Change in pan evaporation over the past 50 years in the arid region of China

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Abstract:
Pan evaporation, as a surrogate of potential evaporation, is reported to have decreased in different regions of the world since the 1950s. There is much literature to explain the decrease in pan evaporation using the so-called evaporation complimentary relationship hypothesis and it is argued that pan evaporation can be understood as a sign of global warming and indication of an accelerating hydrologic cycle. On the other hand, some scientists insist that the pan evaporation trends may be caused by a global dimming, which effectively reduces the solar radiation to the ground surface. However, few reports are available about the changes in pan evaporation and their implications to water balance in arid regions. In the present study, we investigate the trends in pan evaporation in arid regions of China over the past 50 years and attempt to characterize the changes in water balance in these areas. It is found that pan evaporation in these areas has portrayed a statistically significant decreasing trend, which may be attributed mainly to decreases in wind speed and diurnal temperature range and increase in precipitation. The trends in some major meteorological factors such as pan evaporation, precipitation, temperature, wind speed and others imply an enhanced hydrological cycle in the study area. Copyright © 2009 John Wiley & Sons, Ltd.

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INTRODUCTION
Pan evaporation ($E_{\text{pan}}$) has traditionally been used as an estimate of atmospheric evaporative demand, and is widely used in agricultural water management, e.g. irrigation planning. Recent interest in pan evaporation has been provoked by a so-called ‘evaporation paradox’. During the past century, the air temperature near Earth’s surface was observed to increase by about 0.74 °C (IPCC, 2007). Hydrological response to global warming and resultant changes in water resource availability has become a topic of great interest for hydrological communities. It is expected that global warming due to accelerating anthropogenic greenhouse gas emissions will result in a higher evaporative potential of the atmosphere (IPCC, 2001) and an increase in actual evapotranspiration (DelGenio et al., 1991; IPCC, 2001). Subsequently, the hydrological cycle is expected to become more active or enhanced (IPCC, 2001). This assumption is widely adopted in the climatic dynamics schemes of most general circulation models (GCM) for long-term global warming simulation.

However, analyses of the available observation data do not support this assumption completely. Widespread decreases in pan evaporation over several decades were reported in many places of the North Hemisphere, such as the United States and the former Soviet Union (Peterson et al., 1995), India (Chattopadhyay and Hulme, 1997), China (Thomas, 2000; Liu et al., 2004; Chen et al., 2005; Zuo et al., 2005; Yang et al., 2006; Zhang et al., 2007; Liu et al., 2009), Italy (Moonen et al., 2002), Israel (Cohen et al., 2002), Thailand (Tebakari et al., 2005) and Japan (Xu et al., 2005). Decreasing trends have also been reported for the Southern Hemisphere, including Australia and New Zealand (Roderick and Farquhar, 2004, 2005; Rotstayn et al., 2006; Rodrick et al., 2007). Roderick and Farquhar (2002) have suggested that the decrease in pan evaporation might be closely related to global dimming, i.e. the decrease in solar radiation due to global increases of aerosols in the atmosphere (Stanhill and Cohen, 2001). However, in recent analyses from Australia, effects of changes in radiation on pan evaporation were not evident, and most of the decrease in pan evaporation was attributed to wind speed declines (Roderick et al., 2007).

Pan evaporation in China was also reported to have decreased in the past five decades in several regions, including the Yellow River Basin (Qiu et al., 2003), North China Plain (Guo and Ren, 2005), Tibetan Plateau (Zhang et al., 2007) and even the whole of China (Liu et al., 2006; Zeng et al., 2007; Liu et al., 2009). However, pan evaporation trends in the hyper-arid regions...
of China, which are located in the northwestern portion of the country, have never been analysed in detail. The objectives of this study are to investigate the trends in pan evaporation in arid regions of China using Mann–Kendall statistical testing, and to evaluate the major factors related to the changes in pan evaporation and how they relate to the hydrological cycle.

