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Changes of pan evaporation and reference evapotranspiration in the Yangtze River basin

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With 5 Figures

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Summary

For the upper and mid-lower Yangtze River basin trends of pan evaporation and reference evapotranspiration are analysed from 1961 to 2000 using daily data of 115 stations. Both pan evaporation and reference evapotranspiration decreased during the summer months contributing most to the total annual reduction. This trend is more significant in the mid-lower than in the upper Yangtze reaches. The decreasing trends can be associated with trends in net radiation and wind speed. Results are compared with the 20th century evaporation simulated by the general circulation model (GCM, ECHAM5/MPI-OM). Also the GCM's actual evaporation decreases contrasting an overall increase in air temperature.

1. Introduction

The global average surface temperature has increased by about 0.6 °C during the 20th century (IPCC, 2001), which is expected to lead to higher evaporation rates and to enable the atmosphere to transport higher amounts of water vapour. Therefore, global climate warming may accelerate the hydrological cycle, redistribute global water resources (IPCC, 1995), thus inducing changes of further climatic parameters (Cohen et al., 2002; Chattopadhyay and Hulme, 1997). Evaporation (evapotranspiration) is an important component of the surface fluxes coupling the earth's surface with the atmosphere and, in particular, water balance with the heat balance at the surface, which is directly influenced by land use and climate change. The land-surface evapotranspiration takes up 60–65% of the land-surface precipitation and affects hydrological and meteorological processes. It modulates climate by reducing the transport of sensible heat from the radiative energy fluxes, enhances the air humidity increasing (decreasing) the minimum (maximum) air temperature (e.g. Sun and Wu, 2001).

There is evidence for decreasing trends of pan evaporation and potential evapotranspiration (for the USA see Hobbins et al., 2004; Peterson et al., 1995; former Soviet Union see Peterson et al., 1995; India see Chattopadhyay and Hulme, 1997; China see Thomas, 2000; Liu and Zeng, 2004; Liu et al., 2004; Chen et al., 2005; Gao et al., 2006; Ren and Guo, 2006; Australia and New Zealand see Roderick and Farquhar, 2004, 2005). This is paradoxical to common expectation of increasing evaporation rates under the warming climate. There are two interpretations. First, this is an indication of decreasing actual evaporation (Peterson et al., 1995), relating decreasing pan evaporation to increasing cloud cover and/or to the observed decrease in sunlight resulting from increasing cloud cover and aerosol concentration (Roderick and Farquhar, 2002). Secondly, there is a complementary relationship between actual and potential evaporation (Brutsaert and Parlange, 1998; Hobbins et al., 2004): A decrease in potential evaporation hints to an increase in actual evaporation at least for regions, which are not characterised as wet, that is, with limited land-surface moisture. In these regions actual evaporation reduces below the potential evaporation of an open water surface. Therefore, the energy flux from the surface not being used up by actual evaporation, is released as sensible heat flux which, in turn, enhances pan evaporation. Hence, a rise in temperature decreases relative humidity in the atmosphere, enhancing actual but reducing potential evaporation (Cohen et al., 2002). Budyko (1974) pointed out the importance of differentiating between actual and potential evaporation in interpreting changes in surface water balance. Roderick and Farquhar (2004) straighten out that in an energy-limited environment (rainfall greater than potential evaporation), a decrease in pan evaporation, at constant rainfall, implies a decrease in actual evaporation and an increase in runoff and/or soil moisture, and that in a water-limited environment (rainfall less than potential evaporation), changes in actual evaporation are dominated by changes in rainfall (for observations, see also Golubev et al., 2001). Ramírez et al. (2005) note that the complementary theory extends the Budyko (1974) scheme by postulating a physical relation between actual and potential evapotranspiration.

In this paper, changes of pan evaporation (PE) and reference evapotranspiration (ETr) are analysed for 115 stations in the Yangtze River basin (Sect. 2). Trends and relations to meteorological variables are analysed and compared with data from IPCC model simulations of the 20th century climate (Sect. 3). Finally, results are discussed, which includes an assessment of model evaporation compared with observed pan evaporation and reference evapotranspiration (Sect. 4).

