the years due to improvement in radar data processing algorithms. In 1995 the radar data was within ±20% of the gage data only at 13% of the rain gage locations as compared to 63% of the rain gage locations in 1998 and 1999.

The bias in the radar rainfall estimate as described could arise from several possible sources including improper radar reflectivity and rainfall rate relationship, overshooting the cloud systems and sub-cloud evaporation of raindrops (Krajewski and Smith 2002). During the past few years several improvements have been made to the NEXRAD algorithms to reduce this systematic errors/bias in the radar rainfall estimate (Fluton et al. 1998; Seo 1998a,1998b; Seo et al. 1999; Seo et al. 2000; Legates 2000;).

The current study attempts to evaluate the accuracy of recent radar estimated rainfall (2000-2004) due to the improvements in radar processing algorithms primarily to reduce systematic errors described previously. Performance of radar rainfall estimates is evaluated in terms of 1) seasonality, 2) rainfall/storm magnitude and 3) type of rain gage (First-Order Vs COOP stations). Further, in this study daily NEXRAD data (daily accumulations of hourly NEXRAD data) is evaluated rather than hourly NEXRAD data because: 1) such studies have already been conducted by others (e.g. Smith et al. 1996; Young et al. 1999; Jayakrishnan et al. 2004) and 2) large-scale hydrologic/water quality models such as Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) depend heavily on accurate precipitation inputs and operate on a daily time step.

In addition to the bias due to systematic errors, a major source of bias arises due to the difference in the sampling area between rain gage and radar data. A typical rain gage samples rainfall over an area of 0.3m^2, while radar samples the average precipitation accumulation over an area of 16km^2. This huge difference in sampling area of radar and rain gage impose inherent problems for direct comparison (Austin, 1987; Ciach and Krajewski, 1999; Steiner et al., 1999). Other minor factors that add to bias include the combined effects of scale and shape distortions of the coordinate system (HRAP - Hydrologic Rainfall Analysis Project) used for radar data mapping which vary with latitude (Reed and Maidment, 1999), and the location of rain gage relative to the 4km × 4km HRAP radar grid, i.e. location of the rain gage in the center of the grid versus the edge of the grid.

Hence, the current study will also evaluate radar data using three methods of spatial comparison with rain gage data: 1) center cell comparison 2) 9-cell average comparison and c) 9-cell minimum difference comparison. The results from this study will be of major interests to the general meteorological and hydrological community with potential uses in flood forecasting, drought monitoring and regional scale hydrologic and water quality modeling.

Methodology

Study area and Data sets

The study area consists of two NWS River Forecast Center Regions, encompassing the entire states of Texas and Oklahoma and overlapping six other neighboring states: 1) West-Gulf River Forecast Center region (WGRFC) and 2) Arkansas-Red Basin River Forecast Center region (ABRFC) (Fig 1).

WGRFC region comprises about 315,000 square miles and provides operational river and flood forecasting for the region. It covers most of Texas and encompasses regions with a wide variety of climate. The eastern portion is primarily humid and temperate and has a flat terrain. Significant precipitation events in the eastern portion occur primarily during spring with a secondary peak during early autumn season, although large rainfall events are not uncommon during any month of the year (Carr 1967). In contrast, the climate is highly varying in the far western region with sup-tropical desert in the south to highlands in the north with a mountainous terrain. The western portion is characterized by heavy rainfall events primarily during summer. Heavy winter snowfall is also very common in the Rocky Mountain portion of WGRFC. The central portion of WRGRC is characterized by a gradually varying climate from mid-latitude steppe in the north to sup-tropical steppe in the south with a gentle rolling terrain.

ABRFC region comprises about 208,000 square miles that covers entire Oklahoma, North and North-East portions of Texas and five other adjacent states. The terrain range from the mountainous continental divide in the west to the gently rolling southern plains extending to Mississippi River valley. The precipitation varies sharply from east to west except during summer months of July and August when this gradient is not sharp. Heavy precipitation events occur primarily during late spring (May) almost across the entire region east of Texas and Oklahoma panhandle with a secondary peak occurring during early autumn. Most the heavy rainfall events during late spring and early autumn occur as severe thunderstorms. During winter, snowfall is the major form of precipitation for the central and western portion of ABRFC with the snow gradient increasing towards the continental divide in the west from the panhandle regions of Texas and Oklahoma.

The rain gage rainfall data was obtained from the National Climatic Data Center (NCDC) and the NEXRAD radar rainfall data was obtained from WGRFC and ABRFC for five years from 2000 to 2004. There were 701 Cooperative rain gages (COOP) in the WGRFC region and 524 COOP stations in the ABRFC region (Figure 1a). Also, there were 49 First-Order (FO) stations in the WGRFC region and 23 First-Order stations in the ABRFC region. The NEXRAD radar rainfall data used in this study is the hourly Stage III (Fulton et al., 1998) multi-sensor rainfall mosaic created from several radars, corrected using rain gage and mapped to HRAP grid (Reed and Maidment, 1999). Each HRAP grid cell is approximately 4km × 4km in size and is defined in a polar stereographic projection used by the NWS in numerical weather prediction. The hourly Stage III NEXRAD rainfall estimates were obtained for the study period from the NWS archive of River Forecast Center Operational NEXRAD Data (http://dipper.nws.noaa.gov/hdsb/data/NEXRAD/NEXRAD.html).

Data Processing

Hourly Stage III radar rainfall data from WGRFC and ABRFC were accumulated into daily data in two ways: 1) from midnight to midnight for comparison with First-Order rain gage measurements and 2) from 7AM to 7AM for comparison with COOP rain gage measurements. The NEXRAD rainfall data was accumulated for these hours because most of the First-Order rain gage has the observation time during midnight and the COOP rain gage at 7:00AM. For these accumulation hours, rain gage data was available from 326 COOP stations and 39 First-Order stations for the WGRFC region and from 401 COOP stations and 21 First-Order stations for the ABRFC region.

It should be noted that most of the First-Order rain gages used in the current study are used operationally by WGRFC and ABRFC as part of the Stage III radar data processing for periodic calibration, bias adjustment, and even for filling missing radar data. However, information about specific rain gages or specific days or hours during which a particular rain gage data was used for Stage III processing is not readily available from the NWS river forecast centers. Hence, the data from all the First-Order rain gages were used in the analysis without any exclusion. Despite this, comparing radar data with First-Order rain gage measurements will provide useful information to access the radar performance.

The daily NEXRAD rainfall estimates obtained using the process described above was compared with rain gage measurements using three different methods: 1) center cell method 2) 9-cell average method and 3) 9-cell minimum difference method. The comparison of the HRAP cell value directly overlying the rain gage station is called the center cell method; the comparison of the average value of nine HRAP cells adjacent to the rain gage station is called the 9-cell average method; and the comparison of HRAP cell value, from among the nine closest HRAP cells, having the closest rainfall estimate to the rain gage measurement is called the 9-cell minimum difference method.

