CLIMATIC CHANGE ON THE TIBETAN PLATEAU: POTENTIAL EVAPOTRANSPIRATION TRENDS FROM 1961–2000

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Abstract. Time series (1961–2000) of Penman-Monteith potential evapotranspiration estimates for 101 stations on the Tibetan Plateau and surrounding areas are analyzed in this paper. For the Tibetan Plateau as a whole potential evapotranspiration (PET) has decreased in all seasons. The average annual evapotranspiration rate decreased by 13.1 mm/decade or 2.0% of the annual total. Superimposed on this general decline are fluctuations ranging from app. 600 to 700 mm with above average rates in the 1970s and 1980s. On a regional basis, spatial trend distributions remain stable throughout the year with similar seasonal variations. Decreasing PET rates are more pronounced in winter and spring (80% of all stations) as compared to summer and autumn (58% of all stations). Maximum negative (positive) annual rates were recorded at two stations in the southern Qaidam Basin with −79.5 mm/decade (84.8 mm/decade) even though in general negative rates tend to be noticeably higher than positive rates.

Changes in wind speed and to a lesser degree relative humidity were found to be the most important meteorological variables affecting PET trends on the Tibetan Plateau while changes in sunshine duration played an insignificant role. Stable daytime temperatures on the Tibetan Plateau have limited the importance of temperature trends for changes of PET rates. Negative evapotranspiration trends are therefore thought to be linked to a general decrease in intensity of the regional monsoon circulation rather than to reductions in sunshine duration. Reduced PET rates appear to be in contrast to a predicted increased hydrological cycle under global warming scenarios.

1. Introduction

Recent studies of climate change have focused mainly on long-term variability of temperature and precipitation. Evapotranspiration as the third important climatic factor controlling energy and mass exchange between terrestrial ecosystems and the atmosphere has received less attention. Evapotranspiration plays a crucial role in the heat and mass fluxes of the global atmospheric system. Governed by a variety of climatic variables such as sunshine, temperature, wind and atmospheric humidity and its related effects on soil moisture and surface albedo evapotranspiration should provide a sensitive tool to monitor changes of the energy and moisture transfer from the ground to the atmosphere. Feedback between soil moisture and atmospheric humidity, mainly governed by evapotranspiration, may be directly responsible for variations in the strength of regional circulation of the Asian Monsoon System (Webster, 1983). The major part of this energy transfer is conducted through the 'elevated heating surface' of the Tibetan Plateau (TP) (Flohn, 1968; Yanai et al.,

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1999) affecting not only the TP but all of Asia. On a practical side changes in PET directly influence crop production and irrigation requirements.

The general knowledge about evaporative conditions on the TP however is sketchy. For a long time publications of estimates of potential evapotranspiration (PET) rates in Tibet were restricted to generalized maps (Kayane, 1971; Henning and Henning, 1984) or to individual stations (Henning and Henning, 1981). PET estimates based on temperature data alone (Thornthwaite, 1948; Lieth et al., 1996; Walter, 1955) have been shown to be inaccurate underestimating actual evaporative conditions on the TP considerably (Thomas and Chen, 2002). Only recently a number of estimates based on the Penman-Monteith equation have become available (Thomas, 1999, 2002) that were also included in the FAOCLIM data base (FAO, 2001). Mean monthly PET estimates based on satellite measurements have been calculated by Tateishi and Ahn (1996) and Choudhury (1997). With no or only sparse information on wind and humidity conditions which are an important part of the evaporative environment at the high altitude of the TP (Thomas, 2000a) these estimates provide no information on long-term temporal variability and are thought to be less accurate despite their high spatial resolution.

As a consequence there is only unconsolidated knowledge about evaporative changes on the TP. From 1951 to 1993 annual PET rates in the eastern part of the TP showed both increasing and decreasing trends of more than 20 mm/decade (Thomas, 2000a). In the Yarlong Tsangpo valley (Central Tibet) July PET rates have decreased moderately by 7.5 mm/decade between 1954–1993 (Thomas and Chen, 2002). For the upper reaches of the Yellow River Li et al. (2000) reported an annual increase of 3.3 mm during the summer months (May to October) from 1981 to 1998. Spatial PET data fields calculated from an extended station data base (Thomas and Herzfeld, 2004) have shown considerable spatial differences in PET rates and their associated trends.

Recent global temperature increases have been the highest in the last century (IPCC, 2001) accompanied by a wide spread reduction in sunshine duration (Stanhill and Cohen, 2001). To investigate if these changes have affected PET rates on the TP 101 stations with records from 1961 to 2000 were selected covering the TP and surrounding areas. In this paper we describe both averaged and detailed regional PET trends on the TP and adjacent mountain ranges and analyze their spatial and temporal variations. To investigate probable causes for the observed variability a review of related climatic trends observed on the TP is attached and the contribution of individual climatic parameters affecting PET trends is assessed.

2. Study Area and Data

2.1. STUDY AREA

The study area encompasses the TP proper and parts of the surrounding mountain ranges (Figure 1) according to the Atlas of Tibet (Institute of Geography, Chinese

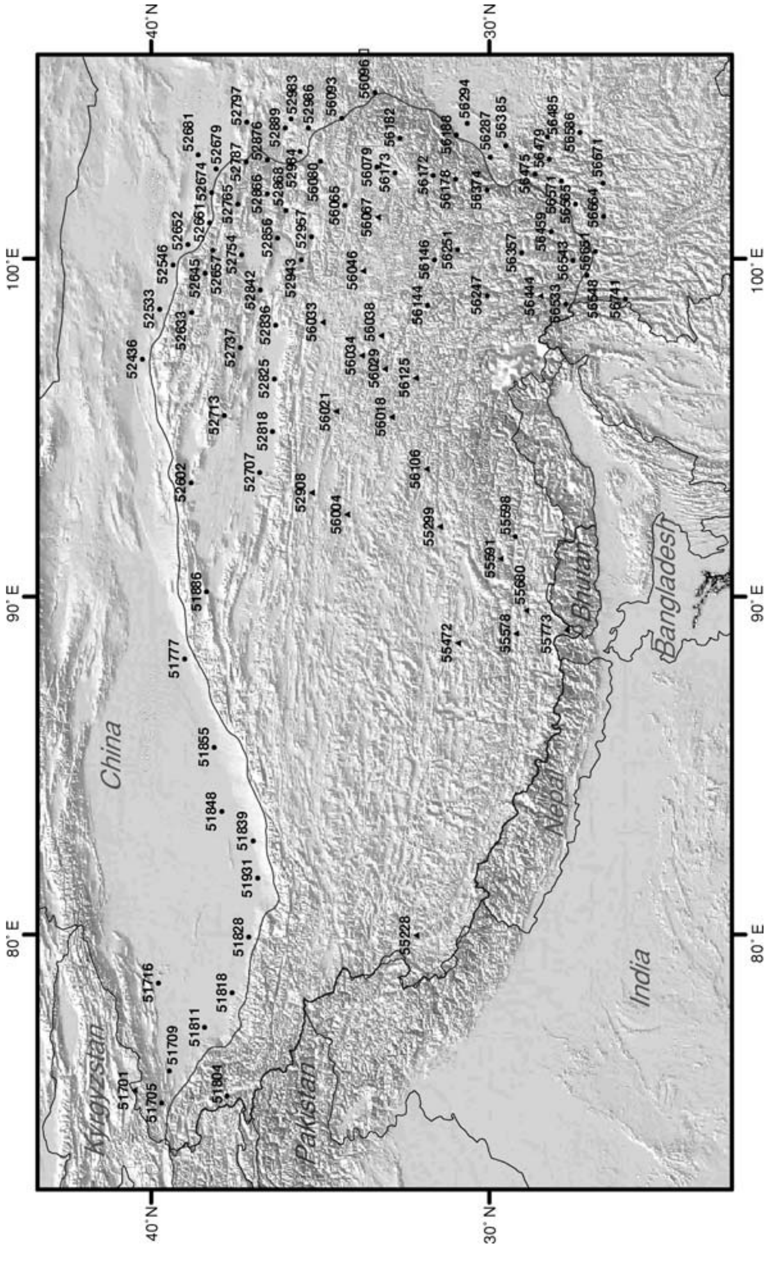

Figure 1. Study area and station distribution. The line marks the boundary of the Tibetan Plateau as used in this study. Stations marked with a triangle are situated above 3500 m. Numbers are WMO station identifiers and refer to Table I.

