Evaporation paradox in the Yellow River Basin, China

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Abstract It is well known that the surface of the Earth has warmed over the past 50 years. It is generally expected that the air will become drier and that evaporation will increase. However, many observations show that pan evaporation has been steadily decreasing all over the world. The contrast is called the evaporation paradox. Using climate data from 140 weather stations and hydrological data from 71 stations, it was found that potential evaporation, both pan evaporation and reference potential evaporation, show a significant decreasing trend, which indicates that the evaporation paradox does exist in the Yellow River Basin. At the same time, actual evaporation estimated by water balance decreased with the decrease in precipitation in most sub-basins. With the increase of precipitation, potential evaporation and actual evaporation have a complementary relationship; while based on yearly results, potential evaporation and actual evaporation have a proportional relationship.

Key words evaporation paradox; Yellow River; potential evaporation; actual evaporation; evaporation

INTRODUCTION

Evaporation paradox

It is now well established that global surface temperatures have increased between 0.4 and 0.8°C since the late 19th century and the rate of temperature increase since 1976 has been over 0.15°C per decade (IPCC, 2001). An expected consequence of this warming is that the air near the surface should be drier, which should result in an increase in the rate of evaporation from terrestrial open water bodies. However, many observations show that the rate of evaporation from open pans of water has been steadily decreasing all over the world over the past 50 years, and the same is apparent for reference evapotranspiration. This trend was found to be generally evident in the United States and the former Soviet Union (Peterson *et al.*, 1995), in India (Chattopadhyay *et al.*, 1997), in China (Thomas, 2000; Liu *et al.*, 2004), in Italy (Moonen *et al.*, 2002), and in Australia (Roderick *et al.*, 2004), but not universal in Israel (Cohen *et al.*, 2002) and in east Asia (Xu, 2001).

The contradiction between expectation and observation is called the evaporation paradox (Roderick *et al.*, 2002). The decrease in pan evaporation may be caused by the reduction in solar radiation resulting from more clouds and/or aerosols (Peterson *et al.*, 1995; Stanhill *et al.*, 2001; Roderick *et al.*, 2002), by the reduction in vapour pressure deficit due to the addition of air humidity (Chattopadhyay *et al.*, 1997), or by the reduction in wind speed (Cohen *et al.*, 2002). Evaporation and transpiration play an important role in the global water and energy cycle, and their change will make a significant effect on global climate, hydrological cycle, water resources, crop growth, and the ecological environment (Chahine *et al.*, 1992; Stanhill, *et al.* 2001; Sun *et al.*, 2001; Roderick *et al.*, 2002).

It is disputed whether the decrease of pan/reference evaporation predicates the decrease of actual evaporation. Peterson *et al.* (1995) concluded that a decrease in pan evaporation indicates a decrease in actual evaporation, which was proven with the increasing runoff of rivers in the former Soviet Union and the United States in the past 20 years. On the other hand, Brutsaert *et al.* (1998) concluded that a decrease in pan evaporation indicates an increase in actual evaporation from the surrounding non-humid environments, which indicates that actual evaporation and pan evaporation exhibit a complementary relationship rather than proportional behaviour.

This study aims to know the behaviour of the evaporation paradox in the Yellow River Basin through understanding the spatial and temporal variability of potential and actual evaporation over the basin.

Yellow River Basin

The Yellow River, also called Huanghe in Chinese, is the second longest river in China, with a length of 5646 km, and the basin is the second largest, with a drainage area of 753 000 km^2. In the 1990s the drying up of the main river along the lower reach in the Yellow River drew much attention from all over the world.

Annual precipitation showed a decreasing trend of –45.3 mm/50 years; annual mean temperature had an increasing trend of 1.28°C/50 years; and river discharge had significant decreasing trends ranging from –28 mm/50 years to –61.5 mm/50 years (Yang *et al.*, 2004).

