THE SPATIAL AND TEMPORAL CHANGES OF PAN EVAPORATION FROM 1971 TO 2000 IN THE YELLOW RIVER BASIN

Weihua FANG[1,2] and Hidefumi IMURA[3]

[1] Assistant Professor, College of Resources Science & Technology, Beijing Normal University
(19, Xinjiekouwai Street, 100875, China)
[2] Researcher, CREST, Japan Science and Technology Agency
E-mail: weihua.fang@gamil.com
[3]Member of JSCE, Professor, Department of Urban Environment,
Graduate School of Environmental Studies, Nagoya University
(Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan)
E-mail: imura@genv.nagoya-u.ac.jp

Evaporation is a critical process in the material and energy cycle of land-atmosphere system. The Yellow River basin (YRB) experienced severe water shortage in the past several decades. The spatial and temporal characteristics of pan evaporation (PE) and their changes are of vital importance to the understanding of the hydrological process and water resources in the YRB.

In this paper, the temporal and spatial changes of PE in the YRB from 1971 to 2000 were examined in detail. The major findings are as the follows: (1) there was an increasing trend in the YRB for PE starting from the late of 1980's although the general trend of global PE change was decrease; (2) the PE decreased in most areas of the YRB in spring and summer, but most parts increased in autumn and winter. At the mean time there exist areas, like the Fenhe River basin, where PE increased in all the seasons; and (3) sunshine hours decrease and wind speed decrease were the major causes for PE decrease from 1971 to 2000 and sunshine increase led to PE increase from the late of 1980's.

Key Words : *pan evaporation, spatial and temporal changes, the Yellow River basin*

1. INTRODUCTION

The climate had experienced various changes in the past several decades both globally and locally under the background of fast industrial process. The global temperature increased approximately 0.3~0.6 degree during the past 100 years according to past climate records and will keep on increasing based onn the results of the climate scenarios of General Circulation Models (GCMs)[1,2,3]. Climate change is likely to have impact on regional water circulation process and available water resources.

Evaporation is a critical indicator in a variety of climate and water resources related fieldss. For example, evaporation has a direct impact on crop irrigation requirement and crop productivity[3]. It is of great importance to assess the spatial and temporal characteristics of evaporation to provide information for water resources assessment and allocation.

Pan evaporation (PE) is one of the most important climatic components next to temperature and precipitation in water and energy cycle processes. It is influenced by a variety of climate variables such as temperature, radiation, humidity and wind speed. PE can be used as a simple measurement or proxy of complex meteorological interactions. Although PE can not fully represent lake evaporation and is even less indicative of ground evapotranspiration, analysis of observed trends in PE is able to provide considerable insights into current climate change and the impact this change may be having on agriculture and water resources.

The Yellow River basin (YRB) is the second largest basin of China and met severe water resources shortage problem in the recent years. The YRB experienced river drying-up many times from the year 1972 and at the mean time the water demand kept increasing with the development of economy. Past studies show that water resources shortage is likely to continue to be a major problem under the global climate change and its regional impact on China[4,5]. To understand the temporal and spatial changes of PE in the YRB is a key part of water resources study.

There are a variety of past studies on PE, ranging from PE changes and its mechanisms and application in various fields. For example, Peterson et al. presented the decreasing trend of PE in a wide range of places[6]. Brutsaert et al. explained the PE decreased from the viewpoint of hydrologic cycle[7]. Michael, et al. suggest PE decrease in Russia was mainly caused by increase in the extent of cloud cover, or by greater concentrations of atmospheric aerosols[8]. Pitman et al. discussed the impact and application of PE changes and its mechanism on regional climate models (RCMs)[9].

A range of PE studies concerning China and the Yellow River basin were also implemented. These studies primarily focus on checking PE data quality, analyzing the characteristics of PE, utilizing PE as a proxy for estimating potential or actual evapotranspiration, and applying PE in fields like ecology and agriculture. For example, the quality of PE records was examined by Song et al.[10]. Qiu and Liu, et al. examined some of the temporal and spatial characteristics of PE changes in the Yellow River basin from 1961 to 2000[11].

The objective of this study is to examine the temporal and spatial characteristics of PE changes in the YRB from 1971 to 2000, and its connection of PE changes to the changes of climate variables. Differing from the past studies on PE changes in the YRB[11], our findings on the PE changes, such as the increase trend starting from the late of 1980's, and typical PE increase area like the Fenhe River basin, are to be reported in this article.