2. Climatological setting, data and methods of analysis

The present study concentrates on the catchment of the Yangtze River, which is about 6300 km long,

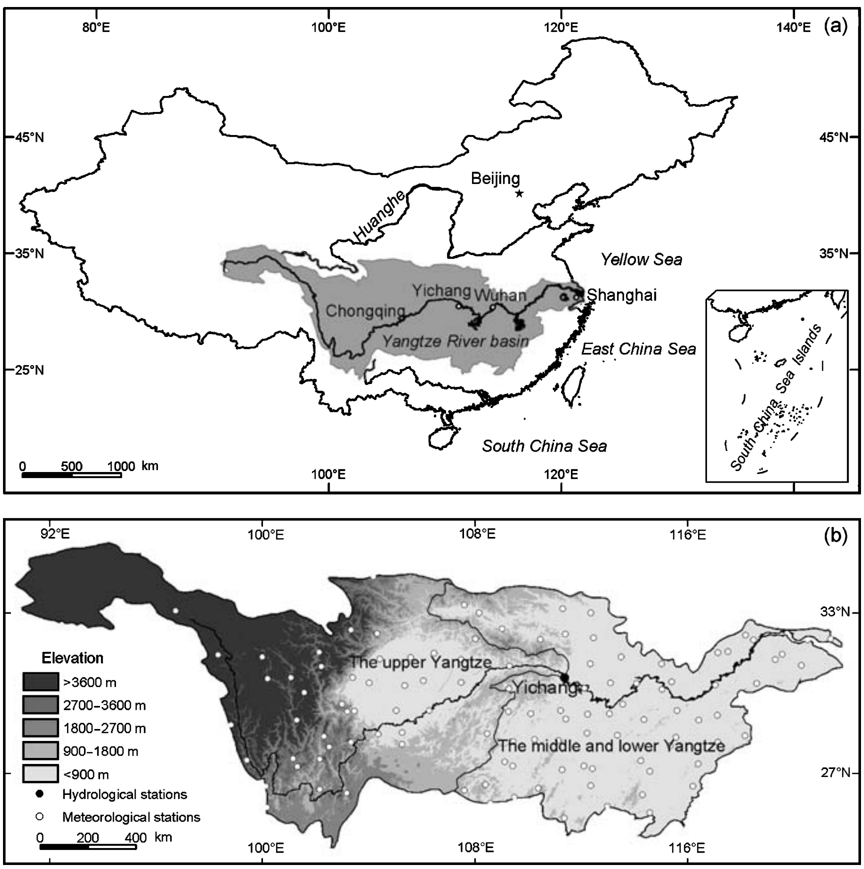

Fig. 1. Yangtze River basin: (**a**) location and (**b**) observatory stations

has a drainage area of $1.8 \times 10^6\,km^2$ (Fig. 1a) and is one of the world's longest rivers. Except for some areas located on the Tibet Plateau, most parts of the Yangtze River basin are dominated by a sub-tropical monsoon climate. Two types of monsoon events, i.e. Siberian north-western winter monsoon and Asian south-eastern summer monsoon (or Indian south-western summer monsoon in the upper Yangtze reaches) occur in a year. The Yangtze River basin not only has dense population and rapidly developing economy, but also suffers from frequent heavy floods. Especially from 1990, it has been exposed to six heavy floods. While climate change studies for the Yangtze River with respect to temperature, rainfall and drought and wetness have been undertaken (Becker et al., 2003; Bordi et al., 2004; Su et al., 2005, 2006; Zhang et al., 2005), studies on changing evaporation in the Yangtze River basin are scarce.

Observations: Data of 115 National Meteorological Observatory (NMO) stations with daily observations of maximum, minimum and mean (near surface) air temperature, wind speed, sunshine hours, vapour pressure, and pan evaporation of 20 cm diameter pans for the period from 1961 to 2000 are used in this study, provided by the National Climatic Centre (NCC) of the China Meteorological Administration (CMA). The Yangtze River basin is divided into two main parts taking the Yichang hydrological station as the boundary: (i) the upper Yangtze reaches (average altitude of about 2250 m) with 44 stations and (ii) the middle and lower Yangtze reaches (average altitude of about 270 m) with 71 stations (Fig. 1b). The average percent of missing data in this study is less than 0.2% for all 115 stations. There are 0.031, 0.036, 0.036, 0.129, 0.203, and 0.268% missing for maximum, minimum and mean air temperature, wind speed, sunshine hours, and vapour pressure, respectively. The homogeneity of the data sets of all stations is analysed by calculating the von Neumann ratio and the cumulative deviations, and the Bayesian procedures (for details see Buishand, 1982; Maniak, 1997): The data sets of all stations prove to be homogeneous with high significance beyond 95% confidence level.

