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Anticipated Changes in Precipitation Events over the 21st Century Using Community Climate System Model, version 4

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I am submitting herewith a thesis written by Scott Tavish DeNeale entitled "Anticipated Changes in Precipitation Events over the 21st Century Using Community Climate System Model, version 4." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

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We have read this thesis and recommend its acceptance:

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(Original signatures are on file with official student records.)
Anticipated Changes in Precipitation Events over the 21st Century Using Community Climate System Model, version 4

A Thesis Presented for the
Master of Science Degree in
Environmental Engineering
The University of Tennessee, Knoxville

Scott Tavish DeNeale
May 2012
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Abstract

Future global daily precipitation data from Community Climate System Model, version 4 (CCSM4) were analyzed to evaluate changes in a variety of precipitation parameters over the 21st century. Multiple ensemble members of 21st century Representative Community Pathways (RCP) radiative scenarios were included in the model to provide an array of potential future climate change results. Multiple ensembles of historic daily precipitation data from CCSM4 were compared with Global Precipitation Climatology Project (GPCP) V1DD daily precipitation data and Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) monthly precipitation data. Annual average and 95th percentile precipitation values were averaged from 1997-2005 among the datasets, and correlation coefficients (R) are relatively high (0.8796 and 0.8530 for average precipitation and 0.8820 for 95th percentile values) between CCSM4 and observational data. Analysis of mid and end-of-21st century changes in average and 95th precipitation values, reveals large increases in most locations and slight decreases across a few regions. Nearly identical spatial patterns exist between the parameters, though the magnitude of change varies. Magnitudes of change in 95th percentile values exceed those of average precipitation, but the relative change is spatially similar. Extreme indices R95T and DA95 indicate widespread increases in the annual contribution of total precipitation from extreme events with a simultaneous increase in frequency of such events, while some locations show decreases. Regional analysis of the four precipitation parameters results in similar findings but provides additional temporal information. Increasing changes in all parameters occur under with increases in radiative forcing. Division of daily precipitation into categories based on intensities reveals sharp increases in annual precipitation contribution from the most intense precipitation events and a subsequent decreasing contribution from less intense events. Under the highest radiative forcing scenario (RCP 8.5), temporal comparison between the annual contribution from the six precipitation categories and atmospheric carbon dioxide concentration yields R values of -0.979, -0.977, -0.753, 0.830, 0.971, and 0.969, respectively. These results indicate a direct relationship between anthropogenic greenhouse gas emissions and global precipitation trends, stressing the need to adapt to and mitigate impacts of climate change.
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1. INTRODUCTION
Anthropogenic greenhouse gas (GHG) emissions are commonly linked to shifts in climate patterns, as has been evidenced over the past century. Previous studies (Meehl et al. 2004; Karl and Trenberth 2003) have revealed a strong relationship between increases in anthropogenic forcing and recent increases in global warming. Further works (Ramanathan et al. 2001; Allen and Ingram 2002; Lambert et al. 2004; Trenberth et al. 2007) have indicated a direct relationship between global warming and increased global precipitation, and have largely attributed the cause to increased evaporation due to vapor pressure increasing with temperature. Additionally, findings from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) have concluded that, in the future, increases in extreme precipitation exceed increases in mean precipitation (IPCC 2007a).

Extreme precipitation events represent a great socio-economic hazard. For instance, floods in Queensland, Australia from December 2010 to January 2011 caused at least 35 deaths and $5-$6 billion in damages (Queensland 2012; PwC 2011). Similarly, flooding over the Mississippi River in the Central United States in 2011 led to at least 7 deaths and an estimated $3-$4 billion in damages, while flooding in the Northeastern United States in 2010 caused 11 deaths and over $1.5 billion in damages (NCDC 2012). From a physical basis, the increasing trend in heavy precipitation events is largely due to rising temperatures leading to increased atmospheric water vapor (Meehl et al. 2005). Previous research (Karl and Trenberth 2003; Alexander et al. 2006; Allan and Soden 2008) has focused on extreme precipitation and indicates a relationship between higher temperatures resulting from anthropogenic climate change and extreme precipitation events. Additionally, empirical and theoretical analyses have shown that under constant precipitation frequency, as total precipitation increases, increased contribution to total rainfall derives from extreme events (Groisman 1999; Katz 1999). Because of the significant impact extreme precipitation events have on societies, the majority of this paper will primarily focus on changes in precipitation extremes but will also include average precipitation analyses to assess average precipitation-related climate change.

In an effort to understand how human-related activities are driving climate change and may influence future climate, the IPCC brings together scientists and researchers from across the globe and provides information which is useful in identifying impacts, adaptation, and vulnerability to climate change as well as methods by which the damage of these impacts may be mitigated. In AR4 the IPCC relied upon the development of multiple new special report emissions scenarios (SRES). These SRES scenarios are largely based on possible changes in demographic, socio-economic, and technological development and provide a useful tool for analyzing how future cultural trends may impact emissions and, thus, climate (IPCC 2007b). In its upcoming Fifth Assessment Report (AR5), the IPCC has developed new scenarios, including Representative Community Pathways (RCP) 2.6, 4.5, 6.0, and 8.5, which better represent future cultural development changes (Moss et al. 2008). The numerical naming system of each pathway refers to the maximum radiative forcing (W/m²) reached by year 2100. “These scenarios include time paths for emissions and concentrations of the full suite of GHGs and aerosols and chemically active gases” (Moss et al. 2008). When integrated into increasingly
sophisticated climate models, these RCP scenarios provide the best available method for examining future climate patterns.

While past analyses have provided a useful conceptual basis by which past, present, and future patterns in precipitation extremes may be explained, a quantitative representation of these patterns has not yet been widely attributed to the newly created future forcing scenarios RCP2.6, 4.5, 6.0 and 8.5. Various manuscripts which analyze future precipitation trends under the RCP scenarios have been recently published or submitted (e.g. Meehl et al. 2011, manuscript submitted to J. Climate). This research provides additional information which enrich precipitation-related climate change knowledge.

In this paper, 21st century extreme precipitation trends are analyzed by incorporating the RCP scenarios into Community Climate System Model, version 4 (CCSM4) for the Coupled Model Intercomparison Project’s 5th phase (CMIP5). Historical and future global precipitation data from simulations using CCSM4 are analyzed to determine the capability of the model to recreate historical precipitation patterns and also simulate changes in average and extreme precipitation at global and regional levels which may occur through the end of the 21st century.

2. DATA
2.1 Observational Data
In order to justify the use of a model in simulating climate, comparison to observational data is needed. In terms of accuracy, gauge-based precipitation monitoring is considered the preferred data source. Since gauge-based precipitation data cannot accurately provide data on a global scale due to a lack of coverage and may contain error from uncorrected data (Gruber et al. 2000), datasets utilizing satellite feedback are often used in studying global climate. According to Yin et al. (2004), two of the more commonly used gauge-satellite precipitation datasets used in analyzing global precipitation are the Global Precipitation Climatology Project (GPCP) (Huffman et al. 1997; Adler et al. 2003) and the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) (Xie and Arkin 1997).

In this research, monthly CMAP data and a newer version of daily GPCP data, GPCP V1DD (Huffman et al. 2001), are used to analyze the validity of CCSM4 historical model data. Since it contains only monthly precipitation data, CMAP is used in comparing CCSM4 average precipitation data and consists of global 2.5 by 2.5 degree resolution coverage. CMAP data is not adequate for analysis of extreme precipitation due to its lack of daily data. Conversely, GPCP V1DD contains daily precipitation data on a 1 by 1 degree resolution and is thus used for comparison of both average and extreme precipitation with CCSM4 data.

2.2 Model Data
Global climate model CCSM4 (Gent et al. 2011; Meehl et al. 2011, manuscript submitted to J. Climate) was used to simulate past and future climate. From 1850-2005, multiple ensemble model runs incorporating natural as well as anthropogenic forcing were constructed using CCSM4. From the model output, temporal and spatial daily precipitation data were analyzed for three ensembles members. A subset of this historical data was compared with the aforementioned observational datasets to validate the model’s ability in simulating realistic global and regional precipitation patterns.
For 2005-2100, the four RCP mitigation scenarios were used as driving forces in CCSM4 to provide realistic representations of future atmospheric conditions. Five ensemble members have been constructed, from which the output temporal and spatial daily precipitation data were analyzed to simulate potential global and regional future changes in precipitation patterns and climate. The atmospheric output data containing precipitation data is compiled globally into grids of a latitude-longitude resolution of 0.9 by 1.25 degrees for both historical and future years.

3. DESIGN METHOD
3.1. Comparison with Observational Data
The accuracy of a climate model may be analyzed by comparing model output data with observational data. Due to limitations of the selected observational datasets and the desire to compare various precipitation parameters, the 9 year period from 1997-2005 was chosen for comparison. While an extended time period would be ideal for statistical purposes, this study also focuses on extreme precipitation data, which requires the use of daily data. Because the GPCP daily data only includes observations collected since 1997, this year was selected for commencing model and observational data comparison. Furthermore, since the CCSM4 historical dataset contains information through 2005, the time period from 1997 through 2005 was established for comparison of all precipitation parameters. Additionally, since three model ensemble runs of daily CCSM4 data are available, all three datasets were used to statistically strengthen the results.

3.1.1. Average Precipitation
Average precipitation is an important parameter in determining climate-related characteristics. Regions with relatively low average precipitation values are climatically dry and may be classified as deserts, while areas of high average precipitation are wet and may include forest, grassland, or rainforest biomes. Monthly CMAP data and daily GPCP, along with daily CCSM4 data were used to calculate average precipitation over the period of 1997-2005. For each of these 9 years, an annual average precipitation value was calculated at each spatial grid point. The resulting annual average precipitation values were then averaged over this time period to provide a single value for average precipitation at each grid point. Furthermore, each of the three available CCSM4 ensembles were analyzed separately, and the resulting spatial values were then averaged to provide a single value for CCSM4. This value is often reported as an average daily precipitation amount or an average annual precipitation total.