2. DATA PREPARATION

The climate dataset being used in this study was obtained from the Chinese National Meteorological

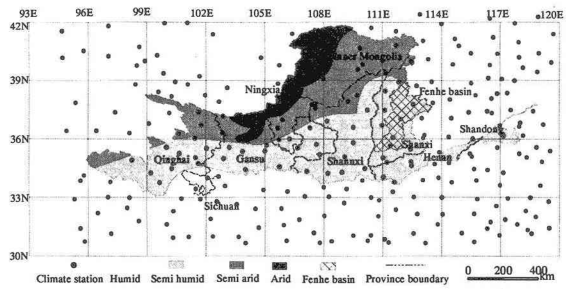

Fig. 1 The 255 climate stations covering the YRB.

Centre (CNMC). The data include the following variables: maximum surface air temperature (T_{max}), minimum surface air temperature (T_{min}), sunshine hours (SH), wind speed (WS), vapour pressure (VP), PE, and precipitation.

The PE values were measured by evaporimeter with dimension of 20-cm diameter and 10-cm height. The evaporimeters were placed on grass, measuring evaporation in a vegetation environment, similar to the Class-A PE measurement in the USA[3].

The dataset presented in this study covers 255 stations over the YRB domain, of which 88 stations are inside the Yellow River basin (Fig. 1). As illustrated, the stations are spatially evenly distributed inside and outside of the YRB. Only in southwest part of Qinghai province exists a small area of coarse station distribution. The time period of the dataset used in this study starts from the year 1971 and ends in 2000 with 10-day interval.

3. RESULTS

In this section, the temporal and spatial changes of PE in the YRB are to be examined. The PE changes, especially after the late of 1980's, the seasonal differences of PE changes will be discussed in detail.

(1) General decreasing trend of PE with increase starting from the late of 1980's

In the past studies in Russia and the US, the general trend of PE changes has been reported as decreasing by a variety of researchers [6,7,8].

The PE time series from 1971 to 2000 of the 4 climate regions and the whole YRB are illustrated in Fig. 2. Differing from past studies, we found in this study, as illustrated in Fig. 2 that, besides the general decreasing trends in the past 3 decades, the PE in all the sub regions have a significant increasing trend approximately starting from 1987.

(2) Spatial changes of PE concerning seasonal difference

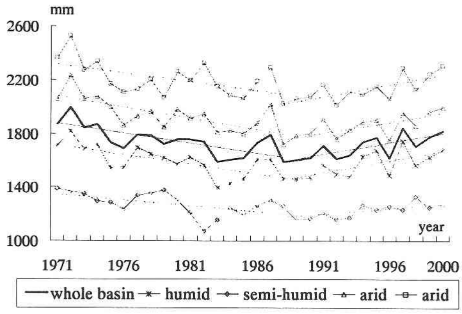

Fig. 2 Changes of PE (1971~2000) by climate area in the YRB.

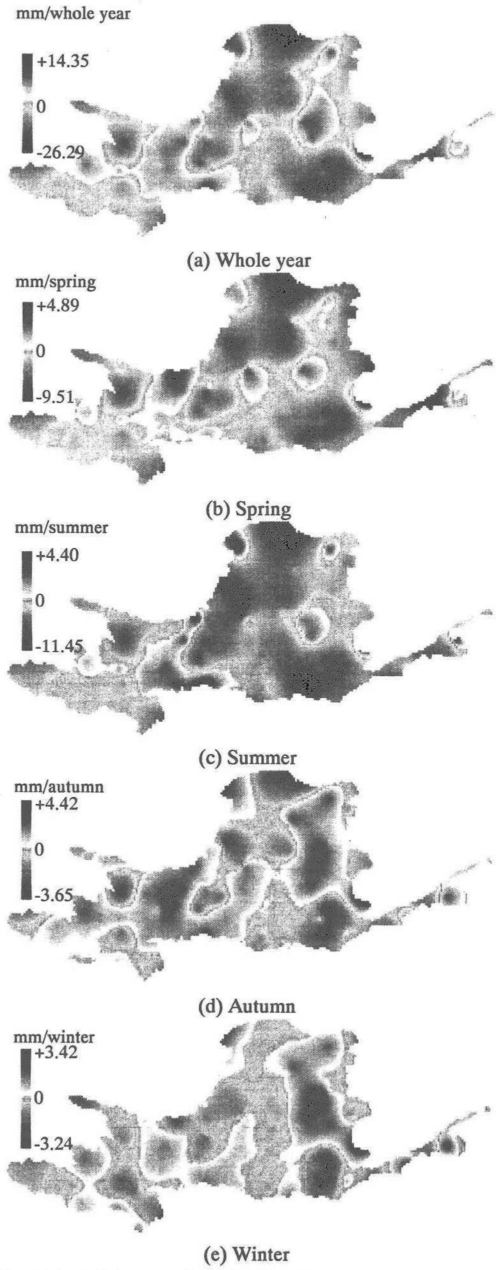

Fig. 3 Spatial change of PE (1971~2000) by year and season.

