QUANTIFYING CHANGES IN EXTREME PRECIPITATION AT HOUSTON AND OKLAHOMA CITY BY 2041-2065 USING THE CANADIAN REGIONAL CLIMATE MODEL (CRCM)

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ABSTRACT

One-half-degree gridded daily-projection precipitation model output from two combinations of the Canadian Regional Climate Model (CRCM)—one driven by the Community Climate System Model (CCSM) and another by the Canadian Global Climate Model 3 (CGCM3)—was obtained from the North American Regional Climate Change Assessment Program (NARCCAP). Gridded observational daily precipitation data were used as a reference to a 1971-1995 historic period and as a basis for validating the projection data. Validation suggested strong bias in the projection data, which necessitated that they be bias-corrected using a mean-value technique. Both the observational and projection data were ranked and assigned percentile values as a means of identifying and quantifying possible changes in extreme precipitation during a historic 1971-1995 and a future 2041-2065 period over two 1/2-degree grid squares centered over Houston and Oklahoma City. Overall results of the percentile analysis suggested that, for the highest percentile rankings, the daily precipitation values associated with a given percentile ranking will increase by the 2041-2065 period. For more moderate percentile rankings, the tendency toward change was less clear. For lower percentile rankings (approximately the 80th), there was indication that the values associated with a given percentile ranking will decrease by the future period. Analysis also suggested that a more sophisticated bias-correction procedure based on rain rate is necessary.

1. INTRODUCTION

An increase over time in extreme precipitation events has been identified as a possible consequence of global warming (Gao et al. 2006; Karl et al. 2009). In fact, in the southern Great Plains of the United States, there is indication that extreme precipitation occurrence may increase, reflecting recent trends, even while overall precipitation decreases and drought frequency increases (Meehl et al. 2007; Wilby and Wigley 2007; Karl et al. 2009). That warmer air temperatures lead to greater evapotranspiration and that warmer air has a greater capacity to contain water vapour drive this indication (Wentz et al. 2007).

It is worthwhile to predict and quantify the temporal change in extreme precipitation because of its impacts on society from flooding, the most costly type of natural disaster in the United States in the 20th century (Perry 2000). A recent example of the impacts of flooding was seen on 14 June 2010, when extremely heavy rains associated with training thunderstorms affected much of the Oklahoma City metropolitan area. Up to 300 mm of rain fell in northern parts of this area, and the 500-y heavy rain event for the six- and 12-h intervals was achieved at the North Oklahoma City Mesonet station. Occurring partially during the morning commute, the extreme rainfall caused many motorists to become stranded in floodwaters

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as they attempted to reach their workplaces (McManus 2010). Other extreme rainfall events in the southern Great Plains have occurred in the last five years at Dallas-Fort Worth (September 2010); Houston (April 2009); and Houston, San Antonio, and Oklahoma City (August 2007).

Since the incidence of extreme rainfall events and associated flooding appears to be increasing in the southern Plains, there is interest in how this incidence might continue to change in the future. Therefore, a study that attempts to examine whether an increase in extreme precipitation will continue and to quantify any possible increases was undertaken for Houston and Oklahoma City, two large cities in this region.

2. DATA AND METHOD

2.1 *Domain of Study*

Two 1/2-degree by 1/2-degree (50-km by 50-km) grid square regions were chosen for the study. One grid square is approximately centered over Houston, Texas, and lies between latitudinal coordinates 29.50^{o}N and 30^{o}N and longitudinal coordinates 95^{o}W and 95.50^{o}W. The second grid square is approximately centered over Oklahoma City, Oklahoma, and lies between 35^{o}N and 35.50^{o}N latitude and 97^{o}W and 97.50^{o}W longitude.

The two cities were chosen because they are the most populous in their respective river basins. Houston is the most populous city in the South-Central/West Gulf basin, and Oklahoma City is the most populous in the Arkansas-Red basin.

Figure 1 shows the locations of the river basins relative to the United States.