MATERIALS AND METHODS

Study area

This study was undertaken to investigate the trends in pan evaporation observed in hyper-arid regions of China, which are mainly distributed in the northwestern part of China including the provinces of Xinjiang, Gansu, Qinghai, Ningxia and the western part of Inner Mongolia. The study area covers around 3.5 million km², extending longitudinally from 73.6E to 112.4E, and latitudinally from 31.5N to 48.9N (Figure 1). The climate is dominated by continental arid conditions with lesser effects of the East Asian Monsoon. Annual precipitation in the study area ranges from less than 20 mm in the center of the Taklamakan desert to 500 mm in the Tienshan Mountains. The precipitation in most of the study area is below 200 mm. Exceptions are the Tienshan Mountains and the Qinghai-Tibet Plateau, where the annual precipitation exceeds 400 mm. Around one-third of the total area has an annual precipitation of less than 50 mm.

Topographically, the altitude of the study area ranges from −155 to 7670 m above sea level. The lowest place in the study area is Aitin Lake in the Turpan depression and the highest place is in the Tibet-Qinghai plateau (Figure 2). The study area comprises desert depressions, mountains, high plateau and alluvial fans, where most oases and major human landscapes are located. The study area includes about 90% of the deserts in China, including the Taklamakan desert, Gurban Tongute desert, Badain Jaran desert, Tengger desert, Qaidam desert, Kum-tagh desert and the southwestern part of the Gobi desert.

Data

The data used in this study are from 126 ground-based meteorological observation sites of the China Meteorological Administration (CMA) (Figure 2). Monthly data on precipitation, pan evaporation, wind speed, air temperature (including minimum, maximum and average), relative humidity, sunshine duration, cloud cover and other parameters from 1955 to 2001 are employed for the analysis.

Trend analysis

A non-parametric trend analysis method, the Mann–Kendall test, was used for detection of trends in pan evaporation and related meteorological factors. In the Mann–Kendall test, the null hypothesis $H_0$ states that the data $(x_1, x_2, \ldots, x_n)$ comprise a sample of $n$ independent and identically distributed random variables. The alternative hypothesis $H_1$ of a two-sided test is that the distribution of $x_k$ and $x_j$ are not identical for all $k$ and $j$. The Kendall’s statistic $S$ is

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \text{sgn}(x_k - x_i)$$

Time series $x_i$ are ranked from $i = 1, 2, \ldots, n - 1$ and $x_j$ from $j = i + 1, \ldots, n$. Each data point $x_i$ is used as a
reference point and is compared with all other data points $x_j$, such that:

$$\text{sgn}(\theta) = \begin{cases} 
1, & \theta > 0 \\
0, & \theta = 0 \\
-1, & \theta < 0 
\end{cases} \quad (2)$$

If the data set is identically and independently distributed, then the mean of $S$ is zero and the variance of $S$ is

$$\text{var}[S] = \left[ \frac{n(n-1)(2n+5)}{18} - \sum_i t(t-1)(2t+5) \right] / 18 \quad (3)$$

in which $n$ is the length of the data set, $t$ is the extent of any given tie and $\sum$ denotes the summation over all ties. Then the test statistic is given as follows:

$$Z_c = \begin{cases} 
\frac{S - 1}{\sqrt{\text{var}(S)}}, & S > 0 \\
0, & S = 0 \\
\frac{S + 1}{\sqrt{\text{var}(S)}}, & S < 0 
\end{cases} \quad (4)$$

The magnitude of the trend is given as

$$\beta = \text{Median} \left( \frac{x_i - x_j}{i - j} \right), \forall j < i \quad (5)$$

in which $1 < j < i < n$. A positive value of $\beta$ indicates an ‘upward trend’ and a negative value of $\beta$ indicates a ‘downward trend’.