In order to compare the model data with both the GPCP and the CMAP observational data, biases were calculated as the difference between each dataset. Since each dataset contained data at varying resolutions, interpolation was performed on the GPCP and CCSM4 data to match the 2.5 by 2.5 degree resolution of the CMAP data. Additionally, since geographic locations have varying climates and, thus, varying precipitation tendencies, percent bias was calculated at each grid point as

$$\frac{A - B}{\text{Observed}} \times 100\%$$

In this equation, “A” represents CCSM4 precipitation values when comparing CCSM4 with GPCP or CMAP. Additionally, “A” represents GPCP precipitation values when comparing
GPCP with CMAP. “B” represents precipitation values from whichever dataset is being compared with “A”. Also, in the above equation, “Observed” represents the mean of the two observational (GPCP and CMAP) average precipitation values. When comparing GPCP and CMAP average precipitation values, the percent bias is identical to the relative difference as reported by Gruber et al. (2000). Since GPCP and CMAP observational data does not match precisely at all locations, dividing by the mean observational average precipitation values from the two observational datasets helps eliminate any source of bias which may arise should a different denominator be chosen. Yin et al. (2004) address sources of error among the GPCP and CMAP datasets and some differences between them.

3.1.2. 95th Percentile
In order to assess the ability of CCSM4 to replicate extreme precipitation events, the 95th percentile of annual daily precipitation was compared between CCSM4 and GPCP. The 95th percentile of annual daily precipitation represents an extreme precipitation value and is computed in this paper as the annual 19th highest daily precipitation total (94.79 percentile). In reality, the 19th highest daily precipitation represents the 94.79 percentile for all CCSM4 and non-leap year GPCP data and the 94.81 percentile for leap year GPCP data; CCSM4 assumes all years contain 365 days, whereas GPCP contains observational data for each day, including February 29 in leap years.

The 95th percentile and values were calculated annually from 1997-2005 and then averaged to provide a single value for each grid point. The use of ensemble averaging was also used in calculating the annual 95th percentile of daily precipitation for CCSM4 data. As with the average precipitation values, bias and percent bias were calculated between the CCSM4 and GPCP for this parameter after performing interpolation. Percent bias for the 95th percentile was also calculated according to the same equation used for average precipitation, but in this case “A” represents CCSM4 data, “B” represents GPCP data, and “Observed” represents GPCP data.

3.2. Model-based Future Precipitation Analysis
3.2.1. Average and 95th Percentile Precipitation
Future precipitation data from CCSM4 was analyzed by computing a variety of precipitation parameters from 2005-2099. Since there are five ensemble model output runs for daily precipitation values available, the use of spatial averaging was used when necessary. Both annual average precipitation and the 95th percentile of annual precipitation were computed for future forcing scenarios RCP 2.6, 4.5, 6.0, and 8.5 according to the methods previously described.

3.2.2. R95T
In addition to average and 95th percentile values, an index named R95T was calculated for each RCP scenario to provide further assessment of changes in future extreme precipitation. This index was included in IPCC AR4 and was developed by Frich et al. (2002) as an indicator for monitoring changes in extreme precipitation. R95T is calculated as a percentage of total annual precipitation contributed by daily precipitation amounts exceeding a base period 95th percentile. The original index developed by Frich et al. (2002) used a base period of 1961-1990 over which a 95th percentile of wet days (≥ 1 mm/day) was computed. However, since the validation stage
of this research uses 1997-2005 for comparison purposes, this same period was desired for use as
the base period to provide continuity in the analysis.

In order to justify using a shortened base period in calculating R95T, coefficients of
determination ($R^2$) were calculated for both average precipitation and the 95th percentile
between the time periods of 1961-1990 and 1997-2005 and are shown in Table 1. For average
precipitation, an $R^2$ value of 0.9965 was found, indicating a high level of spatial agreement for
this parameter between the two periods. The $R^2$ value over the same time period for the 95th
percentile was 0.9947, which is slightly lower but still very high. Over land (excluding
Antarctica), the average precipitation $R^2$ value increases to 0.9988, while the 95th percentile $R^2$
increases to 0.9984. In addition to the high correlation between these time periods, previous
research, including Kamiguchi et al (2006), has relied upon shortened base periods for
calculating R95T. Therefore, the 1997-2005 base period appears adequate for comparing future
precipitation changes and in calculating the R95T index.

The 95th percentile of daily precipitation was calculated for each of the 9 base years, and the
resulting annual 95th percentile values were then averaged to provide a single base period value
for each grid point. The R95T index was then calculated at each grid point by computing the
percentage of annual total precipitation resulting from daily rainfall values exceeding the base
period 95th percentile. Figure S-2 in Appendix B contains ensemble-averaged base period
values for the index averaged from 1997-2005. Comparison with GPCP was not made due to
significant variation in the distribution of light rainfall (<1 mm/day) between model and
observational data. Analysis of future trends in R95T has been considered a useful method for
describing extreme precipitation changes.

3.2.3. DA95

When originally developed by Frich et al. (2002), it was noted that the R95T index may be later
“redefined as a number of events above the threshold”. From a human impact and engineering
perspective, such an index could provide a more meaningful measure of climate change impact
since it would provide a measure of how often very extreme events occur. Therefore, an original
index named DA95 was created which calculates the annual number of days on which
precipitation exceeds a base period’s 95th percentile value (all days included). The same base
period values for 95th percentile precipitation which are displayed in Figure 3b were used in
calculating DA95. Thus, DA95 was calculated at each grid point by annually summing the
number of days exceeding the base period 95th percentile. While extreme precipitation
frequency is a common focus in future climate change research, the use of the DA95 index
provides a unique method by which global extreme event frequency may be compared.

3.2.4. Regional Analysis

Since precipitation patterns vary spatially, separating the globe into regions of continuous
climate similarity provides more useful information on regional and national levels where
important climate-related policies are made. In order to provide useful analyses on a regional
basis, the global land area (excluding Antarctica) was divided into 22 regions. These regions are
identical to the 21 regions defined by Giorgi and Francisco (2000), aside from one exception.
Giorgi and Francisco combined Australia into one region, but the continent is separated in this
research along the 30°S latitude to include two regions which represent northern and southern
Australia individually. Regional analyses of the aforementioned precipitation parameters were performed by spatially averaging data contained within each region. While this method prevents analysis of local variations, it provides a useful measure of what future average and extreme precipitation trends may occur on a smaller scale.

3.2.5. CatP
Finally, global precipitation was analyzed over both the historic and future CCSM4 periods (1850-2099) by separating daily precipitation into 6 precipitation categories based on intensity: 0.1-1 mm/day (Category 1), 1-10 mm/day (Category 2), 10-20 mm/day (Category 3), 20-50 mm/day (Category 4), 50-100 mm/day (Category 5), and 100+ mm/day (Category 6). Sun et al. (2007) use the same precipitation ranges for Categories 1 through 4 but categorize these ranges as very light, light, moderate, and heavy, respectively; rainfall above 50 mm/day is referred to as very heavy. In this research a category including 50 to 100 mm/day intensities, which could be considered very heavy, and a category for intensities above 100 mm/day, which could be referred to as torrential, are included. While other categorization methods, such as percentile-based, could be used, fixed value segregation is sufficient for precipitation analysis on a global scale.

The percentage of annual total precipitation contributed by each category was computed, and this value is henceforth referred to as Cat1, Cat2, etc. The six categories are collectively referred to as CatP. By separating precipitation into these categories, a measure of how precipitation is distributed and a reflection of the planet’s water budget are provided. It was hypothesized that changes in GHG levels will result in noticeable changes in the global water cycle, and the contribution of each precipitation category to the annual precipitation total would be altered. Thus, a correlation coefficient between CatP and atmospheric carbon dioxide levels (a major GHG) was computed for each category and each RCP scenario.

4. RESULTS
4.1. Model Validation
With the establishment of the new RCP climate change scenarios for the upcoming AR5, the qualification of the most recent CCSM version is a necessary step if the model is to be used to simulate future climate. By comparing CCSM4 output with GPCP and CMAP observations, the model has been validated for simulating future climate change under a variety of radiation and GHG forcing.

4.1.1. Average Precipitation
The first parameter examined is average precipitation. Spatial average precipitation values were calculated for the period 1997-2005 as shown in Figure 1. From inspection, the GPCP and CMAP precipitation patterns (Figures 1a and 1b) are spatially and numerically similar, with a few exceptions. The general similarities and differences between these datasets over this time period are synonymous with previous research findings over varying periods. Major defined patterns exist along the intertropical convergence zone (ITCZ), the South Pacific convergence zone (SPCZ), and the South Atlantic convergence zone (SACZ) (Yin et al., 2004). Also, regions of low precipitation are present in both datasets off the western coasts of North America, South America, southern Africa, and Australia and over dry land regions including western North America and the Sahara, Gobi, and Australian deserts (Yin et al., 2004).
As with the findings of Yin et al. (2004), some minor, but noticeable differences between the two observational datasets are present. In order to more effectively illustrate these variations, Figure 2 includes, on the left hand side, bias values between the datasets and, on the right hand side, percent bias values. Bias between GPCP and CMAP are shown in Figure 2e, while percent bias values are shown in Figure 2f. Overall, CMAP average precipitation is higher than GPCP in the Tropics, especially in the seas surrounding Indonesia. On the other hand, CMAP maintains lower values at high latitudes. This phenomenon may be attributed to a lack of gauge data as well as satellite data distortion due to sea ice. Generally, the largest areas of bias include oceanic and polar regions, but areas of high percent bias also exist over Tropical and subtropical land masses, which include western North America, northeast Africa, western Russia, and northwest China. Some of this bias may occur since these regions are largely dry and any difference between observations would cause a large percent bias value. Overall, since average precipitation trends between GPCP and CMAP are very similar to those reported by Yin et al. (2004) and Gruber et al. (2000), and the focus of this paper is on the CCSM4 model, further analysis is excluded and only these general findings are reported.

Since GPCP and CMAP data are accumulated using similar methods based on a combination of satellite and gauge measurements, the similarities which exist across the majority of non-polar regions is expected. While climate models have been known to reliably replicate historical temperature patterns, there have been wide inconsistencies in reproducing precipitation patterns. New versions of global climate models are constantly under progress to continuously improve the design and increase accuracy. CCSM4 average precipitation values averaged over 1997-2005 are shown in Figure 1c and reveal some obvious similarities to observational data, but include multiple areas of bias. General patterns of high average precipitation values are common among CCSM4, GPCP, and CMAP in the oceans along the ITCZ, SPCZ, SACZ, and along the coasts of New England and Japan. Also, dry areas are well represented off the western coasts of North America, South America, southern Africa, and Australia and over dry land masses including the Sahara, Gobi, and Australian deserts.

