Common land model improvements and its application for estimating evapotranspiration in Xinjiang, China

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List of abbreviations

CCSM	Community climate system model
CoLM	Common land model
CRT	The maximum radial soil-root conductance of the entire active root system with a constant value of 0.097
D50	The depths to which root quantities are equal to 50% of all roots
D95	The depths to which root quantities are equal to 95% of all roots
D_i	The depth of soil at the ith soil layer
EC	Eddy covariance flux tower station
EOF	Empirical orthogonal function
ET	Evapotranspiration
EVI	Enhanced vegetation index
E_g	The vapour flux from surface to the atmosphere
$E_{s,a}$	The vapour flux from soil that is not covered by plastic mulch to the atmosphere
$E_{s,c}$	The vapor flux from soil that is not covered by plastic mulch to canopy air
FK	Fukang station
G0	Ground heat flux
Gm	Soil heat flux that is covered by plastic mulch
Gs	Soil heat flux that is not covered by plastic mulch
HR	Hydraulic redistribution
H_g	The sensible heat flux from the surface
$H_{m,a}$	The sensible heat flux from the plastic mulch to the atmosphere
$H_{m,c}$	The sensible heat flux from the plastic mulch to canopy air
$H_{m,s}$	The sensible heat flux between mulch and soil
$H_{s,a}$	The sensible heat flux from the soil to canopy air
$H_{s,c}$	The sensible heat flux from soil that is not covered by plastic mulch to canopy air

I	The irrigation water demand
IMPE	The simulation that is designed to assess the effects of plastic mulch on vapour flux
IRRIG	The simulation that is designed to assess the effects of irrigation on vapour flux
KZ-Ara	Aral Sea station in Kazakhstan
KZ-Bal	Balkhash Lake station in Kazakhstan
LAI	Leaf area index
LCC	Land cover change
LSMs	Land surface models
Qh	Sensible heat flux
Qle	Latent heat flux
RCP	Representative concentration pathways
Rmax	The max root quantity
RWUF	The root water uptake function
$R_{n,g}$	The net radiation absorbed by the surface
$R_{n,m}$	The net radiation absorbed by the plastic mulch
$R_{n,m,s}$	The net radiation absorbed by the soil
SVD	Singular value decomposition
WLWS	WuLanWuSu agro-meteorological experiment station
a_j	The root water uptake efficiency within the jth soil layer
b	An empirical constant
fc	The fraction of vegetation cover
fm	The fraction of plastic mulch cover
$f_{root,j}$	The root distribution fraction within the jth soil layer
m	Empirical coefficient
r(D)	The cumulative amount of roots above the soil profile depth (D)
α he	The experimental coefficient to determine irrigation start time

β	The irrigation demand factor
δ_T	The switch controlling HR
ε_j	The root water uptake fraction and within the jth soil layer
θ_s	The soil porosity
θ_i	The actual soil content
λ	The volumetric latent heat of vaporization
ρ_m	The water density
φ	The soil matrix potential
φ_{50}	The soil water potential when the soil hydraulic conductance is reduced by 50%
φ_{wilt}	The soil wilt potential
φ_{sat}	The soil water matrix potential at the saturation point

CHAPTER 1

Introduction

Over the past decades, climate change and anthropogenic activities, such as irrigation and the use of plastic mulch in oasis agro-ecosystems, have exerted a profound impact on the evapotranspiration in Xinjiang. As an effective tool, the Common Land Model (CoLM) was applied in order to simulate the evapotranspiration in this dissertation.

As a general introduction to this dissertation, the development of land surface models and the association with some key modules are discussed in the following sections. This chapter ends with a formulation of the key research goals and the synopsis, which will be addressed in this thesis.

1.1 **Research background**

Arid and semi-arid ecosystems account for about 41% of the world's land area, raise more than 2 billion of the world population (approximately a third of the world's total population), and are important components of the surface and atmosphere interaction system (Leemans and de Groot, 2003). Water is the most limiting factor for the ecosystem stability in arid and semi-arid regions and whether the water meets the demand or not will determine the ecosystem improvements or degradations. In addition, precipitation, the largest ingoing water flux is one of the main determinants of the plants' types and distribution and its seasonality influences the composition, structure and production of plant communities, as well as the patterns of water use of dominant species (Xu et al., 2007).

Xinjiang Uyghur Autonomous Region of China, characterized by an extremely low precipitation and high temperatures, is one of the typical arid and semi-arid regions in the world and is also faced with water scarcity problems (Liu et al., 2017). Under the warming trend in spring and winter, the proportion of glacial melt water runoff becomes one of the important parts of water resources, which has increased from 41.5% to 46.5% over the past 50 years (Chen et al., 2015; Gao et al., 2010). Evapotranspiration is the highest outgoing water flux in the hydrological cycle and is a primary determinant for water availability in Xinjiang. Further, the water balance is - to large extent- coordinated and maintained by the evapotranspiration. Therefore, an accurate evapotranspiration estimation and prediction in arid and semi-arid regions has a realistic and long-term implication for establishing a reasonable water strategy, improving the local ecological environment and a further understanding of hydrological processes.

Due to the simple structures of the plant communities, the ecosystems in arid and semi- arid regions have less capacity to resist and to recover from disruptive behaviours and are one of the most fragile and vulnerable ecosystems in the world (Smith et al., 2000). Periods of soil and/or atmospheric water deficit often occur during a plant's life cycle in the arid/semi‐arid regions. The reduction of soil moisture content during droughts lowers the plant water potential and decreases transpiration; this in turn causes a reduction of cell turgor and relative water content which brings about a sequence of damages of increasing seriousness (Porporato et al., 2001). Under such conditions, vegetation will suffer from water stress.

In order to adapt to the long-term drought, high temperature and other environmental factors, the desert vegetation gradually evolved into a special morphological and eco-physiological characteristics, such as a high water use efficiency, a deep root system and a high root-shoot ratio (Xu and Li, 2009; Xu et al., 2007). However, their metabolism was still vulnerable to the variations in water availability and the hydrological processes (Horton et al., 2001). Vegetation will adjust the physiological and biochemical reactions by reducing the stomatal conductance, reducing the photosynthesis rate so as to decrease the water consumption and to mitigate the water stress when water scarcity happens. Vegetation shows different strategies of water consumption under different degrees of water stress. Therefore, studying the evapotranspiration is helpful so as to understand the physiological and ecological characteristics of the desert vegetation and their adaptability to environmental changes.

Oases constitutes an extremely important ecosystem to prop up the human activities and the economic developments in the extensive arid regions of northwest China; it accounts for only 4% of the ecosystem coverage but is inhabited by 95% of the area population and most of the oases are distributed in the Xinjiang Uygur Autonomous Region (Guo et al., 2010; Zhou et al., 2012). With the development of social economy and the rapid growth of population, the oasis area has been expanding from 2.5×10^4 square kilometers to 10.4×10^4 square kilometers during the past (nearly half) century (Tao, 2009). In Xinjiang, the amount of water consumption by the oasis irrigation accounts for 94% of the total water consumption in agriculture and the majority of the water was dissipated into the atmosphere under the form of evapotranspiration (Yang et al., 2005). As one of the primary elements of the hydrological cycle, variations in evapotranspiration can influence the regional climate changes and human activities. An accurate evapotranspiration estimation can provide important references for a reasonable allocation of water resources and the sustainable development of the oasis economy in arid and semi-arid regions.

Due to the global warming and human activities, the acceleration and intensification of the global water cycle has become an undisputed fact (Durack et al., 2012; Huntington, 2006). As a link between groundwater, surface water and ecological water, the water cycle and its change profoundly affects the global water resources' security and the evolution of the ecological environment (and also influences the social development and human activities). Great attention has been paid by scientists to the important role of the water cycle in the evolution of the ecosystem, which became an important research topic among the scientific communities. Evapotranspiration plays an important role in the connection between the water and energy balance by exchanging the vapor flux between land and atmosphere. The global land evapotranspiration returns approximately 60% of the annual land precipitation to the atmosphere, indicating that asynchronous changes in evapotranspiration may lead to severe hydrological deficits (Zhang et al., 2015) and it can also dissipate about half of the radiation energy (Trenberth et al., 2009). Previous researches have pointed out that the mean temperature in the northern hemisphere would be 15 °C – 25 °C higher if the land evapotranspiration was assumed to be zero, suggesting important implications for the regional climate variability (Shukla and Mintz, 1982).

On the one hand, climate change can affect evapotranspiration directly through climate factors (such as precipitation, temperature, wind, radiation, etc.). On the other hand, it can also have an indirect influence on evapotranspiration by vegetation changes. Over the past five decades, the climate in the arid region of northwest China has changed notably (Chen et al., 2014; Chen et al., 2015). The temperature increased, associated with the continuous increase in precipitation, the glacial melt water and river runoff during the last decades, as also the water level of inland lakes and the frequency of flood disasters did. As a result, the vegetation cover improved, number of days with sand-dust storms reduced (Shi et al., 2007a). In particular, the previous study reported that the precipitation in the northwest of China increased significantly based on multiple reanalysis data (Global Precipitation Climatology Centre (GPCC), Global Precipitation Climatology Project (GPCP) and Climatic Research Unit (CRU)) (Yuan et al., 2015a) and the variations in precipitation were relevant to the north Atlantic oscillation (NAO) (Dai Xin-Gang and Zhang, 2013). Besides, the annual mean temperatures in this region increased at an average rate of 0.343 °C/decade during 1960-2010, larger than the mean rate for global land areas (0.13 °C/decade), which is mainly caused by the weakening of the Siberian High and the steady increase of greenhouse emission (Li et al., 2012b). Climate factors control the evapotranspiration by both the water vapour demand and the moisture supply. For example, the air temperature affects the evapotranspiration by regulating the air moisture holding capacity and determining the potential water fluxes from the soil to the atmosphere; precipitation can affect the evapotranspiration by controlling the soil water contents (Pan et al., 2015).

The 5th Intergovernmental Panel on the Climate Change (IPCC) assessment indicated that the carbon dioxide has increased by 40%, and that the global average temperature augmented by 0.85 °C over the past (more than one century). As an important kind of the nutrient and external environment, the variations in carbon dioxide and temperature could indirectly lead to changes in evapotranspiration by altering the vegetation’s physiological (e.g. leaf area index) characteristics and ecological processes (e.g., photosynthesis and respiration). Previous studies have shown that the vegetative greenness has improved over the last decades, which is one of the drivers to alter the evapotranspiration globally (Peng et al., 2011; Piao et al., 2011; Zhu et al., 2016).

As a basic functional unit, ecosystems keep the dynamic balance and stability through energy and mass exchange between land and atmosphere. Because the evapotranspiration is not visible, its measurements should be executed with the help of professional tools or techniques. There are numerous methods to estimate the evapotranspiration on a field scale, such as the Bowen Ratio and the Eddy Covariance. With the development of the Eddy Covariance techniques, it has been widely applied on order to get the evapotranspiration directly by measuring the latent heat flux. However, a dense global or regional evapotranspiration coverage cannot be represented using field measurements. On a regional scale, the methods include the water-balance, remote sensing, hydrological model and land surface model, etc.

It is difficult to measure the process of the exchanges of mass and energy fluxes between the land surface and atmosphere, due to their complicated non-linear process, and it is also difficult to measure the mutual effects with climate change. Land Surface Models (LSMs) provide a possible solution for simulating the evapotranspiration and quantifying the contributions of various environmental factors on evapotranspiration (Jorgensen and Bendoricchio, 2001). LSMs are one kind of the most advanced and widely applied models in the field of earth research, which is helpful for us to understand the mass and energy cycle, providing evidence for policy making and to prepare for the future climate change.

Land surface processes contain biophysical and biochemical processes, which involve the exchange and transmission of momentum, energy, water and mass. However, to date, no universal LSM has been accepted as the structures and representations of the ecological processes can differ between them. The diversity of the type of vegetation, soil colour, composition and topography contribute to the complexity of the land surface processes. Most LSMs build on the concept of the plant’s functional types to describe the vegetation attributes. However, it brings challenges for the model parameterization because of the vegetation types’ diversity, and a strong variability in the physiological activities in different geographic and environmental conditions despite the same vegetation type. Further, the soil texture and soil composition affect the vapour and energy transfer between soil layers by changing the soil’s physical properties, such as the soil thermal conductivity, hydraulic conductivity and saturated water content, etc. Also, the soil colour can alter the land surface energy balance by changing the ground reflectivity. Therefore, it is a hard and complicated job/work to investigate the process-based LSMs.

A desert ecosystem is the main land surface in arid areas. Because observations in the arid region in Xinjiang are scarce, the recognition on the physical rule of the land-surface process is limited and most of the land-surface parameters are uncertain and even unknown (Qiang et al., 2002). Because gobi and desert account for the largest part of the area in arid regions, the surface moisture content is relatively low, resulting in a lower energy exchange between the atmosphere and land in form of vapor flux. Thus, the energy exchanges are characterized by a high sensible heat flux and a low latent heat flux (Knorr et al., 2001). The desert vegetation has improved its ability to accommodate the arid environment through long-term evolved eco-physiological and morphological characteristics (e.g. root distribution, root uptake water function and hydraulic redistribution). Most of the LSMs have not formed a complete parameterized scheme for the desert vegetation, which leads to the underestimation of the latent heat and an overestimation of the sensible heat.

The oasis ecosystem is another important land surface in arid regions. Due to the dramatic human activities, the oasis has been gradually expanding from the surrounding natural vegetation. Both the expansion of oasis and limited water resources conjointly contributed to the irrigation technology. Drip irrigation under plastic mulches are widely used to improve the agricultural production by suppressing the soil evaporation and to promote the water use efficiency and soil temperature in the vast arid and semi-arid regions (Cuello et al., 2015; Hou et al., 2010). Drip irrigation under plastic mulch changed the land surface features, associating with a changing water and energy balance. For example, black plastic mulch has obviously altered the energy fluxes because of its lower albedo, which is associated with less radiation penetrating into the greenhouse as well as a portion of energy stored inside the plastic mulch (Fan et al., 2015). Therefore, the process-based module of irrigation and the use of plastic mulch are required for a reasonably accurate evapotranspiration simulation in Xinjiang.

Overall, the scarcity of water resources in Xinjiang is one key factor in supporting the economic development and maintaining the stability of the ecological environment. The agricultural and ecological usage of water are two main approaches for the water consumption. Therefore, the cropland expansion which resulted from anthropogenic activities, will exert an influence of spatio-temporal evapotranspiration changes. Following the development of the social economy, agricultural expansion and the increase in population, more attention should be paid to water resources' studies. Finally, an accurate estimation of the water consumption from evapotranspiration will be of great help to understand the water use situation and the relation between the water consumption and water recharge and will provide scientific support to allocate water resources reasonably in Xinjiang.

1.2 Land surface model

With the development of the atmosphere science and the deep understanding of the weather and climate, the importance of the impact of the underlying surface on the atmosphere has been acknowledged. The mutual effects between the atmosphere and land surface depend on the fluxes' exchange, including energy, material and momentum and also on the physical and chemical characteristics, including the soil structure and colour, slope, aspect and land cover type, et al. The land surface processes contain almost five layers in the global system (i.e. atmosphere, biosphere, lithosphere, pedosphere and hydrosphere). Therefore, the development of the general atmospheric circulation model needs the incorporation of the land surface model. Furthermore, the development of the general atmospheric general circulation model should emphasize the improvement of the manner in which to simulate the physical and chemical processes factually and objectively and how to simulate the fluxes between the atmosphere and land surface accurately.

The research work concerning the mutual effects between vegetation, soil and snowpack has started during the early 50's of the last century. Since the 60s, scientists have been making great progress in the research of the interaction between the atmosphere and land surface and also the land surface model. And since then, many experiments were carried out regarding the sensitivity of the underlying surface to the climatic, ecological and hydrological processes. In particular, Charney (1975) reported that a reduction of the vegetation with a consistent increase in albedo in the Sahel region, at the southern margin of the Sahara, would cause a sinking motion, additional drying and would therefore perpetuate the arid conditions. This hypothesis was also verified by the climate model simulations in his research. Shukla and Mintz (1982) found that the global fields of rainfall, temperature and motion strongly depend on the land surface evapotranspiration and the surface vegetation, producing the evapotranspiration, is an important factor in the earth's climate. Mintz (1982) reported that the evapotranspiration returns approximately 60 percent of precipitation to the atmosphere based on numerically simulated climates. Sud and Smith (1985) found that the ITCZ (inter-tropical convergence zone) with a GLAS (Goddard Laboratory for Atmospheric Sciences), GCM (General Circulation Model) moved southward, to about 14 °N, which is close to its observed location at about 10 °N based on numerical simulations with a GLAS GCM. This was primarily caused by the relative moisture divergence from the smoother Sahara. In other deserts, which had little rainfall in the July simulation of the Control run anyway, there was virtually no change. Xue et al. (2004) found that - under unstable atmospheric conditions-, not only low-frequency mean forcings from the land surface, such as the mean monthly albedo, but also the perturbation of the vegetative processes were important to the monsoon evolution, affecting its intensity, the spatial distribution of the precipitation and the associated circulation on a continental scale. In addition, Yasunari (2007) found that the snowpack, soil moisture, and vegetation are vital to the East Asian precipitation and monsoon circulation.

On the whole, previous scientists dedicated a lot of time to investigate the sensitivity of the land surface features including the soil moisture, albedo, and roughness, to the atmosphere circulation. And all the results (of their research work) show that the effects of the land surface characteristics on the climate are of importance. Therefore, in order to investigate the sensitivity of the land surface characteristics on climate change, the interaction between them and the underlying mechanism, the more complicated and accurate representations of the land surface processes are required. The definition of the land surface model was initially put forward, and has experienced three generations until now.

The first generation of the LSMs was developed in the late 60's of the 20th century. The biggest trait of the models in this stage can be regarded as a "bucket". And the main characteristics can be summarized by the following aspects: the LSMs generally assume that the soil is a bucket. When the soil is moisture saturated, the exceeding water will overflow in the form of runoff. The soil evaporation is determined by the potential evaporation multiplying coefficient. The surface parameters including roughness and albedo, are fixed. The advantage of the first generation of the LSMs is that all of them abided by the energy balance equation. But, the disadvantage of this model type is that the surface parameterization is simple and that the application to a large-scale area is limited. In addition, the first generation of LSMs did not consider the effects of the vegetation on the exchange of matter, energy and momentum between land and atmosphere. Therefore, the surface flux (simulated by the first generation LSMs) has some limitations: the influence of the surface features on the atmosphere is distorted.

From the late 1970's to the 1990's, it was the main development stage of the second generation land surface process models. The land-surface process model at this stage takes into account the complex physical processes between the land and atmosphere gases, and a set of parametric schemes for the flux exchange between the vegetation canopy and the atmosphere have also been constructed using conceptual and theoretical frameworks, including radiation exchange schemes, turbulence exchange schemes and hydrothermal transport flux schemes. This model also takes into account the stomatal conductance of vegetation and establishes the relation between the stomatal conductance and environmental factors. In addition, when calculating the transport of water and energy between the different soil layers, the stratification of the soil is considered. Most of these models treat the canopy as one layer, so these LSMs are also defined as "big leaf" models, such as BATS (Biosphere-Atmosphere Transfer Scheme) (Dickinson, 1986) and SiB (Simple

Biosphere model) (Sellers et al., 1986).

The third generation of LSMs began after the 1990s. Due to the significant progress made in physiology, ecology and the physico-chemical processes in vegetation, favorable conditions have been created for the development of the third generation of LSMs. The third generation of LSMs mainly considered the physicochemical process (photosynthesis) of vegetation. They not only couple the exchange of fluxes between land and atmosphere effectively, but also take into account the physico-chemical processes and enhance the model's simulation ability. The representative model in this stage includes LSM (Bonan, 1996) and SiB2 (Sellers et al., 1996).

In short, after decades of development, the land-surface process model has achieved fruitful results and accumulated a large amount of parameters and observations in different regions. However, there are still many problems to be solved in the current LSMs. In particular, in the arid region, the application of land-based process models is still challenged, due to relatively limited research on the underlying properties, including the surface reflectance, roughness and soil properties. Also, due to the sparse vegetation and the fragile ecosystem (in arid regions), it is vulnerable to be disturbed by human activities. Specific human activities include the use of irrigation and plastic mulch, which have not been considered conjointly by most of the existing LSMs. Therefore, so as to simulate the flux exchange between atmosphere and land reasonably and precisely, the impact of human activities on the surface features and related mechanisms need to be embedded into LSMs.

