Seasonal Changes in Water and Energy Balances over the Appalachian Region and Beyond throughout the Twenty-First Century

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ABSTRACT

The Appalachian Mountains serve as a water source for important population centers in the eastern and midwestern United States. Despite this, the effects of climate change on the hydroclimatology of the region have not been thoroughly assessed, and its effects for water resources remain uncertain. In this study, we analyze the effects of climate change in a holistic approach to consider differential changes between atmospheric water supply (precipitation) and atmospheric water demand (potential evapotranspiration). We analyze the absolute and relative changes in both variables, as well as their relation (aridity index) and future projected shifts in their seasonality. Our findings show that precipitation is projected to increase in the northeastern part of the region and decrease in the southwest with a transition zone in the central Appalachians. Potential evapotranspiration increases consistently throughout the twenty-first century at a higher rate than precipitation, increasing the aridity of the region except for some small localized pockets at high elevations. The seasonality of precipitation indicates different shifts across the region related to changes in the dominant synoptic drivers of the region and changes in the seasonal characteristics of the land surface. All changes are exacerbated in the most extreme future climate scenario, highlighting the importance of local to global policies toward a more sustainable water resources development. In addition, we perform a basin-scale assessment on 20 major rivers with headwaters within the “Appalachian Region.” Our basin-scale results enforce the gridded regional results and indicate that, as temperatures continue to increase, lowland areas will rely more heavily on higher-elevation forested headwater catchments for water supply.

1. Introduction

The Appalachian Mountains, as with many mountain regions around the world, receive more precipitation $P$ than their surrounding lowland areas (Viviroli et al. 2007; Marston and Marston 2016). Large cities in the eastern United States such as Washington, D.C.; New York, New York; Charlotte, North Carolina; and Atlanta, Georgia, as well as central U.S. cities such as Pittsburgh, Pennsylvania; Cincinnati, Ohio; Louisville, Kentucky; Memphis, Tennessee; and New Orleans, Louisiana (Brooks et al. 2018), are located in areas drained from the Appalachian Mountains (Pires 2004; Missimer et al. 2014; Acharya et al. 2017). Climate change as a result of global warming, together with population growth and land-cover changes, can jeopardize regional water supplies on which downstream ecosystems, economies, and communities are dependent (Vörösmarty et al. 2000; Haddeland et al. 2014; Schewe et al. 2014). Understanding the hydroclimatology of this region is paramount for addressing water needs across the region east of the Mississippi River. In this study, we characterize the seasonal hydroclimatology that drives land surface hydrology and assess potential changes across the region.

Water availability is closely linked to the amount of water in the land surface, either as storage components (soil moisture, groundwater, surface water, or snow), or as runoff (surface and subsurface flows) (Vörösmarty et al. 2000; Doll et al. 2003; Hanasaki et al. 2008). The water balance describes the process by which water is partitioned across the landscape. According to water balance, the input volume from $P$ is partitioned into evapotranspiration, runoff, and storage (Black 1997; Milly 1994). From the concept of water balance, water available is the remnant of precipitation in the land surface after evapotranspiration has taken place.

Evapotranspiration is dependent on the availability of water and the atmospheric water demand (Budyko 1974; Roderick and Farquhar 2011). The atmospheric water
demand is mainly driven by solar radiation that supplies the energy required to vaporize liquid water (Guo et al. 2017). Other atmospheric variables such as air humidity and wind speed are also important for regulating the atmospheric water demand (Guo et al. 2017). Potential evapotranspiration $E_P$ describes atmospheric water demand as a function of the aforementioned variables in units that are comparable to $P$.

The balance between available water supply and atmospheric water demand is calculated by the ratio between $E_P$ and $P$, known as the aridity index (AI) (Arora 2002; Roderick and Farquhar 2011; Fu and Feng 2014). Ratios between 0 and 1 are particular to regions where precipitation exceeds potential evapotranspiration (energy limited), and values greater than 1 occur when $E_P$ exceeds $P$ (water limited) (Donohue et al. 2012; Roderick and Farquhar 2011; Wang and Hejazi 2011).

In the midlatitudes of the temperate region where the “Appalachian Region” (see section 2) is located, $P$ and $E_P$ are of comparable magnitudes (Weiss and Menzel 2008; Fernandez and Sayama 2015). However, $E_P$ is directly linked to solar radiation and temperature, which are concentrated in the summer months (Coopersmith et al. 2012). Precipitation $P$, on the other hand, is mostly distributed uniformly, throughout the year, with some months having higher amounts (Coopersmith et al. 2012; Sayemuzzaman and Jha 2014). Since there is less energy available for evapotranspiration during the winter months, most of the precipitation during this season becomes available in the land surface as storage or flows through the stream network of the region. During the summer months, there is more energy available and hence, more of the precipitation is partitioned into evapotranspiration and returned back into the atmosphere (Coopersmith et al. 2012).

Precipitation patterns in Appalachia are driven by external large-scale atmospheric phenomena such as tropical and extratropical cyclones, high pressure systems, and convective storms (Leathers et al. 1991; Leathers and Palecki 1992; Pielke and Landsea 1999; Wood et al. 2002) that regulate the timing at which $P$ occurs in the region (Wise et al. 2015; Ning and Bradley 2016). As a result of global warming, some of these drivers will be affected and change over time, further changing the amount and timing of precipitation throughout the year (Holland and Bruyère 2014; Cai et al. 2015; Steinman et al. 2015; Zhang and Delworth 2016). Global warming will most likely enhance $E_P$, by increasing the duration of active $E_P$ into the seasons of spring and autumn (Reyes-Fox et al. 2014; Zhang et al. 2015; Kutta and Hubbart 2016).

The balance between $P$ and $E_P$ will likely change in the future as well as their intra-annual relationships (Arora 2002; Roderick and Farquhar 2011; Fu and Feng 2014).

In this paper, we explore the absolute changes in $P$ and $E_P$ throughout the twenty-first century using a downscaled and bias-corrected dataset (Abatzoglou and Brown 2012) using an ensemble of 17 different climate models. The main objectives of the study are 1) to quantify the absolute changes of precipitation and potential evapotranspiration and their spatial distribution, 2) to quantify the changes in the relation between $P$ and $E_P$ to identify regions where it is likely to become drier or wetter, and 3) to analyze the seasonal changes of $P$ and $E_P$ by introducing a new seasonality index that quantifies not only the intensity of seasonality but also the timing of the year in which different variables peak. These assessments are performed at a gridded scale throughout the region, and for 20 basins the headwaters of which are located within the region.