Average precipitation in CCSM4 suffers from sources of bias, the most noticeable of which is the issue of a double ITCZ. As reported by Gent et al. (2011), this problem has been common in previous versions of CCSM and will require additional parameterization adjustments in the future to reduce the error. Figures 2a and 2c show the bias of CCSM4 with GPCP and CMAP, respectively, while Figures 2b and 2d show the percent bias. The large bias values clearly highlight the underlying double ITCZ issue, while the percent bias values illustrate that CCSM4 over predicts average precipitation over many land areas. The largest percent bias values, however, occur over very dry regions. Thus, many of the regions of extreme percent bias in Figures 2b and 2d are the result of using the observational average precipitation values as the denominator when calculating this value. For instance, if one compares Figures 1a with Figure 2b, nearly all of the areas of high percent bias in Figure 2b (indicated by dark red or dark blue) are identical to the areas of low observational average precipitation in Figures 1a (indicated by white or light blue). Comparison of average precipitation between CCSM4 and each of the observational datasets reveals very similar patterns due to the high similarity between GPCP and CMAP. The few deviations occur over the same areas previously mentioned as regions containing higher bias between GPCP and CMAP.
A final comparison of average precipitation between the datasets is included in Table 2. Average precipitation values were spatially averaged over the globe and reveal CCSM4 to contain a higher value than either of the observations, with CMAP being slightly lower than GPCP. Additionally, global correlation coefficients (R) between each of the datasets are provided. The R value between the two observational datasets is the highest at 0.9156, while R between CCSM4 and GPCP is 0.8796. Between CCSM4 and CMAP, the R value drops to 0.8530, further justifying the use of GPCP data in validating CCSM4’s performance of extreme precipitation.

4.1.2. Extreme Precipitation
As the second parameter evaluated for model validation purposes, the annual 95th percentile of daily precipitation represents a commonly used indicator for changes in extreme precipitation. Spatial 95th percentile values were calculated for GPCP and CCSM4 datasets from 1997-2005 and are shown in Figures 3a and 3b. Areas of elevated upper percentile rainfall distributions are generally the same regions which experience high and low average precipitation. As with average precipitation, the issue of a double ITCZ in the CCSM4 data is also present. Figure 3c provides the spatial bias between the two datasets and reveals some similar patterns to those seen with average precipitation in Figure 2a. Many of the areas in which CCSM4 overpredicts observed 95th percentile values are the result of the double ITCZ issue. However, in many locations, CCSM4 underpredicts GPCP observational 95th percentile precipitation values, an issue which is not as widespread with average precipitation data.

According to Gent et al. (2011), one of the major issues with the previous version of this model, Community Climate System Model, version 3 (CCSM3), was its inability to produce nearly as many heavy precipitation events in comparison to observations. Gent et al. (2011) have found CCSM4 provides much more agreement with observational extreme precipitation, a claim which is further supported by the generally low percent bias values seen in Figure 3d and the balance of positive and negative bias seen in Figure 3c. Still, it appears, the results indicate an inability of CCSM4 to produce consistent heavy precipitation events since widespread under prediction occurs. Again, as was found with average precipitation data, the majority of large percent bias values in Figure 3d (indicated by dark red or dark blue) are over areas of low observational 95th percentile values as seen in Figure 3a (indicated by white or light blue). The effect of using the observational data as the denominator when calculating percent bias leads to higher values, an issue which may be alleviated in future versions of the model once ITCZ and other thermodynamic issues are minimized.

Globally, 95th percentile values are lower in CCSM4 than in GPCP. Table 3 includes global average values for this parameter and indicates the model underpredicts observations by nearly 1 mm/day, on average. Spatially, CCSM4 correlates relatively well with GPCP for this parameter with an R value of 0.8820.

4.2. Future Changes in Average and Extreme Precipitation
The development of the RCP scenarios for AR5 provides an opportunity to explore potential future climate change with the use of state-of-the-art global climate models. By incorporating climate forcing derived from these scenarios into CCSM4, future trends in precipitation have been examined. As important forcers of climate change, GHGs are useful atmospheric constituents which may impact precipitation. Therefore, analysis of precipitation should
consider major GHG (including carbon dioxide) levels when discussing results from future RCP scenarios. Figure 4 includes atmospheric carbon dioxide concentration from 1850-2099 and reveals a noticeable historical increase from 1950 to 2005. Under the new RCP scenarios, the concentration of carbon dioxide continues to increase through the middle of the 21st century but begins to level off or decrease for RCP 2.6 and RCP 4.5 around 2050 and 2070, respectively. The rate of increase is greater for RCP 8.5 than RCP 6.0, and the concentration under RCP 6.0 shows signs of leveling off by the end of the century. These concentration time paths are important in analyzing the effect of carbon dioxide and other GHGs on precipitation and are considered in this research. While no single pathway will represent future conditions perfectly, the collection of RCP scenarios provides a useful array of information important in examining human impacts on climate.

4.2.1. Average Precipitation
Spatial, annual average precipitation values were calculated using daily precipitation data from the five CCSM4 ensembles for each RCP scenario from 2005-2099. While the values alone are useful in determining changing patterns, comparison of future precipitation with a base period is more meaningful. Therefore, ensemble-averaged percent change in average precipitation from 1997-2005 was selected as more purposeful indicator of climate change, and these changes are included in Figure 5. Since human-related impacts are of primary concern, a mask was used to exclude ocean and sea data, so only global land data is represented. Figure 5 contains contour plots of percent change in average precipitation by the middle (2050-2059) and end (2090-2099) of the 21st century for each climate change scenario.

In general, the spatial patterns of increasing and decreasing change are similar among all scenarios. Most areas are projected to experience increases in average precipitation by the middle and end of the 21st century, but some sizeable decreases are also seen in northern and southern Africa, southern Europe, Central America, and northeastern South America. For RCP 2.6, the majority of locations experience changes in average precipitation of between -20% and +20%, but by the end of the century for RCP 8.5, values below -40% and above +40% are common.

Spatial patterns and percent change values by the middle and end of the century are extremely similar for both RCP 2.6 (Figures 5a and 5b) and RCP 4.5 (Figures 5c and 5d), with RCP 4.5 changes being generally larger. Mild intensification of percent change is seen from the middle to the end of the century for RCP 6.0 (Figures 5e and 5f), while high intensification exists for RCP 8.5 (Figures 5g and 5h). Another trend which is common among all plots projects high latitude areas to experience some of the greatest increases in average precipitation. This effect largely results from increases in temperature as a result of higher GHG concentrations. Higher temperatures and melting sea ice result in more evaporation, thereby causing increases in atmospheric water vapor content which leads to more local precipitation.

4.2.2. Extreme Precipitation
Previous research indicates that in comparison to average precipitation, the intensity and frequency of extreme precipitation is projected to increase more significantly with climate change (Allen and Ingram 2002; Trenberth et al. 2003; Kharin et al. 2007). While examining average precipitation provides a measurable simulation of average climate change, studying
impacts of extreme precipitation events on human populations is of greater economic and health advantage.

4.2.2.1. 95th Percentile
In the same manner as used for average precipitation, percent change in 95th percentile precipitation values for each RCP scenario from 2005-2099 was calculated and included in Figure 6. Daily precipitation data from the five CCSM4 ensembles were analyzed, using the base period (1997-2005) for comparison. Global contour plots for the same future decades (2050-2059 and 2090-2099) are included in Figure 6, and the same contour scheme used in Figure 5 was selected.

Comparison between the two Figures 5 and 6 reveals nearly identical patterns. The high similarity between the plots indicates that, for most locations, the percentage increase or decrease in average precipitation will be very close to the percentage change in this upper percentile of precipitation. This indicates that although the 95th percentile values are considerably higher than average precipitation values, the increase in this parameter will be proportionally greater in the future under all RCP scenarios. To illustrate, a location with a 1997-2005 average precipitation of 2 mm/day and 95th percentile of 10 mm/day may experience a 2050-2059 average precipitation of 2.2 mm/day (a 10% increase) and 95th percentile of 11 mm/day (also a 10% increase). While both parameters increase by the same percentage, the impact of such an increase for the 95th percentile is far more severe and indicates a shift toward more extreme events for areas with an increasing trend.

4.2.2.2. R95T
The extreme precipitation index R95T was calculated for each RCP scenario from 2005-2099 using the five future precipitation data ensembles. Instead of using the 95th percentile of daily precipitation, this index uses the 95th percentile of rainy days (>1mm/day). Thus, the percentile basis used in this calculation could be considered as being at least the 95th percentile of daily precipitation (all days included) since some daily data has been excluded. Naturally, drier climates will have far more daily precipitation values excluded when calculating R95T. In order to illustrate how these two versions of the 95th percentiles vary, Figure S-1 in Appendix B contains global ensemble-averaged values over the base period. Also, Figure S-1c contains a percent difference between the two. Areas which exhibit high percent differences (indicated by dark red) in Figure S-1c are consistent with areas of low average precipitation as seen in Figure 1c. This comparison is mentioned to demonstrate how changes in R95T may not be consistent with changes in annual average or 95th percentile values since a minimum daily precipitation criterion is used to calculate R95T, especially in dry regions.

In examining changes in R95T, index values from 1997-2005 were used as base period values and are included in Figure S-2 in Appendix B. Ensemble-averaged percent changes from the 1997-2005 base period were computed and are shown in Figure 7. The contour level used in Figure 7 was doubled from Figures 5 and 6 to include values from -100 to +100% as the range of percent change values for this parameter are larger. Compared with average and 95th percentile precipitation, the localized spatial variation in values is considerably more noticeable. Since calculation of R95T uses total extreme (above base 95th percentile) precipitation as the
numerator and total annual precipitation as the denominator, changes in either parameter can cause changes in R95T.

Among the plots, general consistency in sign change and spatial intensity exists. Most locations will experience increases in R95T, but a few areas, primarily in northern and southern Africa, central North America, and portions of northern Asia, show decreases in the index. These decreases, while mostly influenced by decreases in intensity or frequency of extreme precipitation, may also arise from large increases in annual average precipitation. Analysis of RCP 6.0 and RCP 8.5 both reveal moderate to large increases in R95T, especially toward the end of the century for RCP 8.5. Compared with changes in average and 95th percentile precipitation over the same time period, changes in R95T will be generally larger.

4.2.2.3. DA95
A second extreme precipitation index, DA95 was calculated annually from 2005-2099 using five ensembles of each RCP scenario. Figure 8 contains contour plots of ensemble-averaged percent changes in DA95 from the 1997-2005 base and uses a contour level from -100 to +100%. The calculation of DA95 uses the 95th percentile of annual precipitation in which all days are included. For the base period, DA95 for all locations is equal to 18 since the 95th percentile was computed as the 19th highest daily precipitation amount.