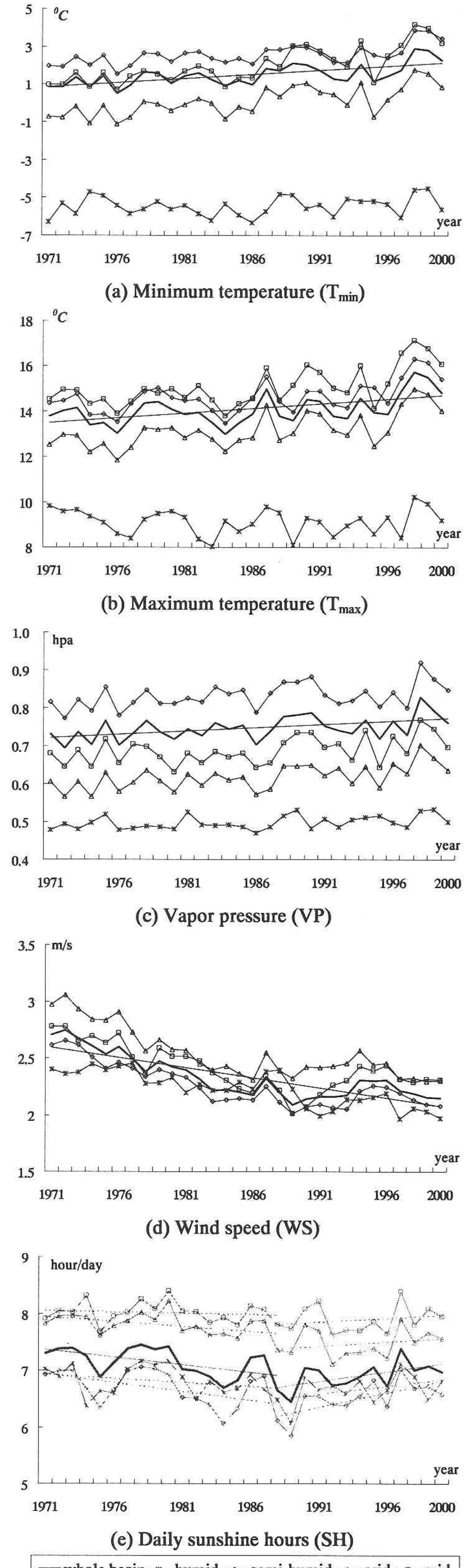

Fig. 4 Changes of climate variables (1971~2000) in the YRB.

In order to reflect the spatial characteristics of PE, the station PE records were processed by the following steps. Firstly, the mean changes of PE of each station from 1971 to 2000 by whole year and by season were computed. Each season has 3 months and the spring starts from March 1st. Secondly, the PE changes were spatially interpolated into 0.1-degree grids by Kriging method[12] in geographic information system (GIS). Lastly, clipping the outside part of the YRB and calculating the statistical values of each climate region. The result of spatial changes of PE is illustrated in Fig. 3.

In most parts of the YRB, PE experienced decrease in the past 30 years, except for the upper and middle streams of Fenhe sub-basin, and the cross boundary areas among Qinghai, Gansu and Sichuan provinces, from the view point of PE inter-annual changes as displayed in Fig. 3 (a). The PE changes ranged roughly from -26 mm to +14 mm spatially, and the mean PE of the whole YRB decreased in the pace of 4 mm per year.

The spatial characteristics of PE changes between the first half and second half of year and among the 4 seasons are quite different. As illustrated in Fig. 3 (b)~(e), the PE in spring and summer decreased in most parts of the YRB. However, the PE of autumn and winter in major parts of the YRB have very obvious increase, especially in the Fenhe River basin, the shangdong part of the downstream of the YRB, and the intersecting part of Qinghai, Ningxia and Sichuan Province. In spring, the PE of approximately 72% part of the YRB increased. In autumn, the PE increased for 57% of the YRB area.

