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The role of temperature in drought projections over North America

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Abstract The effects of future temperature and hence evapotranspiration increases on drought risk over North America, based on ten current (1970–1999) and ten corresponding future (2040–2069) Regional Climate Model (RCM) simulations from the North American Regional Climate Change Assessment Program, are presented in this study. The ten pairs of simulations considered in this study are based on six RCMs and four driving Atmosphere Ocean Coupled Global Climate Models. The effects of temperature and evapotranspiration on drought risks are assessed by comparing characteristics of drought events identified on the basis of Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspration Index (SPEI). The former index uses only precipitation, while the latter uses the difference (DIF) between precipitation and potential evapotranspiration (PET) as input variables. As short- and long-term droughts impact various sectors differently, multi-scale (ranging from 1- to 12-month) drought events are considered. The projected increase in mean temperature by more than 2 °C in the future period compared to the current period for most parts of North America results in large increases in PET and decreases in DIF for the future period, especially for low latitude regions of North America. These changes result in large increases in future drought risks for most parts of the USA and southern Canada. Though similar results are obtained with SPI, the projected increases in the drought characteristics such as severity and duration and the spatial extent of regions susceptible to drought risks in the future are considerably larger in the case of SPEI-based analysis. Both approaches suggest that long-term and extreme drought events are affected more by the future increases in temperature and PET than short-term and moderate drought events, particularly over the high drought risk regions of North America.

1 Introduction

Drought impacts many sectors of society such as agriculture, forestry, and human health (Vicente-Serrano et al. 2010; Wilhite 2010; Dai 2011; Santos et al. 2011; Zarch et al 2011) and

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it also creates major environmental hazards such as lake and wetland loss, soil degradation, and ecological habitat demolition (e.g. Wilhite 2010; Mishra and Singh 2010). Drought related damages are estimated to be of the order of \$6–8 billion per year on average in the USA (FEMA 1995). In general, the main cause of drought is below-normal precipitation and/or above-normal temperature and evapotranspiration.

According to the fourth and fifth assessment reports of the Intergovernmental Panel on Climate Change (IPCC), mean annual precipitation is projected to increase over Canada and the northeast USA, while decreases are projected for the southwest USA during this century (Christensen et al. 2007; Collins et al. 2013; IPCC 2013). Seasonally, precipitation is projected to increase in winter and spring over most parts of North America, while decreases are projected in summer for central and southern North America. Temperature is projected to have larger increases in most areas of North America than the global mean increases during this century. Regionally, the largest increases in temperature are projected in winter for the high latitudes and in summer over southwest regions of North America. Projected increases in global temperature and associated increases in evapotranspiration and decreases in climatic water balance (i.e., difference between precipitation and evapotranspiration) are expected to have a major impact on future droughts (Meehl et al. 2007; Sheffield and Wood 2008; Vicente-Serrano et al. 2010). Based on 17 Atmosphere-Ocean Global Climate Model (AOGCM) simulations, IPCC (2012) suggests increases in the duration and intensity of droughts in central North America. Collins et al. (2013) also suggest widespread drying and droughts across most of southwestern North America by the mid to late 21st century.

The AOGCMs are the main tools used to study projected changes to climate variables including surface precipitation and temperature for different greenhouse gas emission scenarios. The resolution of AOGCMs is often not sufficient for regional impact and adaptation studies and therefore Regional Climate Models (RCMs), because of their increased resolution, are often preferred. The North American Regional Climate Change Assessment Program (NARCCAP) is a multi-RCM experiment over North America aimed at producing high-resolution climate information for regional impacts research and to provide the ensembles required to estimate various uncertainties. The six RCMs that participated in the NARCCAP were driven by a set of AOGCMs at a spatial resolution of 50 km over a North American domain covering the USA and Canada (Mearns et al. 2012). These RCMs were selected to provide a variety of model physics and/or to include those models that have performed multiyear climate change experiments (Mearns et al. 2012). Though several AOGCM-based studies (e.g. Sheffield and Wood 2008; Strzepek et al. 2010; Dai 2011) of future drought conditions are available over North America, detailed regional scale drought projections based on multi-RCMs are not yet available.

Different definitions of droughts are possible based on meteorological, agricultural, hydrological and economical viewpoints (Dai 2011). Classification of droughts based on their duration into short- and long-term events is useful, since their impacts on various sectors vary considerably. For example, short-term droughts can affect surface layer soil water content, reservoir storage and agricultural productivity, while long-term droughts affect groundwater storage, agricultural species and wildlife habitat (e.g. Vicente-Serrano et al. 2010). In this study, two meteorological drought indices, the Standardized Precipitation Index (SPI) (McKee et al. 1993) and the Standardized Precipitation Evapotranspration Index (SPEI) (Vicente-Serrano et al. 2010), based respectively on precipitation and the difference between precipitation and potential evapotranspiration (PET) (hereafter DIF), are used. Both the SPI and SPEI can be applied to detect droughts of different timescales. Many previous studies (e.g. Strzepek et al. 2010; Vicente-Serrano et al. 2010; Wilhite 2010; Dai 2011) have reported significant impacts of temperature and evapotranspiration on drought conditions. The main goal of this study is to identify the role of temperature and hence evapotranspiration on drought severity in future climate over North America by comparing SPI- and SPEI-based analyses and projections of high-resolution RCMs, which have not been attempted earlier. As the SPEI method considers the role of temperature also, it could explain the variability in reservoir storage, ground water level, crop species, and vegetation mortality better than the SPI.

2 Data and methods

We calculate SPI and SPEI for four different timescales (i.e., 1-, 3-, 6- and 12-month), for the current (1970–1999) and future (2040–2069) climates, based on precipitation and temperature series simulated by ten RCM-AOGCM combinations from six RCMs and four AOGCMs (see Table 1). The future RCM simulations correspond to the A2 scenario from the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000). Overall, this scenario is at the higher end of the SRES emissions scenarios.

