HYDROCLIMATOLOGY OF THE U.S. GULF COAST UNDER GLOBAL CLIMATE CHANGE SCENARIOS

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Abstract: The historical climate record and climate change scenarios of the north-central Gulf of Mexico Coast (roughly from Houston, Texas to Mobile, Alabama) was examined to assess past and future temperature and hydrology of the region. Historical temperature data show an annual temperature pattern with high values in the 1920s–1940s, a drop in annual temperatures in late 1950s, persisting through the 1970s, and then an increase over the past two-plus decades. However, recent temperatures have mostly not reached the highs of previous decades. Annual precipitation is generally increasing, with some climate divisions, in particular those in Mississippi and Alabama, having significant long-term trends. Over the entire record since 1919, there was an increase in rainfall, and that, combined with relatively cool temperatures, led to a 36% increase in runoff. To assess future extremes in regional hydroclimatology, the A1B and B1 emission scenarios were examined for the region. Output from an ensemble of 21 global climate models run with the two emission scenarios indicates a wide range of possible climates in the mid-21st century, centered on the year 2050. The models suggest a warmer Gulf Coast region of about 1.5°C ± 1°C. Precipitation projections are more uncertain, with conflicting increases and decreases projected by the various models, although most suggest a decrease in annual rainfall across the Gulf Coast. By compounding changing precipitation with increasing temperatures, overall runoff is likely to remain the same or decrease, while deficits (or droughts) could become less severe because of possible increases in summer and autumn precipitation. Impacts to the natural landscape (geomorphology and ecology) would likely be negligible. [Key words: hydroclimatology, climate change, Gulf Coast, runoff, drought, Thornthwaite model.]

INTRODUCTION

The north-central Gulf Coast of the United States was selected by the United States Department of Transportation as a test case for planning in the face of climate

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Physical Geography, 2011, **32**, 6, pp. 561–582. http://dx.doi.org/10.2747/0272-3646.32.6.561

change. The region selected, roughly from Houston, Texas to Mobile, Alabama (Fig. 1), is important to the nation with regard to the oil and gas industry, strategic port facilities, abundant fisheries, and tourism, and the built environment rests within dynamic and biologically productive wetland environments. Climate change in this region could have dramatic impacts on the built infrastructure as well as on these fragile ecosystems through changes in the hydroclimatology. Regarding the transportation infrastructure, for example, roadbeds for highways desiccate and deteriorate during periods of drought. Conversely, road surfaces are often inundated during periods of heavy rainfall and flash flooding, and bridges are compromised during extreme river basin floods. Therefore, some understanding of past and future droughts and floods is imperative for purposes of planning (e.g., see Svoma and Balling, 2010).

This paper assesses change in the hydroclimatology over the instrumental climate record, as well as how the regional climate may change in the future according to an ensemble of state-of-the-art general circulation models (GCMs). The GCMs used here are also used in the latest Intergovernmental Panel on Climate Change (IPCC) report for future projections at global and regional scales (Christensen et al., 2007; IPCC, 2007; Meehl et al., 2007b). Keim et al. (1995) focused on the hydroclimatology of the region and found that runoff had increased over time in Louisiana, resulting from an increasing trend in precipitation and relatively lower temperatures in more recent decades. Grundstein (2009) also found significantly wetter conditions in much of the eastern United States, including portions of the Central Gulf Coast. However, these papers did not examine climate change scenarios, nor did they examine impacts of climate extremes, which tend to have greater implications for the built and natural environment. Looking beyond changes in global mean temperature signals is critical to better address societally relevant questions at appropriate geographical scales (i.e., regional) for temperatures and other climatic variables, in particular precipitation, and then assess impacts to the hydrology.

DATA AND SCOPE

The north-central Gulf Coast is one of wettest regions in the United States, with annual rainfall averages over 1500 mm per year (NOAA, 2002). This rainfall has little seasonality, yet with slightly higher rainfall values in spring and summer relative to fall and winter. The topography of the region is relatively flat, rising only tens of meters above mean sea level in higher locations.

For examination of change in both the historical record and analysis of climate change scenarios, the baseline climatology is built around climatic data from the United States Climate Division datasets (CDDs) (Guttman and Quayle, 1996) and the United States Historical Climate Network (USHCN) (Karl et al., 1990; Easterling et al., 1996). Because CDDs are used in a portion of this analysis, caution needs to be taken with data from 1905–1930, which are generated from statewide data as described by Guttman and Quayle (1996).

Historical trends and variability are analyzed for temperature and precipitation at the CDD level for the climate divisions along the Gulf Coast from southeastern Texas to the coast of Alabama, including Texas Climate Division 8, Louisiana

