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SPATIAL AND TEMPORAL CHARACTERISTICS OF POTENTIAL EVAPOTRANSPIRATION TRENDS OVER CHINA

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ABSTRACT

This paper analyses the time series (1954–1993) of Penman–Monteith evapotranspiration estimates for 65 stations in mainland China and Tibet, for the country as a whole and for individual stations. The analysis shows that for China as a whole, the potential evapotranspiration (PET) has decreased in all seasons. On a regional basis, northeast and southwest China have experienced moderate evapotranspiration increases, while in northwest and southeast China evapotranspiration has decreased to a much higher extent. South of 35°N, sunshine appears to be most strongly associated with evapotranspiration changes while wind, relative humidity and maximum temperature are the primary factors in northwest, central and northeast China, respectively. In the mountains of southwest China, a positive relation between evapotranspiration change and station altitude has been observed. If observed precipitation and PET trends remain unchanged future agricultural production, particularly in south and southwest China, will have to cope with decreasing water availability in the growing season. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: China; trend analysis; potential evapotranspiration; climate change

1. INTRODUCTION

Potential evapotranspiration (PET) is the most important climatic element next to temperature and precipitation. PET plays a crucial role in the heat and mass fluxes of the global atmospheric system and is a key research topic in international scientific programmes (Ehlers and Krafft, 1996). Changes in PET affect precipitation as well as hydrological regimes, and also have a direct impact on crop production through changes in the agroecological water balance. Analyses of changes of PET rates in the past are important for understanding the influence of past climatic changes on soil moisture budgets and their consequences for terrestrial ecosystems.

PET is, however, difficult to measure directly and in most cases is estimated from meteorological data. The most reliable method under various climates is the Penman–Monteith method (Jensen *et al.*, 1990) which requires data on radiation, temperature, humidity and windiness. Resorting to calculation procedures using only one climatic element, such as in the Thornthwaite method (Thornthwaite, 1948), has proven to be unsatisfactory in many climates (Thornthwaite, 1951). Only with the recent availability of digital climatic databases has research on PET become feasible on larger scales.

After the publication of the long-term instrumental databases of China (Tao *et al.*, 1991), basic properties, such as the spatial distribution of long-term averages of PET over China, have been analysed (Thomas, 1999) showing significantly differing PET totals compared with earlier work carried out by Thornthwaite Associates (1963) and Kayane (1971). Climate change studies for China have either focused on climate change modelling with General Circulation Models (GCMs; Hulme *et al.*, 1992) or have used the inaccurate Thornthwaite calculation procedure (Chen, Y. *et al.*, 1992), but they have not presented PET change over China in detail.

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Climatic change in China during this century has, however, been investigated for meteorological variables affecting PET rates, namely temperature and precipitation (Zhang and Li, 1982; Chen, Y. *et al.*, 1992; Karl *et al.*, 1993; Hulme *et al.*, 1994; Yatagai and Yasunari, 1994; Domrös, 1995, Zhai *et al.*, 1997; Domrös and Schäfer, 1999) and cloudiness and sunshine (Kaiser, 1993, 1998; Kaiser and Vose, 1997). These studies have demonstrated a warming trend over northeast and central China and a cooling trend in southwest China and East Tibet, with both maximum positive and negative trends occurring in northwest China. Decreases in annual mean sunshine were found for northern and southern China, in addition to decreases in mean cloud cover over much of China, especially in the northeast. As a net result, PET rates should have remained fairly constant throughout China with slight decreases in southwest China and East Tibet.

Any major shift in seasonal or spatial PET patterns could have negative consequences for China's food supplies and in turn for the world economy (Harris, 1996). China, having the world's largest population, has been self-sufficient in her food production during the last decades, although agriculturally suitable areas account for only 10% of the national territory.

This paper presents the results of a study on the spatial distribution of annual and monthly PET trends over China in recent decades. It identifies the spatial pattern of the dominant meteorological variables responsible for PET trends and discusses possible mechanisms that could lead to the observed spatial trend of anomalies. The significance of these changes for China is discussed.

2. DATA AND ANALYSIS PROCEDURE

The data to be analysed was taken from the Carbon Dioxide Information Analysis Center (CDIAC) numeric data package NDP039/R1, which is an updated and enlarged version of the original NDP039 data package (Tao *et al.*, 1991). Monthly data are available for the mean, minimum and maximum temperature, precipitation, atmospheric pressure, relative humidity, wind speed and sunshine hours of 65 stations in mainland China and East Tibet (Figure 1). Station altitudes vary between 1 m and 4270 m, with all of the stations above 2000 m located in southwest China and East Tibet.

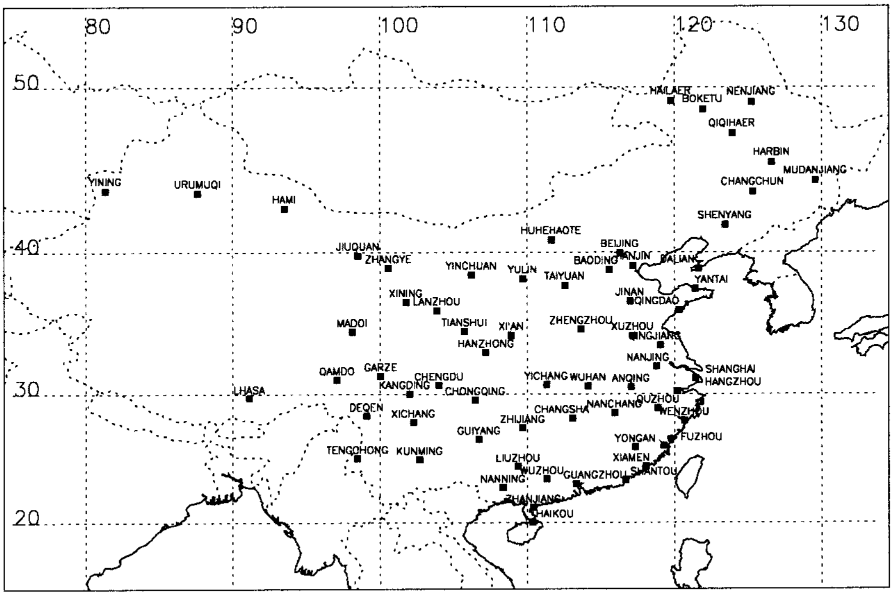


Figure 1. Distribution of stations with complete monthly PET data from 1954–1993

PET estimates were calculated for all months with complete records using the Penman–Monteith approach (Smith, 1992) with the program ET V1.0, which was distributed by Cranfield University (Hess and Stephens, 1993).