1.3 The application of LSMs in arid and semi-arid regions

1.3.1 The application of LSMs in the desert vegetation

The LSMs often encounter the problems of underestimating the latent heat and overestimating the sensible heat in arid regions, which results from the fact that most LSMs cannot simulate the desert vegetation’s response to water stress in arid zones (Lee et al., 2005). At present, some researchers have put forward some proposals so as to solve this problem by clarifying the root distribution of plants in arid areas, the mechanism of root water absorption and forming a set of reasonable parameterization schemes. Therefore, the incorporation of the latest root function into the LSMs is expected to be an effective solution. The main reason is that the root system is the main pathway for all vegetation to absorb moisture and nutrients from the soil (Dawson et al., 1998). However, the water absorption capacity of the root system has a great variability for the root water absorption efficiency (Feddes et al., 2001; Laio et al., 2006). For example, it can uptake more water from deeper soil layers in order to mitigate stress caused by water loss from the surface soil moisture (Lai and Katul, 2000). In addition, the root system has the ablility of hydraulic redistribution where plant roots take-up water from deep moist soils and redeposit it into the upper soil layer at night for the purpose of root uptake to sustain the daytime transpiration (Bleby et al., 2010).

The simulation of the root water uptake process is one of the most active research directions in the field of hydrology and land surface processes at present and forms the key part for studying the hydrology, ecology and environment. In order to study the physical and physiological mechanisms of the root water uptake and its influencing factors, it is necessary to have sufficient knowledge of the plant root water uptake model (Alaoui et al., 2011; Buyuktas and Wallender, 2002). The root water uptake process is usually described in most LSMs as a simple linear function between the root water uptake efficiency and the soil matrix potential and root fraction, which are not able to capture the variability of roots to uptake water, resulting in incorrect models of the water vapour and CO_2 fluxes of plants under water stress conditions (Randall et al., 1996; Saleska et al., 2003). Due to the long-term limits induced by extreme aridity and high temperatures, vegetation in dry land regions has evolved into rich and deep root systems and high root/shoot ratios and adapted to the arid environment by adjusting its own water use efficiency. In the deep soil layers, the root has a higher water absorption efficiency but a water absorption efficiency in the upper soil layers with less water (Lai and Katul, 2000). Since the simple linear model of the root water uptake underestimates the latent heat flux in arid areas, the non-linear model of the root water uptake is expected to improve the simulation accuracy of the latent heat flux. Li et al. (2013b) significantly improved the simulation accuracy of CoLM's latent heat flux at the Fukang Station in Xinjiang by establishing an exponential root uptake water function. Zheng and Wang (2007) established a non-linear function by setting the threshold of the soil water potential so as to allow the root system to obtain more moisture in humid soils for vegetation transpiration. Lai and Katul (2000) improved the accuracy of the simulated evapotranspiration by decomposing the root-efficiency function into two terms: a root “shut-down” mechanism occurring around wilting point and a maximum efficiency when soil moisture availability is not limiting water uptake. Jing et al. (2014) and Li et al. (2012d) also found that the non-linear root water uptake efficiency (function) is more suitable for modeling the latent heat flux in arid areas, as some vegetation types are not exposed to water stress. Hydraulic redistribution is also an important factor except that the vegetation adjusts the water use efficiency through the root system to mitigate water stress during the drought period. Studies have shown that during the drought period, vegetation uses roots at night to lift moisture from deep soil layers to upper layers for transpiration at daytime and also, it transports moisture from upper layers to deeper soils to reduce the surface evaporation and runoff after rainfall. The transported moisture in deeper soils is re-used by vegetation when encountering drought or water stress (Domec et al., 2010; Lee et al., 2005; Ryel et al., 2003). Ryel et al. (2002) found that the hydraulic redistribution could increase the whole canopy transpiration during the drought period. Similar findings were also reported by other studies (Li et al., 2012d; Zheng and Wang, 2007). However, Tang et al. (2015) showed that the accuracy of the soil moisture simulation is still not satisfactory, although the hydraulic redistribution is considered in the LSMs. The possible reasons may be attributed to the driving data, the representation of water processes and the inaccurate model parameterization, etc. (Tang et al., 2015; Zheng and Wang, 2007). Although the above mentioned processes play a vital role in influencing the evapotranspiration within arid/semi-arid regions, few LSMs have taken them into consideration conjointly when simulating the evapotranspiration.

1.3.2 The application of plastic mulch and irrigation in land surface models

Plastic mulch technology constitutes an important aspect of the management of modern agricultural ecosystems. The technology, which was developed in the 1940s and introduced to China in the 1970s, has now widely been adopted around the world. Because of its high water-saving benefits, it is widely used in arid areas. Through a large number of observation experiments, many researches were devoted to the hydrothermal effect caused by the use of plastic mulch. For example, Feng (1980) studied the effects of plastic mulch on light and temperature, as well as the water circulation inside the membrane, by comparing the experimental results (with and without plastic mulch) covering vegetables. They found that the mulched ground had a significant warming effect on the surface temperature relative to the ground without plastic mulch covering. And the warming effect decreased as the soil depth was increasing. The reason for this is that the white plastic mulch has a high transmission of light, leading solar radiation to the ground during the day, as a result of the warming the soil. Due to the air impermeability between the soil surface and the atmosphere under the influence of plastic mulch, the turbulence and the advection flow cannot be heat-transferred between land and atmosphere so that more heat would be saved in the membrane. In the early crop stage, it is also affected by the solar radiation reflecting from the surface. Due to the the mulching film’s high reflectivity, the light effect has also been obtained inside the crop canopy (except for the soil warming). They found that - under the plastic mulch covering - the light temperature inside the crop was 10.5% higher than (the one) in the non-mulch covering condition. Concerning the water cycle inside the membrane: as the membrane blocks the passage between the ground and atmosphere, the water vapour evaporating in the soil can only exist in the gas chamber formed between the soil and the membrane. Xia et al. (1997) investigated the vertical distribution of the soil moisture content and its variation through the experiments with and without plastic film mulch cover. The results showed that the plastic mulch affected the water circulation inside the soil and changed the soil water content and its variation characteristics. Under long-term non-precipitation conditions, the water content within 20 cm depth from the soil surface, can still maintain high/big water contents, so as to provide enough water for the crop vegetation transpiration in the seedling stage. Hou et al. (2010) conducted experiments on potatoes in the Minqin Agricultural Extension Centre in Gansu Province. Under a plastic mulch cover, the average daily soil temperature was 2-9 °C higher than in the uncovered condition. When the period exceeds 60 days, the influence of the plastic film on evapotranspiration is getting smaller. Besides, Wang et al. (2009) found that the crop water use efficiency decreased according to the extension of the mulching period.

Although a large number of observational experiments have been carried out by researchers on the warming and moisturizing effect of plastic mulch, the studies on the mechanism of the process analysis started relatively late. For the first time, Mahrer (1979) established an energy balance on the surface of plastic mulch and simulated the change of the soil temperature under plastic mulch by means of a numerical model. He found that the mulch increases the sensible heat by reducing the loss of the latent heat under the form of soil evaporation and it also reduces the ground longwave radiation so as to increase the soil temperature. His research provided a reference for the process-based studies on the warming and moisturizing effect of plastic mulch. Chung and Horton (1987) established a two-dimensional hydrothermal balance equation on the surface of plastic mulch and conducted numerical simulations and site validation so as to improve the accuracy in simulating the soil water content and soil temperature. Ham et al. (1994) established the energy balance equation on the mulch surface and simulated the temperature of the film surface by the Newton-Raphson equation, which resulted in a solid foundation for the mechanism research of the usage of plastic mulch in oasis agro-ecosystems.

Irrigation is an important agricultural management tool for the oasis ecosystem in arid regions. With the development of a modern agricultural irrigation technology, the irrigation methods have developed from a traditional flood irrigation to more water-saving irrigation methods, such as sprinkler or drip irrigation. Because of the economic development, drip irrigation has become one of the most widely used irrigation methods in the Xinjiang oases. Previous studies found that irrigation affects the agricultural ecosystems’ evapotranspiration, which in turn influences the surface water cycle (Evans and Zaitchik, 2008; Lo and Famiglietti, 2013). However, at present, no widely used irrigation module has been adopted by the land surface model, especially for the drip irrigation which is a high water-saving irrigation technique. The reason is that the irrigation parameters (such as the timing of irrigation and the amount of irrigation water) are difficult to determine. Especially when simulating surface fluxes on a regional level, the irrigation timing and the amount of water used for irrigation in different areas are largely controlled by farmers themselves (Evans and Zaitchik, 2008)

At present, a large number of researches are devoted to develop or improve the existing irrigation parameterization schemes, to integrate them into the land surface model and to further investigate the hydrological effects of irrigation on a regional scale. Most land surface models or ecological models assume that irrigation occurs when the soil moisture is below a certain threshold (which means the soil water potential increases to a certain threshold) (Ozdogan et al., 2010). For example, when simulating the irrigation, Liu et al. (2008b) assumed irrigation occurred when the soil water potential reached 30% of the soil water potential on the vegetation wilting point. Also, previous studies set a fixed irrigation time in the model according to the local situation. For example, Vahmani and Hogue (2014) simulated the irrigation by setting irrigation intervals from one day to three days. Compared with the measurements, it was found that the best simulation was achieved when the irrigation interval amounted to three days. Irrigation water usage is another important parameter that affects the simulation of the irrigation process. Compared to the traditional flood irrigation method, the sprinkler or drip irrigation will not cause the soil moisture to be saturated or to reach the field capacity. Firstly, Pokhrel et al. (2012) created an irrigation demand factor so as to determine the water requirements for drip irrigation. The values of the irrigation factor range from zero to one. When the irrigation demand factor is zero, the irrigation water usage is zero, and when the irrigation water factor amount to one, it means that the soil reaches the field capacity after irrigation. Hanasaki et al. (2008) and Pokhrel et al. (2012) suggested the irrigation demand factor to be 1.00 for rice and 0.75 for other crops. Evans and Zaitchik (2008) assumed that the irrigation amount can be determined by the difference between the soil water content (when the crop is not subject to water stress during the growing season) and the actual water content.

Because various land-surface models have different structures, algorithms and parameter schemes in simulating hydrological processes, a unified solution has not been developed to simulate irrigation. In oasis agro-ecosystems, irrigation is often accompanied by plastic mulch (i.e. drip irrigation) because of water scarcity. The drip irrigation and use of plastic mulch have not been conjointly considered in the current land surface models. Therefore, a reasonable parameterization scheme needs to be developed in order to simulate evapotranspiration precisely in the Xinjiang oasis agro-ecosystems.

1.4 The study area

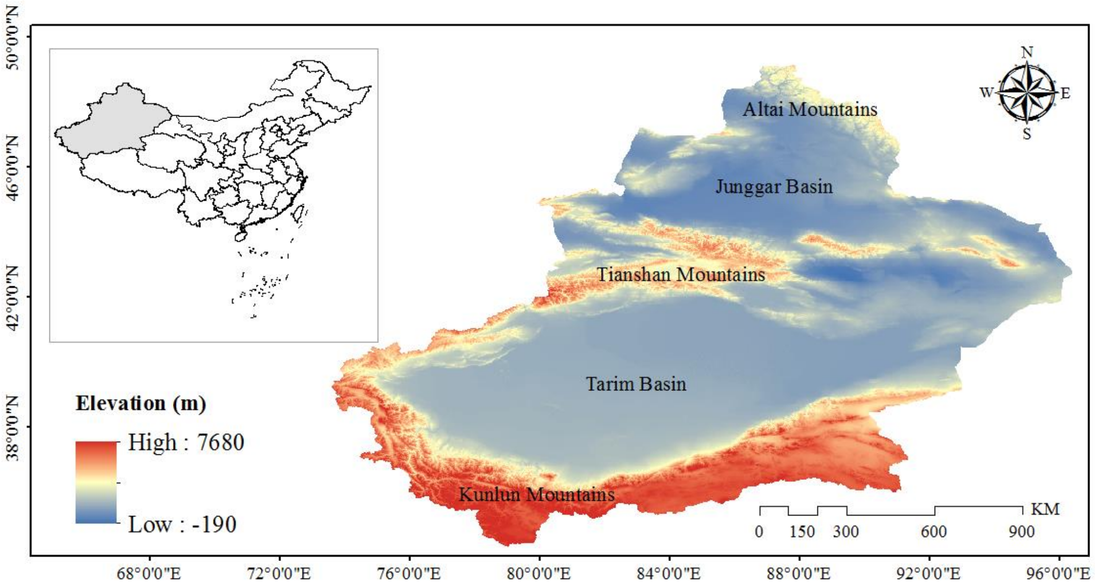

Figure 1.1 The study area.

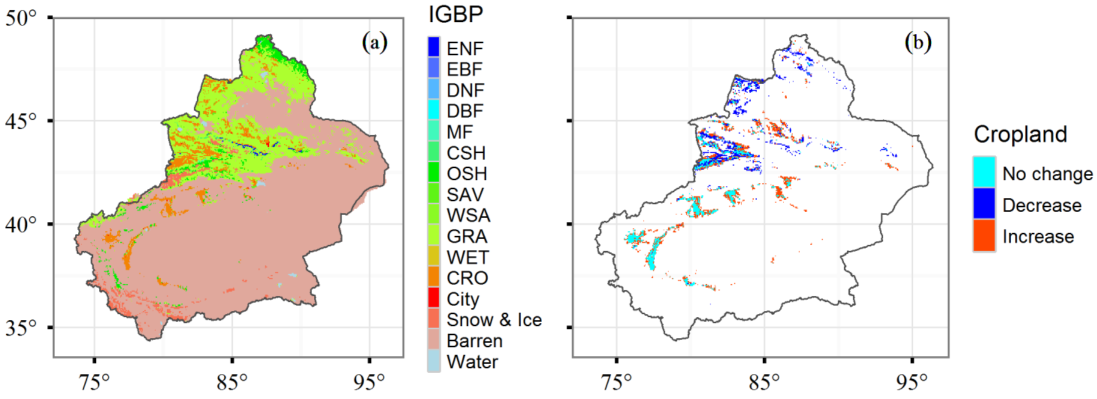

Figure 1.2 Distribution of the vegetation types (a) and the spatiotemporal changes of cropland from 2001 to 2012 in Xinjiang, China (b). ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; DNF: Deciduous needleleaf forest; MF: Mixed forest; CSH: Closed shrub; OSH: Opened shrub; SAV: Savanna; WSA: Woody savanna; GRA: Grassland; Wevapotranspiration: Wetland; CRO: Cropland.

Xinjiang Uyghur Autonomous Region extending between 73°40′ – 96°23′E and 34°25′ – 49°10′N and covering an area of about 1.6 million km^2 is the largest province-level region in China (Figure 1.1). Surrounded by three mountains, Altai, Tianshan, and Kunlun from north to south, the thermodynamic contributions are largely independent of atmospheric circulation, and two vast deserts lie between the mountains, i.e., Taklimakan desert (the second largest shifting-sand desert in the world) located in the Tarim basin and Gurbantunggut desert in the Junggar basin (Zhang et al., 2012). Approximately, 62% of Xinjiang’s total areas are covered by deserts with a low percentage (~ 9%) of desert vegetation coverage, dominated primarily by xeric shrubs (e.g., *Haloxylon ammodendron* and *Tamarix ramosissima*) (Li et al., 2013a) and 4.3% are covered by oases of which over 90% are under agriculture (Mamtimin et al., 2011) (Figure 1.2). Only about 1% is covered by forests of which 85% is coniferous forest that are largely distributed near mountainous areas (Xu et al., 2011). Since the onset of the 21st century, Xinjiang has undergone dramatic land-use changes and cropland increased by 11% from 2001 to 2012.The altitudes ranges from less than -150 m in Junggar basin to more than 7500 m in Kunlun Mountain. Located in the hinterland of the Eurasian continent, and far away from the ocean, Xinjiang is one of the driest regions in the world, and is characterized by a typical continental climate (Wang et al., 2013a) with mean annual precipitation less than 50 mm/year in Taklimakan Desert and more than 400 mm/year in Tianshan Mountains. The mean annual temperature varies from ~ 3 °C in the Tianshan Mountains to ~13 °C in the Taklimakan Desert (Yuan et al., 2017). During the period from the 1980s to 1990s, Xinjiang experienced a significant warming and increasing wet trend (Shi et al., 2003). However, precipitation has diminished and warming trends have stalled and even reversed since the onset of the 21st century (Chen et al., 2015).

1.5 Rationale and synopsis

1.5.1 Research objectives and questions

The Xinjiang Uygur Autonomous Region is located in the deep Eurasian continent with an average annual rainfall of less than 200 mm. This region includes the world's typical arid and semi-arid areas and very fragile ecosystems. Water scarcity has become a key factor in the restriction of the ecosystems’ sound development. The metabolism of the desert vegetation in arid regions is heavily dependent on the available water, so vegetation transpiration is an important indicator to assess the growth and development of the desert vegetation in arid regions. In addition, evapotranspiration is an important part of the water cycle in dry regions. It concerns maximum water vapour fluxes from the land into the atmosphere and its amount directly affects the allocation of water resources directly. Ecological and hydrological processes in arid regions are highly vulnerable to climate change and human activities. The impact of the future climate change on evapotranspiration in dry areas is also one of the hot issues in scientific research.

The process-based LSM is one of the effective tools for studying evapotranspiration in arid regions. It is advantaged by the ability to reconstruct the evapotranspiration over the past and to predict evapotranspiration in the future, as well as the ability to simulate the effects of various environmental factors on evapotranspiration. However, Most LSMs are still faced with many problems in flux simulations in Xinjiang. For example, they often underestimate the latent heat in the arid desert vegetation. In addition, the LSMs still lack relevant modules in their applications in oasis agro-ecosystems, induced by human activities such as irrigation, as well as the use of plastic mulch.

Based on the above background and existing problems, this dissertation uses the Common Land Model (CoLM) as a research platform, and proposes four scientific questions, in order to improve its accuracy to simulate evapotranspiration in Xinjiang, as well as the exploration of the impact mechanism of climate and land cover change on evapotranspiration in Xinjiang on a regional scale (past and future). The four scientific questions are as follows:

1). Can it improve the accuracy in simulating evapotranspiration in oasis agro-ecosystems after adding irrigation and plastic mulch modules into CoLM?

Due to the rapid population expansion and the socio-economic development, the oasis area has been expanding continuously during recent years. The contradiction between the oasis expansion and limited water resources is becoming more and more prominent. Also, because of the modern development in technology, the water-saving irrigation technology and the use of plastic film - to some extent- eased the water demand for the oasis expansion. However, these human activities were caused by changes in surface features and their impacts on the exchange of land-air fluxes have not been considered conjointly by most LSMs. Specially, the surface processes caused by drip irrigation, which is widely used in the oasis agro-ecosystems in Xinjiang, are not covered by most LSMs.

Irrigation has changed the surface water balance and thus has exerted a significant influence on the surface water cycle. A widely accepted and applied module of the irrigation module for LSMs does not exist, because of differences in the structure, as well as in the representation of hydrological processes. The reason is that irrigation parameters are difficult to be determined, such as the irrigation starting time, irrigation water demand, etc. Besides, due to the different circumstances between regions, the irrigation starting time and water demand are largely determined by farmers. In addition, due to the use of plastic film, soil evapotranspiration is significantly inhibited so that the soil can maintain higher water contents for vegetation to evaporate. Therefore, the use of plastic film also changed the surface water circulation. Although previous researchers have studied the mechanism of the exchange of surface energy transmission under the use of plastic film, the processes represented in LSMs are relatively scarce. In this dissertation, we will design a set of irrigation parameterization schemes, in terms of drip irrigation under plastic mulch, and embed them into the CoLM to see if it can improve the CoLM performance in simulating evapotranspiration in oasis agro-ecosystems, Xinjiang.

2). Can it improve the accuracy in simulating evapotranspiration after the integration of the latest root functions into CoLM for the desert ecosystems?

Under the conditions of a prolonged high temperature and water shortage, the desert vegetation has evolved into a root system characterized by deep roots and a high root/shoot ratio. These root system's physiological characteristics allow the vegetation to uptake more water from deep soil layers for transpiration. Because the root system is the main channel for the vegetation's water uptake, the performance of the simulation of the root water uptake in LSM's directly affects the accuracy in simulation of evapotranspiration and thus the precision of the flux exchange between land and the atmosphere.

Based on the observed root distribution and fluxes' data at the Fukang Desert Station in Xinjiang, Jing et al. (2014) comparatively analyzed the different root water uptake functions. Li et al. (2013b) found that the experience-based exponential non-linear root water uptake function can improve the accuracy of the energy fluxes' simulations between the land and atmosphere effectively. Their work pointed out that the non-linear root water uptake function can ameliorate the simulation accuracy of the evapotranspiration compared to the default linear water uptake function in CoLM.

Hydraulic redistribution is another major function of the root system (regarding arid vegetation). Recently, Hao et al. (2010) also found the related functions of this root system in the Tarim River basin in Xinjiang. Li et al. (2012d) and Zheng and Wang

(2007) added such a function in the CABLE (Community Atmosphere-Biosphere-Land Exchange), CLM3 (Community Land Model version 3) and IBIS2 (Integrated Biosphere Simulator version 2) and improved the accuracy of their simulated water vapour flux. Therefore, based on the previous work, root functional modules (root distribution, root water uptake function and hydraulic redistribution) which are related to root characteristics are integrated into the CoLM to test the effect of integrating all the above functions on evapotranspiration simulations in desert ecosystems.

