Estimation of Actual Evapotranspiration by the Complementary Theory-Based Advection–Aridity Model in the Tarim River Basin, China

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ABSTRACT

In this study, the complementary relationship between actual evapotranspiration (ETa) and potential evapotranspiration (ETp) was verified in the Tarim River basin (TRB) in northwest China. The advection–aridity (AA) model that is based on the complementary relationship (CR) was used to calculate ETa. Spatial and temporal trends in the estimated annual ETa and the factors that influenced ETa were investigated. The multiyear average ETa in the TRB for the period from 1961 to 2014 was 178.5 mm. There was an overall significant increasing trend (at a rate of 10.6 mm decade^{-1}) in ETa from 1961 to 2014; ETa increased at a rate of 22.9 mm decade^{-1} from 1961 to 1996 and decreased at a rate of 33.9 mm decade^{-1} from 1996 to 2014. Seasonally, ETa was strongest in summer, followed by spring and autumn. The spatial distributions of the annual and seasonal ETa were mostly consistent, with higher ETa values in the northeast, northwest, and southwest of the TRB, and lower ETa values in the mostly desert lands in the central and southeastern areas. While the energy budget (indicated by net radiation $R_n$) had little influence on ETa over time, the advection budget (indicated by the drying power of the air $E_a$) played an important role, explainable by Bouchet’s complementary relationship. In the Aksu River basin (ARB), ETa has increased because of an increase in the surface water supply (SWS). The change in ETa between 1996 and 1998 may have been caused by changes in the SWS and the advection budget during the same time period.

1. Introduction

Evapotranspiration, which links atmospheric processes and land surface processes in the climate system, is an important process in the hydrological cycle that contributes to the energy balance of the Earth’s surface (Dolman and De Jeu 2010; Ohmura and Wild 2002). Evapotranspiration is also important for predicting plant productivity and species richness (Fisher et al. 2011). To date, many studies of the hydrological cycle have concentrated on streamflow and precipitation (Hao et al. 2008; Fan et al. 2011; Tao et al. 2011), which are easier to observe and record than other elements of the water cycle. It is possible that evapotranspiration, as the most difficult variable to measure in the water balance (Lettenmaier and Famiglietti 2006), has not been given the attention it deserves.

To date, there have been many studies on pan evaporation (Liu et al. 2011; Tabari and Marofi 2011; Kim and Kim 2008) and potential evapotranspiration (ETp; Douglas et al. 2009; Yin et al. 2010; Spies et al. 2015). While pan evaporation and ETp can provide evidence of evaporation when the water supply is sufficient, the actual evapotranspiration (ETa), the process by which liquid water at or near the land surface becomes water vapor under natural conditions (Morton 1983), remains to be estimated. It is difficult to obtain sufficient and reliable data of ETa with in situ measurement instruments; for example, lysimeters are costly to install and maintain. Most studies of evapotranspiration have therefore been based on modeling results and satellite...
data (Barraza et al. 2015). In recent years, progress has been made in this research field through applications of Bouchet’s complementary relationship (CR), which relies on the feedback mechanisms between ETa and ETP.

The CR has been used to calculate and validate estimations of ETa in humid, semiarid, and arid regions (Kahler and Brutsaert 2006; Szilagyi and Jozsa 2008; Jaksa et al. 2013; Liu et al. 2012; Xu and Singh 2005; Lemeur and Zhang 1990; Haque 2003; Huntington et al. 2011; Liu et al. 2010). The CR model can be used to estimate ETa anywhere in the world, and it is particularly useful in areas where the water supply is less abundant (Haque 2003). To calculate land surface evapotranspiration, the CR requires only routine meteorological data and does not include the complex processes and interactions between soil, vegetation, and the atmosphere. The advection–aridity (AA) model (Brutsaert and Stricker 1979), the Granger–Gray (GG) model (Granger and Gray 1989), and the Complementary Relationship Areal Evapotranspiration (CRAE) model (Morton 1983) are all based on the CR. While the AA model is based on relatively few parameters and uses a simple algorithm, it still achieves highly accurate results and has been widely used in different climatic regions, including arid lands (Haque 2003; Lemeur and Zhang 1990; Liu et al. 2010; Xu and Singh 2005).

