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THEMATIC ISSUE

Standardized precipitation evaporation index (SPEI)-based drought assessment in semi-arid south Texas

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Abstract The coastal semi-arid region of south Texas is known for its erratic climate that fluctuates between long periods of drought and extremely wet hurricane-induced storms. The standard precipitation index (SPI) and the standard precipitation evaporation index (SPEI) were used in this study in conjunction with precipitation and temperature projections from two general circulation models (GCMs), namely, the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM) and the UK Meteorological Office Hadley Centre model (HCM) for two emission scenarios—A1B ($\sim$720 ppm CO_2 stabilization) and B1 ($\sim$550 ppm CO_2 stabilization) at six major urban centers of south Texas spanning five climatic zones. Both the models predict a progressively increasing aridity of the region throughout the twenty-first century. The SPI exhibits greater variability in the available moisture during the first half of the twenty-first century while the SPEI depicts a downward trend caused by increasing temperature. However, droughts during the latter half of the twenty-first century are due to both increasing temperature and decreasing precipitation. These results suggest that droughts during the first half of the twenty-first century are likely caused by meteorological demands (temperature or potential evapotranspiration (PET) controlled), while those during the latter half are likely to be more critical as they curtail moisture supply to the region over large periods of time (precipitation and PET controlled). The drought effects are more pronounced for the A1B scenario than the B1 scenario and while spatial patterns are not always consistent, the effects are generally felt more strongly in the hinterlands than in coastal areas. The projected increased warming of the region, along with potential decreases in precipitation, points toward increased reliance on groundwater resources which are noted to be a buffer against droughts. However, there is a need for human adaptation to climate change, a greater commitment to groundwater conservation and development of large-scale regional aquifer storage and recovery (ASR) facilities that are capable of long-term storage in order to sustain groundwater availability. Groundwater resource managers and planners must confront the possibility of an increased potential for prolonged (multi-year) droughts and develop innovative strategies that effectively integrate water augmentation technologies and conservation-oriented policies to ensure the sustainability of aquifer resources well into the next century.

Keywords Climate change · Evapotranspiration · Global warming · Thornthwaite method · Downscaling · Global circulation model

Introduction

Water is vital for the sustainable development of the semi-arid region of coastal south Texas. Unfortunately, the climate of this region has been described as marginal and even problematic (Norwine and John 2007). The rainfall in the region varies spatially with higher precipitation in the northeastern sections of the area and more arid conditions in the west. The region is also heavily influenced by the Gulf of Mexico and the associated hurricane activity. As depicted in Fig. 1, five (Edwards Plateau, South Central, Upper Coast, Southern and Lower Valley) of the ten climatic regimes of Texas can be encountered in south Texas

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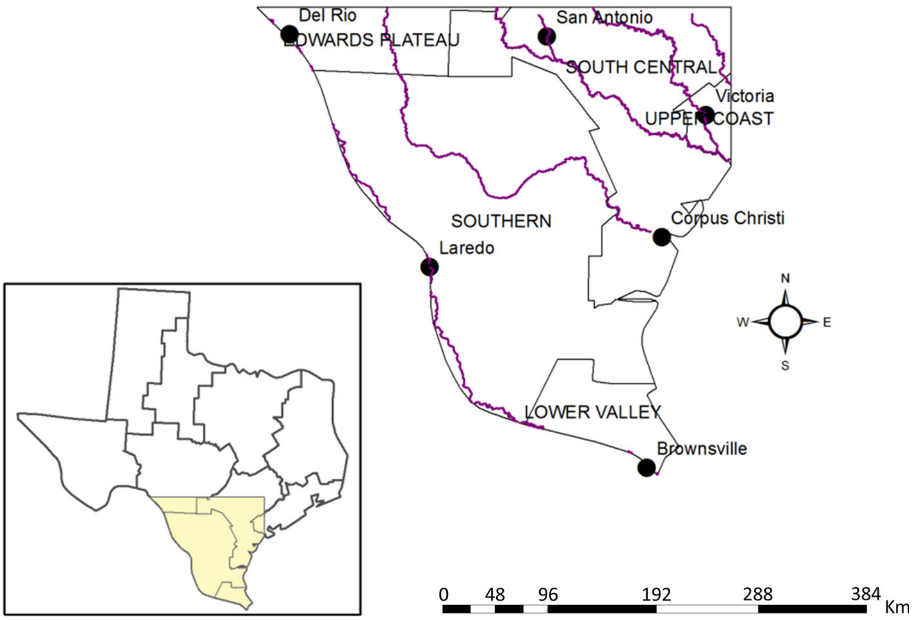


Fig. 1 Study area depicting major cities and climate zones

(Larkin and Bomar 1983). The high spatio-temporal variability of rainfall, temperature and other hydroclimatic variables underscore the considerable influence of climate variability on regional water resources availability.

The major surface water bodies in the area include the Rio Grande River, the Nueces River, the San Antonio River, the Guadalupe River and their tributaries. The surface water sources are largely managed according to the doctrine of “prior appropriation”, except for the Rio Grande River whose waters are adjudicated by a water master. These entire river systems originate (or enter) the study area in the west and flow eastward discharging into the Gulf of Mexico. Most major urban centers, with the exception of San Antonio, currently rely on surface water resources to meet their municipal and industrial needs (TWDB 2012). In spite of that, only 2 % of the study area consists of perennial surface water bodies. Groundwater is therefore an important source of water in south Texas (Uddameri 2005). Aquifers respond more slowly to changing climatic conditions and, as such, provide a buffer against droughts (Tsur 1990). Therefore, many urban centers in south Texas already have backup groundwater supplies or are seriously pursuing developing groundwater reserves. In fact, the city of Brownsville has constructed a 9.46 ML/day (2.5 MGD) desalination facility to use its existing groundwater resources. Also, the city of Corpus Christi has established an aquifer storage and recovery district to develop strategies for storing surplus water in the underlying aquifer for use during periods of drought (TWDB 2012).