The earliest complete records suitable for calculating PET rates date back to 1903; the majority of stations has complete records from 1951 to 1993. As the majority of stations operating prior to 1930 were located along the Chinese coast, a strong spatial bias is introduced into totals calculated from early PET data. In addition, observation methods were not standardized until 1951 with the setting up of the observation network of China. Consequently, trend values have only been calculated for a 40-year period from 1954 to 1993.

Monthly PET estimates were checked for completeness, eliminating all years with missing data for 1 or more months. Flags in the original NDP039/R1 data package indicating possible inhomogenities were used to search for inconsistencies in the resulting PET estimates. Only sporadically were PET estimates found which deviated strongly from the seasonal cycle and were obviously linked to invalid input data.

Linear regression over the period 1954–1993 was performed on the monthly and annual estimates of all stations. For China as a whole, mean (All-China series) linear trends were calculated from the unweighted monthly and annual means of all stations. For the interpretation of the significance of the results, the trend-to-noise ratio (T/N) in the form of a t-test of the regression coefficient was used (Birrong and Schönwiese, 1988). In order to test for non-linear trends, Mann's Q (Hartung, 1993) was applied. This non-parametric test is basically a variation of Kendall's rank correlation and is insensitive to deviations from a standard distribution.

Instead of using traditional seasons, which vary considerably in length in different parts of China (Domrös and Peng, 1988), selected months are shown that represent the hygric monsoon seasons. Seasons are defined as pre-monsoon (April), summer monsoon (June), post-monsoon (October) and winter monsoon (February).

3. OBSERVED PET CHANGES 1954–1993

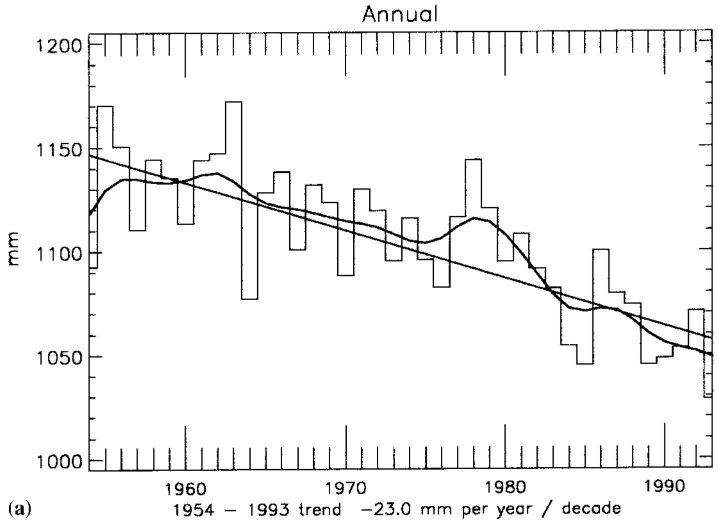
3.1. *All-China series*

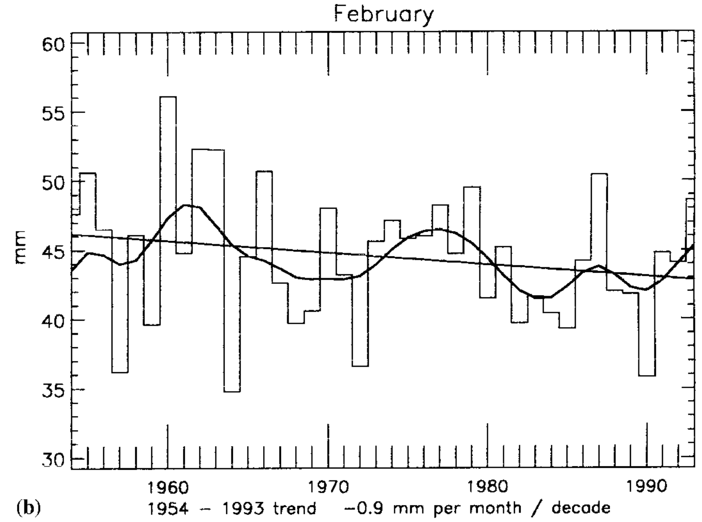
Mean linear trends for the country as a whole show that PET rates have been decreasing in all seasons (Figure 2(a–e)), particularly during the summer monsoon. While only September T/N values are significant at the 95% level (Table I), all months show significantly ($\geq 95\%$) decreasing non-linear trends. Trends vary between -0.4 mm/month/decade in December to -3.1 mm/month/decade in July, with summer and early post-monsoon months contributing primarily to the annual trend of -22.9 mm/year/decade. During the observation period, annual PET totals have decreased by 8.3% relative to the annual mean. Variations prior to 1951 are very likely artefacts of changes in station numbers, station distribution and instrumentation, rather than real changes in PET rates.

3.2. *Annual PET changes*

Figure 3 maps the annual PET changes which shows both negative and positive trends distributed in a symmetric pattern. Fourteen stations reveal positive trends, while 51 stations reveal negative trends. In general, negative trends occur over larger areas and are more pronounced than positive trends. In most cases trends smaller than 40 mm/year/decade are not significant.

Positive trends are found in a band extending from southwest to northcentral and northeast China and in two small isolated cells in south China and on the southeast Chinese coast. Positive trends vary between 4 mm/year/decade (Madoi, Tibet) and 35 mm/year/decade (Zhenzhou), with the majority of trends remaining well below 20 mm/year/decade. Only four stations, in northeast and southeast China, show significant non-linear trends. In relation to long-term annual PET rates, positive trends have changed between 2.0% and 15.8%.