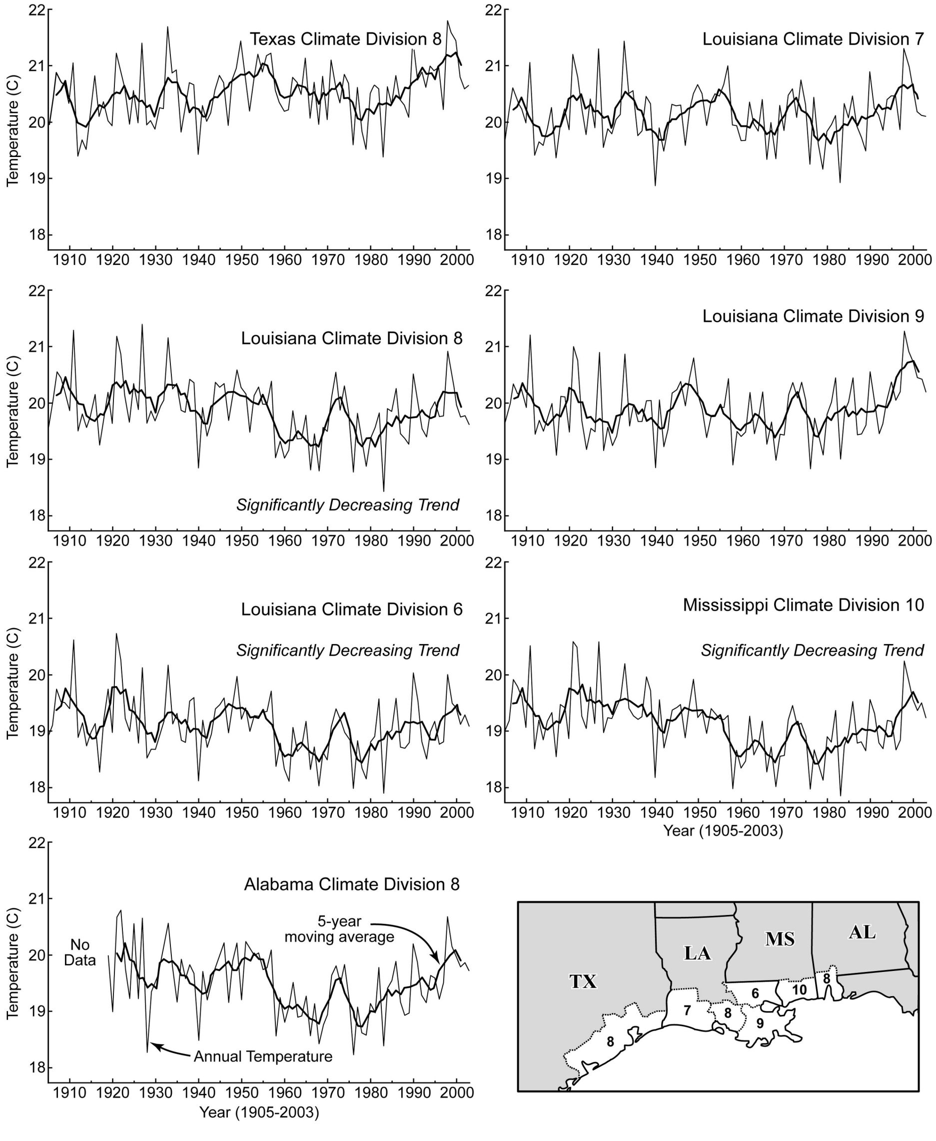

Fig. 1. Temperature variability from 1905 to 2003 for the seven climate divisions constituting the Gulf Coast region.

Divisions 6–9, Mississippi Division 10, and Alabama Division 8 (Figs. 1 and 2). Because Keim et al. (2003) showed that CDD can have spurious temperature trends, this analysis generates CDDs consisting of averages of stations within each division from the USHCN FILNET dataset (Table 1). USHCN data are excellent for this purpose because stations were selected based on length and quality of data. In addition, these data have undergone numerous quality assurances and adjustments to best

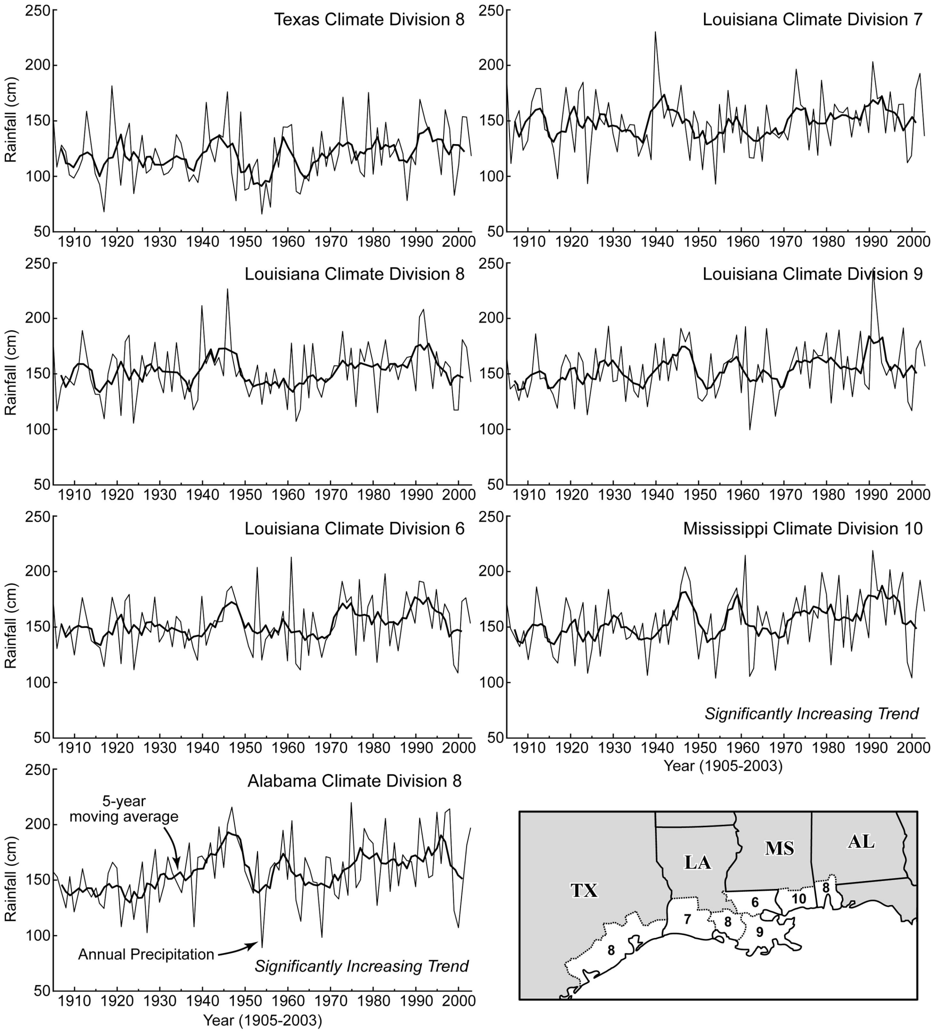

Fig. 2. Precipitation variability from 1905 to 2003 for the seven climate divisions constituting the Gulf Coast region.

characterize the actual variability in climate, including time of observation bias (Karl et al., 1986), changes in instrumentation (Quayle et al., 1991), random relocations of stations (Karl and Williams, 1987), and urban warming biases (Karl et al., 1988). Furthermore, missing data are estimated from surrounding stations to produce a nearly continuous data set for each station.