Prediction of the nature and occurrence of droughts is important during the regional water planning process. In the context of groundwater planning, increased use of this resource should be anticipated and appropriately factored in during periods of drought. Groundwater resources in Texas are often locally managed by publicly elected political sub-divisions, referred to as groundwater conservation districts (GCDs). In addition, neighboring GCDs are grouped into 16 groundwater management areas (GMAs). Groundwater management areas engage in joint aquifer planning activities to establish desired future conditions (DFCs), which in turn are used to determine modeled available groundwater (MAG). Desired future conditions are verbal statements that define the acceptable state of the aquifer at the end of a planning horizon. The state of the aquifer can be defined using hydraulic heads (drawdowns) or water fluxes. Typically, the average drawdown over a groundwater conservation district (or some other convenient geographic entity) is chosen to represent the state of the aquifer. Regional groundwater flow models, referred to as groundwater availability models (GAMs) are then used to develop numeric estimates of groundwater production that will satisfy the adopted DFCs. In other words, regional groundwater flow models are run backwards to estimate the amount of groundwater production that is possible while maintaining the desired future conditions established as part of the joint planning process.

The state of the aquifer (i.e., drawdowns and groundwater fluxes) is not only affected by anthropogenic pumping, but also by natural climatic variability. As discussed previously, the anthropogenic demands on groundwater resources are also dependent on climatic conditions. In particular, temperature and precipitation affect recharge and groundwater evapotranspiration rates. It is estimated that recharge amounts are typically less than 1 % of the total annual precipitation in south Texas (Uddameri and

Kuchanur 2007). In addition, streamflows are also affected by climatic influences. Unfortunately, however, groundwater modeling carried out during the first round of the GMA joint planning process in south Texas (i.e., GMA 15 and GMA 16) assumed constant values for these inputs. Therefore, implicitly these model runs assumed intransient climatic conditions within the 2000–2060 planning horizon (Hutchison 2010). The assumption of time-invariant climatic conditions is clearly unrealistic for a marginal climatic region like south Texas, which is known to experience extreme climatic fluctuations ranging from hurricanes to periods of extreme drought. However, plausible temporal patterns for periods of drought and wetness must be ascertained if temporal climatic variability is to be included within the joint planning process. Based on results from a suite of general circulation models, Norwine and John (2007) conclude that while the annual precipitation volume is likely to remain unchanged, there is likely to be greater variability in storm events with a greater incidence of high-intensity storms and longer periods of drought. Furthermore, the temperature in the region is expected to increase by up to 4 °C by the end of the century. These conditions further emphasize the need for incorporating meteorological drought patterns into the regional-scale groundwater planning process in south Texas. The overall goal of this study, therefore, is to evaluate future drought patterns in south Texas and facilitate the inclusion of such information and understanding in regional-scale groundwater resources planning. More specifically, the study integrates information downscaled from general circulation models with the recently proposed multi-scalar standardized precipitation evapotranspiration drought index (Vicente-Serrano et al. 2010) that is suited for assessing droughts under conditions of global warming.

Methodology

The standard precipitation index (SPI) developed by McKee et al. (1993) is a widely used drought monitoring index and offers advantages of consistency and ease of interpretation (Guttman 1999). The SPI uses only precipitation data and can be computed at multiple time-scales. For example, the National Oceanic and Atmospheric Administration (NOAA) computes the 1, 2, 3, 6, 12 and 24 months SPI to monitor short, medium and long-term droughts in the continental United States. SPI offers several advantages and disadvantages such as it uses only one input (precipitation). As such, it only focuses on the input side of the water balance (i.e., precipitation) and does not account for changes in evapotranspiration. Vicente-Serrano et al. (2010) developed a new drought index called the standardized precipitation evapotranspiration index (SPEI) to overcome this limitation while retaining the multi-scalar advantage of SPI. As the SPEI considers both the gain and loss elements of the meteorological water budget, it is comparable to the self-calibrated Palmer Drought Severity Index (scPDSI). Vicente-Serrano et al. (2012) compared the performance of several drought indices for ecological, agricultural and hydrologic studies and concluded that SPEI was the best index to capture the effects of summer droughts. Being standardized measures, both SPI and SPEI can be compared across geographic locations with markedly different climates.

The calculation of the SPI is a two-step process. A time-series of cumulative precipitation at a given station over a period of time (e.g., last month, last 12 months) is compiled from observed or projected monthly precipitation data. These data are fitted to an appropriate probability distribution function. The two-parameter gamma distribution is commonly used for this purpose based on the recommendation by Thom (1968); however, the Pearson III (also referred to as the 3 parameter gamma) distribution is also noted to be suitable for fitting the precipitation data (Guttman 1999). The fitted distribution is used to calculate the cumulative probability density function for any given precipitation amount. This cumulative distribution is transformed to a standard normal distribution with a zero mean and standard deviation (SD) of unity which is the value of SPI. The transformation to the standard normal distribution is equiprobable in that the probability of being less than or equal to a given value of a variate (i.e., cumulative precipitation) is the same for the transformed variable (SPI) as well. Therefore, SPI retains the statistical characteristics of the rainfall at the station, but facilitates comparison across sites because all SPI values have the same mean of zero and SD of unity. Conceptually, SPI compares the total cumulative precipitation at a given station for a given period of time with historical average cumulative precipitation over the length of the dataset. As SPI values are based on the standard normal distribution, 95 % of the values range between ±3 (i.e., 3 SD). Negative values of SPI indicate dry periods while positive values indicate wet periods where precipitation is higher than the historical average. SPI values between ±0.99 are generally considered normal (as 68 % of the data fall within these ranges). SPI values between -1.00 and -1.99 represent extremely dry conditions and those exceeding -2.00 represent severely dry conditions. A similar scaling is adopted to describe wet conditions using the positive values of SPI.

