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Spatiotemporal variability of reference evapotranspiration and its contributing climatic factors in Yunnan Province, SW China, 1961–2004

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Abstract Evapotranspiration is an important flux term in the water cycle that integrates atmospheric demand and surface conditions. Using the FAO Penman–Monteith method, we calculated monthly reference evapotranspiration (ET0) for 119 stations during 1961–2004 over Yunnan Province (YP), southwest China. Linear trend analysis shows that area-averaged annual and seasonal ET0 rates declined, with most remarkable decreases during pre-monsoon (−1.5 mm decade^{-1}, Mar–May) and monsoon (−0.6 mm decade^{-1}, Jun–Aug) seasons. Most of the stations with negative trends were concentrated in the eastern and northern parts of YP. Over the 44–year period, wind speed (WS), relative sunshine duration (SD) and relative humidity (RH) all showed decreasing trends, whereas maximum temperature (TMX) increased slightly. Multivariate regression analysis indicated that the variability of ET0 rates is most sensitive to the variations of SD, followed by RH, TMX and WS. The temporal evolution of these contributing factors was not stable during the study period, with an increasing contribution of SD and a decreasing contribution of TMX after the 1970s. Temporally changing contributions of climatic variables to ET0 should be taken into account when evapotranspiration rates are calculated with equations that rely on parameterization of climatic variables. Linking the changing contributions of climatic variables to ET0 rates to circulation features may help to better understand how ET0 responds to regional climatic change.

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1 Introduction

Evapotranspiration (ET), the sum of evaporation and plant transpiration, is a central element of the hydrological cycle, governing the moisture transfer to the atmosphere and thereby influencing fundamental properties of terrestrial ecosystems such as runoff, soil moisture and plant growth (Fisher et al. 2011). ET is of particular concern in Asia where the convection above the Tibetan Plateau and hence the transfer of latent energy to the atmosphere directly influences the intensity of the Asian monsoon system (Thomas 2008). Thus, understanding the spatiotemporal variations of ET is a vital component in regional hydrological studies in Asia.

In a warming climate, the hydrological cycle is expected to intensify (IPCC 2007). The main argument is that according to the Clausius–Clapeyron equation a warmer atmosphere will be able to hold more water and hence allow for higher evaporation. However, despite globally increasing temperatures, most studies have shown that measured pan evaporation and calculated potential evapotranspiration (PET) are declining at both global (Roderick et al. 2009; McVicar et al. 2012) and regional scales (Chattopadhyay and Hulme 1997; Thomas 2000; Liu et al. 2004). A decrease of PET clearly points to changes in atmospheric water demand and therefore to changes in the climatic parameters driving evapotranspiration.

The reason for the decreasing PET rates appears to be a decrease in solar radiation and wind speeds, while temperature actually plays a lesser role (Thomas 2000). The observed decline of sunshine duration (Stanhill and Cohen 2001) has partly reversed in the last decade (Wild et al. 2005), while terrestrial wind speeds have been observed to decrease on a global scale (McVicar et al. 2012). However, there is currently only limited knowledge which climatic variables influence the evaporative environment on global or regional scales.

In order to compare the evapotranspiration potential from a climatological point of view and to allow the comparison of different climatic regions independent of actual land cover, the concept of potential evapotranspiration has been introduced, defined as ‘the amount of water transpired in unit time by a short green crop, completely covering the ground, of uniform height and never short of water’ (Penman 1956). The Penman-Monteith (PM) equation is regarded as the most reliable predictor of PET rates under all climatic conditions (Jensen et al. 1990). In the PM equation, four climatic variables (radiation, wind speed, atmospheric humidity and air temperature) are explicitly used to model the evaporative process. This approach does not allow analyzing the evaporative environment in many areas where density and duration of operation of weather stations is sparse. However, formulations relying on a single parameter such as temperature (Thornthwaite 1948; Hargreaves 1974) or a reduced set of parameters (Priestley and Taylor 1972) fail to capture the changing influence of the radiative and aerodynamic forces. From a practical point of view, the knowledge of the relative importance of contributing factors helps to determine which least data-demanding ET estimator can be used regionally.

The East Asia monsoon climate offers an interesting study area with contrasting climatic conditions in the different seasons. In general, PET rates peak in the pre-monsoon season with high insolation and dry air conditions, remain on a slightly lower level during the humid summer monsoon season and decline in the cold and often overcast winter monsoon season (Thomas 2008). Several studies have reported mostly decreasing ET0 trends over China (Thomas 2000; Chen et al. 2006; Gao et al. 2006; Zhang et al. 2011). The spatiotemporal variability of these changes however is considerable, with trends even changing sign over short distances. Declining PET trends in China are mainly related to decreasing sunshine duration and wind speeds (Thomas 2000; Wang et al. 2004; Gao et al. 2006). Although Xu et al. (2006) found that local land-cover change was the primary cause for decreasing wind speeds in China, it is largely uncertain if changes in global circulation properties or land use changes (via changing surface roughness) are responsible for the observed trends. Similarly, Guo et al. (2011) did not find conclusive evidence for decreasing wind speed in the rapidly growing urban areas of China.

We restrict our analysis to Yunnan Province (YP) in the extreme Southwest of the PR China. YP is a climatically complex region, where three different circulation branches of the Asian monsoon system influence the western, eastern and northern parts of the region with seasonal varying intensity (Zhang 1988). In southern Tibet and western YP, sunshine duration is the primary driver of declining evapotranspiration on an annual basis, followed by relative humidity and wind speed (Gao et al. 2006). In Tibet (immediately to the north of YP) wind speed was found to be the primary cause for declining ET0 changes (Chen et al. 2006; Zhang et al. 2009), while Thomas (2000) identified sunshine duration at 3 stations in YP as the main drivers of declining PET rates in most of the seasons.

We provide decadal (1961–2004) linear trends for Penman–Monteith reference evapotranspiration (ET0) rates and analyze spatiotemporal trend variability over YP. We analyze trends of climatic parameters (sunshine duration, wind speed, temperature and relative humidity) and their temporal contribution to ET0 rates. We aim to: (1) evaluate temporal trends and spatial patterns of ET0 rates and other climatic parameters over YP; (2) identify the major climate factors contributing to ET0 variability and (3) determine whether the relationship between ET0 and its driving climatological variables is stable or not. To our knowledge, this is the first study that deals with the temporal evolution of relative importance of climatic variables contributing to ET0 rates.

2 Data and methods

2.1 Study area

The study area encompasses YP in subtropical Southwest China, bordering Myanmar, Laos and Vietnam (Fig. 1). YP covers an area of about 394100 km^2 between 21°09′–29°15′ N and 97°32′–106°12′ E, with an average altitude of 1980 m. Within YP, elevations increase from less than 100 m in the south to more than 6000 m in the north. Intramontane basins in the south and deeply incised river valleys in the north and west add to a rugged topography. The so-called 'Yunnan–Guizhou–Plateau' (Ren et al. 1985) with average elevations of 1500–2000 m is restricted to the eastern part of the study area.