Data Analysis

The rain gage data and the radar rainfall data extracted using the three different methods as described previously were analyzed in four different ways: 1) for all days including zero rainfall 2) for all days excluding zero rainfall days from both rain gage and radar 3) for days with rainfall during different seasons 4) for days with rainfall measuring different thresholds and 5) for days with rainfall during different seasons and at different thresholds. For the purpose of this analysis the four different seasons are defined as

Winter – January to March, Spring – April to June, summer – July to September and Autumn – October to December. The three rainfall thresholds selected for analysis are days with rainfall range: a) 0.01 to 12.70mm (0.5 inch) b) 12.71 to 25.4mm (1 inch) and c) all events greater than 25.4mm. The seasonal analysis was done to evaluate the radar performance to accurately measure different types of storms observed during different seasons within a year; for example, stratiform frontal storm events during autumn and winter or convectional storm events during spring and summer (Carr 1967). The analysis based on different rainfall thresholds was performed to characterize the ability of the radar to capture low and high rainfall intensities in general throughout the year and also at different seasons during the year.

Statistical Analysis

Two statistical measures 1) Estimation Bias (EB) and 2) Modified Coefficient of Efficiency (COE) were used to evaluate radar rainfall estimates based on rain gage measurements.

Estimation Bias (EB): This is the normalized difference between the radar estimate and the rain gage measurement evaluated over long periods (one year or more). In other words, it is the ratio of the total difference to the rain gage total rainfall. Positive values of EB indicate overestimation by the radar and negative indicate underestimation of rainfall by radar compared to the rain gage data.

$$\mathrm{EB}(\%) = \left(\frac{\sum_{i=1}^{N} p_i - \sum_{i=1}^{N} o_i}{\sum_{i=1}^{N} o_i} \times 100 \right) \qquad (1)$$

Modified Coefficient of Efficiency (COE): Squared differences in statistics such as in the calculation of R^2 impose a greater influence in statistics due to extreme values or outliers. Hence, Legates and McCabe (1999) proposed a new statistic called Modified COE. This statistic is the same as Nash-Sutcliffe modeling efficiency (Nash and Sutcliffe, 1970) except that instead of squaring the terms in numerator and denominator, the absolute values of the terms in numerator and denominator are used (Legates and McCabe, 1999). COE is a good measure of the agreement between two time series as it is sensitive to differences in the observed and simulated means and variances as opposed to Coefficient of Determination (Legates and McCabe, 1999) which quantifies only the linear relationships between the variables. The values may vary from -∞ to 1.0. A COE of zero or less than zero indicates that the observed mean (rain gage) is as good a predictor as the model (radar) or better. As COE values approach 1.0 it indicates better agreement between rain gage and radar data.

$$\text{Modified COE} = 1 - \left(\frac{\sum_{i=1}^{N} | o_i - p_i |}{\sum_{i-1}^{N} | o_i - \bar{o} |} \right) \qquad (2)$$

Where, p_i - estimated daily rainfall from the radar, o_i is the observed daily rainfall from the rain gage, $\bar{o}$ is the average rainfall per station for each day and $\overline{p}$ is the average rainfall estimated from the radar per station for each day, and *N* is the number of data points.

Results and Discussion

Method of radar and rain gage data comparison

The daily NEXRAD rainfall estimates was compared with rain gage measurements using three different methods: 1) center cell method 2) 9-cell average method and 3) 9-cell minimum difference method. Figure 2 shows the distribution of modified COE for each of the three different methods of radar rainfall comparison with rain gages at the two river forecast center regions, ABRFC and WGRFC. The box plots are represented by 1st quartile, median and 2nd quartile along with whiskers plotted at 1.5 times the interquartile range. Figures 2a and 2b show the distribution of modified COE inclusive of days with zero rainfall and exclusive of days with zero rainfall respectively, for the First-Order rain gages in the study area. The 9-cell minimum difference method of radar and rain gage data comparison consistently gave better results in both instances than the other two methods. The median of modified COE for the 9-cell minimum difference method was consistently close to 0.9 while it was lower than 0.8 for the other two methods. Further, for the 9-cell minimum difference method, the interquartile range of modified COE was spread across a narrow range (0.85 to 0.95) of values than for the other two methods. This further emphasis that the 9-cell minimum difference method of radar and rain gage data comparison consistently performs better at all stations across the region than the other two methods.

This better performance of 9-cell minimum difference method could be due to geo-referencing errors in rain gage or radar data along with the location of rain gage relative to the 4km × 4km HRAP radar grid, i.e. location of the rain gage in the center of the grid versus the edge of the grid. Further, the scale and shape distortions of the coordinate system used for radar data mapping also vary with latitude (Reed and Maidment, 1999). Hence, the 9-cell minimum difference method of radar and rain gage data comparison is a better method to assess the accuracy of radar performance than the other two methods.

Including days with zero rainfall from both radar and rain gage in the calculation of statistics artificially gives a higher number because; there are more dry days than rainy days in a year in this region. Hence, in order to evaluate the true radar performance in measuring rainfall, the statistics were calculated by including only days when both radar and rain gage measured rainfall above 0 mm. By excluding days with zero rainfall (Figure 2b) the modified COE reduced slightly for all the three methods and spread across a wider range of values (0.8 to 0.9), more so in the other two methods than the 9-cell minimum difference method.

A similar analysis as discussed above for the First-Order rain gages was performed with the COOP rain gages (Figures 2c and 2d) and the results display a similar pattern as observed for the First-Order rain gages. The statistics show that the 9-cell minimum difference method is a better way to compare radar and rain gage data. However, the median of modified COE was consistently lower than 0.8, lower those observed for the First-Order rain gages (above 0.9). Further, the COE is spread across a wide range of values than those of First-Order rain gages, more so with the analysis excluding days with zero rainfall (ABRFC:0.6 to 0.8 and WGRFC: 0.4 to 0.8) (Figure 2d).

Figure 3 shows the distribution of two statistical measures, Estimation Bias and Modified COE, used to evaluate the radar performance (9-cell minimum difference method; exclusive of days with zero rainfall) with reference to First-Order and COOP rain gages located at ABRFC and WGRFC regions. The radar Estimation Bias (Figure 3a), at First-Order rain gages located in both the regions is distributed across a narrow range of values (< 5%) centered on zero when compared to COOP rain gages where the radar under predicts the rainfall by as much as 10% to 20% at most of the rain gages. The interquartile range of modified COE (Figure 3b) also showed that the radar performance was better at First-Order rain gages (0.8 to 0.9) when compared to the radar performance at COOP rain gages (ABRFC: 0.6 to 0.8 and WGRFC: 0.4 to 0.8). The modified COE at First-Order and COOP rain gages did not show any specific spatial trend in the performance of radar (Figure 4).