The SPEI index is constructed in a similar manner as SPI. However, the calculations are carried out using the difference between monthly (or weekly) precipitation and potential evapotranspiration data (referred to as moisture deficit, D). This difference represents a simple meteorological water balance. The monthly difference data are aggregated over an assumed time-period (e.g., last month, last 6 months) and fit to a probability distribution function. It is important to recognize that the difference between precipitation and evapotranspiration (i.e., moisture deficit) can be negative and is commonly so in semi-arid and arid regions. Therefore, a three-parameter distribution is needed to model the deficit values. Vicente-Serrano et al. (2010) indicated that while several three-parameter distributions can be reasonable choices, the log-logistic distribution is recommended as it seems to fit the extreme values better. The fitted cumulative probability density function is transformed to the standard normal distribution, which is also the SPEI. Positive values of SPEI indicate above average moisture conditions while negative values indicate below normal (drier) conditions. The same linguistic scale used for categorizing SPI values can be used for SPEI as well. The SPEI compares the moisture deficit for a given time-period at a station to the historical average of the cumulative moisture deficit. The calculation of SPEI requires one more parameter (i.e., potential evapotranspiration or PET) than SPI. However, PET values have to be obtained indirectly from other measured meteorological variables. The method proposed by Thornthwaite (1948) is particularly advantageous in this regard as it requires only the monthly mean temperature and the latitude of the location of interest.

Data compilation

Downscaled data from general circulation models (GCMs) provide predictions of future climate at specified geographic locations. Wood et al. (2004) have developed the bias-corrected statistical downscaling (BCSD) approach that has been particularly useful in hydrologic impact studies (Maurer 2007). Building on this success, high-resolution ($1/8^{\circ} \times 1/8^{\circ}$ or $\sim 140\ \text{km}^2$) BCSD datasets for precipitation and average monthly temperature have been developed for the conterminous United States using outputs from several GCMs and for three different emission scenarios (Maurer and Hidalgo 2007). This dataset has proved valuable for studying environmental and hydrologic impacts of climate change in California and other western states (Hayhoe et al. 2004; USBR 2011). Similarly downscaled data have been used to develop time-series of drought indicators to assess patterns of wet and dry hydroclimatic regimes in many other arid and semi-arid parts of the world that have hydro-meteorological characteristics similar to south Texas (e.g., Ghosh and Mujumdar 2007; Mishra and Singh 2011). Two climate models, the low-sensitivity parallel climate model (PCM) described by Washington et al. (2000) and the medium-sensitivity UK Met Office Hadley Centre Model Version 3 (HCM) described by Gordon et al. (2000), were selected following Hayhoe et al. (2004). Downscaled monthly data corresponding to two emission scenarios, namely, A1B and B1 discussed in the Special Report on Emission Scenarios (IPCC 2000) were used in this study. Both A1B and B1 emphasize a rapidly growing world whose population will increase to 9 million by 2050 and then slowly decline. While the A1B scenario emphasizes a balance among all energy sources, it is relatively more aggressive in fossil fuel use (i.e., 720 ppm CO_2 stabilization level) than the B1 scenario which assumes economic growth will be largely focused on service-oriented economies (550 ppm CO_2 stabilization level).

Monthly precipitation and average temperature were obtained from the “Bias Corrected and Downscaled WCRP CMIP3 Climate Projections” archive (available online at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections) for the time-period of 1950–2099. For the purpose of this study, the time-period between the years 1950–2099 was divided into three periods. The earliest years 1950–1999 are referred to as the “*historical*” period. The time-frame between the years 2000 and 2049 is referred to as “*early*” as it refers to the early part of the twenty-first century; and the time-frame between the years 2050–2099 is referred to as “*late*” to reference the latter part of the twenty-first century. The differences in precipitation and temperature estimates due to different scenarios occurs only in the twenty-first century predictions for the Hadley Climate Centre model, which provides the same predictions for the period 1950–1999 across both scenarios. Six urban centers within the South Texas region, namely, (1) Del Rio, (2) Laredo, (3) Brownsville, (4) Corpus Christi, (5) Victoria and (6) San Antonio located in five different climatic zones were selected as representative locations for analysis (Fig. 1). Del Rio and San Antonio are underlain by the Edwards aquifer; and Laredo is underlain by the Carrizo Wilcox aquifer while Brownsville, Corpus Christi and Victoria sit over the Gulf Coast aquifer. The long-term (12 months) SPI and SPEI were computed in this study. These indices for this time-period seek to capture the impacts on livestock, urban demands and most agricultural crops and as such focus on a wide range of hydrologic conditions encountered during groundwater planning. All necessary calculations were carried out using the SPEI package and other standard statistical tools available in the R statistical software environment (R Development Core Team 2008).

