Changes of Evapotranspiration and Water Cycle in China during the Past Decades

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UNIVERSITY OF GOTHENBURG
GOTHENBURG, SWEDEN 2010

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ISBN 978-91-628-8014-9
ISSN 1400-3813 A132
Internet-id : http://hdl.handle.net/2077/21737

Printed by Chalmers Reproservice
Gothenburg, Sweden 2010

Abstract

Evapotranspiration is the second largest quantity in the water cycle and an important indicator for climate changes. Accurate estimations and better understanding of evapotranspiration are required in hydrologic studies and water resources modelling under stationary and changing climate conditions. Under the background of global warming and climate change over the last 50 years in China, what was the change in evapotranspiration? How the change has impacted on the water cycle? To address these questions effectively, this thesis focuses on the study of potential evapotranspiration and actual evapotranspiration over China.

This study begins with a comparison between the estimates for potential evapotranspiration using the Penman-Monteith and the Thornthwaite methods as well as the pan data. The Penman-Monteith method is considered as the most physical and reliable method, while the Thornthwaite method is the most practical and widely used method. The comparison focuses on the usefulness of the Thornthwaite estimates, which can guide the use of this simple method in China. In the second stage of the study, the seasonal and annual potential evapotranspiration estimated by the Penman-Monteith method for China as a whole and for the major basins are investigated. Then, the modified Thornthwaite water balance model is used to examine the regional and country scale changing properties of actual evapotranspiration over China during 1960-2002. Finally, a detailed investigation of the regional actual evapotranspiration estimated by using the Thornthwaite water balance method and the two complementary relationship methods (advection aridity (AA) model and Granger and Gray (GG) model) is performed in the Haihe River basin in northern China.

The results show that the Thornthwaite estimates result in different regional patterns and temporal trends, while the pan measurements display a consistent regional pattern and similar trends as compared with that of Penman-Monteith estimates. Overall, the pan measurements are more useful than the Thornthwaite estimates if appropriate pan coefficients are determined. The declining trends in potential evapotranspiration in most part of China during 1956-2000 are detected except for the Songhua River basin in Northeastern China where an insignificant increasing trend is found. Generally, declining trends of sunshine duration and/or wind speed at the same period appear to be the major causes for the negative trend of the potential evapotranspiration in most areas. The annual actual evapotranspiration had a decreasing trend during 1960-2002 in most areas east of 100ºE and there was an increasing trend in the west and the north parts of Northeast China. In the humid southeast part of China, the spatial distribution of the temporal trend for the actual evapotranspiration is similar to and dominated by that of the potential evapotranspiration. But in the arid northwest region, the trend in precipitation controlled the long-term changes of the annual actual evapotranspiration. In the other regions, the combined effects of the changes in precipitation and potential evapotranspiration played a key role.

Keywords: Potential evapotranspiration, Actual evapotranspiration, Spatial and temporal characteristic, Trend, Controlling factors, Water cycle, Thornthwaite water balance, China

Preface

This thesis consists of a summary of research reported in four appended publications:

Paper I:
Chen, D., **G. Gao**, C.-Y. Xu, J. Guo, and G.-Y. Ren (2005), Comparison of the Thornthwaite method and pan data with the standard Penman-Monteith estimates of reference evapotranspiration in China, Climate Research, 28, 123-132

Gao was responsible for the data collection, statistical analysis and calculation, figure plotting and related writing process in the paper.

Paper II:
Gao, G., D. Chen, G.-Y. Ren, Y. Chen, and Y.-M. Liao (2006), Spatial and temporal variations and controlling factors of potential evapotranspiration in China: 1956-2000, Journal of Geographical Sciences, 16(1), 3-12

Gao planned and wrote the first version of the article. She also carried out data collection, statistical analysis and calculation, figure plotting and interpretation.

Paper III:
Gao, G., D. Chen, C.-Y. Xu, and E. Simelton (2007), Trend of estimated actual evapotranspiration over China during 1960-2002, Journal of Geophysical Research, 112, D11120, doi:10.1029/2006JD008010

Gao designed and wrote the first version of the article. She also carried out data analysis, modified and ran the Thornthwaite water balance models and plotted figures.

Paper IV:
Gao, G., C.-Y. Xu, D. Chen, and V. P. Singh (2009), Spatial and temporal characteristics of actual evapotranspiration over Haihe River basin in China estimated by the complementary relationship and Thornthwaite water balance models, Submitted to Water Resources Management

Gao planned and wrote the first version of the article. She also carried out data analysis, ran the models and produced figures.

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Scientific publications which are not included in this thesis:

Chen, Yu, **G. Gao**, G.-Y. Ren, and Y.-M. Liao (2005), Spatial and temporal variation of precipitation over ten major basins in China between 1956 and 2000, Journal of Natural Resources, 20(5), 637-643 (in Chinese with English abstract)

Gao, G., L. B. Gong, and S.S. Zhao (2007), Spatial interpolation method of daily precipitation, Journal of Applied Meteorological Science, 18(5), 732-735 (in Chinese with English abstract)

Gao, G. (2008), The climatic characteristics and change of haze days over China during 1961-2005, Acta Geographica Sinica, 63(7), 761-768 (in Chinese with English abstract)

Gao, G., D. Chen, and Y. Xu (2008), Impact of climate change on runoff in the Huaihe River basins. Journal of Applied Meteorological Science,19(6), 741-748 (in Chinese with English abstract)

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I Summary

1 Introduction

1.1 Relationship between water cycle and climate change

According to the fourth Assessment Report (AR4) by Intergovernmental Panel on Climate Change temperatures at the surface have risen globally and with important regional variations during 1850 to 2006 by instrumental observations. For the global average, two phases warming in the last century occurred from the 1910s to the 1940s and from the 1970s to 2006 (Trenberth et al., 2007). In the latest phase, the increment of temperate is 0.55℃ and stronger than that of the first phase. Apart from the temperature, many evidences such as increasing of sea level, recessing of the glaciers and widespread melting of perpetual snow show the indubitable warming in climate system. Even though a great uncertainty about the magnitude of future increases, most assessments indicate that climate would go on warming in the future. Climate warming and its impacts which are essential to our life currently and in the future are concerned by more and more people than ever before.

In the complicated climate system, water cycle, also known as hydrological cycle, is one of the important subsystems which describes the constant movement of water above, on, and below the Earth's surface. The cycle operates across all scales, from the global to the river catchment and connects the movement of water along evapotranspiration, precipitation, surface runoff, subsurface flow and groundwater. The change of water cycle not only means climate change but also deeply impacts on the human activities and life, such as agriculture production, water resource utilization, meteorological disasters and extreme climate events which seriously threat to survival of people and society development.

Due to the importance of water cycle, and dominant water and environment problem occurred in many places in the world, the change of water cycle under the background of global warming and its feedback to the climate as well as its impact on the society and eco-environment obtained a wide attention. During the past decades, many important international science research programmes covering various scientific questions relating water cycle and its interaction with atmosphere and biosphere have been consecutively carried out by many international organizations, such as *International Hydrological Programme* (IHP) built in 1975 by the United Nations Educational, Scientific and Cultural Organization (UNESCO), *World Climate Research Programme* (WCRP）established in 1980 by the International Council for Science (ICSU) , the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO, a core project of WCRR—*Global Energy and Water Cycle Experiment* (GEWEX) in 1988, and the *International Geosphere-Biosphere Programme* (IGBP) started in 1987 by ICSU as well as a core project *Biospheric Aspects of the Hydrological Cycle* (BAHC) launched in 1991. Achievements have been obtained in the fields of database building, simulations to atmospheric and land surface processes, as well as interaction between

atmosphere and land surface and so on. Which have promoted the understanding to the structure features of water cycle system and roles of water cycle process (Lu and He, 2006). One of the goals by GEWEX is to provide an order of magnitude improvement in the ability to model global precipitation and evapotranspiration.

1.2 Importance of evapotranspiration

Evapotranspiration is the second largest quantity in the water cycle. Its change would affect the whole water cycle. Latent heat is the energy consumption by the surface evapotranspiration. In surface energy balance, net radiation obtained by land surface are balanced by the sensible heat and latent heat exchanges with atmosphere. As the only connecting term between water balance and energy balance and because of complex interactions in the land-plant-atmosphere system, evapotranspiration is perhaps the most difficult and complicated component of the water cycle (Xu and Singh, 2005) and also a very important indicator for climate changes (Peterson et al., 1995; Brutsaert and Parlange, 1998).

In surface water balance, approximately 60-80% of the precipitation on the earth's surface return back into the atmosphere, where it becomes the source of future precipitation (Tateishi and Ahn,1996). The lost water by evapotranspiration will affect the water yield of a region and available water resources. The water management based on evapotranspiration in river basins has become a developing trend in arid and semi-arid areas (e.g. Qin et al., 2009). Comparing with traditional management based on the balance between water supply and demand, the water consumption based management is more efficient in utilization of water resource through reducing evapotranspiration to obtain the destination of reducing overall regional water consumption.

Evapotranspiration has been widely used in guiding agricultural irrigation schedule through the quantitative estimation to the crop water requirement achieving the aims of water saving and agricultural yield increasing (Doorenbos and Pruitt, 1977; Dingman, 2002). Evapotranspiration is also essential for understanding land surface processes in climatology (Chen et al., 2005a). The dry and wet condition analysis of climate based on evapotranspiration is connected with the type of ecosystem which has a sensitive response to climate change. For example, Zhou et al. (2002) estimated the development of desertification in China based on the evapotranspiration.

1.3 Definitions and estimations of evapotranspiration

Evapotranspiration is a collective term for all the processes by which water in the liquid or solid phase at or near the earth's land surfaces becomes atmospheric water vapor (Dingman, 2002). It combines evaporation and transpiration. Evaporation is the water movement from surfaces such as open water, bare soil and vegetation. Transpiration is the water evaporation from within the plant and the subsequent loss

of water as vapor through stomata in its leaves.

Pan evaporation is the evaporation measured daily as the depth of water evaporates from the pan which can be converted to free water evaporation by multiplying a coefficient. Free water evaporation is used for the amount of evaporation from open or free water surface. Reference crop evapotranspiration, reference evapotranspiration, or potential evapotranspiration is the evapotranspiration rate from a reference surface without the limitation of water supply. Actual evapotranspiration or terrestrial evapotranspiration describes all the processes by which liquid water at or near the land surface becomes atmospheric water vapor under natural condition. Comparing to the pan evaporation, free water evaporation and potential evapotranspiration, the actual or terrestrial evapotranspiration is also affected by water availability and surface condition in addition to climate factors.

Accurate estimations and better understanding of evapotranspiration are required in hydrologic studies and water resources modeling under stationary and changing climate conditions. In hydrological models, either pan evaporation or free water evaporation or potential evapotranspiration is usually used as one of the inputs, while actual evapotranspiration is one of the outputs.

Many methods are used to estimate potential evapotranspiration. According to the data requirements, the methods are usually classified into temperature based methods, radiation based methods, mass-transfer equations, combination methods and pan measurement method (Dingman, 2002; Singh and Xu, 1997; Xu and Singh, 2000, 2001). Most methods are empirical derived based on the statistical analysis of the field observation of climate factors except the combination methods. Penman-Monteith method based on sound physical principle is a representation of the combination methods. It is usually considered as a standard method for comparison between the other methods.

About actual evapotranspiration, Rana and Katerji (2000) summarize ten methods for its measuring and estimating. Depending on the purpose, the methods can be divided into hydrological, micrometeorological, and plant physiological. All these methods have their advantages and disadvantages. For example, a weighing lysimeter can provide detailed information about the water balance, however, it is practically and economically impossible to measure evapotranspiration over widespread areas for a considerable long time period (Xu and Chen, 2005). Penman-Monteith method (Allen et al., 1998), considering aerodynamic resistance and surface resistance has been successfully used to calculate actual evapotranspiration from different land covers. But aerodynamic resistance and surface resistance data are not readily available in practical use. The method, where the water consumption of crop is estimated as a fraction of the reference evapotranspiration, depends on the accuracy of the reference chosen, reference evapotranspiration estimation and crop coefficient (Rana and Katerji, 2000). Hydrological models estimate the actual evapotranspiration on basin scale using meteorological and hydrological data as inputs. However, lumped models cannot provide detailed spatial variation patterns and distributed models require the input data may not easily available. Therefore, actual evapotranspiration is usually estimated through less complex physically-based or empirical approaches and

available input data, such as long-term water balance, a fraction of potential evapotranspiration estimates, hydrological water balance models using soil moisture functions, complementary approaches and so on. Some of these methods are introduced in the method section of the thesis.

1.4 Achievements in the study of the changes of pan evaporation or potential evapotranspiration

Under the climate warming background, there is an expectation that evapotranspiration and precipitation will increase. The theoretical basis is the Clausius-Clapyeron relation which implies that specific humidity would increase approximately exponentially with temperature (Huntington, 2006). This expectation is over emphasized the increasing air temperature and assumes that everything else is held constants (Roderick and Farquhar, 2004). Obviously differences are found between the expectation and the evidence of pan observation in most places, which is named evaporation paradox.

Many studies have shown that pan evaporation and potential evapotranspiration had decreased over the past decades in many places of the world (e.g. Peterson et al., 1995; Chattopadhyay and Hulme, 1997; Brutsaert and Parlange, 1998; Lawrimore and Perterson, 2000; Thomas, 2000; Golubev et al., 2001; Roderick and Farquhar, 2002, 2004, 2005; Moonen et al., 2002; Liu et al., 2004a; Tebakari et al., 2005; Xu et al., 2006a,b; Fu et al., 2009). The decreasing trend is general but not universal (Roderick and Farquhar, 2002).

The changes of pan evaporation and potential evapotranspiration will offer a useful clue to the change direction of actual evapotranspiration (Ohmura and Wild, 2002). Because of no limitation by water supply, the explanation to the trends of pan evaporation and potential evapotranspiration mainly focuses on the climate factors relating to the three major controlling factors, such as energy availability, the wind speed above the surface, and the humidity gradient away from the surface. Which climate factors caused the changing trends of pan evaporation or potential evapotranspiration depend on the places and the seasons.

Based on the relationships between climate elements and pan evaporation / potential evapotranspiration the major climate controlling factors are selected and their changes during the past decades are then combined to explain the trend. Peterson et al. (1995) first used the decreasing in diurnal temperature range (DTR) to explain the downward trend of pan evaporation over the most parts of United States and former Soviet Union by the comparison of various climatic parameters and their trends during the past decades, including mean minimum temperature, mean maximum temperature, diurnal temperature range, total cloud cover and precipitation. Roderick and Farquhar (2002) concluded that the observed decrease in pan evaporation is not a paradox considering the observed large and widespread decreases in solar irradiance resulting from increasing cloud coverage and aerosol concentration, and the associated changes in DTR and vapor pressure deficit those have been

observed. Ohmura and Wild (2002) pointed that the direction of the evaporation changing trend is not determined by temperature alone.