Multiple-Regression Analysis of modified COE at COOP rain gages

In order to the analyze the poor performance of the radar data when compared with COOP rain gage measurements, a multiple linear regression analysis was conducted to study the variation of modified COE as a function of four independent variables: 1) Distance between the nearest radar and the COOP rain gage 2) Distance between the nearest coast line and the COOP rain gage 3) Distance between the nearest FOA station and the COOP rain gage and 4) Difference in topographic elevation between the COOP rain gage and the nearest radar. These variables were selected based on the intuition that: 1) as the distance between the radar and rain gage increase the radar accuracy will decrease 2) the rainfall pattern and intensity of storms vary as a function of distance from the coast line and so are the error in radar rainfall estimation 3) the error in operational radar bias correction might increase as a function of distance from the First-Order stations used for correcting radar rainfall data and 4) the elevation differences between rain gage and radar site might influence the radar signal due to topography or ground clutter.

Before calculating the regression coefficients, the independent variables were linearly scaled based on its maximum value so that each variable range between 0 and 1 except for elevation difference which range between -1 and +1. Scaling the independent variables between 0 and 1 makes the variables unit less and hence the relative influence of each of these variables on radar accuracy can be assessed. The coefficients of the variables and the regression statistics are given in Table 1. The R^2 of the regression relationship between modified COE and the four independent variables for both ABRFC and WGRFC was very less ($R^2 < 0.1$). However, the F-statistic indicated a significant regression relationship at the 0.05 level for the WGRFC region and not significant for the ABRFC region. Further, except for the distance to the First-Order rain gage, all the three coefficients of the regression relationship was significant at the 0.05 level indicated by the t-statistic. Based on the relative magnitude of the regression coefficients, distance from the rain gage to the closest radar has the largest influence on the accuracy of radar. The negative coefficient (-0.33064) indicates that the accuracy decreases (modified COE decreases) with the increase in distance from the radar. Similarly, the accuracy also decreases with the increase in distance from the coast, probably due to differences in rainfall patterns between the coast and inland areas. The radar accuracy also seems to decrease with increase in difference between rain gage and radar topographic elevations probably due to the influence of topography or ground clutter on the radar signal.

In spite of the significant regression relationship at the WGRFC region, due to the extremely low R^2 values, it was difficult to identify the pattern or enumerate reasons with certainty for the poor performance of the radar at COOP rain gages. This poor performance of the COOP rain gages at both ABRFC and WGRFC regions could be due to:

1) First-Order rain gages are operated by trained personnel in NWS and Federal Aviation Administration (FAA); the equipments are well maintained and have stringent data Quality Assurance/Quality Control (QA/QC), where as the COOP rain gages are maintained by volunteers in state/federal agencies, local governments, radio stations, businesses, or citizens and operate under less stringent guidelines.
2) The station density of COOP rain gage (WGRFC: 326; ABRFC: 401) is several times higher than the First-Order rain gage (WGRFC: 39; ABRFC: 21). Even though the COOP network operate under less stringent guidelines, most of them operate under highest of standards maintained by conscientious observers and it is a true representative of the weather at where the people live. Hence, the poor statistic of the radar and rain gage rainfall at COOP rain

gage could point to the need for better calibration algorithms for radar and improvement in radar technology.

3) As explained previously, most of the First-Order rain gages used in this study may have been used by NWS in Stage III radar processing; hence comparing the radar data with the same rain gages could bias the statistic in favor of First-Order rain gages.

Analysis of Radar Performance during different seasons

In order to evaluate the efficiency of radar in capturing rainfall due to different types of storm events (e.g. stratiform frontal or convectional) that occur during various seasons of the year, a seasonal comparison was performed with daily rain gage data using 9-cell minimum difference method. Figure 5 shows the distribution of modified COE and estimation bias calculated for the radar measurements at the First-Order and COOP rain gages in the ABRFC and WGRFC regions during different seasons. Except during winter at the First-Order rain gages located in the ABRFC region, the NEXRAD rainfall data compared well with most First-Order rain gages (Figure 5a) during all seasons at both ABRFC and WGRFC regions (Modified COE > 0.8). The estimation bias also ranged between ±5% at the First-Order rain gages except during winter at the ABRFC region (Figure 5b) when the radar tend to overestimate the rainfall at come First-Order rain gage by as much as 10%.

As observed previously, the modified COE at the COOP rain gages were low and distributed across a wide range (Figure 5c). The radar performance seems to be slightly better at the COOP rain gages in the ABRFC region (Modified COE: 0.5 to 0.85) than at the WGRFC region (Modified COE: 0.3 to 0.8). The median of modified COE's during different seasons also confirms that the radar performance was slightly better in the ABRFC regions than the WGRFC regions. Radar underestimated rainfall during all seasons at most of the COOP rain gages in both the regions (Figure 5d). However, as reflected in the modified COE, the underestimation seems to be more at the WGRFC region (1st quartile level estimation bias as high as -45% during winter) than at ABRFC (1st quartile level estimation bias during all seasons was within -25%).

Analysis of Radar Performance in measuring various daily rainfall thresholds

The radar performance in measuring low, medium or high daily rainfall volumes is presented in figure 6. It shows that there is considerable error in radar estimates in measuring medium range (12.71 to 25.4 mm or 0.5 to 1 inch) rainfall events at First-Order rain gages located in both ABRFC and WGRFC regions. The modified COE at the First-Order rain gages ranged between 0.2 and 0.6, much lower than the median of modified COE for the other rainfall thresholds (Figure 6a). For rainfall events less than 12.7mm and for events greater than 25.4mm, the median modified COE was close to 0.8 at both the regions. However, the estimation bias (Figure 6b) did not show considerable differences in measuring various rainfall thresholds (±5%). This was because some rainfall events in the range of 12.71 to 25.4mm were overestimated and some were underestimated by radar, resulting in an overall smaller estimation bias (Figure 6b).

At COOP rain gages the error in radar estimated rainfall was much larger across all the three rainfall thresholds considered in this analysis (Figure 6c). The median of modified COE show that 50% of the rain gages had a modified COE less than 0.5 at the

ABRFC region and less than 0.4 at the WGRFC region. As observed in the First-Order rain gages, the error in radar estimates was high for the medium range rainfall events with the modified COE less than zero at most of the rain gages in the ABRFC region and at almost all of the rain gages in the WGRFC region. A COE value less than zero indicate that the mean of the observed rainfall (rain gage measurements) is a better predictor than the radar. The median radar estimation bias at the COOP rain gages (Figure 6d) for the three rainfall thresholds was close to -20% at both the regions.

Analysis of Radar performance in measuring various rainfall thresholds during different seasons

In order to identify if the errors in radar rainfall estimation observed at the three rainfall thresholds occur during all seasons or only during specific season of the year, the modified COE was calculated separately for the three rainfall thresholds for each of the four seasons (Figures 7 and 8).