Monthly averages from the USHCN stations, from 1905 to 2003 within each climate division, are then averaged for each division by month and year. Data were organized in this fashion to provide some geographical weighting to the various regions, despite the differing number of USHCN stations available within each

Table 1. USHCN Stations within the Seven Climate Divisions of the Gulf Coast Region

Climate division	USHCN stations
Texas CD 8	Danevang, Liberty
Louisiana CD	Jennings[a]
Louisiana CD 8	Franklin, Lafayette
Louisiana CD 9	Donaldsonville, Houma, New Orleans, Thibodaux
Louisiana CD 6	Amite, Baton Rouge, Covington
Mississippi 10	Pascagoula, Poplarville, Waveland
Alabama CD 8	Fairhope

[a] The Jennings climate record only dates back to the late 1960s. As a result, LA-CD 7 consissts of an average of Liberty, TX to the west and Lafayette, LA to the east.

climate division. The year 1905 begins a common period of record for all but one of the USHCN stations utilized in the study. The exception is Fairhope, Alabama, the only USHCN station available in Alabama Climate Division 8, where data begin in 1919. Only USHCN FILNET stations with a continuous monthly record of temperature from January 1905 through December 2003 were included in the analysis, with the exception of Fairhope. The data were not brought further to date because some of the USHCN station records have gaps in the more recent record or quit reporting altogether, especially after the region suffered the ravages of Hurricane Ivan in 2004, and Hurricanes Dennis, Katrina, and Rita in 2005. USHCN precipitation data were not as serially complete as temperature and there were even fewer stations available. As a result, this study incorporated the National Climate Data Center–generated CDD for precipitation. This decision seems reasonable given results of Keim et al. (2005) and Allard et al. (2009), which both showed that the redistribution of stations within a climate division had less severe impacts on precipitation than on temperature, and that impacts were less in the southeastern United States than in the northeastern United States.

WATER BALANCE MODEL

The primary tool used to investigate the regional hydroclimatology is a modified Thornthwaite Water Balance Model, first introduced by Thornthwaite (1948). This model, despite its age, is still widely used in modern applied climate studies (Keim, 2010) and is recommended for assessments of climate change (Gleick, 1986a, 1986b). The Thornthwaite model is simply an accounting of hydroclimatological inputs and outputs (Mather, 1978). We used updated equations by Dingman (2002) to simulate hydrological interactions in subfreezing temperatures.

Monthly values of temperature and precipitation are entered into the budget, and potential evapotranspiration—called reference evapotranspiration—is generated, as well as rain/snow ratios, soil moisture, soil moisture deficits, and runoff. The model is therefore appropriate for use in this study, as the climate-change scenario output data are also temperature and precipitation only. Hydrologic models that require input of additional, more sophisticated data (i.e., humidity levels) could not have been implemented in this study.

The Thornthwaite water balance was modified slightly by using Turc's (1961) estimation of the reference evapotranspiration (ET_o) parameter (Jensen et al., 1997). Turc's ET_o was selected because it more closely simulates FAO-56 Penman-Monteith ET_o with a limited set of meteorological data (Fontenot, 2004). FAO-56 Penman-Monteith $ET_{o,}$, originally conceived in Penman (1948), is considered the standard by the Food and Agricultural Organization of the United Nations. Temperature is used to determine the rain/snow proportion of winter precipitation, and a melt factor applied, though not often in this region (see Dingman, 2002). Field capacity ($SOIL_{MAX}$) was set to 150 mm. After computing soil moisture change using equations found in Dingman (2002), any excess water in the budget is declared as surplus. In these wetland environments, the monthly surplus parameter is synonymous with runoff, because the lag between the generation of surplus water from precipitation and the resultant streamflow is very short: minutes to hours, or perhaps days in some cases. In larger watersheds, however, the lag times to produce runoff after a rainfall event can range from weeks to months, especially at locations far downstream. As such, the monthly lag in the production of runoff from surplus water in the Thornthwaite water balance is more relevant for these larger watersheds, and is entirely inappropriate for the smaller coastal watersheds in this study. We retain surplus as an index for runoff, and dismiss the modeled runoff term as invalid in this study, as it applies to watersheds larger than the scale of this study. Studies of Thorthwaite's surplus/runoff values to estimate measured discharge have found good relationships (i.e., Mather, 1969; Rohli and Grymes, 1995). From this point forward, we will use the term "runoff" for modeled water surplus. If the delivery of moisture through precipitation does not meet the environmental demand for moisture, then a deficit is created. We also highlight the monthly resolution of data, whereby runoff generation is more common in winter and spring, when soils tend to be saturated, and deficits are more commonly generated in summer and fall, when the potential evapotranspiration demand is high and often exceeds precipitation. In each case, the seasonal component of the hydrological cycle is well represented in this study.

HISTORICAL CLIMATE RECORD

Annual temperature variability shows the 1920s to have been the warmest decade for the various climate divisions (Fig. 1). After a reduction in the temperature in the late 1950s, the coolest period occurs in the 1960s and 1970s, while a general warming trend is evident beginning in the late 1970s, extending through 2003. However, temperatures in recent decades in most of the climate divisions still do not reach the highs of the 1920s and 1930s. Of the seven climate divisions, LA6, LA8, and MS10 have significant cooling trends at $\alpha \leq .05$ over the period of record under analysis. Variability in precipitation is such that the 1940s and 1990s were the wettest decades, while the 1950s was generally the driest (Fig. 2). Although the climate

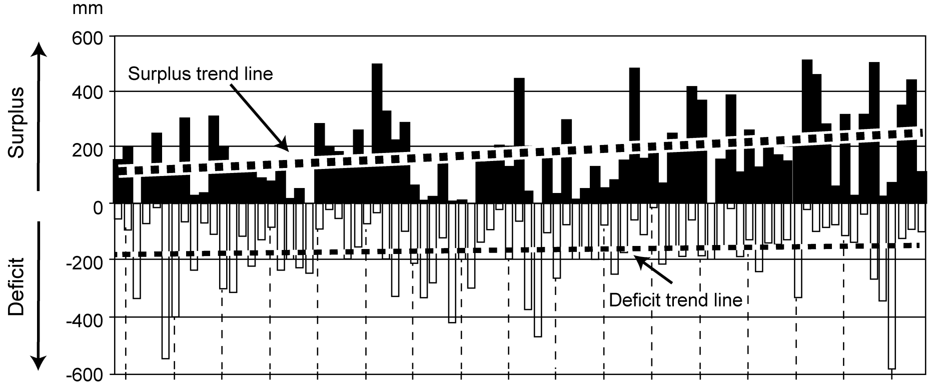

Fig. 3. Inter-annual variability in model-derived surplus (runoff) and deficit accumulated annually from 1919 to 2003 for the Gulf Coast region, with trends lines on each.

division data indicate long-term patterns of increasing rainfall, only MS10 and AL8 had increases that are significant at $\alpha \leq 0.05$.