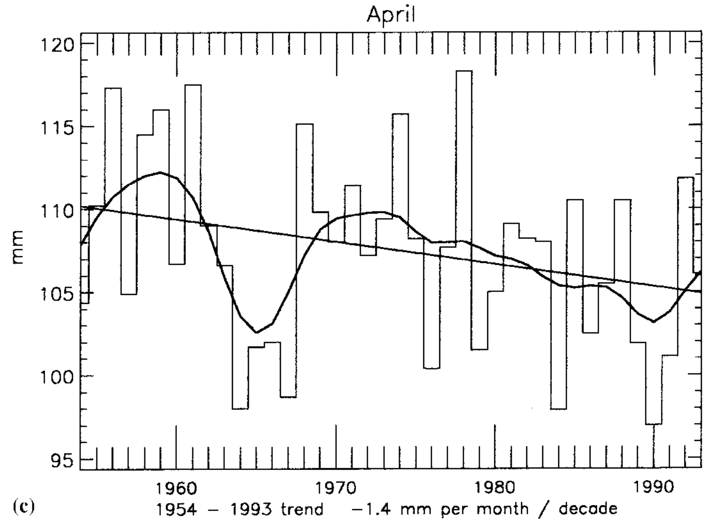
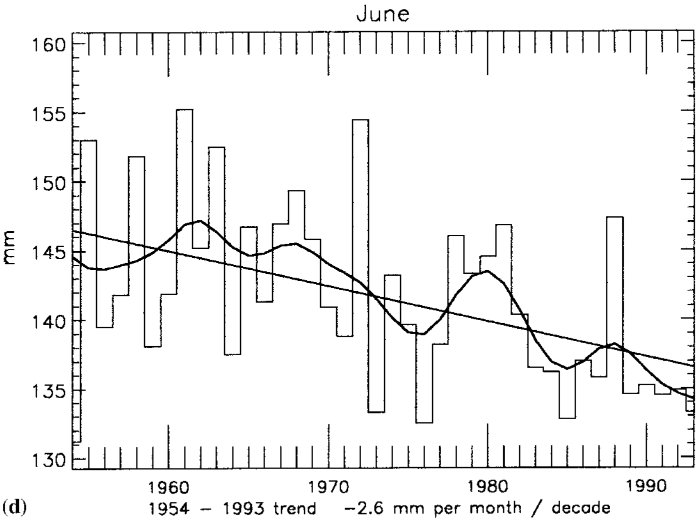


Figure 2. (a–e) Regionally-averaged annual and monthly PET totals (mm/month or year, respectively/decade) from 1954 to 1993 for 65 stations over China. Straight line shows the linear trend from 1954 to 1993. The smooth line results from a Gaussian binomial low-pass filter (10 years) that was applied to suppress high-frequency variations in the data



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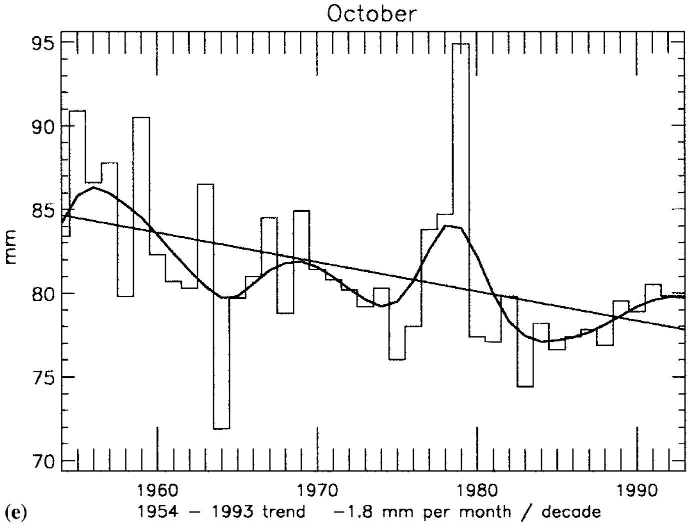

(e)

Figure 2 (*Continued*)

In contrast, nearly all negative trends larger than − 30 mm/month/decade are significant. Negative trends are concentrated in two large structures in the lowlands and hill country of east and south China and in the deserts of northwest China. The maximum significant negative trend of − 153 mm/year/decade (28.7%) occurs at Hami, in the northwest desert region. In east China, negative trends vary between − 79 mm/year/decade (Zhengzou, 22.3%) and − 2 mm/year/decade (Mudanjiang, 0.6%). Negative trends amount to between 0.6% and 28.7% of the long-term annual PET rate. Gradients can reach up to 60 mm/year/decade per 100 km.

Table I. Average 40-year (1954–1993) monthly and annual Penman–Monteith PET trends (mm/month/decade) and relative PET change (%) with respect to the 40-year mean for 65 Chinese stations

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
mm	*−1.4*	−0.9	*−1.6*	−1.4	*−1.9*	*−2.6*	*−3.1*	*−2.4*	***−3.0***	*−1.8*	*−1.3*	−0.4	*−23.0*
%	*−15.1*	−7.7	*−8.8*	−5.0	*−5.5*	*−7.2*	*−8.3*	*−6.9*	***−11.5***	*−8.7*	*−9.7*	−4.3	*−8.3*

Trends derived from linear regression. Trends in bold italic have T/N-ratios significant at the 95% level; trends in italics are non-linear significant at the 95% level.

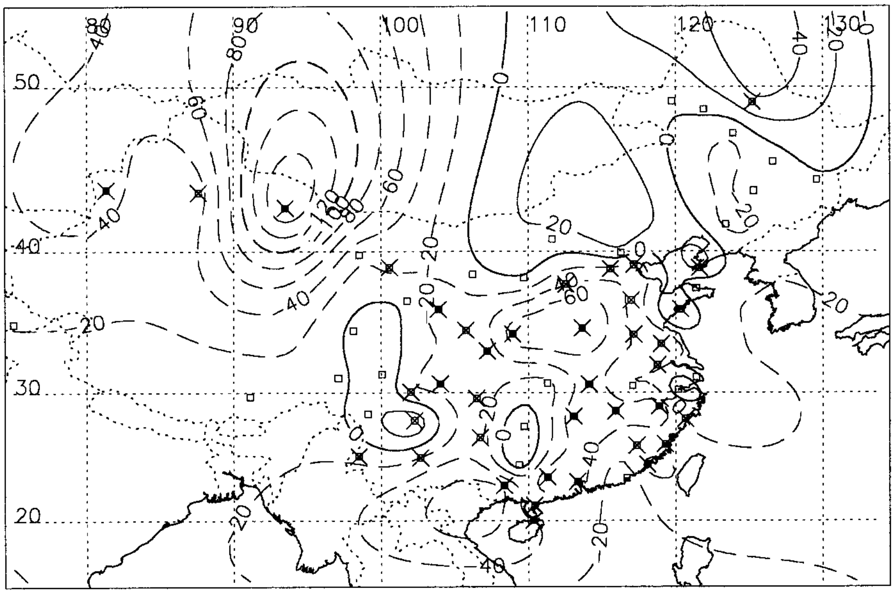

Figure 3. Spatial distribution of annual PET trends over China. Solid lines depict positive trends, broken lines show negative trends. Stations with linear trends significant at the 95% level are marked with a solid square, station symbols with a cross mark significant non-linear trends. Trend values are given as mm PET/month/decade (1954–1993)

Areas with no or small amounts of change are mainly found in the mountains of southwest China and East Tibet. In addition, a zone of constant PET rates divides the area of positive trends centred on northeast and northcentral China.