2. The Appalachian Region

This paper focuses on the Appalachian Region of the United States and basins draining from it. The Appalachian Region is defined by the Appalachian Region Commission (ARC) as 420 counties from 13 states that share cultural and socioeconomic characteristics (Appalachian Regional Commission 2009). The region is rich in natural resources and had prevalent extraction economy. The region is dominated by lagged economic development, high unemployment (Appalachian Regional Commission 2015c), low education (Appalachian Regional Commission 2015a), and low income (Appalachian Regional Commission 2015b), when compared with other regions within the United States.

The region is mostly settled in the complex topography of the Appalachian Mountains, and its geological subregions that are formed by a series of ridgelines and valleys that extend from northern Alabama and Georgia up to the eastern provinces of Canada, although the cultural region reaches only to the southwestern counties of New York (Appalachian Regional Commission 2009). As most mountain eons in the world, the Appalachians receive disproportionate amounts of $P$ in comparison with its underlying lowlands of the eastern Atlantic coast and Mississippi River valley (Viviroli et al. 2007; Marston and Marston 2016). The Appalachians serve as a water tower (Viviroli et al. 2007) to lowlands and contain the headwaters of large river systems, namely the Potomac, the Delaware, the Savannah, and the Chattahoochee–Apalachicola that supply large cities in the eastern coast areas (Pires 2004; Missimer et al. 2014; Acharya et al. 2017). To the west the Appalachians...
supply water through many tributaries of the Mississippi River (Brooks et al. 2018), one of the largest river systems of the world. The water tower effect of the Appalachians is highlighted by supplying the Ohio River, which is the main branch of the Mississippi River by volume, while containing a smaller drainage area than other main branches by length or drainage area (Brooks et al. 2018).

The water supply of large population centers in the East and Midwest are inherently dependent of water from the Appalachians Mountains (Viviroli et al. 2007; Marston and Marston 2016). This makes downstream areas vulnerable to the effects that climate change brings upon them including but not limited to changes in spatial and temporal patterns of precipitation, increases in evaporative energy and changes in extreme events. To assess climatic changes in the Appalachian Region and their potential effects on water resources of dependent lowland areas, this research includes every county that has counties within the ARC definition (Fig. 1, top panel). In addition, we also perform basin-scale assessments in 20 major basins with headwaters within the Appalachian Region (Fig. 1, bottom panel).
3. Data and methods

a. Climate dataset: MACAv2-METDATA

The “MACAv2-METDATA” (Abatzoglou 2013) is a database of downscaled and bias-corrected general circulation model (GCM) outputs from phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) for the continental United States and provides data for two representative concentration pathways (RCPs): RCP4.5, which supposes a shift toward alternate sources of energy by 2050, and RCP8.5, which supposes business as usual. The bias correction and downscaling were performed using the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou and Brown 2012). The method consists of six steps that correct biases at different spatial scales and uses temporal analogs to adjust variable patterns to historical analogs. All GCMs are interpolated to a common grid size of 1° and seasonal and yearly trends are removed before doing a coarse-scale bias correction. The constructed analog component involves finding the 100 best fitted spatial patterns that fit the spatial distribution of a target day on a GCM with the historical data within a 45-day time window. A linear model is then developed using superposition of the best fitted spatial patterns and matrix inversion. The coefficients of the linear model are then applied to the fine-resolution observations and superposed to downscale the GCM patterns. In the final steps of the method, trends are reintroduced to the datasets and biases are corrected again at the fine resolution (1/24°).

The training dataset for the MACAv2-METDATA is the METDATA dataset from Northwestern University (Abatzoglou 2013). The dataset was generated by bias correcting hourly reanalysis data from the North American Data Assimilation System (NLDAS; Cosgrove et al. 2003) and assimilating them to monthly temperature, precipitation, and humidity from the Parameter–Elevation Regressions on Independent Slopes Model (PRISM; Daly et al. 1994). These data have been validated against ground-based weather monitoring networks across the United States (Abatzoglou 2013). The variables provided by the MACAv2-METDATA and used in this study are summarized in Table 1.

b. Estimating potential evapotranspiration from climate model downscaled variables

Potential evaporation $E_p$ summarizes the conditions in the atmosphere that result in demand of water transfer from the land surface to the atmosphere. One of the more complex models used to estimate this atmospheric water demand is the Penman–Monteith equation, which combines components of energy balance and mass transfer while accounting for the effects of wind, vegetation and aerodynamic resistance (Allen et al. 1998). For this study, we use the FAO-56 Penman–Monteith (Allen et al. 1998):

$$E_p = \frac{0.408\Delta(R_n - G) + \frac{900}{T_a + 273}w_{as2}(u_p)\gamma}{\Delta + \gamma(1 + 0.34w_{as2})},$$

(1)

where $\Delta$ is the slope of vapor pressure curve (kPa °C$^{-1}$); $R_n$ is the net incoming solar radiation (MJ m$^{-2}$ day$^{-1}$); $G$ is the ground heat flux (MJ m$^{-2}$ day$^{-1}$), which is negligible at a daily time step (Guo et al. 2017); $\gamma$ is the psychrometric constant, which relates the partial pressure of water to air temperature; $T_a$ is the average daily temperature calculated as the average of $T_{max}$ and $T_{min}$; $w_{as2}$ is the daily average wind speed measured at 2 m (ms$^{-1}$); and $u_p$ is the vapor pressure deficit (kPa). The formula can be used almost directly with the variables provided by MACA except for some minor adjustments described in the following equations. Wind speed $w_{as2}$ was obtained as the vector sum of $u_{as}$ and $v_{as}$ of MACAv2-METDATA using the Pythagorean theorem. However, this wind speed is provided at 10 m above the land surface. A correction factor is used to estimate wind speed at a height of 2 m above land surface as required by the FAO-56 equation:

$$w_{as2} = \frac{4.87}{\ln(67.8z - 5.42)} w_{as} = 0.75w_{as}.$$  

(2)

In addition to the main Penman–Monteith equation, $T_a$ is also used to calculate the slope of vapor pressure curve, which relates the saturation specific humidity to the average daily temperature, given by

$$\Delta = \frac{4098 \left(0.6108 \exp \left(\frac{17.27 T_a}{T_a + 273.3}\right)\right)}{(T_a + 237.3)^2};$$

(3)