Data for each of the seven climate divisions were amalgamated into a regional dataset for the north-central Gulf Coast, by month, and the continuous monthly water balance model was run. Clearly, there is local or subregional variability inherent in the regional data that is not captured in this analysis. As such, input and output data from the model should be interpreted as a regional generalization.

In a typical year, ET_o is low in winter and early spring, and most rainfall is converted to runoff because soil moisture storage remains at, or near, capacity. As temperatures rise in late spring and early summer and the number of hours of daylight increases, ET_o also increases. ET_o will often exceed rainfall in July, August, and September, which leads to soil moisture utilization, on the average. Then in late fall, precipitation often exceeds ET_o, leading to recharge of soil moisture.

Regional trends in model-derived runoff, accumulated by month for each year, show large inter-annual variability with relatively high values in the 1940s and from 1975 to 2003 (Fig. 3). Despite the variability, a long-term trend was detected in the data at $\alpha \leq 0.05$. Moisture deficits show high values from the mid-1940s through the mid-1960s, with 1998–2000 also high, but with no long-term trend (Fig. 3).

GCM ENSEMBLE OF CLIMATE CHANGE SCENARIOS

Two climate change scenarios were computed for the north-central Gulf Coast region on the basis of GCM output at the grid points (land areas only) shown in Figure 4. The scope of these grid points represents the north-central Gulf Coast region, but at a scale somewhat larger than that depicted in our historical analysis. Change in GCM values from grid point to grid point across earth, however, generally occurs gradually. Thus, we feel that these GCM data reflect output for our specific region, while we ensure that we consider output from these large-scale models consistent with their expected skill, which is expected to be greater over larger rather than very limited regions.

Fig. 4. Grid area for the Gulf Coast GCM projections.

Projections of temperature and precipitation change for this region for the middle of the 21st century are presented in the form of probability density functions (PDFs) by applying the method of Tebaldi et al. (2004, 2005) for scenarios A1B (mid-range emission scenario) and B1 (low emissions scenario) (Nakicenovic et al., 2000). These two specific scenarios were selected for analysis by the United States Department of Transportation. Each of these scenarios assumes that society will evolve along a future path characterized by a certain level of future energy use, use of emissions sources, technology changes, and environmental awareness. For example, the A1B scenario has balance across all energy sources, meaning it does not rely too heavily on any one particular future energy source and mixes fossil fuels and clean, renewable sources. It is therefore based on the assumption that improvement rates apply to all energy sources and end-use technologies. The B1 scenario assumes a high level of social and environmental awareness, including an increase in resource efficiency and diffusion of cleaner technologies, making it a more conservative scenario than A1B (Nakicenovic et al., 2000).

Data forming the basis of the PDF estimation shown in Figures 5 and 6 are an ensemble of historical and future climate simulations (from which temperature and precipitation are extracted) by all the GCMs that contributed to the IPCC 2007 Assessment Report, forming the Coupled Model Intercomparison Project (CMIP3) archive (Meehl et al., 2007a). Output from 21 different models (Table 2) is available in the CMIP3 archive for the two scenarios chosen. Area averages of temperature and precipitation projections were extracted from each model/scenario combination, over the four seasons, and over two 20-year periods, one representative of the modern climatology (1980–1999) and one representative of the future mid-century time period (2040–2059), referred to from this point forward as 2050. This period was selected because it represents the time horizon relevant to planning for the

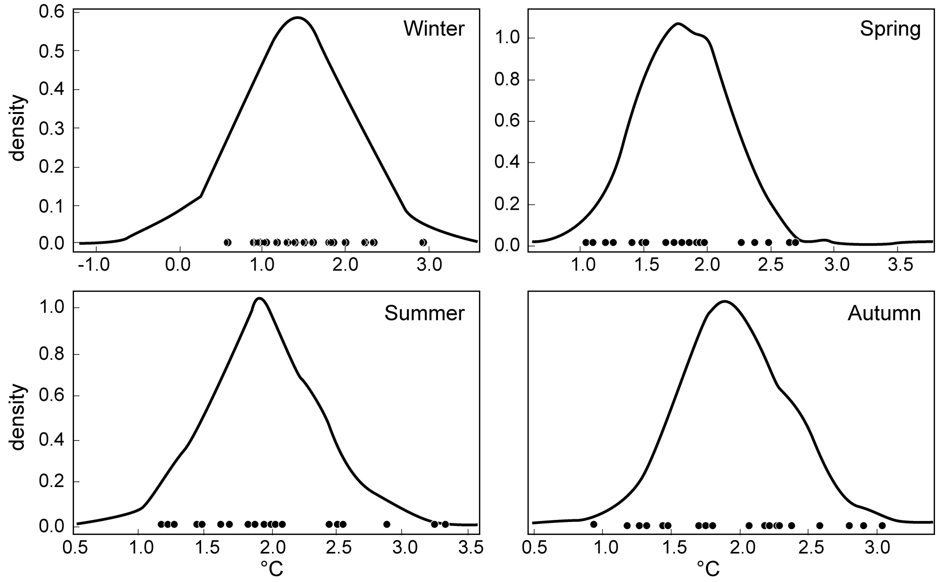

Fig. 5. Probability density functions for seasonal temperature change (in °C) in the U.S. Gulf Coast region for the mid-21st century centered on 2050 using the A1B scenario.

United States Department of Transportation. Thus projections of "change" should be interpreted with respect to these two time periods and are conditional on the scenarios A1B and B1.

The statistical procedure synthesizes the multi-model ensemble of projections into a PDF by applying a Bayesian hierarchical model. Both observations and modeled temperature and precipitation are synthesized in the final estimate of PDFs. At the core of the method is the idea that different models have different reliabilities in simulating climate over the region and the final probabilistic representation of climate change should reflect that, by weighting more those models that agree better with observations, and discounting models with larger biases. In its initial conception, the statistical treatment also rewarded convergence of the different models when considering future trajectories, weighting more those models that agree with one another and downweighting outliers. In the version of the statistical procedure applied here (described in Tebaldi et al., 2004), the convergence criterion is discounted, ensuring that even model projections that disagree with the consensus inform the shape of the final PDFs.