One-month SPI (i.e., SPI1) uses monthly total precipitation series, while 3-, 6- and 12-month SPIs (i.e., SPI3, SPI6 and SPI12) use respectively 3-, 6- and 12-month cumulative precipitation series constructed from monthly total precipitation amounts. Calculation procedures of current and future period SPEI for different timescales (i.e., SPEI1, SPEI3, SPEI6 and SPEI12) are the same as those of SPI except for the input variable. The SPEI values are calculated using the DIF series instead of just precipitation series. The DIF represents the

Table 1 The RCM-AOGCM pairs from the NARCCAP considered in the study and details of the RCMs and AOGCMs

RCM\AOGCM	CCSM3	CGCM3	GFDL	HadCM3
CRCM	X	X		
ECP2			X	
HRM3			X	X
MM5I	X			
RCM3		X	X	
WRFG	X	X		

Details of the RCMs/AOGCMs

CRCM	Canadian RCM (Caya and Laprise 1999)
ECP2	Updated Experimental Climate Prediction Center's version of the Regional Spectral Model (Juang et al. 1997)
HRM3	Third-generation Hadley Center RCM (Jones et al. 2003)
MM5I	Fifth-generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model run by the Iowa State University modeling group (Grell et al. 1993)
RCM3	Abdus Salam International Center for Theoretical Physics RCM version 3 (Pal et al. 2007)
WRFG	Weather Research Forecasting model with the Grell scheme (Grell and Devenyi 2002)
CCSM3	Community Climate System Model, version 3 of the National Center for Atmospheric Research (NCAR) (Collins et al. 2006)
CGCM3	Coupled General Circulation Model version 3 of the Canadian Center for Climate Modelling and Analysis (CCCma) (Flato 2005)
GFDL	Geophysical Fluid Dynamics Laboratory climate model version 2.1 (GFDM GAMDT 2004)
HadCM3	Hadley Centre Coupled Model version 3 (Gordon et al. 2000; Pope et al. 2000)

difference between precipitation P and potential evapotranspiration PET. For a given month *i*, DIF is calculated by:

$$\mathrm{DIF}_i = \mathrm{P}_i - \mathrm{PET}_i \tag{1}$$

Monthly PET series are estimated by the Hamon method (Hamon 1961), which is one of the simplest methods among many temperature-based PET estimation methods. This method uses relationships between PET and maximum possible incoming radiant energy and the moisture-holding capacity of the air at the air temperature. The Hamon method has been recommended for regional applications in the southeastern (Lu et al. 2005) and the north-central USA (Winter et al. 1995).

To calculate SPI and SPEI series for the current climate, the first step is to determine a probability distribution function which describes various precipitation and DIF series. The gamma distribution for SPI (McKee et al. 1993) and the log-logistic distribution for SPEI (Vicente-Serrano et al. 2010) were originally adapted to model respectively precipitation and DIF series at different timescales. These distributions were not found flexible enough for modelling precipitation and DIF series for the entire study area when assessed on the basis of Kolmogorov–Smirnov goodness-of-fit test (Massey 1951). Therefore, the non-parametric kernel distribution function approach is employed to describe precipitation and DIF series corresponding to four different timescales at more than 10,000 regional grid points of each RCM-AOGCM combination. The kernel distribution function estimator $\widehat{F}_h$ is defined by:

$$\widehat{F}_h(y) = \frac{1}{Nh}\sum_{i=1}^{N} K\left(\frac{y-y_i}{h}\right) \tag{2}$$

where y ($y_1, y_2, \ldots, y_N$) is an identically and independently distributed random variable with record length N, $K()$ is a kernel function and h is the bandwidth. The Gaussian kernel function and an optimal value of h, given by:

$$h \approx 1.06\ \widehat{\sigma}\ N^{-1/5}, \tag{3}$$

are adopted (Parzen 1962; Bowman and Azzalini 1997). In the above relationship, $\widehat{\sigma}$ represents the standard deviation of the variable y. After estimating the kernel distribution function of the precipitation and DIF series corresponding to four different timescales at each grid point, the cumulative probabilities of the precipitation and DIF amounts are calculated. The SPI (SPEI) series are produced by mapping the cumulative probabilities of precipitation (DIF) series onto the standard normal (i.e. Gaussian) distribution function at each regional grid point of each RCM-AOGCM combination. For calculating SPI and SPEI series for the future climate, the cumulative probabilities of the future precipitation series are calculated from the estimated kernel distribution function of the current climate at the same grid point of the same RCM-AOGCM combination. Although not considered in this analysis, a bias correction approach can also be used for the current and future precipitation and temperature series of each RCM-AOGCM combination. This approach could generate statistically consistent baselines and bias corrected projections of future SPI and SPEI series of each RCM-AOGCM combination. However, the influence of biases of each RCM-AOGCM might be modest on the SPI and SPEI series as they represent standardized values obtained based on the distributions of precipitation and DIF series at each grid point.

Theoretically, the means of the SPI and SPEI series are zero in current climate. A drought condition is realized when the value of the SPI or SPEI is negative. In this study, the duration of a drought event (D) is taken as the continuous period with negative SPI or SPEI value. The drought severity (S) over the duration D is defined as (Santos et al. 2011; Mishra and Singh 2010):

$$S = -\sum_{i}^{D} \mathrm{SPI}_i \quad \text{or} \quad S = -\sum_{i}^{D} \mathrm{SPEI}_i \tag{4}$$

In other words, drought severity represents accumulated values of SPI or SPEI and reflects a cumulative moisture deficiency over the drought duration.

3 Results

Figure 1 shows ensemble averaged annual mean precipitation, temperature, PET and DIF for the current climate. The 10 RCM-AOGCM combinations reproduce reasonably well the spatial patterns of precipitation and temperature over North America. The spatial pattern of PET is similar to that of temperature. Projected changes to the annual, summer and winter values of the above four climatic variables are also shown in the same figure. The ensemble average suggests decreases in future precipitation in summer for most parts of central and southern North America and in winter for few parts of southwest North America, while increases in precipitation are noted in summer over Canada and in winter for most parts of North America. Consequently, the ensemble average suggests decreases in future annual precipitation for southwest North America, but increases for other parts of North America. The projections suggest larger increases in temperature in summer over the USA, while larger increases in winter are noted over the Canadian high latitude regions. Consequently, the ensemble projects larger increases in PET in summer in future climate for the lower latitude than for the higher latitude regions of North America, which is also visible in the changes to DIF values at the annual timescale. The projections suggest larger decreases in future values of annual DIF for most parts of the USA and southern parts of Canada due to the large increases in future PET. A general decrease in the future values of DIF in summer is observed for most regions of North America.