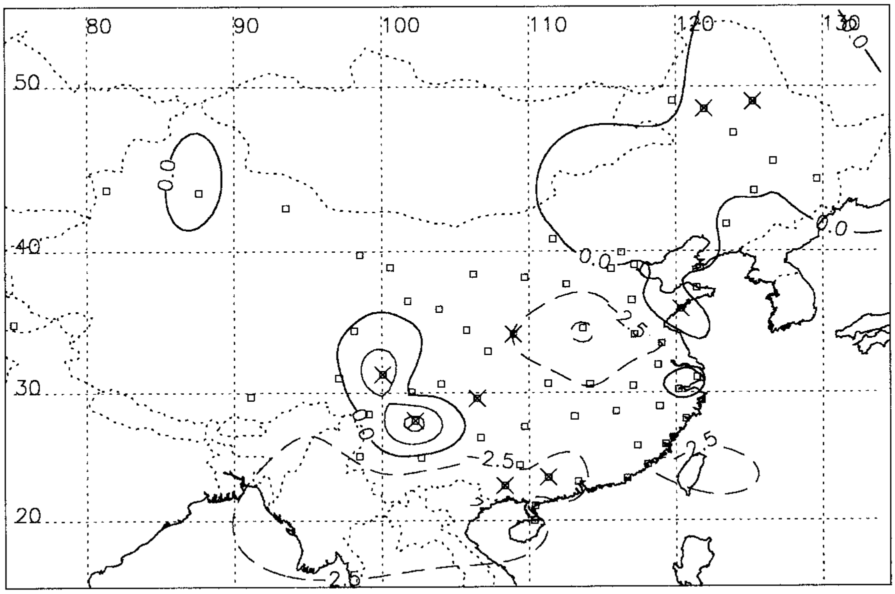

Figure 4. Spatial distribution of February (winter monsoon) PET trends over China. For description refer to Figure 3

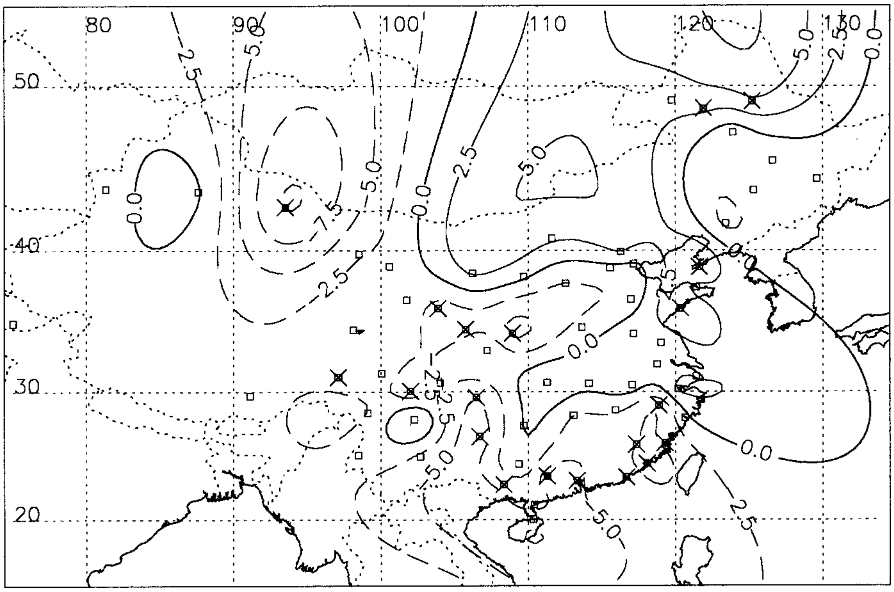

Figure 5. Spatial distribution of April (pre-monsoon) PET trends over China. For description refer to Figure 3

3.3. Winter monsoon PET changes

In February (winter monsoon), only very minor changes in PET rates have occurred (Figure 4), with the exception of southwest and south China. Maximum significant positive trend values reach 6 mm/month/decade in the southwest while significant negative trends of up to − 4 mm/month/decade are found along the south China coast. While most of the trends remain around ± 2.5 mm/month/decade, some of these trends are still significant. The highest positive changes of all months of more than 20% relative to the long-term monthly mean are found during February, both in northeast and southwest China as well as in East Tibet.

3.4. Pre-monsoon PET changes

In April (pre-monsoon), significant positive trends of up to 5 mm/month/decade are concentrated in the extreme northeast (Figure 5). An unusual deep intrusion of significant positive trends from the north as far south as 30°N occurs along the East coast. In contrast, the cell of negative trends in the southwest mountains which was dominant during the winter monsoon has completely disappeared. The major part of south China shows significant low negative trends of ∼ 5 mm/month/decade. The largest negative trends with − 10 mm/month/decade are recorded in the northwest desert, followed by a similar significant trend of − 6 mm/month/decade along the southeast coast. Relative to the long-term monthly mean, both positive and negative trends reach no more than 20%.

3.5. Summer monsoon PET changes

June (summer monsoon) trends (Figure 6) basically show a similar spatial pattern as the annual trends, with areas of positive trends oriented along a northeast–southwest trending axis and two areas of negative trends in northwest and central China. Again, positive trends are lower than negative trends. With the exception of the extreme northeast and south China, all trends are significant. Decreasing PET rates remain between − 6 mm/month/decade and − 14 mm/month/decade for the major part of central and southeast China. The desert station of Hami in northwest China again records the maximum decrease with − 25 mm/month/decade. Significant positive trends are mainly found in the mountains of southwest China and East Tibet, where positive trends of about 5 mm/month/decade are recorded.