3) What are the responses of evapotranspiration to climate and land cover change in Xinjiang?

Over the past few decades, the climate change in Xinjiang has been significant and transformed from the warm-dry to the warm-wet type (Shi et al., 2003). Regional temperatures have also been rising during the past nearly 30 years, and the rate is higher than the global average (0.36 ° - 0.42 °C/10 years vs 0.27° - 0.31 °C/10 years) (Hu et al., 2014). Precipitation in Xinjiang has also increased significantly in the last 50 years (Hu et al., 2017). However, precipitation has been declining since the start of the 21st century (Chen et al., 2015). Due to human activities, land use types have also changed significantly. Since the beginning of the 21st century, the cultivated area has increased by nearly 11%. Climate and land cover change will inevitably lead to changes in evapotranspiration. However, the response of the Xinjiang evapotranspiration to the regional climate change and land cover change is not clear. The land surface model, as an important tool and approach to study the ecosystem, can explore the contribution rate of different environmental factors to evapotranspiration through scenario simulations.

4) How will the evapotranspiration change in the future in Xinjiang?

Regional climate change, to a large extent, determines the evapotranspiration changes in Xinjiang. The impact of future climate change on evapotranspiration in Xinjiang will directly affect the amount of available water resources, as well as the allocation of water resources and the upgrading of the industrial structure in Xinjiang. However, it is unclear how the climate in Xinjiang will change in the next 30 years and how it will influence the evapotranspiration. In this dissertation, we will use the improved land surface model CoLM as a tool to explore the evapotranspiration in Xinjiang in the next 30 years under two scenarios of greenhouse gas emissions (RCP4.5 and RCP8.5).

1.5.2 Outline of the dissertation

The above-mentioned scientific questions and research goals will be analyzed and discussed in the following part of this dissertation. This dissertation was divided in six parts. Figure 1.3 illustrates the structure of this dissertation and the link between them. The first part introduced the research background and the implications of simulation evapotranspiration in Xinjiang, China. The Chapters 2 through 4 correspond to papers which aim to solve the above research questions in detail and all of the three chapters are published or prepared for publication in international peer-reviewed journals. Chapter 5 and Chapter 6 summarize and discuss the results of the previous chapter and shed also some light on future research.

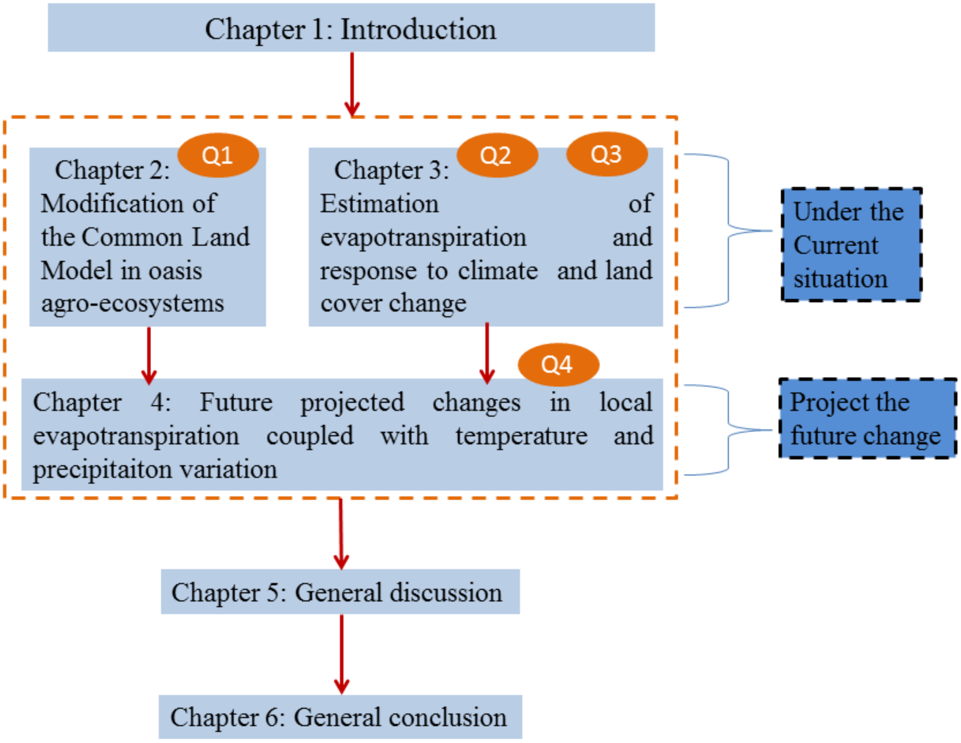

Figure 1.3 Dissertation outline.

CHAPTER 2

Modification of the Common Land Model in oasis agro-ecosystems

Modified from: Xiuliang Yuan, Jie Bai, Longhui Li, Philippe De Maeyer. (2018). Modelling the effects of drip irrigation under plastic mulch on vapor and energy fluxes in oasis agro-ecosystems, Xinjiang, China. (Submitted to Agricultural and Forest Meteorology)

Abstract

Drip irrigation under plastic mulch is a common agricultural practice for oasis agro-ecosystems in the extensive arid regions of northwest China, and it is widely used to improve agricultural production by suppressing soil evaporation. The widespread application of plastic mulch has also obviously altered land characteristics and, thus, altered the partitioning of vapor and energy between the surface and the atmosphere. However, these physical processes, to date, are poorly incorporated into land surface models. In this study, an irrigation scheme and a plastic mulch module were incorporated into the CoLM to examine their influences on vapor (evapotranspiration) and energy fluxes, and the evapotranspiration observations were used to evaluate the model performance of irrigation effects. A sensitivity analysis indicates significant sensitivity relative to both the amount and timing of irrigation on vapor fluxes. In addition, our results show that the revised CoLM with an added irrigation module produced a better simulation of evapotranspiration than the default CoLM. However, large uncertainties still exist such that fluctuation in the simulated evapotranspiration is substantial and could not capture the seasonal patterns of evapotranspiration, without considering the impact of plastic mulch. Incorporating the mulch module improved the CoLM performance for both vapor and energy fluxes. Plastic mulch reduced net radiation and sensible and latent heat fluxes, and it suppressed ground heat fluxes during the daytime and improved ground heat fluxes during the nighttime. Our results indicate that the agricultural practice, drip irrigation under plastic mulch, should be implemented into CoLM and other land surface models for studying vapor and energy fluxes in oasis agro-ecosystems or other similar dry agricultural ecosystems.

Keywords: Oasis agro-ecosystem; Agricultural practice; Physical processes; CoLM; Evapotranspiration; Land characteristics

2.1 Introduction

An oasis, an active component of ecosystems in the extensive arid regions of northwest China, links soil and atmosphere by energy and mass transports and has aroused more interest than ever before from researchers (Liu et al., 2010; Luo et al., 2008a; Zhang et al., 2016). Anthropogenic activities, including irrigation and the use of plastic mulch, have become common practices to support agricultural production in oasis agro-ecosystems (Du et al., 2006; Zhao et al., 2010) and have also exerted impacts on land surface fluxes by changing physical processes and characteristics of the earth surface (Fan et al., 2015; Yang et al., 2012). In particular, studies of these agricultural practices have been shown to affect local and regional climates by modifying the partitioning of vapor and energy between the surface and the atmosphere (Campra et al., 2008; Cuello et al., 2015). Therefore, an accurate description of land-surface processes over oasis agro-ecosystems in arid regions is becoming more and more important. Further, the improvement of the parameterization schemes of land surface models to describe the physical and biochemical processes of the atmosphere-land interactions factually will also be helpful to regional weather forecasting and climate prediction, when coupled with climate models.

The technology of drip irrigation under plastic mulch has been widely applied in recent years in the Xinjiang Uygur Autonomous Region of China. This technology has been proven to have a high potential for suppressing soil evaporation and improving soil temperature and water use efficiency in arid areas (Cuello et al., 2015; Hou et al., 2010; Wang et al., 2009). Many studies have focused on the influence of drip irrigation under plastic mulch on modifying surface characteristics (Bai et al., 2015; Wang et al., 2013b; Zhou et al., 2012). For example, field experiments have documented that the daily mean soil temperature under the plastic mulch was 2–9 °C higher than soil temperature for non-mulching conditions (Wang et al., 2009), and that this agricultural practice reduced the total maize evapotranspiration over the complete growth stages by less than 10%, and thus reduced the irrigation requirement in northwest China (Qin et al., 2016). In addition, plastic mulch could also exert different impacts on evaporation and transpiration. Wang et al. (2016) reported that plastic mulch significantly increased the soil evaporation and decreased transpiration due to its capacity to block moisture transportation downward after rainfall and irrigation. Furthermore, plastic mulch has obviously altered energy fluxes because of its higher albedo, which is associated with less radiation penetrating into the greenhouse as well as a portion of energy stored inside the plastic mulch (Fan et al., 2015). However, descriptions of previous studies are limited at the site level by direct field measurements, and systematic quantification of their effects based on a detailed physical process is needed.

In recent years, numerous LSMs have been developed to allow simulations of biogeochemical and biophysical mechanisms, including representations of water, carbon, and energy processes, and these LSMs have become an effective tool to study ecosystems (Bonan, 1998; Dickinson et al., 1998; Zeng et al., 1998). Many researchers have been committed to developing or optimizing irrigation schemes to simulate the influence of irrigation on hydrological fluxes and states (Ozdogan et al., 2010; Vahmani and Hogue, 2014). For example, Evans and Zaitchik (2008) simulated the effects of drip irrigation on evapotranspiration in Syria and Turkey by assuming that the vegetation always has enough water to transpire without being stressed and without any excess water being added. Liu et al. (2008b) simulated irrigation effects by assuming that irrigation was activated when available soil moisture water decreased to 30% of the maximum available water (field capacity minus wilting point) during the growing season, and after irrigation, the soil moisture would reach the field capacity. Pokhrel et al. (2012) developed an irrigation demand factor to specify the irrigation amount. The irrigation demand factor ranges from zero to one, which means no water was irrigated or the soil reached saturation moisture content after irrigation. However, to date, a universal irrigation scheme has not been accepted, as irrigation practices can differ markedly between regions. In addition, two key irrigation parameters (e.g., irrigation timing and amount) are difficult to determine, especially when LSMs were applied at the regional or the global scale, and sometimes the decisions of individual farmers are important factors in determining the amount of irrigation.

To our knowledge, the physical process of using plastic mulch has been explored by incorporation into LSMs. In particular, Ham and Kluitenberg (1994) developed a mechanistic model for simulating the effects of the plastic and found that the optical properties of the mulch strongly influenced the partition of energy at the surface. Yang et al. (2012) reported that plastic mulch within LSMs can appropriately simulate the water, heat and CO_2 fluxes over an arid cropland. Wu et al. (2007) found that the model is quite satisfactory in simulating the water and temperature profiles during the growth of the winter wheat in a soil–mulch–plant–atmosphere continuum system. However, oasis agro-ecosystems in the Xinjiang Uygur Autonomous Region of China, which are highly irrigated areas, are associated with plastic mulch covering, and few studies have been conducted to incorporate the two physical processes (i.e., irrigation and plastic mulch) conjointly into LSMs and explore their effects on vapor and energy fluxes in irrigated underlying plastic mulch-covered areas.

The primary objective of this study was to develop a drip irrigation scheme with underlying plastic mulch to simulate vapor (i.e., evapotranspiration) and energy fluxes (i.e., net radiation, ground, latent, and sensible heat flux). Two parameters of irrigation (i.e., irrigation trigger and amount) are first calibrated by observation through sensitivity analysis. The plastic mulch module was further incorporated into the CoLM to investigate the combined effects of irrigation and plastic mulch on vapor and energy fluxes at a field experimental site in Xinjiang, China.

2.2 Materials and methods

2.2.1 *Data collection*

One experiment was conducted at the Wulanwusu (WLWS) Agrometeorological Experiment Station (85°49'E, 44°17'N; 469 m asl) (Figure 2.1) from 2009 to 2010, a representation of an oasis ecosystem and a long-term monitoring station in the Xinjiang Uyghur Autonomous Region of China. The oasis is characterized by an arid climate with a mean annual temperature of 7 °C and mean annual precipitation of 210 mm. The primary crop is cotton, and the growth season is from late April to mid-September. The drip irrigation occurs mainly from April to August. Approximately 80% of the surface is covered by a plastic film (0.08-mm-thick) when the cotton is sown (Zhou et al., 2012). An eddy covariance (EC) system was installed to measure latent sensible heat and CO_2 fluxes. The EC system also measured meteorological variables, including downward long wave radiation, downward short-wave radiation, wind speed, pressure, air temperature, and specific humidity, which were used to force the CoLM model. The device placement and data processing programs are described in detail in Bai et al. (2015).

The second experiment was conducted by using a micrometeorological method, the Bowen ratio-energy balance (BREB) system, located at the Southern Border of the Gurbantunggut Desert (SBGD) (87°51'E, 44°29'N; 459 m asl). This SBGD site is in eastern WLWS, 162 km away. The crop is tomatoes that are covered by plastic mulch. The field measurements were conducted between 18 April 2015 to 17 May 2015. Half-hour latent and sensible heat fluxes were measured using the BREB system, which consist of two integrated temperature–humidity probes (THP-1, Radiation and Energy Balance Systems, Seattle, WA) inside radiation-shielded, fan-aspirated housings that were mounted on a chain-driven automatic exchange mechanism (AEM-1, Radiation and Energy Balance Systems, Seattle, WA). The downward radiation and net shortwave radiation were measured with a radiometer (CNR-1, Kipp & Zonen, Delft, The Netherlands) at 2.5 m above ground level. Soil heat flux (G) was measured with two soil-heat-flux plates (HFP01, Hukseflux, Delft, The Netherlands) at an 80-mm depth below the ground surface. Precipitation was measured using a standard 20-cm diameter rain gauge. The wind speed and direction were measured using the EL15-1A wind speed sensor and the EL15-2D wind direction sensor (Zhonghuan TIG, Tianjin, China), respectively. The vegetation fraction at these two sites is derived from a semi-empirical relationship based on the MODerate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) dataset, at a spatial resolution of 500 m and with an 8-day time-step. The detailed information about how to calculate the vegetation fraction is described in the following section.

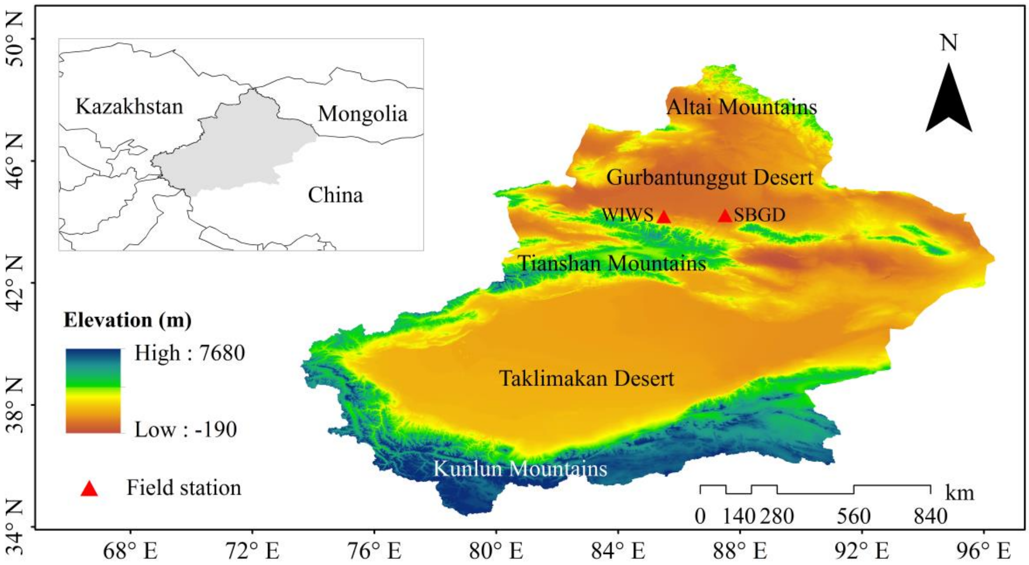

Figure 2.1 Locations of field measurements.

2.2.2 Model description

CoLM used in this study is a process-based land surface model that allows simulations of vapor water, CO_2 and energy fluxes (Dai et al., 2003). CoLM combines the best features of the following three existing successful land models: the LSM (Bonan, 1996), Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson et al., 1993), and Institute of Atmospheric Physics land-surface model (IAP94) (Dai and Zeng, 1997). The initial version of the model (Community Land Model (CLM)) was proposed in order to provide a framework for a true community developed land component for the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM), and has been updated and developed by open scientific collaboration. The overall structure of CoLM includes the following three aspects: the single-column soil–snow–vegetation biophysical process, the land boundary data, and the scaling procedures within a climate model required to interface atmospheric model grid-square inputs to land single-column processes. The primary feature of CoLM is that a one-layered, two-big-leaf submodel was developed to simulate photosynthesis, stomatal conductance, leaf temperature, and energy fluxes

(Dai et al., 2004). Although the CoLM model has been updated by the modeling community, the special management practices of oasis agro-ecosystems (i.e., drip irrigation under plastic mulch) in arid regions have not been considered. The key processes and modifications are presented as follows.

2.2.3 Description of drip irrigation effects

The effects of irrigation practice on the hydrological processes are substantial. However, the CoLM cannot address irrigation effects very well, especially without considering the widespread water-efficient irrigation practice (drip irrigation). In addition, drip irrigation water is usually added under the crops or even directly into the root zones, so the evaporation on the soil surface is minimal and could be negligible, especially considering the plastic film. Two important parameters (i.e., irrigation timing and irrigation amount) are difficult to determine, as irrigation practices can differ markedly between regions. Similar to a recent methodology proposed by Fan et al. (2015)), the irrigation is triggered when soil moisture falls below a prescribed threshold, which means that the soil matrix potential exceeds a threshold:

$$\mathrm{\varphi} = \mathrm{\alpha(t)}\varphi_{wilt}$$

where $\mathrm{\varphi}$ and φ_{wilt} are the soil matrix potential and soil wilt potential (mm), respectively; and $\mathrm{\alpha(t)}$ are is an experimental coefficient to determine irrigation start time.

Irrigation water was calculated by designing an irrigation demand factor, which is proposed by (Pokhrel et al., 2012):

$$\mathrm{I} = \mathrm{\rho_w} \sum_{\mathrm{i}=1}^{6} \max\,(\mathrm{\beta\theta_s} - \mathrm{\theta_i}, 0)\mathrm{D_i}$$

I is the irrigation water demand (kg m^{-3}); $\mathrm{\theta_s}$ and $\mathrm{\theta_i}$ are the soil porosity and actual soil content (m^3 m^{-3}); $\mathrm{\rho_w}$ and $\mathrm{D_i}$ are the water density and depth of soil at the ith soil layer, respectively. $\mathrm{\beta}$ is a water demand factor that ranges from 0 to 1, which means no water was irrigated or the soil reached saturation moisture content after irrigation.

CoLM has ten soil layers with a total thickness of 3.43 m. The top 0.49 m (i.e., top six layers) was considered the soil root zone for the irrigation calculation. Unlike flood irrigation where soil moisture reached saturation with the β value of one after irrigation, in this work, we designed the irrigation demand factor as 0.55, 0.65, 0.75, 0.85, 0.95, to first test the sensitivity of evapotranspiration to the range of β values.

2.2.4 Description of plastic mulch effects

Similar to previous studies (Ham and Kluitenberg, 1994; Yang et al., 2012), the energy balance equations for the surface covered by plastic mulch are based on the following assumption that no water vapor exchange occurs from the surface and that no heat transfer occurs by evapotranspiration or condensation between the mulch and the soil surface. The heat storage within the mulch is negligible, and the planting holes are small enough such that potential effects of water vapor exchanges between mulch and atmosphere can be negligible. Compared to previous studies where the energy balance equations at the soil surface were based on the assumption that the soil surface is fully covered by mulch, we modified the equations by dividing the heat transfer into two portions. One portion is covered by mulch, and the other is not covered by mulch. A detailed representation and implementation of the heat transfer model within the soil-mulch system have been summarized by Yang et al. (2012). This research effort focuses on the energy balance on the soil surface that was covered partially by mulch (Figure 2.2).

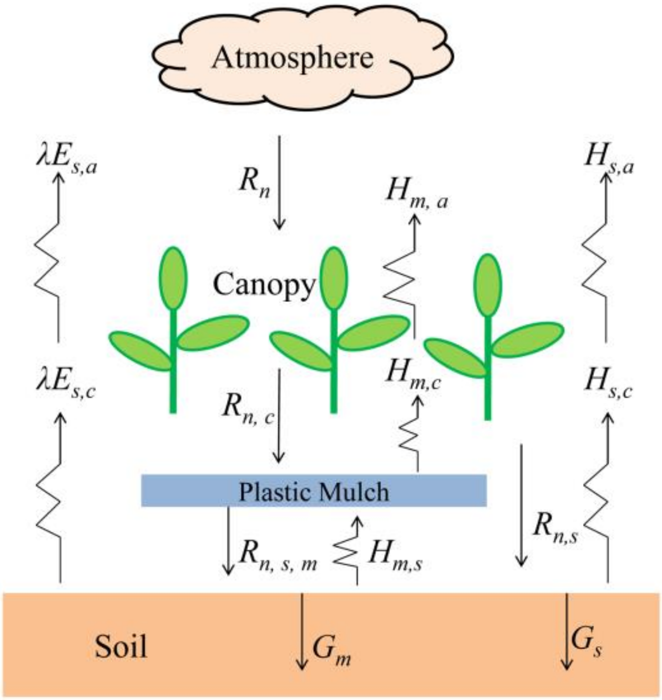

Figure 2.2 Schematic diagram of energy transfer in a soil-mulch-vegetation-atmosphere system.

