Summertime Potential Evapotranspiration in Eastern Washington State*

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ABSTRACT

The demands for water in agricultural regions depend on the rate of evapotranspiration (ET). Daily records of potential ET (pET) are available from the late 1980s through the present for five stations in eastern Washington State (George, Harrah, LeGrow, Lind, and Odessa) through the Pacific Northwest Cooperative Agricultural Weather Network (AgriMet) under the auspices of the Bureau of Reclamation. These records reveal a secular increase in the summer (June–August) mean pET over the period 1987–2014. This increase can be attributed largely to an increase in solar irradiance of 20–30 W m^{-2} over the same period. The seasonal mean solar irradiance accounts for approximately 35%–50% of the variance in the interannual variations in seasonal mean pET at the individual stations and for approximately 60% of the variance from a five-station average perspective. The period of analysis includes a mean increase of temperature of about 0.3°C $(10\,yr)^{-1}$, and the variability in temperature relates more to the year-to-year fluctuations in pET than to the overall increase in pET. The time series of surface relative humidity and wind speed exhibit only minor trends. Daily and seasonal mean data for 500-hPa geopotential height and other variables are used to determine aspects of the regional atmosphere associated with periods of high pET. Anomalous ridging aloft and negative anomalies in 925-hPa relative humidity tend to occur over the study area during the summers with the greatest pET. The relationships that are emerging may provide a basis for empirical downscaling of pET from global climate model projections.

1. Introduction

Evapotranspiration (ET) refers to the total flux of water vapor from the land to the atmosphere. It includes two contributions: 1) evaporation from the ground and 2) transpiration (i.e., the loss of water from plants, primarily through their leaves). ET is a key component of the water cycle, especially in warm weather when the evaporation rate and the growth of plants are often substantial. ET is particularly important in agricultural regions where determining water demand and reservoir levels is critical. The potential or reference ET (pET) represents the flux of water vapor from a location with a low cover of vegetation over the ground and enough soil moisture so that the movement of water within this vegetation is not limited. In other words, the pET is essentially the actual ET when there is adequate soil moisture. It is calculated on the basis of the energy available for evaporation from the ground and transpiration from the vegetation.

The focus of the present summary is to examine how the pET during summer has varied in the Columbia basin of eastern Washington since the late 1980s and the causal factors for these variations. Much of the cropland in the Columbia basin is irrigated, and the pET minus precipitation relates to the amount of water that must be delivered to maintain adequate soil moisture through the dry summer months. The five stations used in this analysis (George, Harrah, LeGrow, Lind, and Odessa) receive on average only about 15% of their annual precipitation during June–August, and the total precipitation of the Columbia basin is low to begin with [~9 in. (23 mm) yr^{-1}]. Many considerations of hydroclimatic interactions include pET as a key element (e.g., Scheff and Frierson 2014). For example, pET, along with precipitation, and temperature, is incorporated in the Palmer drought severity index (Palmer 1965), which is

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used to characterize the overall state of the hydrological conditions. In the present paper we also examine how the fluctuations in summer pET relate to regional atmospheric circulation patterns. Some previous research has been carried out on the relationships between these patterns and heat waves in the Pacific Northwest (Bumbaco et al. 2013; Lau and Nath 2012), and an objective of the present study is to document the circulation patterns with respect to variations in pET. Much of the work on the climate variability of the Pacific Northwest has focused on the winter season; the present effort represents a contribution toward improved understanding of an important parameter related to the summer weather. Understanding the regional atmospheric circulation patterns that are associated with both low- and high-pET events is an important first step in identifying how these patterns and thus ET in the area of interest is liable to change in association with the global climate.

It appears that the variability in pET in the Pacific Northwest has received only modest attention, but there has been some previous work of relevance to the present study. Hamlet et al. (2007) have documented long-term trends in ET (not pET) for the western United States, with a focus on the effects of changes in the late winter/early spring snowpack. The overall warming has meant earlier snowmelt and hence increases in springtime ET, and decreases in summertime ET, with the latter due to decreases in soil moisture. Hamlet et al. (2007) pertains mostly to higher-elevation locations in the Pacific Northwest that experience winter snowpacks, while our analysis focuses on the lower-elevation Columbia basin. Using annual precipitation and stream discharge for the entire Columbia basin, however, Walter et al. (2004) found increases in ET over the period of 1950–2000. Both of these studies consider the actual ET, which is a fundamentally different parameter (i.e., it does not assume that the soil is moist), as for pET as considered here. On the other hand, the latter parameter was included in the analysis of observed trends in the climate of the Pacific Northwest by Abatzoglou et al. (2014). Increasing trends during the growing season were found for multiple multidecadal windows beginning in 1920 and ending in 2012; these increases were attributed to lengthening of the growing season and decreasing relative humidity.

The interval of our analysis (1987–2014) overlaps most of the period of analysis of summertime cloud cover, precipitation, and surface temperature for North America carried out by Tang and Leng (2013). They found decreases of roughly 0.2% yr^{-1} in daytime cloud cover over the interval of 1982–2009. This implies an increase in surface insolation, and hence the energy available to drive pET, as will be elaborated upon below. Changes in the radiative forcing in pET are not restricted to those involving clouds. Systematic differences in clear-sky shortwave radiative fluxes relate to the brightening observed worldwide (Wild et al. 2005), including in eastern Oregon (Riihimaki et al. 2009), attributed to decreasing aerosol loads from volcanoes, black carbon, and sulfur dioxide emissions. A primary objective of the present paper is to document how these kinds of changes were manifested with respect to pET, with implications for water demands.

Our analysis reveals a sizable and systematic increase in pET in the Columbia basin over the period of 1987–2014. The results are based on calculations that include direct measurements of important processes, in particular the solar insolation, whose variations have not generally been considered in previous studies of the climate variability of the Pacific Northwest. The following section details the datasets and methods used in this analysis. Section 3 features time series of pET and its related variables. The regional circulation anomalies associated with anomalies in pET are presented in section 4. We conclude with a summary and final remarks.

2. Data and methods

We use daily values of pET estimated by the 1982 Kimberly–Penman method (Wright 1982) for a tall reference crop (i.e., alfalfa) as provided by the Pacific Northwest Cooperative Agricultural Weather Network (AgriMet) maintained by the U.S. Bureau of Reclamation. AgriMet began modestly with the installation of 3 stations in 1983, and has since expanded to over 90 stations within agricultural regions, with a few of these stations located outside of the Pacific Northwest. The network consists of high quality, automated weather stations and emphasizes annual maintenance and sensor calibration as the first step in the extensive quality assurance/quality control procedures (Palmer 2011). AgriMet data are available online (http://www.usbr.gov/pn/agrimet/webarcread.html). Five low-elevation stations in eastern Washington have records extending back to the 1980s (George, Harrah, LeGrow, Lind, and Odessa). A map with the locations of these stations is shown in Fig. 1. The data from these five stations are considered for the months of June–August (generally the time of year of greatest pET) for the period of 1987–2014.