Projected changes to the 30-year mean values of SPI and SPEI are presented in Fig. 2, where negative values imply possibility of higher drought risk in future climate. Zonally averaged values of the projected changes to the 30-year mean SPI and SPEI values are also presented in this figure. Though the north eastern USA and southern Canada show decrease in drought risks from the SPI-based analysis for both short- and long-term timescales, the SPEI-based analysis suggests increase in drought risks for these regions associated with future increases in temperature and PET. Therefore, increases in future drought risk are expected for these regions on the basis of SPEI-based analysis, due to increases in temperature and PET, despite the small increase in future precipitation. Overall, SPEI-based projections suggest increase in drought risks for regions below 50°N latitude (Fig. 2d). According to the SPEI-based results, changes to long-term (12-month) droughts are larger than those for short-term (1-, 3- and 6-month) droughts for regions below 50°N latitude.

Projected changes of the 10 RCM-AOGCM combinations to the 30-year mean values of SPI6 and SPEI6 are presented in Fig. 3. The ten combinations, albeit some differences, broadly agree on the changes for the future means of SPI6 and SPEI6. More than 8 RCM-AOGCMs generally suggest negative changes for the southwest USA for mean SPI6, and also for most of the USA and southern Canadian Prairies for mean SPEI6. Weaker model agreements are

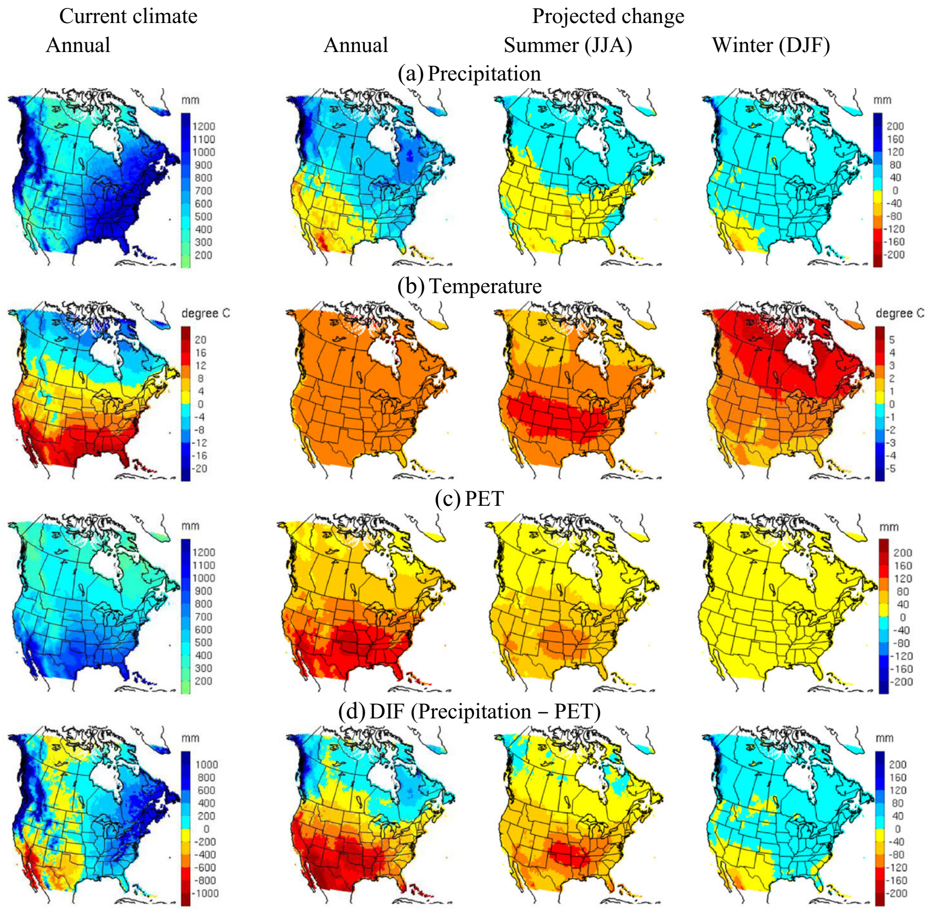

Fig. 1 Ensemble averaged annual mean **a** precipitation, **b** temperature, **c** potential evapotranspiration and **d** DIF for the current (1970–1999) climate (column 1). Projected changes to the mean annual (second column), summer (third column) and winter (fourth column) precipitation, temperature, PET and DIF are also provided

observed for the northwestern and southeastern USA for SPI6 and most of southern Canada (except the southern Canadian Prairies) for SPEI6.

Ensemble averaged projected changes to the standard deviation (SD) of SPI and SPEI series calculated at each grid point are presented in Fig. 4. Increases in SD of both SPI and SPEI series are projected over most regions of North America. This result implies that the future SPI and SPEI series are generally associated with larger temporal variability compared to the current period. Basically, the increases in SD of future precipitation and DIF (results are not shown) are the reasons for the increases in SD of the future SPI and SPEI series. The increase in future temporal variability of the SPI and SPEI series can result in increased likelihood of extreme droughts in future because the severity and frequency of extreme events are considerably affected by the variability. Future SPI and SPEI values of longer timescales are associated with larger increases in the SD than those of shorter timescales. Specifically at lower latitude regions, long-term SPEI values are projected to have larger increases in the SD.