The energy balance equations for the surface (soil and mulch) can been expressed as follows:

$$R_{n,g} - H_g - \lambda_{,g} - G_0 = 0$$

$$R_{n,m} - H_{m,s} - H_{m,c} - H_{m,a} = 0$$

$$R_{n,m,s} + H_{m,s} - G_m = 0$$

$$R_{n,s} - H_{s,c} - H_{s,a} - \lambda_{,s,c} - \lambda_{,s,a} - G_s = 0$$

where $R_{n,g}$, $R_{n,m}$, $R_{n,m,s}$, and $R_{n,s}$ are the net radiation absorbed by the surface, plastic mulch, soil that is covered and not covered by plastic mulch (W m^{-2} s^{-1}); H_g, $H_{m,a}$, and $H_{s,a}$ are the sensible heat fluxes from the surface, mulch and soil that is not covered by plastic mulch to the atmosphere (W m^{-2} s^{-1}); $H_{m,c}$ and $H_{s,c}$ are the sensible heat fluxes from mulch and soil that is not covered by plastic mulch to canopy air (W m^{-2} s^{-1}); $H_{m,s}$ is the heat flux between mulch and soil (W m^{-2} s^{-1}); E_g

and $E_{s,a}$, are the vapor fluxes from surface and soil that is not covered by plastic mulch to the atmosphere (kg m^{-2} s^{-1}); $E_{s,c}$ is the vapor flux from soil that is not covered by plastic mulch to canopy air (kg m^{-2} s^{-1}); G_0, G_m, and G_s are the ground heat flux and soil heat flux that is covered and not covered by plastic mulch (W m^{-2}), respectively; λ is the volumetric latent heat of vaporization (J m^{-3}).

The surface (soil and mulch) net radiation R_n, sensible (H_g), latent (λE_g), and soil heat flux (G_0), can be expressed separately by the following equations:

$$R_{n,g} = f_m R_{n,m} + (1 - f_m) R_{n,s} + f_m R_{n,s,m}$$

$$H_g = f_m f_c H_{m,c} + f_m (1 - f_c) H_{m,a} + (1 - f_m) f_c H_{s,c} + (1 - f_m)(1 - f_c) H_{s,a}$$

$$\lambda,_{g} = (1 - f_m) f_c \lambda(_{s,c} + (1 - f_m)(1 - f_c) \lambda(_{s,a}$$

$$G_0 = f_m G_m + (1 - f_m) G_s$$

where f_m and f_c are the fraction of mulch and vegetation cover.

The f_c is derived from a semi-empirical relationship based on remote sensing data (Mu et al., 2007):

$$f_c = \frac{EVI - EVI_{min}}{EVI_{max} - EVI_{min}}$$

where EVI is the enhanced vegetation index, EVI_{max} and EVI_{min} are the signals from bare soil (leaf area index (LAI)→0) and dense green vegetation (LAI→∞), which are set as seasonally and geographically invariant constants 0.05 and 0.95, respectively. The f_m was determined as 0.8 in this study according to field measurements (Zhou et al., 2012).

2.2.5 Experimental design

We first evaluated the sensitivities of the irrigation module to two parameters (i.e. e first), and next calibrated the parameters by using the observed evapotranspiration data at the WLWS site. The default CoLM with the added irrigation module was designed to assess the effects of irrigation on vapor flux (evapotranspiration), which was termed as “IRRIG” simulation at the WLWS site.

Then, the default CoLM with adding both irrigation and the mulch module was designed to assess the effects of plastic mulch on vapor flux, and this simulation was termed “IPME”. Finally, the same process was executed to assess their effects on energy balance at the SBGD site.

2.2.6 Statistical analysis

We used the slope coefficient of the trend line (slope), linear correlation coefficient (R), and root mean square error (RMSE) between the observed and simulated variables to evaluate the performance of the model.

The slope is calculated as:

$$\mathrm{Slope} = \frac{\mathrm{n}\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{x_i y_i} - \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{x_i} \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{y_i}}{\mathrm{n}\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{x_i}^2 - (\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{x_i})^2}$$

where x_i and y_i are the observed and modeled flux at time step i, respectively, and n is the number of observations. A value of one indicates a perfect match, and the closer to the value of one, the better is the agreement between observations and simulations.

The R is calculated as:

$$\mathrm{R} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{x_i} - \bar{\mathrm{x}}) \sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{y_i} - \bar{\mathrm{y}})}{\sqrt{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{x_i} - \bar{\mathrm{x}})^2 \sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{y_i} - \bar{\mathrm{y}})^2}}$$

where $\bar{x}$ and $\bar{y}$ are the mean value of observed and modeled flux. A value of one indicates a perfect match, and 0 indicates no agreement at all.

The RMSE is calculated as:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{x_i} - \mathrm{y_i})^2}{\mathrm{n} - 1}}$$

The smaller the value of RMSE, the better the agreement between the simulations and measurements.

2.3 Results

2.3.1 Sensitivity of evapotranspiration to irrigation demand factor and timing

The absence of an irrigation module or uncertainties in irrigation parameters (e.g., irritation timing and amount) in LSMs is a causative factor in determining accuracy of simulations of land surface flux. Irrigation elevates soil moisture content, which will change evapotranspiration. In this study, we first examined evapotranspiration (latent heat flux) sensitivity to the amount and timing of irrigation in the revised CoLM. Initially, irrigation demand factor (β) was set as 0.55, 0.65, 0.75, 0.85, and 0.95 (i.e., soil moisture is set as 55%, 65%, 75%, 85%, and 95% of saturation soil moisture content); meanwhile, the irrigation trigger parameter α was set as a constant four. Figure 2.3 shows the monthly variations of evapotranspiration, and the corresponding adjustment of β during the growing season (Apr. – Oct.) for two years, 2009 and 2010. Sensitivity to β is most substantial when β is 0.55, with the maximum evapotranspiration reaching 160 W m^{-2} in July, and minimum evapotranspiration decreasing to less than 20 W m^{-2} in October. Correspondingly, the irrigation volume is also the largest, and the irrigation times are almost 3000 during one growing season. However, less variation of sensitivity to β is shown when the β is raised from 0.65 to 0.95. Similarly, less variation of irrigation volume is also illustrated, with the values ranging from 480 to 620 mm during one growing season, while the irrigation times decreased from eighteen to seven.

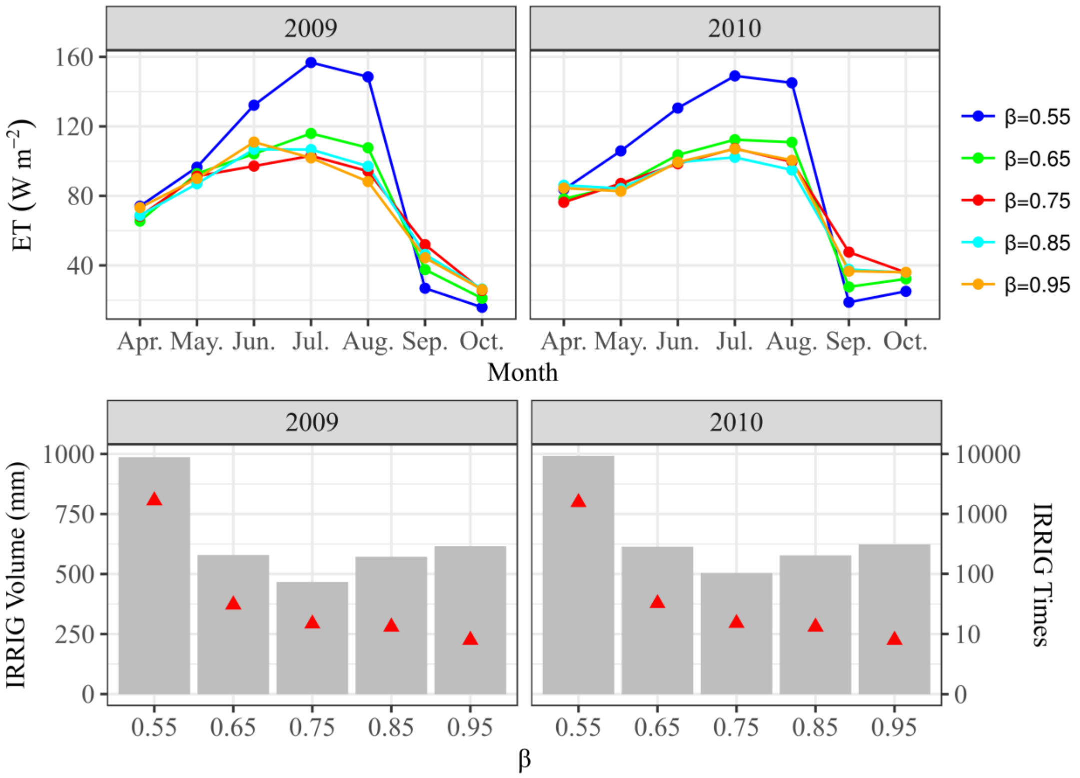

Figure 2.3 The sensitivity of monthly EvapoTranspiration (ET) to the irrigation demand factor β during the growing season (April - October) from 2009 to 2010. The triangle indicates irrigation (IRRIG) times.

To evaluate the sensitivity to irrigation timing scenarios, the irrigation demand factor was fixed at 0.75 and the irrigation trigger parameter was hypothetically set from two to six. Figure 2.4 shows large variations of sensitivity to the irrigation trigger factor. Evident seasonal patterns of evapotranspiration are shown when the irrigation trigger parameter increased from four to six, and peak evapotranspiration increased from 100 W m^{-2} to 150 W m^{-2} in July, while the patterns are comparable when the irrigation timing factor is set at five or six. Correspondingly, the irrigation volume increased from 480 to 820 mm, and irrigation times increased from 17 to 57 during one growing season. In contrast, no or fewer seasonal patterns of evapotranspiration are displayed when the irrigation timing factor is set as two or three, and evapotranspiration decreased from April to October. Correspondingly, the irrigation volume is relatively low from 50 to 200 mm, and the irrigation times range from three to seven.

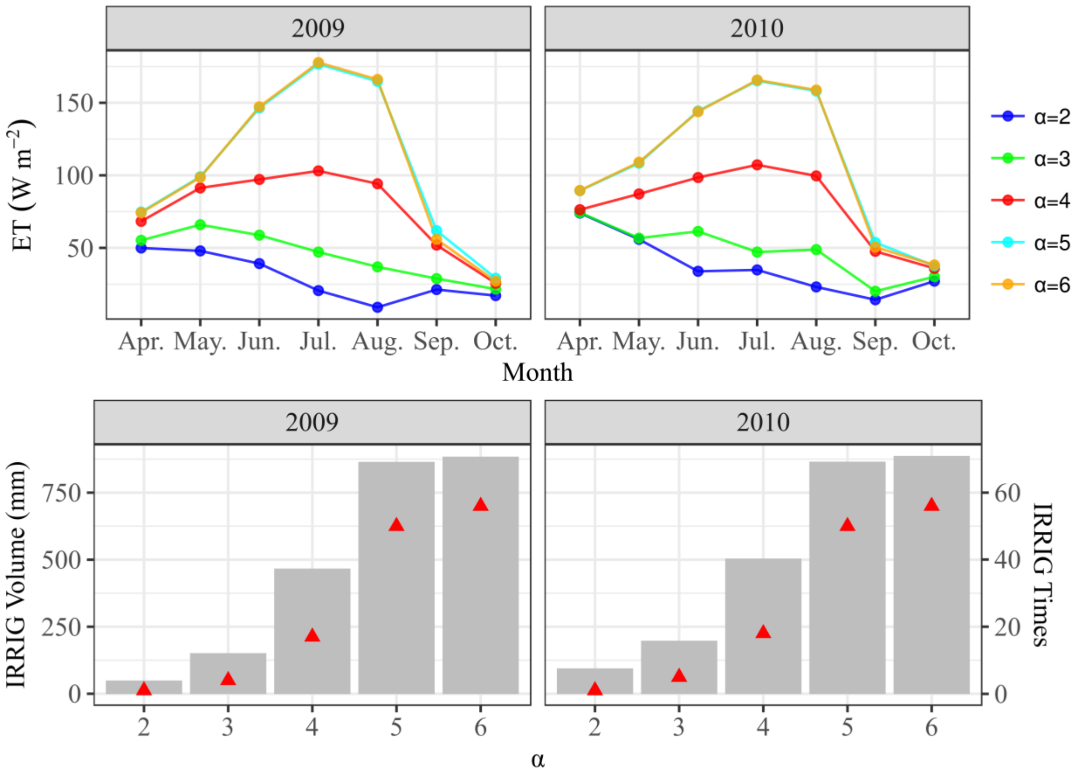

Figure 2.4 The sensitivity of monthly evapotranspiration to irrigation timing α during the growing season (April - October) from 2009 to 2010. The triangle indicates irrigation (IRRIG) times.

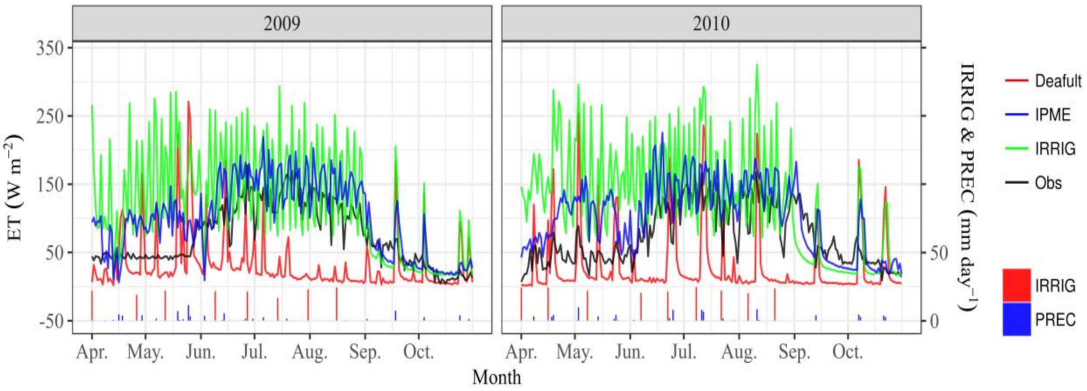

Figure 2.5 Comparisons of EvapoTranspiration (ET) between simulations and observations. Daily averaged evapotranspiration at WLWS station based on the default Common Land Model (CoLM) (Default), the modified CoLM with addition of irrigation effects (IRRIG), the modified CoLM with addition of both irrigation and plastic mulch effects (IPME), and observations.

2.3.2 Evaluation of irrigation and plastic mulch module

Guided by the previous analyses, the irrigation module was incorporated into the revised CoLM with the irrigation demand factor determined as 0.85 and the irrigation trigger factor determined as 4.3. Figure 2.5 shows the comparison of daily evapotranspiration simulated by default and revised CoLM by adding both irrigation and plastic mulch module with observed evapotranspiration at WLWS. The results indicate that evapotranspiration is substantially underestimated by default CoLM, and no seasonal patterns of evapotranspiration were displayed during the growing season. However, evapotranspiration was enhanced by incorporating an irrigation module. The simulated evapotranspiration largely reflected that peak evapotranspiration occurs when it rains or irrigates, and evapotranspiration falls sharply after rains or irrigations. Figure 2.6 shows the scatter plots of the modeled evapotranspiration against observations. The RMSE increased from 76 W m^{-2} to 87 W m^{-2} after incorporating irrigation module, but R increased marginally from 0.2 to 0.4, and slope increased from 0.04 to 0.72. The revised CoLM with adding the plastic mulch module can capture the seasonal patterns of evapotranspiration, while it marginally overestimates evapotranspiration on both April and May. The revised CoLM with the added plastic mulch module shows smaller fluctuations compared to IRRIG simulations and more closely matches the observations. The R values of IPME and slope increase from 0.72 and 0.4 to 0.92 and 0.75, respectively. The RMSE decreases from 87 W m^{-2} to 44 W m^{-2}.

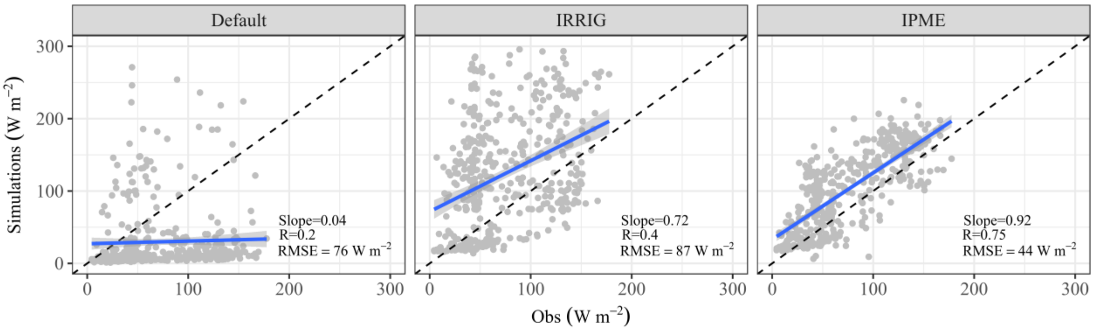

Figure 2.6 Scatter plot of daily averaged evapotranspiration between observations and simulations at WLWS station.

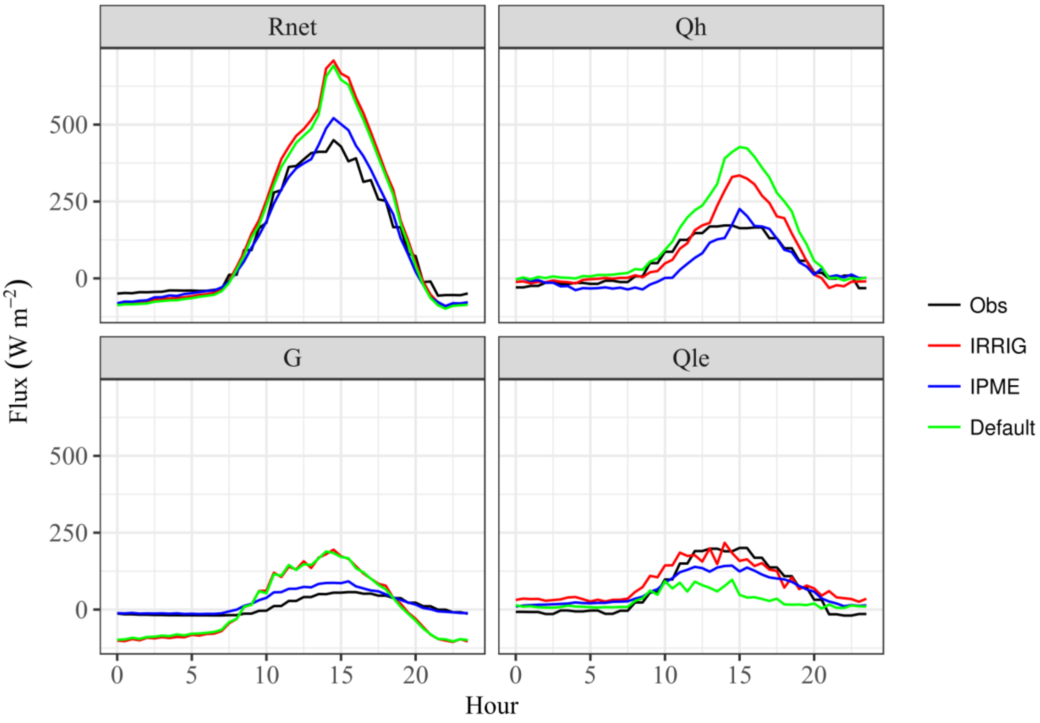

Figure 2.7 Diurnal courses of the observed and simulated energy components: net radiation (Rnet), latent heat flux (Qle), sensible heat flux (Qh), and ground heat flux (G) at SBGD site.