As with Figures 5-7, many of the regions experiencing increases or decreases in precipitation parameters show a similar change in DA95. The change from 1997-2005 exceeds 50% in many locations and approaches 100% in others. Sizeable decreases around the Mediterranean Sea and in southern Africa, Central America, and the northern and eastern edges of South America are seen and decrease further toward the end of the century for most RCP scenarios.

4.3. Regional Analysis of Future Precipitation Trends
In order to better assess future precipitation trends, the inclusion of the full temporal array of future changes was desired. In order to analyze this information on a global scale, regional analysis was performed by dividing the global land area into 22 regions as defined in Table 4 and shown graphically in Figure 9. The acronyms listed in Table 4 will be used during discussion. Variations of the same color were used in Figure 9 to categorize these regions into approximate continental divisions. Although the regions established for analysis generally represent homogenous areas of climate, overlapping of environments occurs. Thus, consideration of the spatial patterns exhibited in the mid and end-of-century contour plots is important.

Regional analysis was performed on future average and 95th percentile precipitation as well as the R95T and DA95 indices through the end of the 21st century using five CCSM4 ensemble datasets. Annual values were computed for each ensemble. From these values, ensemble averages and standard deviations were used to create Figures S-1, S-2, S-3, and S-4. These Figures contain regional time series plots for each region and contain average values for each scenario. Additionally, background shading ranging from one standard deviation below to one standard deviation above the ensemble average value is included. While these Figures are useful in providing better statistical information, some difficulty in discerning information exists. Therefore, these Figures are contained in a separate Appendix (Appendix B), and the contents are not directly discussed to any extent.
Decadal changes in precipitation parameters are included in the discussion and are calculated in comparison to 1997-2005 base values. Table S-1 in Appendix B includes regionally-averaged base period values for each parameter and may be useful in analysis.

4.3.1. Average Precipitation
Regional average precipitation trends from 2005-2099 are shown in Figure 10. Lightly colored background lines represent annual ensemble-averaged values. Five-year centered moving averages from 2007-2097 were then computed from these values and are represented by the darker blue, green, orange, and red lines. From this Figure, dry and wet regions may be immediately realized; SAH and CAS, the driest regions, contain large desert regions, and AMZ, SAS, and SEA, the wettest regions, contain some of the world’s major rainforests. Nearly all regions show increases from the beginning to the end of the 21st century; however, MED and CAM show large decreases and AMZ, slight decreases.

In order to more easily visualize temporal changes in average precipitation, decadal percent changes from 1997-2005 values were computed and are included in Figure 11. Varying levels of change are seen from region to region, but most experience positive changes which increase toward the end of the century, especially under higher radiative forcing scenarios (e.g. RCP 6.0, 8.5). As previously noted, CAM and MED experience large decreases in average precipitation of around 5% for most scenarios during the latter half of the century and decreases of over 10% for RCP 8.5 during the last few decades.

All regions of North America show sizeable increases in average precipitation, and ALA and GRL have the highest increases of any region. In South America, CAM has significant decreases, as previously mentioned, while AMZ will experience general decreases, especially toward the end of the century. SSA average precipitation increases throughout the century but remains below base period values during the first few decades. Changes in the two regions of Europe differ, as MED has large decreases and NEU has moderate increases in precipitation. WAF and EAF, the wettest regions of Africa, show the common increasing trend, while SAF shows small, but consistent decreases in average precipitation. Changes for SAH are large but quite varying, likely due to the desert climate. All regions in Asia have increases in precipitation, and most are quite large. CAS, like SAH, has a large amount of variability but also largely consists of desert climate. The regions of Australia, which also have large desert areas, maintain some variability, especially NAU. Average precipitation in NAU has little consistency in temporal patterns and is altogether largely unchanged. In SAU, an increasing trend is apparent, but most values remain near or below the base values. RCP 8.5 presents an exception, as the last four decades for this scenario are accompanied by large increases in precipitation.

4.3.2. 95th Percentile
As with average precipitation, regional average precipitation trends in the 95th percentile were computed from 2005-2099. Ensemble-averaged values along with further moving averages are included in Figure 12. The similarity between Figure 10 and Figure 12 is obvious and illustrates a direct relationship between the 95th percentile and average precipitation. Heavy precipitation events likely influence average precipitation; a trend toward more intense or frequent precipitation events likely leads to higher average precipitation, while a trend toward less intense or frequent precipitation events likely leads to lower average precipitation.
As noted when comparing the global contour plots in Figures 5 and 6, percent changes in average and 95th percentile precipitation exhibit near identical spatial patterns and values. This concept is further illustrated by comparison of Figure 13 and Figure 11, which reveals high similarity for most regions. Some exceptions exist, the most noticeable of which is with AMZ. While average precipitation generally decreases throughout the 21st century, the 95th percentile increases consistently. Therefore, in this region, the influence of extreme weather effects may be quite noticeable in comparison to past years, despite small decreases in annual precipitation. In NEU and SAH, similar trends are seen in average and 95th percentile precipitation, but the percent change in the extreme precipitation values is nearly double for all scenarios throughout the century.

For many of the regions exhibiting strong increasing trends in average and 95th percentile precipitation, a resemblance to the atmospheric carbon dioxide concentration time paths shown in Figure 4 is apparent (e.g. ALA, GRL, NAS, EAS, SEA, SAS, and EAF). Precipitation trends in CAM and MED, two regions with high precipitation decreases, have inverse relationships with carbon dioxide concentration. Many of the other regions, whether having increasing or decreasing precipitation trends, maintain the largest changes in precipitation under the highest emissions scenario (RCP 8.5) and the smallest changes for more moderate emissions scenarios, especially RCP 2.6. Exceptions, including CNA, SAH, SAF, CAS, and NAU, tend to either have small changes throughout the century or are desert climates. In either of these cases, high annual and decadal variability is reasonable.

4.3.3. R95T
Regional extreme precipitation trends were further examined by analysis of annual ensemble-averaged R95T values from 2005-2099. Annual values and moving averages are included in Figure 14. From the beginning to end of the 21st century, all regions except CAM show increasing trends in the R95T index. For most regions, the largest and smallest increases are seen with RCP 8.5 and RCP 2.6, respectively, and increases for RCP 6.0 are generally slightly higher than RCP 4.5 by the end of the century.

Regional decadal percent changes in R95T values are included in Figure 15. These changes represent percentage changes in comparison to 1997-2005 values and are not a direct measure of the difference in the actual R95T values (also reported as percentages, but defined as fractions). Compared with the base period, all regions show increases in R95T for nearly all decades and scenarios.

In Figure 15, a seemingly artificial initial increase is seen in many regions. In particular, the trend in CAM stands out since values tend to slightly decrease throughout the century but remain higher than in the base period. This situation is difficult to explain, but could be due to low base period R95T values in the region. Additionally, CAM and other relatively dry regions have a large number of dry days (<1mm/day) and would therefore have a base period 95th percentile of rainy days equivalent to a topmost extreme annual daily rainfall value (possibly one of the top 5 days). This scenario could lead to small R95T values during the base period and larger values in the future if even a small increase in extreme precipitation frequency occurs. A second cause of this phenomenon could be decadal oscillations in weather patterns. Since the base period, 1997-2005, does not constitute a beginning to end-of-decade period but rather a mid- to mid-decade
period, representation of any decadal oscillations may not match well between the base period and the future decadal periods. In any case, the general patterns in future R95T values found in Figure 14 are represented well by the percent change values in Figure 15; however, analysis of Figure 15 must consider bias resulting from artificially low base index values.

To avoid confusion, the discussions which follow refer to values in Figure 15 as opposed to changes in Figure 14. All regions have the same upward trend associated with atmospheric carbon dioxide concentration, with lower radiative forcing scenarios showing smaller increases and higher forcing scenarios showing larger increases. In North America, significant increases in R95T occur, especially in northern latitudes. In ALA and GRL, the index increases by well above 10% by the end of the century for all scenarios and reaches over 35% for RCP 8.5. WNA and CNA show more moderate increases, with less than 10% increases for most scenarios and 10-15% increases for RCP 8.5. By the end of the century ENA has increases of 5-10% for RCP 2.6, 10-15% for RCP 4.5, 10-20% for RCP 6.0, and 15-25% for RCP 8.5. In summary, in North America the northernmost regions, ALA and GRL, show the greatest increase in contribution to total annual rainfall from extreme events, while ENA, a region impacted by tropical storm patterns, also shows high increases.

Percent changes in R95T over South America are also high. Changes in CAM have been previously discussed, and may contain minor sources of bias since decadal percent changes are all positive despite the index decreasing over the 21st century. In AMZ and SSA significant increases are expected. AMZ, a region rapidly losing rainforest cover due to deforestation, increases in extreme precipitation are accompanied by slight decreases in annual precipitation. Both trends lead to a greater influence of extreme events on annual climate and thereby cause increases in R95T. SSA also has large increases in R95T throughout the century. Most RCP scenarios result in 10-15% increases by 2100, while RCP 8.5 causes 20-25% increases.

Precipitation trends across Europe indicate an increased influence of extreme precipitation events on climate. In NEU sizable increases of 5-10% occur for moderate emissions scenarios RCP 4.5 and 6.0. Low emissions scenario RCP 2.6 maintains small increases of below 3% throughout the century, while RCP 8.5, the high emissions scenario, leads to 15-25% increases. Despite decreases in both average and 95th percentile precipitation over the 21st century, R95T values moderately increase in MED. This situation could develop from more rapid decreases in average precipitation compared to extreme precipitation, but indicates an increased contribution from extreme events to annual totals. Figure 15 demonstrates MED R95T values for RCP 2.6, 4.5, and 6.0 increase approximately 5-10% over the century. RCP 8.5 results in higher increases of 10-20%.

Regional patterns over Africa tend to vary more than for other continents. SAH, the driest of the 22 regions, shows very large increases in R95T compared to the base period but smaller variation throughout the 21st century. WAF and EAF have similar trends in R95T, but increases in EAF are much more significant, most notably for RCP 8.5. Compared to 1997-2005, R95T is about 20% higher for RCP 2.6 for both regions throughout the century. The other scenarios show larger increases of 20-30% in WAF and 30-40% in EAF. By 2100 values for RCP 8.5 increase by over 40% in WAF and around 60% in EAF. The trend in SAF is much more moderate, as R95T change is negligible for RCP 2.6, less than 5% for RCP 4.5 and 6.0, and slightly higher
than 10% for RCP 8.5. Overall, the largest increases in Africa occur over the central areas, including WAF and EAF.