Many previous studies have attempted to attribute changes in either ETP or reference evapotranspiration to changes in meteorological factors. Such studies have reported, for example, that regional declines in ETP may have been the result of decreased wind speeds and increasing relative humidity on the Tibetan Plateau (S.-B. Chen et al. 2006) or of decreases in surface wind speeds in Australia (Roderick et al. 2007). Studies have also reported that decreases in reference evapotranspiration are most likely a response to increases in precipitation (Irmak et al. 2012). Wang et al. (2015) found that, out of a range of variables, net radiation and wind speed had a greater influence on pan evaporation in low-elevation regions in the Three-Rivers Source Region, while actual vapor pressure and air temperature had a greater influence in high-elevation regions. To our knowledge, few studies have examined the factors that drive changes in ETa. Existing studies have reported that the decline in the global ETa is the result of a limited moisture supply (Jung et al. 2010). A case study of ETa in the Mississippi River basin for the period from 1949 to 1997 showed that increases in precipitation and human water use were the primary and secondary drivers of increases in ETa, respectively (Milly and Dunne 2001). With the exception of southeastern China, where changes in ETa are driven by changes in ETP, precipitation is the main driver for changes in ETa throughout most of China (Gao et al. 2007). It was reported that the declining ETa in the basins of the Yangtze River (Xu et al. 2006; Wang et al. 2011) and the Pearl River (Wu et al. 2017) in China is mainly caused by a decrease in the net total radiation. Hobbs et al. (2004) proposed that the radiative energy and advective budgets should be jointly considered to explain the relationship between pan evaporation and ETa.

In recent years, there have been numerous regional-scale studies of ETa within China in humid, semihumid, semiarid, and arid climatic zones, including the basins of the Yangtze River (Wang et al. 2011), Yellow River (Liu et al. 2006), Haihe River (Gao et al. 2012; Li et al. 2013), and Pearl River (Wu et al. 2017); the Hexi corridor of Gansu Province (Zhang et al. 2008); parts of the Tarim River basin (TRB; Liu et al. 2007; Li et al. 2011; Yuan et al. 2015), central Asia, and Xinjiang Province (X. Chen et al. 2012); and all of China (Gao et al. 2007). However, to date, studies of ETa in either Xinjiang Province or the TRB have only focused on short periods or specific areas, with the result that there is no clear understanding about long-term changes in ETa and the drivers of change for the entire TRB. In this area, the stability and certainty of the water system have already been compromised by climate change and human activity, with considerable impacts on fragile inland ecosystems (Y.-N. Chen et al. 2012; Hartmann et al. 2016). Convincing and reliable ETa data are necessary to ensure the ongoing prosperity of the oases within the river basin, where high-quality water is scarce, and there is competition for limited water resources in the irrigated areas (Brunel et al. 2006). In this study, we examined spatial and temporal variations in the annual ETa over the entire TRB. Further, with the aim of providing robust science to support an understanding of climate change and the status of the water cycle in this arid/hyperarid region, we also investigated the potential contributors to variability in ETa. The information derived from this study may also provide information that will support ecosystem and water resources planning and management.

2. Materials and methods

a. Study area

The TRB (Fig. 1) extends over the area from 34°20′ to 43°39′N and from 71°39′ to 93°45′E and is the largest inland river basin in China. It consists of nine drainage systems with 144 tributaries and covers a total area of 1.02 million km². Mountain and desert areas account for 47% and 33% of the basin, respectively, and plains
account for the remaining 20% (Ling et al. 2013). The high mountains that surround the basin block most of the moisture, thus preventing it from reaching the basin. Accordingly, a hyperarid continental climate, which is characterized by scarce precipitation, a large temperature range, and high ETp, dominates the basin. The TRB is a pure dissipative inland river basin, and river runoff is mainly generated by snow and glacial melt from the high mountains to the north, west, and south of the Tarim River. Several headwater tributaries flow into the main channel of the Tarim River. Among these, the Aksu River accounts for 74.44% of the runoff, the Hotan River accounts for 20.35%, and the Kongqi and Yarkant Rivers account for 4.7% and 0.51%, respectively (Chen et al. 2014).

Precipitation plays an important role for water supply in the TRB. Average annual precipitation across the TRB is about 82 mm (Fig. 2a) and has...
shown a significant increasing trend (at a rate of 12.0 mm decade$^{-1}$) during the period from 1961 to 2014. Because of large topographic differences, precipitation is spatially unevenly distributed. As shown in Fig. 2b, the meteorological stations in the basin are mainly located in the plain area. Precipitation decreases gradually from northwest to southeast. Average annual precipitation in the mountain areas of the Kashgar and Aksu River basins is about 170–200 mm and is greater than or equal to 250 mm in the Kaidu River basin. Annual precipitation decreases to about 50–80 mm in the plain area and even less than or equal to 30 mm in the desert lands.