To explain the changes of pan observation in China, Liu et al. (2004a) believed the decrease in solar irradiance, attributed to increased concentrations of aerosols, was the most likely driving force for the reduced pan evaporation. However, in the other parts of the world, such as North America, declines in solar irradiance are associated with increasing cloud and precipitation (Liu et al. 2004a). In addition to the solar irradiance, the other climate factors such as DTR, wind speed and sunshine duration are also considered as the major controlling factors for the change of pan evaporation during the past decades in China (Liu et al., 2004a; Liu, 2005; Ren and Guo, 2006; Sheng, 2006; Zeng et al., 2007) and some regions such as Yangtze River basin(Xu et al., 2006a,b), Yellow River(Qiu et al.,2003), Huaihe River and Haihe River basins (Guo and Ren, 2005)

Estimations to potential evapotranspiration by Penman-Monteith method are commonly used to analyze the change of potential evapotranspiration during the past decades. Which climate factors used in the method are more important to the decreasing trend in potential evapotranspiration? Thomas (2000) analyzed the potential evapotranspiration by Penman-Monteith method based on 65 stations in China during 1954 and 1993. He found that northeast and southwest China have experienced a moderate evapotranspiration increase, while northwest and southeast China associated with a decreasing trend. Different areas have different climate controlling factors. South of 35º 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. Gong et al. (2006) found relative humidity was the most sensitive variable, followed by shortwave radiation, air temperature and wind speed in Yangtze River basin based on a quantitative analysis to the non-dimensional relative sensitivity coefficients of the four major meteorological variables in the Penman-Monteith formula. The sensitivity method provides a theoretical basis for future research on the response of potential evapotranspiration to climatic change. Paper I and Paper II in the thesis analyzed the changes of potential evapotranspiration and its causes at ten major river basins in China.

1.5 Achievements in the study of the changes of actual evapotranspiration

Compared to the studies of changes of pan evaporation and potential evapotranspiration, fewer studies are carried out on actual evapotranspiration because of the following reasons. (1) There is a lack of widespread and long-term observations. The validation of estimations of actual evapotranspiration is difficult. (2) The controlling factors and their interactions are more complicate requiring to consider the water supply condition, vegetation and soil characteristics, as well as climate factors. Climate change has the potential to affect all of these factors in a combined way (Arnell and Liu, 2001). As a consequence, the earlier methods are usually simple and

are based on the analysis of the limited observations in some locations. Nowadays, a good number of methods are introduced in the literature for the estimation of actual evapotranspiration at various temporal and spatial scales.

Initially, increasing actual evapotranspiration are deduced qualitatively using energy balance principle from the explanation to decreasing pan evaporation holding the perspective of complementary relationship rather then proportional behavior (Brutsaert and Parlange,1998). Increasing terrestrial evapotranspiration may produce more moisture air over the pan and limit the evaporation of the pan. Increasing terrestrial evapotranspiration could give a reasonable explanation and consistent with the conclusion of intensifying hydrological cycle (Huntington, 2006). The concept of complementary relationship introduced by Bouchet in 1963 and different models have been built (e.g. Brutsaert and Stricker, 1979; Granger and Gray, 1989; Morton, 1978, 1983). These models consider the evaporative system as an integrated one including feedbacks in land-surface-atmosphere dynamics and bypass the poorly understood dynamics within each component, and incur minimal data requirements as to the nature of the land surface (Hobbins et al., 2001a). Although these models are derived using the complementary relationship concept, the assumptions and derived model forms are different. Hobbins et al. (2001a) analyzed the trends of actual evapotranspiration over the conterminous United States by one of the complementary relationship models, the Advection-Aridity model (Brutsaert and Stricker, 1979). Besides the above cited references, there are a number of studies on evaluating the validity of the complementary relationship models (e.g., Doyle, 1990; Lemeur and Zhang, 1990; Chiew and Mcmahon, 1991; Granger and Gray, 1990; Hobbins et al, 2001b,c; Xu and Li, 2003; Xu and Chen, 2005; Xu and Singh, 2005).

Another common way to estimate regional actual evapotranspiration is based on the Penman hypothesis that the actual evapotranspiration is proportional to the potential evapotranspiration (Penman, 1948). The discrepancy between the Penman and Bouchet hypotheses is usually highlighted in non-humid regions (Yang et al., 2006). Different change patterns of actual evapotranspiration could be obtained by these two kinds of methods especially in arid regions. This controversy could be reconciled based on Budyko hypothesis considering different mechanism in different climate environments (Milly and Dunne, 2001; Roderick and Farquhar, 2004; Yang et al., 2006).

Golubev (2001) reveals the climatic zones where the change in actual evapotranspiration and pan evaporation are parallel and where they are negatively correlated based on observation of actual evapotranspiration by large weighing lysimeters and pan evaporation. The conclusion indicates that collinear trends occur only in areas with $R<0.7$ (R ratio of potential evapotranspiration to precipitation), while for regions with $R\geq0.8$ an inverse relationship exists. Roderick and Farquhar (2004) give a qualitative and relatively systemic explanation of the change of actual evapotranspiration based on the principle of moisture balance at the terrestrial surface, which can be described as a balance between the atmospheric supply (rainfall) and atmospheric demand (potential evapotranspiration) (Budyko, 1948, 1974; Penman, 1948). In dry environment, actual evapotranspiration is less than potential

evapotranspiration because the supply of water is limiting, the changes in actual evapotranspiration are dominated by changes in rainfall. Conversely, in a wet environment, limited by the energy supply, the change of potential evapotranspiration or pan evaporation will determine the change of actual evapotranspiration. Based on the similar method, Linacre (2004) used the soil moisture to explain the function of water supply instead of rainfall. Using the Budyko hypothesis, Yang et al. (2006) analyzed the actual evapotranspiration variability in non-humid region and Ni et al. (2007) quantitatively assessed the trends of actual evapotranspiration in China during the last half century.

Actual evapotranspiration can also be estimated using water balance approach. Synthetically considering the balance relations among water fluxes for the Mississippi River basin, Milly and Dunne (2001) related an upward trend in actual evapotranspiration and decreasing temperature during 1949 and 1997 primarily to increased precipitation and secondly to increased human water use. The continuing upward in precipitation would intensify the water cycle and suppress warming in the basin. Walter et al. (2004) found increasing rates of actual evapotranspiration throughout larger portions of the conterminous United States over the past 50 years by the method of watershed hydrological budget based on the direct measurements of annual precipitation and stream discharge. It further suggested that the hydrological cycle is accelerating over the conterminous United States.

Recently, hydrological models are also used to study the changes of actual evapotranspiration. Hamlet et al. (2007) analyzed the trends in runoff, evapotranspiration and soil moisture in the western United States during 1916 and 2003 by the Variable Infiltration Capacity (VIC) model. In the model, the actual evapotranspiration is estimated by the Penman-Monteith approach including detailed vegetation characteristics parameterization and transpiration process(Shuttleworth, 2003). The model simulations showed an overall increasing trend in warm season during both 1916-2003 and 1947 -2003 and increasing trends which followed the trends in precipitation.

From the above review, we can find that most studies to the changes of actual evapotranspiration are based on relatively simple approaches and the rationality of conclusions are usually indirectly evaluated from the evidences of other hydrological elements such as precipitation, stream discharge, soil moisture and so on because of the limited observations of actual evapotranspiration. Land surface processes models considering complicated physical processes and detailed information about surface vegetation and soil are seldom used in the studies because of the input difficulty. Qian et al. (2006a) drew a conclusion that global land evapotranspiration closely follows variations in land precipitation based on the inputs of observed precipitation, temperature, cloudiness-based surface solar radiation by the Community Land Model version 3.0 (CLM3) even though the evapotranspiration is systematically overestimated.

Generally speaking, quantitative estimations and detailed distribution about the change of actual evapotranspiration are required not only on regional scale but also on global scale which are important and help to improve the understanding of the

changes of water cycle and water resources closely relating to climate change in different spatial scales. Particularly in China and some key regions with higher climatic sensitivity and serious water problems, more attention needs to be paid on the changes of actual evapotranspiration and water cycle. Different methods based on various theoretical perspectives should be used for the aims of comparison which will add confidence in the lack of observations.

The hypothesis of a warm-induced intensification of the water cycle arising from a theoretical expectation that climate warming will result in increasing in evaporation and precipitation, has been confirmed through the evidence at regional to continental scales during part or all of the 20th century regarding historical trends in the variables, including precipitation, runoff, tropospheric water vapor, soil moisture, glacier mass balance, evaporation, evapotranspiration, and growing season length (Huntington, 2006). Some potential adverse aspects of intensified water cycle can threat the humankind directly and indirectly. The change of local water cycle is important to water resources utilization and security, but few studies have dealt with these issues in a systematic way for China.

1.6 Objectives and Contents

Currently, affected by the pressures of society development, water shortage and water environment security, water resources assessment is required in China for the effective water resources management and plan-making for future. Under the back ground of global warming and climate change in recent 50 years in China, some elements of water cycle which have sound observation such as precipitation and runoff have been analyzed in detail. Even though some studies have been done with the focus on the changes of pan or potential evapotranspiration in China, the analysis and comparison at regional scale such as major river basins is yet to be done and different controlling factors may be vary with regions under the general decreasing trend in potential evapotranspiration. The knowledge to the change of actual evapotranspiration is more important than potential evapotranspiration but rare studies have been carried out in China.

Through the thesis, I try to answer the following questions:

- What has happened in potential evapotranspiration and actual evapotranspiration during the past decades in China and its major river basins?
- Dose the Thornthwaite method which is widely used to estimate potential evapotranspiration and pan observation work well in the studies to the change of potential evapotranspiration?
- Whether the change of estimated actual evapotranspiration are consistent by different methods?

- What are the major controlling factors for the change of potential evapotranspiration and physical mechanism for the change of actual evapotranspiration during the past decades in China?
- How about the relationship between the changes of precipitation, potential evapotranspiration and actual evapotranspiration?
- How the changes in evapotranspiration has impacted on the change of water cycle in China?

As for the questions related to potential evapotranspiration, the answers are given in Paper I and Paper II. Paper I begins with the comparison of the potential evapotranspiration estimated by the Thornthwaite method and the pan data with the Penman-Monteith estimates which is considered as the most physical and reliable method; the usefulness of the Thornthwaite estimates is evaluated in depth. In Paper II, the seasonal and annual potential evapotranspiration estimated by Penman-Monteith for China as a whole and for the major river basins are investigated. Through a partial correlation analysis, the major controlling climate factors which affect the temporal change of the potential evapotranspiration are analyzed.

In Paper III and Paper IV, the answers are addressed concentrating on actual evapotranspiration and water cycle. The modified Thornthwaite water balance model is used to examine the regional and country scale changing properties of actual evapotranspiration and soil moisture over China during 1960-2002. The Thornthwaite water balance model is fairly simple and can indicate seasonal trends in rainfall, evapotranspiration, soil moisture, irrigation needs, and runoff (Tateishi and Ahn, 1996). In the estimation of the actual evapotranspiration using the Thornthwaite water balance approach, the climate factors and water available condition are synthetically and quantitatively combined, which are helpful in better understanding of the water cycle. To perform a detailed investigation in the Haihe River basin in northern China, another two methods based on the complementary relationship concept (i.e. advection aridity (AA) model and Granger and Gray (GG) model) are used in addition to the Thornthwaite water balance approach to estimate actual evapotranspiration. Based on the relationship between precipitation and actual evapotranspiration, the change of water cycle in China and the Haihe river basin are discussed combining with the evidence of the changes in stream discharge and soil moisture as well as extreme precipitation.

2 Study area and data

2.1 Study area

The study area covers the whole China. For the aims of water resources assessment and utilization, analysis on basin scale is also carried out, particularly in the Haihe River basin with serious water resource problem.

2.1.1 Climate and geographic background of China

China is located in southeast part of the Eurasia continent and border on the Pacific Ocean to the east. Affected by the geographic location and environment, cold and dry in winter and warm and wet in summer are the typical climate features of China which is formed from the monsoon. The feature of heat matching with more rain in same season is very beneficial to crop growth and agricultural production. In northwest China where it is far from the sea, the continental climate is significant with large annual and daily range in temperature and small precipitation. Simultaneously, climate in different areas of China are very diverse ranging from mountainous regions to valleys, plains and deserts.

Precipitation is the origin of the water resources and determines their distribution and amount. The normal annual precipitation in China generally increases from northwest to southeast. The 200 mm, 400 mm and 800 mm contour lines of annual precipitation roughly divided China into arid, semi-arid, semi-humid and humid climates from northwest to southeast. Areas where precipitation exceeds 400 mm are mainly affected by the summer monsoon and constitute major agricultural regions. Agriculture is interlaced with animal husbandry at the areas with 200 mm to 400 mm precipitation where the ecosystem is very sensitive to the climate change. In some areas, especially in the arid northwest China, the intra-annual variations of precipitation are greater than in the coastal area. Small amount of precipitation with large variation greatly threat the security of water utilization.

2.1.2 Ten major river basins in China

Besides national scale, the analysis is also carried out on basin scale which is import for basin water resource management and decision-making. The ten major river basins in China which were defined by the Ministry of Water Resources in China for national water resources assessment are used in regional analysis. The ten major river basins are Songhua River basin, Liaohe River basin, Haihe River basin, Yellow River basin, Huaihe River basin, Yangtze River basin, basin of rivers in Southeast (SE) China, Pearl River basin, basin of rivers in Southwest (SW) China and basin of rivers in Northwest (NW) China (Figure 1).

Chen et al. (2005b) analyzed the precipitation characteristics of the ten major river basins in China and showed that the precipitation are less with larger variability in river basins of northern China which lead to insufficient and unstable features of water resources but are abundant with small variability in river basins of southern China which bring about relatively sufficient and stable water resources.