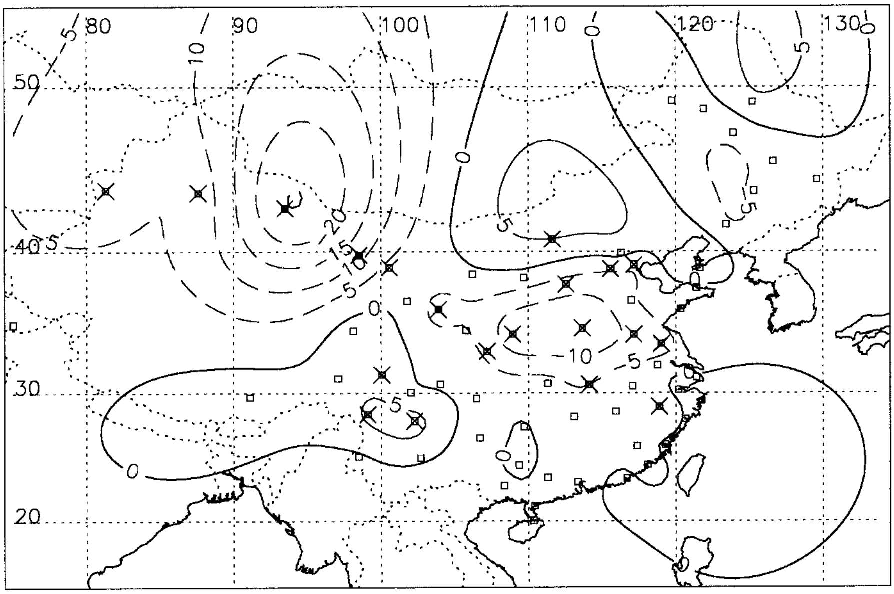

Figure 6. Spatial distribution of June (summer monsoon) PET trends over China. For description refer to Figure 3

3.6. Post-monsoon PET changes

The spatial distribution of trends in October (post-monsoon; Figure 7) again closely resembles the distribution of annual trends. Significant positive trends of moderate strength (up to 4 mm/month/decade) occur in northcentral, northeast, southwest China and East Tibet. Significant negative trends are restricted to south, southeast and northwest China, with maximum decreases reaching − 14 mm/month/decade at Hami. During the post-monsoon season, the strongest relative changes of up to 50% of the long-term monthly PET rate occurred at all northwest Chinese stations.

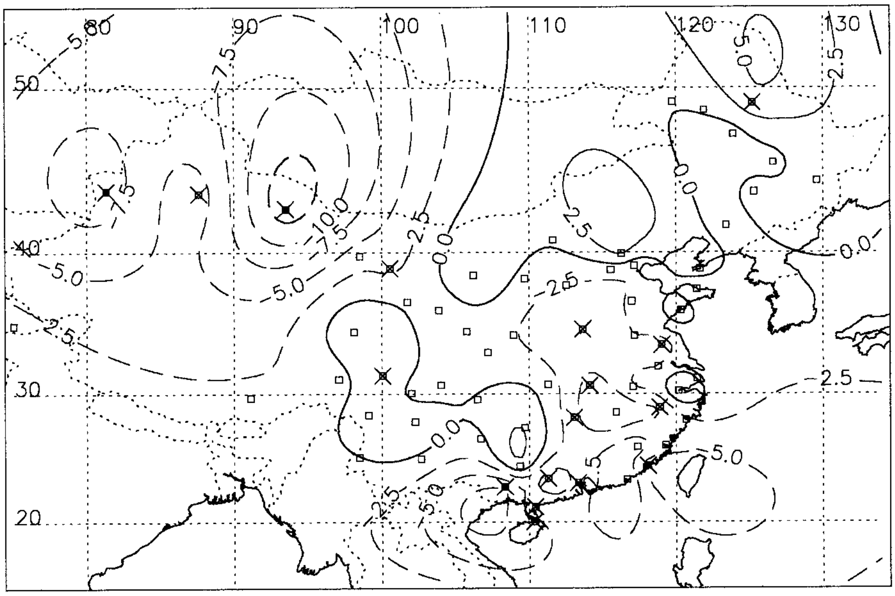

Figure 7. Spatial distribution of October (post-monsoon) PET trends over China. For description refer to Figure 3