The Kimberly–Penman 1982 formulation has two terms: the heat function that combines the effects of the estimated net radiative heating and sensible heat flux in the soil, and the wind function, which relates to the rate of transfer of water vapor from the surface due to the wind. The equation is

$$\lambda \mathrm{pET} = \frac{\Delta}{\Delta + \gamma}(R_n - G) + 6.43\frac{\gamma}{\Delta + \gamma}W_f(e_s - e_a), \quad (1)$$

where R_n is the net radiative heat flux, which includes a measure of shortwave and longwave radiation; G is the soil sensible heat flux; W_f is the wind function (linearly related to wind run); $e_s - e_a$ is the water vapor pressure deficit, with e_s being the saturation vapor pressure and e_a being the vapor pressure of the air; Δ is the slope of the Clausius–Clapeyron relationship; λ is the latent heat of vaporization; and γ is the psychrometric constant.

The heat function term typically comprises about 75% of the estimated pET during summer in the Pacific Northwest. Daily values of pET are based on the measurements of minimum and maximum daily temperatures, relative humidity, daily downward solar radiation, and daily wind run (i.e., the daily mean wind speed multiplied by 24 h) from the AgriMet weather stations. These inputs are used both directly and to infer some variables such as the net longwave radiation. The parameterizations adopted for this purpose can be sources of error. As long as these parameterization errors are relatively stationary with respect to time, they will not unduly influence estimates of the variability in pET at a particular location.

The Penman–Monteith formulation (Jensen et al. 1990) represents another, and closely related, method based on a surface energy balance for estimating reference ET (e.g., Amatya et al. 1995; George et al. 2002; Scheff and Frierson 2014). The primary differences between the formulations are that the Penman–Monteith version includes a surface resistance/conductivity term and a different form for the aerodynamic transfer. For the present application, the two formulations provide very similar estimates. A comparison of daily values at the centrally located station of George for the summers of 2003–14 indicated that the Kimberly–Penman formulation yielded a mean value about 6% greater than the Penman–Monteith formulation. The two time series were highly correlated, with a linear correlation coefficient between the two series of ~0.97. Wright et al. (2000) compared ET estimated from both formulations with direct lysimeter measurements for crops of grass and alfalfa. Their overall results included somewhat lower standard errors for the Kimberly–Penman formulation, especially at the Kimberly, Idaho, site with a landscape resembling that of the Columbia basin. Other simpler schemes (e.g., Hargreaves and Samani 1982) have been devised for applications in which fewer input data are available, but these schemes are prone to larger errors, often require coefficients that are site specific, and are generally less accurate than any of the Penman combination methods when substantial input data are available (George et al. 2002). In summary, while the Penman–Monteith formulation provides similar results, we use the Kimberly–Penman formulation to estimate pET for the present analysis.

FIG. 1. Map of Washington with locations of the five stations used in the analysis.

It is emphasized that pET is a climatic parameter that represents a measure of the flux of water into the atmosphere given adequate soil moisture. It is different from the actual ET, which involves complicated and unmeasured processes and feedbacks linking the properties of the soil, vegetation, and atmosphere to the net flux of water between the land and atmosphere (e.g., Hobbins et al. 2001). Nevertheless, pET is of practical importance in that it corresponds with water requirements and, hence, irrigation demands in a relative sense (e.g., Allen et al. 1998).

The focus here is on mean summer (June–August, JJA) values of pET, as well as of the more basic meteorological variables related to pET. Our objectives are to document the changes in these quantities over the period of record, and to determine the properties of the regional atmospheric circulation associated with occurrences of anomalously low and high summer mean pET. The properties of the regional atmospheric circulation are characterized using the NCEP–NCAR reanalysis (Kalnay et al. 1996). The mean circulation anomalies associated with pET on a seasonal mean basis are compared with their counterparts accompanying short-term high-pET events. The latter are identified using five-station averages of the day-to-day values of pET, specifically the deviations from daily climatological values.

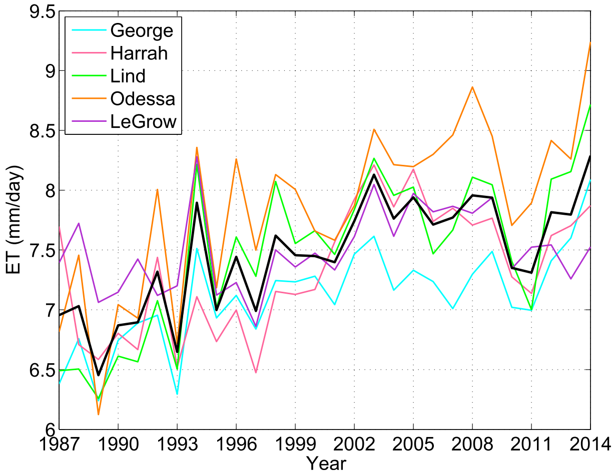

FIG. 2. The summer mean pET ($\mathrm{mm\,day^{-1}}$) for five sites in eastern Washington from the AgriMet Network from 1987 through 2014. The average of the five stations is denoted by the thick, black line. The standard error in the seasonal means for each of the five stations is typically $\sim$0.25 $\mathrm{mm\,day^{-1}}$.

3. Time series of pET and related variables

Time series of seasonal mean pET for the five eastern Washington stations considered (Fig. 2) reveal not just the expected year-to-year fluctuations, but also a prominent upward trend in pET over the period of record. The overall increases equate to 1–1.5 mm of water per day during recent as compared with early years, which are equivalent to differences of about 90–135 mm for the summers as a whole. A Mann–Kendall trend test was carried out to assess the statistical significance of the trend in pET averaged across the five stations. The result of this test is a tau of 0.53 and a two-sided p value of 0.0004, which implies a high degree of confidence (>99.9%) that the upward trend in pET is real.