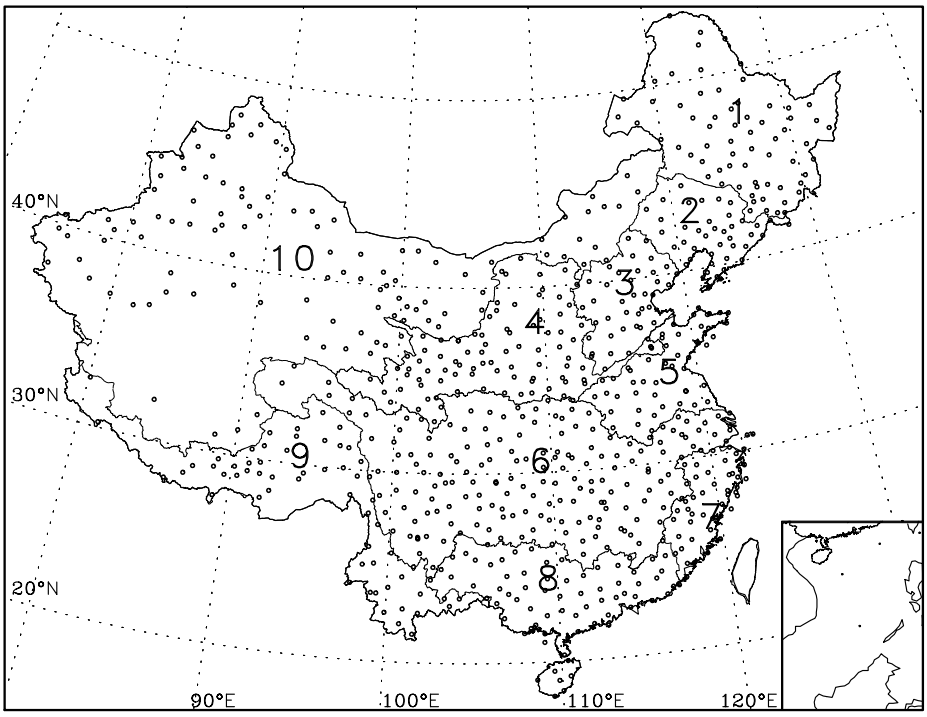


Figure 1 The ten major drainage basins and the distribution of 743 meteorological stations in China . The number denotes the ten drainage basins: 1=Songhua River, 2=Liaohe River, 3=Haihe River, 4=Yellow River, 5=Huaihe River, 6=Yangtze River, 7=Rivers in Southeast China, 8=Pearl River, 9=Rivers in Southwest China, 10=Rivers in Northwest China.

2.1.3 Haihe River basin

The Haihe River basin is located in the northern China surrounded by Bohai Sea in the east, Taihang Mountain in the west, Mongolia Plateau in the north and lower reaches of Yellow River in the South (see Figure 2). The topography decreases gradually from the plateau and mountainous in northern and western part to the plain region in the east part. The basin area is 31.8 $\times 10^4$ Km^2, which contains Beijing, Tianjin, parts of Hebei, Shanxi , Shandong, Henan and Liaoning provinces as well as a small part of Inner Mongolia, and occupies 3.3% of the total area of China. There are three major rivers in this basin, i.e. Haihe River, Luanhe River and Tuhaimajia River.

The basin lies in a transition region between humid climate and arid climate, which belongs to the temperate and east Asia monsoon climate zone. The annual precipitation is not very abundant with uneven spatial and temporal pattern. The normal annual precipitation varies from 371 mm to 742 mm. Affected by monsoon,

the precipitation mainly concentrates in summer as the form of rainstorm. In spring, drought occurred frequently as a result of less precipitation, rapidly increase of temperature, more windy days and larger evapotranspiration. Spring drought is a great threat to the production of winter wheat.

This area is not only a politic, economic and cultural center with higher density of population but also a food and economic crop production area in China. The conflict of water demand and supply is gradually increasing during the process of social developing and climate change.

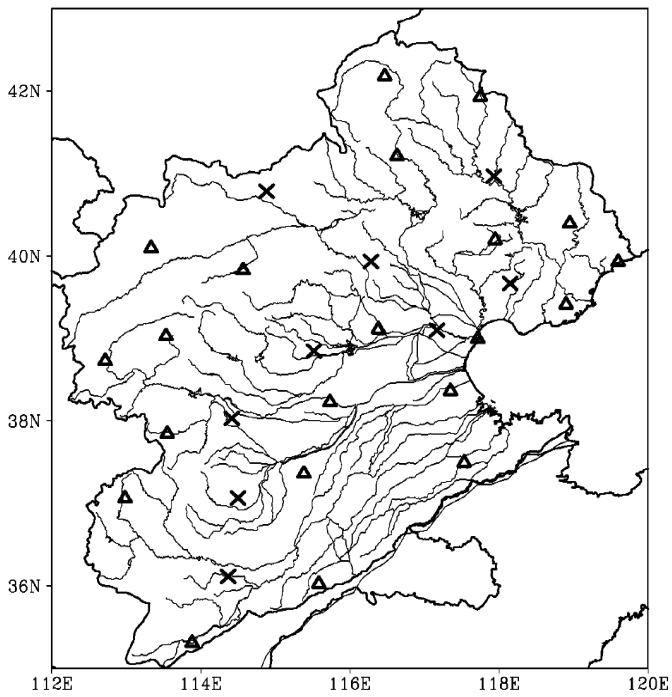


Figure 2 The Haihe River basin and distribution of meteorological stations ("Δ"). The symbols "×" denote the representative meteorological stations at nine selected sub-basins.

2.2 Data

The data used in this thesis include climate, soil parameters, and hydrology.

2.2.1 Climate data

2.2.1.1 Monthly data in China

The climate data from 1951 to 2002 at 743 stations in China are obtained from the National Meteorological Information Center of China Meteorological Administration. The distribution of stations is shown in Figure 1.

Monthly historical data including mean sunshine duration, mean maximum temperature, mean minimum temperature, mean relative humidity and mean wind

speed are used to calculate monthly potential evapotranspiration by Penman-Monteith method (see section 3.1.1). Monthly mean temperatures are used to estimate potential evapotranspiration by Thornthwaite method (see section 3.1.2). Monthly evaporations observed by evaporation pan with different diameters for different observation periods are also collected. In total 580 stations are selected to estimate potential evapotranspiration and compare the changing rates between Penman-Monteith, pan and Thornthwaite method during 1951 to 2000. Since part of the analysis will be made on the basis of ten major hydrological basins, each station is assigned to one of the ten basins. The lengths of time series of most stations are more than 40 years, with only 10% of stations are between 35 and 40 years for pan and 1% of stations for monthly mean temperature.

As for the estimation of actual evapotranspiration by the Thornthwaite water balance model (see section 3.2.3), the monthly precipitation, mean air temperature, potential evapotranspiration estimated by Penman-Monteith are used as input data. The longest time series are from 1951 to 2002. However, not all the stations have complete records and acceptable quality during 1951 and 2002. Only 686 stations are chosen to calculate the averaged water balance components including actual evapotranspiration for 1971-2000. For annual trend analysis, we use data from 1960 to 2002 and required that a station is used in the analysis only if it has data in the start and end of the period, that the total missing data in between is less than 5%, and that it does not have serious inhomogeneity problem. Only 546 stations meet the requirements and are used in this trend analysis. Missing data of the stations are replaced with long term means for the whole study period.

2.2.1.2 Daily data used in Haihe River basin

Daily mean air temperature, maximum and minimum air temperature, wind speed, sunshine duration, relative humidity and precipitation at 30 stations (Figure 2) over the Haihe River basin are used to estimate actual evapotranspiration by the methods based on complementary relationship concept (see section 3.2.4) during 1960-2002. During the study period the percentages of missing daily data for different elements vary from 0.01% to 0.02% except for sunshine duration which is 0.3%. The data are checked for two kinds of potential errors, i.e., outliers and consistency. The outliers are checked by using the threshold value method, and the consistency is checked by using double mass method for annual values (Dingman, 2002). In the above checks, no remarkable errors are found.

2.2.2 Soil parameters

In the Thornthwaite water balance model (see section 3.2.3), soil parameters such as soil water holding capacity and wilting point are required. To our knowledge, these two soil parameters are observed at few and scattered agro-meteorological stations in China. Thus, the two soil parameters from the IGBP-DIS Global Gridded Surfaces of Selected Soil Characteristics database (Global Soil Data Task Group, 2000) are used, although there are several limitations in using this kind of inferred and coarse spatial

resolution data (Tempel et al., 1996; Bajtes, 2002a, b). Originally this data set was derived from the soil physical attributes in the 1995 digital 1: 5 million scale FAO Soil Map of the World and the Global Pedon Database (Tempel et al., 1996; Global Soil Data Task Group, 2000; Batjes, 2002b). Each station's value is extracted from the 5×5 arc-minutes gridded soil parameters for the 0 - 1m topsoil layer in ArcMap. The two soil parameters are assumed static, hence land use changes and their impact on soil physical characteristics and indirectly on evapotranspiration are not considered.

2.2.3 Hydrological data

Long-term averaged annul runoff and basin average precipitation data during 1956-1984 at nine sub-basins of the Haihe River basin are collected from the report of Water Resource Assessment of North China by the Ministry of Water Resources in China. The nine sub-basins distribute evenly from south to north and their representative meteorological stations are shown in Figure 2 marked by symbol "×". These data are used to calculate the long-term averaged annual evapotranspiration for the basin by the long-term water balance equation as 'measured' values (see section 3.2.1) and a reference to select the most suitable evaporation equations in section 3.2.2.

3 Methods

3.1 Estimation of potential evapotranspiration

In this thesis, three methods are chosen to calculate potential evapotranspiration and to compare the spatial and temporal change of potential evapotranspiration. The methods are Penman-Monteith method, Thornthwaite method and pan measurement which represent combination method, temperature based method and pan observation, respectively. Because of sound physical basis, Penman-Monteith method is used as the standard for comparison and for analyzing the details about spatial and temporal change and the causes.

3.1.1 Penman-Monteith method

The Penman-Monteith method is recommended as the sole standard method by FAO (Allen et al., 1998). The classic Penman-Monteith method combines both energy and mass balances to model reference evapotranspiration. It is based on fundamental physical principles, which guarantee the universal validity of the method. Compared to the other two methods, more meteorological variables are needed which may not be available everywhere.

The concept of reference evapotranspiration is introduced to study evaporative demand of the atmosphere independent of crop type, crop development and management practices (Allen et al., 1998). The reference surface is assumed to be a flat surface that is completely covered by a grass with an assumed uniform height of 0.12 m and an albedo of 0.23 under enough soil water supply (Allen et al., 1998). The formula is as following:

$$ET_p = \frac{0.408\Delta(R_n - G_s) + \frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (1)$$

where ET_p is potential/references evapotranspiration (mm·d^{-1}); R_n is net radiation at reference surface (MJ·m^{-2}·d^{-1}); G_s is soil heat flux density (MJ·m^{-2}·d^{-1}); T represents monthly mean temperature (^{o}C); U_2 is the wind speed at 2 m height (m·s^{-1}); e_s is saturation vapour pressure (kPa); e_a is actual vapour pressure (kPa); Δ denotes the slope of vapour pressure curve versus temperature (kPa·℃$^{-1}$); γ is psychrometric constant (kPa·℃$^{-1}$). In calculating the radiation budget, solar radiation R_s is usually evaluated by an empirical formula:

$$R_s = (a_s + b_s S_u)R_a \qquad (2)$$

where R_a is extraterrestrial radiation (MJ·m^{-2}·d^{-1}), S_u is percentage of sunshine, a_s and b_s are empirical constants. The recommended constants a_s=0.25, b_s=0.5 by FAO are not chosen here. Instead, the regional values which were determined based

on the measurement in China by Zhu (1982) are used. Calculation of R_n and G_s follows those of FAO (Allen et al., 1998).

3.1.2 Thornthwaite method

The Thornthwaite method derived by Thornthwaite (1948) that uses only air temperature and latitude of site to estimate potential evapotranspiration. Although the method is not recommended for use in areas that are not climatically similar to the original study region at east central USA, where sufficient moisture water was available to maintain active transpiration (Jensen, 1973), it has also been widely used in many studies in the view of simple data requirement.

The Thornthwaite formula for monthly potential evapotranspiration is:

$$ET_p = 16d(10T / I)^a \tag{3}$$

Where T is monthly mean air temperature (°C) ; I is annual thermal index, which is the sum of monthly indices i, here i = $(T / 5)^{1.514}$; $a = 0.49 + 0.0179\, I - 0.0000771\, I^2 + 0.000000675\, I^3$; d is a correction factor which depends on latitude and month.

3.1.3 Pan measured evaporation

Pan provides a measurement of the integrated effect of radiation, wind, temperature and humidity on the evaporation from an open-water surface. It has been proven its practical value and has been widely used to estimate the evaporation loss from a water surface and potential evapotranspiration by applying empirical coefficients to relate pan evaporation to potential evapotranspiration for periods of ten days or longer (Allen et al., 1998).

Although the pan responds in a similar fashion to the same climatic factors affecting crop transpiration, several factors produce differences in loss of water from a water surface and from a cropped surface (e.g. Allen et al., 1998). Storage of heat within the pan can be appreciable and may cause significant evaporation during the night while most crops transpire only during the daytime. There are also differences in turbulence, temperature and humidity of the air immediately above the respective surfaces. Heat transfer through the sides of the pan affects the energy balance.

Considering the fact that the pan measurements are quite dense and have long historical records in China, it is worthy to be analyzed. For the aim of application, the seasonal and spatial variation of the pan coefficient are also determined by comparing it with Penman-Monteith evapotranspiration.

There are different pans for measuring evaporation. Originally, a small pan with a diameter of 20 cm and a height of 10 cm was widely used after 1950's in China. It is made of metal and with a veil on it. It is installed at 70 cm height from ground surface. The water level is measured at 20:00 pm Beijing time every day. Twenty mm water is poured in it as the base before it is observed and changed everyday. The evaporation is calculated based on the water balance of the pan base + rainfall - remains.

Since the 1980's, another type pan (E-601) with 61.8 cm in diameter, has been

used in China. Parallel measurements at selected stations in China show that the small pan and E-601 pan give different results in terms of the daily variation pattern; however, there is a fairly systematic difference so that a correction factor has been established (Liu et al., 1998). From 1995, E-601 pan was replaced by E-601B pan made of glass fiber reinforced plastics and until June 1998 the whole network of about 600 stations in China had been equipped with this type of pan and the values observed by this pan are closer to actual evaporation of small and middle-sized bodies of water than those of other pans. A coefficient for conversion from small evaporation pan to E-601B pan in China was obtained by Ren et al. (2002).

3.2 Estimation of actual evapotranspiration

The modified Thornthwaite water balance model is used to examine the regional and country scale changing properties of actual evapotranspiration and soil moisture over China during 1960-2002.

Another two methods, i.e. advection aridity (AA) model and Granger and Gray (GG) model based on the complementary relationship concept are used to perform a detailed investigation in the Haihe River basin in northern China in addition to the Thornthwaite water balance approach. The long-term water balance and three different annual evaporation estimation methods (i.e. Schreiber, 1904; Ol'dekop, 1911; Pike, 1964) are used to estimate the long-term annual actual evapotranspiration at basin scale and local station respectively. Through the comparison between the annual evaporation estimation methods and the long-term water balance method, the most suitable annual evaporation method for the region is selected and used as a reference to calibrate and validate the parameters of the AA and GG methods.