Zonally averaged values of the projected changes to the 30-year mean values of SPI and SPEI for the 10 RCM-AOGCM simulations are presented in Fig. 5. Although the ten

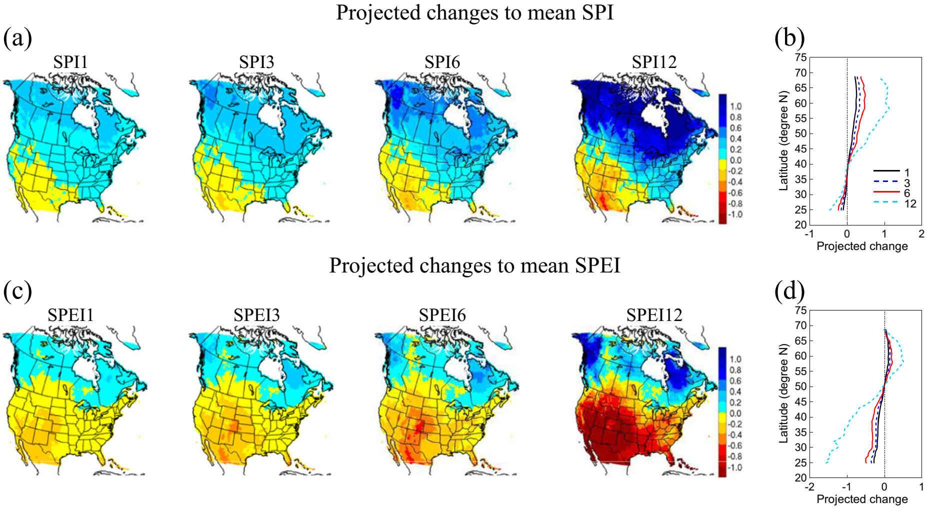

Fig. 2 Ensemble averaged projected changes to the 30-year mean values of **a** SPI and **c** SPEI series for the future 2040–2069 period with respect to the current 1970–1999 period. Zonally averaged values of projected changes to mean **b** SPI and **d** SPEI series are also shown

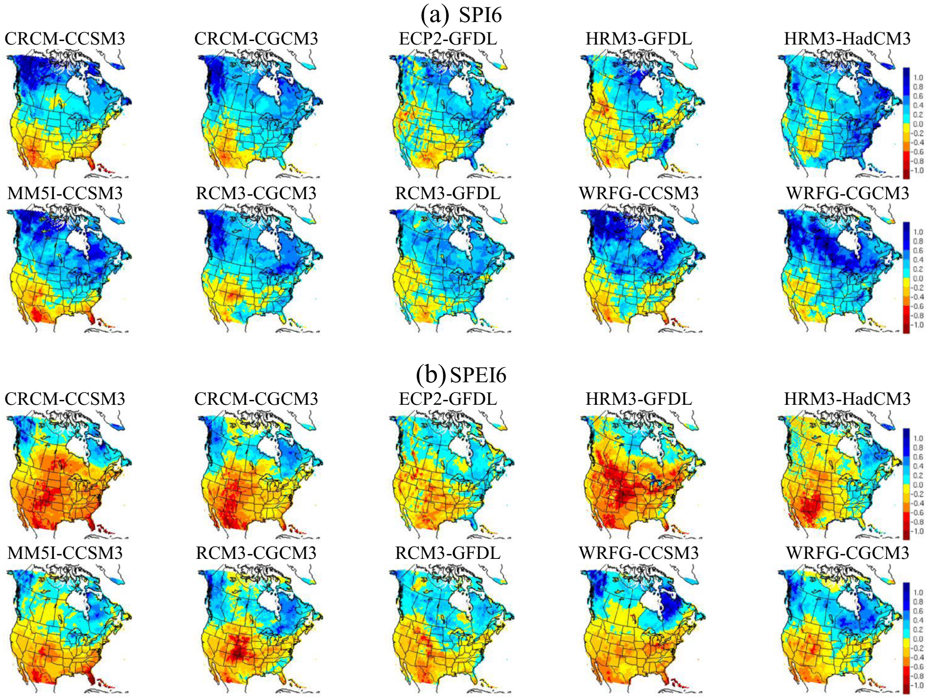

Fig. 3 Projected changes to the 30-year mean values of the **a** SPI6 and **b** SPEI6 series for the future 2040–2069 period with respect to the current 1970–1999 period

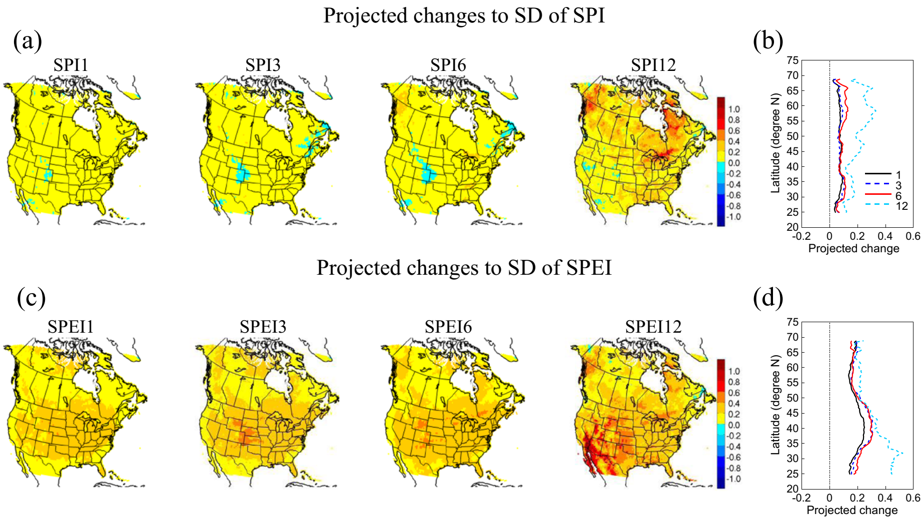

Fig. 4 Ensemble averaged projected changes to standard deviations (SDs) of **a** SPI and **c** SPEI series corresponding to various timescales. Zonally averaged values of the project changes to SDs of **b** SPI and **d** SPEI series are also presented

projections differ in magnitude and sometimes in sign at certain latitudes, the overall pattern appears similar. Among the ten model combinations, CRCM-CCSM3 projects the largest decrease in the mean value of future SPEI series for the low latitude regions. The range of the