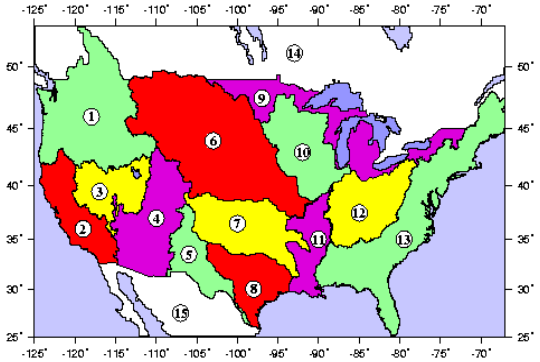

Figure 1. Region (7) is the Arkansas-Red basin, and region (8) is the South-Central/West Gulf basin (after Maurer et al. (2002)).

2.2 *Observational Data*

Daily gridded observational precipitation data were obtained from the University of Washington's Surface Water Modelling Group. In particular, the data as obtained from the website <http://hydro.engr.scu.edu/files/gridded_obs/daily/ncfiles/>, presented in NetCDF format, were prepared by Dr. E.P. Maurer of Santa Clara University.

The spatial resolution of these data is 1/8 degree (12 km). They are available for all the conterminous United States and all the 1950-2010 period. It was noted that the data for 1986 were missing. Hence, we did not consider 1986 in any of the analyses.

2.3 *CRCM Data*

Gridded daily-projection Canadian Regional Climate Model (CRCM) precipitation flux density data were obtained from the North American Regional Climate Change Assessment Programme (NARCCAP). The objective of NARCCAP is to produce high-temporal-resolution climate change simulations for the study of regional climate change. Data are available for several models and several meteorological variables and for a historic 1971-2000 period and a future 2041-2070 period. However, due to much missing data in the 1996-2000 and 2066-2070 periods, output for only 1971-1995 and 2041-2065 was examined. The spatial resolution of the data is 1/2 degree (50 km).

All NARCCAP modeling uses the so-called A2 emissions scenario. The A2 emissions scenario is one of several defined by Nakicenovic et al. (2000) as part of their work on the *Special Report on Emissions Scenarios* (*SRES*), which was commissioned by the Intergovernmental Panel on Climate Change (IPCC). A2 lies at the higher end of the scenarios but is not the highest, taking the view that world development going forward will be more differentiated and moderate than it might be in the worst-case scenario.

The output of several regional climate models (RCMs) was available, but there was an interest in selecting only one for study. The CRCM was the RCM selected because it has been shown to perform the best of any RCM for monthly precipitation time series for the 1981-2002 period in the American Deep South. This conclusion was based upon comparison with 1/2-degree gridded precipitation analysis from the University of Delaware (Gutowski et al. 2011).

CRCM output was available and obtained for study for two RCM-GCM (global climate model, or general circulation model) combinations, the CRCM-CCSM (Community Climate System Model) and the CRCM-CGCM3 (Canadian Global Climate Model phase3). The GCM serves as a driver for the RCM. That is, the GCM forces the boundary conditions of the RCM, the spatial resolution of which is finer. An alternative to so-called statistical downscaling, such driving of RCMs is referred to as dynamic downscaling. Although dynamic downscaling requires considerable computing power, it has a significant advantage over statistical downscaling in that statistical downscaling requires the assumption that statistical relationships existing in the present will continue to exist in the future (Wood et al. 2004).

2.4 *Validation and Bias Correction*

Validation of the CRCM data using the observational data as a historical benchmark was done to identify any biases.

The data-sets extracted for the Houston-centered and the Oklahoma City-centered grid square regions were considered separately. For each grid-square region, the two RCM-GCM combinations were each considered separately.

From the daily observational data, monthly and annual precipitation totals were calculated and arranged as a time series. Similar totals and series were developed for the two RCM-GCM combinations. Then, Pearson's correlation coefficient and the root mean square error (RMSE) were calculated between each monthly RCM-GCM series and the monthly observational series. These two calculations were performed similarly for the annual-based series.