$\gamma$ also requires additional information in order to be calculated by

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### Table 1. Climatic variables provided as part of the MACAv2-METDATA dataset (Abatzoglou 2013) and used in this study of the Appalachian Region and its downstream areas.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>Daily precipitation</td>
<td>mm</td>
</tr>
<tr>
<td>RH&lt;sub&gt;max&lt;/sub&gt;</td>
<td>Max daily relative humidity</td>
<td>%</td>
</tr>
<tr>
<td>RH&lt;sub&gt;min&lt;/sub&gt;</td>
<td>Min daily relative humidity</td>
<td>%</td>
</tr>
<tr>
<td>$R_n$</td>
<td>Net incoming solar radiation</td>
<td>MJ m$^{-2}$ day$^{-1}$</td>
</tr>
<tr>
<td>$T_{max}$</td>
<td>Max daily temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{min}$</td>
<td>Min daily relative humidity</td>
<td>°C</td>
</tr>
<tr>
<td>$u_{as}$</td>
<td>Surface eastward wind</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$v_{as}$</td>
<td>Surface northward wind</td>
<td>m s$^{-1}$</td>
</tr>
</tbody>
</table>
\[ \gamma = 0.00163\left(\frac{P_{\text{atm}}}{\lambda}\right), \]  

(4)

where \( P_{\text{atm}} \) is pressure at \( z \) meters of elevation and \( \lambda \) is the latent heat of vaporization estimated at 2.45 MJ kg\(^{-1}\) at 20\(^\circ\). Although atmospheric pressure may vary according to different atmospheric drivers, the effects on the psychrometric function are small and the average value for a given location is a good estimation (Allen et al. 1998). The elevation for the 4-km grids is acquired from the DEM that is part of the PRISM dataset (Daly et al. 1998). The elevation for the 4-km grids is acquired from the DEM that is part of the PRISM dataset (Daly et al. 1998). The elevation for the 4-km grids is acquired from the DEM that is part of the PRISM dataset (Daly et al. 1998):

\[ P_{\text{atm}} = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26}. \]  

(5)

Vapor pressure deficit is the difference between the atmospheric saturation vapor pressure \( v^s_{\text{pd}} \) and the actual vapor pressure \( v_a \), which depends on temperature. Both of these vapor pressures can be calculated with the RH variables provided by MACA:

\[ v_{\text{pd}} = v^s_{\text{pd}} - v_a. \]  

(6)

The saturation vapor pressure as a function of temperature is calculated by

\[ v^s_{\text{pd}}(T_a) = 0.6108 \exp\left(\frac{17.27 T_a}{T_a + 237.3}\right). \]  

(7)

To calculate the daily average vapor pressure deficit, Eq. (7) is solved using average daily temperature \( T_a \). The actual vapor pressure is a function of temperature and relative humidity and is calculated as

\[ v_a = v^s_{\text{pd}}(\text{RH}), \]  

(8)

where RH is the percentage of moisture in a unit volume of air. As with saturation vapor pressure, the daily average actual vapor pressure is calculated using averaged daily RH from the original MACA dataset.

c. Aridity and seasonality index

The water and energy balances in the temperate regions of the midlatitudes have certain peculiarities that relate to their relative magnitude and timing throughout the year (Weiss and Menzel 2008). Changes in the amount and distribution of energy and water directly affect the partition of precipitation between evapotranspiration and runoff, affecting water availability (Arora 2002; Roderick and Farquhar 2011; Wang and Hejazi 2011). In this study, we use two main characteristics, represented by two indices, of the water and energy balance, to assess the characteristics and projected changes across the region. The first characteristic is represented by the aridity index, simply relating the amount of atmospheric water demand \( (EP) \) to atmospheric water supply \( (P) \) (Arora 2002):

\[ AI = \frac{EP}{P}. \]  

(9)

The critical value of AI is where \( EP \) and \( P \) are equivalent to each other (AI = 1). An AI < 1 represents humid areas, and an AI > 1 represents arid areas.

The second characteristic represents the distribution of either variable \((P \text{ or } EP)\) during the year. The Appalachian Region has a precipitation regime that is relatively uniformly distributed throughout the year, but characteristic of the midlatitudes (Weiss and Menzel 2008) the energy is concentrated in the summer months (Coopersmith et al. 2012). As a result of this concentration of energy during summer, the timing of \( P \) in relation to \( EP \) will have an influence on the way that water is partitioned. If \( P \) takes place while \( EP \) is at its peak, more of the supplied water will be partitioned toward evapotranspiration. On the other hand, if more of the \( P \) falls during winter, then it is likely that \( P \) will be partitioned into runoff or stored in the land surface. The concentration of energy in summer is mostly related to higher solar energy during summer due to the oscillation of Earth’s axial tilt. This is independent of anthropogenic global warming and it is not likely to change in the future. However, with global warming, it is likely that there will be more energy available during longer portions of the year (Fig. 2a), as the period with active \( EP \) extends to earlier in spring and later in autumn (Westerling et al. 2006; Xu et al. 2014). In addition, changes in precipitation, regardless of their direction (±), might not be equally distributed throughout the year. The intra-annual pattern of precipitation might shift toward or away from periods with active \( EP \) (Figs. 2b,c), increasing or decreasing \( P \) in certain parts of the year (Figs. 2d,e).

The schema shown in Fig. 2 are simplified examples of possible changes in \( P \) and \( EP \); however, it is most likely be a combination of all these changes. The importance of identifying how the patterns of precipitation and potential evapotranspiration occur throughout the year is of interest to water resources because it will influence how the partition of precipitation also changes in the future.

Most seasonality indices account for intra-annual variability by comparing the difference between monthly or daily departures from the average or total yearly value, and they relate quantitative thresholds to qualitative distributions of rainfall (Walsh and Lawler 1981; Woods 2009; Coopersmith et al. 2012). The index of Walsh and Lawler (1981) has been the basis for other
indices. This index mainly represents the intra-annual relative seasonality basically referring to the degree of within year variability of monthly rainfall. Walsh and Lawler’s index basically quantifies the sum of deviations of mean monthly precipitation from the overall monthly mean divided by the mean annual precipitation:

$$SI_{WL} = \frac{1}{P} \sum_{m=1}^{12} \text{abs} \left( P_m - \frac{P_{\text{y}}}{12} \right),$$  \hspace{1cm} (10)$$

where the subindices $m$ and $y$ represent monthly or yearly precipitation.