METHODOLOGY

Potential evaporation (ET_p)

Potential evaporation can be expressed by pan evaporation (ET_{pan}) or potential evaporation of extensive free water surface (ET_0). ET_0 is estimated using the Penman-Monteith method (Shuttleworth, 1993; Allen *et al.*, 1998) as follows:

$$ET_0 = \frac{\Delta}{\Delta+\gamma}\left(R_n + A_h\right) + \frac{\gamma}{\Delta+\gamma}\frac{6.43\left(1+0.536U_2\right)D}{\lambda} \tag{1}$$

where, R_n = net radiation exchange for the free water surface, mm day^{-1}; A_h = energy advected to the water body, if significant; U_2 = wind speed measured at 2 m, m s^{-1}; D = vapour pressure deficit, kpa; Δ = slope of saturation vapour pressure curve, kPa°C^{-1}; γ= psychrometric constant, kPa°C^{-1}; λ = latent heat of vaporization, MJ kg^{-1}.

Actual Evaporation (ET_a)

Precipitation (P) and potential evaporation can be measured or calculated at each weather station, and runoff (R) can be measured at each hydrological station in the mouth of the basin. With interpolation, the precipitation and the potential evaporation of sub-basins can be evaluated, and then actual evaporation (ET_a) is estimated using water balance:

$$ET_a = P - R \tag{2}$$

Linear regression and Kendall correlation coefficient

The linear regression model is:

$$y_i = ax_i + b \qquad i = 1, 2, \ldots, n \tag{3}$$

where, y_i = *i*th observation of the response variable; x_i = *i*th observation of the explanatory variable; a = slope; b = intercept.

In addition, slope a can be gained by the following equation:

$$a = \sum_{i=1}^{n}\left(x_i - \overline{X}\right)\left(y_i - \overline{Y}\right) \Big/ \sum_{i=1}^{n}\left(x_i - \overline{X}\right)^2 \tag{4}$$

The Kendall correlation coefficient (Kendall's τ) between two variables can be computed with the method presented in the *Handbook of Hydrology* (Salas, 1993).

DATA DESCRIPTION

Daily climate data from 1951 to 1998 from 140 meteorological stations, covering most regions of the Yellow River Basin have been collected; of which 64 stations were chosen to be used as they had records of more than 30 years. The data include precipitation, maximum air temperature,

Fig. 1 Weather stations and hydrological stations in the Yellow River Basin.

Table 1 Trend of potential evaporation in the Yellow River Basin in the past 50 years

Period	Pan evaporation (ET_{pan})		Potential evaporation (ET_0)	
	Increase ($a > 0$)	Decrease ($a < 0$)	Increase ($a > 0$)	Decrease ($a < 0$)
1951–1998	9	55	24	40
1951–1984	16	48	31	33
1985–1998	35	29	44	20

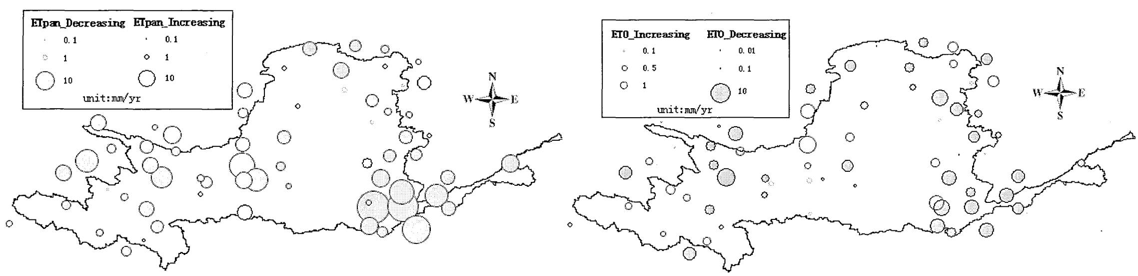

Fig. 2 Trend of potential evaporation in the Yellow River Basin from 1951 to 1998.

minimum air temperature, wind speed, pan evaporation, vapour, sun time, and hemi; from which potential evapotranspiration can be calculated with the Penman-Monteith method. Annual runoff data from 1951 to 1998 from 71 hydrological stations, controlling 71 sub-basins of the Yellow River Basin, have been collected to simulate actual evapotranspiration. The weather stations and the hydrological stations are shown in Fig. 1.