It may be assumed that the systematic increase in pET was accompanied by a rise in regional air temperature. Seasonal mean air temperatures (Fig. 3) have had a positive correspondence with pET in terms of the year-to-year fluctuations. For example, the short period at the end of the record from 2011 to 2014 included prominent increases in both pET and temperature. From an overall perspective, there is a correlation coefficient of $\sim$0.64 between the five-station averages of these two variables over the 28-yr record. On the other hand, the overall trends in air temperature over the period of consideration are rather modest. In more specific terms, the mean temperature trends at the five stations range from about 0.01 to 0.06°C $\mathrm{yr^{-1}}$ over the summers of 1987–2014, with an average of 0.03°C $\mathrm{yr^{-1}}$. This value is comparable to the magnitude of the temperature trend reported by Abatzoglou et al. (2014) for the Pacific

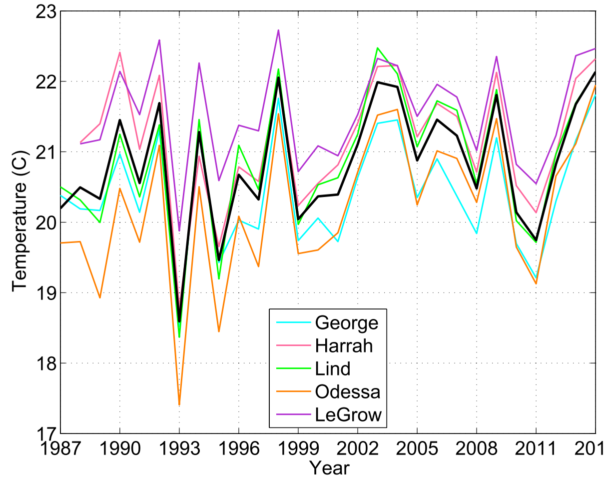

FIG. 3. As in Fig. 2, but for mean summer temperature (°C).

Northwest as a whole over the interval of 1980–2012. The important point to be made here is that the primary increase in pET from the early 1990s to the late 2000s was accompanied by little systematic change in temperature, and so to understand the overall change in pET, it is instructive to examine the variables that form the basis for pET.

The heat function term is the dominant contribution to pET. Especially on daily and longer time scales its value is largely determined by the net radiative heating rather than the soil sensible heat flux (Allen et al. 1998) and, in particular, the insolation (downward solar radiation). Time series of the mean summer insolation from the five stations are shown in Fig. 4. These series feature relatively low values from the late 1980s through the mid-1990s, systematic if not monotonic increases from the mid-1990s through the mid-2000s, and slight to moderate decreases over the last 5–7 yr of the record. The correlation coefficients between the seasonal mean pET and insolation at the individual stations range between 0.58 and 0.73, implying that the insolation explains about 35%–50% of the variance in the pET at the individual stations. The year-to-year fluctuations in insolation at the individual stations correspond with one another positively, but to a lesser extent than their counterparts in temperature. With regard to five-station averages, the correlation coefficient between the seasonal mean pET and insolation is $\sim$0.79, so the insolation accounts for slightly greater than 60% of the variance in pET in an aggregate sense. The overall increases shown in Fig. 4 are consistent with the decreases in daytime cloud cover from the PATMOS-x dataset (Tang and Leng 2013). In more quantitative terms, the average cloud fraction for the region of 46°–48°N, 118°–121°W based on the PATMOS-x product decreased

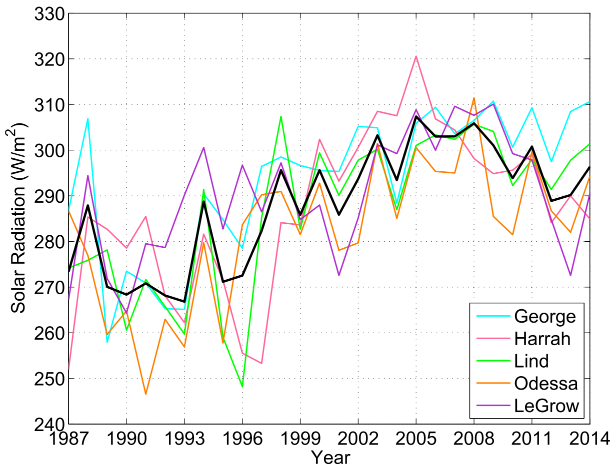

FIG. 4. As in Fig. 2, but for mean summer solar radiation (W m^{-2}).

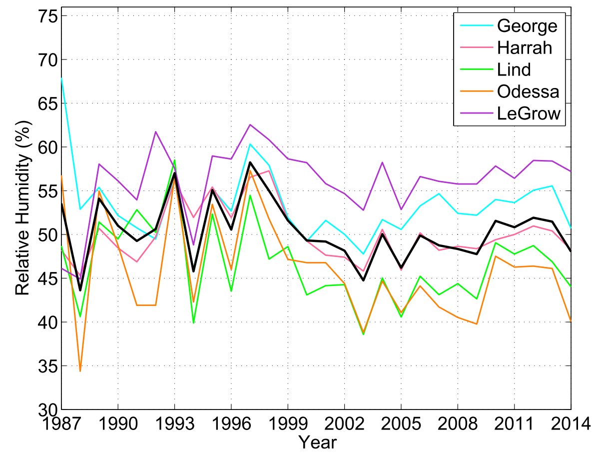

FIG. 5. As in Fig. 2, but for mean summer RH (%).

from 0.372 during the summers (JJA) of 1987–93 to 0.327 during the summers of 2003–09. The increasing solar radiation contributed to the positive trends in estimated pET over the period of record.

Time series of the values related to the wind function term, relative humidity (RH), and wind speed are shown in Figs. 5 and 6, respectively. We use RH here because it is the humidity variable directly measured at the weather stations. It is inversely related to the water vapor pressure deficit factor ($e_s - e_a$) in the wind function term. Based on linear correlations using seasonal mean values from the individual stations, the RH explains about 27%–40% of the variance in the year-to-year fluctuations in pET. The interannual fluctuations were greater in the first half of the record. Overall trends were minimal, with a five-station-average decrease of about 2%. Individual stations exhibited both a modest increase (LeGrow) and decrease (George). The 3-m wind records indicate slower mean wind speeds in the first four or five summers, but little in the way of systematic change over the remaining 20 yr of the record. These results imply that most of the increase in pET resulted from the summers becoming sunnier, which motivates additional scrutiny of this aspect of the weather of the region.