Results

Trends in monthly precipitation and temperature levels

The seasonal Mann–Kendall test (Hirsch and Slack 1984) was performed to detect the presence of monotonic trends

Table 1 Results of the seasonal Mann–Kendall test at various stations for various time-periods

	PCM A1B	PCM B1	HCM A1B	HCM B1
Precipitation				
Historical	Upward	–	–	–
Early	–	–	–	–
Late	Downward	Downward	–	–
Temperature				
Historical	–	Upward	–	–
Early	Upward	Upward	Upward	Upward
Late	Upward	Upward	Upward	Upward

Upward or downward indicates statistically significant trends at $p < 0.10$

in GCM downscaled precipitation and temperature datasets. The general trends were the same at all stations and are summarized in Table 1. As can be seen, there is a clear upward trend in temperature in the first and second half of the twenty-first century that is consistently being predicted by both the models across both scenarios. In addition, the PCM model predicts a decreasing trend in precipitation in the latter part of the twenty-first century. Most locations in South Texas are known to have experienced an increased annual rate of precipitation as well as temperatures (Norwine and John 2007) over the last part of the twentieth century, which the selected models are unable to capture, except for the PCM A1B and PCM B1 runs, respectively. Therefore, the PCM model is probably better in predicting the historical trends observed in the region. Nevertheless, both the models are consistent in their predictions of the precipitation and temperature during the first half of the twenty-first century. During this period, water deficits are likely caused by an increase in temperature more than decreases in precipitation. However, the models diverge in their predictions for the latter part of the twenty-first century, where the PCM model predicts both an increased temperature as well as decreases in precipitation as compared to the HCM model. Therefore, while the choice of the GCM model is unlikely to be of importance for medium-term (50 year) planning horizons, the use of the PCM is likely more conservative for long term (50–100 year) planning exercises.

SPEI and SPI drought indices

The SPI and SPEI drought indices are shown in Figs. 2 and 3, respectively, for the City of San Antonio, TX, over the 150-year study period (1950–2099). Similar graphs were constructed for the remaining five cities but are not included here in the interest of brevity. No trends could be visually ascertained in the estimated SPI for any of the stations. However, the index tends to become more variable (i.e., increased fluctuations) in the latter half of the twenty-first century. In contrast, the SPEI shows a marked downward trend over the 150-year study period. In particular, the SPEI values tend to become more negative during the twenty-first century. The intra-decadal variability of the SPEI appears to be less for the A1B scenario than the B1 scenario, which indicates a greater variability in the data despite an evident downward trend. These results are consistent with the seasonal Mann–Kendall trend analysis, which indicates an increasing temperature trend which, in turn, translates to greater potential evapotranspiration (PET) over the entire twenty-first century. These results indicate that the SPEI is a more conservative indicator of droughts than the SPI in South Texas as the latter does not account for moisture deficits arising from increasing temperature (global warming).

The fraction of time classified under each moisture availability category is summarized in Tables 2 and 3 for SPEI and SPI, respectively. The results from each scenario were relatively similar and as such were aggregated and averaged to produce the results in these tables. The results again indicate that the moisture availability is mostly centered around the historical mean values (±1SD) for at least 50 % of the time-period. However, the SPEI indicate progressive drying throughout the twenty-first century. Brownsville, Corpus Christi and Del Rio are historically drier than Laredo, Victoria and San Antonio and this spatial pattern will continue in the early part of the twenty-first century. However, Laredo, Victoria and San Antonio will be relatively drier during the later part of the twenty-first century. These trend reversals from historical time largely arise due to projected increases in temperature throughout the twenty-first century.

The results of the SPI, summarized in Table 3, also indicate a progressive drying throughout the twenty-first century. Nonetheless, at least 60 % of the time the moisture availability will be close to normal (i.e., ±1SD from the historical average). Furthermore, the shifts in moisture availability are not projected to change drastically during the first half of the twenty-first century. In contrast to the SPEI, the fraction of wet or very wet periods does not decrease as dramatically during the twenty-first century although the wet periods change from ~16 % during the first half of the twenty-first century to ~13 % during the latter half of the twenty-first century. From a spatial standpoint, Corpus Christi, San Antonio and Victoria will experience drier climates than Laredo, Del Rio and Brownsville (the Rio Grande corridor).

The maximum run or the length of the time-period over which a state of moisture will occur is another important variable to ascertain the length of the drought (or wet period) and is particularly significant for water resources

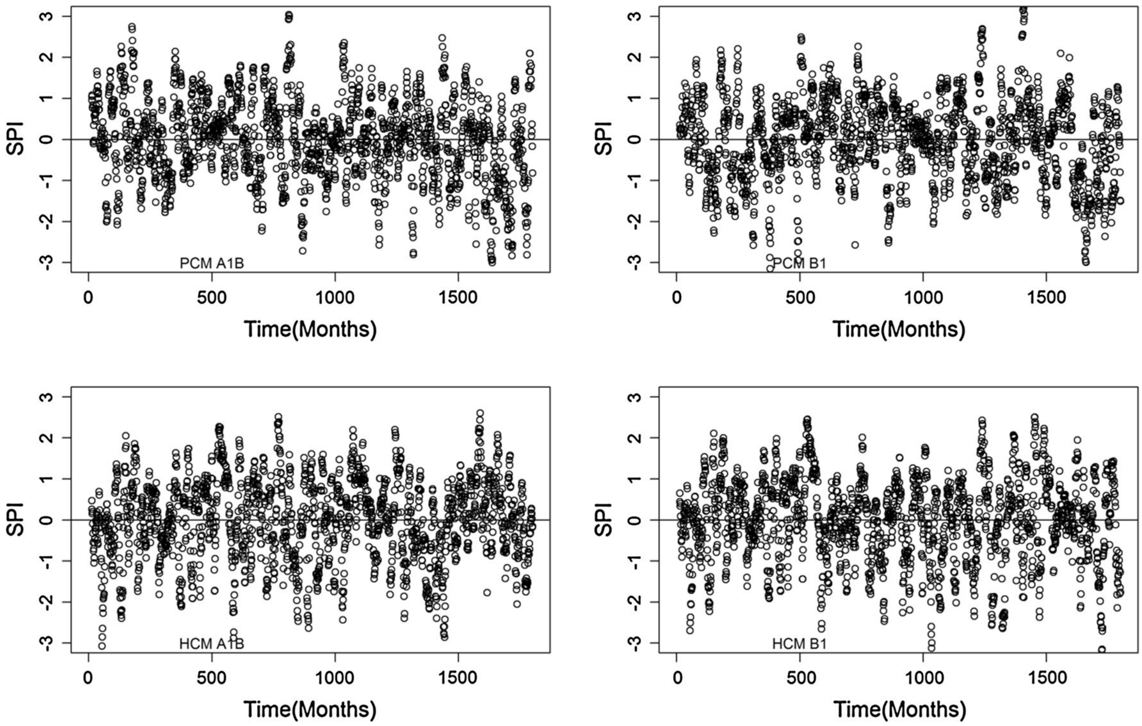


Fig. 2 12-Month standard precipitation index (SPI) for the city of San Antonio, TX, during 1950–2099