3.2.1 Basin-wide long-term averaged annual actual evapotranspiration

Actual evapotranspiration data are usually unavailable because of the limitation of observation. The long-term averaged annual actual evapotranspiration can be estimated by the residual of observed basin-wide long-term averaged annual precipitation and streamflow, which are considered as 'measured' values to validate the estimations of other methods

$$AE = P + Q \tag{4}$$

Where P, AE and Q are the long-term averaged annual precipitation, actual evapotranspiration and streamflow respectively. This method is used in selected sub-basins of the Haihe River basin for the aim of validation of other methods.

3.2.2 Long-term averaged annual actual evapotranspiration

Three commonly used methods based on the relationships between AE/PE and P/PE are used to estimate long-term averaged annual actual evapotranspiration for

each station, namely Schreiber (1904), Ol'dekop (1911) and Pike(1964), which are expressed in equations (5) to (7), respectively.

$$\frac{AE}{PE} = \frac{P}{PE}[1 - \exp(-\frac{PE}{P})] \quad (5)$$

$$\frac{AE}{PE} = \tanh(\frac{P}{PE}) \quad (6)$$

$$\frac{AE}{PE} = \frac{P}{PE} / \sqrt{1 + (\frac{P}{PE})^2} \quad (7)$$

Where AE, P are the same as in eq. (4), PE is the long-term averaged annual potential evapotranspiration calculated by the Penman-Monteith method.

By comparing the values calculated by the three methods with values calculated by the water balance equation (4) in section 3.2.1, the most suitable equations of (5) to (7) is selected. The selected method is used to calibrate the parameter values of the complementary relationship methods described in Section 3.2.4.

3.2.3 Thornthwaite water balance model

The Thornthwaite water balance model (Thornthwaite and Mather, 1955) is used to estimate actual evapotranspiration. A dominant merit of the method is that it can reflect the influence of soil water content dynamically in addition to climatic factors. The change of soil water content is important for actual evapotranspiration especially in arid regions and during the dry season in other climatic regions. Potential evapotranspiration is calculated by the Penman-Monteith method with a correction considering no active vegetation in winter in northern China. The reference evapotranspiration is simply assumed to be 0 mm when the monthly air temperature is less than or equal to 0˚C. This assumption is held realistic since cold months with freezing temperatures in China are often associated with snow cover which prevents effective evapotranspiration from vegetation cover and soil surfaces. To maintain the simplicity of the model, other hydrological processes such as snow pack and melting, are not taken into account. Further, irrigation is not included in the model.

The governing equation of the water balance model can be described as:

$$S = P - ET_a - \Delta W / \Delta t \quad (8)$$

where S is the water surplus, P is the monthly precipitation, ET_a is the actual evapotranspiration, W is the soil water content and t is time. ET_a was calculated as:

$$ET_a = \begin{cases} P + \beta(W - W_p, W_{fc} - W_p)(ET_p - P) & P < ET_p \\ ET_p & P \geq ET_p \end{cases} \quad (9)$$

where ET_p is the potential evapotranspiration, calculated by the Penman-Monteith

method for a reference surface. The soil moisture retention function β depends on the ratio of available soil water content and maximum available soil water content expressed as $(W-W_p)/(W_{fc}-W_p)$, where W_{fc} represents soil water holding capacity (field capacity), and W_p is wilting point. W was calculated on a daily time step assuming equal values of ($P-ET_p$) for each day of the month. The soil moisture values at the beginning and end of each month were used to calculate the monthly change in W .

The calculation procedure is as follows

If $P \geq ET_p$, then $ET_a = ET_p$, W is initially estimated with $S = 0$. If $W > W_{fc}$, then $S = W - W_{fc}$ and if $W \leq W_{fc}$, then $S = 0$.

If $P < ET_p$, the soil water will be depleted to compensate for the water supply. At the same time, $ET_a < ET_p$ and $S = 0$.

Typically the initial soil water content is unknown, therefore a balancing routine (spin-up period) is used to force the net change in soil moisture from the beginning to the end of a specified balancing period to zero. The spin-up period is set to 60 months. When the change of the soil water content at the end of the balancing period is less than 1.0 mm, the spin-up process is over. The soil depth of the model is set to 1 m.

3.2.4 Complementary relationship methods

For the Haihe River basin, the complementary relationship methods are used to estimate actual evapotranspiration and the estimates are compared with those of the Thornthwaite water balance model. The concept of complementary relationship, proposed by Bouchet (1963) on the basis of empirical observations, states that the actual evapotranspiration would reduce when a region changed from a saturated condition to dry and simultaneously an equal, but opposite, change in potential evapotranspiration driven by a certain amount of releasing energy. The complementary relationship corrected the misconception that a larger potential evapotranspiration necessarily signified a larger actual evapotranspiration (Granger, 1989). The complementary relationship is described as

$$ET_a + ET_p = 2ET_w \qquad (10)$$

Where ET_a , ET_p and ET_w are actual, potential and wet environment evapotranspiration, respectively. ET_a is calculated as a residual of $2\,ET_w$ - ET_p . Two of the most widely used models AA and GG are applied to the estimation of actual evapotranspiration in this thesis.

3.2.4.1 AA model

In the original AA model, ET_w^{AA} is calculated by the partial equilibrium

evapotranspiration equation of Priestley and Taylor (1972) and ET_p^{AA} is by Brutsaert and Stricker (1979), so the actual evapotranspiration is estimated as

$$\begin{aligned} ET_a^{AA} &= 2ET_w^{AA} - ET_p^{AA} \\ &= 2a\frac{\Delta}{\Delta+\gamma}\frac{(R_n-G_s)}{\lambda} - (\frac{\Delta}{\Delta+\gamma}\frac{(R_n-G_s)}{\lambda} + \frac{\gamma}{\Delta+\gamma}E_a) \\ &= (2a-1)\frac{\Delta}{\Delta+\gamma}\frac{(R_n-G_s)}{\lambda} - \frac{\gamma}{\Delta+\gamma}f(U_z)(e_s-e_a) \end{aligned} \quad (11)$$

Where R_n is the net radiation near the surface, G_s is soil heat flux, here $G_s = 0.2R_n$; λ is the latent heat, Δ is the slope of the saturation vapor pressure curve at the air temperature, γ is the psychrometic constant, $E_a = f(U_z)(e_s - e_a)$, e_s and e_a are the vapor pressure of the saturation and the air vapor pressure at the air temperature, respectively; $f(U_z) \approx f(U_2) = 0.26(1+0.54U_2)$, $f(U_z)$ is a function of the mean wind speed at a reference level z above the ground, $f(U_2)$ is same as $f(U_z)$ but at 2 m elevation. The calculation procedure of the above mentioned parameters is similar to reference evapotranspiration by Penman-Monteith in previous section. *a* is a parameter with an original value of 1.26, which indicates the capacity of available energy ($R_n - G_s$) to transform latent heat (Eagleson, 2002). Many studies have found the original parameter value of *a* =1.26 is not suitable to many places in China (e.g. Yang et al., 2009, Xu and Singh, 2005) and an underestimation of ET_w^{AA} is reported in the seasons with low or negative net radiation. The following form introduced by Xu and Singh (2005) is used to estimate actual evapotranspiration

$$ET_a^{AA} = 2a_1 + (2b_1 - 1)\frac{\Delta}{\Delta+\gamma}\frac{(R_n-G_s)}{\lambda} - \frac{\gamma}{\Delta+\gamma}f(U_z)(e_s-e_a) \quad (12)$$

where a_1 and b_1 are parameters, a_1 represents the minimum energy available for ET_w^{AA}.

3.2.4.2 GG model

Grange and Gray (1989) derived a modified form of Penman's equation for estimating actual evapotranspiration from different unsaturated land covers.

$$ET_a^{GG} = \frac{\Delta G}{\Delta G+\gamma}\frac{(R_n-G_s)}{\lambda} + \frac{\gamma G}{\Delta G+\gamma}E_a \quad (13)$$

Where G is a dimensionless relative evapotranspiration parameter and is estimated by Granger (1998), $G = \frac{1}{0.793 + 0.2e^{4.902D}} + 0.006D$; D is relative drying

power, $D = \frac{E_a}{E_a + (R_n - G_s)/\lambda}$. An alternative form for G is proposed by Xu and Singh (2005) as

$$G = \frac{1}{a_2 + b_2 e^{4.902D}} + 0.006D \tag{14}$$

Where a_2 and b_2 are considered as parameters to be calibrated.

3.3 Partial correlation

Five climate factors are used to calculate potential evapotranspiration. What are the relative importance of these factors in determining the potential evapotranspiration change? Partial correlation method may be useful in dealing with this problem as it seeks the 'real' correlation between potential evapotranspiration and a factor by eliminating the influences of all other factors. It is assumed that the larger and more significant the partial correlation, the more important the factor is for change of potential evapotranspiration.

T-test method is used to verify the significance of the partial correlation coefficient with the significance level of 5%.

3.4 Trend analysis and associated significance tests

The slope of the simple linear regression method is used to determine the changing rate of trends for the annual potential and actual evapotranspiration as well as other meteorological elements.

Two kinds of significance tests are used in the thesis. One tests the significance of correlation coefficient of the linear trend and the other is Mann-Kendall method. Here more detail is given for the Mann-Kendall method.

The rank-based Mann-Kendall method (Mann, 1945; Kendall, 1975) is a nonparametric and commonly used method to assess the significance of monotonic trends in hydro-meteorological time series (e.g. Ziegler et al., 2003; Yue and Pilon, 2004). This test has the advantage of not assuming any distribution form for the data and has the similar power as its parametric competitors (Serrano et al., 1999). The Mann-Kendall test is mainly based on the test statistic *SS*

$$SS = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{15}$$

Where the x_j are the sequential data values, n is the length of the data. The function $\mathrm{sgn}(\theta) = 1$, if $\theta > 0$; $\mathrm{sgn}(\theta) = 0$, if $\theta = 0$; $\mathrm{sgn}(\theta) = -1$, if $\theta < 0$. When $n \geq 8$, the statistic *SS* is approximately normally distributed with the mean and the variance as

follows

$$E(SS) = 0 \tag{16}$$

$$V(SS) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)}{18} \tag{17}$$

Where t_p is the number of ties for the pth value and q is the number of tied values. Statistic Z is computed by $Z = \frac{SS-1}{\sqrt{V(SS)}}$, if $SS > 0$; $Z = 0$, if $SS = 0$; $Z = \frac{SS+1}{\sqrt{V(SS)}}$, if $SS < 0$, which follows the standard normal distribution with mean of zero and variance of one. The hypothesis that there is no trend will be rejected if $|Z| > Z_{1-\alpha/2}$, here $\alpha = 5\%$, is the significance level of the test.

4 Main results and discussion

4.1 Characteristics of potential evapotranspiration

Potential evapotranspiration represents the synthetic effect of climate factors and is important for estimation of actual evapotranspiration. The spatial and temporal characteristics of potential evapotranspiration are analyzed in China based on the Penman-Monteith method, which provides a background for evaluation of the Thornthwaite method and the pan observations. The distributions and trends of potential evapotranspiration estimated by the Penman-Monteith, Thornthwaite methods and pan measurement are detected and compared. Because of no limitation of water supply, possible causes to the change of potential evapotranspiration, i.e. the major climate controlling factors and their changes during the past decades are evaluated.

4.1.1 Spatial distribution of climate characteristics

Normal annual potential evapotranspiration averaged over China for the period of 1956 to 2000 is 941.5 mm with 28% in spring, 39% in summer, 22% in autumn, and 11% in winter.

Figure 3 gives the distribution of annual potential evapotranspiration in China estimated by the Penman-Monteith method. For annual potential evapotranspiration, the lowest centers are mainly located in Songhua River basin and east part of Liaohe River basin with 600-800 mm because of low air temperature , and some parts of upper reaches of Yellow River and Yangtze River with low air temperature and in the middle of Yangtze River as the result of unfavorable sunshine condition, humid climate and weak wind speed. The high centers with 1000-1400 mm annual potential evapotranspiration are located in most desert areas in the basin of rivers in Northwest China as a result of good radiation condition, strong wind and dry climate. The sub-high centers lie in Yunnan province and Hainan island with 1100-1200 mm because of high temperature and good sunshine condition.

The figures about distributions of seasonal potential evapotranspiration are shown in Paper II. In spring, the pattern is similar to that of annual evapotranspiration but with the values vary from 200 to 450 mm. In summer, the seasonal values increase in most parts of China comparing to those in spring, except decrease in some parts in southwest China with higher humidity. In autumn, the values vary from 150 to 300 mm and are generally lower than those in spring. Zonal pattern is clear in winter and the values vary from 50 to 200 mm with the lowest values of a year.

A comparison is carried out between the Thornthwaite method and pan measurement with the Penman-Monteith based on three measures including relative bias, relative root mean square error (RMSE) and correlation coefficient. It is made for each station on seasonal and annual bases. Figure 4 shows the annual relative bias

of the estimates by the Thornthwaite method and pan measurement. The figures about RMSE and correlation are shown in Paper I.