Thus, we prefer a method that produces conservative estimates of the uncertainty by allowing outliers among model projections to shape our future probabilities of climate change. The result of applying the statistical analysis to the GCM output are PDFs of temperature (as absolute values of change in °C) and precipitation change (as percent change with respect to historical precipitation averages) from which any percentile can be straightforwardly derived. Challenges of interpreting multi-GCM

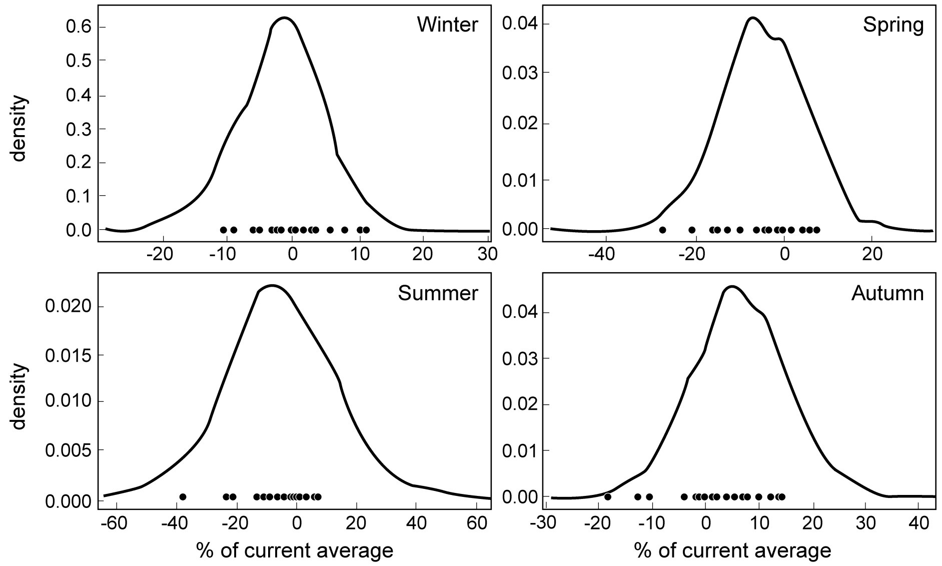

Fig. 6. Probability density functions for seasonal precipitation change (in percent) in the U.S. Gulf Coast region for the mid-21st century centered on 2050 using the A1B scenario.

model results are discussed in Tebaldi and Knutti (2007) and Knutti et al. (2010). A refinement to the statistical model used here is described in Smith et al. (2009).

EXTREME VALUE ANALYSIS

Because extremes are important to both wetland ecology and to the transportation sector, we examine monthly extremes of precipitation, runoff, and deficit in the north-central Gulf Coast. The efficacy of GCMs in analyzing future climatologies of extreme events is still under debate. The problem is that GCMs do not resolve specific weather event types very well, e.g., hurricanes or thunderstorms (Broccoli and Manabe, 1990; Henderson-Sellers et al., 1998; Keim et al., 2004; Tebaldi et al., 2006), because of the fine-scale structures of the events that cannot be effectively represented at the level of discretization in space that these models typically adopt when computing finite difference equations (the median resolution of this generation of GCMs is about 250 km in the horizontal dimension and 1000 m in the vertical). As such, this analysis examines monthly extremes, without analyzing shorter-duration specific weather event types, i.e., thunderstorms, heat waves, or hurricanes.

Measured data from the period 1971–2000 serves as the baseline climatology for the hydroclimatic variables. Using water balance output for this 30-year period, partial duration series (PDS) are generated for the three variables: precipitatation, runoff, and deficit. A PDS includes the number of events (monthly extremes) equal to the number of years under examination (Dunne and Leopold, 1978). As such, the 30 largest monthly totals of precipitation, runoff, and deficit are extracted from each

Table 2. The 21 General Circulation Models (GCMs) Used in This Analysis[a]

GCM	Country of origin
CGCM3.1 (T47)	Canada
CGCM3.1 (T63)*	Canada
CNRM-CM3*	France
CSIRO-Mk3.0*	Australia
GFDL-CM2.0*	USA
GFDL-CM2.1*	USA
GISS-AOM*	USA
GISS-EH*	USA
GISS-ER*	USA
FGOALS-g1.0*	China
INM-CM3.0*	Russia
IPSL-CM4*	France
MIROC3.2 (hires)*	Japan
MIROC3.2 (medres)*	Japan
ECHO-G	Germany/South Korea
ECHAM5/MPI-OM*	Germany
MRI-CGCM2.3.2*	Japan
CCSM3*	USA
PCM*	USA
UKMO-HadCM3*	UK
UKMO-HadGEM1	UK

[a] Note that for precipitation projections, only a subset of 18 models (indicated by asterisk) produced results

30-year dataset, which includes a total of 360 months; hence roughly the top 8% of data for each of these variables are used in the extreme value analysis. These data are then fit to the beta-*p* distribution (Wilks and Cember, 1993; Keim, 1998; Faiers and Keim, 2008), as recommended by Wilks (1993) and the 2-, 5-, 10-, 25-, 50-, and 100-year quantile estimates are determined for each. These data serve as the baseline to assess potential impacts of climate change on these extremes.

CLIMATE CHANGE SIMULATION

This study examines the 5th, 25th, 50th, 75th, and 95th percentiles of the PDFs resulting from synthesizing the seasonal projections from the 21 GCMs through the statistical method described earlier for the two scenarios (Tables 3–6). We note that

Table 3. Predicted Temperature Change from a Suite of GCMs for the 5th, 25th, 50th, 75th, and 95th Percentiles for the A1B Scenario for Mid-21st Century, Centered on 2050 Relative to GCM-Derived 1980–1999 Means

	5th	25th	50th	75th	95th
Winter	0.18	0.95	1.42	1.89	2.56
Spring	1.22	1.55	1.80	2.04	2.38
Summer	1.24	1.66	1.94	2.23	2.70
Autumn	1.31	1.69	1.93	2.22	2.62

Table 4. Predicted Precipitation Change (in percent) from a Suite of GCMs for the 5th, 25th, 50th, 75th, and 95th Percentiles for the A1B Scenario for Mid-21st Century, Centered on 2050 Relative to GCM-Derived 1980–1999 Means

	5th	25th	50th	75th	95th
Winter	–13.30	–5.95	–1.79	2.49	9.01
Spring	–21.07	–11.04	–5.04	1.80	10.17
Summer	–36.10	–17.77	–6.39	6.25	26.24
Autumn	–8.20	0.46	5.97	12.05	21.50

the 50th percentile corresponds to the center of the distribution, given the regular symmetric shape of these PDFs, whereas the 5th and 95th percentiles represent the margins of the PDF.