2.3.3 Effects of irrigation and plastic mulch on energy balance

Irrigation can modify soil moisture, associated with changing evapotranspiration (latent heat flux), which in turn transforms the energy budgets. In addition, plastic mulch can also alter radiation partitioning by changing the surface albedo. Figure 2.7 shows the comparisons of diurnal cycles of energy fluxes (e.g., latent, sensible, ground heat flux, and net radiation) between simulations and observations at the SBGD site. The net radiation simulated by the revised CoLM with only adding the irrigation module remained nearly unchanged and was overestimated at midday, with the slope values of 1.42 and 1.45 and the RMSE values of 99.34 and 104.73 W m^{-2} for default and IRRIG simulations, respectively. The R, slope, and RMSE are listed in Table 2.1. However, the IPME simulated net radiation decreases and is closely matched with observations, with the RMSE decreasing to 36.07 W m^{-2}, indicating that plastic mulch significantly alters the net radiation. Similar results presented in SBGD are compared to WLWS, the latent heat flux was underestimated by the default CoLM, and irrigation evidently enhanced it. However, the sensible heat flux was overestimated at midday with the peak value of ~250 W m^{-2} for default runs. Irrigation reduced peak sensible heat flux at midday, but it was still overestimated with the value of ~200 W m^{-2} at midday. The revised CoLM with the added plastic mulch module reduced the sensible heat flux significantly, which is more comparable with observations. Nevertheless, the plastic mulch decreased latent heat flux significantly, lower than the observations with the value of approximately 50 W m^{-2}. In addition, Irrigation exerted slight impacts on soil heat flux, and that impact was overestimated at daytime and was underestimated at nighttime for both default and IRRIG simulation. Apparently, the IPME simulations captured the diurnal patterns of soil heat flux well and matched the observations closely, although they marginally overestimated soil heat flux in the day time. The R, RMSE and slope presented in Table 2.1 reveal that IMPE simulation overall was more in agreement with the observations than both the default and IRRIG simulations.

Table 2.1 Model performance for simulating Evapotranspiration as indicated by the correlation coefficient (R), slope and the root mean square error (RMSE) at SBGD site.

Simulations	R_{net}	Q_h	Qle	G
Default(R)	0.99	0.95	0.79	0.85
IRRIG	0.99	0.93	0.95	0.86
IMPE	0.99	0.87	0.99	0.92
Default(Slope)	1.42	1.85	0.27	3.07
IRRIG	1.45	1.45	0.69	3.17
IMPE	1.12	0.87	0.58	1.23
Default(RMSE(W/m^2))	94.34	102.93	69.44	78.48
IRRIG	104.73	59.87	38.80	80.31
IMPE	36.07	39.20	34.85	21.18

2.4 Discussion

Irrigation has been shown to affect hydrological cycles and energy balance by changing surface-atmosphere exchanges of vapor and energy fluxes. A reasonable and realistic irrigation scheme within land surface models is essential for simulating and quantifying its effects on hydrological and energy fluxes. The irrigation timing and amount are two key aspects of irrigation in a modeling framework. Compared to flood irrigation, a common widely applied and water-saving irrigation technology is drip irrigation for our study area characterized by high aridity. Less irrigation water will be applied to the soil layer to sustain crop growth without water stress than traditional flood irrigation practices by leading soil to saturation. In this study, we first calibrated the irrigation parameters (irrigation timing and demand factor) to find the optimum irrigation scheme. Our results show that changes in the irrigation demand factor significantly altered the evapotranspiration. The simulated evapotranspiration is evidently greater when irrigation demand factor is set at smaller values (β=0.55, meaning that only 55% of the saturation soil water content will be reached after irrigation). Accordingly, with time going and evapotranspiration consuming, the soil moisture will fall more quickly below a prescribed threshold, and thus irrigation occurs more than three thousand times in one growing season. When the irrigation demand factor is raised from 0.65 to 0.95, indicating more water will be imparted to the soil, the soil moisture will fall more slowly below a prescribed threshold. As a result, the irrigation triggers decrease from more than fifty times to less than ten times. The sensitivity analyses also indicate that the monthly evapotranspiration changed marginally and was comparable, because of similar total irrigation amount when the irrigation demand factor increased from 0.65 to 0.95 (Figure 2.3). The similar irrigation amount resulted from the fact that a higher use of irrigation water was compensated by a decreasing number of irrigation triggers with the increasing irrigation demand factor from 0.65 to 0.95.

With respect to the timing of irrigation, evapotranspiration also shows high sensitivity to the increase in soil moisture potential threshold. When the soil moisture potential threshold increases, it is quicker to trigger irrigation (Figure 2.4). However, sensitivity analyses also show that it does not improve the simulation of evapotranspiration when the irrigation trigger factor is raised from five to six. The almost equivalent simulated evapotranspiration can be explained by comparable irrigation times, and thus results in a comparable total irrigation amount. In one extreme case, the irrigation is only triggered three times when the irrigation trigger factor is only two. The total irrigation amount is less than 50 mm during one growing season, and thus the CoLM could not capture well with the seasonal patterns of evapotranspiration during the growing season. Our results demonstrate that both irrigation demand factor and irrigation timing can significantly affect the irrigation effects, and a reasonably optimized combination of them incorporated into LSMs will produce results at a high level of confidence.

The higher evapotranspiration rates are clearly identifiable when the calibrated irrigation module within revised CoLM is utilized, compared with the no-irrigation simulation. However, the fluctuations of evapotranspiration are substantial and deviated remarkably from observations and peak values occurring at high frequency when the precipitation or irrigation happens. The inconsistency may come from the presence of plastic mulch effects that prevent exchanges of vapor between the land surface and the atmosphere. The variability of evapotranspiration decreased and more closely matched with the observations when the plastic mulch module was incorporated into the revised CoLM.

The development of plastic mulch technology is expected to alter the near surface biophysical process by suppressing soil evaporation and elevating soil temperature for the purpose of increasing crop production (Cuello et al., 2015). Due to the high albedo of plastic mulch, the net radiation decreases especially at midday when the solar radiation is relatively stronger, which has been demonstrated in our study, agreeing with conclusions that surface albedo increased based on field observations, if grassland was covered by plastic film (Fan et al., 2015; Hou et al., 2010). The reduced solar radiation associated with the albedo increase has much potential in mitigating a local warming trend associated with greenhouse gas increases (Campra et al., 2008). However, contradictory conclusions have also been reported that plastic mulch increased global warming potential by significantly improving soil respiration and largely increasing the two major greenhouse gas emissions for methane and nitrous oxide (Cuello et al., 2015). Therefore, more comprehensive and in-depth analyses are still required in the future for better understanding of radiative forcing because of the increase in surface albedo caused by the agricultural plastic mulch.

Our results also indicate that plastic mulch suppresses ground heat flux in the daytime and improves ground heat flux at nighttime. It should be noted that less radiation, owing to the higher albedo of the plastic mulch, will reach the soil surface and, thus, result in lower ground heat flux in the daytime compared to the default CoLM with the absence of the plastic mulch module. In contrast, because of the resistance to heat transfer between soil and mulch, less heat will be transferred into the atmosphere at nighttime in the form of long wave radiation, thus resulting in a higher group heat flux (Ham and Kluitenberg, 1994).

2.5 Conclusions

Anthropogenic activities, including implementing irrigation and using plastic mulch, have changed the physical process or the physical characteristics of the surface, thus affecting the energy fluxes between the surface and the atmosphere. In this study, we incorporated an irrigation module, in combination with a plastic mulch module, to be used in the CoLM and provided an evaluation of their effects on the vapor and energy exchanges in agriculture ecosystems. Our results suggest that both the irrigation demand factor and irrigation timing have a significant impact on vapor exchanges by altering the irrigation amount and times, based on sensitivity analyses. A correct and realistic representation of irrigation amount and timing is essential for a correct simulation of vapor exchanges. The revised CoLM produced a better simulation of evapotranspiration with increased statistical indicators of slope and correlation coefficient. However, large uncertainties still exist, without considering plastic mulch impacts, that fluctuations of simulated evapotranspiration are substantial and could not capture the seasonal patterns of evapotranspiration. In addition, in close agreement with previous model-based and experimental studies, net radiation and sensible heat flux decreased remarkably when the surface was covered by plastic mulch. Further, our results also indicate that plastic mulch suppresses ground heat flux in the daytime and improves it at nighttime. The exploration of the coupled effects of drip irrigation and plastic mulch on heat flux and corresponding mechanism analyses are the primary innovation of this work, which will be helpful to improve the understanding of the processes of surface flux exchanges between soil and atmosphere.

CHAPTER 3

Estimation of evapotranspiration and response to climate and land cover change

Modified from： Xiuliang Yuan, Jie Bai, Longhui Li, Alishir Kurban, Philippe De Maeyer. (2017). The dominant role of climate change in determining changes in evapotranspiration in Xinjiang, China from 2001 to 2012. Plos One. 12 (8):e0183071. Doi: 10.1371/journal.pone.0183071.

Abstract

The Xinjiang Uyghur Autonomous Region of China has experienced significant land cover and climate change since the beginning of the 21st century. However, a reasonable simulation of evapotranspiration and its response to environmental factors are still unclear. For this study, to simulate evapotranspiration and its response to climate and land cover change in Xinjiang, China from 2001 to 2012, we used the CoLM by adding irrigation effects for cropland and modified root distributions and the root water uptake process for shrubland. Our results indicate that mean annual evapotranspiration from 2001 to 2012 was 131.22 (±3 21.78) mm/year and demonstrated no significant trend (p = 0.12). The model simulation also indicates that climate change was capable of explaining 99% of inter-annual evapotranspiration variability; land cover change only explained 1%. Land cover change caused by the expansion of croplands increased annual evapotranspiration by 1.11 mm while climate change, mainly resulting from both decreased temperature and precipitation, reduced evapotranspiration by 21.90 mm. Our results imply that climate change plays a dominant role in determining changes in evapotranspiration, and also highlight the need for appropriate land-use strategies for managing water sources in dryland ecosystems within Xinjiang.

Key words：CoLM; Climte chagne; Land cover change; Evapotranspiration; Dryland ecosystems; Xinjiang

3.1 Introduction

Due to global warming and human activities, acceleration and intensification of the global water cycle is becoming an undisputed fact (Durack et al., 2012; Huntington, 2006). Evapotranspiration, an important component of hydrological processes, plays a critical role in the global water budget. Oki and Kanae (2006) reported that global land evapotranspiration returns approximately 60% of annual land precipitation to the atmosphere, indicating that asynchronous changes in evapotranspiration may lead to severe hydrological deficits (Zhang et al., 2015). Additionally, evapotranspiration consumes more than half of solar radiation in the form of latent heat (Trenberth et al., 2009). Shukla and Mintz (1982) indicated that the Northern Hemisphere would be 15°C – 25°C warmer if land evapotranspiration was assumed to be zero, suggesting important implications for regional climate variability. From 1982 to 1997, global annual evapotranspiration increased at an average rate of 0.71 mm/year but stalled and even decreased coincidently with the last major El Niña event of 1998, with the decreasing trend continuing until 2008 (Jung et al., 2010). However, Zhang et al. (2015) reported that reduced evapotranspiration growth between 1998 and 2008 was an episodic phenomenon, with subsequent recovery for the evapotranspiration growth rate following 2008. Although efforts have been made to investigate evapotranspiration variability on a global scale, a comprehensive analysis of evapotranspiration changes and their response to environment factors (e.g., climate variability and land cover change (LCC)) are still lacking on a regional scale.

Local scale measurements and observations of evapotranspiration have been widely conducted within various ecosystems (Baldocchi et al., 2001). However, dense global or regional coverage evapotranspiration cannot be represented using field measurements. Satellite- and statistics-based technologies have provided an alternative method for estimating evapotranspiration on global and regional scales (Jung et al., 2010; Mu et al., 2011) although neither of these methods can qualify the relative roles of environmental factors in controlling evapotranspiration. The LSMs provide a possible solution for simulating evapotranspiration and quantifying the contributions of various environmental factors on evapotranspiration. However, most global LSMs underestimate evapotranspiration within arid/semi-arid regions (Jing et al., 2014; Li et al., 2013b; Zheng and Wang, 2007). A possible reason for this phenomenon is that most current LSMs cannot capture special vegetation structures and their related functioning. When soil water is limited, most species within dryland ecosystems do not suffer from water stress (Zheng and Wang, 2007). Several adaptive mechanisms can account for this finding. Being challenged with climates with extreme aridity and heat conditions, species have evolved into rich and deep root distributions with high root/shoot ratios (Xu et al., 2007) and these specific morphological root distributions can influence evapotranspiration through impacts on water uptake. Additionally, Zheng and Wang (2007) reported that some stressed portions of the root zone do not necessarily indicate the water stress of entire plants. As a result, reduced water uptake from the stressed portion of the root zone can be compensated for by enhanced water uptake over portions of the root zone where water is more available. Furthermore, hydraulic redistribution (HR) is a widespread phenomenon where plant roots take-up water from deep moist soils and redeposit it into the upper soil layer at night for the purpose of root uptake to sustain daytime transpiration (Brooks et al., 2002; Ryel et al., 2002). Although the above processes play a vital role in influencing evapotranspiration within arid/semi-arid regions, few LSMs have taken conjointly into consideration when simulating evapotranspiration.

The Xinjiang Uyghur Autonomous Region of China is located deep inside the Eurasian continent and is characterized by extremely low precipitation and high temperatures. The region is unique and, over the years, has experienced a dynamic land-use history and climate change (Lioubimtseva and Henebry, 2009). Hu et al. (2014) reported that annual mean temperatures for this region have increased at an average rate of 0.39°C/decade from 1979 to 2011. Additionally, from 1982 to 2011, precipitation within this region has also experienced an increase at a rate of 8 mm/decade (Yuan et al., 2015a). However, this dramatic rise in both temperature and precipitation stalled and even turned into decrease since the 21st century (Chen et al., 2015). With a constant increase in population and accelerating industrial development and urbanization, oases (as a primary site for human settlement due to the availability of fertile soils and fresh runoff from surrounding mountains) have significantly expanded within this region (Luo et al., 2008b). Following the expansion of oases, local native vegetation was modified by irrigation and cultivation, as well as reclamation, and most native vegetation has been changed into cropland. Previous studies have concluded that climate change plays a dominant role in controlling evapotranspiration variability over large regions, whereas land-use changes have dramatically affected evapotranspiration within watersheds with significant land conversion (Yang et al., 2015). Nevertheless, knowledge gaps still exist for understanding evapotranspiration in response to changing climate and land cover in this typical arid/semi-arid region.

For this study, we used a process-based land surface model, the CoLM, to simulate evapotranspiration in Xinjiang Uyghur Autonomous Region of China from 2001-2012. Major objectives of the study were the following: (1) improve the performance of the CoLM for simulating evapotranspiration (shrubland and cropland); (2) restructure the temporal and spatial distribution of evapotranspiration; and (3) investigate the relative contributions of climate change and LCC on evapotranspiration variability.

3.2 Materials and Methods

3.2.1 The study area

Xinjiang Uyghur Autonomous Region (Shown as Figure 3. 1) was chosen in this study. More detailed information can be seen in Section 1.4.

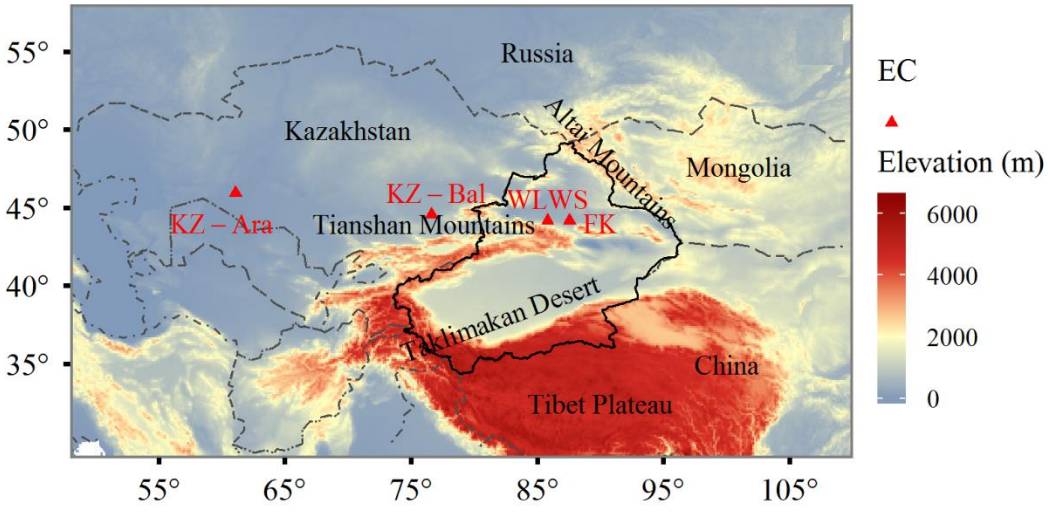

Figure 3.1 The Distribution of the flux tower sites. EC: Eddy covariance flux tower station. FK: Fukang station; KZ-Ara: Aral Sea station in Kazakhstan; KZ-Bal: Balkhash Lake station in Kazakhstan; WLWS: Wulanwusu station.

3.2.2 The Common Land Model

Like most other land surface models, CoLM builds on the concept of plant functional types to describe vegetation attributes. CoLM handles the effects of LCC by changing spatially explicit LCC datasets. However, underestimations of water fluxes still exist because the model cannot capture the form and structure of desert plants and related root functions (root water uptake function and hydraulic redistribution (Figure 3.2)). Besides, it also cannot account for irrigation effects on evapotranspiration for cropland. We provide a brief description of these processes below, in order to discuss the CoLM modifications we employed for cropland and shrubland.

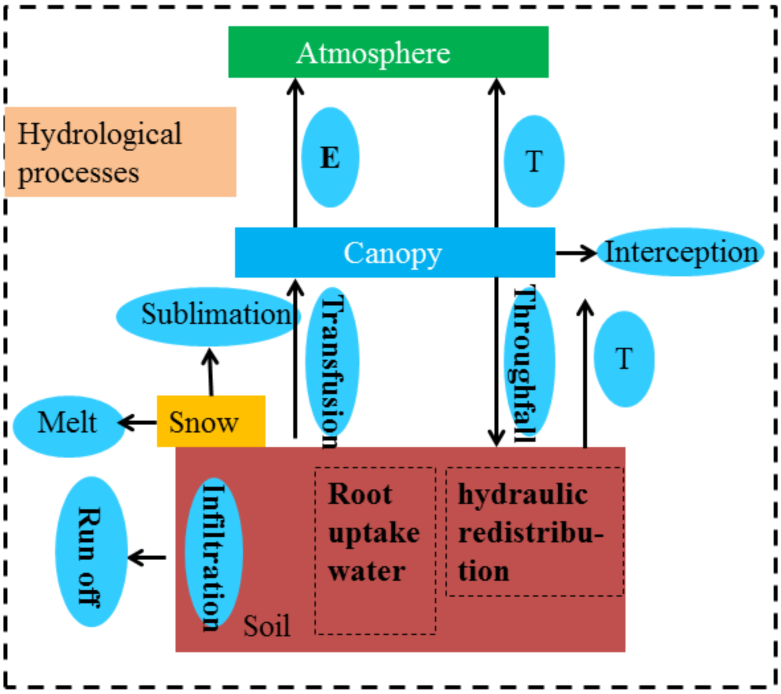

Figure 3.2 The hydrological processes in Common Land Model (CoLM)

3.2.3 The irrigation effects for cropland

Water is the most limiting resource for sustaining crop production in agricultural oases in Xinjiang, and almost 92 percent of agricultural area was irrigated (Xu et al., 2003). Therefore, all the cropland was treated to be irrigated in our study area to account for irrigation effects on evapotranspiration. We hypothesized that the irrigation was activated when available water in the top six soil layers at a depth of 0.49 m decreases to a threshold of the maximum available water (field capacity minus wilting point) during the growing season. After the irrigation, the soil moisture will reach the field capacity. This method has been widely applied in other studies (Liu et al., 2008b; Liu et al., 2012). The flux tower observations from Wulanwusu (WLWS) Agro-meteorology Experimental Station were used to calibrate the threshold, which was experimentally determined as 0.27 in this study.

3.2.4 The root distribution function

For this study, the nonlinear model used for interpolations of root distributions was a logistic dose-response curve (Schenk and Jackson, 2002) that was fitted to the following cumulative root profiles:

$$r(D) = \frac{R_{max}}{1 + (\frac{D}{D_{50}})^{c}}$$

$$c = \frac{-1.27875}{\log_{10} D_{95} - \log_{10} D_{50}}$$

where r(D) is the cumulative amount of roots above the soil profile depth (D); R_{max} is the root quantity, set as 100%; and D_{50} and D_{95} are the depths to which root quantities are equal to 50% and 95% of all roots, respectively. We modified the D_{50} and D_{95} default values of 170 cm and 240 cm to 47 cm and 302 cm according to our observed vertical root distribution for a typical desert plant (*Tamarix*) (Jing et al., 2014).