Academy of Sciences, 1990). The TP is the highest contiguous area of the world covering 1.409 mill. km^2 above 4500 m (Huddleston et al., 2003). This amounts to 79 % of the global area of UNEP-WCMC mountain class 6 (areas with elevations above 4500 m) area. According to Chinese climate classifications the entire study area is classified as a 'plateau climate' (Huang, 1986; Li, 1993), a subtropical to temperate mountain climate unique to the TP. Individual stations in the extreme southern valleys of Tibet at the border to India are already situated on the southern escarpment of the Himalayas and are regarded as 'peripheral tropical' (Ren, 1985).

From a geomorphological point of view a plateau exists only in the central and western part of the study area with average elevations above 4500 m. The eastern part has been deeply dissected by the major rivers of East Asia such as the Jinsha Jiang (the upper reaches of the Yangtze River), the Lancang Jiang (Mekong River) and the Yarlung Tsangpo (the upper reaches of the Brahmaputra in Tibet). The outer rim of the plateau is delineated by a chain of major mountain systems such as the Himalayas in the south and the Kunlun Shan and Qilian Shan in the north with relative elevation differences of more than 2000–4000 m between river valleys and mountain summits.

2.2. DATA

Data of 101 meteorological stations were obtained from the Meteorology Center, National Meteorology Bureau of the PR China (Table I). Stations are identified by their WMO-number and Chinese name; where applicable; local names were added (e.g. 55773 Pali/Yadong). It should be noted that except for four stations no precise PET data have been published before.

According to Figure 1 63 stations are located on the TP with station altitudes varying between 1591 m (56533 Gongshan) and 4670 m (55472 Shenzha/Xainza). 42 stations are located above 3000 m and only 2 stations are situated below 2000 m. An additional 38 meteorological stations surrounding the TP were included for a better regional understanding of PET trends. The altitudes of all 101 stations vary between 505 m (56294 Chengdu) and 4670 m (55472 Shenzha/Xainza) with 36 stations situated below 2000 m. Station network density in high altitude regions is generally much more sparse than in the lowlands. East of a line at app. 89°E station distribution is generally adequate while to the west only 2 stations are available. Most meteorological stations on the TP were established until the middle of the 1950s. In order to obtain complete time series only observations after 1960 were selected. In addition only stations with less than five missing records during the observation period 1961–2000 were retained. With no station histories available homogeneity of the time series was assessed by visual inspection of station time series of air pressure. Previous work has shown that estimated PET time series are much less inhomogeneous than temperature or precipitation data perhaps owing to the influence of the combined effects of several climatic elements on PET that each respond differently to station relocations or instrument changes.

TABLE I
Station list

	WMO-No.	Station names		Longitude (°E)	Latitude (°N)	Altitude (m)
1	51701	Wuyuntuqia		75.40	40.52	3505
2	51705	Wuqia		75.02	39.70	2137
3	51709	Kashi		75.98	39.47	1289
4	51716	Bachu		78.57	39.80	1117
5	51777	Ruoqiang		88.17	39.03	888
6	51804	Tashenkuergan		75.23	37.78	3091
7	51811	Shache		77.27	38.43	1231
8	51818	Pishan		78.28	37.62	1375
9	51828	Hetian		79.93	37.13	1375
10	51839	Minfeng		82.77	37.00	1409
11	51848	Andehe	Andir	83.65	37.93	1264
12	51855	Qiemo		85.55	38.15	1248
13	51886	Mangya	Mangnai	90.15	38.37	3139
14	51931	Yutian		81.67	36.87	1427
15	52436	Yuminzhen		97.03	40.27	1526
16	52533	Jiuquan		98.52	39.77	1477
17	52546	Gaotai		99.83	39.37	1332
18	52602	Lenghu		93.38	38.83	2733
19	52633	Tuole	Qilian Tuole	98.42	38.82	3361
20	52645	Yeniugou		99.58	38.42	3180
21	52652	Zhangye		100.43	38.93	1483
22	52657	Qilian		100.25	38.18	2787
23	52661	Shandan		101.08	38.28	1765
24	52674	Yongchang		101.97	38.23	1976
25	52679	Wuwei		102.67	38.10	1531
26	52681	Minqin		103.08	38.63	1367
27	52707	Xiaozaohuo		93.68	36.80	2767
28	52713	Dachaidan	Da-Qaidam	95.37	37.85	3173
29	52737	Delingha		97.37	37.37	2982
30	52754	Gangcha		100.13	37.33	3302
31	52765	Menyuan		101.62	37.45	2943
32	52787	Wuqiaoling	Wushaoling	102.87	37.20	3045
33	52797	Jingtai		104.05	37.18	1631
34	52818	Germu	Golmud	94.90	36.42	2808
35	52825	Nuomuhong		96.45	36.37	2790
36	52836	Dulan		98.03	36.33	3191
37	52842	Chaka	Uulan Caka	99.08	36.78	3088

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TABLE I
(*Continued*)

	WMO-No.	Station names		Longitude (°E)	Latitude (°N)	Altitude (m)
38	52856	Gonghe		100.62	36.27	2835
39	52866	Xining		101.92	36.58	2261
40	52868	Guide		101.43	36.03	2237
41	52876	Minhe		102.93	36.58	1814
42	52889	Lanzhou		103.88	36.05	1517
43	52908	Wudaoliang		93.08	35.27	4612
44	52943	Xinghai		99.98	35.58	3323
45	52957	Tongde		100.65	35.27	3289
46	52983	Yuzhong		104.15	35.87	1874
47	52984	Linxiatai		103.18	35.62	1917
48	52986	Lintao		103.87	35.37	1887
49	55228	Shiquanhe		79.98	32.18	4232
50	55299	Naqu	Nagqu	92.07	31.48	4507
51	55472	Shenzha	Xainza	88.63	30.95	4670
52	55578	Rikeze	Shigaze	88.92	29.22	3800
53	55591	Lhasa		91.13	29.67	3649
54	55598	Zedang		91.78	29.25	3500
55	55680	Jiangzi		89.60	28.92	4040
56	55773	Pali	Yadong	89.08	27.73	4300
57	56004	Tuotuohe		92.43	34.22	4533
58	56018	Zaduo	Zadoi	95.32	32.90	4068
59	56021	Qumalai	Qumarleb	95.48	34.55	4231
60	56029	Yushu		96.75	33.10	3703
61	56033	Maduo	Madoi	98.13	34.95	4221
62	56034	Qingshuihe		97.13	33.80	4415
63	56038	Shiqu		97.73	33.23	4200
64	56046	Dari	Darlag	99.65	33.75	3968
65	56065	Henanwaisi	Henan	101.58	34.28	3412
66	56067	Jiuzhi		101.23	33.32	3600
67	56079	Ruoergai	Runing	102.72	33.33	3500
68	56080	Hezuo		102.90	35.00	2910
69	56093	Minxian		104.17	34.38	2315
70	56096	Wudu		104.92	33.40	1079
71	56106	Suoxian	Sog Xian	93.78	31.88	4023
72	56125	Angqian		96.48	32.20	3644
73	56144	Dege		98.63	31.83	3201
74	56146	Ganzi	Gerze	99.98	31.63	3394

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TABLE I
(*Continued*)

	WMO-No.	Station names		Longitude	Latitude	Altitude
75	56172	Maerkang	Barkam	102.48	31.66	2670
76	56173	Hongyuan		102.55	32.80	3463
77	56178	Xiaojin		102.37	31.00	2367
78	56182	Songpan		103.57	32.65	2828
79	56188	Guanxian		103.67	30.98	707
80	56247	Batang		98.92	30.08	2589
81	56251	Xinlong		100.27	30.95	3000
82	56287	Ya'An		103.00	29.98	628
83	56294	Chengdu		104.02	30.67	506
84	56357	Daocheng		100.18	29.05	3500
85	56374	Kangding		102.03	30.08	2616
86	56385	Emeishan		103.35	29.52	3137
87	56444	Deqen		98.90	28.50	3593
88	56459	Muli		100.80	28.18	2586
89	56475	Yuexi		102.52	28.65	1662
90	56479	Zhaojue		102.95	28.23	2132
91	56485	Leibo		103.62	28.30	1475
92	56533	Gongshan		98.67	27.75	1591
93	56543	Zhongdian		99.95	27.53	3354
94	56548	Weixi		99.52	27.12	2440
95	56565	Yanyuan		101.62	27.45	2680
96	56571	Xichang		102.30	27.88	1591
97	56586	Zhaotong		103.75	27.33	1950
98	56651	Lijiang		100.22	26.87	2393
99	56664	Huaping		101.27	26.63	1245
100	56671	Huili		102.25	26.65	1787
101	56741	Lushui		98.82	25.98	1792

Where applicable both Chinese and local station names are listed.