An annual runoff of about $400 \times 10^8$ m$^3$ is recorded at the foot of the mountains from where water is supplied to the piedmont plain and mainstream of the Tarim River. The annual runoff depth in the mountain area is about 100–150 mm, and the maximum runoff depth can reach more than 500 mm (Chen et al. 2014). During the period from 1961 to 2014, the average air temperature in the TRB has increased at a rate of 0.3°C decade$^{-1}$ (Fig. 3). Increased runoff was observed in nearly every headwater stream in the TRB during the period from 1957 to 2008 (Chen et al. 2014); this increase cannot be explained by precipitation alone and may include a significant contribution from shrinking glaciers (Shen et al. 2003; Shi et al. 2007; Yao et al. 2007). Wetter conditions have been detected at most stations in the TRB during the warm season since 1986 (Tao et al. 2014). The ecosystems in the lower reaches of the Tarim River have sustained serious damage in recent years as the inflow to the upper-middle reaches has decreased dramatically, such that a channel in the lower reaches of the Tarim River has been cut off, leaving a dried up section that extends up to 321 km (Y.-N. Chen et al. 2006). In these conditions, the vegetation struggles to survive, and 68% of the natural vegetation has been lost and 47% of Populus euphratica have died (Chen et al. 2003). In addition, the area influenced by desertification has increased at a rate of between 150 and 200 km$^2$ every year (Chen et al. 2003).

b. Data

In the current study we analyzed daily observed data from 46 meteorological stations in the TRB that covered the period from 1961 to 2014 and included air temperature, maximum/minimum air temperature, atmospheric pressure, actual vapor pressure, wind speed at a height of 10 m, sunshine duration, and total precipitation. The data quality was checked by means of climatic boundary values, extremum values, and internal consistency at the National Meteorological Information Center of the China Meteorological Administration.

The hydrological data in this study included streamflow from a total of 12 hydrological stations. Annual data were available for the period from 1961 to 2011 for the Shaliguilanke, Xiehela, and Xidaqiao stations in the Aksu River basin (ARB) and the Dashankou and Yanqi stations in the Kaidu River basin (KRB), and for the period from 1961 to 2000 for the Tongguziluoke, Wuluwati, and Xiaota stations in the Hotan River basin (HRB). Multiyear average runoff was available for the period from 1987 to 2011 for the Pochengzi, Kamuluke, Kalasu, and Tuokexun stations in the Weigan River basin (WRB). Annual streamflow data were obtained from the China Hydrological Yearbook–Inland Rivers, published by the Hydrological Bureau of the Ministry of Water Resources of the People’s Republic of China. The locations of the meteorological stations, the hydrological stations, and the subbasins are shown in Fig. 1.

c. Methods

Bouchet (1963) proposed that, under constant external energy and sufficient moisture, evapotranspiration on the surface is wet environment evapotranspiration (ETw), which is equal to half of the sum of ETa and ETp. If soil moisture decreases, ETa will decrease and the energy previously used for evapotranspiration will become available. This remaining energy will cause an increase in ETp, and the increase should be equal to the residual energy. Decreases in ETa, such that it is less than the ETp, influence the temperature, the intensity of turbulence, and the humidity of the air in the surface layer. The relationship between ETa and ETp is complementary, which means that the rate of increase or decrease in ETa is equal to the rate of decrease or increase in ETp. The general equation of the complementary relationship can be expressed as
ETa + ETp = 2ETw.  

(1)

This equation can be used to calculate the annual, monthly (Morton 1976, 1983), and daily ETa (Brutsaert and Stricker 1979), as well as ETa for shorter time steps; for example, Parlange and Katul (1992) reported changes in ETa at a 20-min time step.

The water balance method for closed river basins was used to calculate the annual ETa for the period from 1961 to 2000. This was done to verify the complementary relationship between ETa and ETp and to calibrate the parameters of the ETa model. The annual water balance can be expressed as follows:

\[
\text{ETa} = P - (R_{\text{out}} - R_{\text{in}}) - \Delta W = P + R_{\text{in}} - R_{\text{out}} - \Delta W, 
\]

(2)

where P is precipitation (mm), Rout is runoff (mm) that flows out of the basin, and Rin is runoff (mm) that flows into the basin. The term \(\Delta W\) represents the change in terrestrial water and can be assumed to be negligible for annual values and for multiple years. Equation (3), the Penman equation (Penman 1948), was used to calculate the annual ETp:

\[
\text{ETp} = \frac{k}{k + \gamma} (R_n - G) + \frac{\gamma}{k + \gamma} E_a, 
\]

(3)

where \(k\) represents the slope of the saturation vapor pressure curve at the air temperature, \(\gamma\) is the psychometric constant, and \(R_n\) is the net radiation near the surface. Meteorological factors, including the air temperature, the maximum air temperature, the minimum air temperature, the actual vapor pressure, and the sunshine duration, were used to calculate \(R_n\). Variable \(G\) is the soil heat flux. According to Allen et al. (1998), the magnitude of the daily or 10-day soil heat flux is relatively small compared to \(R_n\) and is often ignored; thus, \(G_{\text{day}} = 0\). The magnitude of the soil heat flux for monthly periods is still very small. We found that the difference of annual ETa calculated with or without \(G\) is <0.1 mm in the TRB. For calculating the daily ETa for the nonfrozen period, \(G_{\text{day}}\) is considered to be 0 in this study. Parameter \(E_a\) is the drying power of the air and is a function of the vapor pressure deficit and wind speed. The meteorological factors used in the Penman equation included air temperature, maximum air temperature, minimum air temperature, atmospheric pressure, actual vapor pressure, wind speed at a height of 2 m, and sunshine duration. The Ångström formula (Ångström 1924) was used to calculate the solar radiation:

\[
R_s = \left(a + b \frac{N}{N} \right) R_a, 
\]