In the current paper, we develop an index based on polar coordinates with the aim of equating a magnitude of seasonality between the interval of 0 to 1, and a directional angle to describe its distribution throughout the year. The procedure to calculate the seasonality index is schematically shown in Fig. 3 for three hypothetical cases and is described below. This index can be applied to any variable with the proper normalization but in this study, we use it to calculate the seasonality of $P$ and $E_P$ by dividing each monthly average by the total $P$ or $E_P$. Monthly proportions are later plotted in polar coordinates, with each month representing intervals of 30° (January = 30°, February = 60°, March = 90°, ..., December = 360°). The choice of polar coordinates allows for the monthly averages to be plotted as a closed polygon that will be skewed toward the month in which a variable reaches its maximum value, or it will be centered in case of no seasonality. The seasonality index itself is later calculated based on the geometric center of the monthly plots, with the intensity being quantified as the distance from origin and the resulting angle being the direction. Contrary to the calculation of a geometric centroid of a finite set of points, we do not normalize the summation by the number of points (i.e., 12 for months) in order to maintain an interval from 0 to 1. In this case, if all the precipitation or potential evapotranspiration were concentrated in only one month, the index would have a magnitude of 1, and if the precipitation is equally distributed throughout the year the magnitude will be 0. The angle is later converted from a scale of 0–360 to a scale of 0–12 to describe the month, that is, 6.5 = middle of June. Figure 3a schematically shows the “climatology” of three hypothetical cases of seasonality. The uniform case presents a situation in which the same amount of a given variable takes place at each month and therefore is centered when plotted in polar coordinates (Fig. 3b). The cases for higher and lower seasonality, for example, show polygons of different geometry skewed toward the month of June as their peak is higher during this month. The sign convention for the coordinates is selected by setting the months of March in the positive $x$ axis, June in the negative $y$ axis, September in the negative $x$ axis, and December in the positive $y$ axis. Therefore, shifts in seasonality in the $x$ axis represent changes in equinox, and shifts in the $y$ axis represent changes in solstice. The components of intensity $S_I$ and direction
The seasonality index are numerically calculated as follows:

\[ S_I = \left\{ \left( \sum_{m=1}^{12} \frac{P_m}{P_y} \sin(m \times 30) \right)^2 + \left( \sum_{m=1}^{12} \frac{P_m}{P_y} \cos(m \times 30) \right)^2 \right\}^{1/2} \]  

and \[ \alpha = \frac{\sqrt{\sum_{m=1}^{12} \frac{P_m}{P_y} \sin(m \times 30)}}{30} \]  

With this index, the seasonal distributions of water and energy across the region are explored and later we inspect the changes projected throughout the twenty-first century. For comparison, we also calculate seasonality using Walsh and Lawler (1981), which has been extensively used (Coopersmith et al. 2012).

d. Twenty-first century change analysis

Although the sources of moisture, predominant wind currents, local effects of orography, and rain shadows can be enhanced or weakened in the future, it is not likely that they cease to be the predominant factors for precipitation across the region (O’Gorman 2015). For this reason, the results focus extensively in the magnitude and relative changes in \( P \) and \( E_P \) of four, approximately 25-yr, periods throughout the twenty-first century—Q1: 2006–25, Q2: 2026–50, Q3: 2051–75, and Q4: 2076–99—that are compared with the historical period (1950–2005). The same periods are used to quantify different states of aridity and seasonality, which
is useful to understand their possible implications for the hydrological cycle and water resources across the region. From the gridded analysis, we determine that the periods with largest changes for each scenario are Q3 for RCP4.5 and Q4 for RCP8.5 and hence we used these extreme changes to assess future conditions at basin scale throughout the region. These results are used to discuss the possible implications of climate change to water resources.

4. Results

a. Absolute changes in hydroclimatic variables

Patterns of \( P \) and \( \text{EP} \) across the Appalachian region are mainly driven by topography, latitudinal position and dominant climatic patterns (Figs. 4a,b). The dominant westerly winds collect moisture through the Great Plains region of the United States and the Gulf of Mexico that are transported into the region. Effects of orographic precipitation and rain shadow are apparent in the western and eastern slopes of the Appalachian Mountains respectively (Fig. 4a). The highest amounts of precipitation in the region is observed in the Southern Appalachians close to the borders of North Carolina, South Carolina, Georgia, and Tennessee, also known as the Blue Ridge.

Potential evapotranspiration \( \text{EP} \) has a spatial distribution related to latitude, which describes the dependence of \( \text{EP} \) on the amount of sunshine hours and therefore, radiation and temperature (Fig. 4b). Elevation is another defining factor for \( \text{EP} \) in the region, as well-defined patterns of lower \( \text{EP} \) are apparent along the Appalachian Mountains. The southern limits of the region have higher amounts of \( \text{EP} \) due to lower elevation and latitude (Fig. 4b).

In comparing the amount of \( P \) in the future with the historic period of 1950–2005, it is apparent that the RCP scenario has a large influence on projected changes (Fig. 5). The RCP4.5 shows an opposite pattern of what the RCP8.5 (Fig. 5b). In the RCP4.5, the \( P \) changes show a slight wetting during Q1 in all areas. The progression into Q2 shows reductions in \( P \) across most of the southern states that is exacerbated into Q3. During Q3 in the RCP4.5 only certain portions in northeastern Pennsylvania and the counties in New York, experience slight wetting. Toward the end of the century, the RCP4.5 displays wetting similar to that in Q1 for most of the region. The RCP8.5 scenario shows drying during P1 on the southeastern portion. Most of the western part of the region shows slight wetting. A slight wetting during Q2 is seen for most of the region. Into Q3, most of the region continues to wet, except for a small area in the border of Tennessee and South Carolina. At the end of the twenty-first century, a marked drying region appears, being larger toward the south portions of the region, and expands north well into parts of West Virginia.

Potential evapotranspiration \( \text{EP} \) shows a different progression than \( P \) throughout the twenty-first century. Regardless of the scenario, \( \text{EP} \) is projected to increase
Increases in $E_P$ are exacerbated under the most extreme RCP8.5 scenario (Fig. 6). The relative changes of $E_P$ display that for both scenarios, places where $E_P$ is lower are projected to have greater percentage increases (Fig. 6b). These changes are more exaggerated and therefore more apparent in the most extreme scenario at the end of the twenty-first century. Higher latitudes experience higher relative changes as well as high elevations throughout the Appalachians. By the end of the twenty-first century, in some cases, the changes are as high as 35% (Fig. 6c).