At the First-Order rain gages in the ABRFC region, the performance of the radar in measuring rainfall events less than 12.7mm was poor during winter with the 1^{st} quartile modified COE as low as 0.45 when compared to other seasons (> 0.7) (Figure 7). However, the median of modified COE for this low rainfall threshold was consistently close to 0.8 during all the four seasons. In the WGRFC region, the distribution of modified COE at the First-Order rain gages was similar during all the four seasons for this low rainfall threshold with the 1^{st} quartile modified COE greater than 0.7 and the median of modified COE closer to 0.8.

As observed in the previous section in figure 6a, the radar error was the highest (low modified COE) in measuring the medium rainfall range (12.71 to 25.4mm). For the ABRFC region this error was the highest during Spring (1st quartile modified COE less than 0.2) and Summer (1st quartile modified COE less than 0) (Figures 7b and 7c) and for the WGRFC region during Autumn (1st quartile modified COE less than 0.1) and Summer (1st quartile modified COE close to 0) (Figure 7a and 7c). The rainfall events tend to be predominantly convective in nature during Summer and frontal stratiform during winter. A combination of convective and frontal stratiform system produces rainfall during Autumn and Spring. The poor performance of the radar during summer and the transition seasons of Autumn and Spring indicate that better radar calibrations and improvements in radar algorithms are needed to capture the convective storm events especially in measuring medium rainfall range.

In measuring rainfall events greater than 25.4mm the radar error was the lowest during Autumn in the ABRFC region with a modified COE > 0.85 at most of the First-Order rain gages (Figure 7a). In the ABRFC region, the radar error was the highest during Spring and Summer (1st quartile modified COE less than 0.5). In the WGRFC region, the modified COE distribution at the First-Order rain gages was similar during all the four seasons for this high rainfall threshold with the 1st quartile modified COE greater than 0.7 and the median of modified COE closer to 0.8 except during winter when the 1st quartile modified COE was close to 0.6.

As observed in the previous section (Figure 6c), the radar error was highest among the COOP rain gages (median modified COE less than 0.5) across all the three rainfall thresholds with the worst performance in measuring medium range rainfall events (median modified COE less than 0.0) in both ABRFC and WGRFC regions.

Summary and Conclusion

From the comparison and analysis of NEXRAD Stage III precipitation estimates with an extensive network of both First-Order and COOP rain gages in the West Gulf and Arkansan Red-River Basin regions, that 9-cell minimum difference method is a better method to compare NEXRAD 16 sq.km rainfall grid data with the rain gage point data than the Center-Cell or the 9-cell average comparison methods. This could be due to geo-referencing errors in rain gage or radar data along with the location of rain gage relative to the 4km × 4km HRAP radar grid, i.e. location of the rain gage in the center of the grid versus the edge of the grid.

Overall the radar error was the lowest at First-Order rain gages in measuring rainfall greater than zero millimeters with the modified COE between 0.8 and 0.9 in both ABRFC and WGRFC region. However, seasonal and threshold analysis showed that the radar error was high in measuring rainfall events between 12.71 and 25.4mm (median modified COE < 0.5). The error was more predominant during Autumn and Summer at the WGRFC region and Spring and Summer in the ABRFC region. The poor performance of the radar during summer and the transition seasons of Autumn and Spring indicate that better radar calibrations and improvements in radar algorithms are needed to capture the convective storm events especially in measuring medium rainfall range.

The radar error was more pronounced in the COOP rain gage network than the First-Order rain gages but followed a similar trend. Although the radar error appear to be random, a multiple regression analysis of modified COE at COOP rain gages showed a week dependence of radar error as a function of distance of the gage from radar center, distance of the gage from the coast and elevation difference between rain gage and radar. However, due to the small R^2 value of the regression it is difficult to identify the reasons for poor comparison between radar and COOP rain gage estimates.

Although COOP rain gages operate under less stringent guidelines than the First-Order rain gages, most of them operates under highest of standards maintained by conscientious observers and it is a true representative of the weather at where the people live. In addition, the poor performance of the radar in measuring medium range rainfall (12.71 to 25.4mm) even at the First-Order rain gages, which are operationally used for radar calibration and bias adjustments, indicate that better radar calibrations and improvements in radar algorithms are needed.

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Figure 1. Rain gage network in WGRFC and ABRFC regions a) First-Order rain gage network b) Cooperative (COOP) rain gage network.