A positive correlation coefficient (near 1.0) and low value of RMSE were desired. If the correlation coefficient was determined not to be sufficiently close to 1.0 or the RMSE to be too high, the nature of any bias in the model data was assessed. This assessment of bias led to a mean-bias-correction procedure. For each RCM-GCM combination in each grid square region, the bias for each member in the daily precipitation data-set was calculated, where bias is the modeled value subtracted from the observational value. A mean bias value over the entire 1971-1995 (less 1986) period was then found. These mean bias values were multiplied by 365 d y^{-1}, the product of which was divided by the average number of precipitation days per year. A “precipitation day” is defined as any day whose liquid-equivalent precipitation total is greater than or equal to 0.254 mm (0.01 in.). According to the National Climatic Data Center, the annual average number of such days is 98 at Houston (based on the 1970-2010 period) and 77 at Oklahoma City (1940-2010). This quotient, calculated for each of the two RCM-GCM combinations in each of the two grid squares, represented a bias-correction factor. This factor was added to every daily precipitation value in the 2041-2065 model-projected data-sets greater than 0.254 mm.

2.5 *Percentile Analysis*

Percentile rankings were employed to examine quantitatively the modeled temporal changes in extreme precipitation between the historic 1971-1995 and future 2041-2065 periods. Two approaches were taken in order to account for any bias present in the model data. For both approaches, each grid square and each RCM-GCM combination were considered separately.

One approach, for which model biases could be assumed not to be a factor, compared each RCM-GCM combination's 1971-1995 output to the same combination's 2041-2065 output. The observational data were ranked in ascending order, and percentile values were assigned to these daily data by the standard calculation. Similar ranking and percentile assignment were performed for the model-projected data. We focused our attention to the percentile values 100, 99.5, 99, 97.5, and 95 to quantify how truly extreme precipitation would change between the 1971-1995 and 2041-2065 periods. That is, for a constant percentile value, whether in the future the associated daily precipitation value was higher than the historical observed value was determined. The percentile values 90 and 80 were also examined for insight into how more typical precipitation might change.

The second approach that was considered relied on comparing the daily observational (i.e., historical) data to the daily model projections of each RCM-GCM combination. Ranking and percentiles were applied similarly to the first approach. However, the results of the validation prevented this second approach from being fully implemented.

3. RESULTS AND DISCUSSION

The results of the validation, bias-correction, and percentile analysis follow, by grid square.

3.1 *Houston*

An approach that compared historic runs of a given RCM-GCM combination to the future run of the same RCM-GCM combination was employed to examine temporal change. Tables 1 and 2 give the results of this second approach.

Percentile Ranking	**1971-1995 CRCM-CCSM Value (mm d^{-1})**	**2041-2065 CRCM-CCSM Value (mm d^{-1})**	**Signed Change Between 1971-1995 and 2041-2065 (mm d^{-1})**	**Percent Change Between 1971-1995 and 2041-2065**
Maximum (~100)	42.7	57.6	14.9	34.8
99.5	22.4	23.0	0.6	2.7
99	19.0	19.6	0.6	3.2
97.5	14.2	13.7	-0.5	-3.5
95	9.8	9.4	-0.4	-4.1
90	5.7	5.4	-0.3	-5.3
80	2.3	1.9	-0.4	-17.4

Table 1. Values corresponding to a constant percentile ranking were calculated for the 1971-1995 historic CRCM-CCSM modeled data and the 2041-2065 future CRCM-CCSM projected data. Signed changes and percent changes were also calculated. Bias correction factors are not applied to the model values in this table.

Percentile Ranking	**1971-1995 CRCM-CGCM3 Value (mm d^{-1})**	**2041-2065 CRCM-CGCM3 Value (mm d^{-1})**	**Change Between 1971-1995 and 2041-2065 (mm d^{-1})**	**Percent Change Between 1971-1995 and 2041-2065**
Maximum (~100)	56.0	69.0	13.0	23.2
99.5	30.4	31.5	1.1	3.6
99	26.5	28.2	1.7	6.4
97.5	21.0	22.1	1.1	5.2
95	16.5	17.1	0.6	3.6
90	11.6	11.4	-0.2	-1.7
80	6.4	5.8	-0.6	-9.4

Table 2. Values corresponding to a constant percentile ranking were calculated for the 1971-1995 historic CRCM-CGCM3 modeled data and the 2041-2065 future CRCM-CGCM3 projected data. Signed changes and percent changes were also calculated. Bias correction factors are not applied to the model values in this table.

The ogives of Figures 2 and 3 present a more complete depiction of this analysis.