3.2.5 The root water uptake function

In the default CoLM, the Root Water Uptake Function (RWUF) is given by the following:

$$\varepsilon_j = \frac{f_{root,j} a_j}{\sum f_{root,j} a_j}$$

$$a_j = (\frac{\varphi_{wilt} - \varphi_j}{\varphi_{wilt} + \varphi_{sat}})^{m}$$

where ε_j and $f_{root,j}$ are the root water uptake fraction and the root distribution fraction within the jth soil layer, respectively; φ_{wilt} is the wilting point potential; φ_{sat} is the soil water matrix potential at the saturation point; φ_j is the soil water matrix potential within the j^{th} soil layer; a_j is the root water uptake efficiency within the jth soil layer; and m is an empirical coefficient. When the value of m is equal to one, a_j is the same as the default value provided by the CoLM. Li et al. (2013b) determined that when m is set lower than one the new root water uptake efficiency always computes values that are larger than the default. The soil water uptake efficiency with the new a_j was thus higher than with a default a_j, especially for low soil water conditions (the low soil water matrix potential). This procedure is appropriate for an assumption that desert plants maintain their physiological activities under low matrix potentials (Xu et al., 2007). For this study, the value of the parameter m was empirically determined to be 0.01 according to Li et al. (2013b).

3.2.6 The hydraulic redistribution function

Water flux amongst various soil layers due to HR through the root conduit was followed by Ryel et al. (2002) and Lee et al. (2005), which can be formulated as:

$$H_j = C_{RT} \sum_{j=1}^{n} (\varphi_j - \varphi_i) \max(c_i, c_j) \frac{f_{root,i} f_{root,j}}{1 - f_{root,x}} \delta_T$$

where C_{RT} is the maximum radial soil-root conductance of the entire active root system with a constant value of 0.097 (cm/MPa/h) (Ryel et al., 2002); n is the number of soil layers; φ_i and φ_j are the soil water potential within the ith and jth soil layer, respectively; $f_{root,i}$ and $f_{root,j}$ are the root fraction within the ith and jth soil layer, respectively; $f_{root,x} = f_{root,j}$ when the soil water content within the j layer is larger than it is within the i layer, or $f_{root,x} = f_{root,i}$ otherwise; and δ_T is a switch controlling HR, which is generally only valid at night, that is equal to 0 during the day and 1 at night. The relative soil-root conductance for water within ith (c_i) or jth (c_j) soil layer, is calculated using the following empirical relationship:

$$c_i = \frac{1}{1 + (\frac{\varphi_i}{\varphi_{50}})^b}$$

where φ_{50} is the soil water potential when the soil hydraulic conductance is reduced by 50%, and b is an empirical constant.

3.2.7 The data source

The 3-hour climate dataset from 1996 to 2012 at one degree was obtained from PRINCETON University and includes temperature, precipitation, downward short- and long-wave radiation, specific humidity, surface air pressure, and wind speed (Sheffield et al., 2006). The PRINCETON dataset is one of the most widely used reanalysis climate datasets for driving land surface models. The vegetation distribution map from 2001 to 2012 was derived from MODIS (Moderate Resolution Imaging Spectroradiometer) land cover type products (MCD12C1.005) at a spatial resolution of 0.05 degree. The classification method was performed according to the International Geosphere-Biosphere Program (IGBP). Other input datasets included soil texture, soil color, and a topographic map (elevation) from the United States Geological Survey (USGS) used to define land surface characteristics.

To evaluate the performance of the CoLM in simulating evapotranspiration, four flux tower observations at the site level were used to validate our model simulation (Figure 3.1). Detailed descriptions of the flux towers are provided in Table 3.1. Two evapotranspiration datasets were used to compare our simulations at a regional level. One was produced by the Penman–Monteith equation driven by MODIS data and daily meteorological data (MOD16A3) (Mu et al., 2011), and the other was produced by a Machine-Learning Algorithm (MLA) by combining flux-tower evapotranspiration measurements and remote sensing observations (Jung et al., 2010).

Table 3.1 The name, location, vegetation type, annual mean temperature (AMT), annual precipitation (AP), and time period of observations used for model

calibration and validation.

Site	Longitude	Latitude	Vegetation type	AMT	AP	Time period
FK	87º56´E	44º17´N	Shurb	6.6 ºC	163 mm	2007 - 2009
KZ-Bal	76º39´E	44º34´N	Grass	5.7 ºC	140 mm	23 May - 6 September 2012
KZ-Ara	61º05´E	45º58´N	Shrub	8.3 ºC	140 mm	30 April - 18 August 2012
WLWS	85º49´E	44º17´N	Crop	7.0 ºC	210 mm	2009 - 2010

FK: Fukang station; KZ-Ara: Aral Sea station in Kazakhstan; KZ-Bal: Balkhash Lake station in Kazakhstan; WLWS: Wulanwusu station.

3.2.8 The experimental design

First, two simulations were designed to assess the irrigation effects for cropland at WLWS station. One simulation was executed with adding irrigation effects and the other without adding irrigation effects. And then the estimated evapotranspiration of above two simulations was compared to observations. Secondly, we ran four simulations to validate the performance of improved CoLM in shrubland at FK station. The first simulation runs with adding HR; the second with modifying RWUF; the third with both adding HR and modifying RWUF; the last with default runs. And then, all the outputs of the above simulations were compared to observations. Finally, six simulations were designed to quantify the relative contributions of the two factors (LCC and climate change) to evapotranspiration variability (Table 3.2). One simulation was termed “LCC_CLIM” and was designed to assess the combined effects of climate and land cover change on evapotranspiration from 2001 to 2012.

Other simulations were designed for assessing evapotranspiration variability on individual factors or a subset of environmental factors. “LCC”, “PREC”, and “TEMP” simulated the individual effects of land cover change, precipitation, and temperature, respectively. “CLIM” simulated the combined effects of all climate factors (e.g., precipitation, temperature, radiation). “COMB” simulated the combined effects of both temperature and precipitation. In the factorial analyses, only the factor(s) under investigation varied over time while other environmental drivers were kept at the 2001 initial level. To prevent abnormal fluctuations, an equilibrium run was designed prior to each simulation in order to make the natural ecosystem reach an equilibrium state. For this step, the model was driven by the initial climate state in 1996.

Table 3.2 The design of the simulation experiments.

Experiment	LCC[b]	Climate		
		Temperature	Precipitation	Others
LCC_CLIM[a]	2001-2012	2001-2012	2001-2012	2001-2012
LCC[b]	2001-2012	2001	2001	2001
CLIM[c]	2001	2001-2012	2001-2012	2001-2012
PREC[d]	2001	2001	2001-2012	2001
TEMP[e]	2001	2001-2012	2001	2001
COMB[f]	2001	2001-2012	2001-2012	2001

[a] LCC_CLIM, combined land cover change and climate change

[b] LCC, land cover change

[c] CLIM, climate change

[d] PREC, precipitation

[e] TEMP, temperature

[f] COMB, combined temperature and precipitation

3.2.9 The statistical analysis

A linear fitting method was used to compute the trend of evapotranspiration and climatic variables. A mean value difference between two individual periods was used to quantify the temporal changes of evapotranspiration, and the two periods are defined as the last and first three years during 2001-2012. The coefficient of determination (R^2) and the Root Mean Square Error (RMSE) were used to evaluate agreement between simulations and observations. The t-test was used to assess the statistical significance (p) of the trend and the R^2. R^2 and RMSE were calculated as follows:

$$\mathrm{R}^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum(\hat{y}_i - y_i)^2}{n - 1}}$$

where y_i, $\hat{y}_i$, and $\bar{y}$ indicate the observed, modeled, and mean of the observed evapotranspiration at time step i, respectively, and n is the number of observations.

3.3 Results

3.3.1 The model performance evaluation

Figure 3.3 shows the performance of CoLM in simulating evapotranspiration with and without adding the irrigation effects at WLWS Agro-meteorology station. The default CoLM without adding the irrigation effects underestimated evapotranspiration especially in the growing season, while the modified the CoLM under considering the irrigation effects improved the accuracy of simulations. The R^2 increased from 0.07 to 0.51 and RMSE reduced from 2.08 to 1.37 mm/day.

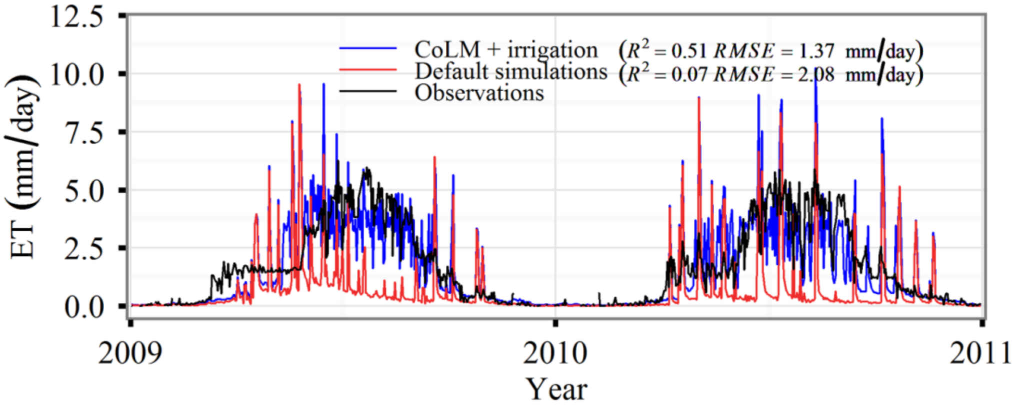

Figure 3.3 A comparison of EvapoTranspiration (ET) between simulations and observations. Daily averaged ET at the Wulanwusu (WLWS) site based on the default common land model (CoLM), and the modified CoLM with the addition of irrigation effects (CoLM + irrigation).

Our results indicated that modified CoLM simulations were more comparable to observations at the FK (Fukang) site than the default CoLM. Figure 3.4 shows that CoLM-estimated evapotranspiration had a higher performance in catching seasonal patterns by adding HR and modifying RWUF. A high evapotranspiration occurred during the growing season and a low evapotranspiration occurred during the winter. However, evapotranspiration was underestimated especially during the growing season by using the default CoLM. The CoLM modified using both the HR and RWUF produced a more significant linear relationship than that modified by HR, with R^2 = 0.72, $p < 0.05$, and RMSE = 1.04 mm/day (Table 3.3). However, the CoLM modified using both the HR and RWUF showed a comparable role with that only by modifying RWUF. The CoLM modified by adding HR showed marginally better performance than default CoLM. The R^2 increased from 0.43 to 0.45, and RMSE decreased from 1.66 to 1.61 mm/day.

Table 3.3 Model performance for simulating Evapotranspiration as indicated by the coefficient of determination (R^2) and the root mean square error (RMSE, mm/day).

Site	Default simulation		CoLM+HR		CoLM+RWUF		CoLM+HR+RWUF	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
FK	0.43*	1.66	0.45*	1.61	0.72*	1.04	0.72*	1.04
KZ-Bal	0.90*	2.71	0.90*	2.71	0.90*	2.71	0.90*	2.71
KZ-Ara	0.36*	1.44	0.36*	1.44	0.37*	1.42	0.37*	1.42

CoLM+HR, CoLM+RWUF, and CoLM+HR+RWUF indicate that the default model CoLM was improved by adding Hydraulic Redistribution (HR), by modifying the root water uptake efficiency (RWUF), and by both (HR and RWUF) combined, respectively. R^2 with an asterisk indicates significance ($p < 0.05$).

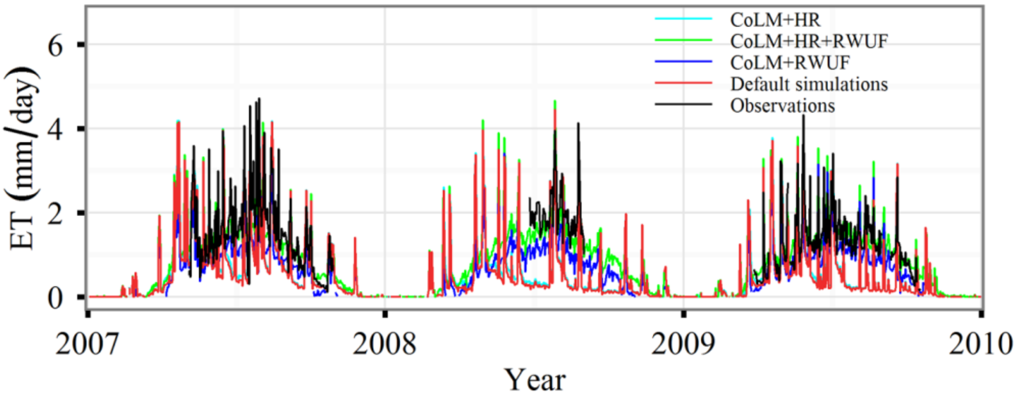

Figure 3.4 A comparison of EvapoTranspiration (ET) between simulations and observations. Daily averaged ET at the Fukang (FK) site based on the default common land model (CoLM), the modified CoLM with the addition of Hydraulic Redistribution (HR) (CoLM+HR), the modified root water uptake efficiency (RWUF) (CoLM+RWUF), their combination (CoLM+HR+RWUF), and the observations.

Because of a lack of in situ observations, two flux tower observations, adjacent to our study area were also used to compare our simulations. A strong linear relationship obtained from the CoLM modified using both the HR and RWUF was determined ($R^2 = 0.90$, $p < 0.05$) at the KZ-Bal site, while the relationship was moderate at the KZ-Ara site ($R^2 = 0.37$, $p < 0.05$) (Table 3.3). The RMSE was 2.71 and 1.42 mm/day at the KZ-Bal and KZ-Ara sites, respectively. The results imply that overall predictions for the modified CoLM matched well with field observations. The CoLM modified by either the HR or RWUF did not impact performance for simulating evapotranspiration for grass types at the KZ-Bal site. Finally, the CoLM modified using both the HR and RWUF was selected for performing regional simulations.

We evaluated the spatial pattern of modified CoLM-simulated evapotranspiration at the regional level by comparing it to the MODIS product (Figure 3.5). Average evapotranspiration estimated using the CoLM agreed well with MODIS evapotranspiration in terms of the spatial pattern from 2001-2012. High evapotranspiration occurred in Tianshan and Altai mountainous areas, and low evapotranspiration occurred in the Taklimakan Desert and adjacent areas. Our estimated evapotranspiration was 131.22 (±321.78) mm /year, higher than the 91.17 (±5.85) mm/year derived from MODIS evapotranspiration over the whole Xinjiang region. The discrepancy may result from a lack of values surrounding Taklimakan Desert areas for MODIS datasets. We further compared CoLM-estimated evapotranspiration to MLA-estimated evapotranspiration which is derived from Jung et al. (2010). Our estimates displayed a similar spatial pattern with MLA estimates, but a discrepancy in magnitude still existed. Evapotranspiration based on the MLA was ~200 mm/year for areas located in the south of our study area and was larger than our estimates of ~100 mm/year. Estimates for evapotranspiration over Xinjiang were also less than MLA estimates, with values of 175.03 (±4.06) mm/year.

We further selected all the grids from MODIS-based and MLA-based evapotranspiration to compare them to our simulations. The results showed a poor correlation between CoLM-estimated and MODIS-estimated evapotranspiration (R^2 = 0.25, Slope = 0.85, and RMSE = 108 mm/year), but a moderate correlation between MLA-estimated and CoLM-estimated evapotranspiration (R^2 = 0.56, Slope = 0.89, and RMSE = 68 mm/year) (Figure 3.6).

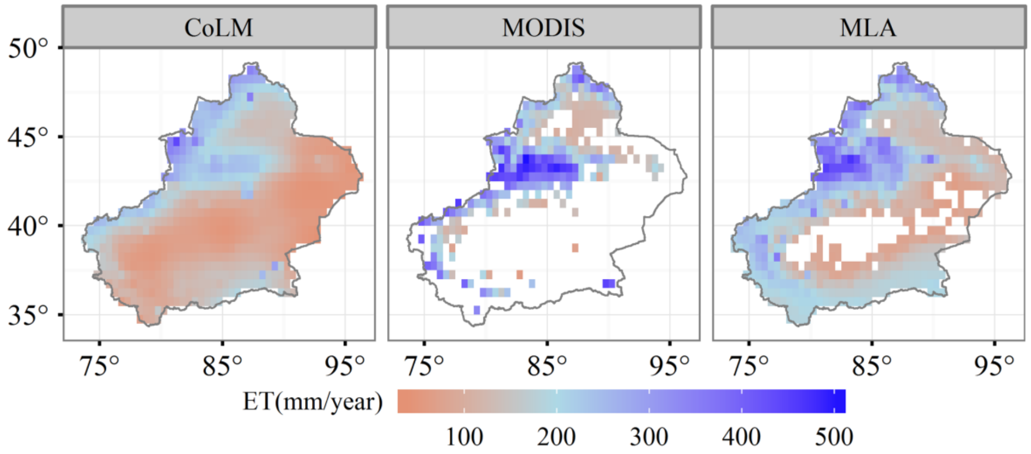

Figure 3.5 Spatial patterns of modified CoLM-simulated, MODIS-estimated, and MLA-simulated evapotranspiration.

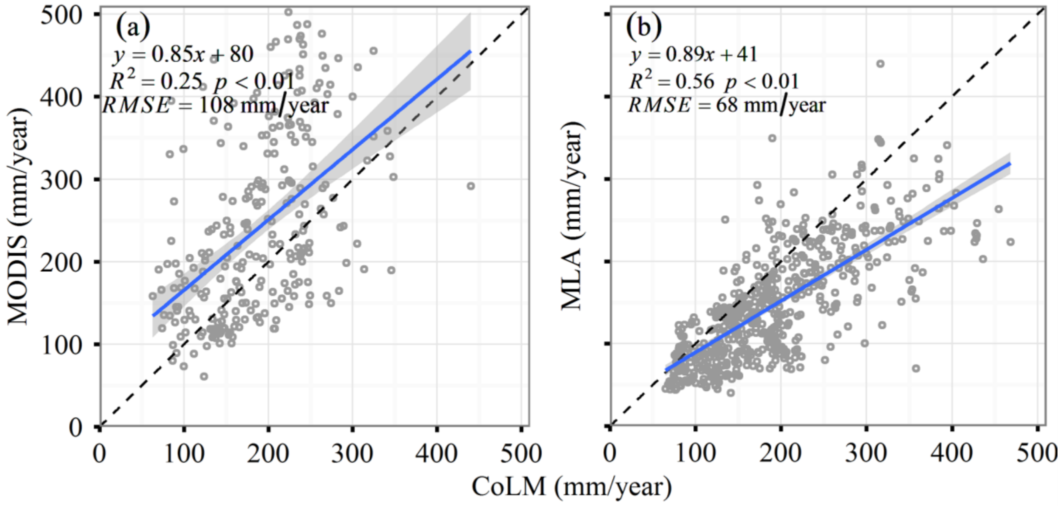

Figure 3.6 Comparisons of CoLM-simulated versus MODIS-estimated (a) and MLA-simulated (b) evapotranspiration. The blue line represents the least squares regression. The dashed line indicates the 1:1 line.

3.3.2 Temporal and spatial changes in evapotranspiration

Figure 3.7 shows the temporal and spatial patterns of CoLM-estimated annual evapotranspiration in Xinjiang Uyghur Autonomous Region of China. From 2001 to 2012, we estimated a mean annual regional land-surface evapotranspiration value of 131.22 (±v21.78) mm/year. Average evapotranspiration in this region exhibited significant inter-annual variability with a maximum in evapotranspiration (166.09 mm) in 2003 and a minimum (97.39 mm) in 2008. No significant trend was determined for our study period ($R^2 = 0.23$, $p = 0.12$). The spatial distribution is provided in Figure 3.7(a). Our results illustrate substantial spatial variations in evapotranspiration across the study area. Approximately 13.5% of the pixels in this region experienced an increase in evapotranspiration and only about 1% of the pixels were significant in southern areas. Decreased evapotranspiration largely occurred in the eastern areas and about 19.7% of the pixels were significant.

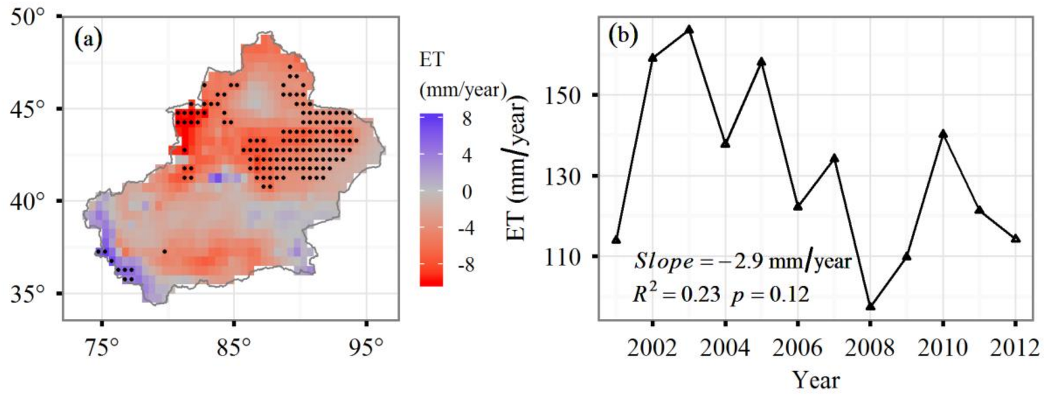

Figure 3.7 The spatial (a) and temporal (b) variability of annual EvapoTranspiration (ET) in Xinjiang from 2001-2012. Pixels with black points are statistically significant at p <0.05. The blue solid line represents the least squares regression and the shadow indicates the confidence interval.