RESULTS AND DISCUSSION

Spatial and temporal variability in potential evaporation

The results of linear regression regarding potential evaporation are listed in Table 1, which indicated that in contradiction with the increase in temperature, both ET_{pan} and ET_0 had decreased at most stations in the Yellow River Basin during the past 50 years, which is also shown in Fig. 2. The trend of pan evaporation is more obvious and decrease occurred in 55 of the total 64 stations with an average Kendall's τ of 0.28. The trend is that ET_{pan} in these 55 stations decreased 28.5 mm/10 years in arithmetic average. Thus, we can conclude that the evaporation paradox occurred in the Yellow River Basin.

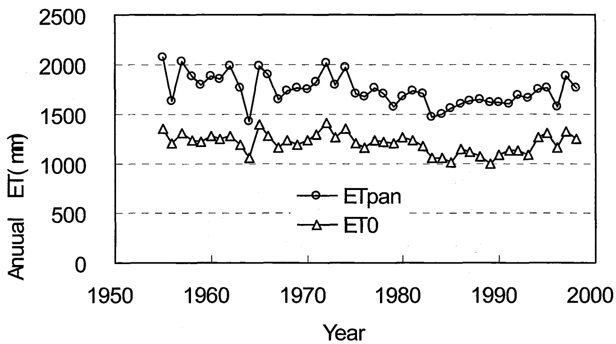

Fig. 3 Trend of potential evaporation at the Taiyuan station in the past 50 years.

Table 2 Trend of actual evaporation in the Yellow River Basin in the past 50 years.

Period	ET_0		Precipitation		Runoff		Actual evaporation	
	$a>0$	$a<0$	$a>0$	$a<0$	$a>0$	$a<0$	$a>0$	$a<0$
1951–1998	26	45	10	61	15	56	16	55
1951–1984	36	34	24	41	13	52	33	32
1985–1998	65	6	15	51	38	28	16	50

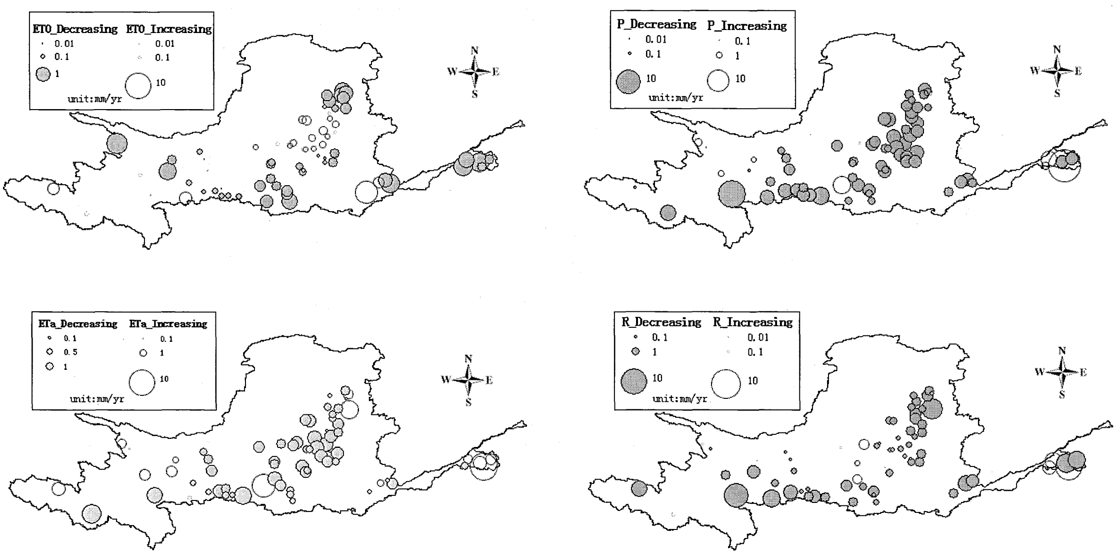

Fig. 4 Trend of actual evaporation in the Yellow River Basin from 1951 to 1998.