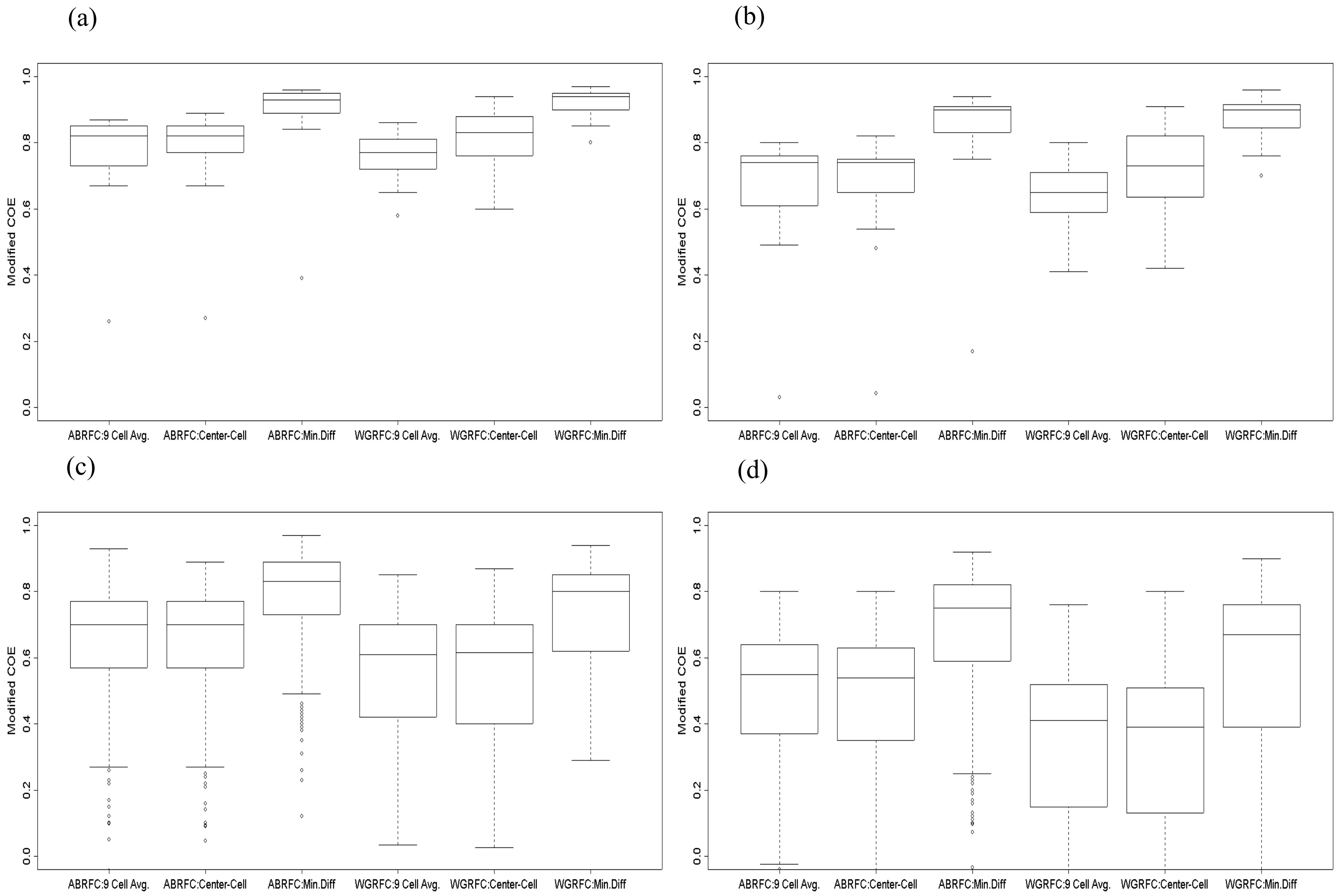

Figure 2. Box plots showing modified COE distribution of radar rainfall estimates in the ABRFC and WGRFC regions using 9-Cell Average, Center-Cell and 9-cell Minimum Difference comparison techniques. A) at First-Order rain gages inclusive of days with zero rainfall B) at First-Order rain gages exclusive of days with zero rainfall from both radar and rain gage C) at COOP rain gages inclusive of days with zero rainfall D) at COOP rain gages exclusive of days with zero rainfall from both radar and rain gage.

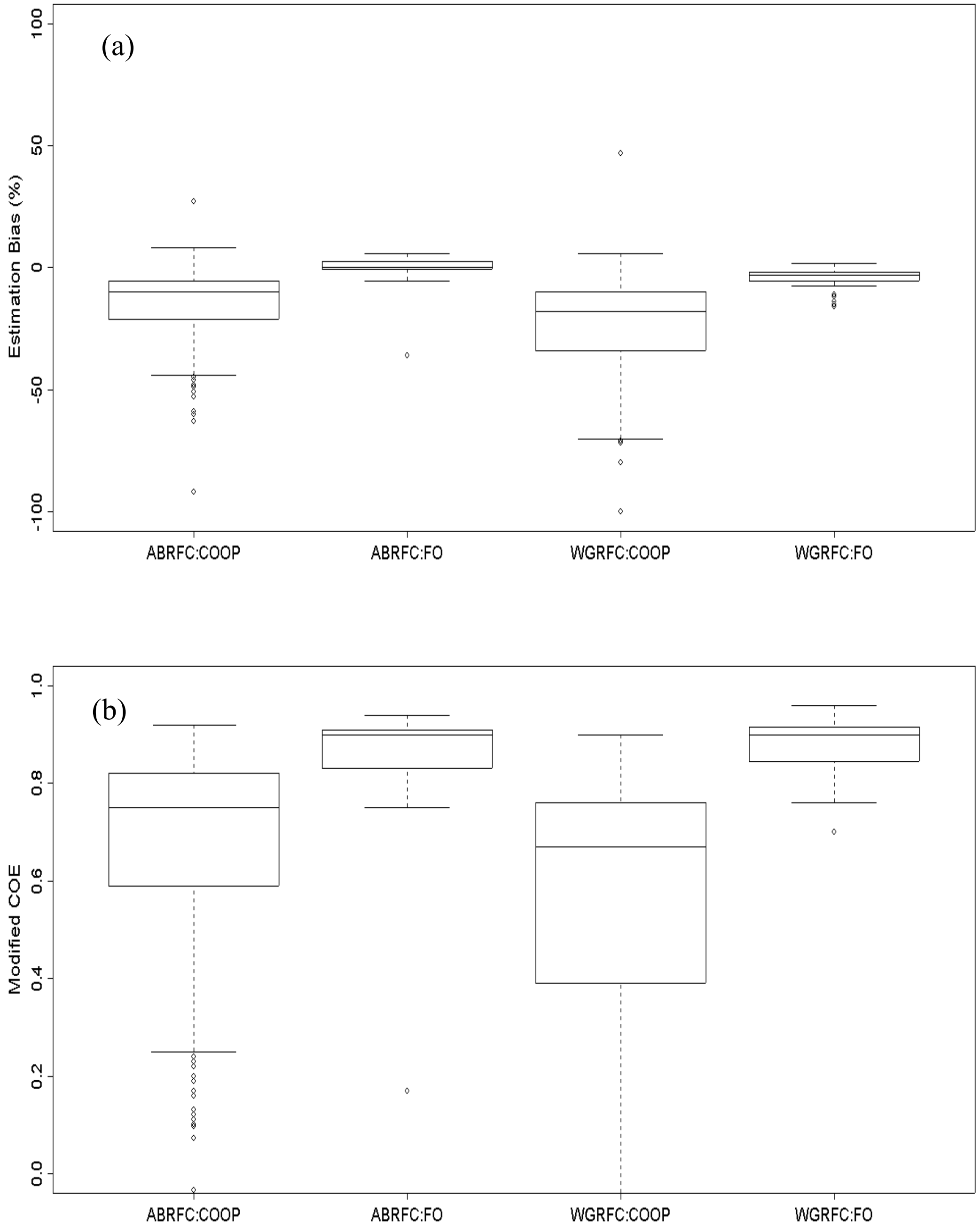

Figure 3. Box plots showing distribution of two statistical measures used to evaluate radar rainfall estimates in the ABRFC and WGRFC regions; exclusive of days with zero rainfall using 9-Cell minimum difference comparison method. A) Estimation Bias (%) and B) Modified COE.