(4)

where \(R_s\) is extraterrestrial solar radiation, \(n\) is the actual sunshine duration, \(N\) is potential sunshine duration, and \(a\) and \(b\) are regression constants. There are two radiation stations in the TRB, Kashi station and Hotan station. For Kashi station, \(a = 0.25\) and \(b = 0.46\), and for Hotan station, \(a = 0.25\) and \(b = 0.48\) (Chen et al. 2004). The constants \(a\) and \(b\) for the TRB were calculated by averaging the values of both stations resulting in \(a = 0.25\) and \(b = 0.47\).

A logarithmic wind speed profile was used to adjust the wind speed data obtained from instruments at a height of 10 m to the wind speed for the standard height of 2 m (Allen et al. 1998):

\[
U_2 = U_z \frac{4.87}{\ln(67.8z - 5.42)},
\]

(5)

where \(U_2\) is the wind speed at 2 m above the ground surface, \(U_z\) is the measured wind speed at \(z\) meters above the ground surface, and \(z\) is the height of the measurement above the ground surface.

The annual ETa and the corresponding ETp plotted against the moisture index EMI (EMI = ETa/ETp) for the period from 1961 to 2000 for the ARB, HRB, and KRB are displayed in Figs. 4a–c, respectively. The evaporative surface moisture index is represented by \(E_{\text{MI}}\) and has a maximum value of 1. It indicates how close the landscape is to the potential conditions (Kahler and Brutsaert 2006). Although there is scatter in the data, there is a complementary relationship between the estimated annual ETa and the estimated annual ETp. As the conditions become increasingly moist, ETa increases while ETp decreases.

For further verification of the CR in the ARB and HRB, the period 1961–2000 was divided into two subperiods (1961–80 and 1981–2000). The CR in the ARB for the subperiods of 1961–80 and 1981–2000 is displayed in Figs. 4d–g, respectively, and that in the HRB is shown in Figs. 4f and 4g. It can be seen in Figs. 4d–g that there is still a CR between ETa and ETp over shorter periods. The obvious complementary behavior of ETa and ETp in the ARB, the HRB, and the KRB mean that Bouchet’s CR can be applied in the TRB.

In the AA model, ETp is calculated using the Penman method (Penman 1948), and the wet environment evapotranspiration ETw is estimated by the Priestley–Taylor equation (Priestley and Taylor 1972), as follows:

\[
\text{ETw} = a \frac{k}{k + \gamma} (R_n - G),
\]

(6)

Values of \(k\), \(\gamma\), \(R_n\), and \(G\) are defined in the Penman equation. The Priestley–Taylor evaporation coefficient
that varies spatially depending on the characteristics of the underlying surface is represented by $\alpha$ (Eagleson 2002). The AA model is calculated as follows:

$$ETa = (2\alpha - 1) \frac{k}{k + \gamma} (R_n - G) - \frac{\gamma}{k + \gamma} Ea.$$  \hspace{1cm} (7)

Using the water balance, $\alpha$ was calibrated for the ARB, HRB, KRB, WRB, and the Taklimakan Desert. In the ARB, HRB, and KRB, the regions that were used for calibration refer to the area between the hydrological stations along the mountain edge and the control stations of the respective subbasins. In the ARB, the calibrated area is located between Xiehela, Shaligulake, and Xidaqiao stations; in the HRB between Tongguiziluoke, Wuluwati, and Xiaota stations; and in the KRB between Dashankou and Yanqi stations. In the WRB, the area between Pochengzi, Kamuluke, Kalasu, and Tuokexun stations was selected for calibration. For these subbasins, the annual ETa was estimated by the regional water balance equation that is equal to the sum of areal precipitation and the runoff residue (input from the hydrological stations along the mountain edge, output from the control stations). In the Taklimakan Desert, only precipitation was included in the water balance to calculate the annual ETa.

The values of $\alpha$ were determined by the minimum relative error between the multiyear average ETa estimated by the AA model and the multiyear average ETa calculated by the water balance method. The relative error $\mu$ can be expressed as

$$\mu = \frac{|ETa_{AA} - ETa_{WB}|}{ETa_{WB}} \times 100,$$  \hspace{1cm} (8)

where ETa_{AA} is estimated by the AA model, and ETa_{WB} is calculated by the water balance method.

We used linear regression to analyze the trends in the variables and the nonparametric Mann–Kendall (MK) test (Mann 1945; Kendall 1975) to assess the significance.
3. Results

of trends. The sequential Mann–Kendall test (Sneyers 1990) was applied to identify abrupt changes in the time series of ETa during the period from 1961 to 2014. We also used the Thiessen polygon method (Thiessen 1911) to calculate the average precipitation over the basin and surface evapotranspiration. We assessed the relationships between the variables using Spearman’s rank correlation coefficients.