3.3.3 Contributions of climate and land cover changes to evapotranspiration

Based on the results of scenario simulations, evapotranspiration in response to LCC varied with time (Figure 3.8). The combined effect of both LCC and climate change reduced evapotranspiration about 21.09 mm during the period from 2001 to 2012. Statistical analyses indicated that the LCC only accounted for 1% of the temporal variability of evapotranspiration. The LCC simulation indicated that evapotranspiration was enhanced by 1.11 mm from 2001 to 2012 (Figure 3.8(b)). More detailed information for LCC impacts on evapotranspiration can be determined using the spatial distribution of evapotranspiration variability based on the LCC scenario (Figure 3.9). Land conversion enhanced evapotranspiration up to approximately 43.3% of pixels, and 13.8% of pixels were significant within southwestern Xinjiang and the northern Tianshan Mountains where the land cover type is primarily cropland (Figure 1. 2(a)). Enhanced evapotranspiration within the northern Tianshan Mountains may have resulted from an increase in croplands following 2001. Approximately 51.2% of pixels underwent a decrease in evapotranspiration but only 6.2% of pixels, such as those in northern areas, were significant.

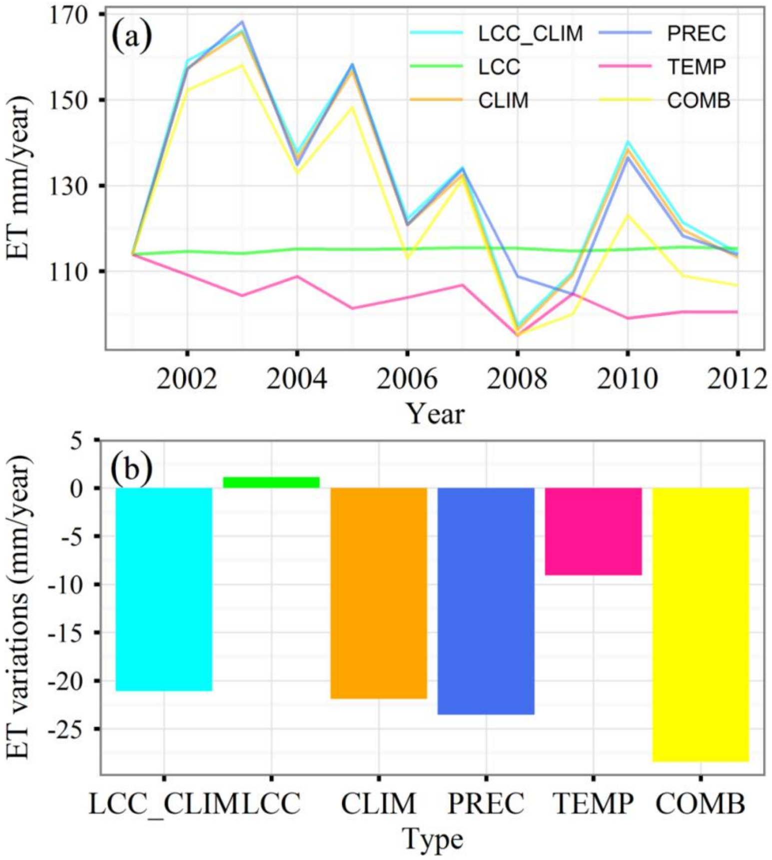

Figure 3.8 Temporal variability of annual EvapoTranspiration (ET) under different simulation scenarios (a) and contributions of environmental factors on ET variability (b). LCC_CLIM: Land cover change and climate change; LCC: Land cover change; CLIM: Climate change; PREC: Precipitation; TEMP: Temperature; COMB: Combined temperature and precipitation.

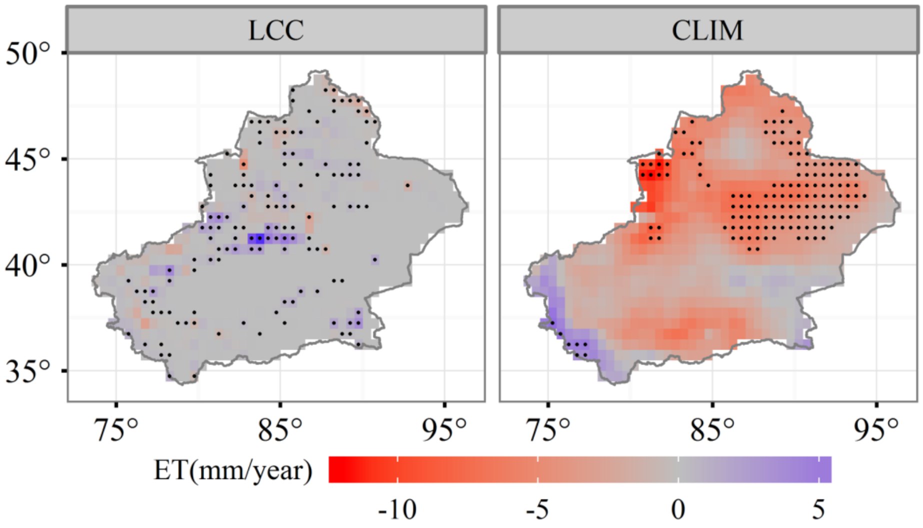

Figure 3.9 The effects of land cover change and climate change on

evapotranspiration variability in Xinjiang.

Our model simulation suggested that climate effects accounted for 99% of the inter-annual variability of evapotranspiration. During 2001-2012, the evapotranspiration decreased with large fluctuations, especially during 2008 when evapotranspiration decreased by approximately 17 mm (Figure 3.8). The CLIM simulation indicated that evapotranspiration decreased by 21.90 mm from 2001 to 2012. Among climate factors, temperature change resulted in a 9.09 mm reduction and precipitation change resulted in a 23.55 mm reduction (Figure 3.8(b)). To illustrate the temporal correlation between evapotranspiration and climate factors, we computed linear trends for temperature and precipitation from 2001 to 2012 (Figure 3.10). Our results indicated no significant trend for precipitation while temperature significantly decreased from 2001-2012 at a rate of 0.08 °C/year. The temporal pattern of evapotranspiration simulated using the CLIM scenario was coincident with precipitation. According to both PREC and TEMP simulations, the evapotranspiration in 2008 was almost the lowest (Figure 3.8(a)), suggesting that the dramatic decline in evapotranspiration in 2008 may have resulted from a decrease in both precipitation and temperature.

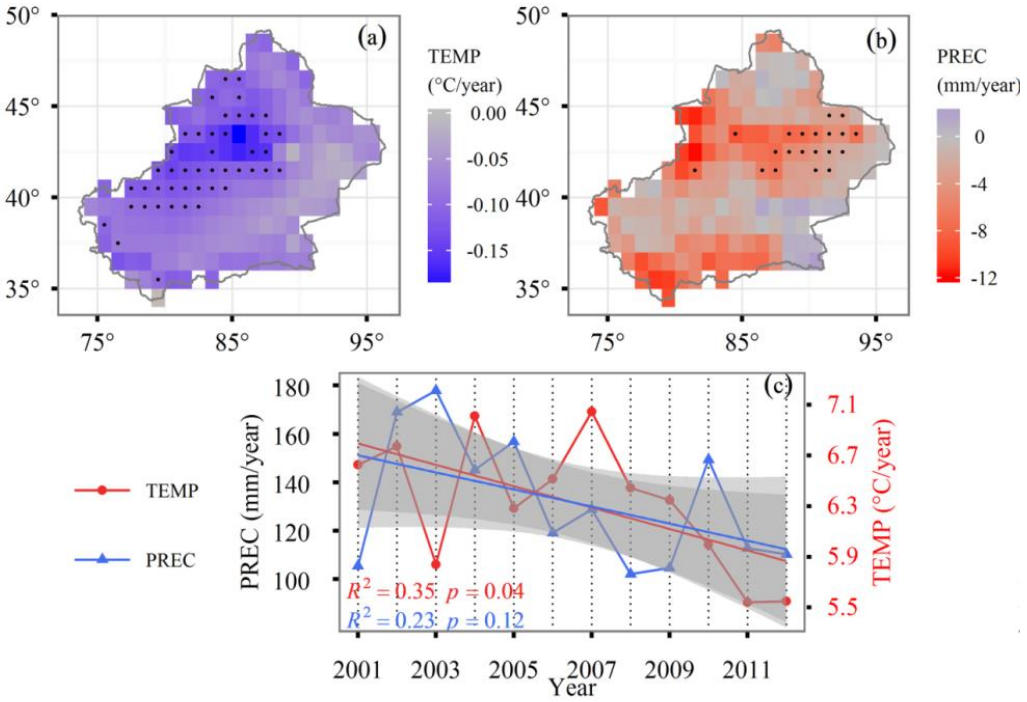

Figure 3.10 The temporal and spatial variability of annual mean temperature and precipitation in Xinjiang from 2001-2012. The spatial pattern of annual mean temperature (a), precipitation (b), and the temporal trend of annual mean temperature and precipitation (c). The solid line represents least squares regression and the shadow area indicates the confidence interval.

Climate impacts on evapotranspiration were negative over the majority of the study area. Approximately 88.3% of areas experienced a decrease in the CLIM-only scenario and only 20% of areas were significant. The spatial patterns of evapotranspiration changes were very similar to precipitation. In the Tianshan Mountains the rate of decrease in evapotranspiration exceeded 8 mm per year in some pixels and precipitation significantly decreased, indicating that the declining trend in evapotranspiration was limited to the decrease of precipitation.

3.4 Discussion

3.4.1 A comparison of CoLM-simulated evapotranspiration with previous studies

Assessments of evapotranspiration variability and dynamics from the past to the future on either a global or regional scale have been comprehensively conducted (Pan et al., 2015; Yang et al., 2015). However, a lack of available field measurements (partially due to very limited or possibly biased samples) has made it difficult to gain a comprehensive view of evapotranspiration estimates over the entire Xinjiang region.

We compared our simulations with previous studies. The evapotranspiration depths for Xinjiang region during May-September is 105.20 mm according to Chen et al. (2012). It is highly comparable to our simulations 107.86 mm during the same period. Based on the process-based CoLM, we estimated a mean annual evapotranspiration of 131.22 (±o21.78) mm/year for the period from 2001 to 2012. However, in recent studies using a remote sensing method, Mu et al. (2011) estimated a regional terrestrial evapotranspiration of 91.17 (±5.85) mm/year, which is much lower than the CoLM-simulated terrestrial evapotranspiration. A detailed comparison between the evapotranspiration of the CoLM and other estimates is provided in Table 3.4. Recent studies have indicated several issues and uncertainties when retrieving evapotranspiration using a remote sensing approach, and most of these uncertainties are related to surface variables such as land surface temperature, solar radiation, etc. (Pan et al., 2015). Furthermore, the MODIS evapotranspiration product from Mu et al. (2011) does not cover sparse vegetation areas (i.e., deserts and the Gobi) due to limitations of retrieved vegetation index with negative values for dryland ecosystems, especially in Xinjiang.

Table 3.4 Comparisons of EvapoTranspiration (ET) between our study and past studies.

Methods	ET (mm/year)	Time period	Reference
Process-based model (CoLM)	131.22 (±321.78)	2001-2012	This study
MODIS improved ET algorithm	91.17 (±15.85)	2001-2012	Mu et al (2011)
Machine learning approach	175.03 (±74.06)	2001-2011	Jung et al (2010)
Process-based model (CLM)	119.2 (±19.9)	1960-2005	Liu et al (2008)

Our estimated mean value of evapotranspiration is lower than that of Jung et al. (2010) who reported a regional terrestrial evapotranspiration of 175.03 (±4.06) mm/year from 2001-2011. The evapotranspiration estimation of Jung et al. (2010) was upscaled from eddy covariance flux measurements to the global scale using a MLA method based on auxiliary remote sensing data. However, the method is a highly empirical mathematical model that does not consider environmental factors and mechanisms. As reported, climate variability and LCC play a vital role in controlling evapotranspiration changes (Liu et al., 2012). In addition to these uncertainties, the MLA evapotranspiration was largely based on flux tower measurements. However, flux towers in Xinjiang are sparse and highly uneven in distribution. In addition to these shortcomings, flux tower measurements themselves are often associated with an energy balance closure problem. All of the above-listed uncertainties could make the data less representative for the entire Xinjiang region.

The CoLM-estimated evapotranspiration was larger than a regional terrestrial evapotranspiration of 119.2 (±9.9) mm/year estimated by Liu et al. (2008a), who used another process-based model (CLM 2.0). The differences may come from different forcing datasets. Liu et al. (2008a) used global reanalysis forcing data from Qian et al. (2006) and interpolated surface data based on meteorological observations in order to feed the CLM 2.0. We used global reanalysis data from PRINCETON (Sheffield et al., 2006). Hu et al. (2016) reported that reanalysis data sets contain large discrepancies for arid/semi-arid areas that have different accuracies in capturing terrain- and long-term drought-induced effects.

Additionally, current LSMs studies have a common problem with regard to underestimating evapotranspiration in dryland ecosystems. Although deep root distribution and related root water uptake processes are important for the structure and function of dryland ecosystems, deep-root mechanisms are rarely considered in most land surface models (Li et al., 2012d). In comparison, the improved CoLM in this study can address root distributions in deep soils based on field measurements. Besides, the process of RUWF is an important factor in controlling evapotranspiration. Li et al.(Li et al., 2013b) has reported that linear RUWF in the default CoLM is the main reason that resulted in underestimating evapotranspiration. An adjustment of RUWF from linear to nonlinear is expected to a reasonable solution to improve the performance of CoLM in simulating evapotranspiration. In this study, the value of m in RUWF has been determined empirically from 1 to 0.01 based on the field measurements at FK station, which indicates that more soil water in modified CoLM will be absorbed than that in default CoLM. HR is also an important physical process contributing to dynamic root water uptake in plants that plant roots take-up water from deep moist soils and redeposit it into the upper soil layer at night for the purpose of root uptake to sustain daytime transpiration. This phenomenon has also been widely verified by previous studies in our study area (Hao et al., 2010; Hao et al., 2013). Therefore, all above modifications in CoLM could provide a more reasonable estimation of evapotranspiration.

3.4.2 The effects of climate factors and land cover changes on evapotranspiration

We modeled the spatial and temporal pattern of evapotranspiration changes and determined that the LCC contributed to the increase of regional evapotranspiration. The increase in evapotranspiration mainly occurred in regions where croplands were distributed. In these regions, the area of croplands underwent an increase of up to 11% that resulted in an upward trend for evapotranspiration. Our results support previous conclusions that areas with significant land conversions dramatically affect evapotranspiration on regional scales (Yang et al., 2015). Luo et al. (2010) reported that all increased cropland in Xinjiang resulted from dryland ecosystems such as shrublands, grasslands, and deserts that sustain their growth through irrigation. Due to irrigation and large leaf area indices, cropland has a higher evapotranspiration than other land cover types. Tao et al. (Tao et al., 2011) reported that local human activities (such as irrigation) led to a decrease of the water volume diverted into the main stream of the Tarim River Basin in Xinjiang. The results of our study emphasized the significant impact of human activities on land-surface water sources, especially in arid/semi-arid regions where fresh available water largely results from runoff.

Our model simulation indicated that climate change and variability plays a negative role in controlling evapotranspiration changes. Climate change reduced evapotranspiration by 21.90 mm from 2001 to 2012. Among climate factors, temperature change resulted in a 9.09 mm reduction and precipitation change resulted in a 23.55 mm reduction. The combined effects of TEMP and PREC contributed to 28.45 mm reduction. Therefore, a large proportion of evapotranspiration variability could not be explained by both precipitation and temperature alone. And other factors such as solar radiation and wind, etc. should be taken into consideration when interpreting climate change impacts on evapotranspiration. According to our correlation analysis, the determination coefficient (R^2) between evapotranspiration and temperature (0.01) was less than that between evapotranspiration and precipitation (0.94), indicating that precipitation has more influence on evapotranspiration variability than temperature.

Climate change and variability directly impact the spatial distribution of evapotranspiration changes. In the Tianshan Mountains, temperature decreased significantly and was associated with decreasing evapotranspiration. As is known, temperatures in high elevation regions are generally low and limit vegetation activity. Such a finding is supported by multiple remote sensing studies that have determined that the Normalized Difference Vegetation Index (NDVI), an indicator of vegetation activity, in high altitudes is negatively correlated with temperature (Yuan et al., 2015b). Decreased precipitation also contributed to the decreased evapotranspiration that was largely determined over northeastern Xinjiang.

3.4.3 Uncertainties and future research

Our modified model performance evaluation yielded a reasonable representation for evapotranspiration estimates at the site level, and some differences may exist when compared to other surface evapotranspiration products. The following uncertainties should be taken into consideration in interpretations of model estimates. As discussed above, the climate forcing data set is the primary factor controlling evapotranspiration estimates, so assessments of different forcing data set impacts on evapotranspiration estimates should be made and more accurate climate datasets at regional scales should be investigated in future research. Model structures and simplifications for some of the hydrological processes may also cause uncertainties. With the exception of climate and land cover change, we did not include the effects of other factors such as nitrogen deposition, ozone pollution, nitrogen fertilizer application, and elevated atmospheric carbon dioxide. Although former studies have indicated that nitrogen deposition and elevated carbon dioxide may not be as important as climate variability and land cover change on evapotranspiration variability (Liu et al., 2012), they may impact evapotranspiration dynamics over long-term periods.

3.5 Conclusions

For this study, we provided a modified process-based land surface model (CoLM) for estimating evapotranspiration in Xinjiang, China. Following modification by adding irrigation effects for cropland and modifying root distributions and the root water uptake process for shrubland, the CoLM was determined to provide high performance in simulating evapotranspiration when compared to field measurements. The CoLM estimated a mean regional evapotranspiration of 131.22 (±o21.78) mm/year for Xinjiang from 2001-2012. Due to the relatively short time period, our estimate did not show a significant temporal trend for evapotranspiration variability. The results of this study indicated that climate change plays a negative role in evapotranspiration variability. Reduced precipitation, in conjunction with decreased temperature, reduced evapotranspiration by approximately 28.45 mm. Our results also suggest that climate change played a dominant role in determining inter-annual variability in evapotranspiration. Furthermore, cropland conversion was a critical factor for altering the spatial pattern of evapotranspiration in Xinjiang. Our study highlights the need for taking appropriate strategies to manage water sources in Xinjiang, China.

CHAPTER 4

Future projected changes in local evapotranspiration coupled with temperature and precipitation variation

Modified from: Xiuliang Yuan, Jie Bai, Longhui Li, Alishir Kurban Philippe De Maeyer. (2018). Future projected changes in local evapotranspiration coupled with temperature and precipitation variation in Xinjiang, China. (*Draft*)

Abstract

Evapotranspiration is the highest outgoing flux in the hydrological cycle in Xinjiang Uyghur Autonomous Region, China, thus quantifying the temporal and spatial patterns of future evapotranspiration is vital to appropriately manage water resources in Xinjiang. In this study, the CoLM was used to estimate the regional evapotranspiration during the period 2021-2050, and its changes projected in response to climate change under two Representative Concentration Pathways (RCP) scenarios (i.e., RCP4.5 and RCP8.5) was also analyzed by the Singular Value Decomposition (SVD) technique. The results indicate that the mean regional evapotranspiration were comparable under the two scenarios during 2021-2050 with the value of 127 (±11.9) mm/year under the RCP4.5 scenario and 124 (±11.1) mm/year under the RCP8.5 scenario, respectively. Compared to the historical period (1996–2005), the annual mean evapotranspiration during 2041-2050 will marginally decrease by 0.3 mm under the RCP4.5 scenario and by 0.4 mm under the RCP8.5 scenario, respectively. The Empirical Orthogonal Function (EOF) analyses show that the evapotranspiration in relative high altitudes areas in Xinjiang presented strong variations. The SVD analyses suggest that the changes in evapotranspiration were more closely linked to local precipitation variations than to temperature. The results can provide beneficial reference to understand the future evapotranspiration changes and improve the regional strategy for water resource management in Xinjiang region.

Keywords: Evapotranspiration; CoLM; EOF; SVD;

4.1 Introduction

Located deep inside the Eurasian continent, the Xinjiang Uyghur Autonomous Region of China is characterized by extremely low precipitation and high temperatures (Wang et al., 2013a). Water resource is a critical limiting factor for economic and social sustainable development in Xinjiang (Jia et al., 2004; Su et al., 2007). Under the impact of global warming, the water cycle has intensified, and consequently the proportion of glacial melt water runoff has increased significantly over the past 50 years (Chen et al., 2015; Gao et al., 2010). Also the annual precipitation has also experienced an increase at a rate of 0.67 mm/year (Hu et al., 2017; Xue et al., 2002). As an important component of the hydrological cycle, evapotranspiration is the highest outgoing water flux or a major pathway of water loss in the water budget (Liljedahl et al., 2011), and thus is a primary factor in determining water availability in Xinjiang (Anderson et al., 2012; Oki and Kanae, 2006). Although great efforts have been devoted to investigate the evapotranspiration change in Xinjiang in the past period (Chen et al., 2012; Liu et al., 2008a; Yuan et al., 2017), how the evapotranspiration change in the future has not yet been well explored.