Since the magnitudes of PE changes in autumn and winter, ranging roughly -11~4 mm, and -4~4 mm, are smaller than that of the spring and summer, i.e., -8~5mm, and -20~14mm, the PE changes of the whole year have a decreasing trend.

4. DISCUSSION

In this section, the PE increase starting from the late of 1980's, the seasonal characteristics, and the connection between PE changes and climate variables are to be discussed respectively.

(1) PE increase starting from the late of 1980's

There exists an increasing trend from the late of 80's in the last century. In the past PE studies, the PE in Russia and the U.S.[6,7,8], the general decreasing trend has been found and explained as the decrease of both irradiance and diurnal temperature range (DTR). The PE in the YRB from 1971 to 2000 was reported as increase in the past study[11].

However, based on the result of this study, there exists an increasing trend according to the PE records covering the YRB, which has seldomly been reported. The PE changes starting from the late of 1980's were unlikely to be caused by systematic errors, because the dataset presented in this study only the data of the evaporimeters with dimension of 20-cm diameter were used, and the data quality has been carefully checked[10].

(2) Seasonal characteristics of PE changes

In the spring and summer, PE in the YRB decreased in most areas. However, in the autumn and winter, major parts experienced PE increase, instead of decrease. The seasonal characteristics are important in some fields like agriculture, especially for irrigation scheme design. The PE decrease in the spring and summer, the growing season for most plants, means the water cycle weakened, which consequently will influence crop water requirement and irrigation water requirement.

An exception area of the above principle is located in the Fenhe River basin, where is a highly populated agriculture area. The PE from 1971 to 2000 in all seasons has a very stable increase trend. According to the field study[13], the Fenhe River basin has been almost complete drying-up in the whole year from the start of the 1980's. The major water supply sources were groundwater for a long time period. From 2004 partially water was transferred from the main stream of the Yellow River. The PE increase over this area agrees very well to the severe water shortage in the basin.

(3) Connection between PE and climate variables

The temporal changes of T_{min}, T_{max}, VP, WS and SH of the 4 climate regions are displayed in Fig. 4.

In order to check the contribution order of different climate variables to PE changes, linear step-wise multivariate regressions were performed with annual mean PE as dependent variable and T_{min}, T_{max}, VP, WS and SH as independent variables in the 4 climate areas. Probability of F to enter or selected was set less than or equal to 0.05. The linear step-wise multivariate analysis selects (or enters) the variables playing a significant part in influencing PE. On the contrary, if an independent variable is not significant correlated to PE, it is removed.

The correlation coefficient (R) and adjusted R square (R^2) are listed out in Table 1. The relationships between each climate variable and PE change was analyzed respectively as follows:

T_{max} or T_{min}, which are highly correlated, was selected as the most significant variable for humid, semi-humid and semi-arid areas. However, from Fig. 4 (a) and Fig. 4 (b), both T_{max} and T_{min} were increasing, which should have accelerated the water evaporation process. The increase of T_{max} and T_{min} played the most significant negative effect on PE decrease. In humid areas T_{min} was removed, which indicated Tmin was highly correlated to T_{max}.

SH was the second significant variable for PE decrease. The general trend of SH was decreasing from 1971 to 2000 according to Fig. 4 (e), which implied SH decrease played the most positive effect on PE decrease. There are a variety of reasons for the decreasing of sunshine hour decrease. With the global warming process, the density of aerosol increased and it will cause more cloudiness[14,15].

WS was the third significant variable for humid, semi-humid and semi-arid areas, and the most significant variable in arid area for PE decrease. WS decrease also played a positive role in PE decrease.

VP increase, as illustrated in Fig. 4 (c), would have caused PE decrease. However, it was insignificant compared to SH decrease and wind speed decrease.

The PE increased from the late of 1980's. By considering the SH increase started almost simultaneously to PE increase, as illustrated in Fig. 4 (e), the PE increase from the late of 1980's can be explained mainly by increase of sunshine hours.

In general, the sunshine hours can be regarded as the most significant driving factor because it decides other climate variables like temperature and humidity directly. At the mean time, wind speed is influenced both by global scale circulation and regional or local environment conditions. Increasing CO_2 concentration may also contribute to the temperature increase by absolving more long-wave radiation from the earth surface[16]. Therefore, the above variables have very complicated interactive mechanisms and some of them are highly correlated. In addition to the stepwise multivariate regression analysis in this paper, further study to understand the detailed mechanisms of PE change is required.