As a general rule, the GCMs in the A1B and B1 scenarios are predicting a warmer north-central Gulf Coast region, with the greatest increase in temperature occurring, surprisingly, in summer when variability is considerably less than in winter, with minimal increases in winter (Tables 3 and 5); these results are consistent with findings reported in IPCC Assessment Report 4–Working Group 1 (Christensen et al., 2007). The 5th percentile even shows some modest winter cooling in the B1 scenario. The models, however, are inconsistent regarding precipitation. For both scenarios, the 5th percentile depicts reductions in precipitation in all seasons, up to 36% and 27% in summer, for A1B and B1, respectively (Tables 4 and 6). The 50th percentile shows only modest changes to precipitation, with three of four seasons showing small reductions in both scenarios. The 75th and 95th percentiles show increases in precipitation for all seasons. At the 75th percentile, the season with the largest projected change is autumn in both the A1B and B1 scenarios, while at the 95th, the largest projected changes are in summer in both scenarios.

Because the two scenarios demonstrate a large degree of similarity—a well-known feature of projections by the mid-term of the century caused by the inertia of the system responding to different forcings that diverge only gradually from the end of the 20th century—the A1B scenario is retained for further analysis because it shows slightly greater levels of regional change. Therefore, to determine potential changes

Table 5. Predicted Temperature Change from a Suite of GCMs for the 5th, 25th, 50th, 75th, and 95th Percentiles for the B1 Scenario for Mid-21st Century, Centered on 2050 Relative to GCM-Derived 1980–1999 Means

	5th	25th	50th	75th	95th
Winter	–0.31	0.44	1.02	1.53	2.32
Spring	0.67	1.05	1.32	1.62	2.03
Summer	0.64	1.09	1.35	1.63	2.03
Autumn	0.62	1.04	1.33	1.62	2.07

Table 6. Predicted Precipitation Change (in percent) from a Suite of GCMs for the 5th, 25th, 50th, 75th, and 95th Percentiles for the B1 Scenario for Mid-21st Century, Centered on 2050 Relative to GCM-Derived 1980–1999 Means

	5th	25th	50th	75th	95th
Winter	–9.77	–4.37	–0.52	3.36	9.51
Spring	–16.94	–7.96	–2.94	2.41	11.38
Summer	–27.06	–14.16	–3.36	7.43	24.19
Autumn	–7.83	–0.06	5.63	11.13	19.40

to hydrological extremes across the region, paired percentiles (i.e., the 5th, 50th, and 95th) for temperature and precipitation from the A1B PDFs in Tables 3 and 4 (from Figs. 5 and 6) were used, as in Groves et al. (2008). The paired percentiles include the 5th percentile projections for both temperature and precipitation, the 50th for both temperature and precipitation, and the 95th combined. In addition, because the models generally suggest increasing temperatures and less precipitation across the region, a "worst case scenario" is developed that pairs the 5th percentile precipitation (dry) with the 95th temperature (large increases in temperature), which could lead to more intense and protracted drought conditions. In contrast, a "best-case scenario" is also developed, pairing the 95th percentile precipitation (wet) estimate with 5th percentile (modest) temperature increases. The terms best-case and worst-case are used loosely here because of the anticipated impacts on runoff and deficit, fully realizing that a 95th percentile estimate in precipitation could create a host of other problems involving trends in extreme storms (e.g., Karl et al., 1996; Keim, 1997). There is physical grounding for the worst-case (and best-case) scenario(s) in that temperatures generally trend upward during periods of deficient precipitation (and vice-versa). This could be particularly acute in summer, when the A1B scenario shows a possible (95th percentile) increase in temperature of 2.7°C and a possible (5th percentile) 36.1% decrease in precipitation. These paired percentiles examine most of the range of GCM output. In addition, we also analyze the middle of the PDF, or region under the curve, where there is most agreement between the models.

Table 7. Emission Scenario A1B Probability Density Function Combinations Utilized in This Study (in percent)

Description	Temperature probability	Precipitation probability
Modest warming/dry	5	5
Central tendency	50	50
Extreme warming/wet	95	95
Extreme warming/dry	95	5
Modest warming/wet	5	95

The 1971–2000 monthly temperature and precipitation data were therefore adjusted by season according to the predicted changes presented in Tables 3 and 4 for each of the five combinations of paired temperature and precipitation probabilities (Table 7). The water balance model was then re-run using the five "paired quantile datasets" to simulate the hydrology under these altered climate conditions. These datasets provided the means necessary to produce new PDFs of precipitation, runoff, and deficit for additional extreme value statistical processing.

RESULTS OF CLIMATE CHANGE SIMULATION

The 2-, 5-, 10-, 25-, 50-, and 100-year return periods for monthly precipitation show only modest differences between the current climate and the projected climate in 2050 at the three PDF percentiles (Fig. 7). As expected, there is a decrease in monthly precipitation extremes at the 5th percentile for the less rare return periods (2- to 25-year), relative to the current climate, which would be expected given the reduction in precipitation by up to 36% in summer. However, the 100-year precipitation event is slightly larger than the baseline, an artifact of estimating a 100-year return period from a 30-year dataset and of the distribution shape. Results for the 50th percentile indicate that the less rare return periods are on par with current climate, but that the rare return periods may have modestly larger monthly totals. At the 95th percentile, monthly rainfall totals are generally larger at all recurrence intervals.