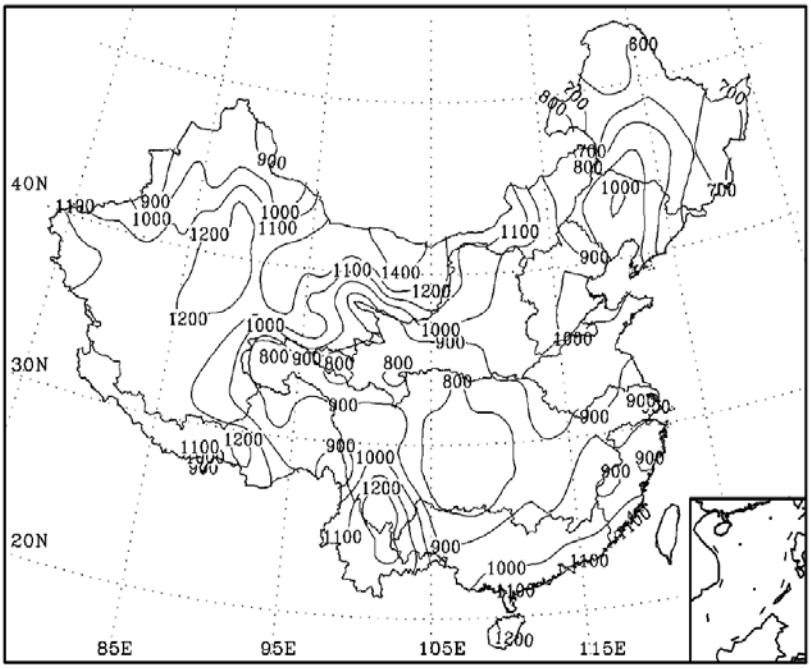
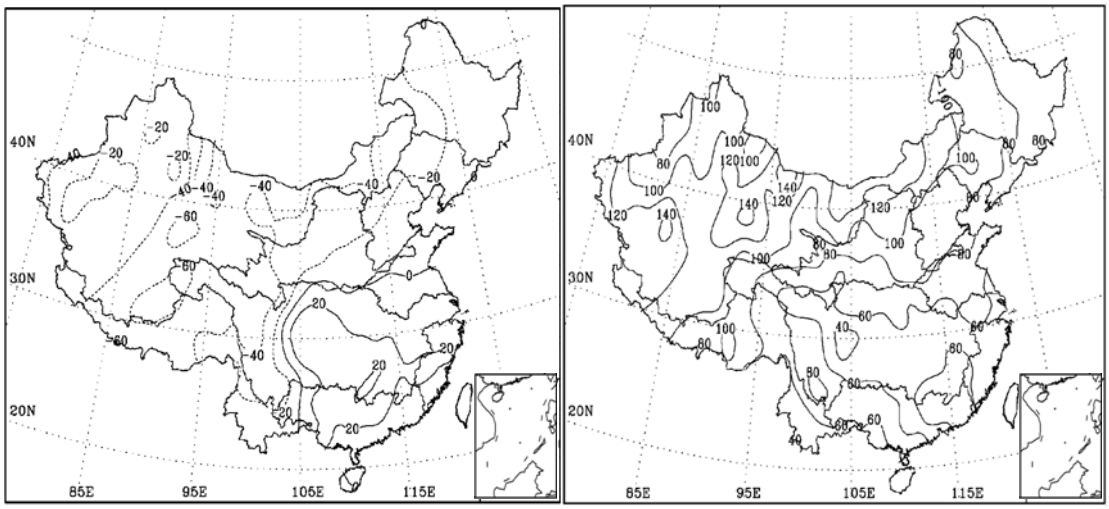


Figure 3 Distribution of annual potential evapotranspiration averaged from 1956 to 2000 over China estimated by Penman-Monteith method. Unit: mm. From Paper II.



(a) (b)

Figure 4 The annual relative bias of the estimates by the Thornthwaite (a) and pan measurement (b) compared to those of the Penman-Monteith. Units: %. From Paper I.

Great differences are shown for the estimation between the Thornthwaite and Penman-Monteith methods. On seasonal basis, the overestimation by the former is found in southeast China and underestimation in other parts of China in spring, summer and autumn, whereas an underestimation in winter over the entire country. The annual bias indicates that the Thornthwaite method overestimates over the monsoon affected area where climate is relatively humid, while for arid and semiarid parts of China it produced an underestimation (Figure 4a). The annual relative RMSE ranges from 3.8 to 65.7%. The correlation coefficients indicate that the Thornthwaite method only accounts for a small part of the temporal variability over China. Particularly in Northwest China and part of inner Mongolia show a negative correlation, which implies that different change directions lie in the two methods. Generally, application of the Thornthwaite method under Chinese climatic conditions may be problematic, at least with its original parameter values.

The pan measurement is expected to have positive bias comparing to Penman-Monteith estimations because it is measured at water surface of a relative small area. High bias are found in North and Northwest areas, whereas low bias in the South (Figure 4b). Caused by the consistent positive bias, a large relative RMSE is found except in parts of the south China. The deviation of pan measurement from the Penman-Monteith estimate is fairly systematic over various regions in China. The positive and high correlation between them indicates that temporal variation in pan measurement follows that of the Penman-Monteith estimates and the pan measurement simulates the change in all relevant meteorological conditions fairly well.

A correction of pan measurement could be made by multiplying a ratio. The ratio is Penman-Monteith estimate to that of the pan measurement. As a whole the ratio varies between 0.4 and 0.8 with an average of 0.6. The correction factors could be used to calculate potential evapotranspiration for areas only pan measurement is available.

4.1.2 Trends of potential evapotranspiration

As for the changes of potential evapotranspiration during the past decades, a decreasing trend in potential evapotranspiration is the general feature in China based on the analysis to decadal variation, trends of annual and seasonal potential evapotranspiration on basin scale as well as climatic comparison between the two periods, 1980-2000 and 1956-1979.

As for the ten river basins and the whole country, the 10-year mean annual potential evapotranspiration of China and most basins are more than normal during 1960s to 1970s and less than normal since 1980s. In basins of the Songhua River, the Yellow River, the Huaihe River as well as the basin of rivers in Southeast China, the 10-year mean annual potential evapotranspirations arrived the bottom during 1980s and were on the rise though still less than normal during 1990s with one exception in the Yellow River basin.

Table 1 gives the rate of trends of annual and seasonal potential

evapotranspirations of the ten river basins and the whole country during 1956-2000. The annual potential evapotranspirations of the country and most basins have decreasing trends except for the Songhua River basin where a slight increasing trend appeared. Annual potential evapotranspiration of the whole country decreases at a rate of -11.8 mm/10a which is statistically significant at the 1% level. This agrees with the results of Ren and Guo (2006) who study the trend of pan measurement in China during the same period of time. The significant decreasing trends of spring, summer and autumn are responsible for the decreasing annual trends.

Table 1 Trends of annual and seasonal potential evapotranspiration of the ten river basins and whole country during 1956 to 2000. Unit: mm/ 10a.

Basins	Annual	Spring	Summer	Autumn	Winter
Songhua River	2.1	0.5	0.4	0.6	0.6
Liaohe River	-7.3	-4.3*	-2.6	-0.9	0.4
Haihe River	-12.0#	-4.5	-5.4	-1.4	-0.7
Yellow River	-4.3	-1.0	-3.4	0.2	-0.1
Huaihe River	-13.0#	-0.1	-10.8*	-1.5	-0.3
Yangtze River	-17.3*	-1.6	-11.5*	-3.0*	-1.2
Rivers in SE China	-22.0*	-1.5	-13.1*	-5.1*	-2.0
Pearl River	-15.7*	-6.0*	-4.6#	-3.0	-2.3
Rivers in SW China	-2.8	-0.1	-0.7	-1.0	-0.6
Rivers in NW China	-16.7*	-4.7*	-7.7*	-3.9*	-0.2
China	-11.8*	-2.5#	-6.5*	-2.1*	-0.7

(Note: * statistically significant at the 1% level, # statistically significant at the 5% level.)

In south of China, the values of the basins of the Huaihe River, the Yangtze River, the rivers in Southeast China and the Pearl River show significant decreasing trends on annual scale and in summer during the past 45years. But in the basin of the rivers in Southwest China, no clear trends are found for the four seasonal and annual values. The changes of the basins in northern China are more complicated. In the Songhua River basin, all seasonal and annual values have slightly increasing trends. In the other basins, on the other hand, the annual and seasonal values have slightly decreasing trends. But in the basin of rivers in Northwest China, all seasons except winter show a significant decreasing trend.

Considering that the first water resources assessment of China is done for the period from 1956 to 1979 and the temperature climate in China has changed significantly since 1980s with a warming trend (e.g. Wei et al., 2003), the spatial patterns of potential evapotranspiration between 1980-2000 and 1956-1979 are compared. The results show that the mean annual values of later period appear decreasing trends in most areas of China. But in some areas of Shandong Peninsula, western and middle basins of rivers in Southwest China, Ningxia Hui Autonomous

Region as well as the source area of Yangtze River and Yellow River, the values have a slightly increment during the second period. Li et al. (2000) also found that the evapotranspiration has been increasing in upper reach area of the Yellow River since 1980s using the Penman formula.

4.1.3 Trends by different methods

In this section, the temporal trends of potential evapotranspiration estimated by the Thornthwaite methods and pan measurement are compared with those of the Penman-Monteith for whole China as well as for the ten major river basins.

Figure 5 show the long-term variation properties of pan measurements and reference evapotranspirations estimated by the Penman-Monteith method and the Thornthwaite method, as measured by the temporal trend and the correlation coefficient of the linear trend (the linear trend is the slope of the linear regression, with evaporation as dependent variable and time as independent variable). The Penman-Monteith estimates show that the evapotranspiration in three catchments have an increasing trend, of which the Songhua River in northeastern China is significant; seven of the ten basins have a decreasing trend, of which four are significant. In nine of ten basins the pan estimates show the same trend direction as those of Penman-Monteith method but are greater in magnitude in most cases. The only exception is the Yellow River basin where a decreasing trend is found with pan measurements.

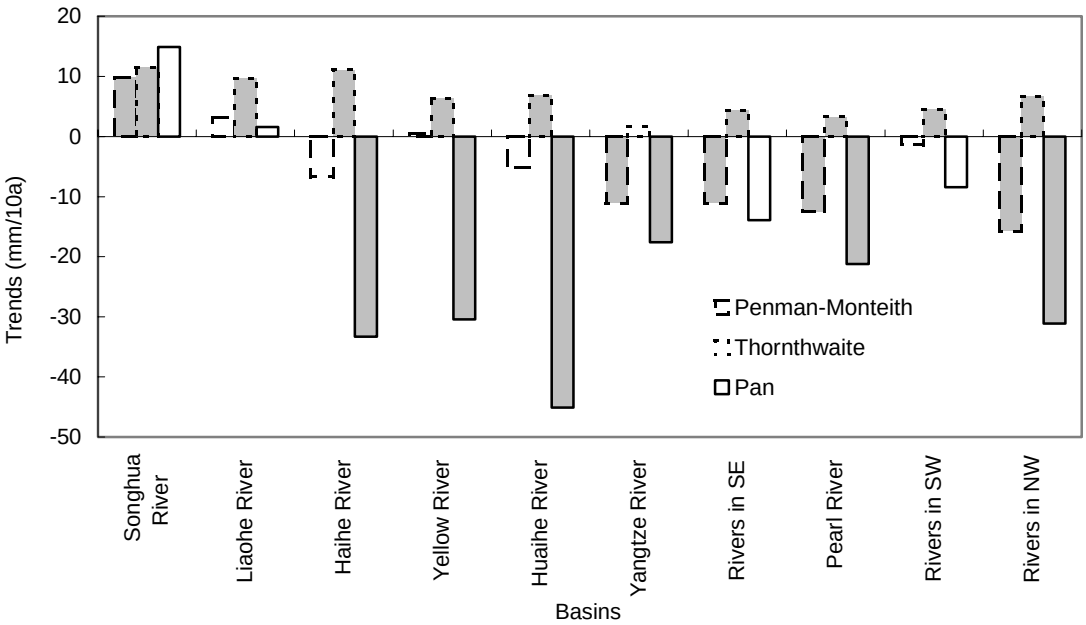


Figure 5 Trends of potential evapotranspiration estimated by Penman-Monteith, Thornthwaite methods and pan evaporation during 1951-2000 over ten river basins in China. The stuffed bar indicates statistically significant test of liner trend at 5% level.

The Thornthwaite estimate gives an increasing trend for all the basins which is very much different from the other two methods. The reason is that in most regions of China air temperature has been increasing during last decades, while wind speed and solar radiation have been significantly decreasing during the period (e.g. Li et al., 1998; Ren et al., 2005; Qian et al., 2006b). Accordingly, the evapotranspiration calculated by the Thornthwaite method that only uses air temperature as input data shows an increasing trend for all basins, while the Penman-Monteith method and pan evaporation reflect integrated effects of radiation, wind, temperature and humidity on the evapotranspiration / evaporation.

4.1.4 Causes of changing trend for potential evapotranspiration

Table 2 list the major climate factors on a descending order which have obvious relationships with potential evapotranspiration according to the partial correlation coefficients and their trends during 1956-2000 at ten river basins and whole country on annual and seasonal scales.

Table 2 Relationships between climate factors and annual/seasonal potential evapotranspiration of the ten river basins and the whole country.

Basins	Annual	Spring	Summer	Autumn	Winter
Songhua River	***-Hu***, ***Su***,**Tm**	*-Hu*,***Wn***,***Su***,**Tm**	*-Hu*,*Su*,***Wn***,Tm	***-Hu***,Tm,***Wn***	*-Hu*,***Wn***,**Tm**,**Tn**
Liaohe River	*-Hu*,***Su***,**Tm**,***Wn***	***Wn***,-Hu,**Tm**,***Su***	***Su***,*-Hu*,***Wn***,Tm	*-Hu*,***Wn***,Tm	*-Hu*,***Wn***,**Tm**
Haihe River	***Wn***,*-Hu*,***Su***,**Tm**	*-Hu*,***Wn***,Tm,***Su***	***Su***,*-Hu*,***Wn***,Tm	*-Hu*,***Wn***	*-Hu*,***Wn***,**Tm**
Yellow River	***Wn***,***Su***,*-Hu*	*-Hu*,***Wn***,*Su*,Tm,**Tn**	***Su***,-Hu,***Wn***,**Tn**	***Wn***,*-Hu*,**Tm**,*Su*	*-Hu*,***Wn***,**Tm**,***Su***
Huaihe River	***Su***,*-Hu*,***Wn***	*-Hu*,*Su*,***Wn***,Tm	***Su***,-Hu,***Wn***,*Tm*	*-Hu*,***Wn***,Tm	*-Hu*,***Wn***,Tm,***Su***
Yangtze River	***Su***,**Tn**,-Hu,***Wn***	*-Hu*,***Su***,***Wn***	***Su***,**-Hu**	***Wn***,*-Hu*,***Su***	-Hu,***Wn***
Rivers in SE China	***Su***,*-Hu*,***Wn***,**Tn**	***Su***,***-Hu***,Tn	***Su***,-Hu,***Wn***,*Tm*	*-Hu*,***Wn***,***Su***	-Hu,***Wn***,***Su***,**Tn**
Pearl River	***Su***,*-Hu*,***Wn***,**Tn**	***Su***,***Wn***,-Hu,Tn	***Su***,*-Hu*,***Wn***,**Tn**	***Su***,*-Hu*,***Wn***,**Tn**	-Hu,***Wn***,***Su***
Rivers in SW China	*Su*,*Wn*,**-Hu**,Tm	Su,*Wn*,**-Hu**,Tm,**Tn**	*Su*,*-Hu*,*Wn*,**Tn**	*Su*,***Wn***	***Wn***,Su,Tm,**-Hu**
Rivers in NW China	***Wn***,-Hu,**Tm**,***Su***	***Wn***,Tm,-Hu,Su	***Wn***,**-Hu**,**Tm**,***Su***	***Wn***,-Hu,Tm	***Wn***,*-Hu*,**Tn**,**Tm**
Whole country	***Su***,***Wn***,*-Hu*,**Tm**	*-Hu*,***Wn***,***Su***,Tm	***Su***,***Wn***,-Hu,Tm	***Su***,*-Hu*,***Wn***	*-Hu*,***Wn***,***Su***,**Tn**

Note: Su, Wn, Hu, Tm, Tn are sunshine duration, wind speed, relative humidity, maximum and minimum air temperature respectively. The table lists the factors having significant (≤5% level) partial correlation with potential evapotranspiration in descending order. The minus (-) denotes negative partial correlation between potential evapotranspiration and climate factors. Italic type character represents the climate factors decline during 1956-2000 years. Thick type character represents the trend with statistical significant at ≤ 5% level. From Paper II.