Since the changes in solar radiation account for most of the upward trend in pET, it is prudent to delve into potential measurement errors or discrepancies that might impact the validity of these time series. The procedure used was to determine the peak hourly values of downward solar radiation each year from the centrally located station at George, assuming that virtually all summers would include clear conditions near solar noon on a day near the summer solstice for evaluating the "quality" of the solar measurements. The results from this exercise using the high-frequency measurements from George are shown in Fig. 7. The peak values were consistently lower during the late 1980s and early 1990s, with a minimal trend over the latter two-thirds of the record. Is this time series an indication of an instrumental problem? While we cannot rule out the possibility that contamination/degradation of the sensor or other sources of errors impacted the solar radiation measurements and hence the derived values of pET, we note that at least the sense of the changes shown in Fig. 7 is consistent with global increases in clear-sky irradiance over the period of the 1990s (Wild et al. 2005). With regard to the Pacific Northwest, Riihimaki et al. (2009) found about a 1% increase per decade from 1980 to 2007 in the annual average clear-sky irradiance at Hermiston, Oregon, which is about 40 km south of LeGrow. This rate of increase is comparable to that in the peak annual values at George for the period of 1987–2007. A thorough analysis of the clear-sky solar irradiance in the record of

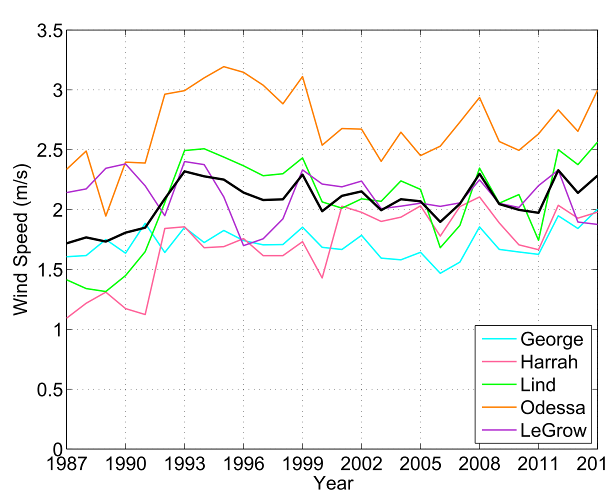

FIG. 6. As in Fig. 2, but for mean summer wind speed (m s^{-1}).

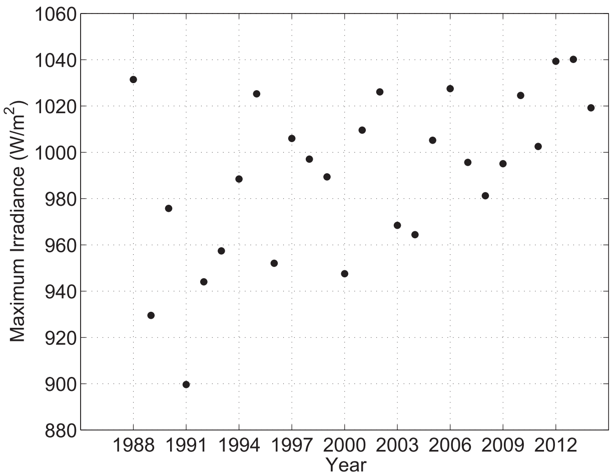

FIG. 7. Peak hourly values of insolation (W m^{-2}) during the summers of 1988–2014 at George.

interest is beyond the scope of the present study. The point we wish to stress here is that the changes in clear-sky values are equivalent to only about one-third to one-half of the 5%–10% increase in summer mean downward solar radiation (Fig. 4) observed at the five stations. The implication is that the majority of this increase in insolation can be attributed to a decrease in cloud cover. Presumably the variations in cloudiness, and inferred pET, are associated with deviations in the regional circulation, as addressed in the following section.

4. Regional circulation associated with anomalous pET

Our objective here is to document the regional atmospheric circulation patterns accompanying extreme pET events on daily time scales and to compare these patterns to those associated with highly anomalous pET on seasonal time scales. Our focus is on high-pET events and seasons because these are the periods with greater water demands. There are substantial differences in the nature of these patterns that were found, as will be demonstrated below.

First, we consider how the occurrence of short-term extreme events has been distributed temporally over the period of consideration. For this purpose the five-station-average daily pET anomalies are used; the extreme events (low and high) were arbitrarily defined as those with anomalous pET values of magnitudes greater than 1.5 standard deviations (1.8 mm day^{-1}). This threshold was selected with the twin goals of isolating the higher-amplitude events, but also including enough independent realizations to form meaningful composites. The number of both kinds of events per year is plotted in Fig. 8. Not surprisingly, there is a negative correspondence between the number of low- and high-pET events in the same year (the correlation coefficient between the two indices is about −0.35). It is interesting that with time there has been a more prominent drop in the number of low-pET events when compared with the rise in the number of high-pET events. For example, the summer of 1992 included eight high-pET events even though the mean values of pET that summer were less than average (Fig. 2), and the summer of 2005 included only two high-pET events but also above average values of mean pET. In other words, the seasonal mean pET appears to be more related to the number of especially low-pET days with thick clouds, with the recognition that fluctuations in baseline (seasonal mean) conditions can influence the counts of extreme days of both types. The year 2013 is an exception in that it has a relatively high number of both low- and high-pET days, especially considering that the seasonal mean pET is among the highest in the record (ranked eighth).

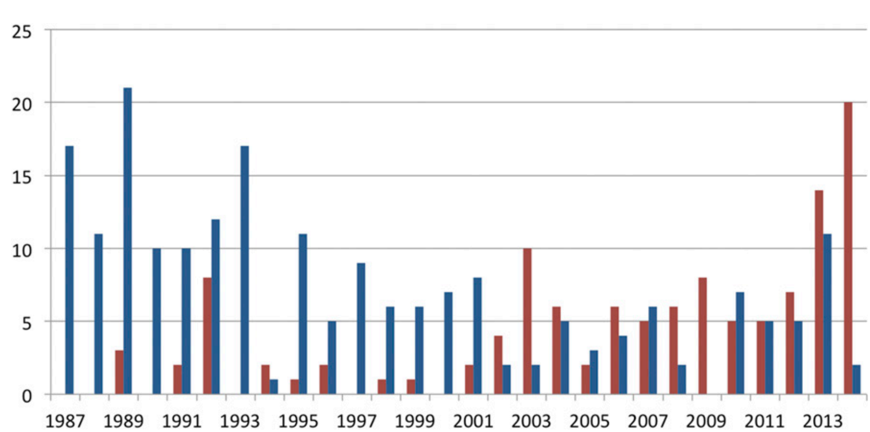

FIG. 8. The number of low- (blue) and high- (red) pET days per summer defined as those for which deviations in the five-station average from climatology exceed 1.5 standard deviations.