PET rates were estimated with the Penman-Monteith equation (Monteith, 1965). The Penman-Monteith method is the most reliable way to estimate PET under various climates (Jensen et al., 1990), as it reflects changes in all meteorological factors affecting evaporation and plant transpiration. In this study the concept of 'potential evapotranspiration' is used to quantify the combined effects of soil evaporation and plant transpiration from a vegetation surface. PET is defined as 'the rate of evapotranspiration from a hypothetic crop with an assumed height of 12 cm, a fixed canopy resistance of 70 sm^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and not short of water', (Smith, 1992,

p. 57). As such PET is a theoretical value that is not necessarily approached in reality due to differing soil cover and water availability. Jensen et al. (1990) have proposed the term ‘reference evapotranspiration’ instead of PET to underline this meaning. PET does not directly give an indication of actual evapotranspiration rates that are governed by soil (soil type, infiltration capacity), relief (slope, exposition and relief form), plant (vegetation type, soil cover, LAI, rooting depth) and climate (precipitation amount and intensity, PET and the temporal distribution of both variables) characteristics. One main advantage of the concept of PET is that it provides a standardized value that allows to compare evaporative environments under different climatic settings. This concept has been developed by the Food and Agriculture Organization of the United Nations (FAO) during the last decades (Doorenbos and Pruitt, 1979; Doorenboos and Kassam; 1986, Smith, 1992; Allen et al., 1998) and has been applied on a global scale to land use studies (Fischer et al., 2000).

The Penman-Monteith method relies on a number of parameterizations to take into account environmental conditions. Values for crop surface resistance, albedo and crop height were set to 70 sm^{-1}, 0.23 and 0.12 m, resp. as recommended by Allen et al. (1998). Shortwave radiation as the primary source of energy for evapotranspiration is estimated from observed sunshine duration with the help of an empirical relationship. Incoming solar radiation R_s is estimated according to

$$R_s = (a_s + b_s n/N)R_a \tag{1}$$

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 bright sunshine duration per day (in hours), N total day length (in hours) and R_a extraterrestrial radiation. R_a is calculated according to Duffie and Beckman (1980). The Angstrom coefficients a_s and b_s for the study area were determined by Weng et al. (1986) from local radiation data. Heat transfer from the soil was neglected as the magnitude of daily soil heat flux over the period of a month is very small (Smith, 1992).

The Penman-Monteith equation requires wind speed measurements at 2.0 m above ground. For the standardized reference crop with crop height of 0.12 m the wind function relating the wind speed at a given height above ground to the standard height of 2 m above ground can be written as

$$U_2 = 4.87U_z(\ln(67.8z - 5.42))^{-1} \tag{2}$$

where U_2 is wind speed at 2 m above ground (m s^{-1}), U_z measured wind speed at z m above ground (m s^{-1}) and z height of measurement above ground surface (m).

Snow cover, land use or freezing of soil that lead to seasonal changes in albedo and water transfer through the soil were not taken into account when calculating PET but would have to be considered when estimating actual ET.

Computation of PET was done with ET V1.2 software from Cranfield University (Hess, 1998) that implements the calculation procedures proposed by Smith (1992) and published in detail by Allen et al. (1998). Monthly records for temperature, relative humidity, air pressure, wind speed (measured at 10 m above ground) and sunshine duration for each station were combined and reviewed for completeness and possible errors. PET estimates were calculated only for months with complete records. Annual PET was calculated as the sum of monthly PET estimates.

3. Data Analysis Procedure

Linear regression analysis (least squares method) was used to detect trends in all time series:

$$y_x = a + bx + e_x \tag{3}$$

where y_x denotes estimated monthly or annual PET from the Penman-Monteith model at time x (year) and e_x is the deviation of the data from the straight line defined by a (the intercept) and trend b (the slope), which represents the rate of increase or decrease of the PET anomalies. Linear regression of PET over the period 1961–2000 was performed on monthly and annual estimates of all stations. The use of higher order regressions on relatively short time series is not recommended as the decision for a certain order can in most cases not be based on climatological reasons (Rapp and Schönwiese, 1996). For the TP as a whole, a spatially averaged ‘All-Tibet’ time series was calculated as an unweighted monthly regional average from all 63 stations with data for the given month. For the interpretation of the significance of the results a t-test of the regression coefficient was used. A 10-year smoothing average was applied to all time series when calculating trends. This approach follows the usual procedure to suppress high-frequency signals by applying low-pass filters of various designs (Mitchell, 1966). SPSS software was used to calculate all statistics. In order to understand how individual meteorological factors affect PET rates, partial correlation between PET rates and meteorological data used to estimate PET was applied in an additional step.

Based on the observed trend rates changes of PET estimates over 1961–2000 (trends) were calculated as

$$\Delta\mathrm{PET} = (\mathrm{PET}_{2000} - \mathrm{PET}_{1961})/4 \tag{4}$$

where ΔPET is the trend, signifying the change of PET rates per decade (in mm PET/decade) with PET_{2000} and PET_{1961} as monthly or annual PET values in the year 2000 and 1961, resp. as calculated from (1). Trend values given in this paper generally refer to this value. Relative trend values are given as a percentage of the respective long term mean.

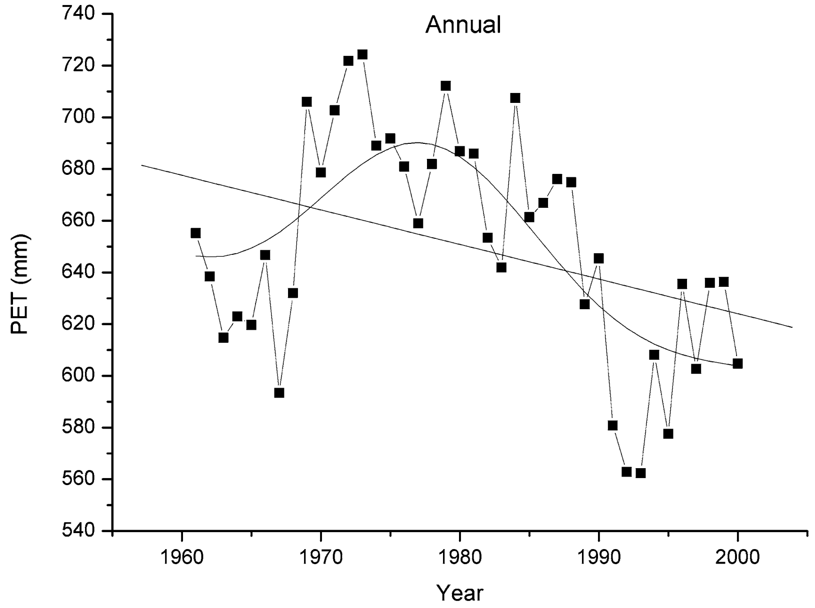
January, April, July and October were selected to describe the seasonal variation which in the case of the TP consists both of hygric seasons (winter monsoon or ‘dry season’, pre-monsoon, summer monsoon or ‘wet season’ and post-monsoon season) and thermic seasons (‘winter’ , ‘spring’, ‘summer’ and ‘autumn’).

4. PET Changes 1961–2000

4.1. 'ALL-TIBET' PET SERIES

Mean linear trends for the TP as a whole show that PET rates have been decreasing in all seasons and on an annual basis (Figure 2 a–e). However only January, April and annual values are significant at the 95% significance level (Table II). Trends show a seasonal variation with high values in summer and low values in winter. The annual maximum in April is out of step with the relatively smooth seasonal variation. If changes relative to the long-term mean are considered the situation is more or less reversed, but again with the highest value in April. The relative annual trend is similar in magnitude to the relative monthly values.