In contrast to the other parts of southern China, YP lies under the influence of the 'Indian Monsoon'. In late spring first a south–westerly circulation component and then a south–easterly component converges along the so-called 'Kunming quasi-stationary front', a transitional zone at appr. 102–105 °E. The northern part of Yunnan is already under the influence of the westerlies. In winter, dry and relatively warm air masses from the north–west lead to sunny and moderately cold conditions despite high elevations and set this region apart from all surrounding areas which experience cold and damp weather. In the intramontane basins of South Yunnan, strong radiational cooling leads to persistent fog in winter (Nomoto et al. 1988). ET0 lapse rates tend to be non-linear, with a maximum at around 2400 m (Thomas 2002) and higher ET0 rates in the wind shadow areas of the large mountain ranges that run perpendicular to the prevailing circulation direction. Many river valleys experience extremely arid conditions (Tang et al. 2004). ET0 rates are therefore influenced through multiple topoclimatological factors.

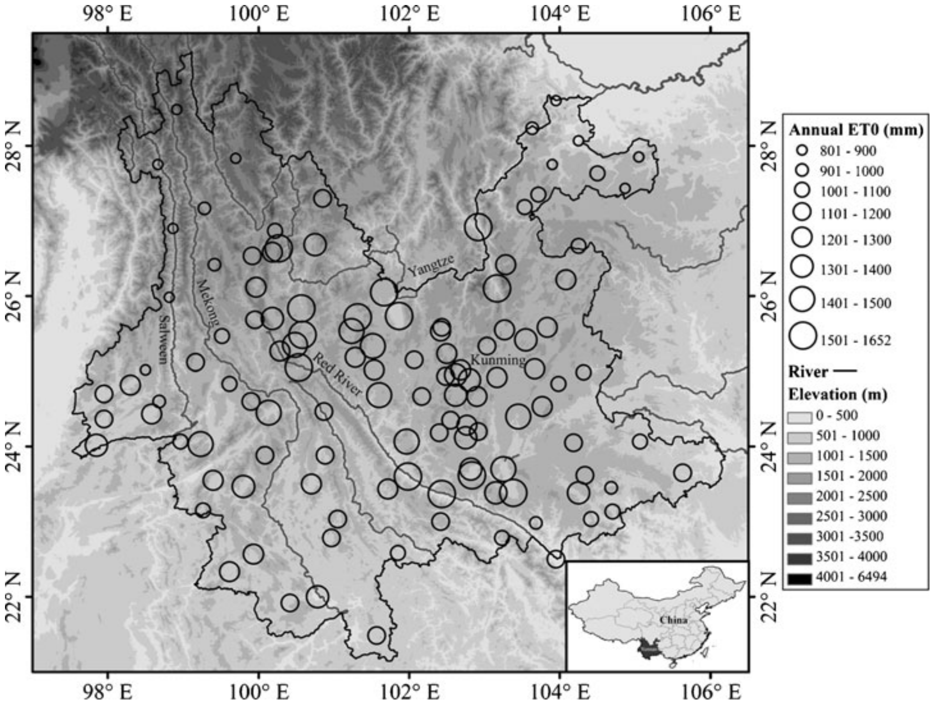


Fig. 1 Spatial distribution of mean annual reference evapotranspiration (ET0) for the period 1961–2004 of 119 meteorological stations in Yunnan Province. Topographic data are from GTOPO30

2.2 Meteorological data

Monthly mean data on sunshine duration (SD, h), relative humidity (RH, %), maximum temperature (TMX, °C) and wind speed (WS m s^{-1}) for 119 stations in Yunnan Province were obtained for the years 1961–2004 (44 years) from the National Meteorological Information Centre of China. Stations cover an altitudinal range of more than 3000 m from 137 to 3319 ma.s.l. The dataset has been quality checked by NMIC. We further performed routine quality assessment and necessary error correction procedures on the data following the methods described by Peterson et al. (1998). Missing values are infrequent and generally account for only 0.2–0.4 %, which were replaced with estimated values predicted from multiple regression relationships established among a few (up to five) neighbouring and highly correlated stations (Fan et al. 2011).

2.3 FAO Penman–Monteith method

The FAO Penman–Monteith (FAO–PM) approach is regarded as a global standard and is referred as reference evapotranspiration (ET0) (Allen et al. 1998). The FAO–PM equation to estimate ET0 (mm day^{-1}) is given as:

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\,\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34u_2)},$$

where R_n is net radiation at the crop surface (MJ m^{-2} d^{-1}), G is soil heat flux (MJ m^{-2} d^{-1}), T is mean daily air temperature at 2 m (°C), u_2 is wind speed at 2 m (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), Δ is the slope of the saturation vapour pressure curve at air temperature T [kPa °C^{-1}] and γ is the psychrometric constant [kPa °C^{-1}].

Monthly FAO–PM ET0 rates were calculated according to Allen et al. (1998) using AWSET software (Hess 2002). The reference surface is defined as "a hypothetical reference crop with height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. Solar radiation (R_s) is the primary source of energy for evapotranspiration. With no directly measured R_s available we relied on the conversion of observed sunshine duration to R_s (Doorenbos and Pruitt 1977; Allen et al. 1998). R_s is estimated from observed sunshine duration using the Ångström formula (Ångström 1924): $R_s = (a_s + b_s n/N)R_a$, where a_s is the fraction of extraterrestrial radiation on overcast days, a_s+b_s is the fraction of extraterrestrial radiation on clear days, n is the actual duration of sunshine (in hours), N is the total day length (in hours), R_a is extraterrestrial radiation. Ångström coefficients of $a_s=0.23$ and $b_s=0.46$ were used for the study area according to calibrations with local radiation data (Weng et al. 1986). Wind speed (WS) at 2 m height was converted from the normal measurement at 10 m based on the logarithmic wind speed profile equation given by Allen et al. (1998).

2.4 Trend analysis

In order to reflect the seasonal variation of the monsoonal climate of the study area, we calculated seasonal and annual means of ET0, as well as of four other climate variables (WS, RH, SD and TMX), for the four hydrological seasons pre-monsoon (MAM), summer monsoon (JJA), post-monsoon (SON) and winter monsoon or dry season (DJF), rather than for the usual thermal seasons that do not properly reflect the seasonal variation of the monsoonal climate of the study area.