Generally, sunshine duration, mean wind speed, mean maximum temperature and minimum temperature have positive relationship with potential evapotranspiration, while relative humidity has negative relationship. For most river basins and the whole country, sunshine duration, mean wind speed and relative humidity are major control factors to most seasonal and annul potential evapotranspirations, whereas mean maximum temperature and minimum temperature play a relatively minor role.

For annual potential evapotranspiration, the major controlling factors change with latitude from relative humidity in the Songhua River and the Liaohe River basins to wind speed in the basins of the Haihe River, the Yellow River and the rivers in Northwest China and further to sunshine duration in the other southern basins of China, which are similar to the analysis by Thomas (2000). For the whole country, sunshine duration is the most important controlling factor. Similar latitudinal changes of major controlling factors for potential evapotranspiration are also found in spring. In most basins of northern China, relative humidity or mean wind speed have close relationship with potential evapotranspiration. In southern basins of China, the situation change and the sunshine duration appear to be more important. In summer, sunshine duration and humidity are major controlling factors that are affected by summer monsoon except for the basin of the rivers in Northwest China. In autumn and winter, relative humidity or wind take the control position in most basins. Only in the some southern basins, such as the Pearl River and the rivers in Southwest China, the sunshine duration still plays an dominant role.

In order to identify the relative contributions of all the factors to the changes of potential evapotranspiration, the changes of each factor during 1956 - 2000 are further analyzed. From Table 2, it is seen that sunshine duration and mean wind speed of most basins and the whole country show significant declining trends this period. The declining trends of annual sunshine duration and wind speed are consistent with previous studies (e.g. Li et al., 1998; Wang et al., 2004). Li et al. (1998) found that the global radiation and direct radiation in most part of China had significant decreasing trends during 1960 and 1990 as the result of the increased atmospheric turbidity and aerosol. Wang et al. (2004) attributed the significant decline of wind speed in China during the past 50 years to the weakening winter and summer monsoon. Besides the change of atmosphere circulation, change of land use such like urbanization may also had an impact on the decreased of wind. Significant decreasing trends in sunshine duration (or solar irradiation) and wind speed may have resulted in the declining tendencies of the potential evapotranspiration in most basins and the whole country. Relative humidity of different basins and seasons do not show a consistent and significant trend. These lead to the conclusion that the change of relative humidity is probably not the dominating factor for the trend of potential evapotranspiration during 1956-2000. But in the Songhua River basin, the relative humidity is the principle controlling factor in all seasons. As a result of the decreasing relative humidity and increasing maximum/minimum temperature, the potential evapotranspiration there shows a slightly increasing trend. These results are similar to the studies of pan evaporation (Liu et al., 2004a; Guo and Ren, 2005; Ren and Guo, 2006) .

As a whole, the variations of annual and seasonal potential evapotranspirations of each basin reflect the comprehensive function of each climate factors. Among these factors, the changes of principle factors play a key role to the change of potential evapotranspiration. The other factors would enhance or offset the impact of the major factors according to their change and relation with potential evapotranspiration.

The trends analysis of the estimated potential evapotranspiration involves remarkable uncertainties, which are mainly from the simplifications in the estimation method used in the Penman-Monteith equations, non-consistency problem and errors in the observation data affected by the impacts of non-climate factors such as urbanization, changes of instruments, measuring location and obstacles surrounds of the measure site.

For example, in estimating solar radiation, the method is based on the sunshine duration that usually brings about 10% monthly mean absolute relative error and more for short duration, which would affect the estimation of potential evapotranspiration and its trend.

More studies have discussed the uncertainty involved in the wind speed measurement, which is more sensitivity to the impact of urbanization, instruments change and environment of the observation (Fu et al., 2009). Other opinions are also available, Jiang et al. (2009) pointed that urbanization, change of anemometers, or relocation of stations are mildly responsible for the decreasing trend of mean wind speed in China. The main reason is the changes of atmospheric circulation under the background of global warming, such as the contrasts of the sea level pressure and near-surface temperature between the Asian continent and the Pacific Ocean have become significantly smaller, and the east Asian trough has shifted eastward and northward and has weakened as well. Nevertheless, different conclusions itself shows that the issue is debatable and more study is needed. Moreover, the trend of a time series depends on the choice/availability of the data period and its length; it also depends on the appearance of the outliers in the time series.

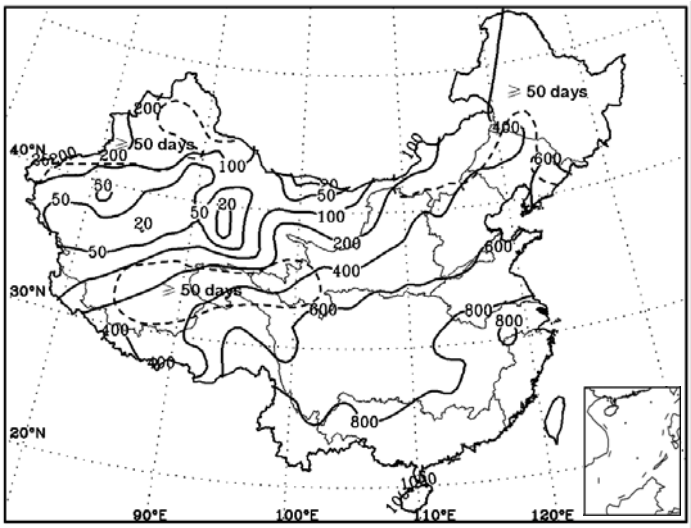
4.2 Characteristics of actual evapotranspiration

The spatial characteristics and trends of actual evapotranspiration over China are based on the estimates by the Thornthwaite water balance model (WB). The causes for the change of actual evapotranspiration during the past decades are discussed. A comparison to the estimates by the complementary relationship methods at Haihe River basin is also included in this section. The detailed steps of calibration and verification of the complementary relationship models can be referred to Paper IV.

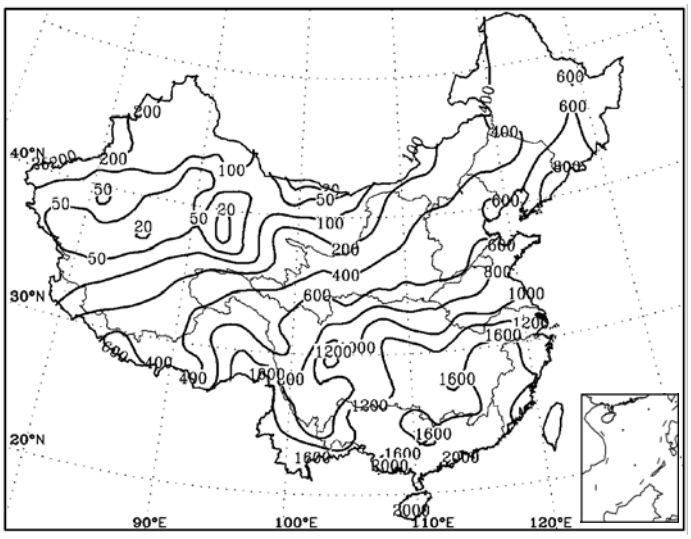
4.2.1 Spatial distribution of climate characteristics

The spatial patterns of the annual actual evapotranspiration and annual precipitation averaged over 1971-2000 in China are shown in Figure 6. The southward increase in annual actual evapotranspiration from 20 mm in the northwest to 1000 mm in

southeast resembled the pattern of precipitation. The 200, 400 and 800 mm contour lines of annual precipitation roughly divided China into arid, semi-arid, semi-humid and humid climates from northwest to southeast. In arid and semi-arid areas, the actual evapotranspiration and annual precipitation display similar distribution and magnitudes. Similarly, in semi-humid areas with annual precipitation varying between 400 and 800 mm, the annual evapotranspiration and annual precipitation are analogous except for eastern Liaohe River basin where precipitation is higher. For humid areas, the annual actual evapotranspiration is clearly lower than the annual precipitation. In Northeast China, north parts of Xinjiang and Tibetan plateau the mean number of days with snow cover are longer than and equal to 50 days in Figure 6a.



(a)



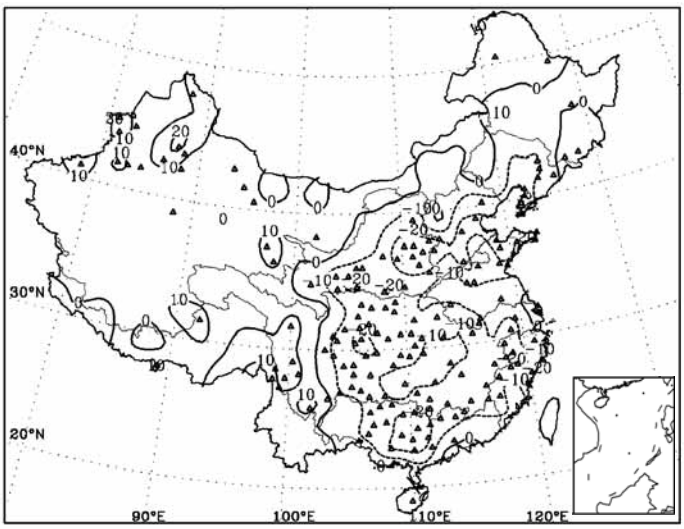
(b)

Figure 6 Averages of annual actual evapotranspiration (a) and annual precipitation (b) for 1971-2000. The dash lines in Figure 6a show the areas where the mean number of snow cover days are longer than or equal to 50. Units: mm. From paper III.

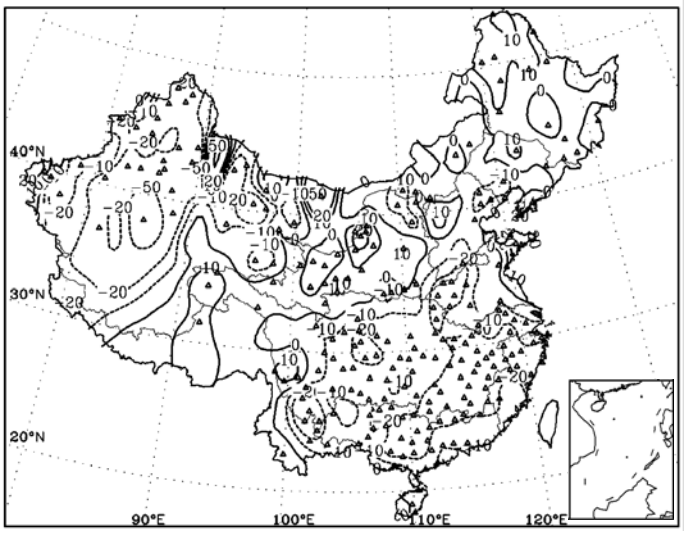
Snow accumulation and melting processes are not explicitly considered in the calculation, which may cause a bias in the estimated potential evapotranspiration, actual evapotranspiration and the ratio of them in areas which are covered by snow for long time. However, this bias is considered of minor importance since these areas are very cold with air temperatures far below zero in winter.

4.2.2 Trends of annul actual evapotranspiration

Figure 7 shows the spatial distributions of temporal trends for annual actual evapotranspiration and potential evapotranspiration for comparison during 1960-2002.



(a)



(b)

Figure 7 Trends for annual actual evapotranspiration (a) and potential evapotranspiration (b) during 1960-2002 calculated using linear regression method. Units: mm/10a. Triangles indicate stations with significant trend at the 5% significance level tested by Mann-Kendall method. From Paper III.

The estimated annual actual evapotranspiration tends to decrease in most areas at east of 100 º E and increase in areas at west of it. The negative trends range from about -30 mm/10a to -10mm /10a and are significant for most parts of the Haihe River basin, low and middle reaches of the Yellow River basin, middle part of the Yangtze River basin, middle and north part of the Pearl River basin and the rivers in southeast China. Contrarily, in the west and adjacent areas of the 100º E longitude, in northern Songhua River basin and the rivers in northwest China, the annual actual evapotranspiration tends to increase. Particularly in southeast Tibetan, north of Xinjiang area , the trends vary between 10 mm/10a and 20 mm/10a. However, the increasing trends are insignificant with a few exceptions.

4.2.3 Comparison of the actual evapotranspiration estimations between different methods over the Haihe River basin

Figure 8 shows monthly variation of actual evapotranspiration averaged over 1971 to 2000 estimated by the AA, GG and the Thornthwaite water balance (WB) models. For comparison purposes, mean monthly values of precipitation and soil moisture simulated by the WB model are also shown in the figure. Long-term average actual evapotranspirations estimated by the three methods have a similar monthly variation feature with maximum in summer and minimum in winter. Comparing to WB, the mean absolute errors of monthly long-term average actual evapotranspiration are smaller by AA than that by GG. Particular in July and August, AA has smaller error.

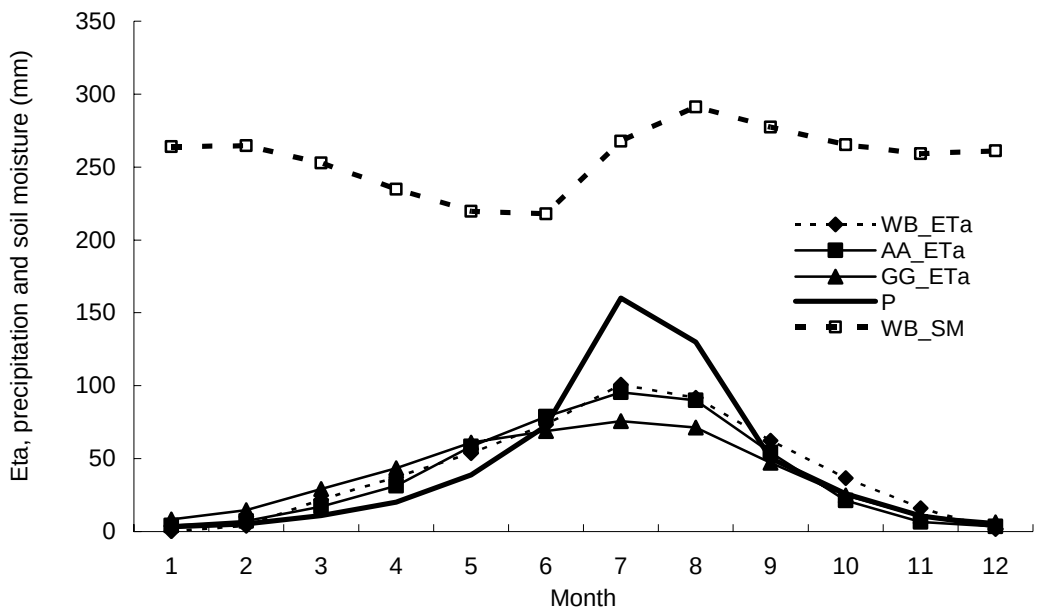


Figure 8 Comparison of regional mean monthly actual evapotranspiration averaged over 1971 to 2000 estimated by AA (AA_ETa), GG (GG_ETa) and WB (WB_ETa) as well as precipitation (P) and soil moisture at top 1 m estimated by WB (WB_SM) over the Haihe River basin. Units: mm. From Paper IV.