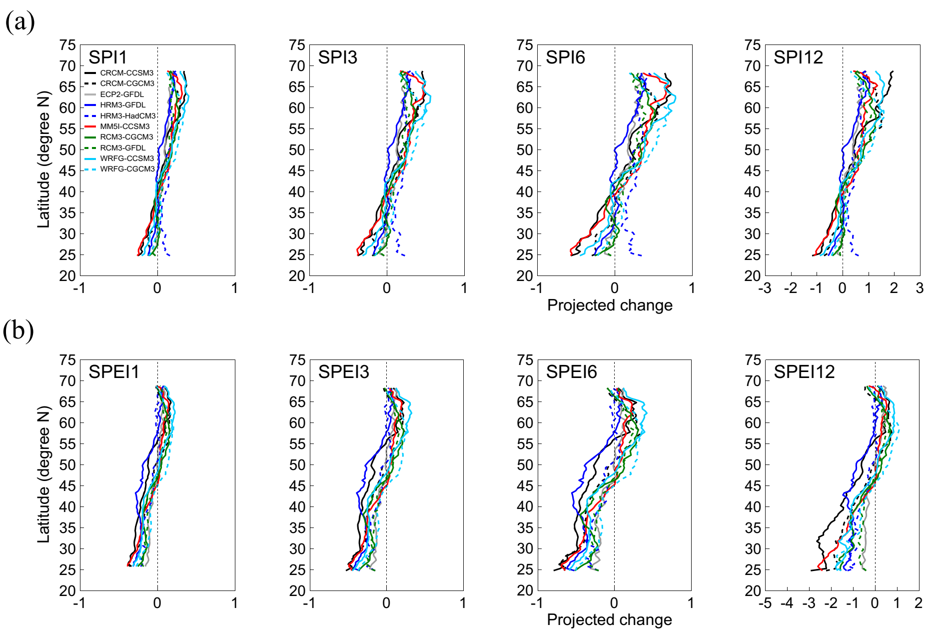

Fig. 5 Zonally averaged projected changes to mean values of **a** SPI and **b** SPEI series corresponding to various timescales for the 10 RCM-AOGCM combinations presented in Table 1

projected changes among the ten model combinations is larger in the case of SPEI than SPI, which also increases as the timescale of SPI and SPEI increases from 1- to 12-month. Especially, the ten model combinations suggest large range of the projected change for the case of long-term (12-month) SPEI at low latitudes.

Cumulative severity of all drought events and the 90th percentile severity (assumed as an indicator of extreme drought) for the future and current climates are calculated at each grid point for each of the 10 RCM-AOGCM combinations. The ensemble averaged projected changes to the cumulative severity and the 90th percentile severity are presented in Fig. 6. To estimate a reliable value of the 90th percentile, a sufficient number of drought events is necessary. For the SPI12 case, grid points located in the northern part of North America generally have fewer number of drought events compared to the grid points located in the other regions due to large increases in the values of future SPI12 associated with higher precipitation

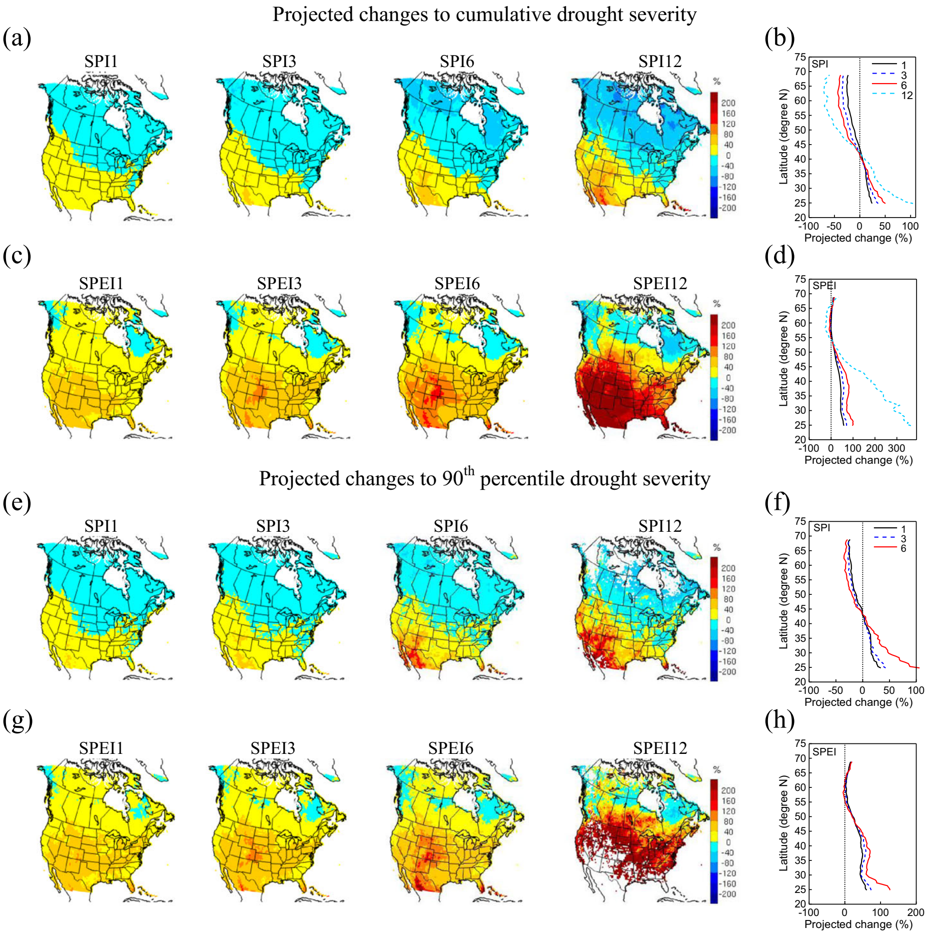

Fig. 6 Ensemble averaged projected changes to SPI- and SPEI-based [**a** and **c**] cumulative drought severity and [**e** and **g**] the 90th percentile drought severity. The 90th percentile severity for the SPI12 and SPEI12 cases are not provided for those grid points where the future number of drought events is less than 6 in any RCM-AOGCM combination. Zonally averaged values of the cumulative drought severity and the 90th percentile drought severity are also presented in (**b**), (**d**), (**f**) and (**h**), except for the 90th percentile drought severity for the SPI12 and SPEI12