An ordinary linear regression in the form of $\hat{y}=\alpha t+\beta$ is used to estimate the rate of change α, with t as the time (year), $\hat{y}$ being the annual and seasonal climate variables including ET0, SD, RH, TMX and WS. Statistical significance of linear trends was evaluated using Student's *t*-test. The magnitude of the trends was calculated by the slope of the linear trends and expressed in decadal scale. Spatial distributions of the linear trends (slopes) were interpolated on the map using ArcMap software (version 9.0). Monthly and seasonal trends were averaged over the study area, and a linear regression and a 10-years low-pass filtered line was fitted to emphasize long-term fluctuations. All data analysis was carried out using R data processing and analysis language (R Development Core Team 2004).

The relationship between ET0 rates and climatic variables was analyzed with stepwise multiple regression, with ET0 as dependent variable and SD, RH, TMX and WS as the predictors. Variables were selected into the final model based on the lowest Aikaike Information Criterion (AIC), using the 'lm' and 'step' functions in R software. The contribution of each significant variable was determined by explained variance (R^2). In order to analyze the temporal variability of the contributions of different climatic variables, we further performed stepwise multiple regression for moving windows of 10 years width (1961–1970, 1962–1971,…, 1995–2004), which produces a time series of explained variances for each station. The 'explained variance' time series for all individual stations were averaged and numbers of significant (enter the final model) stations were counted for each climatic variable.

2.5 Empirical orthogonal function (EOF) analysis

Empirical orthogonal function (EOF) analysis has been widely used in meteorology and climatology to define the spatial and temporal variability of a large set of variables

(Richman 1986). The correlation-based varimax-rotated empirical orthogonal function (REOF) method was employed to detect spatial patterns of annual ET0 at 119 stations and their temporal variability for the period 1961–2004. Determining the number of EOF modes to be rotated is an important issue in REOF analysis, as it directly affects the resulting spatial patterns and temporal variations, facilitating or misleading the search of physical interpretation (Hannachi et al. 2009). We performed a rigorous 'red noise' version of the Rule N test (Preisendorfer 1988; Li et al. 2008), which is based on the Monte Carlo procedure.

3 Results

3.1 Seasonality and spatial distribution

Owing to the topographical complexity, this study region displays a wide variety of micro-climates. Figure 1 presents the spatial distribution of average annual ET0 over YP from 1961 to 2004. Mean annual ET0 over YP was 1175 mm and ranged from 804 mm (Weixi) to 1652 mm (Yuanjiang). The highest annual ET0 rates occurred along the upper branches of the Red River and the central part of YP, whereas the lowest ET0 rates were found in the mountain regions of northwest and east YP.

ET0, as well as other climatic variables, exhibited strong seasonal fluctuation in YP (Fig. S1 in Supplementary material). ET0 was high during the pre-monsoon season from March to May and peaked in May. In general the climatic water balance (precipitation-ET0) showed a surplus during June–October. Area-averaged annual ET0 was 81 mm higher than annual precipitation. Wind speed and sunshine duration were high during winter and the pre-monsoon season, whereas relative humidity was particularly low before the rainy season.

3.2 Temporal and spatial trends of ET0

Area-averaged annual and seasonal ET0 rates over YP declined except in the winter season (Table 1, Figs. 2 and 3). Due to large inter-annual variations all annual area averaged trends were not significant. Annual ET0 trends at individual stations varied from −69.2 to 32.6 mm per decade, with an area–averaged decrease of −6.5 mm per decade. Trends at 46 % of all stations, in general those larger than 10 mm per decade, were either significant or highly significant (Table 1, Table S1 in Supplementary material). The changes were most pronounced in the pre-monsoon and the summer-monsoon season, both in terms of trend rates and in terms of percentage of stations with decreasing ET0 rates (Table 1, Fig. 3). During the post-monsoon period more stations (52 %) exhibited increasing ET0 rates despite an area-averaged moderately decreasing trend (Table 1).

Most of the stations with negative trends are concentrated in the eastern and northern parts of YP (Fig. 2). This pattern was confirmed by REOF analysis, with the first two REOFs, which describe ET0 variability in the north and eastern parts of the YP, exhibited significant declining trends (Fig. 4). On a seasonal basis, this spatial distribution was again most evident in the pre-monsoon and monsoon season while during post and winter monsoon no dominant pattern is discernible (Fig. 3). The inter-annual variation of the annual ET0 rates showed a clear maximum around 1980 and a broad minimum during the 1990s. The same pattern was visible on a seasonal basis during pre-monsoon and monsoon months while in post-monsoon and winter season the minimum was the most prominent feature (Figs. 2 and 3).

Table 1 Statistics of seasonal and annual linear trends of reference evapotranspiration (ET0, mm/decade), relative sunshine duration (SD, %/decade), relative humidity (RH, %/decade), maximum temperature (TMX, °C/decade) and wind speed (WS, m s^{-1}/decade) for all 119 meteorological stations in Yunnan Province. Percentage of stations (bold) and percentage of stations shown significant ($p<0.05$) trends (italics) are indicated in parenthesis, for both increasing and decreasing trends

	Season	Mean (/decade)	Standard deviation	Decreasing (percent)	Increasing (percent)
ET0	Annual	−6.5	18.4	77 (**65 %**, *30.3 %*)	42 (**35 %**, *16.0 %*)
	Pre–monsoon	−1.5	2.37	88(**74 %**, *25.2 %*)	31(**26 %**, *4.2 %*)
	Summer–monsoon	−0.6	1.87	76(**64 %**, *22.7 %*)	43 (**36 %**, *10.9 %*)
	Post–monsoon	−0.12	1.24	57 (**48 %**, *15.1 %*)	62 (**52 %**, *11.8 %*)
	Winter–monsoon	0.00	1.31	54 (**45 %**, *10.1 %*)	65 (**55 %**, *15.1 %*)
SD	Annual	−0.26	0.52	85(**71 %**, *37.0 %*)	34(**29 %**, *9.2 %*)
	Pre–monsoon	−0.40	0.61	92(**77 %**, *29.4 %*)	27(**23 %**, *3.4 %*)
	Summer–monsoon	−0.40	0.68	87(**73 %**, *31.9 %*)	32(**27 %**, *5.0 %*)
	Post–monsoon	−0.03	0.11	74(**62 %**, *8.4 %*)	45(**38 %**, *2.5 %*)
	Winter–monsoon	−0.13	0.44	73(**61 %**, *8.4 %*)	46(**39 %**, *2.5 %*)
RH	Annual	−0.15	0.60	72(**60 %**, *37.0 %*)	47 (**40 %**, *14.3 %*)
	Pre–monsoon	0.06	0.66	57(**48 %**, *31.1 %*)	62(**52 %**, *9.2 %*)
	Summer–monsoon	−0.14	0.59	73(**61 %**, *31.1 %*)	46(**39 %**, *13.4 %*)
	Post–monsoon	−0.31	0.60	95(**80 %**, *39.5 %*)	24(**20 %**, *7.6 %*)
	Winter–monsoon	−0.17	0.77	72(**60 %**, *26.1 %*)	47(**40 %**, *10.1 %*)
TMX	Annual	0.06	0.10	26(**22 %**, *5.0 %*)	93(**78 %**, *27.7 %*)
	Pre–monsoon	−0.06	0.12	84(**71 %**, *5.9 %*)	35(**29 %**, *0.8 %*)
	Summer–monsoon	0.06	0.11	28(**24 %**, *3.4 %*)	91(**76 %**, *30.3 %*)
	Post–monsoon	0.07	0.10	23(**19 %**, *0 %*)	96(**81 %**, *16.0 %*)
	Winter–monsoon	0.17	0.12	9(**8 %**, *0 %*)	110(**92 %**, *16.8 %*)
WS	Annual	−0.07	0.10	93(**78 %**, *63.9 %*)	26(**22 %**, *8.4 %*)
	Pre–monsoon	−0.09	0.11	98(**82 %**, *62.2 %*)	21(**18 %**, *5.0 %*)
	Summer–monsoon	−0.04	0.09	81(**68 %**, *39.5 %*)	38(**32 %**, *14.3 %*)
	Post–monsoon	−0.06	0.09	90(**76 %**, *50.4 %*)	29(**24 %**, *10.1 %*)
	Winter–monsoon	−0.10	0.11	102(**86 %**, *65.5 %*)	17(**14 %**, *5.0 %*)