In Asia, all regions show strong upward trends in R95T which are similar in magnitude. Compared to the base period, RCP 2.6 values generally increase by about 10-15% by 2100. Additionally, RCP 4.5, 6.0, and 8.5 values increase by about 15-20%, 20%, and 30-40%, respectively. The largest increases occur in TIB, a region which includes both desert and high altitude environments. To summarize, R95T values in the Asian continent increase with high temporal and magnitudinal similarity and maintain some of the largest 21st century increases in this study.

Changes in Australia are sizable, and increases are common among all scenarios, especially RCP 8.5. The first several decades show decreases from base period values in SAU, which may be due to higher than normal extreme precipitation during the base period. Only small increases occur in this region, except for RCP 8.5, which results in a 10-15% increase by the end of the century. NAU also has increases in R95T, nearly all of which are above base period values. Inspection of Figure 14 reveals high similarity between NAU and SAU, but the base period values of R95T vary considerably for the two regions, leading to a somewhat different appearance between the regions as seen in Figure 15.

4.3.4. DA95

The last precipitation parameter analyzed on a regional scale, DA95 was computed through the end of the 21st century, and values are shown in Figure 16 for each RCP scenario. As with the other parameters, nearly all regions have increasing trends which follow patterns in carbon dioxide concentration. Strong decreasing trends exist in CAM and MED, and slight decreases are seen in SAH, SAF, and CAS. Decadal percent changes from the base period of 1997-2005 were calculated and included in Figure 17. Base period values for DA95, the annual number of days above base 95th percentile values, are exclusively equal to 18 days as a result of the definition used in calculating the 95th percentile. Therefore, analyzing decadal percent changes from this base benefits from using a common value of comparison.

All regions of North America have increases in DA95. Increases in WNA and ENA are generally 5-10% larger than in CNA. ALA and GRL have the largest increases of any region globally. In ALA, 20% more days exceed the base 95th percentile for RCP 2.6. The increase over ALA is much higher for the other scenarios; RCP 4.5, 6.0, and 8.5 correspond to 30%, 35-40%, and 55-70% increases, respectively, during the last decades of the century. The values are slightly lower in GRL, but are still significantly high, reaching a maximum of around 50% for RCP 8.5.

In CAM, higher emissions scenarios may lead to far fewer extreme precipitation events. While RCP 4.5 leads to a less than 5% decrease in DA95, RCP 6.0 and 8.5 result in 10% and 20% decreases, respectively. The number of high precipitation events for RCP 2.6 is primarily 0-5% above base values. The small positive percent change values in DA95 during the initial 21st century decades represent a potential cause for artificially high values in R95T percent change values in CAM. This explanation may also apply to other regions in which artificial jumps in decadal R95T changes occur.
Increases in extreme precipitation frequency in AMZ are consistent throughout the 21st century and remain about 10% above base period frequency, whereas the index in SSA steadily increases. Compared to 1997-2005 values, DA95 in SSA increases by about 10% throughout the century for RCP 2.6, reaches 10-15% for RCP 4.5 and 6.0, and peaks at over 17% for RCP 8.5.

Increases of DA95 in NEU are similar to those found in the northern North American regions, but are somewhat reduced. Whereas ALA had maximum increases of approximately 25%, 30%, 40% and 70% for RCP 2.6, 4.5, 6.0, and 8.5, respectively, NEU increases are more moderate: 15%, 18%, 23%, and 28%, respectively. In MED, percent change patterns are similar to those in CAM; decreases in extreme event frequency occur throughout the century and are most noticeable with higher emissions scenarios. However, most values are above the base DA95 values.

In Africa, the northern and southern regions, SAH and SAF show small increases in DA95 which remain relatively constant, but decrease slightly over time. The wetter regions, WAF and EAF display strong upward trends in DA95. Increases in both regions for RCP 2.6 are similar, around 10-15%, while RCP 4.5, 6.0, and 8.5 reach maximum 21st century values of around 20%, 20%, and 28% in WAF, respectively, and 25%, 28%, and 45% in EAF, respectively.

All regions in Asia show large increases in extreme precipitation frequency, except CAS. In this desert region, DA95 remains fairly constant with a few decreases but remains 5-15% above base values for most decades. Generally, in this region, lower emissions scenarios have higher frequency of strong precipitation events, and vice versa. DA95 percent change in NAS is very similar to increases across other northern latitude regions, including ALA, GRL, and NEU. The magnitudes of increase are large and are approximately the same as those found in NEU; however, the rate of increase for RCP 8.5 is larger in NAS, and, as a result, leads to a maximum increase of 40% by 2100. TIB and EAS have similar plots and maximum increases of around 18%, 20%, 25%, and 30% for RCP 2.6, 4.5, 6.0, and 8.5, respectively. SAS has slightly lower increases of 13%, 15%, 15%, and 23%, respectively, for the future RCP forcing scenarios 2.6, 4.5, 6.0, and 8.5. Among the Asian regions, SEA has the largest increases; 16%, 22%, 29%, and 43% for RCP 2.6, 4.5, 6.0, and 8.5, respectively.

Compared to the base period, more extreme events occur during the 21st century in the Australian regions of NAU and SAU, yet the trends are somewhat different. Whereas SAU shows a slightly upward trend for RCP 6.0 and 8.5, NAU shows wide variability and little change overall. Percent increase from 1997-2005 is generally below 10% in both regions, but sharper increases exist for RCP 8.5 in SAU, leading to a 20% increase by 2100.

### 4.4. Categorical Precipitation Trends

Global precipitation was finally analyzed by dividing daily totals into six precipitation categories. By dividing annual precipitation into categories based on intensity, trends in the global water budget can be analyzed. Three ensembles from historic CCSM4 data and five ensembles from future CCSM4 data were used to calculate CatP, the percent of total annual precipitation contributed by each category. Results are seen in Figure 18. Darker, foreground lines represent ensemble-averaged annual values for each category, and lighter, background
shading represents the range between one standard deviation below and above average values. Annual values are included from 1850 to 2099.

As seen in Figure 18, from 1850-1950 the fraction of annual precipitation from Cat1 (very light precipitation, 0.1-1 mm/day) varies annually, but remains very close to 6.05% throughout the period. Around 1975 the fraction begins to steadily decrease to around 5.95% by 2005. Categorical precipitation analysis of future RCP scenarios begins in 2005 and includes the remainder of the century, through 2099. All scenarios have decreasing trends in Cat1 by the end of the century. For RCP 2.6, Cat1 values decline steadily until 2050 and thereafter remain fairly constant at around 5.85%. A similar trend is seen for RCP 4.5 data; however, the decline in values is slightly larger. Values tend to decrease more rapidly for RCP 4.5 than for RCP 2.6 and reach approximately 5.78% before leveling around 2070. RCP 6.0 data indicate fairly constant decreases in Cat1 throughout the 21st century which reach a minimum of 5.73% by 2100. Cat1 values decreases sharply and continuously for RCP 8.5 and show slight inverted-exponential characteristics. By 2100, Cat1 precipitation contributes to less than 5.6% of the annual total. Thus, for RCP 8.5, Cat1 decreases approximately 1.8 times more from 2005-2100 than from 1850-2005.

Light precipitation (Cat2) represents the majority of annual precipitation and includes daily totals ranging from 1-10 mm/day. Changes in Cat2 values are similar to those for Cat1. A slight decrease in annual light rainfall contribution occurs around 1920 and causes Cat2 values to drop from approximately 47.5% to 47.3%. Another more noticeable decrease begins around 1975 and continues through 2005, leading to Cat2 values around 46.7% by 2005. Each RCP scenario for Cat2 shows similar decreasing and leveling trends as was found for Cat1. For RCP 2.6, values level out near 2050 at around 46% but begin to increase in 2075 to around 46.2%. Under RCP 4.5 forcing, Cat2 decreases until 2065 and remains near 45.4% thereafter. The decrease for RCP 6.0 is relatively steady, and values reach 45% by 2100. Again, RCP 8.5 forcing leads to the most significant decreases among the scenarios, as Cat2 decreases to around 43.7% by the end of the century. From 2005 to 2099, Cat2 decreases nearly 2.3 times more than in the previous 150+ years.

Cat3 (moderate) precipitation is more temporally stagnant than the previous categories. Figure 18 reveals relatively small changes in Cat3 compared to other categories. The general trend among future forcing scenarios is of slight decreases in the moderate precipitation fraction. A general slight decrease in historic data is noticeable during the last half of the 20th century. For RCP 2.6, very little change in Cat3 is seen, as values remain close to 23.5%. Values for both RCP 4.5 and 6.0 have slight decreases to approximately 23.4%. In contrast, RCP 8.5 causes more significant changes, with the most significant decreases in Cat3 occurring after 2065. End-of-century values are approximately 23% for this high emissions scenario and decrease 4 times more from 2005-2100 than from 1850-2005.

While lighter precipitation categories maintain decreasing contributions to total precipitation over time, Cat4 (heavy) and other intense precipitation categories exhibit increasing trends. The fraction of annual precipitation from Cat4 is approximately 18.3% until 1920, increases to 18.6% by 1960, and remains steady until 1975. Thenceforth contribution steadily increases to almost 18.9% by 2005. The four RCP scenarios all result in increases in Cat4. As with other scenarios,
RCP 2.6 and 4.5 level out around 2050 and 2065, respectively. Values for RCP 2.6 reach 19.2% before decreasing slightly to 19.1% by 2100, whereas RCP 4.5 values are around 19.3% after 2065. In contrast to Cat1 and Cat 2, RCP 6.0 Cat4 values appear to level out before the end of the 21st century, around 2080, and remain near 19.4%. Increases for RCP 8.5 also begin to slow by 2060 but continue increasing to around 19.6%. Compared to increases over the historic period, future Cat4 values increase around 0.2 times more from 2005-2100 under RCP 8.5 forcing, much less than increases seen in other categories. Since all scenarios result in Cat4 slowing or decreasing by 2100, heavy precipitation contribution exhibits small relative future changes compared with other precipitation categories.

Accounting for 3.6% of annual precipitation from 1850-1920, Cat5 (very heavy) maintains a steady increase from 1920-2005 and peaks near 4.1% at the end of the historic period. Strong increasing trends occur with future forcing scenarios. While values for RCP 2.6 and 4.5 level in 2050 and 2075, respectively, RCP 6.0 and 8.5 values continue increasing throughout the 21st century. Once the lower forcing scenarios (RCP 2.6 and 4.5) level, Cat5 remains steady at 4.3% and 4.75%, respectively, through 2100. RCP 6.0 and 8.5 data result in Cat5 reaching 4.9% and 5.8%, respectively. From 2005-2100, Cat5 under RCP 8.5 increases nearly 2.8 times more than from 1850-2005.