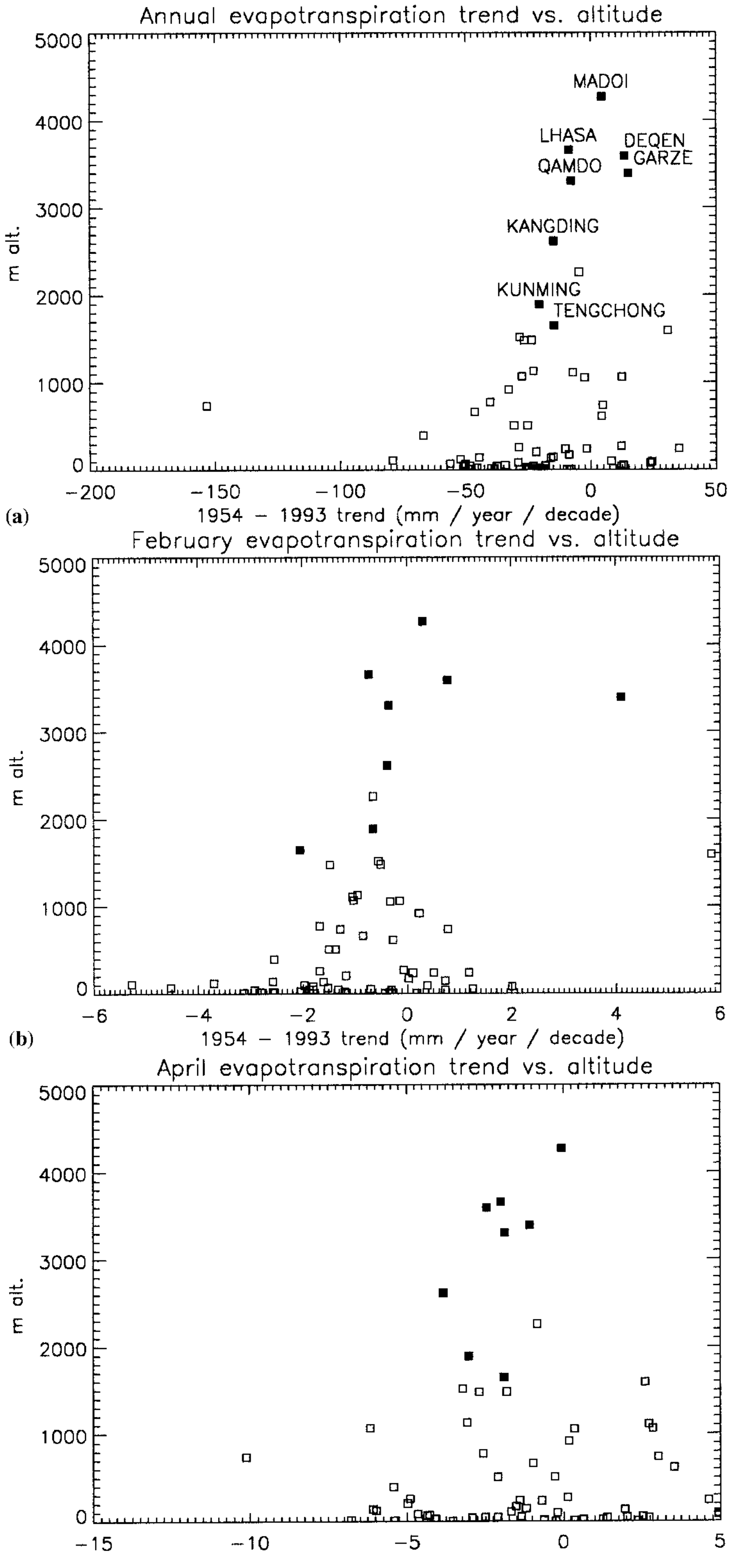

Figure 8. (a–e) Penman–Monteith PET trends (1954–1993) versus station altitude. Stations belonging to the southwest China climatic subgroup are marked with filled squares and are labelled with their names in (a)

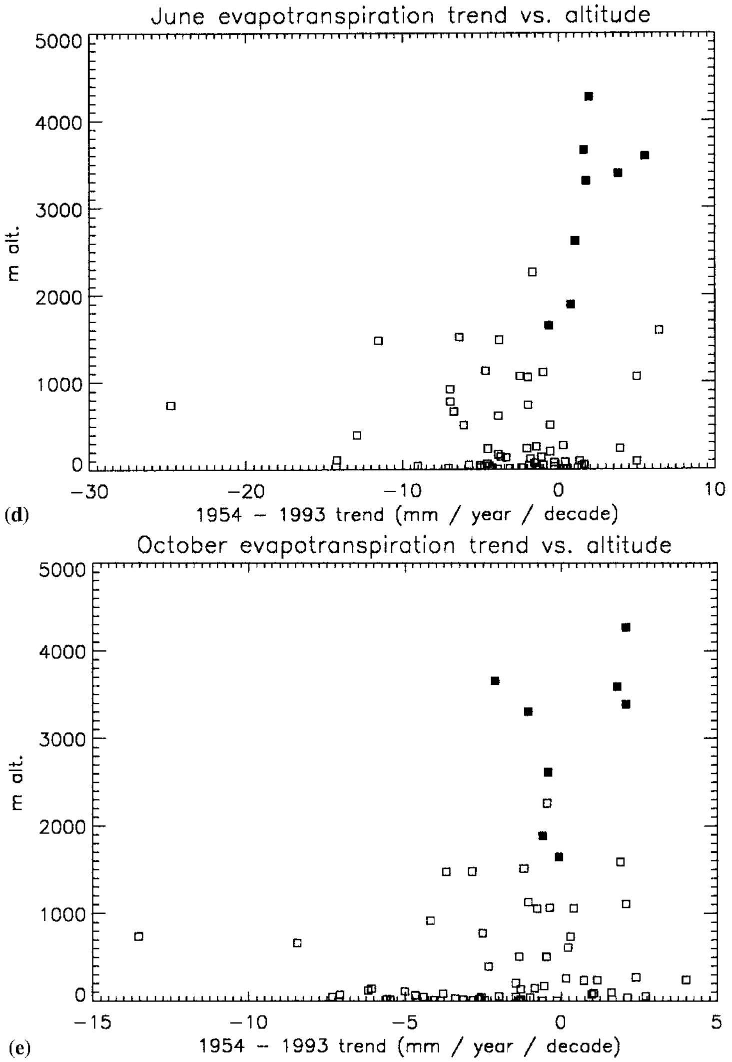

Figure 8 (*Continued*)

3.7. Altitude-related PET changes

In light of the large altitudinal extent of the stations, not only should changes related to their two-dimensional distribution on the land surface be investigated, but also those related to their altitude. No significant correlation between station altitude and PET trends was found for China as a whole. On regional scales, significant correlations do, however, occur if stations belonging to a common climatic group are selected. The most evident case are eight stations located in the highlands of southwest China and East Tibet which display a positive relationship between PET trend and station altitude in all seasons (Figure 8(a–e)). Correlations for April (pre-monsoon), June (summer monsoon) and annual values ($r^2 = 0.7837$, 0.6685 and 0.6729, respectively) are significant at the 95% level. Visual inspection of the data reveals that other regions, most conspicuously northeast China, may exhibit similar altitude-related gradients.

3.8. *Influence of meteorological variables on PET changes*

Despite generally increasing temperatures in China there has been a decreasing trend in PET in most parts of the country. Regional anomalies persist most notably in southwest China and East Tibet, where PET rates have increased while temperatures have decreased. In order to identify those meteorological variables that contribute to this change in PET, a linear stepwise multivariate regression was performed with maximum temperature, minimum temperature, sunshine, relative humidity and wind speed as independent variables. On an annual basis, sunshine appears to be the most important variable contributing to changes in PET rates, followed by relative humidity and maximum temperature (Table II). Seasonal variations are evident with relative humidity assuming increasing importance within the course of the year, while maximum temperature shows a reverse course during the same period of time. In the post-monsoon season, relative humidity accounts for most of the variance of the individual regression equations. For China as a whole decreasing sunshine duration, therefore, appears to have been the most important factor leading to reduced PET rates during the recent decades. Temperature, in contrast, appears to have played a negligible role.