The projections of both hydroclimatic variables represent some level of uncertainty linked to the physics resolution of each individual model that we quantify with the standard deviation of each model’s mean annual values for each period (Fig. 7). Precipitation $P$ exhibits higher uncertainty than $E_P$, and the models present a wider range toward the southern part of the region in both scenarios. The largest uncertainties in $P$ take place in Q3 for RCP4.5 and Q4 for RCP8.5, periods that exhibit the largest changes for each scenario. Regionally, the largest uncertainty in precipitation do not necessarily take place where precipitation is higher but where there is larger changes. The case of $E_P$ is different as there is larger uncertainty in portions of the

![Fig. 5. Precipitation changes in the Appalachian Region throughout the twenty-first century: (a) mean annual precipitation, and (b) relative changes with respect to the historic period.](image-url)
region where $E_P$ is larger and the uncertainty is smaller where there are larger changes. Although, the uncertainty in $E_P$ maintains the pattern of being higher in the south, it is more homogeneously distributed throughout the region. The lower uncertainty of $E_P$ with respect to $P$ can be attributed to its higher dependency on temperature and solar radiation (Guo et al. 2017), which also have lower uncertainty in GCM’s projections, as opposed to other less influential variables such as relative humidity and wind, which have higher uncertainty in GCMs.

b. Changes in aridity

The changes in atmospheric water demand and supply provide insight into how water resources might be affected in the future. Parameters $P$ and $E_P$ showed different relative and absolute changes (Figs. 5, 6) but these assessments only provide limited information. We also examine changes in aridity index across the region to determine places where the balance between water and energy supplies might change, further affecting hydrological changes on the land surface. Places with higher elevations and the western parts of the region are much more humid than low-lying regions (Fig. 4c). The aridity throughout the twenty-first century as projected by the RCP4.5 shows increasing dry regions (AI > 1) (Fig. 8). Regions that are already water limited seem to be becoming drier. At the same time, regions that are water limited seem to be decreasing in area. The humid
Fig. 7. Standard deviation of model's mean annual (a) precipitation, (b) potential evapotranspiration, and (c) aridity index as an indication of model uncertainty in future projections.
regions are constrained to portions of New York, central Pennsylvania, and West Virginia following the Appalachians onto eastern Kentucky and Tennessee, and western North and South Carolina. These regions were projected to shrink throughout the twenty-first century in both scenarios, but most markedly in the RCP8.5. The wettest areas of the Appalachians appear to be disappearing in the southern Appalachians and central West Virginia. On the RCP4.5 scenario, the aridity of the region seems to recover to earlier states toward the end of the century.

Changes in aridity generally show drying under both scenarios, but more accentuated under the RCP8.5 scenario (Fig. 8). The largest changes in aridity are in the southwest of the region. The valleys between the Appalachian Mountains also exhibit some of the largest increases in aridity. Humid places such as the ridges of the Appalachians experience the least changes although they become less humid.

The AI, being a derived variable of $P$ and $E_p$, exhibits a similar regional pattern in its uncertainty. However, this uncertainty is higher in low-lying areas and lower at higher elevations.

c. Changes in seasonality

Figure 9 shows seasonality of $P$ and $E_p$ across the region calculated with Walsh and Lawler (1981) index...
and our newly introduced seasonality index. Both indices perform similarly for both variables, highlighting the capacity of our index to quantify the intensity as the Walsh and Lawler’s index. It is worth noting that both indices have different ranges so Fig. 9 serves only as a comparison to show that both indices display high/low values in the same regions. However, Walsh and Lawler’s index does not reflect any information about the timing of the year when a variable is more concentrated, whereas our new index does (discussed below). Additionally, our index provides relative information of seasonality in an interval from 0 to 1, which is an easier concept to transfer to practitioners and policy makers. The seasonality of \( P \) is generally low, reaching maximum intensities of 0.2–0.25 in the northern portions of Ohio and West Virginia, Pennsylvania, and New York. Areas with less seasonality in \( P \) include southern portions of Georgia and South and North Carolina east of the Appalachians.

Potential evapotranspiration \( E_P \) is much more seasonal than \( P \), mostly because of its dependency on sunshine hours, which is related to Earth’s axis oscillation. Hence, the seasonality of \( E_P \) is directly related to latitude. It is worth highlighting that at same latitudes, \( E_P \) seems to be more seasonal farther inland in continental areas, such as in western Ohio. An important aspect of seasonality is the timing of the year at which a variable peaks. This is included in our developed index as the direction \( \alpha \). At the latitudes of this region, \( E_P \) is highly seasonal and it peaks around the summer solstice and having a direction of around 6–7 (June–July). Since the seasonality of \( E_P \) is related to the oscillation of Earth’s axis, a geophysical feature that is independent of atmospheric forces, this is unlikely to change throughout the twenty-first century and projections reflect it.

The timing of peak in \( P \) varies throughout the region (Fig. 9). A small portion in New York, namely the coast of Lake Erie, has peak precipitation during winter. On the western side of the Appalachian Mountains, the timing of precipitation gradually shifts from summer months in western Pennsylvania and northern Ohio, to spring months in Tennessee, Mississippi, Alabama, and western Georgia. The area between the border between the Carolinas and Georgia, where the southern tip of the Blue Ridge geological region of the Appalachians is located, has a complex distribution of \( P \) peak, attributed to the complex topography and high altitude in the region. However, an apparent pattern of winter-dominated \( P \) on the western side and summer \( P \) on the eastern side can be observed (Fig. 9). The southern portion of the region is dominated by winter precipitation.

Climate change related to global warming is likely to alter large-scale phenomena that drives \( P \) intra-annual...
temporal distribution. Depending on the scenario, different changes can be observed (Fig. 10). In the RCP4.5 scenario, the first apparent change is that areas with higher seasonality become more seasonal at the beginning of the twenty-first century. As the century progresses, most of the region returns to similar states after Q3. On the western side of the Appalachians, the seasonality of $P$ increases, especially in the southwestern part of the region. The northern part of the region becomes more seasonal at the beginning of the century, but by the end of the century, it becomes less seasonal. The RCP8.5 shows a different progression of seasonality. The southeast of the region becomes progressively less seasonal with end-of-century values close to 0. The southwestern part of the region becomes more and more seasonal as the century progresses, expanding northerly. Areas of central Appalachia such as Kentucky, West Virginia, and Ohio seem to become slightly more seasonal at the beginning of the century, although they once again lose seasonality in periods Q2, Q3, and Q4. By the end of the century, it is apparent that the seasonality of this region returns to the averages of the 20C pattern (Figs. 9 and 10). The northern part of the region becomes progressively less seasonal. This decrease in

Fig. 10. Seasonality changes in the Appalachian Region throughout the twenty-first century: seasonal intensity and seasonal intensity changes.
seasonality is marked in the states of Pennsylvania and New York.