In this study, the nonfrozen period was selected to analyze the annual ETa from 1961 to 2014 (Fig. 5). We defined spring, summer, and autumn as the periods from the first day of the nonfrozen period to 31 May, from 1 June to 31 August, and from 1 September to the end of the nonfrozen period, respectively.

3. Results

The ARB, HRB, KRB, WRB, and the Taklimakan Desert were selected as regions to calibrate α. The calibration period was from 1961 to 1980, and the validation period was from 1981 to 2000 for the ARB, HRB, and KRB. For the WRB, hydrological data were only available for the period from 1987 to 2011, and for the Taklimakan Desert, precipitation data were only available from 1996 to 2014; these data were used for calibration only. The results listed in Table 1 show α values of 0.945, 0.994, 1.023, 0.795, and 0.888 for the ARB, HRB, KRB, WRB, and the Taklimakan Desert, respectively. For the remaining areas of the TRB, the α value was calculated as the area-weighted average of the α values from the five calibration areas (0.933). Compared with ETa calculated by the water balance equation, the relative error of ETa estimated by the AA model is about 7.4% and 7.5% in the ARB, 23.8% and 23.6% in the HRB, and 10.7% and 11% in the KRB for the calibration period and the validation period, respectively. ETa estimated by the AA model and ETa calculated by the water balance method are basically equal over the time period of 40 years for the ARB, HRB, and KRB and during the shorter periods of available data for the WRB and the Taklimakan Desert.

a. Temporal changes of actual evapotranspiration

The annual ETa in the TRB from 1961 to 2014 is presented in Fig. 6a. The multiyear average ETa in the TRB was about 178.5 mm. ETa in the basin showed a significant increasing trend at a rate of 22.9 mm decade\(^{-1}\) for the period from 1961 to 1996 and a sharp declining trend at a rate of 33.9 mm decade\(^{-1}\) for the period from 1996 to 2014. There was an overall significant increasing trend at a rate of 10.6 mm decade\(^{-1}\) for the period from 1961 to 2014. The annual ETa was higher from 1987 to 2006 than during other time periods. The temporal variation in the seasonal ETa is shown in Fig. 6b. Over the analysis period, the seasonally averaged ETa was highest in summer (ETa = 114.8 mm), followed by spring (ETa = 42.0 mm), and autumn (ETa = 21.8 mm). The summer and autumn ETa values peaked in the mid-1990s and the spring ETa in the early 2000s. ETa showed consistent increases from 1961 until the mid-1990s or the early 2000s, followed by an obvious declining trend. Overall, ETa for spring, summer, and autumn still increased from 1961 to 2014 at rates of 3.3, 5.6, and 1.6 mm decade\(^{-1}\), respectively.

The decadal variations in the annual and seasonal ETa and the amplitude of the variations relative to the mean ETa in the TRB are listed in Table 2. The annual and seasonal values of ETa were at the maximum in the 1990s, followed by the period from 2000 to 2014, and the 1980s. ETa was relatively low in the 1960s and 1970s, less than the multiyear mean of the period of analysis. An abrupt change was detected in 1979 and ETa has increased significantly since 1984 (Fig. 7).

b. Spatial variations in actual evapotranspiration

The spatial distributions of the annual and seasonal ETa over the TRB are shown in Fig. 8. Although the distribution patterns of annual ETa (Fig. 8a) and ETa in the different seasons (Figs. 8b–d) seemed to be diverse, they were roughly consistent, and ETa values were higher in the northeast, northwest, and southwest of the TRB than in the central and southeastern areas. High ETa values were mainly confined to the Kaidu, Aksu, Kashgar, Yarkant, and Hotan River basins. In these regions, the annual ETa is mostly greater than 200 mm, the spring ETa is mostly greater than 50 mm, the summer ETa is for the most part greater than 130 mm, and the autumn ETa is mostly greater than 20 mm. The highest annual and autumn ETa values were found in the HRB, and the maximum ETa reached 363.6 and 59.9 mm, respectively. The highest spring and summer ETa values with 106.1 and 220.6 mm were detected in the KRB. The ETa values in the desert lands in the central, southwestern, and northern TRB were relatively low. A large part of this area had an annual ETa of
less than or equal to 110 mm. The spring, summer, and autumn ETa values were less than 30, 80, and 10 mm, respectively. The ETa values at Kuche station in the WRB and in the Taklimakan Desert were very low, with annual, spring, summer, and autumn ETa values lower than 23, 7, 18, and 2 mm, respectively.