In light of the seasonal changes evident in the regression results and the large latitudinal extent of China, results obtained on the basis of mean values should only be regarded as a general indication. In order to analyse the spatial distribution of the regression coefficients a simple regionalization of the regression data was performed, mapping the frequency and seasonal distribution of the first regression coefficient of all seasons for each station (Figure 9). At 24 stations (37% of all stations) in south and southwest China up to a latitude of 30°–35°N sunshine duration is most strongly associated with changes in PET rates in at least three out of four seasons. Relative humidity is the most important factor at 11 stations (17%) in east China with additional stations, particularly in the extreme northeast, experiencing

Table II. Frequency of occurrence of meteorological variables, in order of declared variance, in linear stepwise multivariate regressions for 65 stations over China (1954–1993)

	SU	TX	RH	WI	TN
February (winter monsoon)					
1	24	22	13	5	1
2	0	24	19	21	1
3	4	18	20	22	1
4	21	1	13	16	8
April (pre-monsoon)					
1	23	19	19	4	0
2	4	25	20	16	0
3	8	17	14	26	0
4	29	4	12	19	1
June (summer monsoon)					
1	33	5	21	6	0
2	4	20	21	20	0
3	13	20	11	21	0
4	14	20	12	17	1
October (post-monsoon)					
1	20	4	31	10	0
2	6	22	6	31	0
3	5	20	17	22	1
4	18	19	11	1	11

Numbers in the first column identify the position of the regression coefficients according to their contribution of variance to the individual regression equation. Regression coefficients are significant at the 95% level. Only the first four coefficients are shown. SU, TX, RH, WI and TN indicate sunshine hours, maximum temperature, relative humidity, wind speed and minimum temperature, respectively.

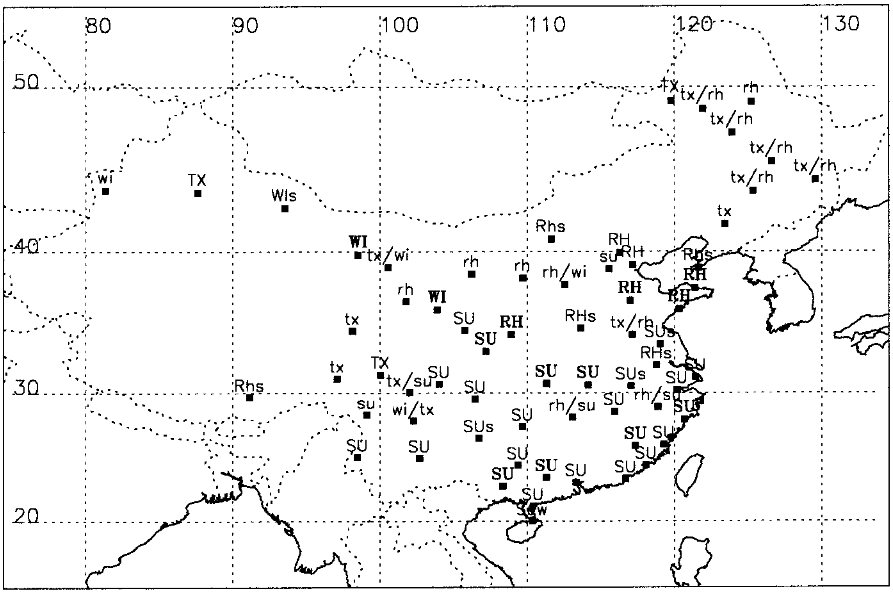

Figure 9. Contribution of meteorological variables to PET rates over China (1954–1993). Frequency and seasonal distribution of the first regression coefficient in each season for each station are shown. SU, TX, RH and WI indicate sunshine hours, maximum temperature, relative humidity and wind speed, respectively. Bold letters indicate an influence of the same variable in all four seasons, uppercase letters in three seasons with lowercase 's' indicating dominance in 'summer' half-year (pre-monsoon, summer monsoon and post-monsoon) and 'w' indicating dominance in 'winter' half-year (post-monsoon, winter monsoon and pre-monsoon). Lowercase letters indicate dominant influence of the same variable in two seasons

a lower influence in only two seasons per year. Stations for which wind accounts for most of the PET changes are confined to the northwest (three cases or 5%), while in another three cases maximum temperature is the dominant factor in more than two seasons. At a comparatively large number of eight stations (12%) in northeast and southwest China, maximum temperature in combination with relative humidity, sunshine duration or wind speed plays the dominant role in two out of four seasons.

According to Figure 9 sunshine duration emerges as the single most important factor in controlling PET rates, both in spatial and in temporal terms in subtropical China south of approximately 35°N. North of this line, relative humidity dominates central China while in northeast and west China changes in PET rates are related to changes in maximum temperature and wind speed, respectively.

4. DISCUSSION AND CONCLUSIONS

On the basis of monthly Penman–Monteith PET estimates (1954–1993), calculated from meteorological data of the CDIAC numeric data package NDP039/R1, annual PET totals were found to have decreased significantly in the southeast and northwest quadrants of China by up to 153 mm/year/decade and to have increased by up to 35 mm/year/decade in most parts of the northeast and southwest sectors over 1954–1993. In northeast China and parts of south China and East Tibet, no significant changes in annual PET rates have occurred.

Analysis of monthly trends reveals that the strength of the annual trends in most regions depends primarily upon the trends of individual seasons or months, rather than on those of all months taken together. There is, however, no consistent spatial pattern underlying the contribution of individual monthly trends to the annual trend. The highest decreases over the northwest desert region and in central China are as a result of strong negative trends during the summer monsoon months. Positive annual trends in the mountains of southwest China are related to increases during the summer and late winter months. Positive annual trends over northcentral China, however, cannot be traced to individual months but are based on slight increases during all months of the year. Over northeast China, all except the summer months contribute to the observed positive trend.

While decreasing pan evaporation rates observed in India, Russia and the US (Peterson *et al.*, 1995; Chattopadhyay and Hulme, 1997) are thought to actually provide a strong indication of increasing terrestrial evaporation in some cases (Brutsaert and Parlange, 1998), PET estimates, as a calculated rather than a measured value, do not suffer from such observational problems. In both cases, however, PET is only a good indicator of the actual situation as long as the atmospheric water demand is met, that is under fully humid conditions. Actual evaporation or actual evapotranspiration has to be estimated by water balance calculations or by other hydrological methods.

For China as a whole, both annual and monthly PET rates have been decreasing despite increasing temperatures over the last four decades, but show a much smoother and steadier change over time than corresponding temperature time series that exhibit the characteristic rapid increase in temperature since the mid-1970s (Hulme *et al.*, 1994). An analysis of the contribution of various meteorological variables to the observed PET change has indeed shown that temperature contributes only to a very limited extent to the observed PET changes, mostly in northeast China, southwest China and East Tibet. These results are broadly similar to those obtained by Chattopadhyay and Hulme (1997) who found increasing temperature and decreasing PET trends (1976–1990) in all seasons for India as a whole. For a larger part of South Asia and East Asia, decreasing PET rates have obviously occurred during the last decades. Rising global temperatures may, therefore, not lead in any case to rising PET rates as expected by Hulme *et al.* (1994).