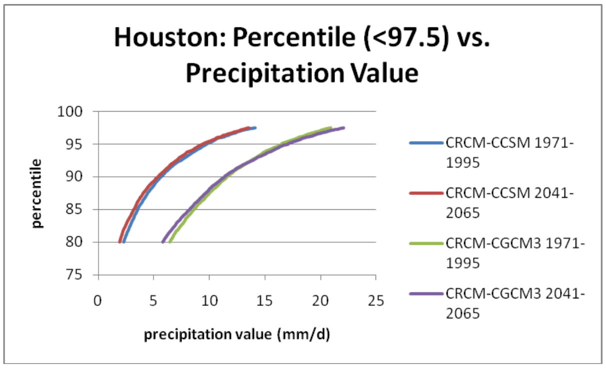

Figure 2. An ogive plot of lower-value percentile against corresponding precipitation value for both historical (1971-1995) and future (2041-2065) output for both RCM-GCM model combinations for the Houston grid square. Bias correction factors are not applied.

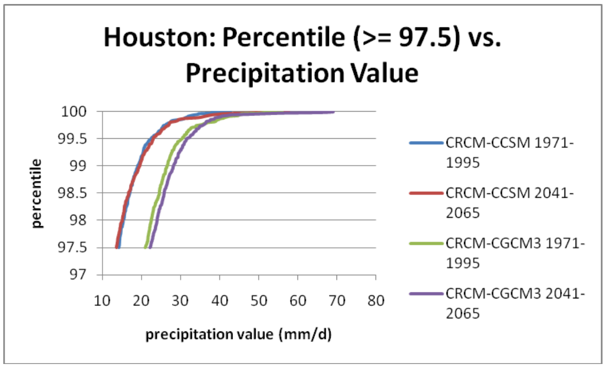

Figure 3. An ogive plot of higher-value percentile against corresponding precipitation value for both historical (1971-1995) and future (2041-2065) output for both RCM-GCM model combinations for the Houston grid square. Bias correction factors are not applied.

Comparison of the historic and future CRCM-CCSM output suggested that the maximum daily rainfall value during the 2041-2065 25-year period will be just over a third greater than during the historic 1971-1995 25-year period. For somewhat lower, more moderate percentile values, the signal was much less clear, tending toward little change with percent changes between the historic and future periods at or less than five percent. Interestingly, the change in the 80th-percentile values between the two periods was more substantial at nearly a fifth (17.4%) less in the future compared to the historic period.

A similar comparison of the historic and future CRCM-CGCM3 output suggested that the maximum daily rainfall value during the future 25-year period will be nearly a quarter (23.2%) greater than during the historic 25-year period. Similar to the CRCM-CCSM output, the CRCM-CGCM3 output forecasted relatively little change in the precipitation values associated with more moderate percentile rankings. In contrast to the CRCM-CCSM, the CRCM-CGCM3 showed a somewhat lesser change in precipitation value for the lowest percentile rankings examined.

Overall, these results were consistent with the expectation that extreme precipitation will be more extreme in the future and that overall precipitation may decrease, as shown by the decreases in more moderate percentile precipitation values.

A second approach where observational data were to be compared to model-projected data seemed obvious. First, validation of the model data was performed.

The validation procedure yielded the following results (Tables 3-4) when the observational and historical RCM-GCM data were examined from the perspective of 1971-1995 monthly time series:

RCM-GCM Combination	**Correlation between RCM-GCM and Observational**
CRCM-CCSM	-0.02
CRCM-CGCM3	0.01

Table 3. Pearson correlation coefficients were calculated comparing each RCM-GCM combination's 1971-1995 monthly time series to the 1971-1995 observational monthly time series.

RCM-GCM Combination	**RMSE (mm month^{-1})**
CRCM-CCSM	91.7
CRCM-CGCM3	97.4

Table 4. The root-mean-square error between the elements of each RCM-GCM combination's 1971-1995 monthly time series and the 1971-1995 observational monthly time series was calculated.