In spring, the estimated actual evapotranspiration is greater than precipitation. The additional water used for evapotranspiration mainly comes from soil, and as a consequence soil moisture decreases in the period. In July and August, precipitation is obviously more than actual evapotranspiration, the surplus of water is partly stored in the soil, which results in an increase of soil water content until it reaches the peak in August. During autumn, soil moisture decreases gradually because of the decrease in precipitation. In winter, both values and variations of precipitation and actual evapotranspiration are small and soil moisture changes a little. In this region, spring is the key period when a large amount of water is required for crop growth, drying soil would affect the growth of crop as a result of large actual evapotranspiration. Generally speaking, the monthly variation of the actual evapotranspiration estimated by AA and GG are also reasonable even though the function of soil moisture is not included in these methods.

Table 3 shows the rate of trends of regional mean seasonal and annual actual evapotranspiration estimated by the three methods during 1960-2002 at the Haihe River basin. As for actual evapotranspiration of AA and GG, the rates of trends depend on the change rate of potential and/or wet environment evapotranspiration. Consistently decreasing trends of annual actual evapotranspiration are obtained by the three methods with different rates. Significant decreasing trends with -7.0mm/10a in summer for GG and WB and in autumn for GG lead to the significantly decrease in annual actual evapotranspiration. For AA, the major contribution for the decreasing trend of annual actual evapotranspiration can also be explained by the significant decrease in summer and autumn with reducing rate -6.1mm/10a and -2.1mm/10a respectively. But obviously different to GG and WB, spring actual evapotranspiration by AA shows a significant increase.

Table 3 Trends of seasonal and annual actual evapotranspiration estimated by AA, GG and WB at the Haihe River basin during 1960-2002. Unit: mm/10a. * denotes the trend is significant at the 5% significance level tested by Mann-Kendall method.

Periods	ET_a^{AA}	ET_a^{GG}	ET_a^{WB}
Spring	2.6*	-0.7	-3.9
Summer	-6.1*	-7.0*	-7.0*
Autumn	-2.1*	-1.7*	-5.4
Winter	0.1	-0.1	0.9
Annual	-5.3	-9.3*	-15.2*

Figure 9 show spatial characteristics of trends of annual evapotranspiration by AA, GG and WB. Take results of AA as an example, in most areas of the Haihe River basin, the annual actual evapotranspiration showed a significant decreasing trend and the

rate of trend varied from -0.1 mm/10a to -30mm/10a (Figure 9a). In some areas at northeast and southeast part, increasing rates of trend are greater than 5mm/10a. In most stations, the trends of annual actual evapotranspiration estimated by the three methods are consistently decreasing with different rates.

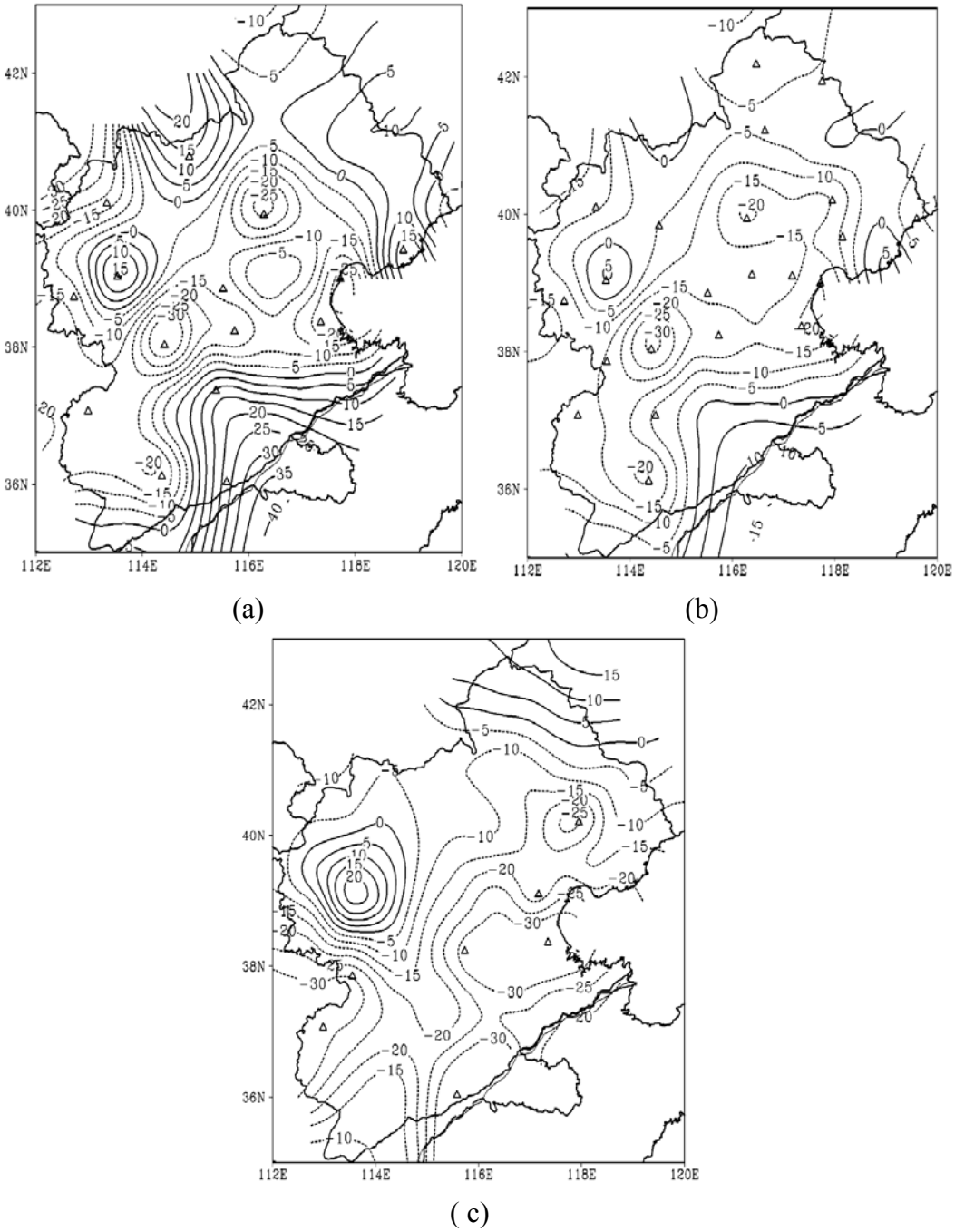


Figure 9 The trends of annual evapotranspiration by AA (a), GG (b) and WB (c) during 1960-2002 over the Haihe River basin. Units: mm/10a. Triangles indicate stations with significant trend at the 5% significance level tested by Mann-Kendall method.

4.2.4 Causes of changing trends for actual evapotranspiration

As for actual evapotranspiration, the controlling factors are more complicated than those for potential evapotranspiration. Besides driven essentially by climatic factors, the actual evapotranspiration is also constrained by the amount of available water when the complicated influences of vegetation and soil are ignored. For easy understanding, the potential evapotranspiration is used to represent the combined effect of climatic factors including solar radiation, wind speed, humidity, temperature and reflects energy available for evapotranspiration. The relationship between potential evapotranspiration and climatic factors as well as impact of climatic factors have been discussed in the previous section. The available water is reflected directly by soil moisture content or indirectly by precipitation. So the explanation to the trend of actual evapotranspiration could be simplified to the discussion of the major controlling factors and their changes during the past decades between potential evapotranspiration and precipitation.

The trends comparison of annual actual evapotranspiration and potential evapotranspiration during 1960-2002 have been shown in Figure 7. The trends of annual precipitation can be seen in Figure 10 .

Figure 7b illustrates a widespread decreasing trend of potential evapotranspiration in most parts of China during 1960-2002. The trends of potential evapotranspiration are particularly significant in south and northwest China. The belt from northeastern China through middle and upper Yellow River basin and southwestwards east of Tibetan plateau has a slight increasing trend. Most of these areas belong to semi-arid / semi-humid regions or lie in the transition zone from animal husbandry to grain agriculture with high climatic sensitivity.

The function of controlling factors changes with the different climate regions and seasons. In the more humid southeast part of China, the trend of actual evapotranspiration, is similar to that of potential evapotranspiration (Figure 7b) but is contrary to that of precipitation (Figure 10), restricting by the evaporative demand (or energy available for evapotranspiration as reflected by potential evapotranspiration), hence an “energy limited” system. In the arid northwest part of China, the trend of actual evapotranspiration, is similar to that of precipitation (Figure 10) but is contrary to that of potential evapotranspiration (Figure 7b). Most incoming precipitation evaporates back to the atmosphere and the actual evapotranspiration is controlled by the amount of precipitation, regardless of the potential evapotranspiration amounts. Thus, this can be referred to as a “water limited” system.

In other regions, such as some areas in north east and south west parts of China, the intra-annual and inter-annual variations in precipitation and potential evapotranspiration are manifested in the soil moisture content, and consequently, actual evapotranspiration varies between the two limiting systems. As a result of combined effects of precipitation and potential evapotranspiration, the actual evapotranspiration in such regions shows an inconsistent changing pattern.

From the quantitative analysis of actual evapotranspiration, the causes for the change of actual evapotranspiration are consistent with that of the well-known

Budyko thesis (Roderick and Farquhar, 2004; Ni et al., 2007), i.e. different climatic regions have different mechanisms for actual evapotranspiration.

It should also be kept in mind that the Thornthwaite balance model is quite simple and ignores some physical processes, changes of parameters and human activities which are also very important to the determination of actual evapotranspiration. Compared to the nature condition influencing actual evapotranspiration, other important factors are yet to be considered. Such as irrigation, withdraw of underground water and cross basin water transfer would have great impact on the estimation of actual evapotranspiration and its trend. The actual evapotranspiration will increase as irrigation increases, which is the situation in most part of China and has been seriously impacted on the water cycle (Liu et al., 2004b) and strengthened the water resources shortages especially in north China and during dry period. The assumption of constant soil parameters would bring about impact on the estimation of actual evapotranspiration because the great change of land use during the past decades cannot be ignored. It has been demonstrated by Feddema (1998) through the model tests that soil degradation occurring during 1950 - 1980 in Africa has had a significant impact on local water resources.

4.3 Changes of water cycle

The changes of water cycle are analyzed based on the matching relationship between the changes of precipitation and actual evapotranspiration on annual scale. More precipitation and actual evapotranspiration means the acceleration of the water cycle. But decreasing in precipitation and actual evapotranspiration brings about weakening of the water cycle. The changes of water cycle are further demonstrated by the observation evidence of runoff, soil moisture and extreme precipitation events based on the previous studies. In order to give a full picture of the temporal and spatial changes of water cycle in the case of lacking long-term and widely available observations of soil moisture data in China, the trends of observed annual precipitation and mean temperature are shown in Figure 10 and Figure 11 respectively , the trends of estimated annual runoff and annual mean soil moisture by the Thornthwaite water balance model are shown in Figure 12. According to the distinctive spatial features of trends of precipitation during the past decades, the changes of water cycle are discussed from eastern China to western China.

4.3.1 Eastern China

The annual precipitation has decreased over parts of the Songhua Rive basin, the Liaohe River basin, the Haihe River basin, the Yellow River basin, the Huaihe River basin and the middle part of the Yangtze River basin. For northern China the general decreasing trend in precipitation is partly explained by a weakening of the East Asian summer monsoon during the past decades (e.g., Wang et al., 2004; Ding et al., 2008). Similarly, the annual actual evapotranspiration in these areas show negative trends

even though the surface air temperatures have increased significantly during this period (Figure 11). In the above mentioned areas reduced amounts of precipitation have played an important role for the decreasing trend in the estimated actual evapotranspiration, which is further strengthened by decreasing potential evapotranspiration. Decreases in precipitation and actual evapotranspiration denote a weakening of the hydrological cycle in these areas.

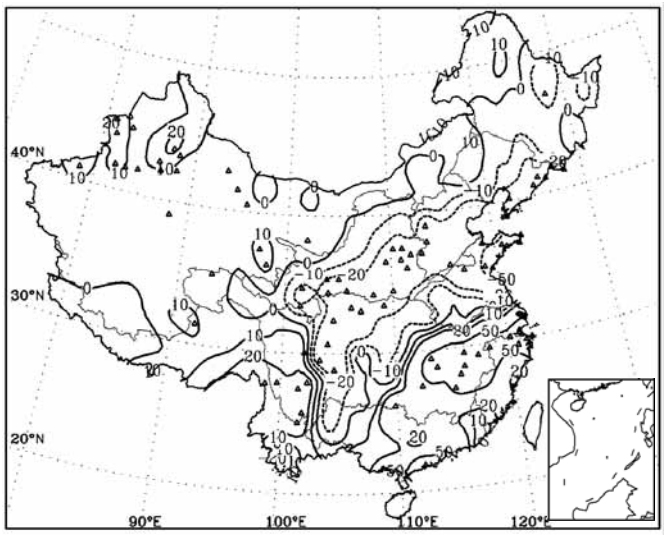


Figure 10 Trends of annual precipitation during 1960-2002 over China. The rates of trends are calculated using linear regression method. Unit: mm/10a . Triangles indicate stations with significant trend at the 5% significance level tested by Mann-Kendall method.