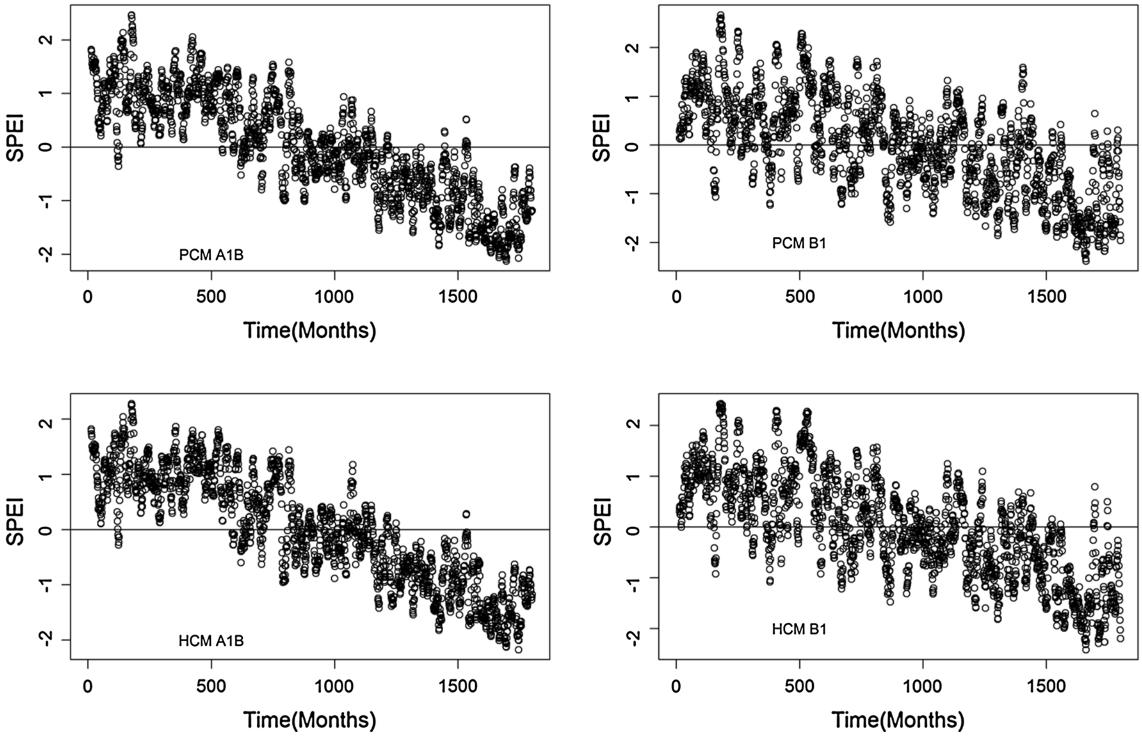


Fig. 3 12-Month standard precipitation evapotranspiration index (SPEI) for San Antonio, TX, over the period 1950–2099

planning. The maximum run length corresponding to each GCM model run and emission scenario was therefore determined for early and late time-periods of the twenty-first century for both SPI and SPEI. The run lengths for early and late twenty-first century are depicted in Figs. 4 and 5, respectively, for the SPEI.

Table 2 Fraction of time-period (%) under each SPEI drought index category

	Category	Brownsville	Corpus Christi	Del Rio	Laredo	San Antonio	Victoria
Historical time-period (1950–1999)	Ext. dry	0.0	0.0	0.0	0.0	0.0	0.0
	Dry	1.6	1.6	1.3	0.1	0.2	0.3
	Normal	50.0	50.0	49.8	51.0	53.7	53.1
	Wet	45.9	46.0	46.5	45.7	41.8	42.4
	Ext. wet	2.4	2.4	2.4	3.3	4.2	4.3
Early twenty-first century (2000–2049)	Ext. dry	0.0	0.0	0.1	0.0	0.0	0.0
	Dry	8.1	8.1	8.3	5.1	4.4	3.3
	Normal	83.3	83.3	84.0	88.0	86.8	87.6
	Wet	8.5	8.5	7.5	6.9	8.8	9.0
	Ext. wet	0.1	0.1	0.1	0.0	0.0	0.1
Late twenty-first century (2050–2099)	Ext. dry	2.63	2.54	3.13	2.58	2.50	3.00
	Dry	44.38	44.46	43.75	47.33	47.29	48.38
	Normal	52.67	52.67	52.92	49.75	49.83	48.21
	Wet	0.33	0.33	0.21	0.33	0.38	0.42
	Ext. wet	0.00	0.00	0.00	0.00	0.00	0.00