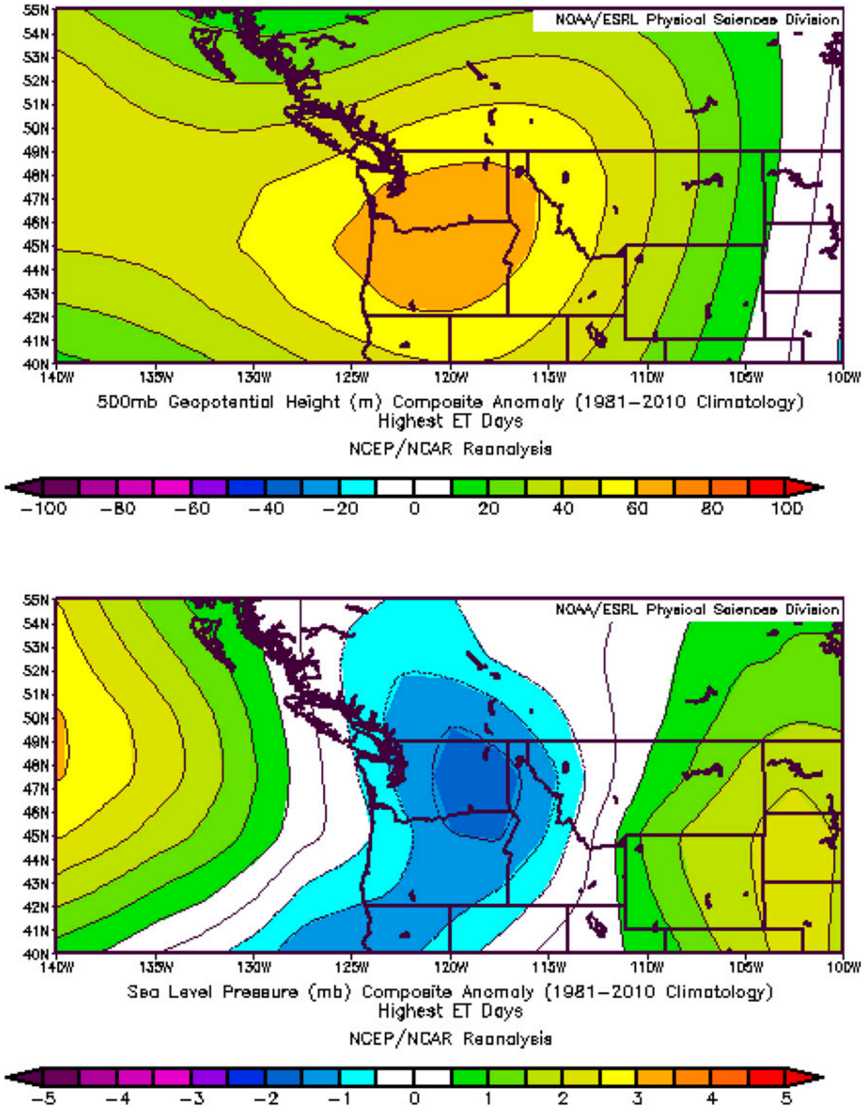

FIG. 9. Composite (top) 500-hPa Z anomalies (contour interval is 10 m) and (bottom) SLP anomalies (contour interval is 0.5 hPa) on the days in which the five-station-average pET anomalies exceed 1.5 standard deviations.

The atmospheric circulation associated with high-pET days is summarized in terms of 500-hPa geopotential height Z and sea level pressure (SLP) composite anomaly maps (Fig. 9). For eastern Washington State, these days include positive 500-hPa height anomalies in the mean of about 50 m over the area of interest, and SLP anomalies of about −1.5 mb. These situations resemble those with thermally induced troughs that accompany hot weather in the Pacific Northwest (Brewer et al. 2012; Bumbaco et al. 2013). The signature aloft on average is actually stronger on the day prior to the highest-pET days.

It might be expected that summers with relatively high pET in the mean would have circulation anomalies resembling, if weaker than, those during the days with short-term high-pET events. Indeed, a regression of the seasonal mean 500-hPa Z against pET yields a very similar pattern (Fig. 10, top) as its counterpart for the higher-pET days, with magnitudes significantly greater than zero over and south of the region of interest. A regression of the seasonal mean SLP against pET (Fig. 10, bottom) also resembles that for the higher-pET days (Fig. 9, bottom), with a smaller region of negative SLP anomalies significantly different from zero at the 95% confidence level over eastern Washington State.

Another way of characterizing the regional circulation with substantial anomalies in seasonal mean pET is