The Mann–Kendall test may be thereby stated simply as follows:

- Null hypothesis $H_0$: $\beta = 0$, ($\beta$ is the slope of trend)
- Significance level: $\alpha$
- Test statistics: $Z_c$

Rejected $H_0$: $|Z_c| > Z_{1-\alpha/2}$, in which $\pm Z_{1-\alpha/2}$ are the standard normal deviates and $\alpha$ is the significance level for the test. In this study, we use the significance level of $\alpha = 0.05$; therefore, the standard normal deviate equals $1.96$.

RESULTS

Pan evaporation trends over past 50 years

Pan evaporation was aerially averaged after interpolation using the inverse distance weighted method (IDW) over the study area. Trends in the pan evaporation anomaly were calculated relative to the average value for the period 1971 to 2000 (Figure 3), in which the average pan evaporation was 1986 mm in the study area. Figure 3 clearly shows that the pan evaporation in the study area has an obvious decreasing trend from 1960 to 1990 and an increasing trend in the 1990s. This phenomenon was also reported by Sun (2007).

The trends of pan evaporation observed at each site were examined in order to understand the spatial distribution of pan evaporation trends. As detected by the Mann–Kendall test, most of the observation sites show decreasing trends of pan evaporation in the study area over the past 50 years (Figure 4). Among the 126 sites, 93 sites had overall decreasing trends in pan evaporation for the study period, 60 of which were statistically significant. Only 14 sites had statistically significant increasing trends.

The pan evaporation trends were also analysed seasonally (Figure 5). Spring evaporation trends (MAM) are mostly increasing. Around half of the sites show decreasing trends in summer (JJA) and autumn (SON). In winter (DJF), most sites show increasing trends, with the exception of sites in the Qinghai Plateau. This phenomenon suggests that decreases in annual pan evaporation mainly stem from decreases in summer and autumn, which may relate to increased summer precipitation (see Figure 7), because most of the precipitation falls in these seasons. With regard to the fast increase in pan evaporation during spring, we investigated the other factors such as temperature, humidity, wind speed, etc. and failed to find clear reasons for this increase.

Influencing factors

Pan evaporation is a synthetic measure of the climate, influenced by both radiation factors and atmospheric factors. Roderick et al. (2007) used the PenPan model, a modified Penman–Monteith model for calculating latent heat flux from pan evaporimeters, to evaluate the causes of decreasing pan evaporation in Australia. They found that aerodynamic factors are dominant relative to radiation factors. Among aerodynamic factors, change in wind speed was the major factor but changes in vapor pressure and air temperature also contributed.

In this study, the factors potentially affecting pan evaporation can be categorized into two types: wetness-related factors such as precipitation (P), relative humidity (RH) and low cloud cover (Lcloud) and thermodynamic...
factors such as wind speed (WS), air temperature ($T_a$) and diurnal temperature range (DTR). For aerially averaged pan evaporation across the full study area, the most closely related factor to decreasing pan evaporation is diurnal temperature range (DTR), which decreases with a similar trend as pan evaporation over the study period (Figure 6). The correlation coefficient between DTR and $E_{\text{pan}}$ is 0.69, passing the $F$-test at a significance level of 0.01. The second closest related factor is wind speed, which has a statistically significant decreasing trend as well. Precipitation changes have a negative correlation with the changes in pan evaporation. Although the correlation coefficient is moderate ($r = 0.51$), it passes the $F$-test at a significance level of 0.01. Changes in low cloud cover and relative humidity also appear to contribute to the decrease in pan evaporation with weak positive correlations. In contrast, temperature portrays a statistically significant increasing trend.

There is good correspondence in the spatial distributions of the sites with decreasing pan evaporation and those with increasing precipitation, decreasing wind speed and decreasing diurnal temperature range (Figure 7). Almost all of the observation sites have detectable increasing trends in temperature (Figure 7g) over past 50 years. At most sites, an increasing trend in low cloud cover is also apparent. The relative humidity increase suggests that vapor pressure of near surface air has increased, which may be related to the expansion of irrigated areas. Although the physical mechanism linking DTR and pan evaporation is unclear, statistically the two have corresponding trends. The decrease in DTR is mainly caused by a faster increase in minimum temperature than maximum temperature, indicating a warming climate (Liu et al., 2009). This decrease in DTR might be mainly contributed from the increase in vapour and aerosols in the air, which reduces the daytime incoming solar radiation and also the nighttime outgoing longwave radiation from the land surface, resulting in a higher minimum temperature. Lack of observations on solar radiation and aerosols prevent quantitative analyses of this hypothesis at this stage.