Simulations: Ensemble simulations with ECHAM5/MPI-OM of the 20th century climate scenarios are also analysed. Three model realisations are initialized by a pre-industrial control run at different states; their respective forcings are observed anthropogenic greenhouse gases (CO_2, CH_4, N_2O, CFCs, O_3 and sulfate). The model consists of the European Centre/Hamburg Model (ECHAM5, Roeckner et al., 2003) and the Ocean Model (MPI-OM, Marsland et al., 2003). ECHAM5 runs with horizontal T63 (about 1.8°) and vertical 31 layer resolution. The upper and the mid-lower reaches of the Yangtze River basin are represented by 73 (90° E to 108.75° E and 23° N to 36.5° N) and 62 model grid-points (108.75° E to 122° E, 23° N to 36.5° N). The model diagnostics provides the water cycle with evaporation, precipitation and runoff, which is shown to be comparable with the observed components (see Hagemann et al., 2006). Net radiation for the GCM is calculated as sum of net surface shortwave solar and net surface thermal radiation, which are provided by model diagnostics.

Reference evapotranspiration: The FAO Penman–Monteith method is recognized as standard computation of reference evapotranspiration (ETr) from meteorological data and used for calculating daily ETr ($mm\,day^{-1}$) (Allen et al., 1998); it consists of two terms, the radiative (first) and ventilation (second) contribution:

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

where ET_r = reference evapotranspiration [$mm\,day^{-1}$], R_n = net radiation at the crop surface [$MJ\,m^{-2}\,day^{-1}$], G = soil heat flux density [$MJ\,m^{-2}\,day^{-1}$], T = mean daily air temperature at 2 m height [°C], u_2 = wind speed at 2 m height [$m\,s^{-1}$], e_s = saturation vapour pressure [kPa], e_a = actual vapour pressure [kPa], $e_s - e_a$ = saturation vapour pressure deficit [kPa], Δ = slope vapour pressure curve [kPa °C^{-1}], γ = psychrometric constant [kPa °C^{-1}]. Net radiation is of primary importance and estimated by:

$$R_n = 0.77 \times \left(a + b\frac{n}{N}\right) R_a - \sigma\left[\frac{T_{\max}{}^4 + T_{\min}{}^4}{2}\right] \times (0.34 - 0.14\sqrt{e_a})\left(1.35\frac{a + b\frac{n}{N}}{a + b} - 0.35\right)$$

where σ is Stefan–Boltzmann constant ($4.903 \times 10^{-9}\,MJ\,K^{-4}\,m^{-2}\,day^{-1}$), n is actual sunshine duration [hour], N is the maximum possible duration of sunshine [hour], Ra is the extraterrestrial radiation [$MJ\,m^{-2}\,day^{-1}$], e_a is actual vapour pressure [kPa], T_{max} [K] and T_{min} [K] are maximum and minimum temperature, a and b are empirical constants, FAO suggests the values of $a = 0.25$, $b = 0.50$ (Allen et al., 1998). The mean annual and seasonal pan evaporation (PE) and reference evapotranspiration (ETr) are computed for each station by accumulating the daily values. The seasons are spring (March–May), summer (June–August), autumn (September–November) and winter (December–February).

Analysis: The trend tests applied are both the linear regression method and nonparametric Mann–Kendall test (MK-test, Kendall and Gibbons, 1981; Libiseller, 2002). Linear regression is used to estimate the magnitude of climate change in terms of a linear trend. The MK-test is used to examine the nonlinear trend of climatic or hydrological data; this test is performed on all stations to detect mean annual and seasonal trends. Confidence levels of 90, 95 and 99% are taken as thresholds to classify the significance of positive and negative trends. Trends at significance levels below 90% are not considered.

3. Trends in evaporation: analysis and results

Trends of pan evaporation and reference evapotranspiration (observed from 1961 to 2000) are presented in this section. Their possible causes are discussed in view of the trends of the meteorological variables net radiation, saturation vapour pressure deficit, air temperature and wind speed. In addition, trends of the 20th century evaporation simulated by the general circulation model ECHAM5/MPI-OM are analysed.

3.1 Trends of pan evaporation

Mann–Kendall tests are performed for 115 meteorological stations to identify trends of the annual and seasonal pan evaporation (PE) during the recent 40 years in the Yangtze River basin. To get to know how much the pan evaporation has changed, linear regression is applied for annual pan evaporation in different regions of the Yangtze River basin (Table 1). Figure 2a shows the number of stations with significant positive or negative trends for PE beyond 90% confidence level. The following results are noted:

Table 1. Change rates of annual mean pan evaporation and reference evapotranspiration in the Yangtze River basin for 1961–2000 (slope of linear regression)

	Annual mean PE trend	Annual mean ETr trend
The whole basin	−2.84	−1.37
The upper Yangtze reaches	−4.68	−0.65
The middle and lower Yangtze reaches	−3.65	−1.85