Changes in the timing of precipitation ($\alpha$) during the year are important in the midlatitudes because of the high concentration of atmospheric water demand in the summer months (Fig. 2). Partition of precipitation between evapotranspiration and runoff is directly dependent on the energy to evaporate water from the land surface. Hence, changes in $\alpha$ during the year will affect its partitioning. There is a notable regionalization of $\alpha$ across the region being concentrated in the summer months in the north, gradually shifting toward spring in the central portion and toward winter months toward the south of the region (Fig. 11).

Changes in the timing of $P$ ($\alpha$) across the region occur in spatial patterns that are similar in both projected scenarios (Fig. 11). In Ohio and West Virginia, $\alpha$ indicates at changes in seasonality of $P$ to earlier in the year, to the months of May and April in Q1 and Q2, for both scenarios. During Q3, $\alpha$ indicates a seasonality in $P$ back in summer, similar to that of the historic period. By the end of the century, $\alpha$ in Ohio has relatively small changes when compared with the historic period, whereas the rest of Ohio and West Virginia have a slight

![Figure 11](image-url)
change of $\alpha$ toward earlier in the year, into May and April. The northern part of the region, including the states of Maryland, Pennsylvania and New York exhibit changes in $\alpha$ shifting to later in the year progressively onto Q3. By Q4 the pattern returns to earlier in the year except for the coastal area of Lake Erie. The last regional pattern includes the south of the region, which progressively transitions from late winter into early winter.

d. Basin-scale assessment

Figure 12 displays the results of a basin-scale assessment. These assessment was performed with the spatial average of $P$ and $E_P$ for all the grids within each basin presented in the bottom panel of Fig. 1. These spatial averages are calculated for all the grids within a basin including the downstream areas that are outside of the counties within the region. The aridity and both components of seasonality were calculated from these spatial averages. For simplicity only the results for the most extreme changes are presented (Q3 for RCP4.5 and Q4 for RCP8.5). The basin-scale results reaffirm most of the results that were presented in the gridded portion of this analysis. Historically, precipitation is larger in basins in the south and decreases progressively toward the north. Additionally, basins that drain to the west, toward the Ohio or the Mississippi Rivers receive more precipitation than rivers that drain to the east coast at similar latitudes. This is due to the rain shadow formed by the Appalachian Mountains and the west to east predominant winds. Changes in the twentieth century are similar in both scenarios but they are exacerbated in RCP8.5. In both scenarios there are drying trends in the southern basins and higher changes in the north with a transition in basins along the central Appalachians. Changes range between $-12\%$ and $12\%$.

Potential evapotranspiration $E_P$ shows a pattern inversely proportional to latitude being lower toward the north. In basins at similar latitudes $E_P$ is lower in inland continental basins that drain toward the Ohio and Mississippi Rivers, and its higher in basins draining directly in the Atlantic Ocean. Similar to the gridded analysis $E_P$ has larger relative changes where it is lower, that is, in the north. Relative changes in $E_P$ are much larger than changes in $P$ and consistently increase throughout the region. These changes range from 10% to 15% in the RCP4.5 and from 15% to 30% in RCP8.5. These changes are also larger inland as opposed to coastal basins in similar latitudes.

The aridity of the basins indicates the balance between atmospheric water supply and demand and its change given the differential changes between $P$ and $E_P$. In the historical period, there is higher aridity in the
eastern coast basins as compared to basins inland. For basins draining to the Atlantic Ocean aridity increases toward the south of the region. This balance is a composite of higher coastal $E_P$ and lower $P$ due to the rain shadow of the Appalachian Mountains (explained above). For the future projections, aridity generally increases most markedly in the south. This is a result of increasing $E_P$ and decreasing $P$ in this portion. Additionally, even basins in the north undertake increases in aridity resulting from much lower increases in $P$ than in $E_P$. An important characteristic of aridity that was described in the gridded analysis is its dependence on elevation. Figure 13 shows the correlation between aridity and elevation for each basin. The negative correlation indicates an inverse relation as elevation increases, aridity decreases. Most of the basins have a significant correlation except for the Roanoke basin. Table 2 shows some additional information of the relation between elevation and aridity and its changes throughout the twenty-first century. Columns 2–4 of the table show the minimum aridity for the grids within each basin. All of the basins except for the Yadkin–Pee Dee, the Licking (KY), and the Licking (OH) rivers have at least one grid below the critical value of 1. In the RCP4.5 Q3 the James, the Roanoke, the Kinetucky, and the Genesee cease to have a hummid portion, and in the RCP8.5 Q4 the Potomac and the Allegheny loose their humid portions in addition to the aforementioned basins. Columns 5–7 show the areas of the humid regions for each basin and it can be seen that these areas decrease substantially in the twenty-first century. Moreover, columns 8–10 show the average elevation of the grids with AI below 1 for each basin. For all the basins, this elevation becomes higher in the future projections except for the Santee, Kanawha, Monongahela, and Oswego, for which the elevation is lower in RCP8.5 than in RCP4.5, although the RCP8.5 elevations are substantially higher than the historical elevation except for the Santee River basin.

For the basin assessment, the seasonality of each basin is observed higher in the northern basins and lower toward the south with a few exceptions. Similar to the gridded results, the projections show an increase in seasonality in the southern basins and a decrease in the north and central eastern basins. The direction of the seasonality is spread throughout the region being in winter in the south, and progressively shifting into spring and summer toward the north. In general, the direction of the seasonality shifts to earlier in the year throughout the basins. The direction of the seasonality in the southern basins shifts to earlier in winter, shifts from summer to late spring throughout the central and most of the northern basins and shifts from early autumn or late summer toward summer in the northernmost basins.