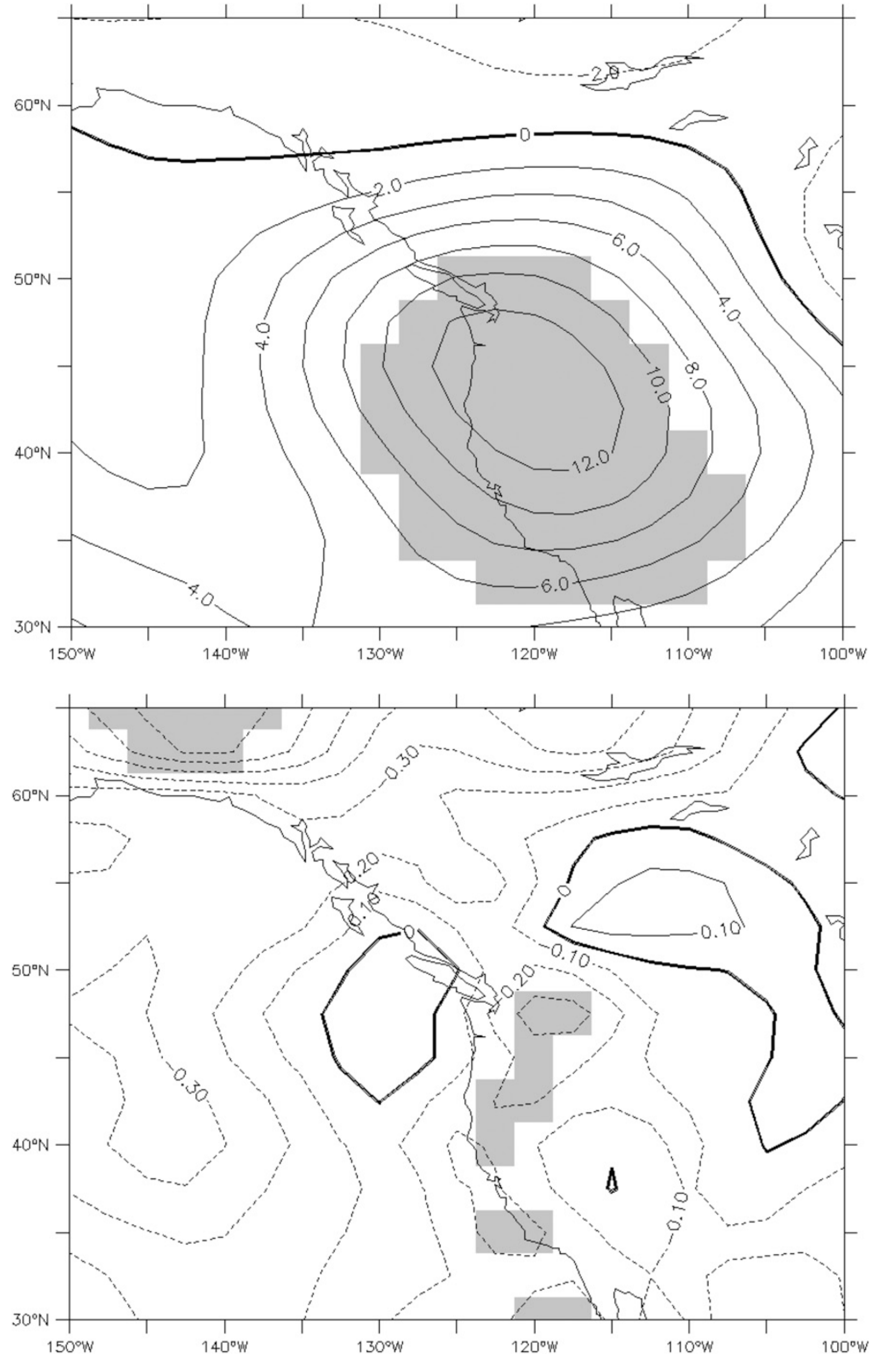

FIG. 10. Regression of (top) seasonal mean 500-hPa Z (contour interval is 2 m) and (bottom) SLP (contour interval is 0.1 hPa) against the five-station-average pET for the summers of 1987–2014. The shaded areas indicate regions where the magnitude of the signal is significantly different from zero with a confidence level of 95% or greater.

through examination of individual summers. Figure 11 illustrates the 500-hPa Z anomaly patterns for the four highest-pET summers of 2003, 2005, 2008, and 2014. Note that only the mean anomaly pattern for 2003 (Fig. 11a) bears a close resemblance to the patterns from the event composite (Fig. 9, top) and seasonal regression (Fig. 10, top). Of the four lowest-pET summers of 1989, 1990, 1991, and 1993 (Fig. 12), the 500-hPa Z patterns in 1989 and 1993 might be expected to be accompanied by relatively cool and cloudy weather. That is not very

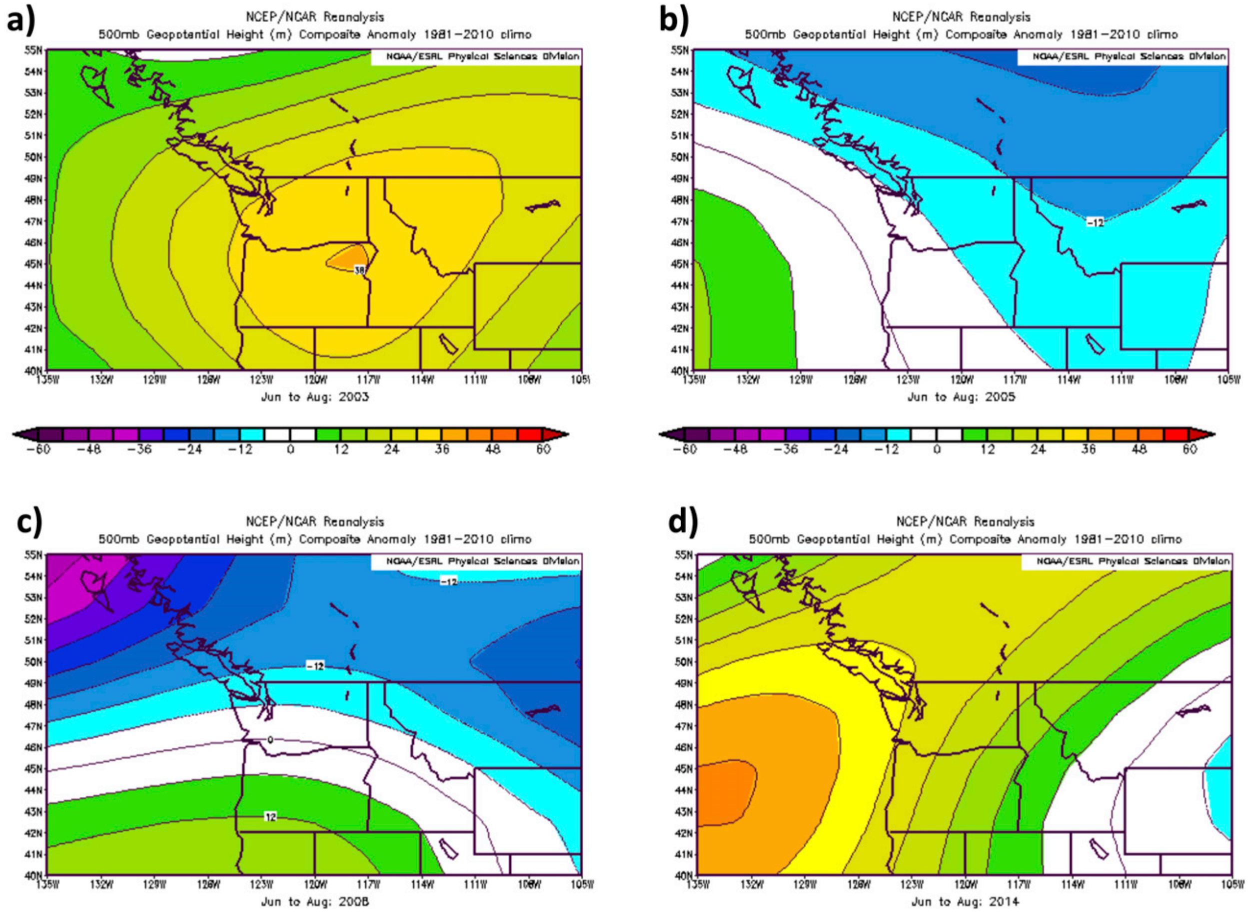

FIG. 11. Mean summer (JJA) 500-hPa Z anomalies (contour interval is 6 m) for the highest four pET summers [(a) 2003, (b) 2005, (c) 2008, and (d) 2014].

much the case for the other two summers. Our overall impressions based on these results, and inspection of 500-hPa Z anomalies for other years (not shown), is that summers in eastern Washington that are relatively sunny with high pET tend to be associated with positive Z and westerly flow anomalies at 500 hPa. The summers with negative pET anomalies tend to have lower 500-hPa Z and easterly to southeasterly flow anomalies aloft. A similar examination of the SLP in the summers with the highest and lowest pET also revealed a diversity of anomaly patterns. Here, the consistency with the overall regression pattern (Fig. 10, bottom) was less for the highest- than for the lowest-pET summers.