The spatial distributions of the annual and seasonal ETa trends are presented in Fig. 9. The seasonal variations are similar to the annual variations, in that ETa was increasing in most areas, but showed random decreasing trends throughout the TRB. There were significant increasing trends (significant at the 0.01 level) across wide areas in the northeast, north, west, and in the central desert lands. Significant decreases in the annual and seasonal ETa were only detected at four stations in the Kaidu, Kashgar, Keriya, and Weigan River basins.

c. Impact factors of actual evapotranspiration

1) Correlation between ETa and surface water supply

We attempted to determine whether the variations in ETa were caused by changes in the SWS. The Aksu River is the main supply to the Tarim River and accounts for about 75% of the Tarim River’s streamflow; we therefore used it as an example to assess the correlation between ETa and SWS.

The Aksu River is fed by two headwaters, the Kumarik and Toxkan Rivers, about which flow information is recorded at the Xiehela and Shaliguilanke hydrological stations, respectively. Glacier melt contributions to runoff are 35%–48% for the Kumarik River and 9%–24% for the Toxkan River (Duethmann et al. 2015). The SWS consists of streamflow measured at the Xiehela and Shaliguilanke stations and areal precipitation in the Aksu River basin. We considered the period from 1961 to 2011 using the hydrological data that were available for up to 2011. The relationship between the basin-averaged ETa and SWS for the period from 1961 to 2011 is presented in Fig. 10. Overall, ETa in the ARB increased significantly at a rate of 13.8 mm decade$^{-1}$ from 1961 to 2011 and was similar to the trends of ETa in the TRB. The positive trend continued until 1996, after which ETa decreased by 50.0 mm decade$^{-1}$. Examination of the period from 1961 to 2011 showed that SWS also increased significantly at a

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Calibration area (km²)</th>
<th>$\alpha$</th>
<th>$R_{in} - R_{out}$</th>
<th>Precip</th>
<th>AA model</th>
<th>Relative diff.</th>
<th>Calibration period (1961–80)</th>
<th>Validation period (1981–2000)</th>
</tr>
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<tbody>
<tr>
<td>Aksu</td>
<td>11 141</td>
<td>0.945</td>
<td>123.5</td>
<td>107.5</td>
<td>213.8</td>
<td>7.4%</td>
<td>112.9</td>
<td>135.5</td>
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<tr>
<td>Hotan</td>
<td>14 312</td>
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<td>247.7</td>
<td>31.1</td>
<td>212.4</td>
<td>23.8%</td>
<td>237.3</td>
<td>43.1</td>
</tr>
<tr>
<td>Kaidu</td>
<td>3494</td>
<td>1.023</td>
<td>263.6</td>
<td>58.8</td>
<td>288.0</td>
<td>10.7%</td>
<td>233.0</td>
<td>88.8</td>
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<tr>
<td>Weigan (1987–2011)</td>
<td>8738</td>
<td>0.795</td>
<td>13.5</td>
<td>143.6</td>
<td>157.3</td>
<td>0.2%</td>
<td>—</td>
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</tr>
<tr>
<td>Taklimakan Desert (1996–2014)</td>
<td>330 000</td>
<td>0.888</td>
<td>0</td>
<td>23.9</td>
<td>23.7</td>
<td>0.2%</td>
<td>—</td>
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</tr>
<tr>
<td>Other regions</td>
<td>0.933</td>
<td>—</td>
<td>—</td>
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FIG. 6. Temporal variation in the annual and seasonal ETa in the TRB from 1961 to 2014: (a) annual ETa and (b) seasonal ETa.
rate of 26.4 mm decade\(^{-1}\). More specifically, SWS increased from 1961 to 1998 and then decreased. Although there were some differences between the trends for SWS and ETa, the overall increasing trends were consistent. The correlation coefficient between ETa and SWS reached \(\rho = 0.79\) for the period from 1961 to 2011. Similar to ETa, SWS was relatively low during the period from 1961 to 1985. SWS increased from 1986 to 1998 and then decreased, and ETa also increased until 1996 and then decreased. SWS was somewhat insufficient in 2009 but increased in 2010, and again, ETa mirrors this variation. In addition, changes in ETa and the SWS were consistent from 1996 to 1998, which shows that ETa and the SWS are closely correlated. Sufficient SWS is the basic requirement for ETa in arid regions. Here, the basic SWS for soil moisture quickly evaporates into the air; when SWS is inadequate, ETa is weak, while when SWS is abundant, ETa is strong.