The validation procedure yielded the following results (Tables 5-6) when the observational and historical RCM-GCM data were examined from the perspective of 1971-1995 annual time series:

RCM-GCM Combination	**Correlation between RCM-GCM and Observational**
CRCM-CCSM	0.41
CRCM-CGCM3	-0.09

Table 5. Pearson correlation coefficients were calculated comparing each RCM-GCM combination's 1971-1995 annual time series to the 1971-1995 observational annual time series.

RCM-GCM Combination	**RMSE (mm y^{-1})**
CRCM-CCSM	638.9
CRCM-CGCM3	359.2

Table 6. The root-mean-square error between the elements of each RCM-GCM combination's 1971-1995 annual time series and the 1971-1995 observational annual time series was calculated.

From both the monthly and annual perspectives (Tables 3 and 5), correlation values were generally distant from the ideal value of 1.0 and were even negative in the case of the CRCM-CGCM3 examined on an annual basis. Only the CRCM-CCSM examined on an annual basis showed even a moderate correlation (0.41) between the observational and modeled. Root-mean-square errors were elevated, approaching 50 percent of the corresponding annual total and 80 percent of the mean monthly total. Model bias was clearly present, which necessitated implementation of the bias-correction procedure (Table 7).

RCM-GCM Combination	**Bias Correction Factor (mm d^{-1})**
CRCM-CCSM	5.93
CRCM-CGCM3	4.84

Table 7. The bias correction factor for each RCM-GCM combination was calculated based on 1971-1995 observational data and historical output for the pertinent combination.

The bias correction factors given in Table 7 were then added to the model-projected values. Both the observational and bias-corrected model-projected values were ranked and percentile values were assigned to them, as in Table 8.

Percentile Ranking	**1971-1995 Observational Value (mm d^{-1})**	**2041-2065 CRCM-CCSM Value (mm d^{-1})**	**2041-2065 CRCM-CGCM3 Value (mm d^{-1})**
maximum (~100)	163.7	63.5	73.8
99.5	52.0	28.9	36.3
99	40.2	25.5	33.0
97.5	26.6	19.6	26.9
95	17.9	15.3	21.9
90	10.1	11.3	16.2
80	4.8	7.8	10.6

Table 8. Percentile values were calculated for the 1971-1995 observational and both RCM-GCM model combinations' data-sets. The appropriate bias correction factor (Table 5) was applied to the model values.

Although bias-correction was applied to the model-projected values, there were still aberrations in the data. The full non-bias-corrected time series indicated that biases were much greater for the more extreme precipitation values and somewhat less or even negative for lower-percentile precipitation values (i.e., percentile values below the 90th). That there is large underestimation bias in the most extreme values is due to a noted bias of GCMs. Therefore, although simply applied, a mean-bias-correction procedure was not adequate, and a more sophisticated bias-correction procedure based on a rain-rate function is best pursued in future work.

3.2 *Oklahoma City*

As with the Houston grid square, comparisons of the historic run of a given RCM-GCM combination with its future run were performed. The results follow in Tables 9 and 10.

Percentile Ranking	1971-1995 CRCM-CCSM Value (mm d^{-1})	2041-2065 CRCM-CCSM Value (mm d^{-1})	Signed Change Between 1971-1995 and 2041-2065 (mm d^{-1})	Percent Change Between 1971-1995 and 2041-2065
Maximum (~100)	69.4	70.7	1.3	1.9
99.5	22.8	23.7	0.9	3.9
99	18.1	19.2	1.1	6.1
97.5	11.7	12.8	1.1	9.4
95	7.8	8.1	0.3	3.8
90	4.1	3.9	-0.2	-4.9
80	1.7	1.4	-0.3	-17.6

Table 9. Values corresponding to a constant percentile ranking were calculated for the 1971-1995 historic CRCM-CCSM modeled data and the 2041-2065 future CRCM-CCSM projected data. Signed changes and percent changes were also calculated. Bias correction factors are not applied to the model values in this table.