in future climate. On the contrary, for the future SPEI12, grid points located in the southwestern part of North America have fewer number of drought events due to large decrease in the values of future SPEI12 associated with small values of DIF (precipitation) in future climate. Therefore, the 90th percentile values are not shown for those grid points with less than six drought events in future in Fig. 6. Consequently, the zonally averaged values of the 90th percentile drought severity for the SPI12 and SPEI12 are also not provided in Fig. 6. The spatial patterns of projected changes to the two characteristics of drought events presented in Fig. 6 are similar to those of the mean values of SPI and SPEI presented in Fig. 2, with increases in cumulative drought severity for the low latitude regions in future climate. Comparison of the SPI- and SPEI-based results indicates that the future increases of temperature (and PET) significantly affect future cumulative drought severity over the entire North American domain. Specifically, the southwestern USA is projected to experience large increases in cumulative drought severity due to decreases in precipitation and increases in temperature and PET, while the rest of the USA and southern Canada will have increased cumulative drought severity mainly based on increases in temperature and PET. Roughly, projections indicate that the regions below 42.5°N (54.5°N) latitude according to the SPI-based (SPEI-based) analysis will have increased future drought severity. The high drought risk areas according to the SPEI-based analysis broadly coincide with previous studies conducted with soil moisture and the Palmer Drought Severity Index (PDSI) using outputs from AOGCMs for the entire globe (Sheffield and Wood 2008; Dai 2011).

Droughts of longer timescale are affected much more than those associated with droughts of shorter timescale due to increases in temperature and PET, especially in the low latitude regions. In Fig. 6, increases in future cumulative and the 90th percentile severity based on long-term SPEI values are much larger (more than 100 %) than those based on the short-term SPEI values at the low latitude regions. Generally, RCM-AOGMs suggest increases in SD of future monthly precipitation. This is also reflected in the cumulative precipitation values of short- and long-term timescales. However, the temporal variability is relatively higher for longer timescales. Due to this reason and due to increased potential evapotraspiration (as a result of increased temperature) in future, the future DIF and SPEI series exhibit larger temporal variability compared to that of current period. The relative increase in the temporal variability is much larger for the case of long-term timescale than the short-term timescale. This also causes large variations in the magnitude of drought duration and severity for longer timescales compared to short timescales. It is also obvious from Fig. 6 that future extreme droughts are affected more than moderate droughts.

Figure 7 presents zonally averaged values of the projected changes to the SPI- and SPEI-based cumulative and the 90th percentile drought severities for the 10 RCM-AOGCM combinations. The results of the cumulative and the 90th percentile severities are generally similar to those of the mean values of SPI and SPEI series presented in Fig. 5. Among the 10 RCM-AOGCM model combinations, CRCM-CCSM3 and MM5I-CCSM3 project larger decrease in the SPEI-based cumulative and the 90th percentile severities in future for the low latitude regions.

The ensemble averaged projected changes to the cumulative drought duration and the 90th percentile drought duration are presented in Fig. 8. These results of drought duration are generally similar to those of cumulative severity presented in Fig. 6, though the percentage increases in future drought duration are smaller than those of future drought severity at the low latitude regions. Increases in future cumulative number of drought months and the 90th percentile drought duration are much larger for the case of long-term SPEI than the short-term SPEI for the low latitude regions. It is also observed that the future extreme drought duration is affected more than moderate duration of drought events from the future increases in

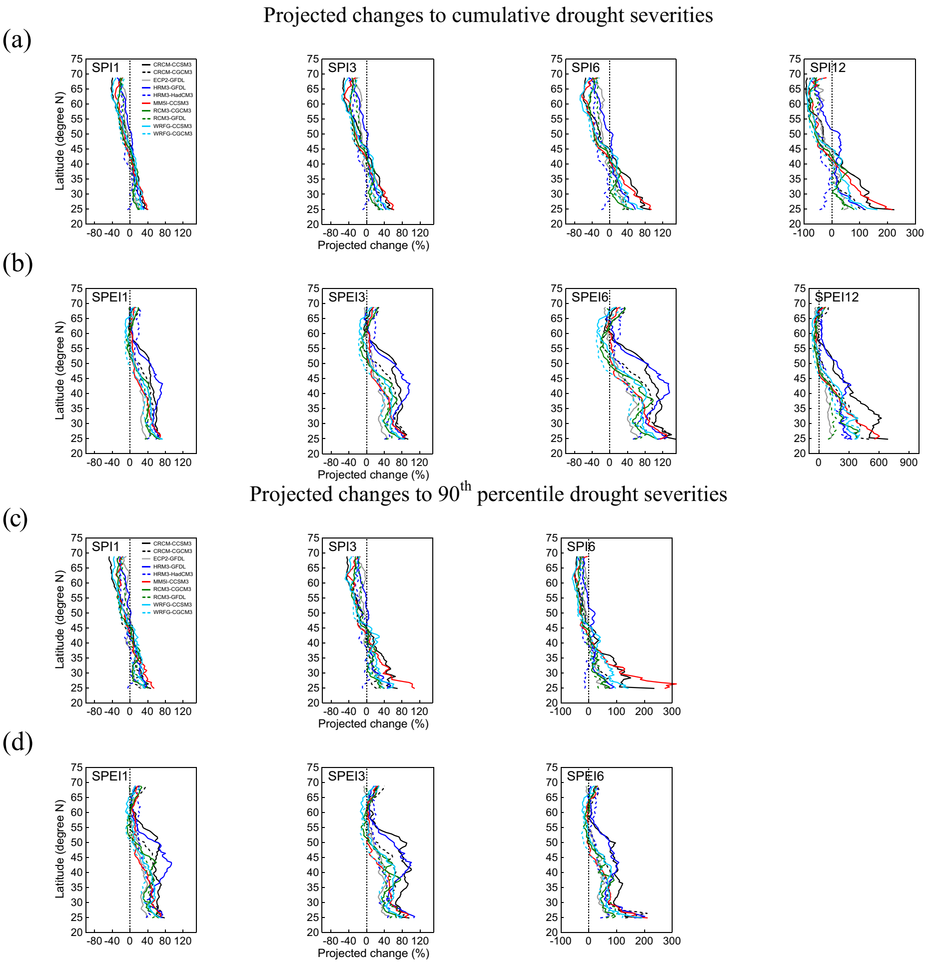

Fig. 7 Zonally averaged projected changes to SPI- and SPEI-based [**a** and **b**] cumulative drought severity and [**c** and **d**] the 90th percentile drought severity for the 10 RCM-AOGCM combinations. Zonally averaged values of the 90th percentile drought severity for the SPI12 and SPEI12 are not provided

PET. SPI- and SPEI-based 90th percentile drought durations usually show larger increases than those of the cumulative number of drought months in future in drought risk areas.