Table 3 Fraction of time-period (%) classified under each SPI drought index

	Category	Brownsville	Corpus Christi	Del Rio	Laredo	San Antonio	Victoria
Historical time-period (1950–1999)	Ext. dry	1.0	1.6	1.4	1.7	2.2	1.7
	Dry	11.2	11.3	11.2	11.7	11.0	11.8
	Normal	71.6	70.2	67.3	69.6	69.6	70.2
	Wet	15.1	16.3	17.8	16.3	15.4	14.7
	Ext. wet	1.1	0.6	2.2	0.8	1.8	1.5
Early twenty-first century (2000–2049)	Ext. dry	2.1	1.3	2.0	1.7	2.0	1.9
	Dry	11.8	13.7	12.1	12.9	13.4	13.5
	Normal	67.3	67.1	72.8	68.7	69.7	68.0
	Wet	15.9	15.2	11.3	13.8	13.8	15.2
	Ext. wet	2.9	2.7	1.8	3.0	1.0	1.4
Late twenty-first century (2050–2099)	ext. dry	3.21	4.25	3.76	3.59	4.18	4.26
	Dry	15.14	16.97	16.76	16.53	16.67	16.07
	Normal	68.10	64.49	64.67	65.69	63.85	66.28
	Wet	10.80	11.46	12.46	11.77	12.95	10.89
	Ext. wet	2.75	2.83	2.34	2.42	2.34	2.50

The graphed results indicate that for most of the early twenty-first century, normal conditions (i.e., ±1SD) are likely to persist for longer periods of time than extreme conditions (Fig. 4). The persistence of "dry" or "wet" conditions is likely to be no longer than a few months and not likely to exceed one year. In addition, the length of "wet" periods is likely to be slightly longer than that of "dry" periods. These conditions tend to be fairly uniform across South Texas. However, the second half of the twenty-first century is likely to see a greater persistence of droughts. "Very dry" conditions are likely to persist for approximately a year or so while the milder "dry" conditions can persist for several years. In general, the A1B scenario projects greater runs of "dry" periods than the B1 scenario for the models considered. Corpus Christi and Victoria, along the coast, as well as San Antonio and Laredo are projected to see longer dry periods than Brownsville and Del Rio though multi-year droughts in these areas cannot be ruled out.

The maximum run lengths for various moisture categories in the early part of the twenty-first century for the SPI are presented in Fig. 6. The results shown here are similar to those obtained using the SPEI in the normal category (i.e., ±1SD); however, the maximum run length is about 5 times shorter indicating a much greater variability in moisture availability. From a spatial standpoint, the run

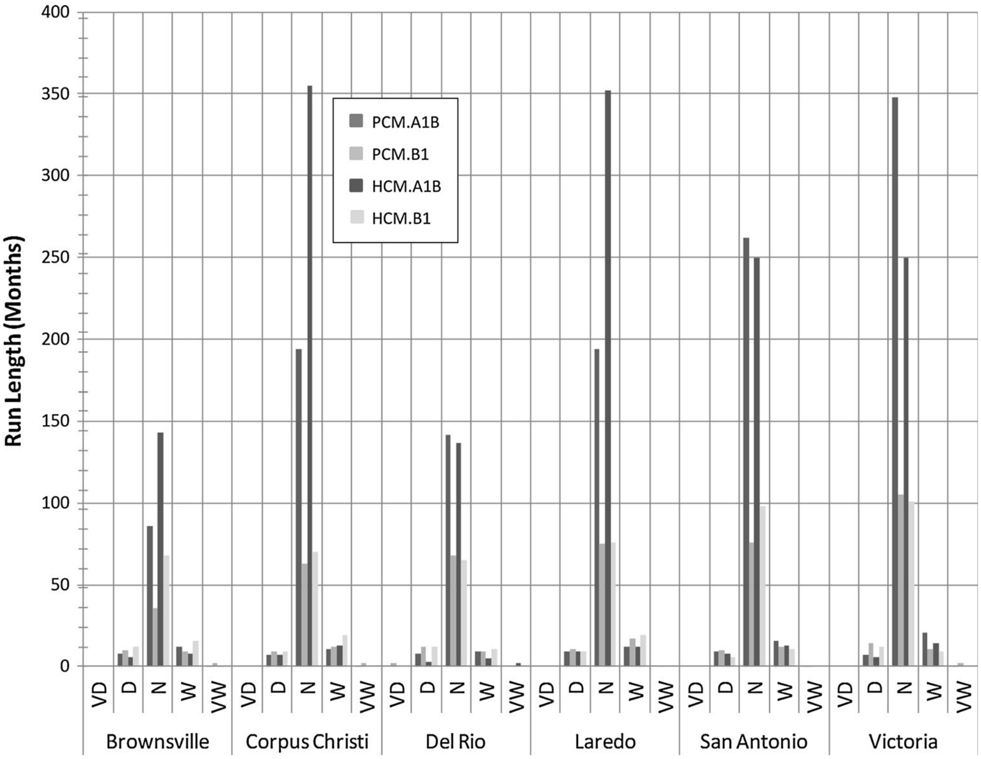


Fig. 4 Maximum run lengths for the SPEI for the early twenty-first century. *VD* very dry, *D* dry, *N* normal, *W* wet, *VW* very wet