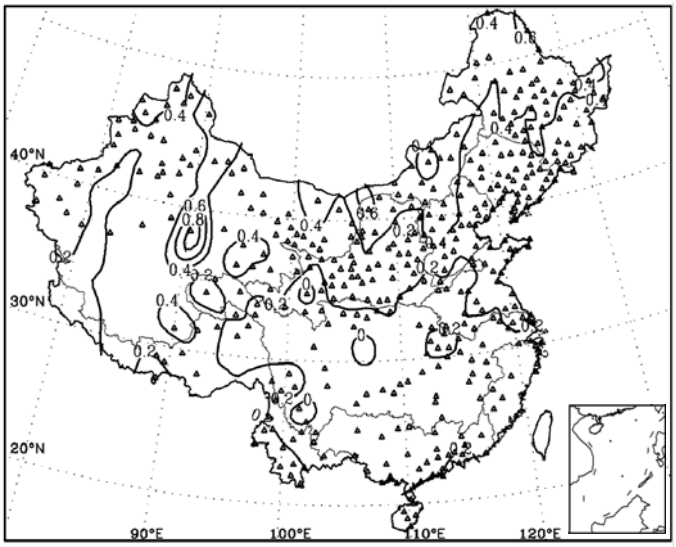
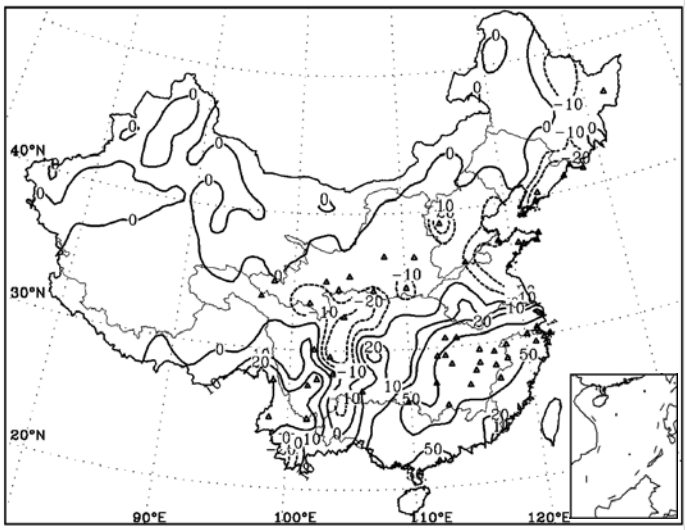


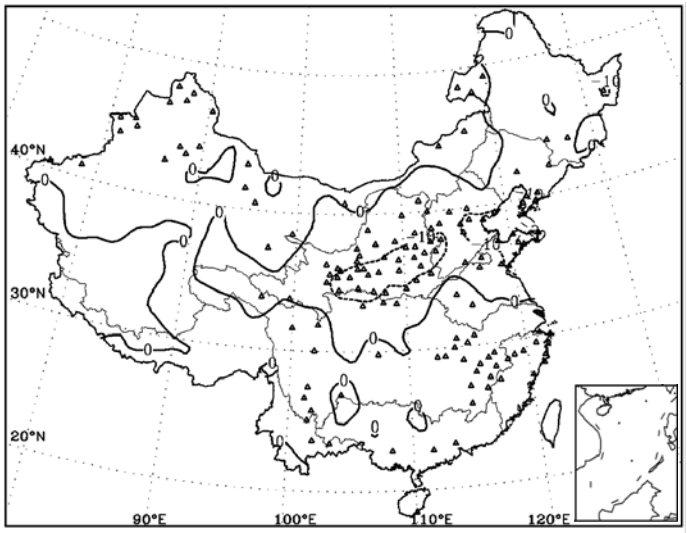
Figure 11 Same as for Figure 10 but for annual mean temperature. Unit:℃/10a.

Studies have shown that the runoff of rivers in these areas tend to decrease since 1950s (e.g. Zhang et al., 2008a). Particularly in the Haihe River and the Yellow River annual runoff decreased remarkably in the recent twenty years as a result of less precipitation and increasing human activities (e.g., Liu et al., 2004b; Li and Yang,

2004; Ma, 2005). Using the index of annual precipitation minus actual evapotranspiration to learn the change of net water supply to land surface, the long-term averaged annual net water supply during two periods 1960-1979 and 1980-2002 are compared. The annual net water supply decreased by about 40% and 48% during the second period under the actual evapotranspiration estimates by AA and Thornthwaite water balance model. This decreasing feature is consistent with the changes of runoff in the area with decrements about 40-80% (Zhang et al. 2008a). Droughts became more frequent and serious (Zhai et al., 2005). Haihe River basin in particular, suffered from continuous and serious droughts in the late 1990s and early 2000s. The similar decreasing trends in the estimated annual runoff and soil moisture in these areas can also be found in Figure 12 .



(a)



(b)

Figure 12 Same as for Figure 10 but for annual runoff (a) and annual mean soil moisture (b) estimated by the Thornthwaite water balance model during 1960-2002 over China. Units: mm/10a.

In southeast parts of China, including the river basins in southeast China, eastern Yangtze River basin and the middle of Pearl River basin, the annual precipitation has

increased (significant in some parts) along with significant increasing of air temperatures during 1960-2002. The changes of precipitation are explained by rain belt shift in China. The inter-decadal variability of the summer precipitation in East China is characterized by much precipitation in North and Northeast China during 1951-1978, rapid southward shift to the Yangtze River basin during 1978-1992 and further extension to South China during 1993-2004 (Ding et al., 2008). The weakening of the East Asia summer monsoon limits water transport to North China and results in more water vapor budget in the Yangtze River basin and the south areas in China (Zhang et al., 2008b).

At the same period, in these humid areas, affected by energy limitation, the trend of actual evapotranspiration follows the decreasing trend in potential evapotranspiration. Based on the analysis of the major controlling factors for potential evapotranspiration, the significant decreasing trend in sunshine duration (or solar radiation) which is mainly affected by increasing aerosol under rapid economic development has impacted the changes of potential evapotranspiration and actual evapotranspiration (Qian, 2006b).

The combination of increasing precipitation and decreasing actual evapotranspiration has amplified runoff in the lower reaches of the Yangtze River (Qin et al., 2005) and enhanced the soil moisture in southeastern China (Figure 12b). Significant increases in extreme precipitation have also found in the mid-lower reaches of the Yangtze River and in parts of south China coastal area (Zhai et al., 2005).

4.3.2 Western China

In western China, the increasing annual precipitation drives the increasing actual evapotranspiration, accompanied by significant increasing in annual mean air temperature (Figure 11). Particularly in southwest part of China, the increasing actual evapotranspiration is further strengthened by increasing potential evapotranspiration. The precipitation increase in warm and cold seasons in western China is due to the increase in both precipitation frequency and intensity and extreme precipitation also appears significant increases during 1951-2000 (Zhai et al., 2005). Accordingly, the hydrological cycle was intensified generally in western China during the past decades.

In Xinjiang region, located in the northwest of China, the total runoff tend to increase particular after 1987 (e.g. Ding et al.,2007).The increasing runoff and wetting in soil moisture in the area are also exhibited in Figure 12 which are consistent with the change of climate pattern from warm and dry to warm and humid proposed by Shi et al. (2003) and further demonstrated the accelerating water cycle. However, in some parts of the source areas of the Yangtze River and the Yellow River and west part of Qinghai-Tibet plateau, the annual actual evapotranspiration increased accompanied with decrease in annual precipitation, which had brought about a drier climate. The responses of decreasing runoff in the upper reaches of the two rivers to the change of climate are also found in the study of Ding et al. (2007). The similar decreasing trend of these areas in estimated runoff and soil moisture can be seen from Figure 12.

5 Conclusions and future outlook

Like many other places in the world, which have been reported by the previous studies, the potential evapotranspiration estimated by the Penman-Monteith method exhibits a decreasing trend in most areas and most seasons in China during the past decades. For China as a whole and the basin of the rivers in Northwest China, the annual and seasonal potential evapotranspiration all have a significant decreasing tendency except in winter during 1956-2000. The seasonal and annual potential evapotranspirations for most other basins show declining tendencies except for the Songhua River basin with slightly increasing tendencies. Particularly in the basins of southern China (except for the basin of the rivers in Southwest China) the declining trends are significant on annual scale and in summer.

Different methods are used to estimate potential evapotranspiration. As for the change of potential evapotranspiration, the methods considering various controlling climatic factors synthetically and with sound physical basis, which are close to the real climate change, showed a consistent trend such as the Penman-Monteith method and pan measurement. The methods based on single element, as is the case of the Thornthwaite method, may bring about wrong estimates. More attention should be paid and more tests should be done in the research of climate change impact on runoff and water resources, before the conclusions can be generalized.

Since 1980s, the annual mean temperature in China has been increasing, particularly during the end of the 1990s. However, the potential evapotranspiration calculated by the Penman-Monteith method during the same period does not showing an increasing trend as people expected. It further showed the existing evaporation paradox by the estimation of potential evapotranspiration. The analysis showed that, the air temperature is not a major controlling factor for the change of potential evapotranspiration when are compared to other climate elements such as solar radiation, wind speed and relative humidity. Generally, sunshine duration or solar radiation and wind speed are the major climate factors which affect the change of potential evapotranspiration in China during 1956-2000. It is worth of noting that, everything is changing, the major controlling factors could also be changing with the time, regions, the change of single climate elements and interrelationship to other elements. Surface solar radiation observations from 1990 to the present indicate that the solar are changing from dimming to brightening primarily in the Northern hemisphere (Wild et al., 2005; 2007). Evidence from China also supports that above findings (e.g. Yang et al., 2007). Such change would affect potential evapotranspiration, which was put forward by Fu et al. (2009) as one of major research priorities in the future.

The change of actual evaporation in China are quantitatively analyzed based on the estimation of the Thornthwaite water balance model. There are obvious differences in east and west parts of China. A decreasing trend is shown in most areas east of the 100ºE longitude during 1960 and 2002, except in northeastern Songhua River basin in northeast parts of China. An increasing trend is shown in the areas west

of the 100ºE. It should be kept in mind that the water balance model used in this study is highly simplified. For example, different vegetation covers across China in reality is replaced with the reference vegetation. Furthermore, a number of choices regarding the potential evapotranspiration and soil parameters (e.g. soil depth) used in the water balance model have been made, which certainly have impacts on the estimated water balance, including the actual evapotranspiration. The process of snow and snow melting are not included in the model which are important for the evapotranspiration in winter season and snow-melting season. Future studies are needed to further identify the roles played by these choices and by processes that are unaccounted for in the water balance model.

Synthetically considering the change of annual precipitation and potential evapotranspiration in China, which represent the water supply and energy available for actual evapotranspiration respectively, the causes for the change of annual actual evapotranspiration are explained at different climate regions. In the humid southeast part of China, the spatial distribution of the temporal trend for the actual evapotranspiration is similar to and dominated by that of the potential evapotranspiration. But in the arid northwest region, the trend in precipitation controlled the long-term change of the annual actual evapotranspiration. In the other regions, the combined effects of the changes in precipitation and potential evapotranspiration played a key role. The analysis are consistent to the results based on Budyko thesis (Ni et al., 2007).

For the detailed study performed in the Haihe River basin, the complementary relationship methods are also used to estimate actual evapotranspiration. The results further add the confidence to the decreasing trend in annual actual evapotranspiration in this region. It is essential to used different methods with different principles for estimating the actual evapotranspiration and verifying the results by cross comparison, since the long term and widespread observation data on actual evapotranspiration do not exist.

Based on the changes of precipitation and actual evapotranspiration, as well as evidence from runoff observations and precipitation extreme events, water cycle is preliminarily analyzed in China. The water cycle was intensified in western China as reflected by the increasing of precipitation, runoff and actual evapotranspiration. Whereas it was weakened in the Yellow River basin and northwards eastern China, as reflected by the decreases in precipitation and actual evapotranspiration as well as the remarkable decreases in runoff of many rivers. More frequent and serious drought events have occurred in recent years. As a consequence of the weakening water cycle in the Haihe River basin, the water supply capacity has decreased. In southeastern China, the contrary change of precipitation and actual evapotranspiration can't provide the obvious evidence of strengthening water cycle. But the increasing trend of annual precipitation minus annual actual evapotranspiration amplified the runoff in lower reaches of the Yangtze River.

Even though some interesting results have been obtained in this study based on different modeling approaches, the complex nature of the problem makes such modeling exercise challenging, and the interpretation of the results difficult.

Uncertainties exist in every step of the study, which may influence our conclusions. These uncertainties include the equipment and methods in the observation system, data quality and consistency, synthetic analysis with different study time periods (Fu et al., 2009), interactions and interdependence between the factors involved, accuracy of the estimation methods. All of these uncertainties are commonly difficult to be assessed and resolved thoroughly. Recognizing these uncertainties will improve our understanding of the conclusions.

The estimation of potential and actual evapotranspiration has a wide application. For hydrological model simulations, the direct estimation to actual evapotranspiration will reduce the number of parameters and increase accuracy, which are beneficial to improve the runoff simulation. Water requirement estimation and drought monitor index can be improved based on the knowledge of evapotranspiration. The analysis to water supply and demand can be carried out further in the future studies. Studying the past will yield lessons for the future, the changes of evapotranspiration and water cycle in the future are also an important research direction.

6 Acknowledgements

I feel very happy that I have had the opportunity to study in Sweden. The experiences in this beautiful country left me with a deep impression and I will remember these forever. During the study period, I enjoyed the gradual progress. However, many people who have helped me are more unforgettable.

Firstly, I want to express my gratitude to all the people at the Department of Earth Sciences at University of Gothenburg and National Climate Center of China Meteorological Administration, who supported me throughout my Ph.D. thesis work.

I want to send my sincere thanks to my two respectable supervisors, Prof. Deliang Chen and Prof. Chongyu Xu who is working at the Department of Geosciences at University of Oslo in Norway. I gained great enlightenment, helps and supports from their abundant knowledge, experience and the greatest patients not only for my study and research, but also for my life. A special thank also goes to their families; kindly care and friendly help made me feel at home, especially during holidays.

I would like to thank respectable directors of my institute in China, the National Climate Center. Encourages and supports are from Director Ziniu Xiao, Wenjie Dong (former director), Weijing Li, Yong Luo and Yongyuan You. My colleagues are very kind and helped me to deal with the work and things when I studied in Sweden. They are Prof. Qiang Zhang, Prof. Changhan Zhu, Prof. Peiqun Zhang, Dr.Fengjin Xiao, Ms. Zhen Li and Yu Chen, Dr. Shanshan Zhao, Dr. Shuiqing Yin, Dr. Yuping Yan, Dr. Yanxiang Liu, Yan, Dr. Bo Liu and Hongling Zeng.

My study in Sweden was carried out at the Regional Climate Group, University of Gothenburg. I can feel a cordial, energetic and harmonious atmosphere in the research group. I would like to thank all the past and present colleagues for fruitful discussion, kindly suggestion and help, and happy cooperation. Especially I wish to thank Prof. Hans Linderholm, Dr. Elisabeth Simelton and my friends Dr. Lin Tang and her husband Mr. Yongfeng Gu，Dr. Tinghai Ou and Ms. Yumei Hu.

Thanks also go to Dr. Lu Li and Dr. Ziqi Yan, with whom I shared a wonderful time while visiting University of Oslo.

Finally, this thesis is dedicated to my parents and my husband as well as my brother and sister and their families.

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