3.3 Temporal and spatial trends of climatic variables

With the exception of TMX, area-averaged annual means of SD, RH and WS all decreased during the study period (Fig. 5). Over the 44 year-period, area-averaged WS decreased by $-0.073\ \mathrm{ms}^{-1}$ decade $^{-1}$ (highly significant), with the largest decline in winter ($-0.10\ \mathrm{ms}^{-1}$ decade^{-1}) and the least in summer ($-0.04\ \mathrm{ms}^{-1}$ decade $^{-1}$). The decreasing trend of WS was almost monotonic since 1970. SD decreased by −0.26 % decade $^{-1}$ ($p<0.05$). All variables showed distinct variations over the study period (Fig. 5). Particularly obvious was a distinct TMX maximum around 2000, the decline of annual WS after 1970, and the pronounced SD minimum around 1990. Spatial patterns were not evident. On a seasonal basis, the strongest changes occurred in different seasons depending on the climatic variable (Fig S2–S5 in Supplementary material): RH was declining in the post-monsoon season, SH was decreasing in the pre-monsoon and monsoon seasons, WS was decreasing in all seasons. In contrast to the general negative (positive) trend of RH (TMX) in other seasons, RH (TMX) slightly

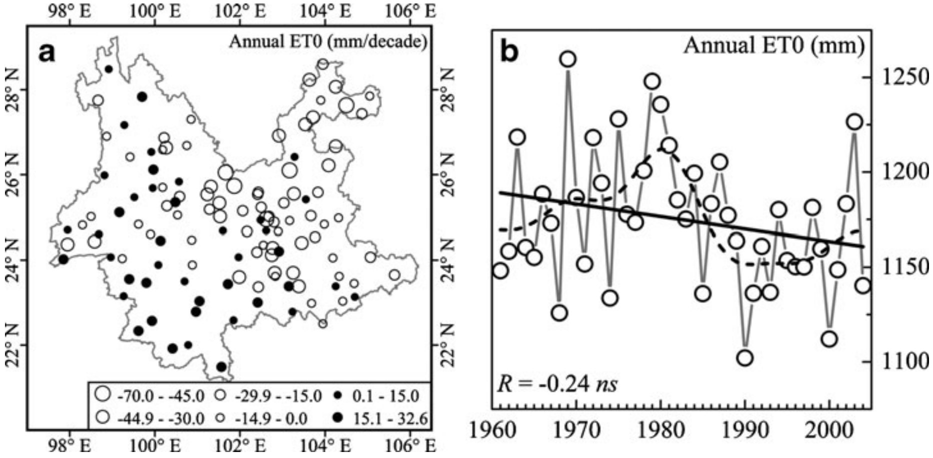


Fig. 2 Spatial patterns of the linear trend (mm/decade) of annual reference evapotranspiration (ET0). The linear trends were calculated for the data of all 119 meteorological stations in Yunnan Province during the period 1961–2004. Linear regression (*bold*) and 10-year low-pass filter (*dashed*) are shown. *ns* not significant

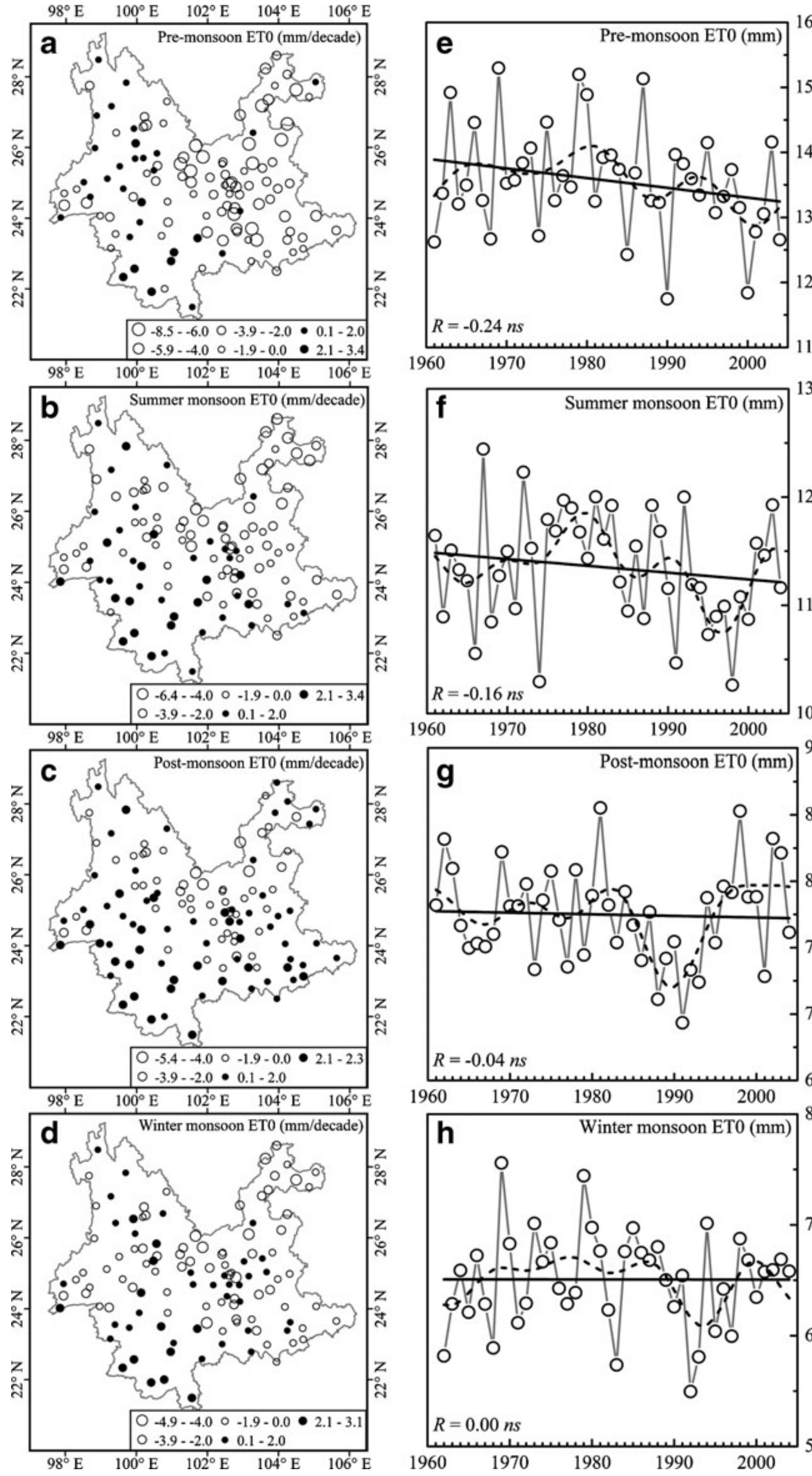
increased (decreased) in the pre-monsoon season. WS was the only variable to show highly significant trends in all seasons, all other seasonal trends with the exception of RH in post-monsoon season were not significant.