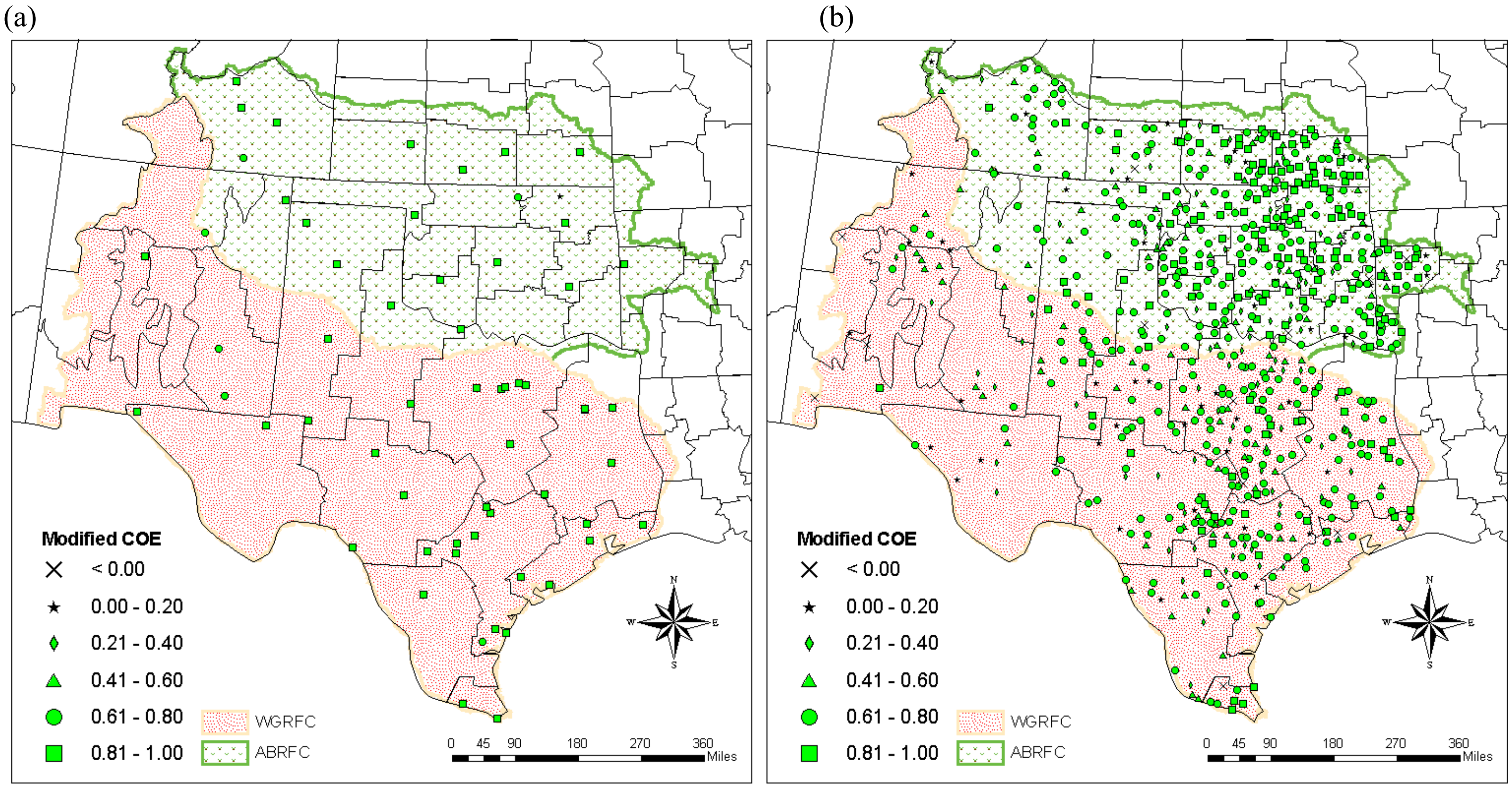

Figure 4. Distribution of modified COE exclusive of days with zero rainfall using 9-Cell minimum difference comparison method a) First-Order rain gage network b) Cooperative (COOP) rain gage network.

Table 1: Multiple-regression relationship between modified COE at COOP rain gages and four independent variables.

Variables	WGRFC			ABRFC		
	Coefficients	*t Stat*	*P-value*	*Coefficients*	*t Stat*	*P-value*
Intercept	0.76590	18.80946	0.00000	0.75784	12.12066	0.00000
Distance to the closest Radar	-0.33064	-3.92477	0.00011	-0.17399	-2.77125	0.00585
Distance to the Coast	-0.20122	-3.33361	0.00096	-0.02628	-0.33167	0.74031
Distance to closest First-Order Rain gage	0.02106	0.24329	0.80794	0.01508	0.22652	0.82092
Elevation difference (COOP - radar)	-0.12963	-2.51044	0.01255	0.02657	0.63519	0.52567

WGRFC: R^2 = 0.0869; F-statistic = 8.73, significant at 0.05 level
ABRFC: R^2 = 0.0119; F-statistic = 2.21, not significant at 0.05 level