As a means of better understanding regional atmospheric properties related to pET, we also considered humidity patterns. Not surprisingly, there is a negative association between seasonal mean pET and 925-hPa RH over eastern Washington, as illustrated in the regression of 925-hPa RH on pET shown in Fig. 13. It is interesting that statistically significant signals were found for large areas over Alaska and the eastern North Pacific Ocean south of about 40°N. The regression of pET on the 500-hPa geopotential height (Fig. 10, top) and SLP (Fig. 10, bottom) yielded patterns restricted much more to the Pacific Northwest, especially for the 500-hPa geopotential height. The seasonal mean 500-hPa geopotential height is highly correlated with the 925-hPa RH locally over the Columbia basin ($r \sim -0.77$) and it is unclear why the regression patterns are so different in character outside of the region of interest. Conceivably, these results reflect overlap but not coincidence in the hemispheric-scale modes of variability (i.e., teleconnection patterns), related to regional atmospheric properties associated with pET in the Columbia basin. A full exploration of these connections is outside the scope of the present study.

A stronger relationship with pET was found with 925-hPa RH than with surface values of RH, presumably because the former is more strongly linked to overall boundary layer humidity and hence cloudiness. The linear

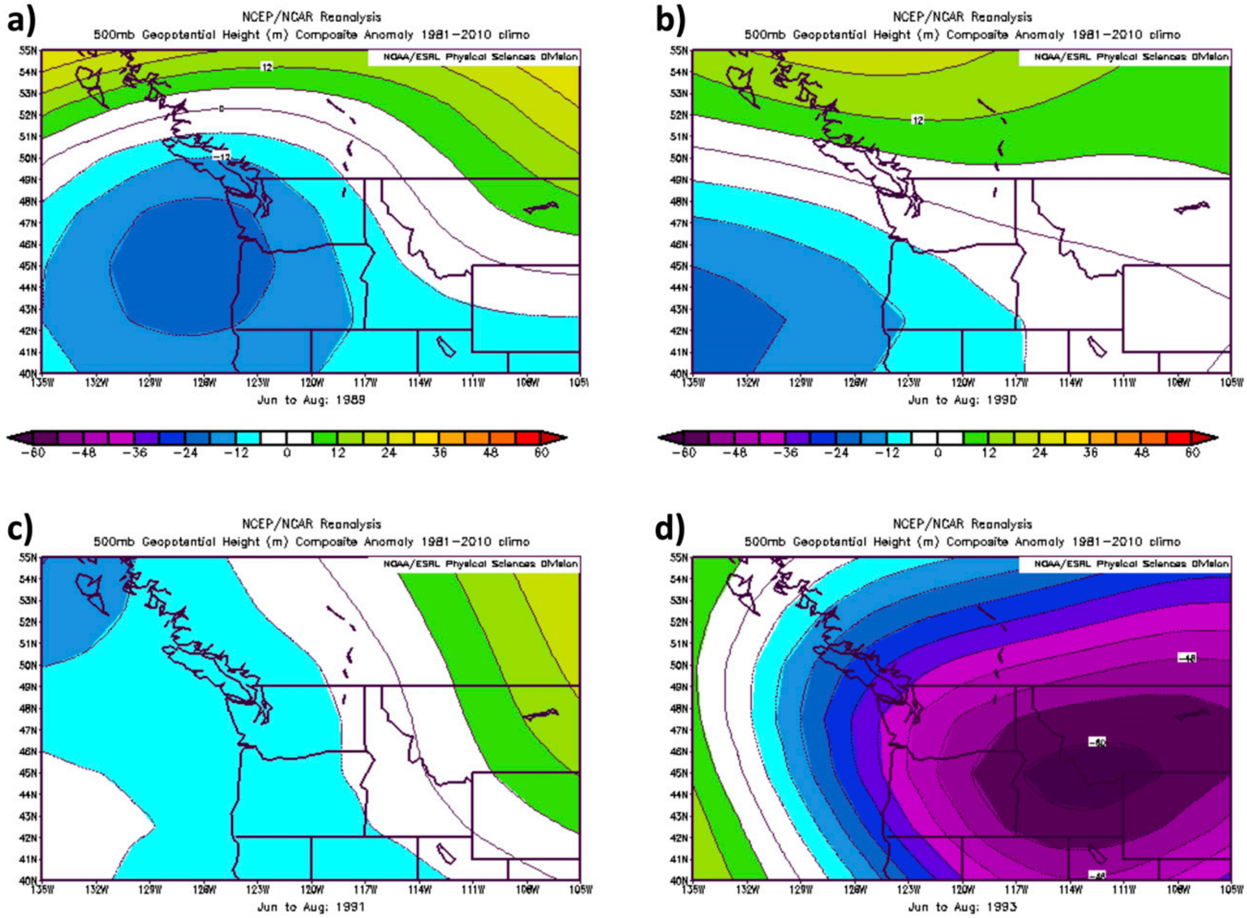

FIG. 12. As in Fig. 11, but for the lowest-pET summers [(a) 1989, (b) 1990, (c) 1991, and (d) 1993].

correlation coefficient between the seasonal mean pET and 925-hPa RH is essentially equal in magnitude (~0.69) to its counterpart between the seasonal mean pET and 500-hPa Z (~0.66) for a region (46°–48°N, 121°–118°W) encompassing the Columbia basin of eastern Washington State.