5. Discussion

a. Water and energy balance changes throughout the region

There has been a consistent trend of increasing temperature since the 1970s in the eastern United States that has been closely linked to global warming induced climatic change (Hayhoe et al. 2007). Our results agree with findings of other studies at the regional (Hayhoe et al. 2007; Kang and Sridhar 2018), national (Sagarika et al. 2014; Wobus et al. 2017; Duan et al. 2017), and global scales (Zhao and Dai 2015, 2017). In particular, there is an agreement that a more severe emission scenario or representative concentration pathway leads to exacerbated changes when compared with a scenario or pathway with lower emissions (Hayhoe et al. 2008). Previous studies have used coarser-resolution data constrained mainly by the scale at which the study was designed (Zhao and Dai 2015, 2017), or by the state-of-the-art of climate models and downscaling techniques at the time of publication (Hayhoe et al. 2007). Hayhoe et al. (2008) highlighted that higher resolutions allow for better representations of topographical assets and geographical characteristics but can also increase uncertainty given the downscaling technique. The MACAv2-METDATA dataset (Abatzoglou 2013) provides a new tool that allows for higher-resolution analysis, with a robust downscaling and bias-correction technique that takes advantage of the high availability of data in the continental United States. MACAv2-METDATA also presents the necessary climatic variables.
that allow the estimation of derived measures such as \( EP \), with which more detailed analysis can be performed on water balance than just with temperature. With this dataset we have found that geographical features such as orographic rainfall, rain shadow effect and lake effect snow are better represented. These data are also able to better represent the aridity index and link it to headwater regions located across Appalachia. These results display detailed regionalization in the seasonality of \( P \) and possible changes in the future. The results of changes in \( EP \) also agree well with what other studies have found when analyzing changes in temperature. The highest increases in \( P \) and \( EP \) the northeast portion of the region is consistent with increases in temperature found in previous studies in nearby areas (Burns et al. 2007) and more generalized studies that have found greater increasing temperature and \( EP \) in colder regions (Wuebbles et al. 2014; Liu et al. 2017; Wobus et al. 2017) including colder catchments across the northeastern United States. (Pourmokhtarian et al. 2017). Our results are congruent with projections for this region in global assessments of aridity and \( EP \) (Zhao and Dai 2015, 2017), establishing the foundation of this study for future drought assessments across the region. It is important to highlight that GCMs generally underestimate winter warming (Hayhoe et al. 2007) making it possible that \( EP \) might even increase more than what has been reported here.

An important contribution of our study is the inclusion of a seasonal timing \( \alpha \). The timing at which precipitation takes place in a given location has implications for how \( P \) will be partitioned (Naz et al. 2018). Regionally, the contrasting changes in the northern and southern part of the region have been previously identified (Sagarika et al. 2014). However, increasing \( P \) does not necessarily result in increased runoff and therefore, does not necessarily result in either increased water supply or flood risk (Mahat et al. 2017). The seasonality of \( P \) and its synchronicity with \( EP \) (Pourmokhtarian et al. 2017), an important characteristic that affects the partition of \( P \) into evaporation or runoff, seems to shift onto winter across the northeast (Huntington et al. 2009).

### b. Potential mechanisms driving hydroclimatic changes

The main drivers of atmospheric water supply in the form of precipitation and its seasonal patterns are largely driven by synoptic factors that are external to the region (Leathers et al. 1991; Roller et al. 2016; Doubler et al. 2015). Cold fronts (Bosart et al. 1973), tropical and extratropical cyclones (Atallah et al. 2007; Kam et al. 2013), the polar jet stream (Belmecheri et al. 2017), and convection systems over the continental United States are the main drivers of moisture flows to the Appalachian Region (Higgins et al. 1997; Basara and Christian 2017). These moisture fluxes, combined with physical features such as the ridges and valleys of the Appalachian Mountains (Barros and Kuligowski 1998) and the Great Lakes (Niziol et al. 1995), generate the different patterns that are observed across the region. Additionally, other
phenomena such as El Niño–Southern Oscillation (Ropelewski and Halpert 1986), the Pacific decadal oscillation, and the Atlantic Multidecadal Oscillation produce different $P$ patterns across the region (Sagarika et al. 2015). As shown in this study, the spatial distribution of precipitation does not change drastically into the future. Predominance of $P$ in the western side of the Appalachians and rain shadows on the eastern side highlight that the driving forces of climate across the region do not change in the future. However, differential changes in the magnitudes of $P$ and $E_P$, aridity, and seasonality across the region emphasize that these climate drivers can be enhanced or weakened under expected future climate. There is a notable separation between increasing $P$ in the northern extent of the region ($P$ is enhanced closer to the Great Lakes region) and decreasing $P$ in the southwestern extent with a transition across central Appalachia (Kentucky, West Virginia, and North Carolina). One of the main drivers of $P$ in the north region is the lake effect, which results from high-pressure systems carrying strong dry winds from the North Pole that pick up moisture from the lakes’ surface, which precipitates over land into the Appalachian Mountains (Bosart et al. 1973; Niziol et al. 1995). This pattern is historically observed during autumn and spring, when weather is cold but the lakes are not frozen. When the lakes freeze, available moisture becomes limited. Under global warming, it is likely that the lakes will be frozen for less time, allowing for longer periods with increasing lake effect snow (Notaro et al. 2015). This is further supported by how the seasonality index shifts, as seasonality intensity decreases and shifts toward winter.

Northeasters also play an important role in the $P$ patterns of the eastern part of the region (Zielinski 2002). Northeasters usually provide moisture flows to the coast from the Carolinas to New England and even into Canada in the months of November–March. Under climate scenarios, northeasters are not only increasing in intensity but also shifting farther north (Frumhoff et al. 2007; Wuebbles et al. 2014). This could also be responsible for enhancing $P$ in north counties but decreasing $P$ in the southern portion of the region.

Tropical cyclones in the Atlantic Ocean are also expected to be affected by global warming (Walsh et al. 2016). According to most projections, hurricanes are expected to increase in intensity but decrease in frequency. The marked seasonality of precipitation toward the summer months in the Atlantic coast and regions of Georgia, South Carolina, and North Carolina is largely driven by precipitation related to tropical cyclones and low pressure systems that make landfall or meander around off of the eastern coast (Atallah et al. 2007; Kam et al. 2013). Decreases of $P$ and changes to its seasonality could be related to fewer cyclones and pressure systems. The shift in $P$ seasonality from the summer months to the autumn months could also be related to an extension of the tropical cyclone season into autumn months (Walsh et al. 2016).