If the interannual variation of the 'All-Tibet' series is considered all trends follow a steady downward trend at least since 1961. PET rates in individual years however showed considerable variations remaining above normal from about 1970 to 1985 for April and July rates and to 1990 for January, October and annual rates, resp., and below normal before and after this period. Annual rates peaked at more than 700 mm in the 1970s and remained below 600 mm in the 1960s and 1990s. April



(a) 1961--2000 trend -13.05mm/month/decade

Figure 2. (a–e) Regional averaged annual and monthly PET totals (mm/decade per month or per year, resp.) from 1961 to 2000 for 63 stations on the Tibetan Plateau. The straight line shows the linear trend from 1961–2000, the curve represents a smoothing 10 year-average from 1961 to 2000.

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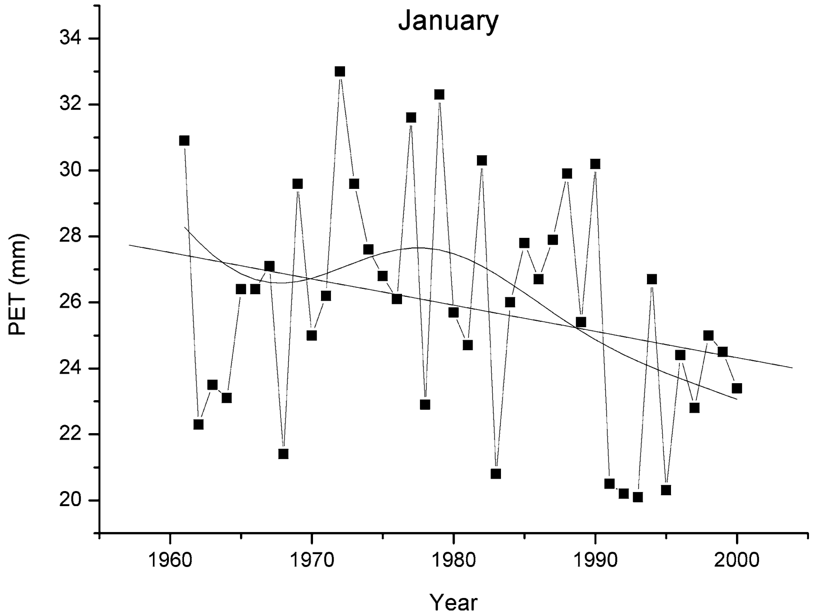
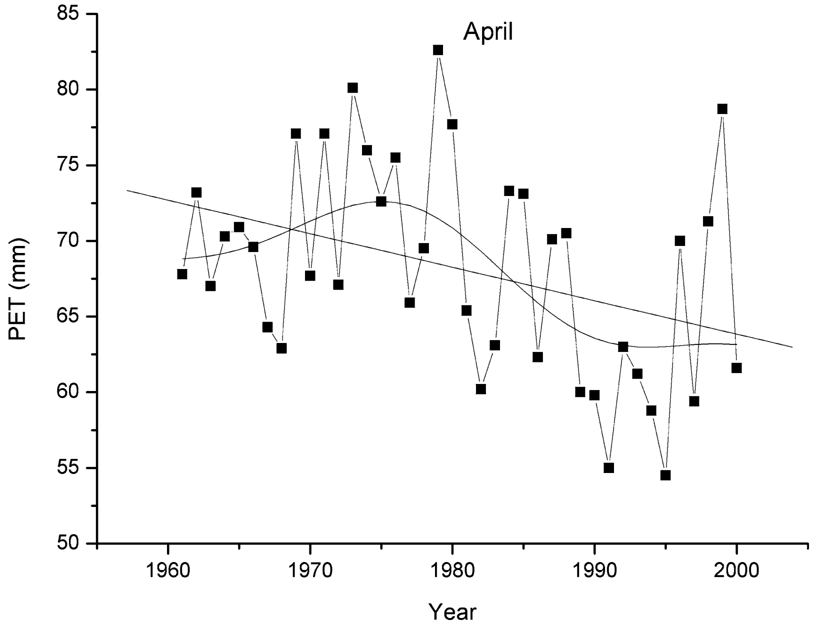
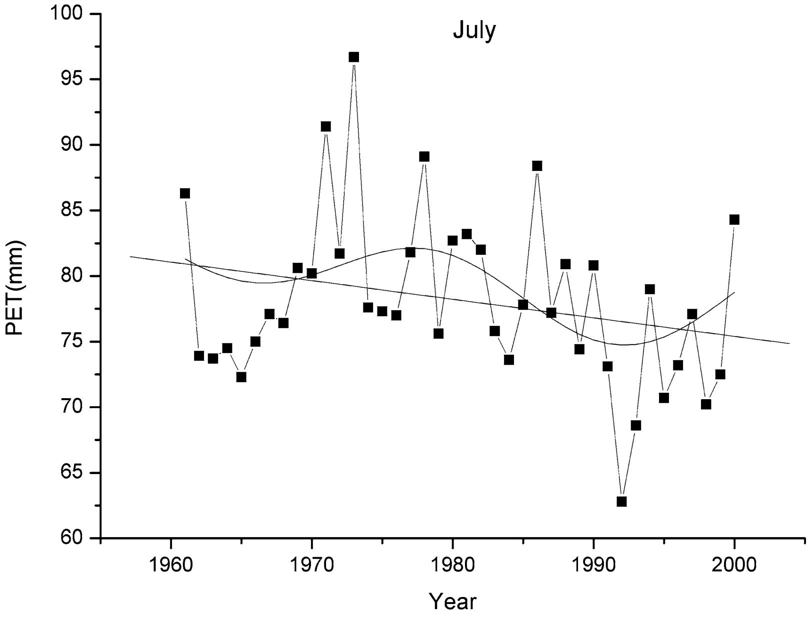


(b) 1961--2000 trend -0.78mm/month/decade

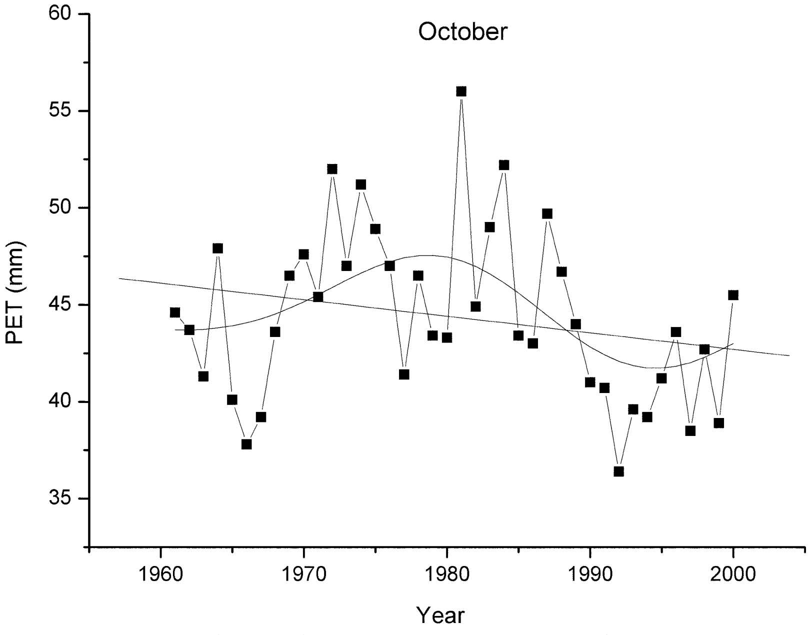


(c) 1961--2000 trend -2.16mm/month/decade

Figure 2. (Continued)



(d) 1961--2000 trend -1.38mm/month/decade



(e) 1961--2000 trend -0.83 mm/month/decade

Figure 2. (Continued)

TABLE II

All-Tibet series absolute and relative trends
average 40-year (1961–2000) monthly and annual Penman-Monteith PET trends

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Trend rate (mm/decade)	*−0.8*	−0.6	−1.2	*−2.2*	−1.2	−1.2	−1.4	−1.2	−0.8	−0.8	−0.3	−0.7	*−13.1*
Relative trend (%)	−3.0	−1.8	−2.3	−3.2	−1.5	−1.6	−1.8	−1.6	−1.4	−1.9	−1.1	−2.8	−2.0

Trends derived from linear regression. Values in italics are significant at the 95% level. Relative trends are given as a percentage of the long-term monthly or annual mean.