This result motivated further analysis of the 925-hPa RH record for the Columbia basin region. A linear fit to the time series of its seasonal means indicates an overall decline of about 5%, and conceivably this decline could explain a meaningful fraction of the increase in pET over the 28-yr record considered here. Toward quantifying this effect, the strength of the correspondence between the 925-hPa RH and pET on a year-to-year basis was determined using detrended versions of their time series; the correlation coefficient between the two detrended series is ~0.64. Assuming the strength of this relationship in the year-to-year variability also applies to longer-term (28 yr) trends, and given that the magnitude of the normalized trend in 925-hPa RH is about one-half that in pET, the result is that the rate of decline in 925-hPa RH accounts for about one-third of the linear trend in pET.

5. Final remarks

Time series of summertime pET in the Columbia basin of eastern Washington State based on measurements from five surface meteorological stations have been examined for the period of 1987–2014. A secular increase on the order of 1–1.5 mm day^{-1} was found for this period; the upward trend in an overall sense is highly significant (with a confidence level exceeding 99.9%). The increase in pET can be attributed in large part to a concomitant increase in seasonal mean insolation of about 25 W m^{-2}. While a portion (between one-third and one-half) of the change in insolation is likely due to a trend of global brightening (i.e., greater clear-sky irradiance in recent years when compared with the 1990s), it appears most of the increase in pET is due to the tendency for less cloudiness locally. This finding is corroborated by an overall decline of about 5% in 925-hPa RH from 1987 through 2014 based on NCEP–NCAR reanalysis data, assuming that 925-hPa RH corresponds positively with cloudiness.

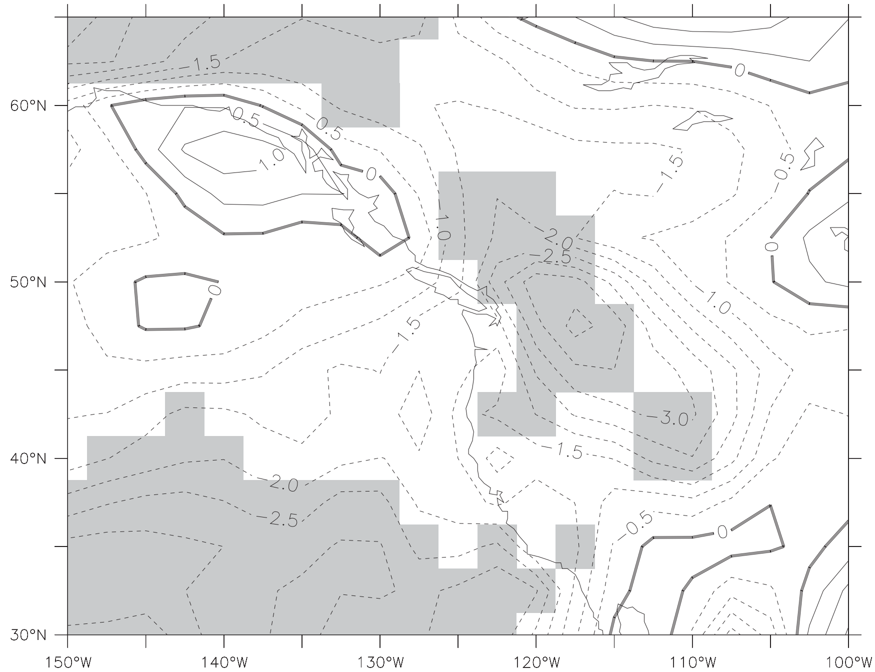

FIG. 13. Regression of seasonal mean 925-hPa RH (contour interval is 0.5%) against the five-station-average pET for the summers of 1987–2014. The shaded areas indicate regions where the magnitude of the signal is significantly different from zero with a confidence level of 95% or greater.

Our analysis included consideration of regional atmospheric circulation anomalies accompanying both short-term high-pET events and anomalous pET summers as a whole. Interestingly, an excess of high-pET days does not always occur in summers with greater mean seasonal pET. Instead, the mean summer pET appears to be more related to the number of low-pET days, which is indicative of cloud cover. High-pET days (greater than 1.5 standard deviations above the mean) were associated with composite anomalies of 50 m in 500-hPa Z and -1.5 hPa in SLP. These composite patterns more resemble, rather than match, their counterparts associated with hot temperatures in the Pacific Northwest (Brewer et al. 2012; Bumbaco et al. 2013). Summers with positive pET anomalies in an overall sense can include 500-hPa Z and SLP anomalies of a similar nature, if of lesser magnitude, than those during high-pET days, but that is not always the case. Examination of individual seasonal averages revealed a variety of regional circulation patterns for summers with higher, and lower, pET. There is more variation among the synoptic patterns on both the daily and seasonal time scales that bring about low pET. That being said, there is a tendency for high-pET summers to have had positive 500-hPa Z anomalies with westerly flow aloft while low-pET summers commonly possessed easterly to southeasterly flow anomalies aloft with negative 500-hPa Z anomalies. High-pET summers also tend to be associated with low values of regional 925-hPa RH and vice versa.

This paper represents an element of the ongoing effort by the Office of the Washington State Climatologist to better describe and understand the climate variability of Washington State. Our principal objectives have been to document the sizable changes that have occurred in summer pET, which is a climate parameter of practical importance with respect to agricultural water needs, and to begin determining how pET relates to the regional atmospheric circulation. Additional work using daily pET anomalies and different combinations and aspects of the circulation could help determine the best predictors in the regional circulation of pET. If it is indeed feasible to infer pET from global climate model simulations of these aspects, empirical downscaling may represent a reasonable method for estimating how pET is liable to change over future decades. While a drawback of using empirical downscaling is the ambiguity with which the statistical relationships will remain the same in a warming future climate, it may be a good choice for this problem. Simulated cloud amounts from high-resolution NWP models are sensitive to the parameterization scheme (Otkin and Greenwald 2008); dynamical downscaling includes its own source(s) of uncertainty.

Previous studies using global climate models (GCMs) show increases in pET in future climate scenarios between about 10% and 45% worldwide, with greater increases at higher latitudes (Scheff and Frierson 2014). Scheff and Frierson (2014) found that the increase in pET is due to the projected temperature warming itself, not because of an increase in net surface radiation. This increase in pET results in a trend toward drought and aridity globally (Feng and Fu 2013). The increase in pET observed in the Columbia basin as described here is mostly not related to increasing temperatures. A possible exception is the last few years of the record, which features rising values of pET and temperature, but little net change of insolation. This represents much too short of a period, however, to draw conclusions about whether anthropogenic climate change is becoming manifested with respect to pET in the Pacific Northwest. Still, further research into GCM representation of the key synoptic patterns associated with high pET could help indicate whether the relatively high values of pET over the past decade are liable to remain high or even increase locally, or revert back more to values characteristic of the earlier part of the record.

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