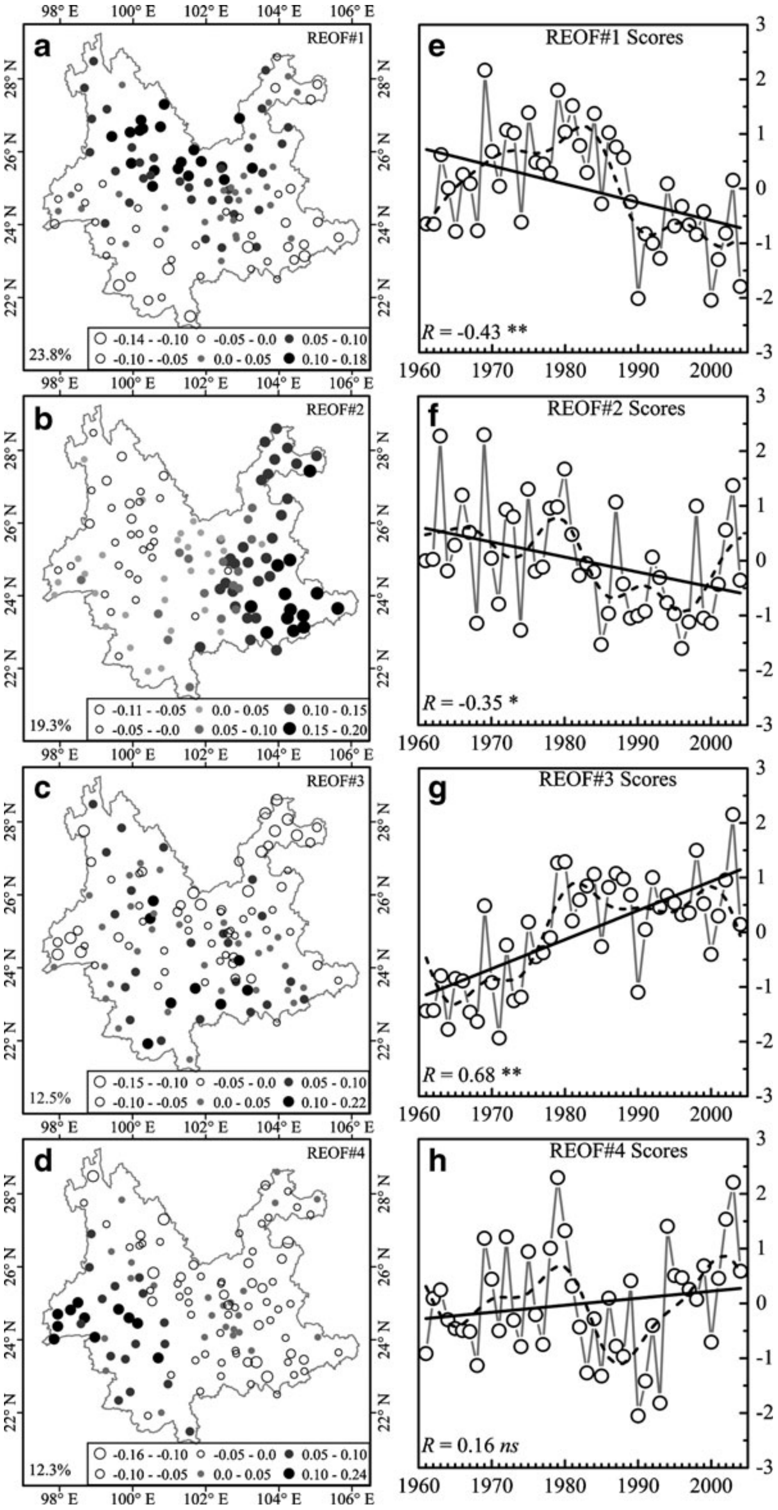
3.4 Attribution of climatic variables

The temporal evolution of the relation between annual ET0 rates and climatic variables showed marked changes over time (Fig. 6, Table S2 in Supplemental material). Prior to 1975, the contributions of SD and RH were equal, after which the contribution of SD rose substantially, with RH remaining on a lower level. The contribution of TMX peaked at around 1975, and declined afterwards. The contribution of WS remained on a low, slightly declining level during the whole study period. Despite the observed strong decreasing trend of wind speed, WS displayed the least important contribution to ET0 changes (Table S3 in Supplementary material; Fig. 6).

When individual seasons were analyzed, a clear distinction between humid (summer and post-monsoon) and dry (winter and pre-monsoon) seasons became obvious (Fig. S6 in Supplementary material). SD shows the highest contribution during the summer and post-monsoon seasons. In the pre-monsoon and winter monsoon seasons all variables show correlations on a similar level. Wind speed always remains the least important variable in all seasons. In the summer monsoon season, the temporal development shows a similar break around 1980 (Fig. S6 in Supplementary material), which is not evident in other seasons. A visual inspection of the spatial distribution (Fig. 6, Fig. S6 in Supplementary material) does not show any conclusive signs that the relative contribution of climatic variables follows any patterns.