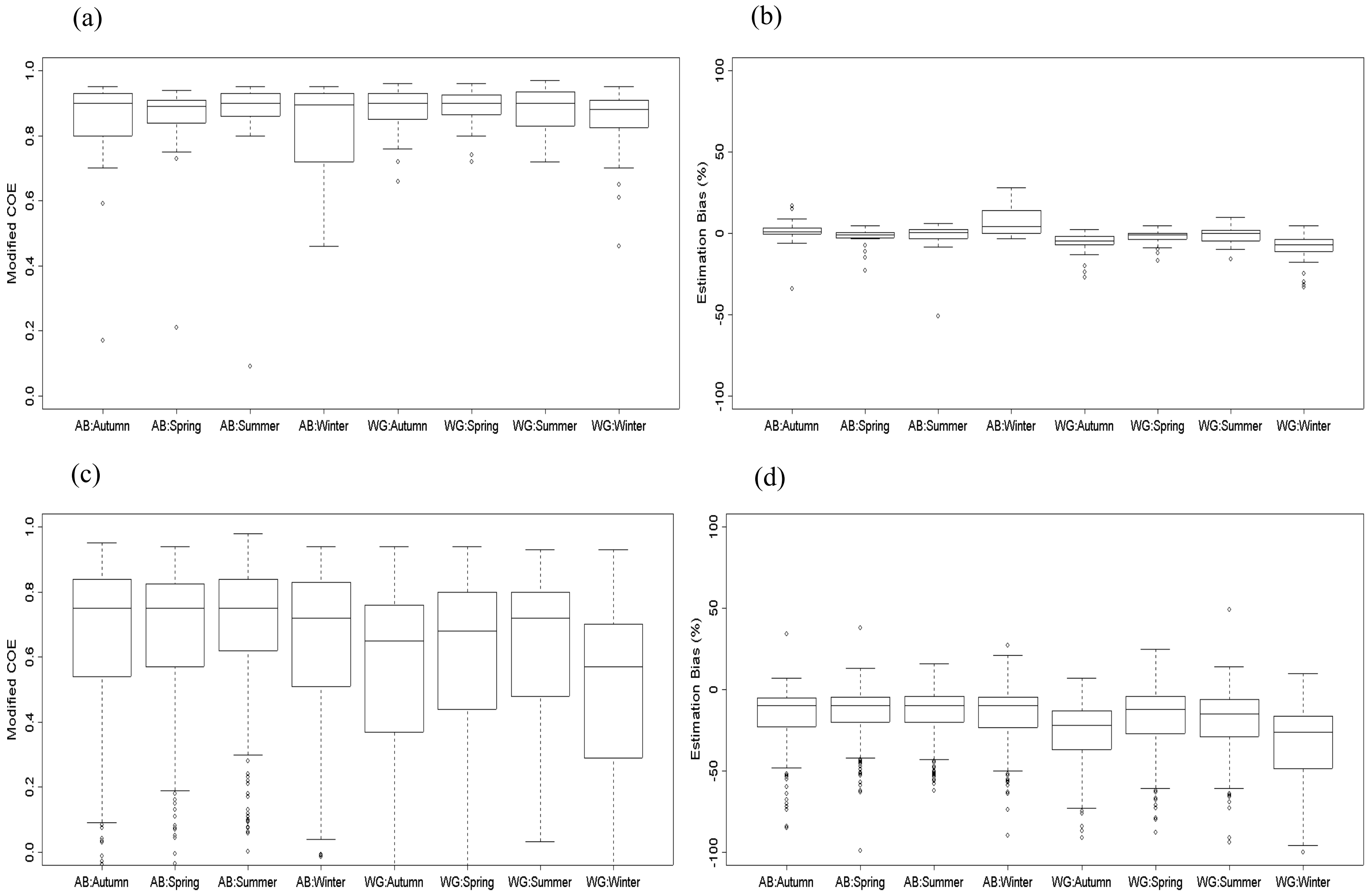

Figure 5. Box plots showing distribution of statistical measures for four seasons at ABRFC (AB) and WGRFC (WG) regions. a) modified COE at First-Order rain gages b) estimation bias at First-Order rain gages c) modified COE at COOP rain gages and d) estimation bias at COOP rain gages. [Winter – January to March, Spring – April to June, summer – July to September and Autumn – October to December].

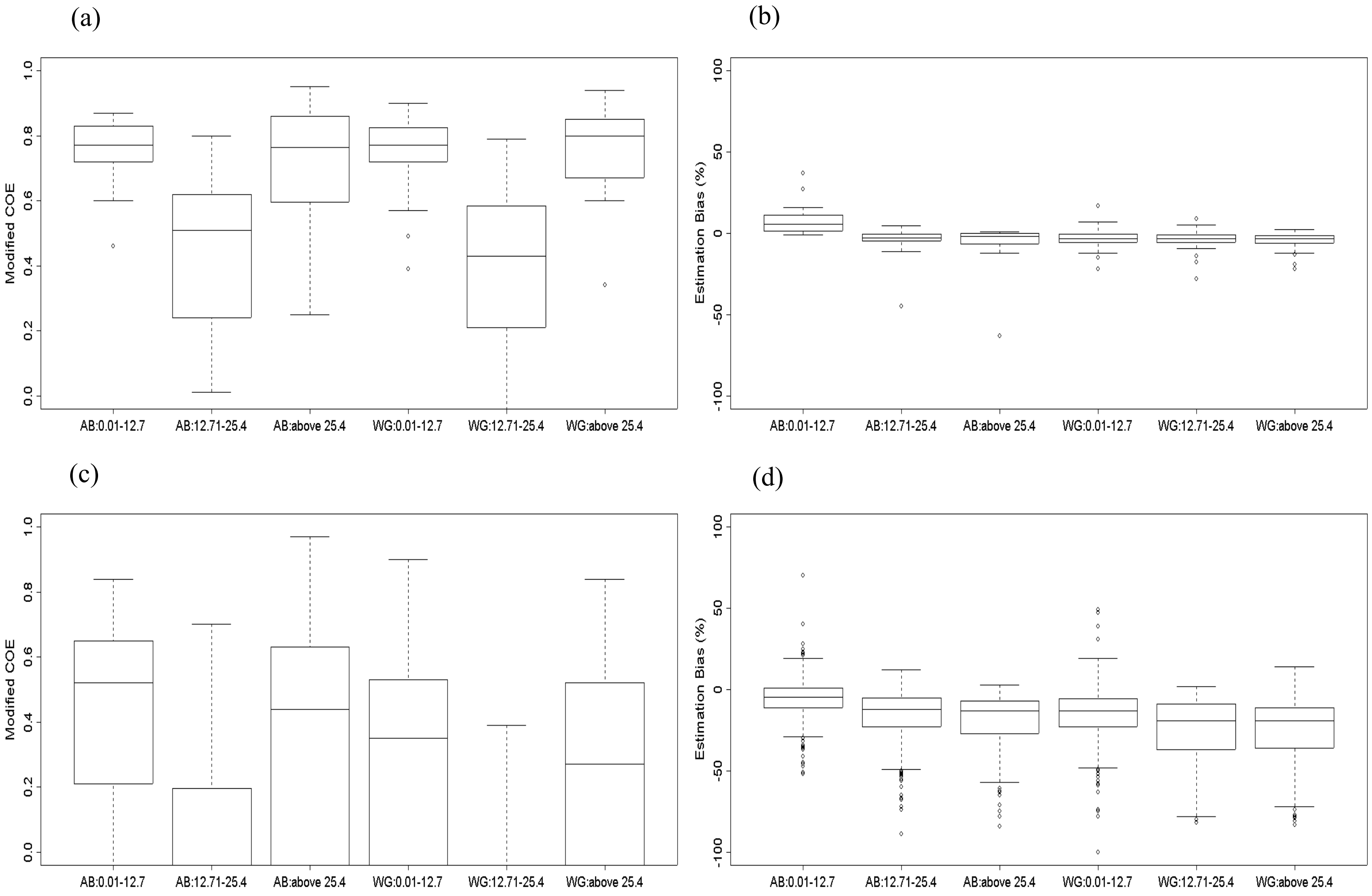

Figure 6. Box plots showing distribution of statistical measures for three rainfall thresholds at ABRFC (AB) and WGRFC (WG) regions. a) modified COE at First-Order rain gages b) estimation bias at First-Order rain gages c) modified COE at COOP rain gages and d) estimation bias at COOP rain gages. [0.01-12.70mm (0.5 inch), 12.71-25.4mm (1 inch) and all events above 25.4mm].