4 Discussion and conclusions

This study aimed at assessing the impact of future temperature and evapotranspiration increase on drought risks over North America. To assess this effect, two drought indices, i.e. SPI and SPEI based respectively on precipitation and DIF (difference between precipitation and potential evapotranspiration), are considered. Compared to the previous studies on this subject, an exclusive feature of the present study is that it provides information on impacts of future temperature rises on both drought severity and duration at different timescales for the entire North America using outputs of high-resolution RCMs.

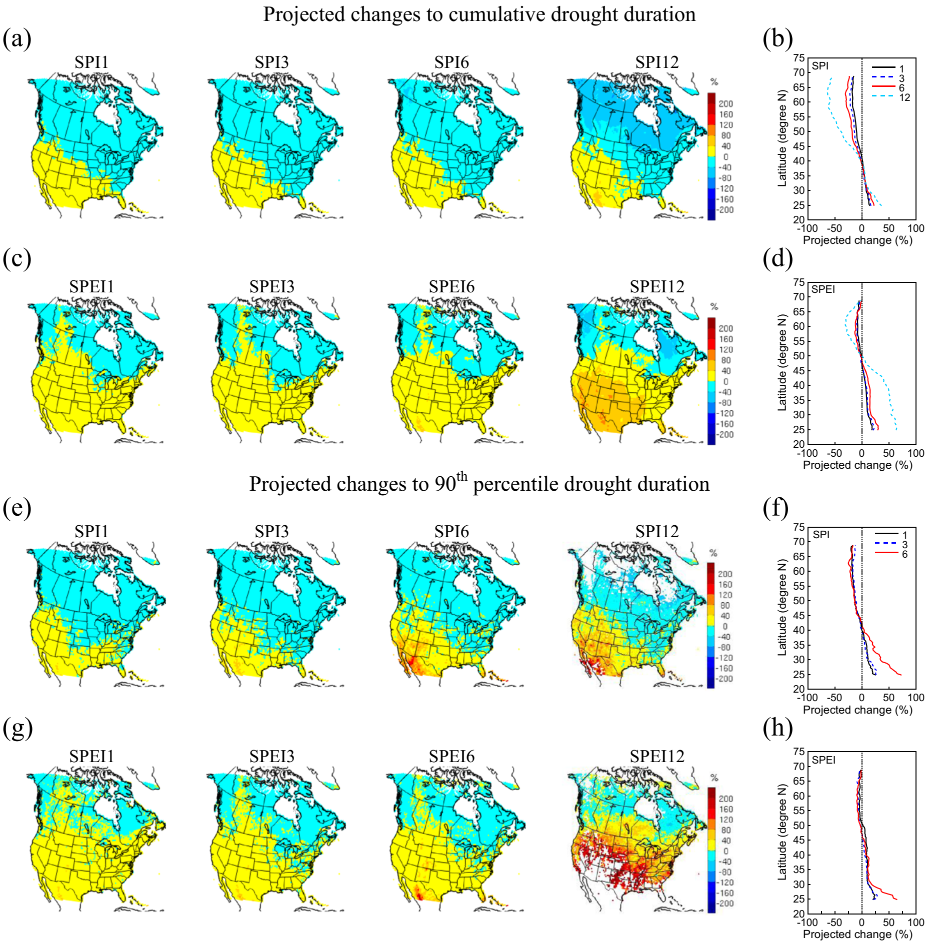

Fig. 8 Ensemble averaged projected changes to SPI- and SPEI-based [**a** and **c**] cumulative drought duration and [**e** and **g**] the 90th percentile drought duration. The 90th percentile drought duration for the SPI12 and SPEI12 are not provided at those grid points where the future SPI12 and SPEI12 of any RCM-AOGCM combination produce less than 6 drought events. Zonally averaged values of projected changes to the cumulative drought duration and the 90th percentile drought duration are also presented in (**b**), (**d**), (**f**) and (**h**), except for the 90th percentile drought duration for the SPI12 and SPEI12

The results of the study suggest that future increases of temperature and PET significantly affect future droughts over USA and southern Canada. According to the SPI-based analysis, southwestern USA is projected to experience large increases in drought risks in future due to decreases in precipitation. The drought risks are even higher for this region according to the SPEI-based analysis which also considers the effects of rising temperature and evapotranspiration explicitly. According to the SPEI-based analysis, regions that will experience increased drought risks, i.e. increased drought severity and duration, are more widespread covering almost the entire USA and southern Canada. Similar differences between projections of drought risk areas over USA in future climate based on precipitation- and temperature-based indices were also demonstrated by Strzepek et al. (2010), who compared the SPI12 and PDSI indices calculated from 22 AOGCM simulations for three SRES emissions scenarios. It is worth noting though that future drought risk areas over North America projected on the basis of soil-moisture outputs of AOGCMs are less clear. For instance, Trnka et al. (2013) reported that soil-moisture dryness of the USA Central Plains projected by AOGCM outputs were uncertain and dependent on the selected AOGCMs, while Hoerling et al. (2012) suggest decreases in soil-moisture over the USA Great Plains, and modest changes over other areas of North America during the twenty-first century, using the CCSM version 4 (CCSM4).

Both SPI and SPEI methods suggest that long-term and extreme drought events will be affected more than short-term and moderate drought events from the future increases in temperature and PET, particularly over the high drought risk regions of North America. While increases in the severity and duration of short-term droughts during the growing season can reduce surface soil moisture that can impact agricultural productivity (Heim 2002), increases in severity and duration of long-term droughts can severely impact water resources and environmental sectors, as it reduces deep soil moisture, groundwater level, and reservoir storage. Though more detailed studies of the potential impacts of droughts on agriculture, water, and environmental sectors are necessary, this analysis highlights regions that may require adaptation responses to drought impacts in these sectors.