TABLE III

Correlation coefficients between PET and meteorological elements

	RH	T	W	SD	P	AP
Annual	−**0.6774**	**0.8491**	**0.9687**	*0.4191*	−0.2956	**0.5692**
January	−**0.6487**	**0.8684**	**0.8939**	−0.1617	0.0665	**0.3517**
April	−**0.8609**	**0.9619**	**0.9272**	0.1893	−0.1952	0.0851
July	−**0.7700**	**0.9111**	**0.9457**	0.1516	−0.0876	0.1338
October	−**0.8010**	**0.9324**	**0.9600**	0.1627	−0.1204	0.0686

RH: Relative humidity, T: Temperature, W: Wind speed, SD: Sunshine duration, P: precipitation, AP: atmospheric pressure.
Bold values are significant at 99% level, values in italics are significant at 95% level.

and July PET rates began to increase again from about 1996 onwards. If a low pass filter is applied to suppress year to year variations all changes occur in a very similar manner in all months despite the large differences in actual PET rates.

4.2. ANNUAL PET TRENDS

The general decline of PET rates on the TP however is spatially not consistent. When annual trends are considered about one-third (24) of the stations show an increase in PET rates with an average increase of 12.0 mm/decade. The remaining 39 stations experienced an average trend of –26.8 mm/decade. Figure 3 maps the spatial distribution of annual PET trends. Large changes occurred mainly along the mountainous periphery of the TP while the central part experienced relatively small changes. The largest absolute decreases occurred in the northern and southeastern parts of the TP. Individual stations with the largest observed reductions (significant at the 95% level) are 52825 Nuomuhong (−79.5 mm/decade, 6.6%), 52866 Xining-(−62.3 mm/decade, 9.7%), 52876 Minhe (−78.8 mm/decade, 11.4%) and 56251 Xinlong (−69.4 mm/decade, 9.5%).

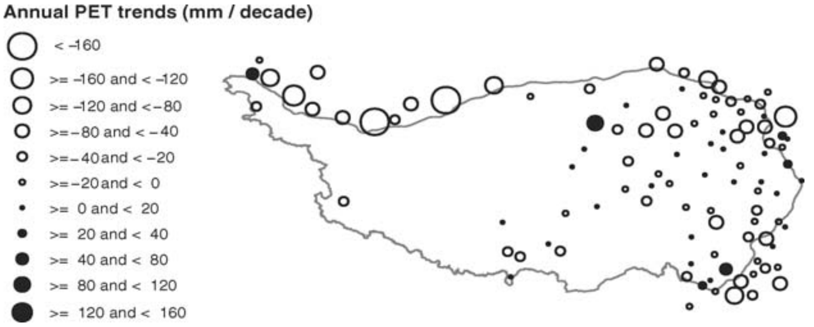


Figure 3. Spatial distribution of annual PET trends on the Tibetan Plateau. Trend values are given as mm/decade and are calculated according to (2)

Positive trends were found in the northern and extreme eastern and southeastern part of the TP. With a trend of 84.8 mm/decade (52707 Xiaozhaohuo, 6.9%) absolute maximum positive values are in the same range as maximum negative trends. Increasing trends in the southeast at 56459 Muli (47.6 mm/decade, 5.5%) and in the east at 56093 Minxian (26.0 mm/decade, 6.6%) are clearly lower than stations with high negative trends.

The entire western half of the TP west of 89°E is represented by only two stations (55228 Shiquanhe and 51804 Tashikuergan). Moderate negative PET trends between −1 mm to −4 mm prevail in all seasons with an annual trend of −22.0 mm (5.9%) and −23.9 mm (2.0%), resp.

Considerably higher trends are found at the stations outside of the TP, particularly along the southern border of the Taklimakan desert. In this region annual PET rates range from 1100 to 1800 mm so absolute trends can surpass those on the TP considerably. Even in relative terms however trends in this region are considerably higher reaching a maximum of 15.4% (−178.9 mm) at 51931 Yutian.

4.3. WINTER PET TRENDS

In January only 14 stations show positive monthly trends (0.82 mm/month/decade) while at the remaining 49 stations trends declined at a rate of –1.26 mm/month/decade.

The basic pattern of the distribution of January PET trends (Figure 4) is similar to that of the annual trend distribution. Positive trends remain all below 3 mm/month/decade with highest increases in the north at 52707 Xiaozhaohuo (1.3 mm/month/decade, 5.5%), east (56093 Minxian, 1.5 mm/month/decade, 10.8%) and the southeast (56459 Muli, 3.1 mm/month/decade, 4.3%). Negative trends are again found over a larger area with maximum values at 56251 Xinlong (−3.9 mm/month/decade, 9.3%) and 56018 Zaduo (−3.3 mm/month/decade,

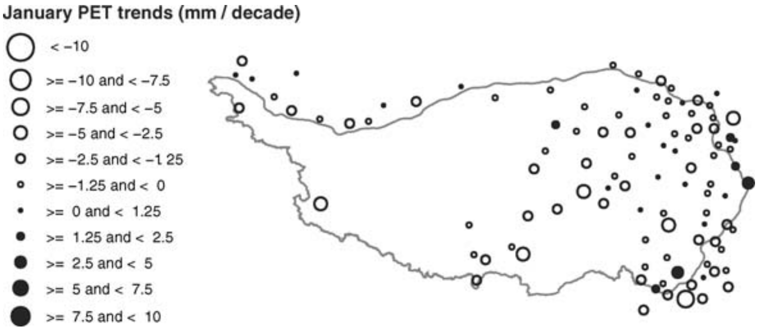


Figure 4. Spatial distribution of January PET trends on the Tibetan Plateau. For description refer to Figure 3.

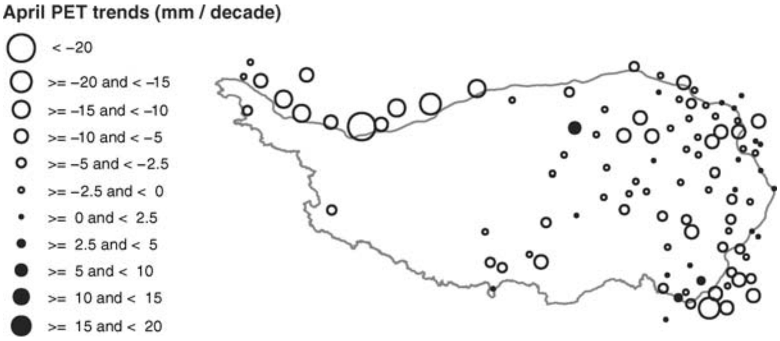


Figure 5. Spatial distribution of April PET trends on the Tibetan Plateau. For description refer to Figure 3.

17.9%). All abovementioned trends except at 52707 Xiaozhaohuo are significant at the 95% level.

4.4. SPRING PET TRENDS

April is the month with the maximum monthly trend with station frequencies similar to January with 12 stations (average 1.4 mm/month/decade) with positive trends and 51 stations with negative trends (average −2.8 mm/month/decade).

In April three distinctive regions with positive trends exist (Figure 5). Again maximum positive PET trends are found at 52707 Xiaozhaohuo (6.2 mm/month/decade, 5.8%) followed by 56093 Minxian (1.8 mm/month/decade, 4.2%) in the east and 56459 Muli (5.0 mm/month/decade, 4.1%) in the southeast. Larger negative trends are distributed mainly in the northwestern and southern parts of the TP around 52825 Nuomuhong (−7.0 mm/month/decade, 5.4%, 55598 and 56251 Xinlong (−9.2 mm/month/decade, 11.5%) All values are significant at the 95% level.

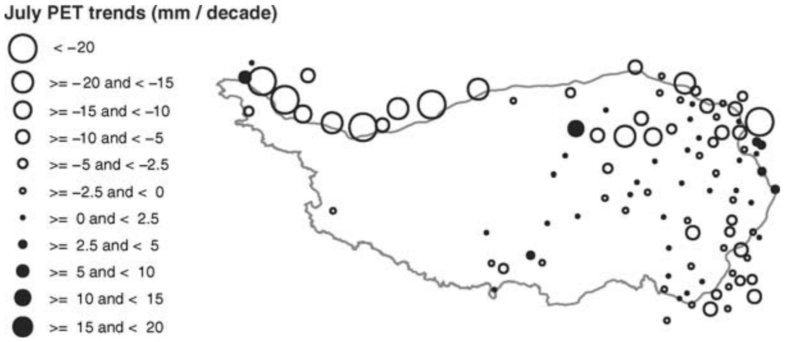


Figure 6. Spatial distribution of July PET trends on the Tibetan Plateau. For description refer to Figure 3.