Fig. 3 Spatial patterns of the linear trends per decade (**a**–**d**) and area-averaged curve (**e**–**f**) of reference evapotranspiration (ET0) during the pre-monsoon (**a**, **e**; Mar–May), summer monsoon (**b**, **f**; Jun–Aug), post–monsoon (**c**, **g**; Sep–Nov) and winter monsoon (**d**, **h**; Dec–Feb) seasons over Yunnan Province during 1961–2004. Linear regression (*bold*) and 10-year low-pass filter (*dashed*) are shown. *ns* not significant ▶


a
Pre-monsoon ET0 (mm/decade)
-8.5 - -6.0
-3.9 - -2.0
0.1 - 2.0
-5.9 - -4.0
-1.9 - 0.0
2.1 - 3.4
b
Summer monsoon ET0 (mm/decade)
-6.4 - -4.0
-1.9 - 0.0
2.1 - 3.4
-3.9 - -2.0
0.1 - 2.0
c
Post-monsoon ET0 (mm/decade)
-5.4 - -4.0
-1.9 - 0.0
2.1 - 2.3
-3.9 - -2.0
0.1 - 2.0
d
Winter monsoon ET0 (mm/decade)
-4.9 - -4.0
-1.9 - 0.0
2.1 - 3.1
-3.9 - -2.0
0.1 - 2.0
98° E
100° E
102° E
104° E
106° E
22° N
24° N
26° N
28° N
e
Pre-monsoon ET0 (mm)
R = -0.24 ns
110
120
130
140
150
160
f
Summer monsoon ET0 (mm)
R = -0.16 ns
100
110
120
130
g
Post-monsoon ET0 (mm)
R = -0.04 ns
65
70
75
80
85
90
h
Winter monsoon ET0 (mm)
R = 0.00 ns
50
60
70
80
1960
1970
1980
1990
2000


a
REOF#1
23.8%
○ -0.14 - -0.10 ○ -0.05 - 0.0 ● 0.05 - 0.10
○ -0.10 - -0.05 ● 0.0 - 0.05 ● 0.10 - 0.18
b
REOF#2
19.3%
○ -0.11 - -0.05 ● 0.0 - 0.05 ● 0.10 - 0.15
○ -0.05 - -0.0 ● 0.05 - 0.10 ● 0.15 - 0.20
c
REOF#3
12.5%
○ -0.15 - -0.10 ○ -0.05 - 0.0 ● 0.05 - 0.10
○ -0.10 - -0.05 ● 0.0 - 0.05 ● 0.10 - 0.22
d
REOF#4
12.3%
○ -0.16 - -0.10 ○ -0.05 - 0.0 ● 0.05 - 0.10
○ -0.10 - -0.05 ● 0.0 - 0.05 ● 0.10 - 0.24
98° E
100° E
102° E
104° E
106° E
22° N
24° N
26° N
28° N
e
REOF#1 Scores
R = -0.43 **
f
REOF#2 Scores
R = -0.35 *
g
REOF#3 Scores
R = 0.68 **
h
REOF#4 Scores
R = 0.16 ns
1960
1970
1980
1990
2000
3
2
1
0
-1
-2
-3

◀ **Fig. 4** The four factor loadings (**a**–**d**, *left*) and their corresponding normalized REOF scores (**e**–**h**, *right*) based on rotated REOF analysis of annual reference evapotranspiration (ET0) for the period 1961–2004. The percentage variance accounted for by each factor is labelled in each map. Linear regression (*bold*) and 10-year low-pass filter (*dashed*) are applied for the REOF scores. *R* represents the correlation coefficient. *, $p<0.05$; **, $p<0.01$; *ns* not significant

4 Discussion

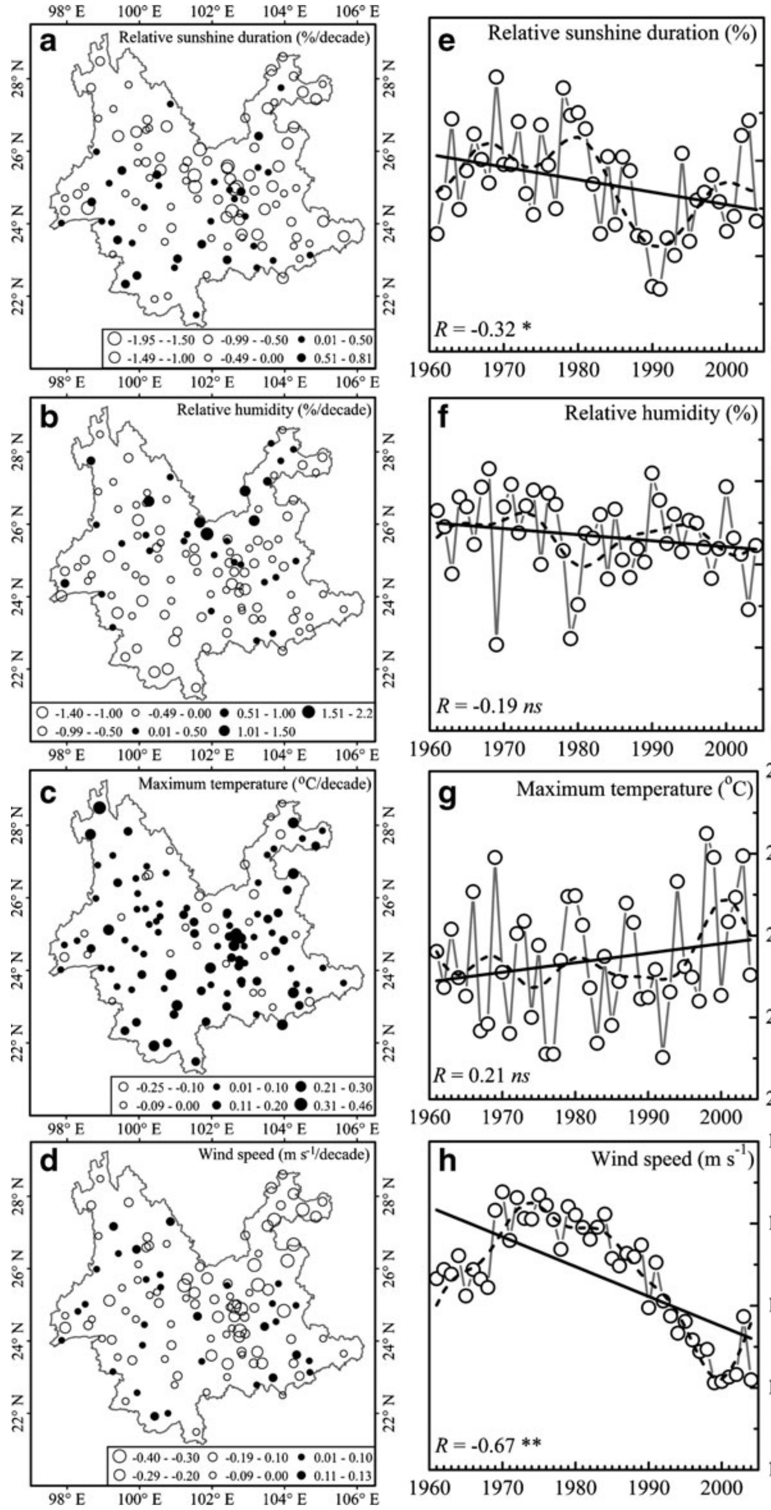
Yunnan Province (YP) shows a wide range of evapotranspiration rates (Fig. 1), due to the complex topography and the influence of regional domains of different monsoon circulation branches (Thomas 1993). High ET0 rates over YP are not untypical compared to other subtropical mountain environments. Climatic conditions at stations with highest annual ET0 rates of ~1500 mm, mostly located in basins or valleys, are similar to other stations found along the southern escarpment of the Himalayan range influenced by dry foehn winds. Unusual however are high winter ET0 rates that are related to the dry and sunny weather of the winter monsoon circulation in Southwest China (Thomas 2008).