**DISCUSSIONS AND CONCLUSION**

Pan evaporation measurements contain integrated information on atmospheric conditions. Changes in pan evaporation are often considered an indicator of climate change. Many factors can affect pan evaporation, including radiation, aerodynamic and land surface factors. Many researchers have argued that increasing aerosol
abundance is the major causal factor of decreases in pan evaporation in the Northern Hemisphere by decreasing solar radiation to the surface (Stanhill and Cohen, 2001). In the case of Australia, Roderick et al. (2007) attributed the decrease in pan evaporation to radiative factors only at two sites in the northwest of the country; decreases at other Australian sites have mainly been attributed to aerodynamic factors, wind speed being the most prominent. In the present study, even without benefit of radiation observations, the observations of decreased diurnal temperature range (DTR) and increased low cloud cover imply that solar radiation might also have decreased in the study area, which is likely to contribute to the decrease in pan evaporation. The decrease in DTR is mainly caused by the amplitude of minimum temperature increasing by a faster rate than maximum temperature (Liu et al., 2009).

The present study suggests that, like in Australia, the decrease in wind speed in arid northwestern China is one of the major reasons for the decline in pan evaporation. The decrease in wind speed probably relates to changes in large-scale circulation associated with climate warming. Wang et al. (2004) reported that the decrease in wind speed in China can be attributed to the weakening of the East Asian Monsoon over the last 50 years. However, an increase in land surface roughness due to reforestation and urban development near observation sites (which were usually located at the fringe of cities or towns when they was established) can also result in observations of decreasing wind speed. Further modelling and monitoring studies are needed to address this question.

Most sites in arid western China show detectable increases in precipitation and air temperature (Figure 7). Chen et al. (2006) also reported that precipitation in Xinjiang portrays an increasing trend. These trends indicate that the climate in the hyper-arid regions is changing to warmer and wetter conditions. In most parts of the study area, the aridity index (the ratio between annual potential evaporation and precipitation) has decreased over the study period, except in the southeast part where it has increased (Figure 8). This suggests that the climate of most of the study area has become slightly less arid during the past half century. Under this changing climate, the terrestrial hydrological cycle will also change. On the basis of evaporative complimentary theory, which has shown to be effective in non-humid regions (Sun, 2007), actual evaporation has increased over the past five decades (Sun et al., 2007). Chen et al. (2006) and Xu et al. (2009) have also reported an increasing trend in runoff in the past five decades. It can be concluded that the major components of the hydrological cycle, i.e. precipitation, runoff and evapotranspiration, are all...
undergoing increasing trends in the arid region. This phenomenon indicates an enhanced hydrological cycle in arid regions of China over the period of monitoring. However, it is necessary to clarify to what extent water can be renewed in the enhanced hydrological cycle or how much water/vapour may join the local cycle in the arid regions. Detailed research on water cycle processes and tracing technologies can help elucidate mechanisms of change in these hydrological processes at both the local and basin scales.

From the current study, it can be concluded that (1) pan evaporation has gradually decreased over the past 50 years in arid China; (2) an increase in precipitation and decrease in wind speed are the major causal factors leading to decreasing pan evaporation in the study area; (3) diurnal temperature range shows strong correlations
with pan evaporation, which may imply that increasing aerosol concentrations reduce solar radiation and hence contribute to declining pan evaporation and (4) the climate in arid western China is changing towards warmer and wetter conditions, and this change may lead to an accelerated hydrological cycle.

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