4.5. SUMMER PET TRENDS

Compared to winter and spring summer shows a far larger number of stations with positive trends (27 stations, 1.8 mm/month/decade) than those with negative trends (36 stations, −3.5 mm/month/decade). Despite this increase the average summer trend remains negative. Due to the annual maximum of PET rates in summer some individual trends are also the largest among all annual and seasonal trends.

Positive trends in summer are found mainly in two regions in the northern and central TP (Figure 6). They include the highest station 55472 Shenzha/Xainza and stations in the eastern and southern peripheral mountain ranges with trends up to 5 mm/month/decade. Maximum positive PET trends occur again at 52707 Xiaozhaohuo (12.8 mm/month/decade, 6.7%). Regions with negative trends therefore are restricted to the northeastern (maximum negative PET trend at 52825 Nuomuhong, −18.3 mm/month/decade, 11.1%) and southeastern (56251 Xinlong, −5.1 mm/month/decade, 8.0%, 56178 Xiaojin −4.9 mm/month/decade, 4.6%) TP.

4.6. AUTUMN PET TRENDS

The station distribution in October resembles that of July with 26 stations with positive (1.1 mm/month/decade) and 37 stations with negative (–2.0 mm/month/decade) trends.

The trend range in October remains mostly below ±3 mm/month/decade (Figure 7). Positive trends occur in the northern parts of the TP (maximum at 52707 Xiaozhaohuo, 5.7 mm/month/decade, 7.2%) extending to the south and the southeast to 56459 Muli (3.6 mm/month/decade, 7.2%). The largest negative PET trend in autumn occurs at 56251 Xinlong (−5.3 mm/month/decade, 10.4%).

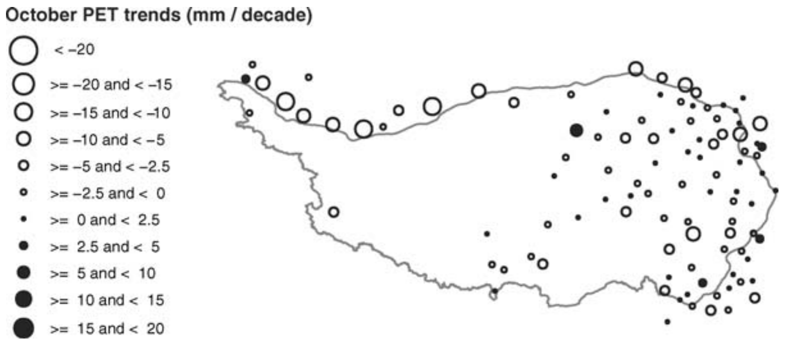


Figure 7. Spatial distribution of October PET trends on the Tibetan Plateau. For description refer to Figure 3.

As noted before the spatial distribution of trends remains remarkably stable throughout the year: seasonal trends at selected stations are basically identical with annual trends.

4.7. PET TRENDS IN RELATION TO ALTITUDE

Based on a small sample of eight stations Thomas (2000a) found a significant positive relationship between monthly PET trends and altitude on the eastern TP for stations above 1650 m. Data for the entire TP lack a clear correlation between altitude and trends with the exception of high-altitude stations which show only negative trends. Omitting 2 stations west of 89°E that are thought to belong to a different climatic region (Leber et al., 1995) 12 stations above 4000 m show a significant negative correlation between altitude and annual trends (significant at the 95% level).

When relative trends are considered a visual inspection suggests that low relative trends (neglecting their sign) are found exclusively at stations above 3500 m representing the high altitude core of the TP (see Figure 1). The mean relative trend at 20 high altitude stations is considerably lower (mean 1.9%, maximum 5.2%) than at the remaining 43 stations at altitudes below 3500 m (mean 3.3%, maximum 11.4).

4.8. CORRELATIONS BETWEEN PET AND CLIMATE VARIABLES

To analyze in detail which meteorological factors contributed most to the observed reduction of PET rates on the TP correlations between estimated PET rates and the meteorological variables used to estimate PET or thought to affect PET were calculated.

Significant correlations exist for wind speed, temperature, relative humidity and atmospheric pressure (in decreasing order of importance). Changes of wind speed explained the largest amount of variance in any season.

5. Discussion

5.1. SPATIAL AND TEMPORAL CHARACTERISTICS OF PET TRENDS

Monthly PET estimates for the TP and areas surrounding the TP were calculated using the Penman-Monteith equation based on meteorological data from the Meteorology Center of the National Meteorology Bureau of the PR China. Trend rates of mean annual PET averaged on the TP are negative (−13.1 mm/decade). Negative trends are mainly found in the central, northeastern and southeastern regions of the TP. The maximum negative and positive values at a single station were observed at 52825 Nuomuhong (−79.5 mm/decade) and at 52707 Xiaozhaohuo (84.8 mm/decade), resp.

The basic spatial pattern of seasonal trends is similar to that of the annual pattern (Figures 3–7). 35 stations exhibit the same sign of trend in all season and on an annual basis. 18, 7 and 3 stations show opposing trends in one, two and three seasons, resp. as compared to the annual trend. In general there are more stations with negative than with positive trends. PET rates decrease over a larger area in winter and spring (80% of all stations) as compared to summer and autumn (58% of all stations). In addition decreasing PET rates tend to be far higher than increasing rates.

The spatial distribution of trends throughout the seasonal course is remarkably stable. Maximum positive and negative trends each occur at the same stations throughout the year and the extent of regions with predominately positive or negative trends does change only marginally. In several regions steep spatial gradients between regions with positive and negative trends can be observed. Large differences of trends (even change of sign) occur over short distances. In some cases topography obviously plays an important role in demarcating regions of opposing trends as in the case of 55773 Pali/Yadong located south of the Himalayan main range. Here the range can be regarded as a barrier effectively separating 55773 Pali/Yadong from the climatic situation of the TP. In other cases however no such evident topographic forcing can be discerned as in the case of 52707 Xiaozhaohuo and 52825 Nuomuhong. Both stations are located in the southern Qaidam basin at a distance of only 300 km and at comparable altitudes (2767 m and 2790 m, resp.) under generally similar climatic and topographic conditions.

A survey of the effects of altitude on PET trend rates has shown a decrease of PET trend rates with altitudes above 4000 m. A general increase of PET trends with altitude as proposed by Thomas (2000a) seems highly unlikely. Relative PET trends however clearly decrease with altitude. As noted earlier most of the stations below 3500 m are located in the mountain ranges of the eastern TP where local climatic conditions create highly variable PET gradients (Thomas, 1997, 2002). In view of these findings a detailed analysis of possible PET trend gradients should consider not only altitude but also the topographic situation of the stations.

For China as a whole PET trends from 1954–1993 were calculated and analyzed using the same method as applied here (Thomas, 2000a). The TP showed both positive and negative trends with the strongest decrease of PET rates in spring. When stations contained in both data sets were compared trends in individual seasons have remained stable with minor changes since the early 1950s. The eastern part of the TP has therefore experienced a widespread general decrease of PET rates during the second half of the last century.

5.2. REPRESENTATIVITY OF DATA

Both absolute altitude and relative position in relation to the surrounding relief determine the local climate at any given meteorological station. While altitude alone would qualify the major part of the stations in this data set as ‘mountain stations’, in fact most of them are situated either on high-altitude plains, intramontane basins or along valley bottoms. A considerable number particularly of the highest stations are situated on plains or in basins. High-mountain relief with its related topoclimatological effects like rain-shadows or forced orographic precipitation is found mainly in the mountain ranges surrounding the TP. Most of the stations in this area are valley stations below 4000 m which may observe a number of relief-induced climatic phenomena like dry valley winds or inversion fog that influence PET rates.