The final precipitation category, Cat6, represents the most intense, torrential daily precipitation totals. Although events in this category include the smallest collection of annual precipitation events, they represent the greatest impact to human civilization and show the greatest increases under future forcing scenarios. From 1850-1950, Cat6 averages close to 0.74%, and by 2005 the values increase to 0.9%. In future scenarios RCP 2.6 and 4.5, Cat6 levels around 2050 and 2075, respectively, while exponential-like increases are seen for RCP 6.0 and especially for RCP 8.5. By 2100, Cat6 values for RCP 2.6, 4.5, 6.0, and 8.5 are around 1.0%, 1.3%, 1.5%, and 2.4%, respectively. Increases for this category are the largest among those defined by CatP, and the future (2005-2100) RCP 8.5 increase is approximately 8.8 times more than the historic (1850-2005) increase.

All precipitation categories have similar trends which appear similar those for atmospheric carbon dioxide shown in Figure 4. In fact, most categories exhibit a leveling point for RCP 2.6 and 4.5 around the years 2050 and 2070, respectively. Inspection of Figure 4 reveals a similar characteristic in carbon dioxide concentration for each scenario. Additionally, a few categories associate RCP 6.0 and 8.5 with large increases and, in some cases, exponential or inverted-exponential growth. These characteristics are also common in temporal atmospheric carbon dioxide changes. Finally, CatP analysis reveals common increasing or decreasing transitions over the historic period, the most noticeable of which occur near or following 1950. This transition also exists in historic carbon dioxide concentrations, which begin steadily rising in 1950.

Since such similarities exist between CatP and carbon dioxide trends, temporal correlation coefficients were calculated as shown in Table 5. Thirty different R values are shown, one for each future forcing scenario and another for the historic period. Each R represents the correlation coefficient between atmospheric carbon dioxide concentration and annual values of categorical precipitation fractions (CatP). Negative values indicate indirect relationships
between carbon dioxide and CatP, while positive values indicate direct relationships. For Cat1, Cat2, and Cat3, negative correlation coefficients are found. In contrast, positive correlation is found for Cat4, Cat5, and Cat6.

Since precipitation parameters are often quite variable from year to year, moving averages are often used when calculating correlation; however, the strong degree of correlation exhibited in Table 5 is significant without smoothing the data. The results indicate a high level of similarity between trends in carbon dioxide and CatP. The degree of correlation generally increases with high forcing scenarios (e.g. RCP 8.5) and is greatest for light, moderate, very heavy, and torrential rainfall (Cat1, Cat2, Cat5, and Cat6). Over the historic period, less correlation generally exists, but values are still relatively high, especially considering annual CatP values are used.

As a final note, higher precipitation intensities contribute more to annual precipitation. Therefore, the decreasing influence of lower precipitation categories on annual totals likely results from a shift toward more events occurring at higher intensities. It is important to realize that most of the regions analyzed for regional impacts have 95th percentile values representative of Cat3, while the driest and wettest regions have values representative of Cat2 and Cat4, respectively. Thus, a significant portion of annual total precipitation derives from events exceeding regionally-averaged 95th percentile values. As previously mentioned, the relative increases in percent contribution for Cat6 are the highest among the categories, and future increases are approximately 8.8 times higher than historic 1850-2005 increases for RCP 8.5. Thus, one may conclude the frequency of the most extreme precipitation events will increase more than annual 95th percentile events.

5. IMPACTS ON SOCIETIES
5.1. Impacts from Changing Climates
In this research, both average and extreme precipitation were analyzed to determine what changes may be expected over the 21st century. While the physical properties of a warming planet are important to human understanding, the impacts such changes may cause are essential to human health, safety, and civilization. In examining the changes in future precipitation, it would be remiss to ignore the impacts such events have on societies.

5.1.1. Influence of Average Precipitation
Projections of future average precipitation change, as shown in this paper, reveal wide regional variation. Globally, average precipitation increases only slightly, but sizable increases and decreases are seen in various locations. In particular, since average annual precipitation constitutes the annual total availability of direct influent fresh water, societies which experience decreases in this parameter could experience severe repercussions. While fresh water is also available via river systems which feed lakes and reservoirs, Figure S-7 in Appendix B reveals many of the regions void of any major river basin are also regions projected to experience decreases in average precipitation (Figure5). In combination, decreasing annual precipitation in regions without major fresh water resources may be disastrous. This trend is common across western United States, Central America, northern South America, eastern Brazil, southern Europe, the Sahara, Saudi Arabia, and Australia and indicates a direct need for improved retention and conservation efforts in these regions.
As a primary necessity for human populations, fresh water availability has seen increasing stress over time as populations and consumptive behaviors increase. UNEP (2012) contains a comprehensive summary of current global fresh and marine water resources and environments along with present impacts and projected future impacts, including information related to global water withdrawal for 1995 and projections for 2025, shown in Figure S-8 in Appendix B. Significant increases in the fraction of available water withdrawn, and thus increases in water stress, occur over many regions, including the United States, Europe, northern and southern Africa, India, China, and Southeast Asia. Figure S-8 makes use of model simulation precipitation data, similar to those from CCSM4, and blends future projections of population, land use, and technological changes to reveal such impacts related to water availability. By decreasing water supply, increased competition occurs. UNEP (2012) suggests by 2025, more than 2.8 billion people, mostly in West Africa, North Africa, and sub-Saharan Africa, will experience scarce water conditions, making effective public policy decisions extremely important to human health.

5.1.2. Influence of Extreme Precipitation

Extreme precipitation events are a major concern for societies. From the perspective of this research, future decreases in extreme precipitation events cannot be directly associated with climate or impact trends aside from decreases in annual precipitation totals; however, increasing trends in extreme precipitation intensity and frequency are projected over most locations and may cause a variety of severe consequences.

Many studies have examined the effects extreme precipitation events have on floods. Costs associated with such events are largely driven by the affected area’s economic wealth. Even after adjusting for inflation, damages resulting from floods have escalated over time, which indicates increases in extreme precipitation have augmented flood effects (Pielke and Downton 2000; Kunkel et al. 1999; Karl and Knight 1998). In addition to flood damages, damages from hurricanes, a parameter not explored in this research, account for a significant portion of annual losses from weather events (Kunkel et al. 1999). However, a large number of studies, which are summarized by Bouwer (2011), have normalized loss values to account for “economic losses for inflation and changes in exposure and vulnerability that are related to growth in population and wealth”. Many of these studies indicate normalized losses associated with flood and hurricane events have shown no historic trend and, therefore, argue climate change has little impact on economic losses associated with floods. Instead, these studies consider increasing wealth and population in disaster-prone locations to be the major cause for increasing losses over time. Bouwer (2011) concludes by mentioning “considerable uncertainties remain in some of these studies”, mainly due to a lack of information on risk reduction efforts. Furthermore, most of these research efforts only include relatively wealthy regions where large efforts have been taken to improve warning and reduce risk associated with extreme precipitation events.

Although considerable uncertainty remains as to the direct influence of changes in extreme precipitation events, such as floods or hurricanes, on loss totals, the increases in intensity and frequency of extreme events projected over many regions of the globe indicate high susceptibility for an increasing population. Despite some claims that climate change does not negatively affect disaster loss, the changes in precipitation extremes projected over the coming decades are far greater than those experienced in recent past.
In addition to floods and tropical storms, disease is a common problem associated with precipitation events. Water-borne diseases, such as cholera, have become increasingly prevalent as a result of increasingly dense populations and declining living conditions in many parts of the world, particularly Africa, Asia, and South America. Such diseases are spread most easily as a result of flooding just after relative dry periods (UNEP 2012). With a future climate characterized by more frequent heavy precipitation and regional drying in many of the cholera-stricken areas, great concern over further spread of water-borne diseases exists.

5.2. Effective Public Policy and Engineered Systems
While this research makes no claims as to which forcing scenarios may best represent future global atmospheric and surface conditions, the results indicate a variety of desired and undesired results may occur in different regions should certain pathways be followed. Increases in atmospheric carbon dioxide and other GHGs has been previously linked to increased global temperature (IPCC 2007b; Meehl et al. 2004; Karl and Trenberth 2003), precipitation (IPCC 2007b; Ramanathan et al. 2001; Allen and Ingram 2002; Lambert et al. 2004; Trenberth et al. 2007), and extreme precipitation trends (IPCC 2007b; Karl and Trenberth 2003; Alexander et al. 2006; Allan and Soden 2008), all of which cause potential harm to societies. This research has consistent findings, the impacts of which stress a need for action in alleviating anthropogenic GHG emissions and other man-made contributors to climate change. Most importantly, the increases in future climate change may be greatly reduced through effective public policy and the establishment of better engineered systems. By better preparing societies to deal with potential disasters, significant losses can be averted and lives may be saved.

A significant amount of research efforts constantly examines the ways in which authorities have been enacting and may pursue adaptation to climate change, but continuous monitoring and improvement are needed (IPCC 2007a). A government’s responsibility to the safety and welfare of its public includes ensuring the impacts of future global warming do not significantly reduce quality of life. Water shortages as well as flood and hurricane impacts are the most likely negative impacts associated with average and extreme precipitation change, yet assessing methods for adapting to climate change includes many opportunities.

As a result of water resource disaggregation, numerous conflicts have occurred in regions across the globe. Most deal with quantity disputes or water resource infrastructure, yet amid increases in tension, far more water treaties have been negotiated compared to conflicts (UNEP 2012). In order to increase water availability where it is needed most, many collaborative initiatives have been established, including the West Africa Water Initiative (WAWI). Composed of 14 international institutions, the WAWI was launched in 2001 to improve living conditions for populations in West Africa. The initiative consists of four primary objectives: (1) increasing sustainable, safe water and sanitation, (2) reducing the prevalence of water-borne diseases, (3) ensuring sustainable management of water quality and quantity, and (4) fostering a new model of partnership and institutional synergy (Nichols 2004). A large number of similar cooperative events have brought together nations in hopes of resolving issues related to water scarcity and providing assistance to populations despite demographic differences. For instance, the Permanent Indus Water Commission, a treaty which guides water sharing and dispute resolution in the Indus River region, has maintained favorable status and remained effective despite two
major wars between India and Pakistan (UNEP 2012). Thus, effective public policy can exist anywhere and should be valued as an essential tool toward climate change adaptation.