(i) There are more stations with significant negative (58) than positive (22) pan evaporation trends in the annual totals.
(ii) The annual mean PE decreases at a rate of −2.84 mm/yr, −4.68 mm/yr and −3.65 mm/yr in the whole Yangtze basin, the upper Yangtze reaches and the mid-lower Yangtze reaches, respectively.
(iii) The PE series show increasing (or positive) trends in spring, summer, autumn, and winter at 18, 9, 25 and 16 and negative trends at 41, 61, 33 and 43 stations, respectively.
(iv) The decreasing (or negative) trend in summer contributes most to the annual mean PE. The significance of the negative trends (in annual and summer PE) is higher in the mid-lower than in the upper Yangtze reaches.
(v) Details of the Mann–Kendall statistics (1961–2000) are shown in Table 2. In the *upper* Yangtze reaches, significant negative trends are found in spring, autumn, and

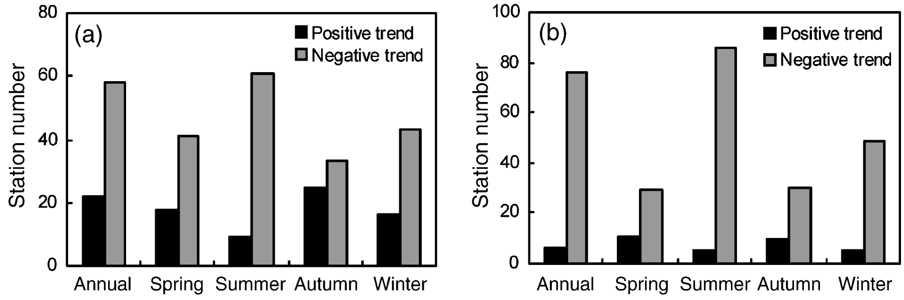

Fig. 2. Number of stations with observed trends: (**a**) pan evaporation (beyond 90% confidence level) and (**b**) reference evapotranspiration (beyond 90%)

Table 2. Mann–Kendall statistics for mean annual and seasonal pan evaporation in the Yangtze River basin for 1961–2000

	Annual	Spring	Summer	Autumn	Winter
The whole basin	−2.98***	−1.47*	−3.08***	−2.00**	−2.14**
The upper Yangtze reaches	−2.31**	−2.52***	−0.51	−2.38***	−2.38***
The middle and lower Yangtze reaches	−2.49***	−1.44*	−3.01***	−1.24	−1.26

* Denotes beyond 90% confidence level; ** denotes beyond 95% confidence level; *** denotes beyond 99% confidence level

winter PE (>99% confidence level), and in the annual PE (>95% confidence level); the summer PE shows only a slightly decreasing trend. In the *mid-lower* Yangtze reaches, significant negative trends are observed in the annual and summer totals (>99% confidence level) and in spring (>90% confidence level), but not in autumn and winter.

3.2 Trends of reference evapotranspiration

The trends of mean annual and seasonal reference evapotranspiration (ETr) have been analysed by applying Mann–Kendall test for all of the 115 stations. The magnitude of the trends of mean annual ETr has been calculated by linear regression in different regions of the Yangtze River basin (Table 1). The number of stations with observed positive and negative ETr trends (above 90% confidence level) is shown in Fig. 2b. The following results are noted:

(i) The trends for reference evapotranspiration are similar to those for pan evaporation, but there are much more stations with negative than positive trends in both annual and seasonal mean ETr, especially in summer and winter.

(ii) The size of the trends for mean annual ETr is −1.37 mm/yr, −0.65 mm/yr and −1.85 mm/yr in the whole Yangtze basin, the upper and mid-lower Yangtze reaches, respectively.

(iii) In annual ETr series a rising trend is observed at 6 stations and a falling trend at 76 stations. The spring, summer, autumn and winter ETr show a decreasing trend at 29, 86, 30, 49 and an increasing trend at 11, 5, 10, 5 stations, respectively. The decreasing annual means (beyond 99% confidence level) are largely due to the reduction in summer ETr (beyond 99% confidence level).

(iv) The Mann–Kendall statistics for annual and seasonal ETr in different regions in the Yangtze River basin are presented in Table 3. From the whole Yangtze basin perspective, both annual and seasonal reference evapotranspiration show significant negative trends, except for spring (slight change). Spatially, the reduction of the mean annual ETr in the mid-lower Yangtze reaches contributes much to that in the whole Yangtze basin. In both the upper and mid-lower Yangtze reaches, significant negative trends are found in mean annual and summer ETr, whereas the negative trends observed in the other three seasonal ETr are small.