Compared to these more or less sheltered locations exposed terrain like ridges or slopes may expect higher PET rates due to increased wind speeds or higher insolation. PET trends should however be less affected by station location than actual PET rates. PET trends are subject to external forcing by several climatic variables (see following sections). Only if one or several of theses variables change systematically over space and time will PET trends exhibit spatial inhomogeneities. It is highly unlikely that all variables would act in concert leading either to higher or lower PET rates. The remarkable stability of spatial PET trend structures in all months indicates that such changes did not occur. The lack of a clear correlation between altitude and PET trends may be regarded as a further indication that station location does not bias PET trends in a noticeable way.

Increasing urbanization in China has been shown to introduce bias in meteorological time series (Wang et al., 1990). With the exception of the capital Lhasa meteorological stations on the TP are located near small, rural settlements that have experienced only limited development in recent decades. In this respect it is unlikely that urbanization has had a discernible influence on meteorological measurements on the TP.

As the empirical foundations of the Penman-Monteith equation were developed for sites at lower elevations it might be questioned if the equation holds true at high elevations. In the Penman-Monteith equation altitude is used to estimate atmospheric pressure if not available from observations as in this study. Atmospheric pressure in turn is employed to calculate the psychrometric constant. All other values remaining constant Penman-Monteith PET estimates at 4000 m are about

26% lower than at sea level (pers. comm. J. Grieser). Short-wave transmissivity of the atmosphere may also change locally with increasing elevation which should be taken into account by using locally calibrated Angstroem coefficients as in this study.

Empirical studies support the validity of Penman-Monteith PET estimates at high elevations. A comparison of Penman-Monteith PET estimates with lysimeter measurements on the Bolivian Altiplano (altitudes between 3600 – 4000 m) have shown that differences remain in the range of −2.3–3% (or −0.11 mm/day–0.14 mm/day) during the cropping season (Garcia et al., 2004). In Southwest China pan coefficients relating Pan A evaporation measurements to Penman-Monteith PET estimates (altitudes between 640 – 4370 m) remained in the range of 54–64% depending on season (Chen et al., 2005). Both theoretical considerations and empirical data suggest that Penman-Monteith PET estimates are valid at the elevation of the TP.

5.3. RELATED CLIMATIC TRENDS ON THE TP

Surface temperature changes on the TP during the last decades have been a concern for Chinese scientists for a long time. Temperature variations on the TP during the last 100 years show substantial fluctuations and appear to be similar to the Northern Hemisphere, but with a larger magnitude of change and starting at an earlier time (Feng et al., 1998). Annual and winter temperatures from 1955–1996 on the TP were increasing by 0.16 °C/decade and 0.32 °C/decade with weaker trends in spring and summer (Liu and Chen, 2000).

Temperature trends at stations below 3000 m were generally found to be decreasing in the south and the southeast and increasing in the central part of the TP (Zhu et al., 2001) while Liu and Chen (2000) found generally decreasing trend rates with altitude for the whole TP. Altitude related trends have also been observed in the European Alps (Beniston and Rebetez, 1996) where they have been attributed to the topographic situation of the stations (valley vs. mountain stations). As noted earlier station altitudes are not a reliable indicator of topographic situation on the TP so that similar conclusions can not be drawn from the Tibetan data without an in-depth analysis of individual station settings.

Annual mean maximum temperature virtually remained constant (0.01 °C/decade, 1969–1998) as compared to 0.28 °C/decade for the annual mean minimum temperature (Yao and Wu, 2002). Similar results have been obtained by Karl et al. (1993) on a global scale. Variability of mean monthly temperatures in July remained constant while variations in January temperatures were increasing by about 0.2–1.0 °C/month/decade. The number of days with temperatures $>10\,^\circ$C have increased by 2–4 days/decade from 1950 to 1990 (Zhao et al., 2002). Regional interdecadal variations with three cold periods and three warm periods were found for the central river valley area of central Tibet from the early 1980s to 1998 (Kang et al., 1998; Wei et al., 2003).

TABLE IV
Linear temperature trend rates from 1961–2000 in °C/decade for selected stations

ID	Name	Annual	January	April	July	October
52825	Nuomuhong	*0.32*	*0.38*	−0.02	0.17	0.25
52866	Xining	*0.15*	*0.33*	0.04	0.04	−0.12
56251	Xinlong	0.08	0.22	−0.09	−0.01	0.03
55591	Lhasa	*0.40*	*0.50*	*0.36*	*0.30*	*0.48*
56093	Minxian	*0.19*	*0.83*	0.01	*0.21*	−0.01
56459	Muli	*0.74*	*0.91*	*0.61*	*0.45*	*0.72*
52707	Xiaozhaohuo	*0.68*	*0.55*	*0.59*	*0.70*	*0.61*

Values in italics are significant at 95% level.

TABLE V
Linear precipitation trend rates from 1961–2000 in mm/decade for selected stations

ID	Name	Annual	January	April	July	October
52825	Nuomuhong	2.6	*0.3*	0.1	*2.7*	−0.3
52866	Xining	7.2	*0.3*	0.2	5.0	−1.5
56251	Xinlong	18.5	0.2	2.8	1.3	1.4
55591	Lhasa	0.0	*0.3*	0.1	−1.7	−0.7
56093	Minxian	−35.5	0.4	−4.2	−7.2	*−4.6*
56459	Muli	4.0	0.5	2.2	4.6	2.7
52707	Xiaozhaohuo	1.7	0.2	−0.1	0.8	*0.1*

Values in italics are significant at 95% level.

These general findings are supported by data from selected stations (Table IV) that cover the major physiographic regions of the TP. According to our data there is only one station on the TP where temperatures have decreased in all months (56065 Henan). Only at 2 stations temperatures decreased in more than 2 seasons (spring, summer or autumn). In contrast positive trends occurred at most stations: at 54, 39, 49 and 53 stations temperature increased in winter, spring, summer and autumn, resp. At 41, 7, 15 and 28 stations trend rates surpassed 0.2 °C/month/decade. Therefore negative PET trends seem to have occurred under a general warming trend on the TP in the past decades.

Precipitation changes during 1961–2000 on the TP show that increasing trends occurred in winter and spring with weakly (not significant) decreasing precipitation in summer (Table V). Maximum precipitation increased more than 10 mm/season/decade in the southeastern mountain ranges of Tibet both in winter and in summer (Zhu et al., 2001). Precipitation trends at selected stations are positive in most months with the exception of 56093 Minxiang which is peripheral to the TP (Table V). Based on our data there are only 6 stations with negative trends

TABLE VI
Linear trend rates for meteorological variables affecting PET rates

	RH	T	W	SD	P	PET
Annual	*0.4*	*0.25*	*−0.13*	−10.32	4.19	−13.1
January	*1.5*	*0.26*	*−0.11*	−0.72	*0.49*	−0.8
April	0.5	0.04	*−0.16*	−0.25	1.02	−2.2
July	−0.1	0.13	*−0.12*	0.19	−0.17	−1.4
October	0.1	0.18	*−0.10*	−2.47	0.61	−0.8

RH: Relative humidity, %/month decade; T: Temperature, °C/month decade; W: Wind speed, ms^{-1}/month decade; SD: Sunshine duration, hr/month decade; P: Precipitation, mm/month decade. PET trends are given for comparison.
Values in italics are significant at 95% level.

in all seasons compared to 38, 52, 44, 28 and 35 stations with positive trends in the whole year, winter, spring, summer and autumn, resp. Cyclical variations of 3–5, 8–11 and quasi-cyclical variations of 19 years were reported by Wei et al. (2003). Therefore negative PET trends occurred in combination with regionally distributed increasing and decreasing trends of precipitation on the TP.

Sunshine duration has decreased on the TP in all seasons except summer during recent decades (Table VI) which is in accordance with global observations (Stanhill and Cohen, 2001). A significant decrease of annual cloud amount (1954–1994) in the eastern and northern TP was reported by Kaiser (2000). This should lead to increased sunshine duration over much of the TP which is not compatible with the decreases in sunshine duration shown in our data. However Kaiser (2001) also noted that sunshine duration has decreased over much of China despite decreasing cloud amounts. He attributed this effect to the highly polluted atmosphere over China that introduces a bias into sunshine recording instruments by sensing less bright sunshine. While this may be a viable explanation for the industrialized eastern part of China it is an unlikely explanation for the sparsely populated TP lacking any industries.