In addition we can note that the trend changed after 1985, which was also found by Yang (2004). The change is also due to the increase in solar radiation after 1985, but this is not clearly understood. The typical trend in the past 50 years is shown in Fig. 3, using data from Taiyuan station.

The spatial distribution of the trend is shown in Fig. 2. The decreasing trend is more obvious in the upstream basin and the downstream basin than in the middle stream basin.

Spatial and temporal variability in actual evaporation

The results of linear regression regarding reference evapotranspiration, precipitation, runoff, and actual evaporation of catchments are listed in Table 2. Actual evaporation, estimated with water balance (equation (2)), had reduced continuously in the past 50 years, even with the increase in runoff, due to the decrease in precipitation. The decreasing trend of actual evaporation, about 10.5 mm/10 years in area weighted average, is smaller than that of potential evaporation, about 15.4 mm/10 years. The decreasing trend of precipitation, about 18.4 mm/10 years, caused serious aridity in the Yellow River Basin, but it also reduced the water supply, so actual evaporation decreased in the past 50 years. These trends can also be seen in Fig. 4.

Relation between actual evaporation and potential evaporation

From the above results, in general, both actual evaporation and potential evaporation diminished in the past 50 years. From Table 3, we can find: in most basins, both actual evaporation and potential evaporation reduced from 1951 to 1998; after 1985, actual evaporation still declined even if potential evaporation started to increase.

Table 3 Relation between actual evaporation and potential evaporation.

ET_0	$a > 0$	$a < 0$	$a > 0$	$a < 0$
Actual evaporation	$a > 0$	$a < 0$	$a < 0$	$a > 0$
1951–1998	5	34	21	11
1951–1984	13	9	23	20
1985–1998	12	2	48	4

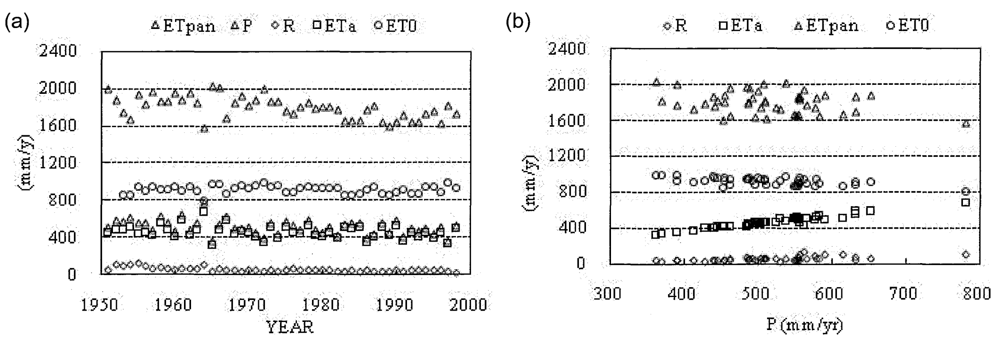

Fig. 5 Relation of actual evaporation and potential evaporation in the Yellow River Basin from 1951 to 1998.

Complementary relationship

The trend of the average pan evaporation (ET_{pan}), potential evaporation (ET_0), actual evaporation (ET_a), precipitation (P), and runoff (R) over the whole basin can be seen in Fig. 5(a). It can be concluded that actual evaporation and potential evaporation have a proportional relationship since they both declined in the past 50 years.

According to the same data, if we make precipitation as the abscissa, it can be found that actual evaporation decreases while pan evaporation and potential evaporation increase, as shown in Fig. 5(b). Therefore, we get a complementary relationship between actual evaporation and potential evaporation.