2) CORRELATIONS BETWEEN ETa AND METEOROLOGICAL FACTORS

Whether the energy or advective budget could contribute to the evapotranspiration in the TRB was tested in this part. The net radiation \(R_n\) (solar radiation) is the dominant source of the energy budget, while drying power of the air \(E_a\) is a good indication of the advective budget. Accordingly, \(R_n\) represents the energy budget, and \(E_a\) represents the advective budget. The annual variations in \(R_n\) and \(E_a\) in the TRB from 1961 to 2014 are shown in Figs. 11a and 11b, respectively. The average \(R_n\) over the TRB was about 2471.7 MJ m\(^{-2}\). The \(R_n\) showed an overall significant increase \((P < 0.01)\) from 1961 to 2014, and the rate of increase reached 15.4 MJ m\(^{-2}\) decade\(^{-1}\), which equates to a 54-yr increase of 83.16 MJ m\(^{-2}\). The \(E_a\) averaged over the TRB was about 0.9 mm. The \(E_a\) decreased significantly \((P < 0.01)\) from 1961 to 2014 at a rate of \(3.3 \times 10^{-2}\) mm decade\(^{-1}\), which translates to a 54-yr decrease of 0.18 mm. The significant decrease of \(E_a\) (Fig. 11b) had ceased during 1996–98, after which point \(E_a\) began to increase. Trends in \(E_a\) and ETa in the TRB were completely contrasting, but both reached a turning point during 1996–98.

The relationships between ETa and the meteorological factors that may have caused the increase in ETa were examined at the annual scale across the entire TRB. The correlation coefficients between ETa and \(R_n\) and between ETa and \(E_a\) are \(\rho = 0.44\) and \(\rho = -0.93\), respectively. This suggests that \(E_a\) might have more influence on ETa than \(R_n\).

To quantify the impacts of \(R_n\) and \(E_a\) on ETa, the following sensitivity experiment was carried out: at first, time series of \(R_n\) and \(E_a\) were linearly detrended. Then, ETa was recalculated using either the detrended \(R_n\) or the detrended \(E_a\) time series, but with the original data of the other climate variables. After that, the difference of the recalculated ETa and the original ETa was calculated to assess the impact of \(R_n\) and \(E_a\). Removing the decreasing trend of \(E_a\) resulted in a large difference between the original annual ETa and the recalculated ETa. The recalculated ETa increases only at a rate of 5.6 mm decade\(^{-1}\), which is about half of the increasing rate of the original ETa; moreover, no sharp decreasing trend was found after the mid-1990s. Removing the increasing trend of \(R_n\) resulted in a smaller difference between the original ETa and the recalculated ETa. This
indicates that the declining $E_a$ is predominantly important for the increasing trend of ETa, while the impact of $R_n$ on ETa is limited (Fig. 12).

4. Summary and discussion

In this study, the complementary relationship (CR) between basinwide actual evapotranspiration (ETa) and potential evapotranspiration (ETp) was verified for the Tarim River basin (TRB). The advection-aridity (AA) model was used to calculate ETa at each station to facilitate examination of the temporal and spatial variations in ETa. Moreover, the impact factors of ETa were identified. From our analyses, we arrived at the following main conclusions.

There is complementary behavior between ETa and ETp in the Aksu River basin (ARB), the Hotan River basin (HRB), and the Kaidu River basin (KRB). In previous studies a CR between ETa and ETp was proved in arid shrubland environments in eastern Nevada (Huntington et al. 2011), in semiarid desert ecosystems of southern Idaho (Jaksa et al. 2013), and in semiarid and arid regions of China, for example, in the arid Yarkant River basin (Shang et al. 2008), in Xinjiang (Liu et al. 2008), and in northwest China (Xu 2011). It was found that the CR is asymmetric for certain conditions (Huntington et al. 2011; Kahler and Brutsaert 2006; Pettijohn and Salvucci 2006; Pettijohn and Salvucci 2009; Szilagyi 2007), when the rate of decrease in ETp is greater than the rate of increase in ETa in an extremely arid region. In this study, the CR-based AA model was applied in a semiarid to arid region. It was shown that the AA model that is based on the CR yielded accurate estimates of ETa in the semiarid and arid Urumqi River basin (Lemeur and Zhang 1990). The AA method with locally calibrated parameters performed well in the semiarid to arid Potamos tou Pyrgou River basin in northwest Cyprus (Xu and Singh 2005) and for both the maize and canola crops in the Coleambally Irrigation Area located in southeastern Australia (Liu et al. 2012). In this study the CR was verified in the TRB, and a CR-based model was applied to estimate ETa. The multiyear average ETa estimated by the AA model is equal to that calculated by the water balance method during the period from 1961 to 2000 in the ARB, HRB, and KRB and during the calibration period in the Weigan River basin (WRB) and the Taklimakan Desert. Compared with ETa calculated by the water balance method, ETa obtained by the AA model is underestimated during the calibration period and
overestimated during the validation period. This is because great changes in wind speed and actual vapor pressure during the 1980s led to a great change in the drying power of the air, which exerted different influences on ETa for the two periods in the ARB, the HRB, and the KRB.