5.4. INFLUENCES OF METEOROLOGICAL VARIABLES ON PET TRENDS

Previous research has shown that in China different combinations of meteorological factors control PET rates in different regions. For 8 stations on the eastern TP maximum temperatures and to a lesser extent relative humidity, wind speed and sunshine duration were found to particularly affect PET rates (Thomas, 2000a). A recent study (Xu et al., in press) shows that decreasing pan evaporation rates over China are the result of a decrease in wind speed and net radiation.

Table III shows that wind speed, temperature and relative humidity are the most important variables that governed changes of PET rates during the last decades.

To a lesser extent changes in atmospheric pressure affected winter PET trends. Changes in sunshine duration did only explain a marginal amount of variance on an annual basis. Precipitation, which may have indirect effects on PET through reduced temperatures and sunshine duration as well as increased relative humidity, did not affect PET trends in a relevant way.

Taking the signs of the correlation coefficients into account declining PET rates are negatively correlated with relative humidity and positively correlated with temperature and wind speed. Wind speeds were decreasing in all seasons (Table VI) which is consistent with the way meteorological factors control evapotranspiration: decreased wind speeds lower PET rates by not removing saturated air from the evaporating surfaces. Increasing temperatures (significant trends only for January and annual values) however seem to contradict that relationship as increasing temperatures should lower relative humidity and increase PET rates. As noted earlier maximum (daytime) temperatures on the TP have virtually remained constant with only minimum (nighttime) temperatures contributing to the observed mean temperature increases (Yao and Wu, 2002). PET rates are primarily affected by daytime temperatures so the observed increases in mean temperatures do not lead to higher PET rates.

While reductions in sunshine duration are evident in all season except in summer the statistical evaluation showed no significant contribution to declining PET rates. In view of the possible bias in sunshine recordings a contribution of changes in sunshine duration to observed PET trends cannot be ruled out.

5.5. IMPACTS OF PET TRENDS

Any changes in PET rates will have an impact both on terrestrial ecosystem in general and on crop production in particular. Negative PET rates as observed in all seasons will lower the need for irrigation in the semi-arid environment of the TP and will be beneficial for the natural vegetation as well. Positive PET trends have however been observed in the main growing season in summer (75% of annual precipitation concentrated in summer) where they should have far more impact on crop production than decreasing PET trends in winter. Based on data of 8 stations Thomas (2000b) could show that between 1954 and 1993 the water balance on the eastern TP calculated with the FAO water balance model (Doorenbos and Kassam, 1986) has decreased by about 3–10%. The TP was identified as the only large contiguous region in China were potential yields were declining. This is underlined by a regional study where decreasing precipitation and increasing PET rates in summer have been shown to affect the largest crop growing region in central Tibet (Thomas and Chen, 2002) by lowering potential yields by up to 12% during the last 50 years. Despite generally decreasing PET rates water balance studies therefore point to generally decreased water availability for field crops during the last decades.

Projections of future climatic conditions based on GCM results for China have been presented by Hulme et al. (1992) and Tao et al. (2003) who foresee slight increases in temperature and some decreases in potential yield rates on the TP. GCMs are however not able to adequately simulate evaporative conditions (Hulme et al., 1992; Chattopadhyay and Hulme, 1997; Palutikof et al., 1994) and are available only at low spatial resolutions ($>0.5^\circ$) that are barely able to resolve the major topographical features of the TP. In view of contrasting climatic trends on the TP any projections, recommendations and subsequent adjustments of crop irrigation will have to be made based on detailed spatial data sets that can portrait seasonal and regional changes in PET and precipitation regimes.

The same applies to the question if climatic changes occurring on the TP have a diagnostic value for the climatic evolution of East Asia in general. The TP is regarded as a 'climatic startup region' with climatic changes on the TP occurring some time ahead of those in eastern and northern China (Feng et al., 1998). If this relation exists PET trends on the TP should herald similar changes in northeastern China where in recent years droughts had a considerable impact on crop production. In view of the complex distribution of positive and negative trend rates on the TP in summer no simple answer can be given if decreasing PET trends could occur over Northeast China and alleviate some of the drought experienced in recent years.

6. Conclusion

Our study shows that average PET trends (1961–2000) on the TP are negative in all seasons and on an annual basis with an average annual PET trend of -13.1 mm/decade. Maximum and minimum negative trend values were found in spring (April) and winter (January), resp. The largest positive trend occurred in summer (July). Both temporal and spatial distributions of trends remain stable throughout the year.

PET trends on the TP are mainly influenced by changes in wind speed and relative humidity. The observed changes in PET rates are in line with the anticipated changes when considering how the observed trends of meteorological elements should affect PET rates according to the Penman-Monteith model. Particularly decreasing wind speeds have led to decreasing PET rates. Stable daytime temperatures on the TP have limited the importance of temperature trends for changes of PET rates. Sunshine duration trends were found to play an insignificant role.

Observed interannual PET variations may indicate a cyclical behavior (Figures 2 a–e). If this assumption holds true PET rates should increase again in the near future. Slightly increasing values in summer and autumn may indicate that this new period of increased PET rates has already started. When low pass filtered variations of all 4 seasons are compared variations occur in a very similar manner indicating that forcing factors are generally the same in all months. Small differences in winter and spring as compared to summer and autumn may however be indicating that forcing factors during the wet summer monsoon season evolve differently than those of the dry winter season. A detailed analysis of the interannual variability of the contributing meteorological factors is necessary to decide if the observed relationships between PET rates and contributing meteorological factors (namely decreasing wind speeds) have remained constant in the past. This in turn would enable to pinpoint any changes related to variations in the regional and global circulation.

Most of the available stations are concentrated east of 89°E in the middle and eastern part of the TP. There is no direct evidence that negative trends observed at the two stations in the western part of the TP are not representative for the region as a whole. In view of the fact that nearly the entire western half of the TP is not directly covered by stations any conclusion drawn for this region should however be regarded with caution. Remote sensing techniques, either alone (e.g. Li and Lyons, 2002) or in combination with ancillary data (Choudhury, 1997) and geostatistical techniques (Petkov et al., 1996) may provide means to directly obtain spatial PET estimates over the western plateau.

Wind speed turned out to be the most important meteorological variable affecting changes in PET rates on the TP. This is in accordance with Barry (1992) who argues that wind is probably the most important factor controlling PET rates in all high altitude environments. PET estimates without inclusion of wind data should be regarded with caution. It is however the least frequently measured meteorological element and it is the factor most affected by topography. Underestimation of PET rates on the Tibetan Plateau (Choudhury, 1997) may be related to insufficient wind data.

Similarly temperature alone cannot be used to reliably estimate PET rates on the TP. This conclusion was also drawn when estimating PET rates for the mountains of Yunnan Province that are part of the southern mountain ranges of Tibet (Thomas, 2002). Temperature based Thornthwaite (1948), Walter (1955) or Priestley-Taylor (Priestley and Taylor, 1972) PET estimates should be regarded as unreliable under such circumstances. The same conclusion was reached by Garcia et al. (2004) for PET estimates on the Bolivian Altiplano and Chen et al. (2005) for China.

Sunshine duration is commonly regarded as the most significant contributor to PET rates. Estimating PET rates with the help of small scale sunshine duration maps is recommended particularly in areas where meteorological data (and hence wind speed measurements) are scarce (Doorenbos and Pruitt, 1977). In view of the results shown here this approach may not be valid for high altitude areas and in the case of the TP would lead to erroneous PET estimates. Reductions in sunshine duration have been reported both on a global scale (Stanhill and Cohen, 2001), for China in general (Kaiser, 2001) and for the TP (Table VI). Decreases in sunshine duration are discussed as a possible cause for declining PET rates both in China (Thomas, 2000a) as well as on regional scales in general (Cohen et al., 2002) but cannot explain declining PET rates on the TP.

Decreased wind speeds as the primary cause of decreasing PET rates point to changes in the strength of the local circulation system (the monsoon) which in turn would affect a far larger region than the TP alone. Decreases in the strength of the regional circulation system of the Asian monsoons (Chase et al., 2003; Gong and Ho, 2002; Kripalani et al., 2002) which may lead to the observed reductions in wind speed on the TP could be responsible for observed lower PET rates in recent years. This is in contrast to predicted increased monsoonal activity and an increased hydrological cycle under global warming scenarios (IPCC, 2001).

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