Percentile Ranking	1971-1995 CRCM-CGCM3 Value (mm d^{-1})	2041-2065 CRCM-CGCM3 Value (mm d^{-1})	Signed Change Between 1971-1995 and 2041-2065 (mm d^{-1})	Percent Change Between 1971-1995 and 2041-2065
Maximum (~100)	66.0	70.7	4.3	6.5
99.5	27.3	26.1	-1.2	-4.4
99	21.5	20.4	-1.1	-5.1
97.5	14.3	13.7	-0.6	-4.2
95	9.1	8.5	-0.6	-6.5
90	4.9	4.3	-0.6	-12.2
80	1.9	1.5	-0.4	-21.1

Table 10. Values corresponding to a constant percentile ranking were calculated for the 1971-1995 historic CRCM-CGCM3 modeled data and the 2041-2065 future CRCM-CGCM3 projected data. Signed changes and percent changes were also calculated. Bias correction factors are not applied to the model values in this table.

The ogives of Figures 4 and 5 give a more complete depiction of the results.

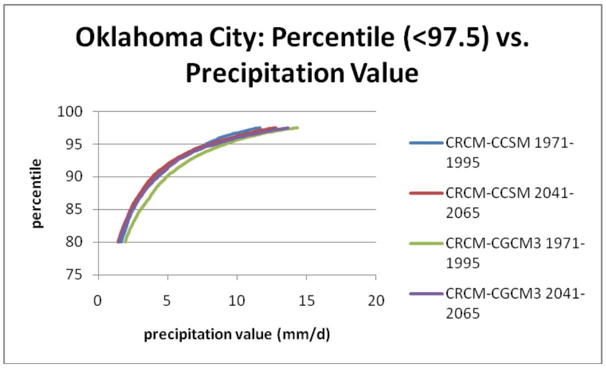

Figure 4. An ogive plot of lower-value percentile against corresponding precipitation value for both historical (1971-1995) and future (2041-2065) output for both RCM-GCM model combinations for the Oklahoma City grid square. Bias correction is not applied.

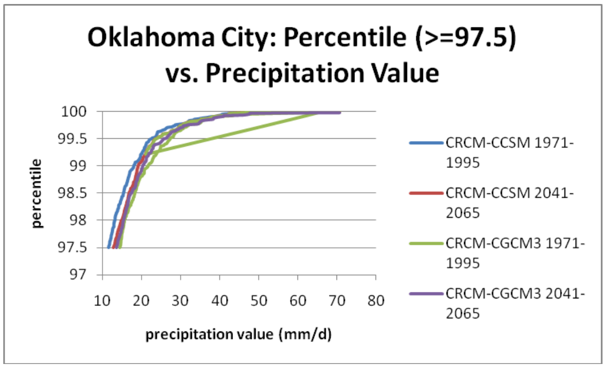

Figure 5. An ogive plot of higher-value percentile against corresponding precipitation value for both historical (1971-1995) and future (2041-2065) output for both RCM-GCM model combinations for the Houston grid square. Bias correction is not applied.

Comparison of the historic and future CRCM-CCSM output suggested that the higher percentile precipitation values may not increase as much as in Oklahoma City compared to Houston in the future. The percent increases were not much greater than zero. For somewhat lower, more moderate percentile values, the signal tended toward increase, with the greatest change for the 97.5th-percentile precipiation value (9.7%). Decreases were noted for the 90th- and 80th-percentile precipitation values, highest for the 80th-percentile value at 17.6%.

A similar comparison of the historic and future CRCM-CGCM3 output suggested that the maximum daily rainfall value may increase slightly (6.5%) in the future period. For more moderate percentile rankings, there was a slight tendency toward decreases in future (by 4-6%). Interestingly, the greatest percentage change was represented by a decrease of just over one-fifth (21.1%) compared to the historic for the 80th-percentile value.

These results were somewhat consistent with the expectation that extreme precipitation will be more extreme in the future and that overall precipitation may decrease, as shown by the decreases in more moderate percentile precipitation values. The evidence for the latter relationship was stronger in the case of the Oklahoma City grid square.

Again, we attempted the approach of comparing observational data to model-projected data. The validation procedure yielded the following results (Tables 11 and 12) when the observational and historical RCM-GCM data were examined from the perspective of a 1971-1995 monthly time series:

RCM-GCM Combination	Correlation between RCM-GCM and Observational
CRCM-CCSM	0.22
CRCM-CGCM3	0.17

Table 11. Pearson correlation coefficients were calculated comparing each RCM-GCM combination's 1971-1995 monthly time series to the 1971-1995 observational monthly time series.