In general, potential evaporation will increase with decreasing precipitation, but it does not occur in the Yellow River Basin. In this basin, potential evaporation decreased because radiation became smaller; this is also called *global dimming*. Thus, potential evaporation decreased in spite of the reduction of precipitation, as shown in Fig. 5(a). Meanwhile, the influence of radiation reduction is ignored in Fig. 5(b) because the year is confused and the complementary relationship comes back.

CONCLUSION

The major findings can be summarized as follows:

(a) During the past 50 years (1951–1998), both potential evaporation by Penman-Monteith and pan evaporation show a significant downward trend in the Yellow River Basin. At the same time, air temperature shows a significant increasing trend, so the evaporation paradox does occur in the basin.

(b) After 1985, both potential evaporation and pan evaporation show an increasing trend.

(c) During the past 50 years (1951–1998), both precipitation and runoff in most basins show a significant downward trend in the Yellow River Basin.

(d) During the past 50 years (1951–1998), actual evaporation estimated using water balance shows a continuous downward trend in the Yellow River Basin.

(e) In the Yellow River Basin, with the increase of precipitation, potential evaporation and actual evaporation have a complementary relationship; while based on yearly results, potential evaporation and actual evaporation have a proportional relationship.

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REFERENCES

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper 56*, FAO, Rome, Italy.

Brutsaert, W. & Parlange, M. B. (1998) Hydrologic cycle explains the evaporation paradox. *Nature* **396**, 29–30.

Chahine, T. M. (1992) The hydrological cycle and its influence on climate. *Nature* **239**, 373–381.

Chattopadhyay, N. & Hulme, M. (1997) Evaporation and potential evapotranspiration in India under conditions of recent and future climate change. *Agric. For. Met.* **87**, 55–73.

Cohen, S., Ianetz, A. & Stanhill, G. (2002) Evaporative climate changes at Bet Dagan, Israel, 1964–1998. *Agric. For. Met.* **111**, 83–91.

IPCC Third Assessment Report – Climate Change (2001) The Scientific Basic (http://www.ipcc.ch/).

Liu, B., Xu, M. Henderson, M. & Gong, W. (2004) A spatial analysis of pan evaporation trends in China, 1955–2000. *J. Geophys. Res.-Atmospheres* **109**(D15).

Moonen A. C., Ercoli, L., Mariotti, M. & Masoni, A. (2002) Climate change in Italy indicated by agrometeorological indices over 122 years. *Agric. For. Met.* **111**, 13–27.

Peterson, T. C., Golubev, V. S. & Groisman, P. Y. (1995) Evaporation losing its strength. *Nature* **377**, 687–688.

Roderick, M. L. & Farquhar, G. D. (2002) The cause of decreased pan evaporation over the past 50 years. *Science* **298**, 1410–1411.

Roderick, M. L. & Farquhar G. D. (2004) Changes in Australian pan evaporation from 1970 to 2002. *Int. J. Climatol.* **24**, 1077–1090.

Salas, J. D. (1993) Analysis and modeling of hydrologic time series. In: *Handbook of Hydrology* (ed. by D. Maidment), Chapter 19. McGraw-Hill, Inc. New York, USA.

Shuttleworth, W. J. (1993) Evaporation. In: *Handbook of Hydrology* (ed. by R. D. Maidment), Chapter 4. McGraw-Hill, New York, USA.

Stanhill, Gerald & Cohen, Shabtai (2001) Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. *Agric. For. Met.* **107**, 255–278.

Sun, Lan & Wu, Guo-Xiong (2001) Influence of land evapotranspiration on climate variations. *Science in China (Series D)* **44**, 838–846.

Thomas, A. (2000) Spatial and temporal characteristics of potential evapotranspiration trends over China. *Int. J. Climatol.* **20**, 381–396.

Xu, J. (2001) An analysis of climatic changes in Eastern Asia using the potential evaporation. *J. Japan Soc. Hydrol. Water Resour.* **14**, 141–170.

Yang, Dawen, Li, Chong, Musiake, Katumi & Kusuda, Tetsuya (2004) Analysis of water resources variability in the Yellow River of China during the last half century using historical data. *Water Resour. Res.* **40**, W065021-W0650212.