The average ETa in the TRB for the period from 1961 to 2014 was 178.5 mm. Our results indicate that ETa in the TRB increased at a rate of 22.9 mm decade\(^{-1}\) for the period from 1961 to 1996 and after that decreased by 33.9 mm decade\(^{-1}\) until 2014. Although ETa decreased after 1996, when considering the entire time period from 1961 to 2014, there was an overall significant increase at a rate of 10.6 mm decade\(^{-1}\). Using a lysimeter in the Tien Shan, an ETa value of 260.8 mm was observed for dense grass during the summer (June–August) of 1986 (Zhang et al. 2003). From April to October 2005, ETa measured by the eddy covariance method was about 210 mm in the oasis–desert ecotone in Fukang, Xinjiang (Li et al. 2012). By means of MODIS ET data, an average annual ETa of about 214 mm was found for the oasis area in the TRB from 2000 to 2014 (Deng et al. 2017). The estimated ETa of at least 307.8 mm in the mountain area and of about 210 mm in the oasis area in the present study is consistent with previous studies.

The trend of ETa in the TRB agrees with trends in global averaged evapotranspiration, which increased from 1982 to 1998 and decreased after that (Jung et al. 2010; Zeng et al. 2012). Within China, the overall increase in ETa in the TRB is consistent with the changes in ETa in the Songhuajiang basin in northeast China (Wen et al. 2014), but is not consistent with the decrease in ETa as observed in the Pearl and the Yangtze River.
basin in southern China (Wang et al. 2011; Wu et al. 2017).

On the decadal scale, seasonal variations were similar to the interannual variations; ETa reached a maximum in the 1990s, followed by the period from 2000 to 2014, then the 1980s, 1960s, and the 1970s. ETa was strongest during summer, followed by spring and autumn.

Annual and seasonal ETa distribution patterns were almost consistent, with higher ETa values in the northeast, northwest, and southwest of the TRB and lower ETa values in the central and southeastern areas, which mainly consist of deserts with very limited water resources. Trend analyses also illustrated that the annual and seasonal ETa showed increasing trends in most areas.

In the ARB, the surface water supply (SWS) increased from 1961 to 1998 and decreased after this until 2011. Here, the change in SWS is coincident with the change in ETa. While the trend in the drying power of the air $E_a$ contrasted with that of ETa in the TRB, its tendency to decrease ceased between 1996 and 1998, after which point it increased. Coincident turning points in ETa, SWS, and $E_a$ were observed during the period from 1996 to 1998. The Tarim River is fed via its tributaries by snow and glacier meltwater. Precipitation is very low, especially in the desert area. Our results show that the basic SWS for soil moisture quickly evaporates into the atmosphere, and that ETa is strong when SWS is abundant, but relatively weak when SWS is insufficient. However, the strong correlation between ETa and SWS was only found in the ARB, while it was not detected in the HRB, KRB, and WRB. The physics behind the relationship of ETa and SWS in the TRB needs further research. The energy budget (indicated by $R_n$) seemed to have a minimal influence on ETa in the TRB; however, the advection budget (indicated by $E_a$) played an important role. The change of ETa in humid regions is mainly caused by a decrease in the net total radiation (Xu et al. 2006; Wang et al. 2011; Wu et al. 2017).

The energy budget may have a greater impact on ETa in humid than arid regions. ETp is positively related to $E_a$, as was shown in Eq. (3). The complementary relationship between ETa and ETp causes ETa to be inversely related to $E_a$. Decreases in $E_a$ are expected to be associated with increases in ETa, which is consistent with the findings of Hobbins et al. (2004), who proposed that the increases in ETa as a result of decreases in $E_a$ in the United States outweighed the effect of decreasing net radiation and could only be explained in the context of the CR. The change of ETa during the period from 1996 to 1998 might have been the result of a similar change in the SWS and the advection budget. The trends in $E_a$ and the SWS in the TRB were contrasting; we suppose that SWS not only provides the basic conditions for ETa, but also has an influence on the advective budget and on ETa.

Climate change could boost the regional glacier mass-loss rate; indeed, it is estimated that half of the total glacier ice volume in the Tien Shan will be lost in the 2050s (Farinotti et al. 2015). It is reported that glacier
melt runoff will increase until about 2040 in the Naryn River basin, central Asia (Gan et al. 2015) and will reach a tipping point between 2011 and 2030 in the Beida River basin, western China (Zhang et al. 2012). In the TRB, glacier melt is also projected to be high in the initial stages of the twenty-first century and to decrease rapidly between 2040 and 2060 (Duchethmann et al. 2016). As a result, regional ETa may change corresponding to the changes of streamflow fed by glacier melt.

This study presents the first application of the model based on complementary relationships across the entire TRB and resolves the difficulty of accurately computing actual evaporation in arid areas. By calculating correlation coefficients between ETa and SWS, and between ETa and the meteorological factors, we determined the main influences on variations in ETa for the first time. The quantification of the contributions of SWS and the various meteorological parameters to ETa remains a challenge and requires further study. In the next step, the GG model (Granger and Gray 1989) and the CRAE model (Morton 1983) will be applied to estimate ETa in the TRB as comparison studies to evaluate the uncertainty.

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