Compared to pan evaporation, the annual and seasonal trends for reference evapotranspiration are similar, only the significance levels of the nonlinear trends show differences (Fig. 4): For the whole Yangtze basin, the annual and seasonal trends for both pan evaporation and reference evapotranspiration are decreasing. The annual trend is more significant for reference evapotranspiration than pan evaporation, while the seasonal trends are just reverse. For pan evaporation, the significant annual trend in the upper Yangtze

Table 3. Mann–Kendall statistics for mean annual and seasonal reference evapotranspiration in the Yangtze River basin for 1961–2000

	Annual	Spring	Summer	Autumn	Winter
The whole basin	−3.26***	−0.44	−3.38***	−1.61*	−1.54*
The upper Yangtze reaches	−1.49*	−1.00	−2.07**	−0.63	−0.23
The middle and lower Yangtze reaches	−3.26***	−0.65	−3.59***	−0.93	−1.21

* Denotes beyond 90% confidence level; ** denotes beyond 95% confidence level; *** denotes beyond 99% confidence level

reaches contributes much to that in the whole Yangtze basin. As for the reference evapotranspiration, the significant annual decreasing trend in the whole basin is due to obvious negative contributions in the mid-lower Yangtze reaches.

3.3 Meteorological relations

Increases in cloud cover and thus decreases in net radiation were most likely responsible for decreasing potential evapotranspiration in the United States and the former Soviet Union (Peterson et al., 1995). In India, Chattopadhyay and Hulme (1997) found increasing relative humidity to be strongly related to the overall decrease in pan evaporation, and that increases in relative humidity and decreases in radiation were both correlating with the decreasing trend in potential evapotranspiration. Thomas (2000) reported regionally and seasonally diverse trends in potential evapotranspiration in China. For China as a whole seasonal and annual trends decrease. Decreasing sunshine duration appears as the major cause of reduced potential evapotranspiration south of 35° N, while in northern parts changes are most likely associated with maximum temperature (northeast China), relative humidity (central northern China) and wind speed (northwest China). Liu and Zeng (2004) reported the decrease of pan evaporation over the Yellow River basin in China between 1960 and 2000 was mainly related to reductions in sunshine duration and solar irradiation, while Liu et al. (2004) associated their observed decrease in pan evaporation in eight different climatic regions in China to the changes in solar irradiance and water conditions. From these eight regions the South-West and East China regions embed the upper and mid-lower reaches of the Yangtze, respectively. Given this information we analyse the following meteorological variables on their likely influence on changing pan evaporation (PE) and reference evapotranspiration (ETr): net radiation (R_{net}), wind speed (W_{speed}), saturation vapour pressure deficit (SVPD), and air temperature (T_{air}).

Correlations: To identify the dominant variables associated with the changes in pan evaporation and reference evapotranspiration in the Yangtze River basin, they are correlated with all meteorological variables: Pan evaporation and reference evapotranspiration have positive correlations with all meteorological variables defined above; they are significant for all seasons with net radiation and saturation vapour pressure deficit. Only in summer and on the annual scale reference evapotranspiration and wind speed correlate significantly (see Table 4, also for more details).

Trends: The trend analysis (1961–2000, for the upper, the mid-lower Yangtze reaches and the whole Yangtze basin, Fig. 3) shows significant negative trends in the mean annual and seasonal net radiation and wind speed. (i) The intra-annual net radiation change has the most significant negative trend in summer (beyond 99%) compared to all other seasons (beyond 95%). (ii) The negative wind speed trend is more significant in the mid-lower than in the upper Yangtze reaches and less significant in summer than in all other seasons. (iii) The mean annual saturation vapour pressure deficit shows no significant trends but, for the seasons, we note a significant decreasing trend in summer; significant increasing trends in spring and autumn occur in the mid-lower reaches. (iv) The annual mean air temperature

Table 4. Correlation coefficients between pan evaporation, reference evapotranspiration and various meteorological parameters

	Pan evaporation				Reference evapotranspiration			
	R_{net}	SVPD	T_{air}	W_{speed}	R_{net}	SVPD	T_{air}	W_{speed}
Year	0.71	0.66	<u>0.27</u>	0.49	0.87	0.74	<u>0.20</u>	0.54
Spring	0.82	0.82	0.57	0.32	0.82	0.86	0.60	<u>0.26</u>
Summer	0.93	0.93	0.76	0.54	0.98	0.93	0.75	0.52
Autumn	0.75	0.71	<u>0.06</u>	0.34	0.83	0.85	<u>0.18</u>	<u>0.16</u>
Winter	0.75	0.84	<u>0.28</u>	<u>0.28</u>	0.79	0.93	0.42	<u>0.06</u>