ET0 rates over YP have been generally decreasing over the last decades, with a maximum in the early 1980s and a broad minimum from the late 1980s to 2000, both on annual and seasonal scales (Fig. 2, Fig. 3). A generally decreasing ET0 trend at a global scale as well as over China was found by several previous studies, although the temporal and spatial variability of these changes in China is considerable (Thomas 2000; Gao et al. 2006; Zhang et al. 2011). The spatial variability of ET0 trends is also evident in our study area, with a small-scale spatial distribution of opposite trends. A similar spatial variability of temporal trends was observed in Tibet immediately north of YP (Chen et al. 2006; Zhang et al. 2009). From a climatological view, southeastern Tibet and northern Yunnan is a homogenous region, sharing the same seasonal climatic characteristics. The observed temporal similarities suggest a common origin of the temporal variation. As WS is the primary driver of ET0 rates in Tibet (as compared to SD in Yunnan) and the common observation period is still relatively short additional research is needed to verify the assumption of a common climatic forcing.

A more uniform predominance of negative trends can be found east of 102 °E (or roughly east of the Red River valley), which appears to point to the influence of different monsoonal air masses, as this line coincides with the ‘traditional’ boundary between the ‘Indian’ and ‘Chinese’ monsoon (Zhang 1988). These observations are corroborated by EOF analysis as REOF#1 and REOF#2 clearly delineate a northern and an eastern region that experience rather uniform ET0 variations (Fig. 4).

During the study period SD, RH and WS decreased while TMX increased (Fig. 5). Changes in the ET0 rates over YP are mainly attributed to decreased sunshine duration (Fig. 6), which is consistent with the findings from subtropical and tropical humid regions of China (Yin et al. 2010). Previous research has shown that, for China as a whole, sunshine duration has appeared to be the most important controlling factor leading to reduced ET0 (Thomas 2000; Gao et al. 2006). Li et al. (1998) found that the global radiation and direct radiation in most parts of China had significant decreasing trends from 1960 to 1990 as the result of increased atmospheric turbidity and aerosol content. Zhang et al. (2011) found that in the regions east of 100 °E, net total solar radiation is the main cause of decreasing ET0 rates, whereas relative humidity is recognized as the most sensitive variable for ET0 in northwest China. In east China, urbanization greatly influences ET0 rates by directly decreasing net solar radiation.

In YP, WS has decreased from 1.7 ms^{-1} in the 1970s to 1.2 ms^{-1} in 2000 (Table 1, Fig. 4). This is consistent with a global decrease of terrestrial WS (McVicar et al. 2012). Guo


a
Relative sunshine duration (%/decade)
-1.95 - -1.50
-1.49 - -1.00
-0.99 - -0.50
-0.49 - 0.00
0.01 - 0.50
0.51 - 0.81
b
Relative humidity (%/decade)
-1.40 - -1.00
-0.99 - -0.50
-0.49 - 0.00
0.01 - 0.50
0.51 - 1.00
1.01 - 1.50
1.51 - 2.2
c
Maximum temperature (°C/decade)
-0.25 - -0.10
-0.09 - 0.00
0.01 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.46
d
Wind speed (m s-1/decade)
-0.40 - -0.30
-0.29 - -0.20
-0.19 - 0.10
-0.09 - 0.00
0.01 - 0.10
0.11 - 0.13
98° E
100° E
102° E
104° E
106° E
22° N
24° N
26° N
28° N
e
Relative sunshine duration (%)
R = -0.32 *
f
Relative humidity (%)
R = -0.19 ns
g
Maximum temperature (°C)
R = 0.21 ns
h
Wind speed (m s-1)
R = -0.67 **
1960
1970
1980
1990
2000
20
22
24
26
70
72
74
76
78
22.0
22.5
23.0
23.5
24.0
1.0
1.2
1.4
1.6
1.8

◀ **Fig. 5** Spatial patterns of linear trends per decade (**a**–**d**) and area-averaged curve (**e**–**f**) of annual relative sunshine duration (**a**, **e**; SD, %), relative humidity (**b**, **f**; RH, %), maximum temperature (**c**, **g**; TMX, °C) and wind speed (**d**, **h**; WS, m s^{-1}) over Yunnan Province during 1961–2004. Linear regression (*bold*) and 10–year low-pass filter (*dashed*) are shown. *R* represents the correlation coefficient. *, $p<0.05$; **, $p<0.01$; *ns* not significant

et al. (2011) found a significant weakening trend in annual and seasonal WS over China. Wang et al. (2004) attributed the significant decline of surface WS in China during the past 50 years to a weakening of winter and summer monsoon.

With decreasing SD and WS, ET0 is expected to decrease as observed in YP (Fig. 2). Wind speeds are often reported to be as important as SD changes, as already noted for Tibet (Zhang et al. 2009). Despite the observed decline of wind speeds, the contribution of WS to ET0 rates ranked as the least important variable in all seasons and almost over the complete study period. This is in contrast to many studies that report decreasing WS to be a decisive factor in declining PET rates. A sensitivity analysis shows that given the typical area-average values of SD, RH and TMX for YP, annual ET0 rates vary by less than 2 % if the WS varies by ±0.25 ms^{-1} from the observed area-averaged mean of 1.45 ms^{-1}. Temperature is often seen as the primary driver of ET changes (IPCC 2007). However, the relative contributions of the climatic variables show that TMX is not a decisive factor for the ET0 in YP, even though TMX has increased almost constantly over the last 40 years.