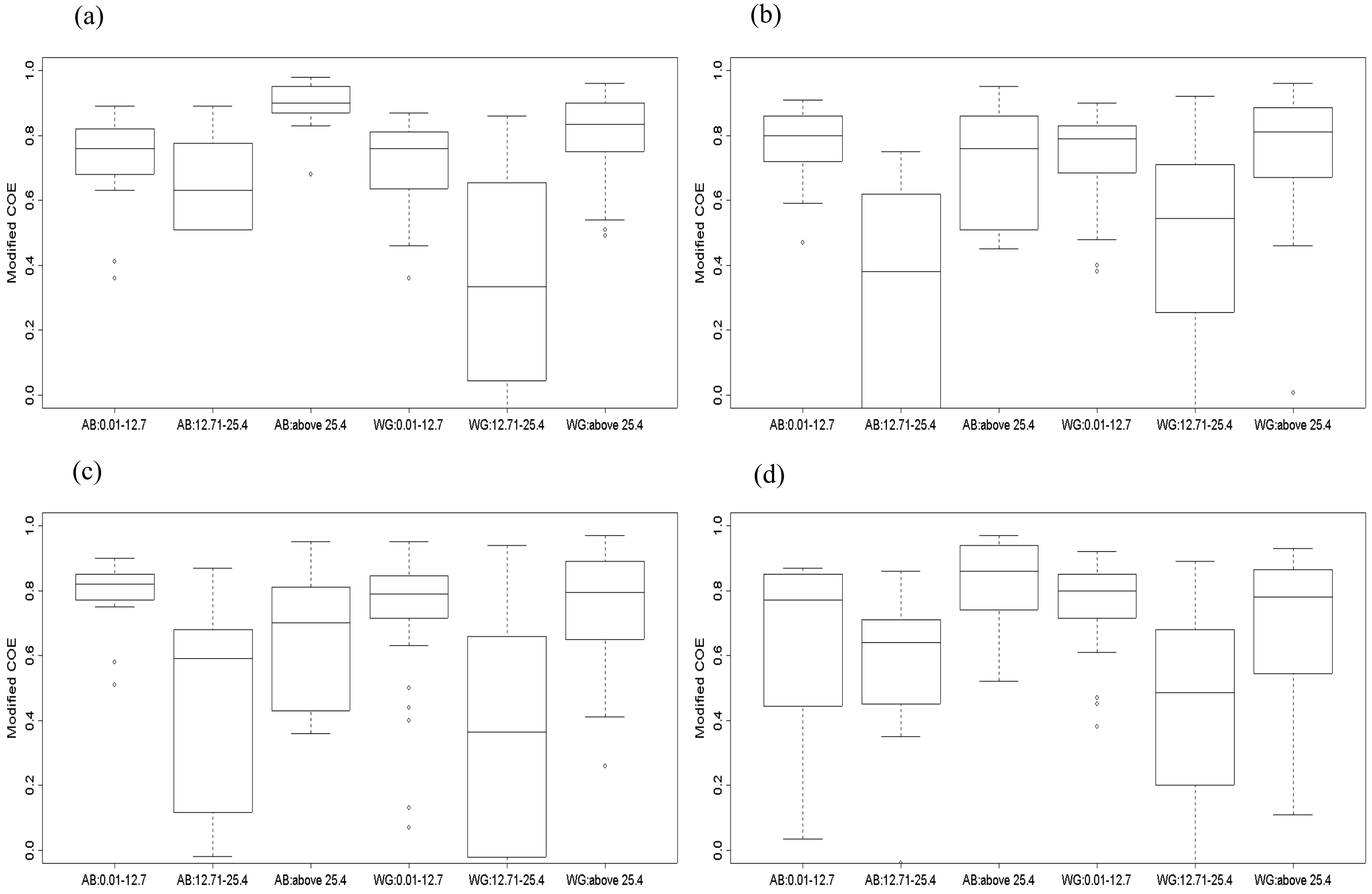

Figure 7. Box-plots showing distribution of modified COE for three rainfall thresholds at First-Order rain gages in ABRFC (AB) and WGRFC (WG) regions during four seasons. a) Autumn b) Spring c) Summer and d) Winter. [Winter – January to March, Spring – April to June, summer – July to September and Autumn – October to December].

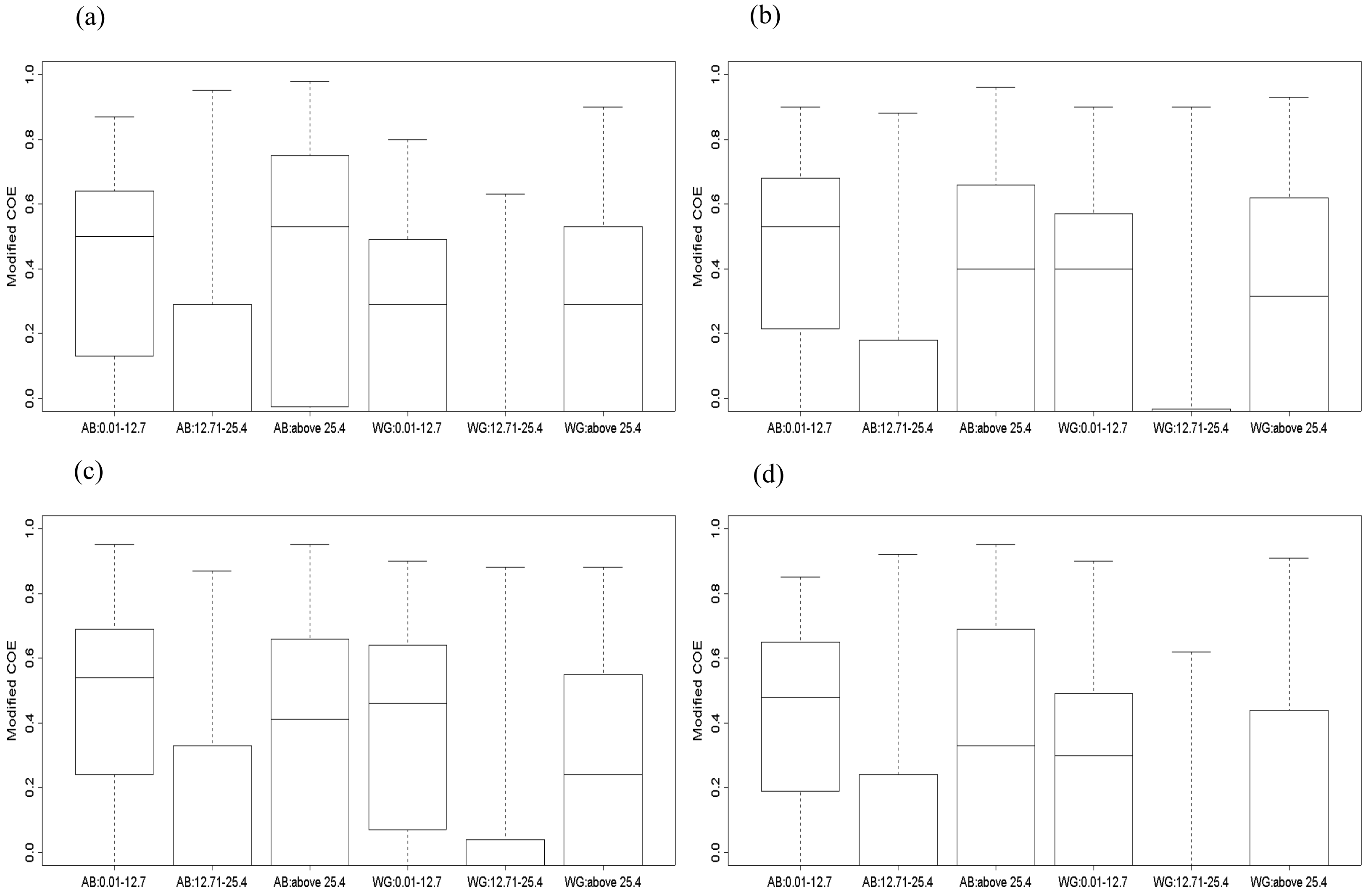

Figure 8: Box-plots showing distribution of modified COE for three rainfall thresholds at COOP rain gages in ABRFC (AB) and WGRFC (WG) regions during four seasons. a) Autumn b) Spring c) Summer and d) Winter. [Winter – January to March, Spring – April to June, summer – July to September and Autumn – October to December].