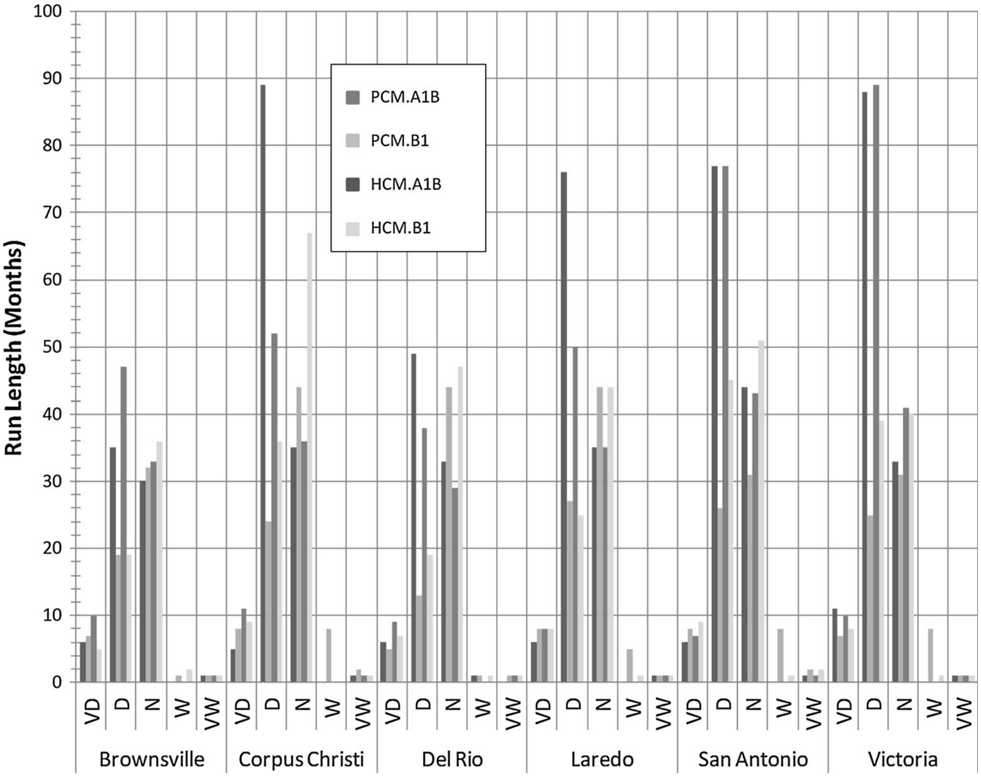


Fig. 5 Maximum run lengths for the SPEI for the late twenty-first century. *VD* very dry, *D* dry, *N* normal, *W* wet, *VW* very wet

lengths for "very dry" are considerably higher for Brownsville while longer lengths of normal moisture availability are forecasted for San Antonio and Victoria. The "very wet" conditions are more likely to be of longer duration than "very dry" conditions. However, the "dry" moisture condition is more likely of longer duration than the "wet" condition for most locations in South Texas during the early part of the twenty-first century.

Fig. 6 Maximum run length for SPI for the early twenty-first century. *VD* very dry, *D* dry, *N* normal, *W* wet, *VW* very wet

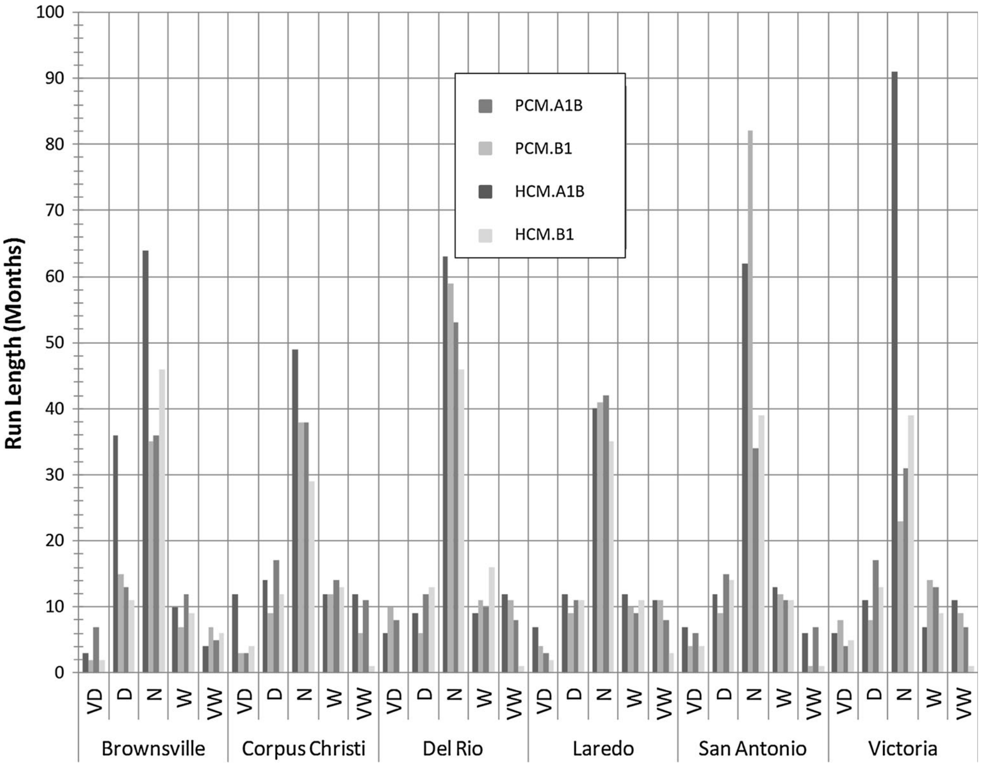
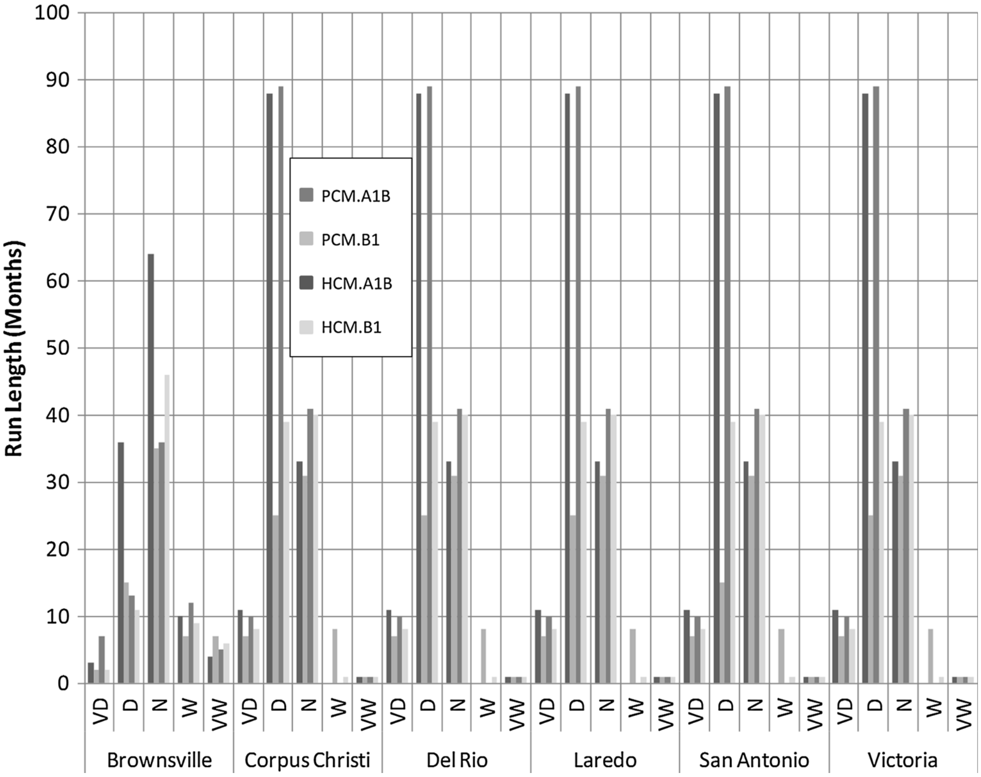