Underline figures have not passed the statistical test with 0.05 significance level

R_{net}, SVPD, T_{air} and W_{speed} denote net radiation, saturation vapour pressure deficit, air temperature and wind speed, respectively

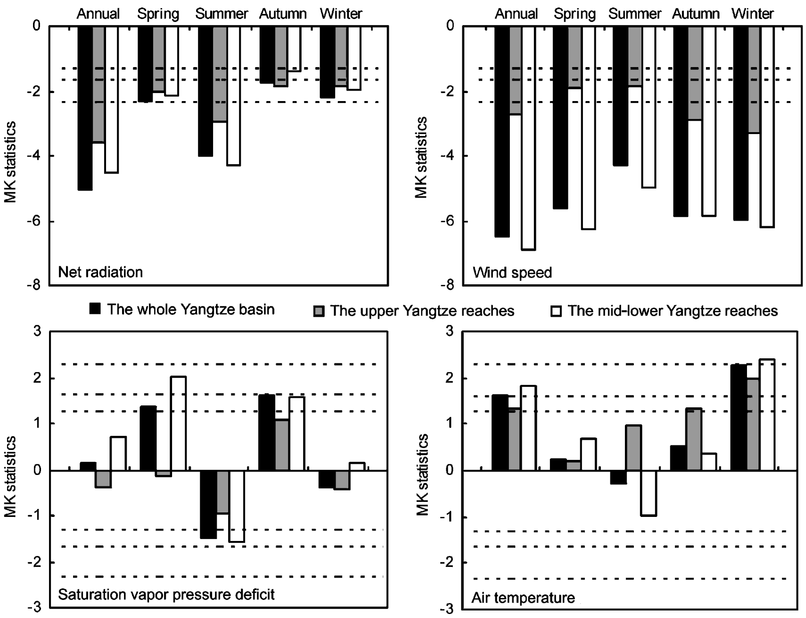

Fig. 3. Mann–Kendall trends of net radiation, wind speed, air temperature and saturation vapour pressure deficit in the Yangtze River basin for 1961–2000 (dashed lines denote 90, 95, 99% confidence levels)

increase over the Yangtze River basin is dominated by the rising winter mean. In the upper Yangtze reaches seasonal mean air temperatures (except for the summer mean) show positive (or rising) trends; in the mid-lower Yangtze reaches the summer trend is negative but insignificant.

The trends of saturation vapour pressure deficit match the findings of Liu et al. (2004), who show no trend for the warm season (May–September) for China (1955–2000). There is a very weak decrease in East China (middle-lower reaches of the Yangtze), and a slight increase for South-West China (partially the upper reaches), but none of which is significant. Air temperature during the warm season shows a significant increase in South-West China, while in East China an insignificant weak increase is observed.

In summarizing: Despite the general rise in annual mean air temperature during the recent 40 years over the Yangtze River basin (with the exception of summer in mid-lower reaches) both pan evaporation and reference evapotranspiration have decreased (in particular in summer in both upper and mid-lower basins). This is accompanied by a decreasing net radiation and wind speed and, to a lesser extent in summer in the mid-lower Yangtze reaches, by a decreasing saturation vapour pressure deficit and air temperature.

The main factor associated with reducing pan evaporation and reference evapotranspiration is net radiation. Thus it is not surprising that, in particular in the mid-lower reaches, this is accompanied by an increase in precipitation (Liu et al., 2004). In addition, Becker et al. (2006) find this increase to be associated with an earlier onset and a lengthening of the Mei-Yu season. The precipitation trends (increasing in the mid-lower reaches and decreasing mainly in the upper reaches) are confirmed by a study of Qian and Lin (2005), who postulate that regional changes in extreme precipitation are correlated with changes of the mean climate state. Kaiser (2000, Fig. 1a) reports a general decrease in cloud cover over contiguous China. But a close inspection of the Yangtze River basin only indicates insignificant rising and falling trends there.

3.4 Trends of Yangtze River basin evaporation in IPCC ensemble simulations

The ensemble mean of the three ECHAM5/MPI-OM simulations of the late 20th century climate (1961–2000) is examined in this section. Annual and seasonal time series and trends of the whole Yangtze River basin with its upper reaches and its mid-lower reaches are analysed. Figure 4 presents the results of the Mann–Kendall (MK) trend test for the ensemble mean evaporation E:

(i) The trends of E for the whole Yangtze catchment are negative for the annual, spring and autumn (beyond 95, 90, 95% confidence level). Summer and winter trends show only slight changes.