Another large-scale driver that will be affected by climate change is the polar jet stream, which mediates the flow of moisture from the Gulf of Mexico and from convection systems in the U.S. central Great Plains (Seidel et al. 2008; Francis and Vavrus 2015). Projections for the twenty-first century have the jet stream weakening and maintaining at lower latitudes (Cohen et al. 2014). This would block moisture inflows from the Gulf of Mexico into the southwestern part of the region, providing an explanation for $P$ decreases in the region. A lower jet stream also prevents the formation of tropical cyclones in the Gulf of Mexico and drives low pressure systems out of the southwest (Seidel et al. 2008). This condition would decrease precipitation in the months of October and early November, resulting in enhanced seasonality and a shift in the peak of precipitation toward winter.

c. Potential implications of water balance and energy changes in the region

The balance between atmospheric water demand and supply is responsible for the amount of water available at the land surface, mostly as a remnant of evapotranspiration (Vörösmarty et al. 2000; Doll et al. 2003; Hanasaki et al. 2008). Atmospheric water demand is driven by geophysical processes that are predominantly dependent on solar radiation (Arora 2002). Although we observed changes in the magnitude of $E_P$, there is no significant changes in its seasonal distribution. The increases in $E_P$ are largely driven by increases in temperature that result from global warming and dependent on elevation and latitude. The absolute changes in $E_P$ overwhelm the quantitative changes in $P$ in most of the region, implying that evapotranspiration could be enhanced, leaving less water for society and ecosystems. However, the changes in seasonality of $P$, or changes in just some months, can buffer the loss of water partitioned to evapotranspiration.

Because of the comparable magnitudes of precipitation and potential evapotranspiration, a substantial proportion of the water falling as precipitation returns to the atmosphere through evaporation. Precipitation changes that occur in summer are likely to be partitioned to evapotranspiration due to the availability of energy during this season (Coopersmith et al. 2012, 2014). For instance, in the southeastern part of the region, precipitation is projected to decline in the summer months.
This would potentially result in decreases in runoff and evapotranspiration, but a larger portion of the decrease in $P$ would be absorbed by evapotranspiration than by runoff, given the available energy. However, the southwestern part of the region has $P$ decreases in the autumn and winter months. During this period, there is less energy for evapotranspiration, partitioning water mostly toward land surface storage or direct runoff. Decreases during this season will likely affect water availability. Additionally, increase in the number of months when precipitation is active is also likely to enhance evapotranspiration into the autumn months. In Ohio, and portions of West Virginia and Pennsylvania, $P$ is shifting from late spring well into summer. These increases are also likely to be partitioned toward evapotranspiration.

In the northeastern part, precipitation that now peaks in summer is likely to increase in magnitude and peak at different parts of the year outside the period during which $E_P$ is active. This additional water is likely to be partitioned toward runoff.

The fact that the wettest places across the region are located at higher elevations highlights a “water tower effect” (Viviroli et al. 2007) from the Appalachian Mountains to adjacent low-lying areas where a vast majority of urban systems in the east coast are settled. If the majority of the precipitation takes place in the mountains, this means that the availability of water in the adjacent lowlands depends directly on the climatic changes impacts upstream. This also highlights the importance of conservation and management of highland forests and headwater catchments. These is enhanced by the results showed in Table 2 that project a marked decrease in humid areas throughout the region and a higher concentration of these areas at higher elevations.

The implications of atmospheric changes to the water cycle, and its effect on water availability for society, needs to be further expanded by hydrological modeling. Hydrological modeling would allow for a detailed mechanistic assessment on how $P$ is partitioned between evapotranspiration, runoff and storage. A spatially distributed parameterization of a hydrological model allows for a more comprehensive assessment on how the changes in aridity and seasonality of $P$ and $E_P$ are translated into changes in evapotranspiration, runoff and storage. Additional analysis of the changes in climate at finer temporal and spatial scales should be performed to further understand long-term changes in evapotranspiration and runoff. For instance, the current analysis is limited to explaining changes in average $P$ and $E_P$ in certain periods to infer how the average partition of $P$ will change in the future. Changes in $P$ events (intensity and duration) can result in different changes in $P$ partitioning than average changes.

Last, there are substantial differences between the results in both scenarios. The RCP8.5 shows much larger increases in $E_P$ and larger changes in $P$ than the RCP4.5. More importantly, the RCP4.5 scenario, which supposes a change in the world’s economy into a more sustainable system with less carbon emissions around the year 2040 (van Vuuren et al. 2011), shows a smaller increase rate in $E_P$ toward the end of the twenty-first century, and similar $P$ conditions to those of the twentieth century, suggesting that policies toward lower carbon emissions may have a significant impact on future climatic patterns.

6. Conclusions

Although the effects of climate change driven by global warming have been extensively assessed in many regions of the United States, changes in the Appalachian Region are poorly understood. In this study we analyze changes in atmospheric water supply and demand in the forms of precipitation and potential evapotranspiration in all the states that include Appalachian Region designated counties and downstream areas to quantify changes in their balance and seasonality that could affect future water availability. We do this by analyzing their relation through AI and a newly introduced seasonality index.

We find that both, $P$ and $E_P$ are differentially changing across the region and throughout the twenty-first century. In general, the changes in $P$ show the north wetting up and the south drying, with differential transition zones in the central Appalachians throughout the twenty-first century. Potential evapotranspiration, which is mainly dependent on temperature, shows consistent increases, although these increases are inversely related to latitude and elevation (higher elevation and higher latitude generally have larger increases). Despite these changes, $P$ and $E_P$ still maintain the same spatial patterns across the region, highlighting that geographical features still dominate regional climatology. An important feature of the changes is that $E_P$ is increasing at a higher rate than $P$ except for some small pockets at high elevations, highlighting the importance of mountainous landscapes to supply to adjacent lowlands with water.

We introduce a new seasonality index that performs similarly to previous well established indices (Walsh and Lawler 1981) but with the added value of a timing component that identifies the month in which a variable has its highest values. This index can be transferred to other variables aside of $P$ and $E_P$, such as streamflow, storage components, or other atmospheric variables with the proper normalization. This region, in general, has low seasonality in precipitation although the seasonality
is expected to shift in the future. The changes in seasonality across the region might be a reflection of changes in larger synoptic patterns such as cold fronts, tropical cyclones and the polar jet stream, as well as changes in seasonal characteristics of the land surface, for example, reduced frozen periods of the Great Lakes, enhancing winter precipitation related to the lake effect phenomenon.

This study spatially describes regions with different changes in $P$ and $E_p$ as well as their relation and distribution during the year at a gridded and basin scales. The more holistic assessment of analyzing changes in the relation between $P$ and $E_p$, as well as their temporal distribution, provides a better understanding on changes in partitioning of $P$ to actual evapotranspiration and runoff. However, hydrological modeling may be necessary to mechanistically understand how the changes in $P$ and $E_p$ relate to surface water availability, under uncertain future climate. In conclusion, our research highlights the importance of precipitation at higher elevations for supplying adjacent lowlands with water, highlighting the dependency of large cities in the eastern coast and the Mississippi Valley to the Appalachian Mountains and the need for adequate conservation measures.

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