In addition to physical allocation of water resources, numerous methods exist which may improve the use of available resources and optimize changes in precipitation distribution. Among some of the best management practices and technologies which assist in meeting these goals, drip irrigation is an agricultural method for decreasing water loss by directly applying water to plant roots via plastic piping and recapturing excess water (WBCSD 2009). As seen in Figure S-9 in Appendix B, the agricultural sector is the primary user of freshwater globally, especially in Africa and Asia where 85-90% of freshwater use derives from agriculture (UNEP 2012). The use of drip irrigation in such regions can have lasting impacts on water supply and potentially save lives. Improvements in technology have also lead to innovative ways of increasing supply efficiency of water systems. Reverse osmosis, for instance, has been implemented in an Israeli desalination plant to bring Mediterranean Sea water to drinking quality standards and, in the process, reduced costs by 80% (WBCSD 2009). Similarly, a new filtration technology in Singapore has been established to recycle wastewater to drinking quality standards (WBCSD 2009). Continuous technological improvement will provide more resources for alleviating climate change impacts, but the start-up and maintenance costs associated with such technology prevents many locations from adapting such methods. Public policy and international efforts can assist in making smart decisions affordable, but education of climate change impacts is an essential first step.

6. SUMMARY AND CONCLUSIONS
Prior to conducting analysis of future precipitation trends, global climate model CCSM4 was validated through observational comparison. Comparison of historic CCSM4 precipitation data to GPCP and CMAP data from 1997-2005 indicates strong correlation with observed precipitation. The major source of precipitation bias in the model derives from a double ITCZ issue in CCSM4 which causes artificially high average precipitation values, primarily over the tropical oceans. The same issue affects extreme precipitation values, which are both above and below observational values across the tropics. This problem has been a focus of past and present efforts to improve CCSM (Gent et al. 2011) but has hitherto been only slightly improved. Aside from the double ITCZ, output precipitation from CCSM4 matches well with observations, qualifying the model as a reliable model in examining future precipitation-related climate changes.

Newly developed RCP radiative forcing scenarios were integrated into CCSM4 in order to provide the most up-to-date, realistic simulation of future climate conditions. Future changes in a variety of precipitation parameters were measured over global land by calculating the percent change from present values at the middle and end of the 21st century. Analysis indicates a general increase in annual precipitation across most locations, especially over northern latitudes, Central Africa, East and Southeast Asia, and Antarctica. Decreases are seen across Central America, northern and eastern South America, and around the Mediterranean Sea. More significant changes in average precipitation occur under higher forcing scenarios and tend to increase more toward the end of the century. Future annual precipitation trends from a large collection of climate models are widely highlighted in the IPCC AR4. Many of the reported
shifts in precipitation (IPCC 2007b), especially those consistent among models, are consistent with those reported in this research.

A primary focus of this research was to provide a wide array of future precipitation analysis, especially related to extreme wet events. First, the 95th percentile of annual precipitation was analyzed. Compared with average precipitation, nearly identical spatial changes and magnitudes occur for this upper percentile, indicating trends in extreme weather events likely transmit to increases in average precipitation values. The areas in which the greatest changes in average precipitation occur may transition into somewhat different climates, while increases in 95th percentile values could heavily impact land due to increased flooding. Examination of R95T indicates that more areas will experience increases in this extreme precipitation index than will experience increases in average and 95th percentile precipitation values, and the percent change will be larger. More spatial variation in changes is present with R95T since it includes both annual total precipitation and the 95th percentile of wet days in its calculation. Finally, future changes in the number of extreme precipitation events were simulated by analysis of DA95. Spatial patterns in DA95 are similar to those seen for other precipitation parameters, and the percent change by the end of the century is well above 50% in many locations under various RCP scenarios.

While analysis of changes in these precipitation parameters at both the middle and end of the 21st century resulted in useful findings, examination of changes on regional scales was considered more useful for policymaking. Temporal trends in each precipitation parameter were evaluated from 2005-2099 under the four RCP forcing scenarios by calculating ensemble average and standard deviation values as well as 5-year centered moving averages on the data. Decadal percent changes from 1997-2005 were also calculated to provide more readable plots. In nearly all regions, increasingly higher forcing, the highest resulting from RCP 8.5, results in the more significant changes over the 21st century, indicating anthropogenic GHG emissions and other contributors to radiative forcing have large influences on precipitation.

Regional analysis of average precipitation indicates the northern regions of North America and Asia, along with East and Southeast Asia may experience the most significant wetting trends, and Central America and the Mediterranean basin will dry significantly. Most other regions exhibit small to moderate increases in precipitation, except southern Africa and northern Australia where slight decreases occur. Future patterns in 95th percentile precipitation values indicate increases in this upper percentile are nearly proportionate to increases in annual precipitation totals, a notable exception being the Amazon basin in which general increases in 95th percentile values are coupled with small decreases in average precipitation. These findings may indicate a direct influence of extreme events on average precipitation, as both parameters show nearly proportional trends. These results indicate a shift toward more intense precipitation over many parts of the globe, a situation which could influence public policy decisions on climate change.

Extreme precipitation index R95T increases over all regions except Central America. When comparing future index values to those of the base period, decadal percent changes are artificially higher in some locations. This anomaly likely results from artificially low base period indices due to wet day criteria, an explanation which is further validated by examination
of DA95 trends. Increases in R95T are proportionately larger than increases in average and 95th percentile precipitations. The highest consistent increases in R95T occur in northern North America, eastern and western Africa, and all of Asia. Although average and 95th percentile values decrease around the Mediterranean region, the contribution to annual precipitation derived from extreme events increases over time.

Precipitation index DA95 measures trends in the frequency of extreme precipitation events. All regions exhibit near-term increases from the base number of precipitation events exceeding 1997-2005 95th percentile values, but Central America and the Mediterranean Basin, the two regions showing decreasing annual totals, have eventual decreasing DA95 values by mid-century. Overall, northern North America, North Asia, eastern Africa, and Southeast Asia have the largest relative increases, but many regions show greater than 10% increases in extreme event frequency, especially under high forcing.

A final evaluation of global precipitation was conducted through assessment of categorical precipitation trends using historic and future CCSM4 data. Establishment of six precipitation categories provides a useful method for extracting trends in a variety of precipitation intensities. Analysis indicates a general increasing contribution to annual precipitation from the most intense categories begins around 1950-1970 and continues through 2005, the end of the historic period. In contrast, a decreasing trend in contribution from low intensity categories occurs over the historic period, yet general stagnancy and an onset of decreasing contribution occur at nearly the same periods as intense category stagnancy and onset of increasing values, roughly 1850-1950 and 1950-1970, respectively. Moderate to heavy precipitation are more variable over the historic period than other intensity groups.

The increasing and decreasing trends in categorical precipitation which occur after 1970 continue past 2005 in the future RCP scenario data. For all categories, the largest changes in contribution fractions occur under the highest forcing scenarios. For RCP 2.6 and 4.5, a leveling in values is generally seen around 2050 and 2070, respectively. RCP 6.0 and 8.5 data indicates continuous increases (decreases) throughout the 21st century in very heavy and torrential (very light and light) precipitation events. Contribution from moderate rainfall remains only slightly changed under future radiative forcing, while increasing contribution from heavy rainfall begins to slow or decline by mid-century. Remarkable similarity of temporal changes in categorical precipitation with changes in atmospheric carbon dioxide concentration is evident through high correlation values among all categories. The highest correlation exists when comparing atmospheric carbon dioxide concentration with very light, light, very heavy, and torrential contributions to annual precipitation, and positive (negative) R values are common among the three highest (lowest) intensity categories. Additionally, increasing correlations are common for the highest radiative forcing scenarios.

The results of this research stress the importance in taking action to alleviate potential harmful impacts of global warming. Adaptation to climate change and mitigation of its effects is essential to providing societies with safe living environments. Availability and allocation of water resources will become increasingly important as populations grow, but effective public policy decisions and advanced engineered systems may improve regional resistance to shortages. As more frequent intense precipitation events occur, increased damages may ensue as a result of
improper living arrangements. The establishment of high population densities in coastal and disaster-prone locations increases the likelihood of costly precipitation-related disasters, such as flooding and tropical storms. Improved early warning systems and risk-reduction strategies have mitigated impacts to an extent, but better education and effective public policies are essential in curtailing consequences of increased future extremes.
REFERENCES


APPENDICES
APPENDIX A: Tables and Figures

Table 1. Coefficients of determination between 1961-1990 and 1997-2005 spatial, annually averaged CCSM4 precipitation parameters.

<table>
<thead>
<tr>
<th></th>
<th>Average Precipitation</th>
<th>95th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>0.9965</td>
<td>0.9947</td>
</tr>
<tr>
<td>Land Only (excl. Antarctica)</td>
<td>0.9988</td>
<td>0.9984</td>
</tr>
</tbody>
</table>
Figure 1. Global average precipitation values averaged over 1997-2005 from GPCP, CMAP, and CCSM4 data.
Figure 2. Bias (left column) and percent bias (right column) between CCSM4, GPCP, and CMAP 1997-2005 average precipitation values as shown in Figure 1.
Table 2. Global average values of average annual precipitation and spatial correlation coefficients among datasets, calculated for the period 1997-2005.

<table>
<thead>
<tr>
<th>Global average (mm/day)</th>
<th>CCSM4</th>
<th>GPCP</th>
<th>CMAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.441</td>
<td>2.178</td>
<td>2.064</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Correlation coefficient (R)</th>
<th>CCSM4 / GPCP</th>
<th>CCSM4 / CMAP</th>
<th>GPCP / CMAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8796</td>
<td>0.8530</td>
<td>0.9156</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3. Global 95th percentile values (top row) of daily precipitation averaged over 1997-2005 from GPCP and CCSM4 data. Bias (bottom left) and percent bias (bottom right) between GPCP and CCSM4 1997-2005 95th percentile values as shown in Figures 3a and 3b.
Table 3. Global average values of the annual 95th percentile of daily precipitation and spatial correlation coefficients among datasets, calculated for the period 1997-2005.