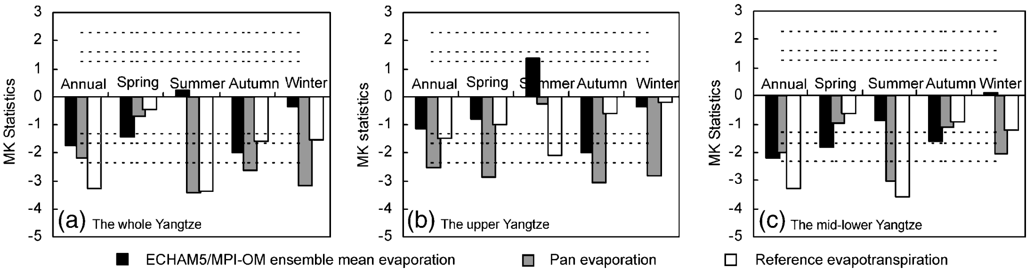

Fig. 4. Mann–Kendall trends of simulated ECHAM5/MPI-OM ensemble mean evaporation, observed pan evaporation and calculated reference evapotranspiration (1961–2000; dashed lines denote 90, 95, 99% confidence levels)

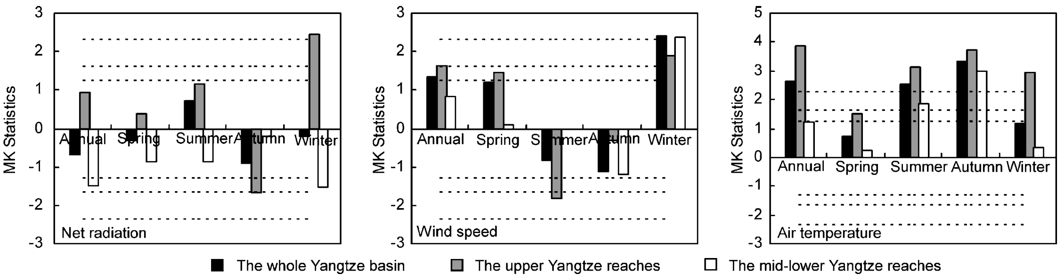

Fig. 5. Mann–Kendall trends of the ECHAM5/MPI-OM ensemble mean for net radiation, wind speed, and air temperature in the Yangtze River basin (1961–2000; dashed lines denote 90, 95, 99% confidence levels)

(ii) Significant negative trend is also seen in regional time series for annual evaporation: the upper and mid-lower reaches (beyond 95% and 90%), while spring is significant only in the mid-lower reaches (beyond 95%). Summer trends realize insignificant decreases in the mid-lower and significant increases in the upper reaches (beyond 90%). All winter trends are insignificant.

Figure 5 presents the MK trends of the ensemble mean air temperature, net radiation and wind speed; note that ensemble averaging may smooth partly opposite trends, by which the meteorological parameters are more affected than evaporation.

(i) The near surface air temperature shows a significant (beyond 99%) rise for annual, summer, autumn and winter (but 90% for spring) in the upper reaches. In the mid-lower reaches only the air temperature increase for summer and autumn is significant (beyond 95%); the other seasonal and annual mean trends are insignificantly positive. The trend for the whole Yangtze River basin reflects the regional behaviour; significant increase (>99%) for year, summer and autumn, and insignificantly positive for spring and winter.

(ii) The ensemble mean net radiation trends shows no general pattern for the whole Yangtze River basin. The upper reaches show a significant increase in winter and a significant decrease in autumn. The mid-lower Yangtze shows a decreasing trend, which is significant only in winter and for the year.

(iii) The wind speed trends are significantly positive on all regional scales for winter (beyond 95%). For the other seasons only the upper reaches show significant trends increasing for spring (beyond 90%) and decreasing summer (beyond 95%).

In summarizing: For the whole Yangtze basin annual evaporation in simulations decreases with a significant trend, with simulated evaporation in summer slightly increasing (due to a significant positive trend in the upper reaches). The modelled annual trend of increasing air temperature is significant (more in the upper than in the mid-lower reaches). Trends of the other ensemble mean meteorological variables, net radiation and wind speed, do not exhibit clear patterns.