In summary, the decrease of SH played the most important role in PE decrease from 1971 to 2000. WS decrease was another important factor that has caused PE decrease. In addition, PE increase started from the late of 1980's was caused by SH increase at the same period.

(4) Possible impacts and implications of PE

The downward trend of PE in most of the YRB implies that the evaporation component of the hydrological cycle has been decreasing. Dramatic hydrological process may cause flood and drought.

Table 1 Step-wise multivariate regression between PE and climate variables.

Area	Climate Variables				
Humid	T_{max}	SH	WS	VP	T_{min}
R	0.422	0.531	0.566	0.603	removed
Adjusted R^2	0.172	0.271	0.304	0.344	
Semi-humid	T_{max}	SH	WS,	VP	T_{min}
R	0.473	0.712	0.760	0.820	0.821
Adjusted R^2	0.224	0.505	0.576	0.671	0.673
Semi-arid	T_{min}	SH	WS	T_{max}	VP
R	0.595	0.795	0.853	0.877	0.878
Adjusted R^2	0.353	0.631	0.726	0.766	0.768
Arid	WS	SH	VP	T_{max}	T_{min}
R	0.479	0.566	0.612	0.805	0.813
Adjusted R^2	0.227	0.316	0.319	0.644	0.656

PE changes will influence the volume, spatial distribution and temporal characteristics of surface runoff, river runoff and available water resources. At the other hand, there exists significant regional difference in PE changes. Some areas, like major parts of Fenhe River basin, experienced PE increase in all the season from 1971 to 2000. The heterogeneous pattern of PE at regional scale requires cautious consideration in the fields like irrigation water requirement estimation.

One of the most significant impacts of PE changes to agriculture is that the PE decreased in growing season in most areas of the YRB except the Fenhe River basin. Combined with the change of precipitation, the water requirement for irrigation is also likely to change. For example, the Fenhe River basin, hit by the continuous increase in PE in addition to the decrease in precipitation for the past 3 decades[17], has experienced severe water shortage.

5. CONCLUSIONS

(1) There was an increasing trend for PE starting from the late of 1980's

The general trend of PE in the YRB is decreasing. However, based on the result of this study, we find there exists an increasing trend starting from the late of 1980's, which has seldom been reported.

(2) The PE decreased in most areas of the YRB in spring and summer, but major parts increased in autumn and winter

The PE changes of the whole year is in agreement to the global PE change trends[6,7,8]. However, for PE changes, magnificent differences exist among seasons.

(3) Sunshine hours decrease and wind speed decrease were the major causes for PE decrease

The Step-wise multivariate regression implemented in this study shows that sunshine hours decrease and wind speed decrease are the 2 major causes for the PE decrease from 1971 to 2000. The sunshine hours increase from the late of the 1980's is the major reason for PE increase.

(4) There exist areas, like the Fenhe River basin, where PE increased in all the seasons

The spatial change of PE shows great spatial heterogeneity. While most areas in the YRB decrease in spring and summer, some areas like the Fenhe River basin experienced PE increase in all the season. It implies that the local climate may not be synchronous to the whole basin and implication of PE should be checked very cautiously. Taking the precipitation decrease trend in the coming future into consideration, the Fenhe River basin may have to face more severe water resources shortage problems.

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黄河流域におけるパン蒸発量の変化（1971～2000）について

方　偉華・井村　秀文

蒸発は，地圏の物質とエネルギー循環の重要なプロセスである．黄河流域は，過去数十年来，深刻な水不足に悩んできた．パン蒸発（PE）の空間的・時間的な特徴は，黄河流域において水循環と水資源を解析するのに重要である．本研究では，1971年から2000年の黄河流域におけるPEの空間的・時間的変化を詳細に検証することを目的としている．

以下に，本研究で得られた知見をまとめる．(1)　世界的なPEの変化は減少傾向にあるが，逆に，黄河流域では1980年代後半からPEが増加傾向にある．(2)　黄河流域の多くの地域では，PEは春と夏に減少し，秋と冬に増加する．しかし，フン河流域のように，PEが全季節で増加する地域も存在する．(3)　主な傾向として，1971年から2000年の間で，日射時間と風速の減少によりPEが減少した．また，日射時間の増加が1980年代後半からのPEの増加につながった．