Multivariate regression techniques indicate that increasing temperatures can readily explain increasing PET rates in northeast China, where temperature has been identified as the most important variable in winter and pre-monsoon seasons. Significant increases in the frequency of occurrence of clear sky conditions (1954–1990) over much of north and northeast China, particularly from October to April (Kaiser and Vose, 1997) could be responsible for increased maximum temperatures. Kaiser and Vose (1997) have indicated that these variations may be linked to shifts in the strength and/or position of the Siberian winter high pressure system. Maximum temperature, along with sunshine and wind, also appears to determine changes in PET in the mountains of southwest China and East Tibet, where PET rates have slightly increased in all seasons. Southwest China is the only region in China with decreasing January temperatures (Domrös and Schäfer, 1999). Yatagai and Yasunari (1994) have been able to identify an increase in cold surges into southwest China as the likely source of decreasing temperatures. This again implies changes in the influence of the Asiatic winter high pressure system. A close inspection of the contribution of the meteorological variables to the PET changes of the individual stations has shown, however, that no single variable can primarily be linked to the slight, mostly insignificant increases in PET rates that have been found for southwest China.

A far greater influence than temperature has to be attributed to sunshine duration. Particularly over the subtropical regions of China (i.e. south of 30°–35°N) sunshine duration is more closely linked to PET than at higher latitudes, where maximum temperature and relative humidity seem to control PET to a greater extent. Reductions in PET rates agree very well with striking decreases of sunshine duration (1954–1988) over most of southern China (Kaiser, 1993). Latitudinal gradients of PET totals also show a clear distinction between areas south and north of a line located approximately along 35°N (Thomas, 1999) that coincides with the mean northerly extent of summer monsoon frontal systems over East China (Domrös and Peng, 1988). Variations in the strength of the summer monsoon and the associated cloudiness are obviously a major cause of variations in PET south of 35°N. Kaiser (1993), however, reported little evidence of increased cloudiness on a seasonal or on an annual basis. One possible explanation is a change in cloud climatology rather than in cloud cover, which is not detected by sunshine recorders (Kaiser and Vose, 1997). It is interesting to note that in neighbouring India, only during the summer monsoon months, radiation was the most important variable regulating PET rates (Chattopadhyay and Hulme, 1997). Changes in the winter and pre-monsoon seasons were most strongly associated with changes in relative humidity, while in the post-monsoon season both radiation and relative humidity were associated with decreases in PET rates. This seasonal cycle is broadly similar to that of south China (south of ~30°N) where radiation is the most important variable in all seasons except for the post-monsoon season, where decreases in PET appear to be a result of increases in relative humidity in nine out of 15 stations.

Environmental controls appear to be primarily in effect in the desert regions of west China, where PET is mostly controlled by windiness. At Hami, the station with the highest absolute annual PET decrease of − 153 mm/year/decade, wind was most strongly associated with PET in all seasons, except in winter. The dominant influence of wind can be readily explained by the constant winds encountered in desert regions. In addition, advection of hot air from the surrounding bare lands could create an 'oasis effect' affecting PET rates more than under undisturbed conditions (Doorenbos and Pruitt, 1977). Decreasing wind speeds would again point to changes in the strength or position of the regional circulation system.

Positive relationships between PET change and station altitudes have been found at stations above 1650 m altitude in the mountains of southwest China and East Tibet. Meteorological variables have a rather complex impact on changes in PET rates when a large altitudinal range is considered. Decreases of temperature and actual saturation vapour pressure could even be overcompensated by increases of radiation, actual vapour pressure and wind speed with altitude, leading to increases of PET with altitude (Henning and Henning, 1981). At each station a different seasonal combination of maximum temperature, sunshine duration, relative humidity and to a lesser extent wind speed is involved, so that the observed gradient cannot be attributed to the influence of a single meteorological variable.

The above findings imply that there is no single factor controlling changes in PET rates, but rather regionally and seasonally differing sets of variables. Applying multivariate statistical techniques on the basis of the explained variances of all meteorological variables involved, instead of simply using the most important variable, will allow us to identify their individual contribution in greater detail and to better explain their influence on changing PET rates. Visual inspection of the smoothed station time series has shown cyclical variations of PET trends on time scales of decades and less, which are correlated with similar variations at other stations in the region. Variable linear trend analysis allows for the placing of a lower limit on the temporal stability of the trends and for the closer examination of the temporal and spatial representativity of the observed trends (Rapp, 1997). In light of the integrating nature of PET containing the influence of four important meteorological variables, more emphasis should be placed on incorporating PET into climate classifications, particularly those trying to evaluate the agroclimatic potential of China (e.g. Chen, S. *et al*., 1992; McGregor, 1993).

Of more practical importance is the effect that changing PET rates will have on terrestrial ecosystems in general and on agriculture in particular. This is largely determined by the associated change in precipitation: in dependence on the spatial and seasonal distribution of both trends, water availability could regionally vary in either direction. Historical records have shown increasing precipitation over south China in January and both increasing precipitation over central China and decreasing totals over much of eastern China in July (Yatagai and Yasunari, 1994; Domrös and Schäfer, 1999). An unchanged continuation of these trends would pose a threat to agricultural production, particularly in south and southwest China which would have to cope with decreasing water availability in the growing season.

Results from GCMs predict that by 2050 the net balance of precipitation and PET over China will be negative, affecting both rice and wheat growing areas in south, east and north China (Hulme *et al*., 1992). Calculated fields of annual total precipitation over China in Hulme *et al*. (1992) are, however, unable to capture the essential distribution and magnitude of the current precipitation distribution, calling into question the accurateness of PET predictions from these models. In addition, Kattenberg *et al*. (1996) observe that comparatively small changes in GCM experiments modelling Indian monsoon rainfall lead to a reversal of precipitation–PET ratios. Chattopadhyay and Hulme (1997) point out that the results from such experiments still have to be regarded as provisional, while according to Grotch (1989) and Kittel *et al*. (1998) the poor agreement between different model simulations of the current climate and observed historical climatical data calls into question the ability of the models to project the amplitude of future climatic change on a regional scale. In light of these inconsistencies, the further analysis of observed PET changes could provide additional constraints for GCMs to more closely predict PET changes and resulting changes in water availability.

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