The differences in drought risk projections, derived on the basis of the two indices used in this study, highlight the need to consider proper indices and related climate parameters in the investigation of future changes to drought characteristics. However, it is important to note that the estimates of SPEI used in this study are based on a simplified PET estimation method that does not consider the impacts of other variables such as humidity, wind speed, soil and vegetation characteristics. Sheffield et al. (2012) showed that a simplified temperature-based method of PET overestimates drought risks detected on the basis of PDSI over the past 60 years (1950 to 2009). Hoerling et al. (2012) also showed that the meteorological drought index PDSI with a simplified temperature-based PET estimation method can overstate projected changes of surface water imbalances in the twenty-first century. Therefore, future research should investigate the uncertainty associated with temperature-based drought risks assessed using simplified PET estimation methods.

Though the model uncertainty is considered by using 10 RCM-AOGCM combinations, the assessment is limited to only North America and the SRES A2 emission scenario. A more comprehensive evaluation of drought risk would involve RCMs driven by a much broader set of AOGCMs than the four considered in this study.

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References

Bowman AW, Azzalini A (1997) Applied smoothing techniques for data analysis. Oxford University Press, London

Caya D, Laprise R (1999) A semi-implicit semi-Lagrangian regional climate model: The Canadian RCM. Mon Weather Rev 127:341–341

Christensen JH, Hewitson B, Busuioc A et al (2007) Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Collins WD et al (2006) The Community Climate System Model version 3 (CCSM3). J Clim 19:2122–2143

Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichefet T, Friedlingstein P, Gao X, Gutowski WJ, Johns T, Krinner G, Shongwe M, Tebaldi C, Weaver AJ, Wehner M (2013) Long-term Climate Change: Projections, Commitments and Irreversibility. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Dai A (2011) Drought under global warming: a review. WIREs Clim Chang 2:45–65

FEMA (1995) National mitigation strategy: partnerships for building safer communities. Federal Emergency Management Agency, Washington, DC

Flato GM (2005) The Third Generation Coupled Global Climate Model (CGCM3). Available online from http://www.ec.gc.ca/ccmac-cccma/default.asp?n=1299529F-1

GFDL GAMDT (The GFDL Global Model Development Team) (2004) The new GFDL global atmospheric and land model AM2-LM2: evaluation with prescribed SST simulations. J Clim 17:4641–4673

Gordon C et al (2000) The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim Dyn 16:147–168

Grell GA, Devenyi D (2002) A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. Geophys Res Lett 29:1693–1697

Grell GA, Dudhia J, Stauffer DR (1993) A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-398+1A, 107 pp

Hamon WR (1961) Estimating potential evapotranspiration. J Hydraul Div Proc Am Soc Civil Eng 87:107–120

Heim RR (2002) A review of twentieth-century drought indices used in the United States. Bull Am Meteorol Soc 83:1149–1165

Hoerling MP, Eischeid JK, Quan X-W, Diaz HF, Webb RS, Dole RM, Easterling DR (2012) Is a transition to semipermanent drought conditions imminent in the U.S. Great Plains? J Clim 25:8380–8386

IPCC (2012) In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 582 pp

IPCC (2013) Annex I: Atlas of Global and Regional Climate Projections. In: van Oldenborgh GJ, Collins M, Arblaster J, Christensen JH, Marotzke J, Power SB, Rummukainen M, Zhou T (eds.). In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom

Jones RG, Hassell DC, Hudson D, Wilson SS, Jenkins GJ, Mitchell JFB (2003) Workbook on generating high resolution climate change scenarios using PRECIS. UNDP, 32 pp

Juang H-M, Hong S-Y, Kanamitsu M (1997) The NCEP regional spectral model: an update. Bull Am Meteorol Soc 78:2125–2143

Lu JB, Sun G, McNulty SG, Amatya DM (2005) A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. J Am Water Resour Assoc 41:621–633

Massey FJ (1951) The Kolmogorov-Smirnov test for goodness of fit. J Am Stat Assoc 46:68–78

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology, Anaheim, CA, January 17-23, 1993. American Meteorological Society. Boston, MA, pp. 179–184

Mearns LO et al (2012) The North American regional climate change assessment program: overview of phase I results. Bull Am Meteorol Soc 93:1337–1362

Meehl GA, Stocker TF, Collins WD et al (2007) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol 391:202–216

Nakicenovic N, Alcamo J, Davis G et al (2000) Special report on emission scenarios. Cambridge University Press, Cambridge, 599 pp

Pal JS et al (2007) Regional climate modeling for the developing world: The ICTP RegCM3 and RegCNET. Bull Am Meteorol Soc 88:1395–1409

Parzen E (1962) On estimation of a probability density function and mode. Ann Math Stat 33:1065–1076

Pope VD et al (2000) The impact of new physical parameterizations in the Hadley Centre climate model: HadAM3. Clim Dyn 16:123–146

Santos JF, Portela MM, Pulido-Calvo I (2011) Regional frequency analysis of drought in Portugal. Water Resour Manag 25:3537–3558

Sheffield J, Wood EF (2008) Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim Dyn 31:79–105

Sheffield J, Wood EF, Roderick ML (2012) Little change in global drought over the past 60 years. Nature 491: 435–438

Strzepek K, Yohe G. Neumann J, Boehlert B (2010) Characterizing changes in drought risk for the United States from climate change. Environ Res Lett 5(4). doi: 10.1088/1748-9326/5/4/044012

Trnka M, Kersebaum KC, Eitzinger J, Hayes M, Hlavinka P, Svoboda M, Dubrovský M, Semerádová D, Wardlow B, Pokorný E, Možný M, Wilhite D, Žalud Z (2013) Consequences of climate change for the soil climate in Central Europe and the central plains of the United States. Clim Chang 120:405–418

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim 23:1696–1718

Wilhite DA (2010) Drought as a natural hazard: concepts and definitions (Chapter 1). In: Wilhite DA, Keller AZ (eds) Drought: a global assessment. Hazards and disasters: a series of definitive major works. Routledge Publishers, London

Winter TC, Rosenberry DO, Sturrock AM (1995) Evaluation of 11 equations for determining evaporation for a small lake in the north central United States. Water Resour Res 31(40):983–993

Zarch MAA, Malekinezhad H, Mobin MH, Dastorani MT, Kousari MR (2011) Drought monitoring by Reconnaissance Drought Index (RDI) in Iran. Water Resour Manag 25(13):3485–3504