Monthly runoff extremes show a very different relationship to the current climate (Fig. 8). In the worst-case scenario, runoff is reduced by approximately 25% across all recurrence intervals. This reduction is driven by the predicted reduction in precipitation combined with predictions of large temperature increases that would increase evapotranspiration rates. Results are similar but less dramatic using the paired 5th percentiles because the smaller increases in temperature lead to smaller increases in evapotranspiration rates as compared to the worst-case. The paired 50th percentile estimates have near normal precipitation combined with moderate increases in temperature. The resulting 5 to 10% reductions in runoff are therefore mostly attributable to increases in projected temperature and evapotranspiration demand. The paired 95th percentile parameters include dramatic increases in both temperature and precipitation. The projected precipitation increases, anywhere from 9 to 26%,

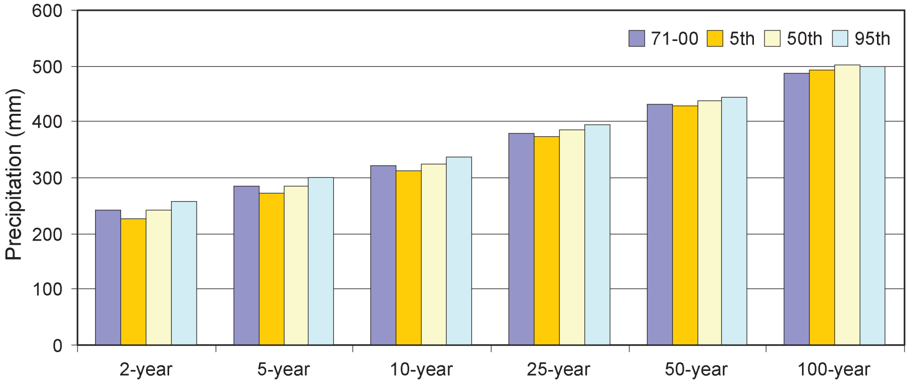

Fig. 7. Quantile estimates of precipitation for the 2- to 100-year return period using the 1971–2000 baseline period relative to GCM output for the A1B climate change scenario at the 5%, 50%, and 95% quartiles.

depending on season, neutralize the impact of the higher temperatures and lead to little or no overall change in the extreme runoff regime. The best-case scenario represents the same precipitation regime, but with less dramatic increases in temperature, leading to only modest increases in runoff over the baseline, although these increases are somewhat more pronounced at the 2- and 5-year return periods.

Extremes in monthly deficit show a more complex pattern between the quantiles and over the various return periods (Fig. 9). Note that deficit represents an atmospheric demand for moisture that is not met by the environment. Therefore, deficit represents environmental stress due to a lack of available water and can be used as an index for drought potential. The worst-case scenario shows a 60% increase in moisture deficit in 2050 at the 2-year return period over the 1971–2000 baseline, due obviously to extreme reductions in precipitation combined with dramatic increases in temperature. However, the gap narrows between the projections and the baseline at more rare recurrence intervals. The paired 5th percentile parameters show a similar, though muted pattern as compared to the worst-case because of the less dramatic increases in projected temperature. Negligible reductions in precipitation at the 50th percentile do not appear to have dramatic impacts on deficit, even despite the temperature increases, as values remain similar to the baseline, especially at less rare return periods (2- to 25-year). With the paired 95th percentiles, increases in temperature are more than offset by the dramatic increases in precipitation. Because deficits are generally produced in summer and autumn, and the projected 95th percentile increases in precipitation during these seasons is dramatic at 26.2% and 21.5%, respectively, deficits are substantially reduced in their intensity. In fact, at the 100-year recurrence interval, the projected 2050 (mid-century) deficit is only about half the magnitude of the current climate. Results and interpretation are similar for the best-case scenario. In this latter case, results suggest that extreme drought impacts would not be the problem that they are today—e.g., a 100-year event in the future may only be as intense as a modern-day 10-year event, assuming

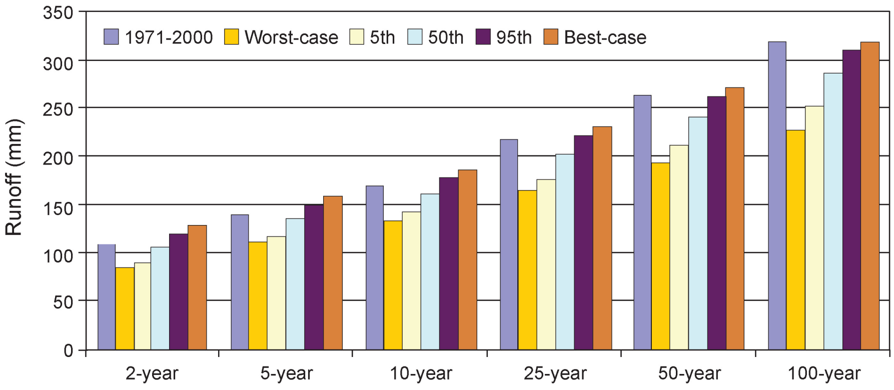

Fig. 8. Quantile estimates of runoff for the 2- to 100-year return period using the 1971–2000 baseline period relative to GCM output for the A1B climate change scenario at the 5%, 50% and 95% coupled quartiles and for the worst-case (5% precipitation and 95% temperature) and best-case (95% precipitation and 5% temperature).

these scenarios (the combined 95th percentiles or the best case) were to play out into the future.

GEOMORPHOLOGICAL AND ECOLOGICAL IMPLICATIONS

The most likely climate change scenarios of some warming and less rainfall in coming decades may have only modest impacts on earth surface and ecological processes, which could be overshadowed by land use changes as reported by Cruise et al. (2010). Erosion and sediment transport in small and middle-size drainage basins are directly related to overland flow and stream discharge. In a humid region like this one, vegetation cover also plays an important role in geomorphic processes. Most erosion and deposition occur during extreme high rainfall and discharge events. In this region, high annual average precipitation supports luxuriant forests, underlain by a thick organic ground cover that largely stabilizes hill slopes. Also, this is a region of low relief and, except during extreme rainfall events, runoff and sediment transport are minimal. Projected changes in precipitation, especially near the 50th percentile, are unlikely to affect forest cover or lead to changes in runoff that would ultimately affect small stream sedimentation. Even toward the rarer (or drier) end of rainfall distributions, soil moisture should be adequate to support forest vegetation, though moisture stresses in summer could become more acute if the worst-case scenario, as defined in this study, were to play out. This hot and dry scenario during the growing season could adversely affect agricultural endeavors in the region, as well as have negative impacts in wetland environments, e.g., encouraging an affliction called brown marsh that is believed to be related to protracted drought, increased salinity levels, low input of fresh water, excessive heat and evaporation, etc. (Subudhi et al., 2008.) Further, moderate precipitation and low flow conditions generally have little effect on fluvial landforms. Another large unknown is how tropical storms and hurricanes might be affected. The models used in this investigation,