4. Summary and conclusions

For the upper and mid-lower Yangtze River basin we analyse changes of observed pan evaporation

(PE) and reference evapotranspiration (ETr, FAO Penman–Monteith equation) from 1961 to 2000:

1. Significantly decreasing PE and ETr trends are observed for wide regions of the Yangtze River in all seasons (but spring for ETr) with summer trends being most significant. This agrees with the results of (i) Wu et al. (2006) for the trend of potential evapotranspiration in China during 1971–2000, (ii) Gao et al. (2006) analysing spatial and temporal variations of potential evapotranspiration in China during 1956–2000, and (iii) Ren and Guo (2006) investigating changes in pan evaporation and the influential factors over China during 1956–2000. This decrease is more notable in the mid-lower than in the upper Yangtze reaches.
2. Annual pan evaporation and reference evapotranspiration decrease with about $-2.8\,\text{mm/yr}$ and $-1.4\,\text{mm/yr}$, which is nearly consistent with trends given by (i) Gao et al. (2006), who estimate an annual reference evapotranspiration trend of about $-1.7\,\text{mm/yr}$ in the Yangtze basin for the period of 1956–2000, (ii) Wu et al. (2006), whose estimated trend in reference evapotranspiration is about $-1.3\,\text{mm/yr}$ in China from 1971–2000, and (iii) Ren and Guo (2006), who estimate an annual decrease of $-3.8\,\text{mm/yr}$ for pan evaporation during 1956–2000.
3. The PE and ETr trends are influenced by significant reductions of net radiation and wind speed over the whole basin and all seasons. This agrees with the results of Ren and Guo (2006), Xu et al. (2006) and Gao et al. (2006). An insignificantly decreasing summer temperature should be noted in the mid-lower Yangtze basin. In summer and for the mid-lower Yangtze reaches the significantly decreasing summer saturation vapour pressure deficit contributes to the overall trend.
4. The reduced summer saturation vapour pressure deficit in the mid-lower Yangtze reaches suggests that actual evaporation in summer may have increased following the complementary relationship (Brutsaert and Parlange, 1998). This would require more rainfall. The increasing precipitation leads to increasing surface runoff and soil wetness which, in turn, generates more evaporation (Brutsaert and Parlange, 1998). According to several previous studies on the trends of rainfall and runoff in the Yangtze basin, the summer rainfall shows a significant increasing trend in the mid-lower Yangtze reaches (Becker et al., 2003; Su et al., 2005, 2006; Zhang et al., 2005). A significant upward trend in summer runoff is noticed at Datong hydrological station, which almost controls the whole Yangtze basin with a coverage area of $1{,}705{,}383\,\text{km}^2$ (Qin and Jiang, 2005; Jiang et al., 2005).

The observed annual decrease of pan evaporation and reference evapotranspiration may be associated with the changes of actual evaporation from ensemble GCM-scenario simulations of the 20th century climate (for IPCC):

1. The decreasing annual trend is the strongest (beyond 99% confidence level) for the reference evapotranspiration (ETr, FAO Penman–Monteith equation), becomes weaker for the pan evaporation and is weakest for the simulated evaporation in the whole Yangtze basin (Fig. 4). The annual trend is more significant in the mid-lower reaches in the simulated evaporation and reference evapotranspiration, while higher significance occurs in observed pan evaporation in the upper Yangtze River basin. Summer evaporation trend in the scenario ensemble is slightly *increasing* due to a significant positive contribution by the upper reaches, while the summer trend is *decreasing* (due to significant negative contributions in the mid-lower basin) in the observations.
2. The trends of the simulated meteorological variables show differences with observations: Observed net radiation and wind speed decrease in all seasons and upper and mid-lower Yangtze reaches while the simulated net radiation shows a decrease only in the mid-lower reaches (which is significant only in winter). Simulated trends in wind speed and upper basin net radiation do not provide a uniform pattern as the observed ones.
3. The simulated rise in air temperature on the annual scale is significant over the Yangtze basin, dominated by summer and autumn trends. The observed increase in air temperature for the Yangtze basin shows also significant warming on annual time scale which, however, is dominated by the winter trend.

Comparing model simulations with observations underline the reduced ability of state of the art general circulation/climate models in assessing the influence of anthropogenic greenhouse gases on regional scales as compared to the larger scales, which they are representative for. In addition, three ensemble members do not provide statistically meaningful representations of variability in complex climatic settings such as the Yangtze River basin. In addition, our results do not allow an assessment of actual evaporation. Given the mechanisms proposed (see Sect. 1) we conclude that increasing precipitation together with decreasing potential evaporation hint to a more humid mid-lower reaches of the Yangtze River basin, while decreasing precipitation and enhanced potential evaporation may characterize the more arid upper reaches. The observed combined trends in evaporation, wind speed and precipitation may indicate a complex change in meso- and/or large-scale atmospheric circulation, an analysis of the details will be reported separately.

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