RCM-GCM Combination	RMSE (mm month^{-1})
CRCM-CCSM	71.7
CRCM-CGCM3	70.0

Table 12. The root-mean-square error between the elements of each RCM-GCM combination's 1971-1995 monthly time series and the 1971-1995 observational monthly time series was calculated.

The validation procedure yielded the following results (Tables 13 and 14) when the observational and historical RCM-GCM data were examined from the perspective of a 1971-1995 annual time series:

RCM-GCM Combination	Correlation between RCM-GCM and Observational
CRCM-CCSM	-0.07
CRCM-CGCM3	0

Table 13. Pearson correlation coefficients were calculated comparing each RCM-GCM combination's 1971-1995 annual time series to the 1971-1995 observational annual time series.

RCM-GCM Combination	RMSE (mm y^{-1})
CRCM-CCSM	480.9
CRCM-CGCM3	403.9

Table 14. The root-mean-square error between the elements of each RCM-GCM combination's 1971-1995 annual time series and the 1971-1995 observational annual time series was calculated.

As with the Houston grid square data, correlation coefficient values were similarly (or more) distant from the ideal value of 1.0, and root-mean-square error values were again very high. Again, the bias-correction procedure was employed (Table 15).

RCM-GCM Combination	Bias Correction Factor (mm d^{-1})
CRCM-CCSM	6.00
CRCM-CGCM3	-0.41

Table 15. The bias correction factor for each RCM-GCM combination was calculated based on 1971-1995 observational data and historical output for the pertinent combination.

The pertinent bias-correction factor values were added to the future model-projected precipitation values, which, along with the observational values, were ranked and assigned percentile values. These results appear in Table 16.

Percentile Ranking	1971-1995 Observational Value (mm d^{-1})	2041-2065 CRCM-CCSM Value (mm d^{-1})	2041-2065 CRCM-CGCM3 Value (mm d^{-1})
maximum (~100)	146.8	76.7	70.3
99.5	38.6	29.7	25.7
99	30.4	25.2	20.0
97.5	21.7	18.8	13.3
95	15.1	14.1	8.1
90	8.4	9.9	3.9
80	3.2	7.4	1.1

Table 16. Percentile values were calculated for the 1971-1995 observational and both RCM-GCM model combinations' data-sets. The appropriate bias correction factor (Figure X) was applied to the model values.

The degree of bias, as with the Houston model data, was not homogeneous for all magnitudes of precipitation value. The full daily time series of precipitation values showed that biases were greater for more extreme precipitation values. Hence, the mean-value bias-correction procedure was not ideal, resulting in poor representation of the model projections.

4. CONCLUSION

Many studies have suggested that global warming will lead to the increased incidence of extreme precipitation events, particularly in temperate mid-latitude areas of the planet. Hence, there was interest in exploring quantitatively the nature of such change by the 2041-2065 period in two cities in the southern Great Plains of the United States, Houston and Oklahoma City.

Daily-projection output from NARCCAP-produced RCM-GCM model combinations (CRCM-CCSM and CRCM-CGCM3) was compared to gridded observational data for the two locations of study. Considerable biases were determined to exist in the model output, which necessitated the employment of a mean-bias correction procedure. However, since the magnitude and direction of the bias were not homogeneous for all magnitudes of daily precipitation value, this correction procedure did not yield representative results. Therefore, an analytical method that relied on comparison of historic (1971-1995) output of a given RCM-GCM combination to future (2041-2065) output of the same combination was employed.

Overall, results of that second method suggested that precipitation values associated with the highest percentile values will be greater in the 2041-2065 period than in the 1971-1995, that precipitation values associated with somewhat more moderate (i.e., percentile values between the 90th and 95th) will not change much if at all, and that precipitation values associated with somewhat lesser percentile values still (i.e., the 80th) will decrease. This pattern was particularly evident for the Houston grid square. The ramifications of such a pattern would be the increased risk of flash flooding interspersed by drought in these high-population areas of the southern Great Plains.

In follow-up work, it would be beneficial to use a more sophisticated bias-correction procedure based on rain rate due to the non-homogeneity of the biases with respect to precipitation value.

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