<table>
<thead>
<tr>
<th></th>
<th>CCSM4</th>
<th>GPCP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global average</strong></td>
<td>9.66</td>
<td>10.57</td>
</tr>
<tr>
<td>(mm/day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Correlation coefficient (R)</strong></td>
<td>CCSM4 / GPCP</td>
<td>0.8820</td>
</tr>
</tbody>
</table>


Figure 4. Atmospheric carbon dioxide concentration from 1850-2099. [Data available online at http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download.]
Figure 5. Percent change in average precipitation calculated in relation to the 1997-2005 base period average precipitation values as shown in Figure 1c. Values are shown for RCP 2.6 (first row), RCP 4.5 (second row), RCP 6.0 (third row), RCP 8.5 (fourth row) for two time periods, middle of 21st century (2050-2059, left column) and end of 21st century (2090-2099, right column).
Figure 6. Percent change in the 95th percentile of annual daily precipitation calculated in relation to the 1997-2005 base period 95th percentile values as shown in Figure 3b. Values are shown for RCP 2.6 (first row), RCP 4.5 (second row), RCP 6.0 (third row), RCP 8.5 (fourth row) for two time periods, middle of 21st century (2050-2059, left column) and end of 21st century (2090-2099, right column).
Figure 7. Percent change in R95T calculated in relation to 1997-2005 base period R95T values as shown in Figure S-1. Values are shown for RCP 2.6 (first row), RCP 4.5 (second row), RCP 6.0 (third row), RCP 8.5 (fourth row) for two time periods, middle of 21st century (2050-2059, left column) and end of 21st century (2090-2099, right column).
Figure 8. Percent change in DA95 calculated in relation to 1997-2005 base period DA95 values (18 days/year). Values are shown for RCP 2.6 (first row), RCP 4.5 (second row), RCP 6.0 (third row), RCP 8.5 (fourth row) for two time periods, middle of 21st century (2050-2059, left column) and end of 21st century (2090-2099, right column).
Table 4. List of regions used in regional analysis. Only land grid points within the ranges are used.

<table>
<thead>
<tr>
<th>Name</th>
<th>Acronym</th>
<th>Latitude (degrees)</th>
<th>Longitude (degrees)</th>
</tr>
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<tbody>
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<td>Alaska</td>
<td>ALA</td>
<td>60N-72N</td>
<td>170W-103W</td>
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<td>Greenland</td>
<td>GRL</td>
<td>50N-85N</td>
<td>103W-10W</td>
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<td>WNA</td>
<td>30N-60N</td>
<td>130W-103W</td>
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<td>CNA</td>
<td>30N-50N</td>
<td>103W-85W</td>
</tr>
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<td>25N-50N</td>
<td>85W-60W</td>
</tr>
<tr>
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<td>CAM</td>
<td>10N-30N</td>
<td>116W-83W</td>
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<td>82W-34W</td>
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<td>56S-20S</td>
<td>76W-40W</td>
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<td>NEU</td>
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<td>10W-40E</td>
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<td>10W-40E</td>
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<td>SAH</td>
<td>18N-30N</td>
<td>20W-65E</td>
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<td>WAF</td>
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<td>30N-50N</td>
<td>75E-100E</td>
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<td>EAS</td>
<td>20N-50N</td>
<td>100E-145E</td>
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<td>South Asia</td>
<td>SAS</td>
<td>5N-30N</td>
<td>65E-100E</td>
</tr>
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<td>SEA</td>
<td>11S-20N</td>
<td>95E-155E</td>
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<td>NAU</td>
<td>30S-11S</td>
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<td>Southern Australia</td>
<td>SAU</td>
<td>45S-30S</td>
<td>110E-155E</td>
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Figure 9. Regions used in future precipitation trend analysis.
Figure 10. Regional average precipitation time series plot from 2005-2099 for each RCP scenario. Values shown are in mm/day and represent ensemble averages. Lighter, background lines are annual values, and darker lines are after applying 5-year centered moving averages (2007 to 2097).
Figure 11. Decadal percent change in average precipitation compared to 1997-2005 base period for each RCP scenario. Year along bottom axis represents the start year for each decade (i.e. 2010 represents average percent change from 2010 to 2019).
Figure 12. Regional 95th percentile precipitation time series plot from 2005-2099 for each RCP scenario. Values shown are in mm/day and represent ensemble averages. Lighter, background lines are annual values, and darker lines are after applying 5-year centered moving averages (2007 to 2097).
Figure 13. Decadal percent change in 95th percentile precipitation compared to 1997-2005 base period for each RCP scenario. Year along bottom axis represents the start year for each decade (i.e. 2010 represents average percent change from 2010 to 2019).
Figure 14. Regional R95T time series plot from 2005-2099 for each RCP scenario. Values shown are percentages and represent ensemble averages. Lighter, background lines are annual values, and darker lines are after applying 5-year centered moving averages (2007 to 2097).
Figure 15. Decadal percent change in R95T compared to 1997-2005 base period for each RCP scenario. Year along bottom axis represents the start year for each decade (i.e. 2010 represents average percent change from 2010 to 2019).
Figure 16. Regional DA95 time series plot from 2005-2099 for each RCP scenario. Values shown are number of days and represent ensemble averages. Lighter, background lines are annual values, and darker lines are after applying 5-year centered moving averages (2007 to 2097).
Figure 17. Decadal percent change in DA95 compared to 1997-2005 base period for each RCP scenario. Year along bottom axis represents the start year for each decade (i.e. 2010 represents average percent change from 2010 to 2019).
Figure 18. Percent of total annual precipitation contributed by each precipitation category (CatP) for historical and future CCSM4 data. Categories are defined as: 0.1-1 mm/day (Category 1), 1-10 mm/day (Category 2), 10-20 mm/day (Category 3), 20-50 mm/day (Category 4), 50-100 mm/day (Category 5), and 100+ mm/day (Category 6). Lighter, background shading represents the range between one standard deviation below and one standard deviation above the annual average percent contribution, and the darker line represents the average.
Table 5. Global temporal correlation coefficients between atmospheric carbon dioxide concentration and CatP for historical and future CCSM4 data.

<table>
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<tr>
<th>Precipitation Category</th>
<th>Correlation Coefficient (R)</th>
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<th></th>
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<td></td>
<td>Historic</td>
<td>RCP 2.6</td>
<td>RCP 4.5</td>
<td>RCP 6.0</td>
<td>RCP 8.5</td>
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<tr>
<td>1</td>
<td>-0.792</td>
<td>-0.630</td>
<td>-0.929</td>
<td>-0.951</td>
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<td>2</td>
<td>-0.582</td>
<td>-0.623</td>
<td>-0.916</td>
<td>-0.937</td>
<td>-0.977</td>
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<tr>
<td>3</td>
<td>-0.221</td>
<td>-0.039</td>
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<tr>
<td>4</td>
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</tr>
<tr>
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<tr>
<td>6</td>
<td>0.368</td>
<td>0.393</td>
<td>0.783</td>
<td>0.888</td>
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Figure S-1. Global 95th percentile values of rainy days (>1mm/day, top left) and 95th percentile of daily precipitation (no minimum, top right) averaged over 1997-2005 from CCSM4 data. Percent difference between Part a) and Part b) is shown below.
Figure S-2. Global values of extreme precipitation index R95T averaged over 1997-2005 from CCSM4 data.
Figure S-3. Regional annual average precipitation values from 2005-2099 for each RCP scenario. Values shown are in mm/day. Lighter, background shading represents the range between one standard deviation below and one standard deviation above the annual ensemble average of this parameter, and the darker line represents the ensemble average.
Figure S-4. Regional annual 95th percentile precipitation values from 2005-2099 for each RCP scenario. Values shown are in mm/day. Lighter, background shading represents the range between one standard deviation below and one standard deviation above the annual ensemble average of this parameter, and the darker line represents the ensemble average.
Figure S-5. Regional annual R95T values from 2005-2099 for each RCP scenario. Values shown are percentages. Lighter, background shading represents the range between one standard deviation below and one standard deviation above the annual ensemble average of this parameter, and the darker line represents the ensemble average.
Figure S-6. Regional annual DA95 values from 2005-2099 for each RCP scenario. Values shown are number of days. Lighter, background shading represents the range between one standard deviation below and one standard deviation above the annual ensemble average of this parameter, and the darker line represents the ensemble average.
Table S-1. Regionally-averaged base period values for various precipitation parameters.

<table>
<thead>
<tr>
<th>REGION</th>
<th>AVG (mm/day)</th>
<th>95th (mm/day)</th>
<th>R95T (%)</th>
<th>DA95 (days)</th>
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<tbody>
<tr>
<td>ALA</td>
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<td>ENA</td>
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<tr>
<td>CAS</td>
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<td>25.80</td>
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Figure S-7. Map of the world’s major river basins. (UNEP 2012)
Figure S-8. Global water withdrawal as a percentage of total available water. (UNEP 2012)
Figure S-9. Freshwater use by sector at the beginning of the 2000s. (UNEP 2012)
VITA

Scott DeNeale was born on December 28, 1988 in Winchester, Virginia to the parents of Stephen and Cynthia DeNeale a mere four minutes after his twin brother Sean. He was preceded in life by an older sister Jennifer and older brother Christian. His family moved to Knoxville, Tennessee in 1997 where he graduated from Halls High School in May 2007 as co-valedictorian with his twin brother. In August 2007 he began coursework at the University of Tennessee, Knoxville studying Civil Engineering as a member of the Chancellor’s Honors Program. He earned a Bachelor of Science in Civil Engineering in May 2011, graduating Summa Cum Laude and a successful graduate of the Chancellor’s Honors Program. He began limited graduate level coursework while an undergraduate and will receive a Master of Science in Environmental Engineering in May 2012.

As a freshman undergraduate student, he met the love of his hitherto short, yet wonderful life, Brianna Jones, whom he has been dating since February 2008. He was a member of UT’s American Society of Civil Engineering Student Chapter and TeamVOLS and participated on a number of intramural sports teams. He enjoyed participating in volunteer activities on campus including de-trashing “the Hill” and Third Creek with Keep Knoxville Beautiful and Ijams Nature Center.

He worked for UT Conferences as a Special Events employee, completing many tasks for Destination Imagination’s 2009 Global Finals and the 2009 Covenant High in Christ conferences held in Knoxville. During the summer of 2010, Mr. DeNeale worked as a Materials Engineering Technician at the Materials Laboratory of the Federal Highway Administration’s Eastern Federal Lands Highway Division located in Sevierville, Tennessee. From September 2009 to May 2010 he worked with Dr. Lee Han as an Undergraduate Student Assistant, assisting with research related to driver behavior at red light camera intersections and license plate recognition technology. From January to May 2010 he worked with Dr. Joshua Fu, assisting with research and literary editing related to climate change impacts and modeling. He continued work with Dr. Fu in June 2011 to learn how to use various computer programming languages and tools to perform data analysis related to the contents contained in this Master’s Thesis and has been employed as a Graduate Research Assistant with him since August 2011.

During his spare time, he loves to travel, hike, play tennis, soccer, disc golf, and other sports, watch movies, and venture onto Norris Lake in East Tennessee. Mr. DeNeale aspires to convey to this world the same love and care his family, friends, and acquaintances have bestowed upon him.