Fig. 7 Maximum run length for SPI for the late twenty-first century. *VD* very dry, *D* dry, *N* normal, *W* wet, *VW* very wet



The maximum run lengths for each SPI category during the second half of the twenty-first century are depicted in Fig. 7. While the maximum run lengths for normal periods are fairly long (~40 months), longer periods of droughts ranging from 5 to 8 years are projected. In contrast, the periods of "wet" and "very wet" (i.e., moisture surplus) are fairly short and typically less than a year. Once again, the projections of SPI have similar trends as those of the

SPEI (Fig. 5). From a spatial standpoint, drier periods are less pronounced in Brownsville possibly due to hurricane-induced effects than the rest of South Texas. The A1B emission scenario predicts a relatively drier regime than the B1 emission scenario.

Summary and conclusions

Climate change and implications on groundwater resources management in the twenty-first century

The SPEI and SPI provide an insight into the natural stresses on regional water budgets that are likely to be experienced during the twenty-first century. While the SPI focuses solely on the precipitation, SPEI aims to account for both precipitation and potential evapotranspiration (PET). Precipitation has a direct impact on the recharge of the aquifers. The impact of PET on groundwater systems is indirect and considerably more complex. PET is a measure of evaporation from water bodies such as lakes and is seen to represent the maximum possible use by plants when sufficient moisture is available. Plants tend to adapt to moisture deficits by reducing their transpiration rates by closing their stomata (Eagleson 1978) and the actual evapotranspiration rate (AET) is often lower than the PET. The evaporation from water bodies is also affected by decreases in radiative energy due to particulates and cloud cover (i.e., global dimming phenomena) as well as decreases in advective energy due to increased moisture in the atmosphere for instance due to precipitation (Brutsaert and Parlange 1998). As such, it is important to recognize that the available data from GCMs only allow us to include evaporation effects in a cursory fashion.

As discussed previously, the occurrence of a drought, in general, places an increased stress on groundwater resources. Human adaptation is necessary to combat droughts and sustain groundwater resources for future generations. Many groundwater conservation districts (GCDs) in South Texas have put forth drought contingency plans that call for proportional curtailment from various water user groups. Nonetheless, these plans have not been tested under the persistent multi-year droughts that are projected to occur by the SPEI and SPI, particularly during the later part of the twenty-first century. The droughts during the first half of the twenty-first century are projected to be caused by increasing temperature (i.e., demand side droughts). Human adaptations for droughts caused by stresses on the demand side are relatively easier to tackle than those caused by supply-side deficits, which require significant commitment to improve water use efficiencies and practice conservation-oriented measures to reduce the use of groundwater in the long run. The prognosis of worsening drought conditions during the latter half of the twenty-first century implies that conservation of groundwater resources during the first half of the century is vital to sustain this resource into the next century.

The increased warming conditions projected over the twenty-first century along with increased fluctuations between wet and dry periods also points toward the increased use of aquifers for storage of water. Aquifer storage and recovery (ASR) systems are advantageous over conventional surface water storage as they are not subject to evaporative losses which will tend to increase with increased warming of the atmosphere (Uddameri 2007). The more drastic drought conditions predicted during the latter half of the twenty-first century caused by decreased precipitation and increased temperature indicate the need for large, regional-scale ASR facilities, which can store significant amounts of water possibly over several decades. Being a coastal region, South Texas is endowed with significant brackish and seawater resources, which offer another source of water for the future. However, exploitation of these resources requires identification of energy sources (preferably non-fossil fuel based) and technologies for waste (concentrate) disposal.

The South Texas region is often referred to as the “last great habitat” (Fulbright and Bryant 2002) and bays and estuaries in this region are unique ecosystems that contribute significantly to the economy of the region. Many of these bays and estuaries are dependent on groundwater inflows for regulating salinity (Uddameri et al. 2013). As such, while brackish groundwater desalination offers promise as a future water resource, its development must be planned carefully. In conclusion, the projected climate change over the twenty-first century highlights the growing importance of groundwater resources and an increased role for aquifer storage and recovery efforts. Groundwater resource managers and planners must confront the possibility of prolonged (multi-year) droughts and think of integrated use of technologies and conservation-oriented policies to ensure the sustainability of aquifer resources into the next century.

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