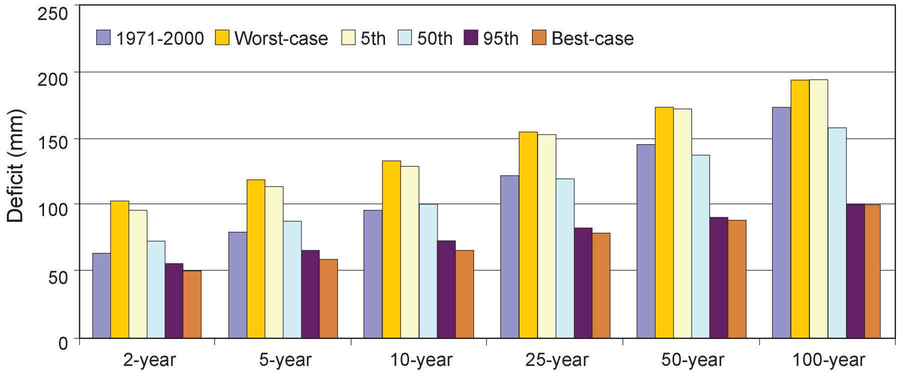

Fig. 9. Quantile estimates of deficit for the 2- to 100-year return period using the 1971–2000 baseline period relative to GCM output for the A1B climate change scenario at the 5%, 50% and 95% coupled quantiles and for the worst-case (5% precipitation and 95% temperature) and best-case (95% precipitation and 5% temperature).

however, do not address changing frequency of tropical cyclones in this region (see e.g., Bender et al., 2010). This portion of coastline is highly active with hurricane strikes in the modern climate (Keim et al., 2007), and these storms have changed the regional landscape, as documented by Stone et al. (2004, 2005). Storms like this, and even some frontal storms, can produce 25–50 mm of rain per hour, resulting in significant overland flow, soil erosion, and stream sedimentation, even in forested watersheds. As a result, any changes in the hurricane climatology of the region can have large impacts in these delicate coastal environments.

Large rivers flowing through this region, include the Mobile and Pearl rivers draining sections of Alabama and Mississippi, respectively; the Sabine, Trinity, Brazos, and Colorado rivers with headwaters in Texas; and of course, the Mississippi River that drains much of the United States from the Appalachian Mountains westward toward the Rockies. Only the lowermost reaches of these rivers flow through the study area before reaching the Gulf. Geomorphic processes in these channel sections will be largely unaffected by climate change in the Gulf Coast region. Discharge and sediment loads are directly related to climate and landscape characteristics in the middle and upstream sections of each watershed, which for each river includes a much larger area than the Gulf Coast region. Therefore, even the most dramatic changes noted at the rarer end of precipitation distributions will have almost no affect on large river discharge and geomorphic processes.

The most probable climate change scenarios will also have little if any affect on forest vegetation occupying this region. The large rivers dissecting this section of the Gulf Coast have broad alluvial valleys. Floods, surface impoundments, and a high water table that have a dominant influence on bottomland vegetation are determined by river processes independent of climate processes near the coast. In contrast to floodplain vegetation, upland species are directly affected by local climate. The most likely climate change scenarios, however, will have little if any ecological impact. Average monthly rainfall for most of the growing season ranges from 120 to 150 mm

(NOAA, 2002). A moderate decrease in growing season precipitation will have no effect on trees because these sites still have an annual soil moisture surplus. Most tree species will only be affected by a dramatic decrease in annual average precipitation, which is unlikely to occur.

Average conditions may not always be the major determinant of vegetation patterns. Regeneration for many trees is highly episodic, and regeneration may be dependent on extreme conditions. For some species, those with a narrow range of conditions necessary for regeneration, unusually favorable conditions such as above average rainfall, may be necessary for regeneration. Conversely, harsh conditions could lead to high mortality rates, particularly among young individuals that are not well established. However, the frequency of extreme events in coming decades is largely unknown.

SUMMARY AND CONCLUSIONS

The historical climate record of the past century, in addition to climate change scenarios, were examined to assess the past and future hydrology of the north-central Gulf Coast of the United States. The historical record of the region shows an annual temperature pattern with high values in the 1920s to 1940s, and a drop in annual temperatures in the late 1950s persisting through the 1970s. Annual temperatures then increased over the past two-plus decades, but still have mostly not reached the highs of previous decades. Annual precipitation depicts a pattern toward increasing annual values, with significant long-term trends in coastal Mississippi and Alabama. There is also a long-term trend of increasing modeled runoff regionwide. To assess future extremes in regional hydroclimatology, the A1B and B1 scenarios were examined for the region. An ensemble of 21 models for each scenario indicates a wide range of possible climates during the mid-21st Century. The models agree to a warmer Gulf Coast region of about 1.5°C ± 1°C. Precipitation projections are mixed, which is common to many mid-latitude regions of the world (Meehl et al., 2007b), with indications of increases or decreases, but the models lean slightly toward reducing annual rainfall in the Gulf Coast. Analysis of hydrological extremes using extreme value statistics suggests that under the global climate change scenarios, monthly precipitation extremes should only change modestly. However, by compounding changing precipitation with increasing temperatures, regional runoff is likely to remain the same or decrease, while deficits (or droughts) are more likely to become less severe due primarily to increases in summer and autumn rainfall. Hence, the historical record shows this region as cooling and getting wetter, whereby the model results suggest warming with less rainfall. Nevertheless, impacts to the natural landscape in this specific region do not appear great, especially if the future regional climate plays out more toward the consensus of GCM guidance. It is likely that more severe impacts from climate change would come with changes in extremes through changes in tropical cyclone frequency and/or intensity, rather than changes in the mean climatology of this region, and we stress that our analysis does not address this area of change, nor that of relative sea level rise. Very high subsidence rates over the past 50 years in parts of this region (Morton et al., 2005), combined with eustatic sea level rise, and land-loss issues would likely be more complicating to the transportation sector and the built infrastructure than regional change in the hydroclimatology under this global climate change scenario. We are also limiting our analysis to mid-term changes, while longer-term changes might intensify the effects of uncurbed greenhouse gas emissions.

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