In all previous studies of the relative importance of climatic variables for ET0 so far, only long term means have been evaluated, neglecting any temporal changes. Analyzing the temporal dimension of changes in the individual variables allows monitoring of ET0 changes in more detail, relating them to changes in the climatic environment. In YP, SD clearly dominates the evaporative environment. The contribution of SD to ET0 rates always ranked first during the summer monsoon and post-monsoon seasons (Fig. S6 in Supplementary material). Only during the winter monsoon and for a short period of the pre-monsoon seasons did RH rank first. Only occasionally did TMX rank as the second most important variable and it always ranked third in the summer monsoon season.

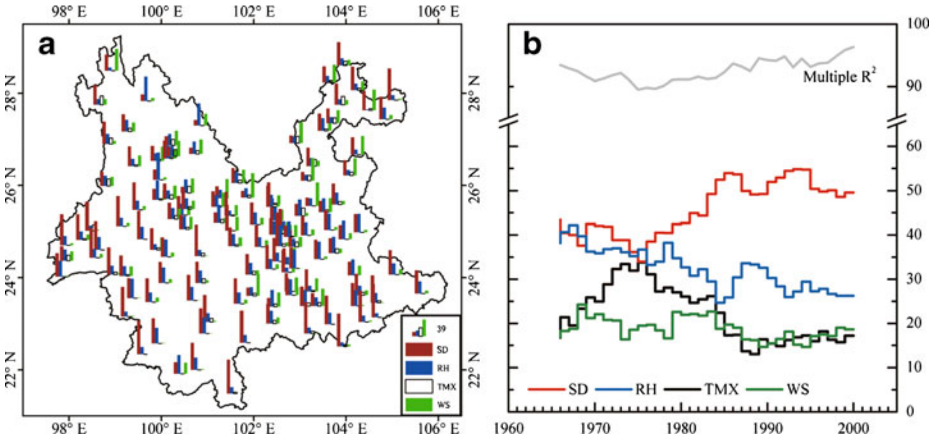


Fig. 6 Spatial patterns (**a**) and corresponding time series (**b**) of explained variance (R^2, %) derived by stepwise multiple regression with annual reference evapotranspiration (ET0) as dependent variable and annual means of relative sunshine duration (SD, %), relative humidity (RH, %), maximum temperature (TMX, °C) and wind speed (WS, m s^{-1}) as predictors

The relative contributions of the different climatic variables vary considerably over time. Particularly obvious is the sudden increase in SD variance from about 1985 (with the exception of the winter monsoon season), which is related to a pronounced SD minimum during that period. Individual changes such as the increase (decrease) in WS contribution since 1995 in the pre-monsoon (post-monsoon) season may point out that onset and withdrawal dates of the monsoons that control regional wind activities are reflected in the data. Similarly, the sudden increase in pre-monsoon SD variance can be explained in terms of less SD due to an earlier monsoon onset and hence increased monsoon activity. In general, the most obvious difference is the distinction between the warm and partially humid pre-monsoon/summer monsoon months, dominated by increased SD variance (declining SD), and the cold and dry post-monsoon/winter monsoon months, characterized by a varying mix of influences.

In order to estimate PET in case only a limited set of climatic data is available a number of PET estimators have been developed (e.g. Thornthwaite 1948; Haude 1954; Turc 1961; Hamon 1963; Priestley and Taylor 1972; Hargreaves 1974). To integrate either aerodynamical or radiation processes or both they make use of constants that usually have to be calibrated locally. In the case of the Hamon (1963) and Priestley and Taylor (1972) equations these constants are explicitly called calibration coefficient and calibration constant, respectively. As our analysis shows, the relative importance of the aerodynamical or radiation component of the evaporative process may vary considerably over time and in space. Analyzing individual stations shows that, in the northern mountain region, the relative importance of WS surpasses the SD contribution in selected months. Neglecting the temporal or spatial aspect of the relative contributions while calibrating a PET estimator with the help of long-term average climatic records may therefore considerably under- or overestimate the actual conditions. In the future this problem may become more pressing as climate change assessment studies need to calculate PET from statistically downscaled GCM data or to derive them from NCEP/NCAR data. Less data demanding PET estimators are likely to give unstable results under changing climate conditions (Sperna Weiland et al. 2012). This is particularly true in alternating climates with wet/dry or hot/cold transitions such as the Asian monsoon climate.

5 Summary and conclusions

We found that the ET0 rates have been decreasing during the past four decades, particularly in the eastern and northern parts of YP. Declines of ET0 rates appear to be linked primarily to decreasing SD in the humid summer and post-monsoon seasons. RH and TMX contribute to some extent in the dry post-monsoon and winter seasons. The contribution of WS is minimal.

The temporal evolution of these contributions was not stable during the study period. This has implications for the use of PET estimators that rely on locally calibrated coefficients that integrate the influence of wind and radiation in the equation such as the widely used Hargreaves (1974) or Priestley and Taylor (1972) equations. Neglect of adapting calibration coefficients to changing climatic conditions may lead to errors in the resulting estimates.

Changes in relative contributions of climatic variables can be linked to observed inter-annual variations of climatic variables. As an example, the contribution of SD increased rather abruptly in the 1980s due to a sharp decrease in SD. The different contribution of SD as opposed to RH and TMX in wet and dry seasons points to the monsoon circulation with seasonally alternating air mass characteristics as the primary driver of temporal varying changes in the contribution of climatic variables to ET0 rates. Temporal variations in the contribution of WS in the pre-monsoon and post-monsoon seasons particularly in northern YP may be regarded as an indication for the changing of begin and duration of the monsoon season linking them also directly to the regional circulation system. As the strength of the relative contribution of WS could also be the result of changes in other contributing variables further research is needed to quantify direct links between regional circulation and PET changes.

Declining ET0 rates due to a combination of decreasing SD and WS trends despite increasing TMX are representative for many regions in China. This pattern appears to be characteristic of a larger region encompassing the East Asian Monsoon System indicating that drivers on a continental scale are responsible for the observed changes. Our results underline evidence from a large number of publications that the current warming of the atmosphere will not automatically lead to increased ET as claimed by the IPCC (2007). In the global review of McVicar et al. (2012) 19 out of 26 publications and 46 out of 55 publications found that ET0 and pan evaporation rates, resp, decreased in the vast majority of surveyed regions. Due to a lack of studies in Africa and South America a uniform global decline of terrestrial ET rates still needs to be verified. Combined with our results however we find little evidence for an intensification of the water cycle under a warming climate as proposed by Huntington (2006).

We propose that further research should concentrate on:

- Analyzing the temporal evolution of climatic contributions to ET0 over a wide range of climates and locations;
- Comparing ET0 rates derived from GCM results to ET0 rates derived from observations to see if GCM models are able to reflect our current observations of a global ET0 decline;
- Analyzing spatiotemporal variations of calibration coefficients of less data demanding PET estimators under a wide range of climatic settings and comparing the resulting model skills.
- Analyzing regional ET0 rates in relation to atmospheric circulation features to increase our knowledge of ET0 – circulation relationships.

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