The future projection of climate change reported by the 5th intergovernmental Panel on Climate Change (IPCC) assessment indicated that the global mean temperature will continue to rise for the rest of 21th century, and the amplitude for 2081–2100, relative to 1986–2005 ranges from 0.3 °C to 4.8 °C under four Representative Concentration Pathways (RCP) scenarios (Stocker, 2014). Hu et al. (2014) reported that Xinjiang has a high potential in temperature rise at a higher rate than the global average and surrounding areas, which means that a higher temperature than the global average, will occur in Xinjiang in the near future. The projection of precipitation also showed a prominent increase tendency at the end of the 21st century (Li et al., 2012c). Shi et al. (2007b) reported that the climate in Xinjiang has been experiencing a change from warm-dry to warm-wet, and the transition is expected to continue in the future. Such changes in climate would exert a profound effect on evapotranspiration. Therefore, a comprehensive analysis of evapotranspiration in response to future change is necessary and helpful to assess and understand the future water cycle and water resource management.

Evapotranspiration changes and in response to climate changes have been widely conducted at regional and continental scales. Climate factors affecting evapotranspiration include three independent factors: demand, supply and energy (Zhang et al., 2015). Demand depends on air temperature and wind speed, while supply and energy are determined by precipitation and solar radiation, respectively. In particularly, Jung et al. (2010) reported that global evapotranspiration had experienced a rising trend, and correlated well with the interannual variability of the temperature from 1982 to 1997, but the rising trend disappeared after the last big El Niña event in 1998, which resulted in a decline in precipitation in the Southern Hemisphere, associated with a decrease in soil moisture to be dissipated by evapotranspiration. Zhang et al. (2015) indicated that approximately 29% of the global land area shows significant increases in evapotranspiration from 1982 to 2013, mainly driven by a general global warming trend and associated increases in air vapor pressure deficit. In high elevation regions, such as Tibetan Plateau, the wind stilling and solar dimming together contributed to the decrease of evaporation (Yang et al., 2014). Besides, precious studies also suggested that climate factors played the dominant role in determining spatial patterns of water fluxes over large regions (Yang et al., 2015; Yuan et al., 2017). It is evident that evapotranspiration changes in response climate change are divergent with respect to different geographical locations (Shi et al., 2013). Therefore, a comprehensive understanding of response of evapotranspiration to climate changes is required on a regional scale.

The LSMs have been becoming an effective tool in simulating terrestrial evapotranspiration (Liu et al., 2008b; Liu et al., 2012; Shi et al., 2013). However, large uncertainties in simulations still exist in the current stage due to different structures and representations of land-atmosphere interactions among LSMs. Attention has been given to the underestimation of the evapotranspiration within arid/semi-arid regions by previous studies for most LSMs (Jing et al., 2014; Li et al., 2013b). The possible reason is that most LSMs can not capture the special vegetation structures that deep root systems and high root/shoot radios has been involved into from long-term limits induced by extreme aridity and high temperatures (Xu et al., 2007). The associated functioning, such as nonlinear root water uptake and hydraulic redistribution are not considered in most current LSMs that can mitigate the effect of high temperature and provide more for supporting evapotranspiration (Li et al., 2012d; Xu et al., 2007). Therefore, a practically applicable land surface model considering above processes is needed to quantify the changes in evapotranspiration.

In this study, we used a process-based land suface model, CoLM to project the evapotranspiration changes in Xinjiang during the future period 2021-2050. The purposes of this study are : 1) to project the temporal and spatial changes of evapotranspiration during 2021-2050 under two scenarios (i.e., RCP4.5 and RCP8.5); 2) to investigate the evapotranspiration changes in response to climate factors (i.e., temperature and precipitation).

4.2 Materials and methods

4.2.1 Study area

Xinjiang Uyghur Autonomous Region (Shown as Figure 1. 1) was chosen in this study. More detailed information can be seen in Section 1.4.

4.2.2 Model description

CoLM was chosen in this study. More detailed information can be found in Section 2.2 and 3.2

4.2.3 Data sets

The 3-hour projected climate data for 1991-2050 at the resolution of 1.25 × 0.9 degree under two RCP scenarios (i.e., RCP4.5 and RCP8.5), including precipitation, temperature, long- and short-wave radiation, pressure, specific humidity, and wind, from climate model CCSM4 were used to drive CoLM. The RCP4.5 scenario is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level, while the RCP8.5 scenario is a high baseline emission scenario, which is characterized by increasing greenhouse gas emissions over time, representative of scenarios in the literature that lead to high greenhouse gas concentration levels (Van Vuuren et al., 2011). Land cover data from the United States Geological Survey (USGS) with 24 categories were used to describe vegetation attributes.

4.2.4 The statistical analysis

The annual changes in evapotranspiration and climate factors (i.e., temperature and precipitation) were defined as differences between two individual periods:

$$D = A_{2041\text{-}2050} - A_{1996\text{-}2005} \quad (4)$$

where D indicates the annual change of variables between two periods; A is the mean value of variables during the corresponding periods, and the period 1996-2005 was selected as historical period.

Since variables in terrestrial ecosystems are characterized by non-linearity and high dimensionality, the Empirical Orthogonal Function (EOF) analysis has high potential in extracting a relatively small number of principal modes which contains as much of the original information as possible (Hannachi et al., 2007). In this study, EOF was applied to analyze temporally varying spatial patterns of evapotranspiration according to the spatial mode, and corresponding time coefficients which describe the magnitude of the variation of the spatial mode. To further examine evapotranspiration changes linked to climate factors, Singular Value Decomposition (SVD) was used to analyze the coupled correlation between two spatial-temporal fields. The SVD technique provides an effective way to separating coupled modes of variability between two field (Wallace et al., 1992). In SVD analysis, each pair of spatial mode was used to explain cross-covariance of the two fields. The correlation between time coefficients of each coupled spatial mode indicates the degree of coupling between two variables. The ratio of each squared singular value to the total value is used to describe how many fractions can be explained by corresponding coupled spatial modes.

4.3 Results

4.3.1 The future changes in precipitation and temperature

The future temporal variations of the annual precipitation and temperature under two scenarios were analyzed during the period 2021-2050 (Figure 4.1). The temperature under both RCP4.5 and RCP8.5 scenario showed a significant increasing trend at a rate of 0.03 and 0.04 °C/year, respectively. Compared with the referenced historical period (1996-2005), the annual mean temperature during 2041-2050 will increase by 1.3°C under RCP4.5 and 1.6 °C under RCP8.5. The annual precipitation under both scenarios showed a large fluctuation between 100 and 180 mm/year, and demonstrated no significant trend. The two scenarios showed a comparable change for precipitation compared with the reference history period with a small rise of 2.5%.

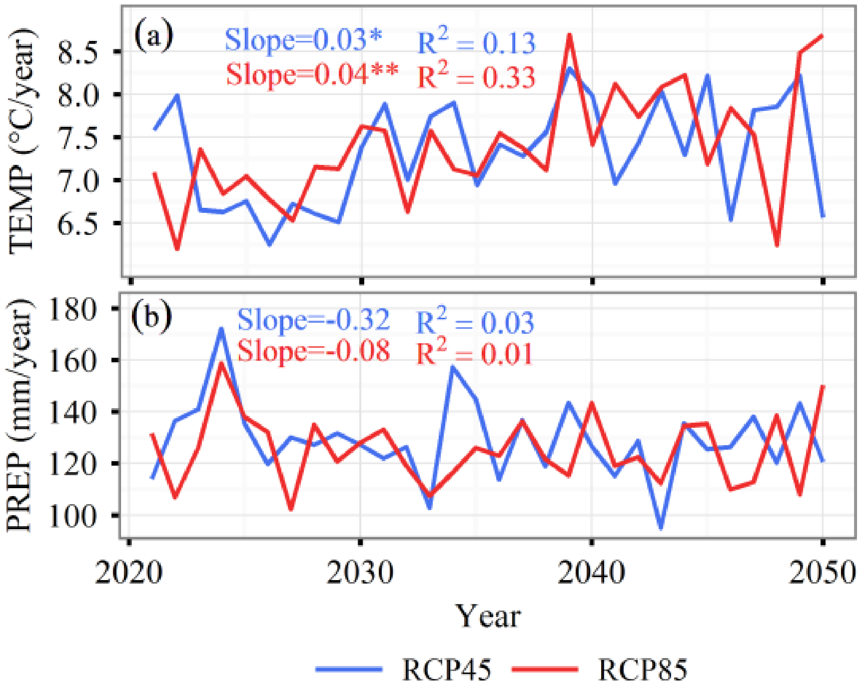

Figure 4.1 Temporal changes in temperature (a) and precipitation (b) during 2021-2050 under RCP4.5 and RCP8.5 scenarios.

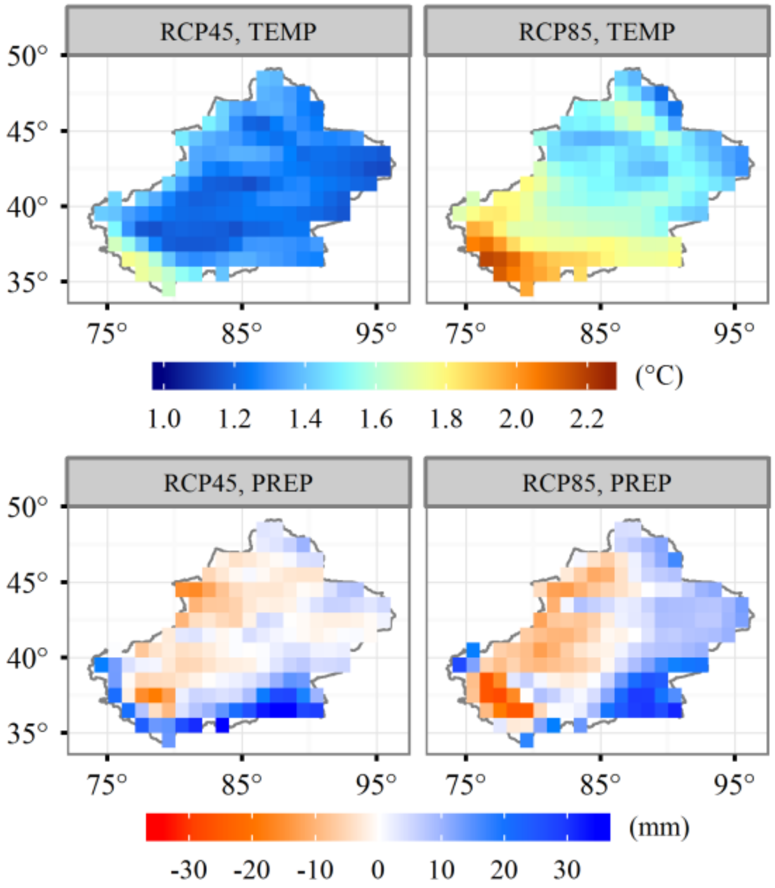

Figure 4.2 Spatial variations in temperature (a) and precipitation (b) during 2041-2050 compared to the historical period during 1996-2005 under RCP4.5 and RCP8.5 scenarios.

Figure 4.2 shows the spatial patterns of variations of both temperature and precipitation during the period 2041-2050 compared with the period 1996-2005. For the temperature, the positive differences appeared across almost the entire region, and the values in southern regions are higher than that in northern regions, which indicates that almost the entire region will experience a warming and the increase rate of temperature in the southern region is larger than that in northern region. Moreover, the positive differences under the RCP8.5 scenario are larger than that under the RCP4.5 scenario. The increase in temperature is relatively high at a rate of 2.2 °C in Kunlun Mountains under the RCP8.5 scenario that is higher than the value of about 1.7°C under the RCP4.5 scenario. For precipitation, opposite signs of difference values occurred under both scenarios where positive values appeared in eastern and southern areas and negative values occurred in western areas, which means that eastern and southern areas in Xinjiang will experience a wet trend and western areas will experience a dry trend. Moreover, there is no noticeable difference in magnitudes in the difference values of precipitation between the both scenarios.

4.3.2 Temporal and spatial variations of the annual evapotranspiration

Figure 4.3 shows the temporal trend of predicted future evapotranspiration in Xinjiang during 2021-2050 under the two scenarios. The mean annual regional evapotranspiration was estimated at the value of 127 (±11.9) mm/year under the RCP4.5 scenario and 124 (±11.1) mm/year under the RCP8.5 scenario. The regional evapotranspiration exhibited a large inter-annual variability under both scenarios, ranging from 100 to 160 mm/year, and no significant trend was determined during the study period ($p > 0.05$). Compared with the referenced historical period (1996-2005), the annual mean evapotranspiration during 2041-2050 will decrease by 0.3 mm under the RCP4.5 scenario and by 0.4 mm under the RCP8.5 scenario, respectively.

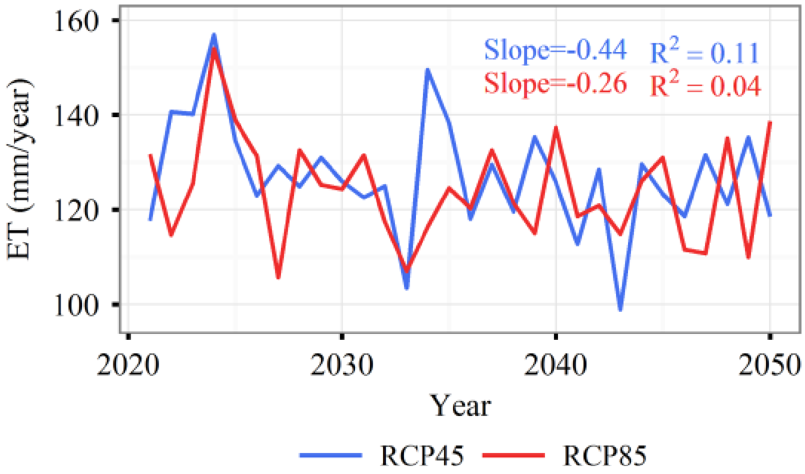

Figure 4.3 Temporal variations in evapotranspiration during 2021-2050 under RCP4.5 and RCP8.5 scenarios.

The spatial patterns of changes of evapotranspiration are shown in Figure 4.4, which is similar with the patterns of changes in precipitation. Opposite signs of difference values occurred under both scenarios that positive values appeared in eastern and southern areas and negative values occurred in western areas. In the central regions of

Xinjiang, the evapotranspiration showed less variability than the other regions.

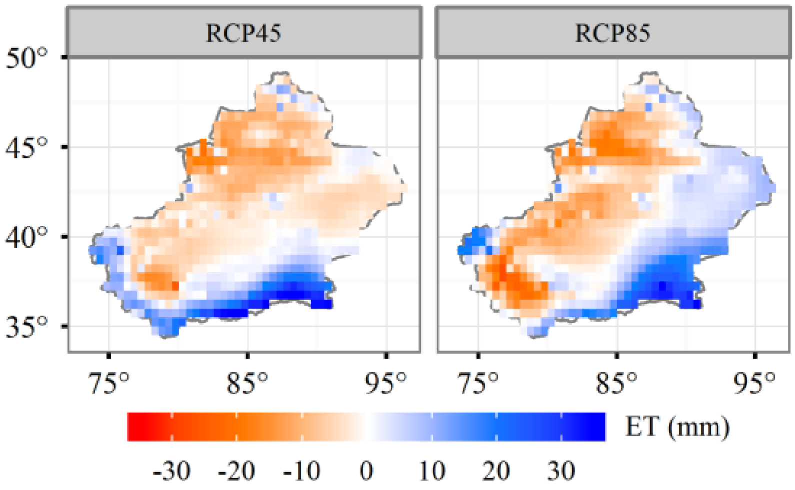

Figure 4.4 Spatial variations in evapotranspiration during 2041-2050 compared to the historical period during 1996-2005 under RCP4.5 and RCP8.5 scenarios.

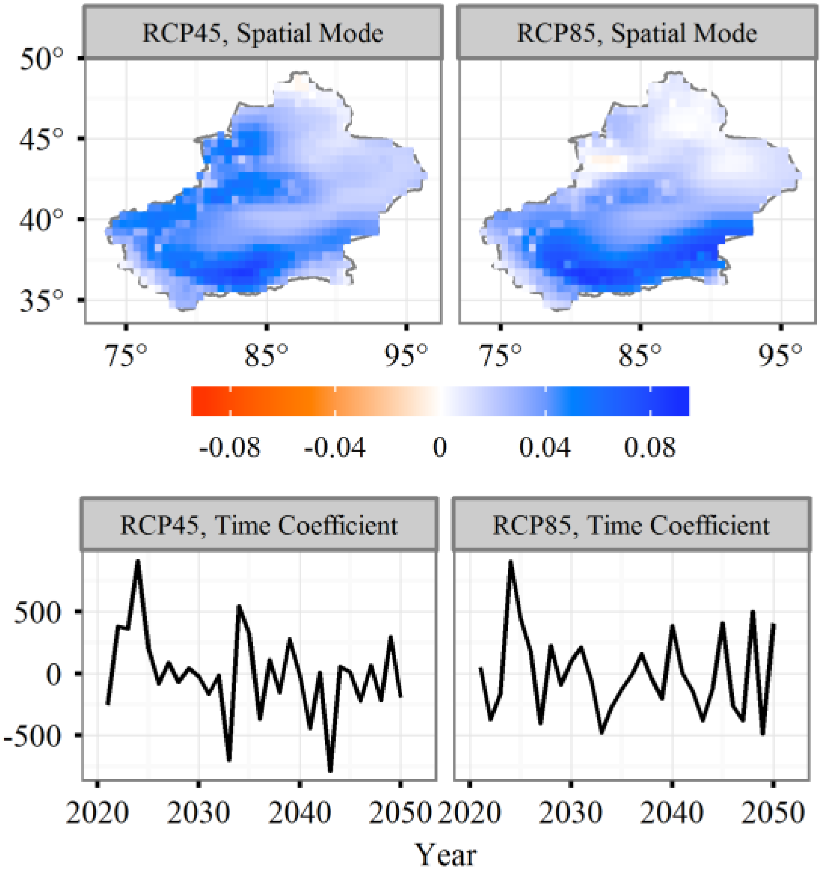

Figure 4.5 The first leading spatial mode and associated time coefficients of evapotranspiration obtained from EOF analyses.

In order to further investigate the spatially coherent patterns of temporal variations of regional evapotranspiration, the first EOF spatial mode and corresponding time coefficients was analyzed (Figure 4.5). Under the RCP4.5 scenario, the first EOF spatial mode represents 36.1% of total variance in evapotranspiration, and almost the entire region showed positive values, which indicates a uniform variation. It should be noted that higher positive values occurred in Tianshan and Kunlun Mountains areas, implying that evapotranspiration varied more significantly in these high altitude areas. The time coefficients showed a large inter-annual variability, which showed a high comparability with the temporal changes of annual mean evapotranspiration in Figure 4.3. The first EOF spatial mode for RCP4.5 was comparable with that for RCP8.5, which explains about 36.4% of total variance in evapotranspiration. Similarly, relatively strong variations occurred in Tianshan and Kunlun Mountain areas and weak positive areas distributed in Taklimakan desert and Junggar basin areas. The corresponding time coefficients also showed a strong inter-annual evapotranspiration variation during the period 2021-2050.

4.3.3 Evapotranspiration changes related to precipitation and temperature

In this section, the SVD analysis was used to examine inter-annual variations of evapotranspiration linked to changes in temperature and precipitation for the whole period during 2021-2050. Figure 4.6 shows the spatial structures and corresponding time coefficients of first paired modes of evapotranspiration-precipitation and evapotranspiration-temperature under the RCP4.5 scenario. The first spatial mode of evapotranspiration-precipitation explains about 74.2% of the total squared covariance between two fields, with a correlation of 0.98 between the two time series of coefficients. The spatial patterns of evapotranspiration fields were characterized by high positive values in Tianshan and Kunlun Mountain areas and small values in Taklimakan desert and Junggar basin areas, which is similar to the corresponding precipitation fields. The strong relationship of covariance between evapotranspiration and precipitation indicates that more precipitation will yield more evapotranspiration. The first paired spatial mode of evapotranspiration-temperature under RCP4.5

explained 67.9% of covariability, with a correlation of 0.37 between two time series of coefficients. The evapotranspiration patterns showed an obvious separation that positive evapotranspiration anomalies were found in southeastern areas and negative evapotranspiration anomalies mainly distributed some areas of northwestern Xinjiang. For the temperature fields, almost the entire region showed the positive anomalies, which indicates a uniform variation for the temperature. The features of evapotranspiration and temperature for the first mode revealed that the higher temperature will give rise to a reduction of evapotranspiration in southeastern parts of Xinjiang in the future period 2021-2050.

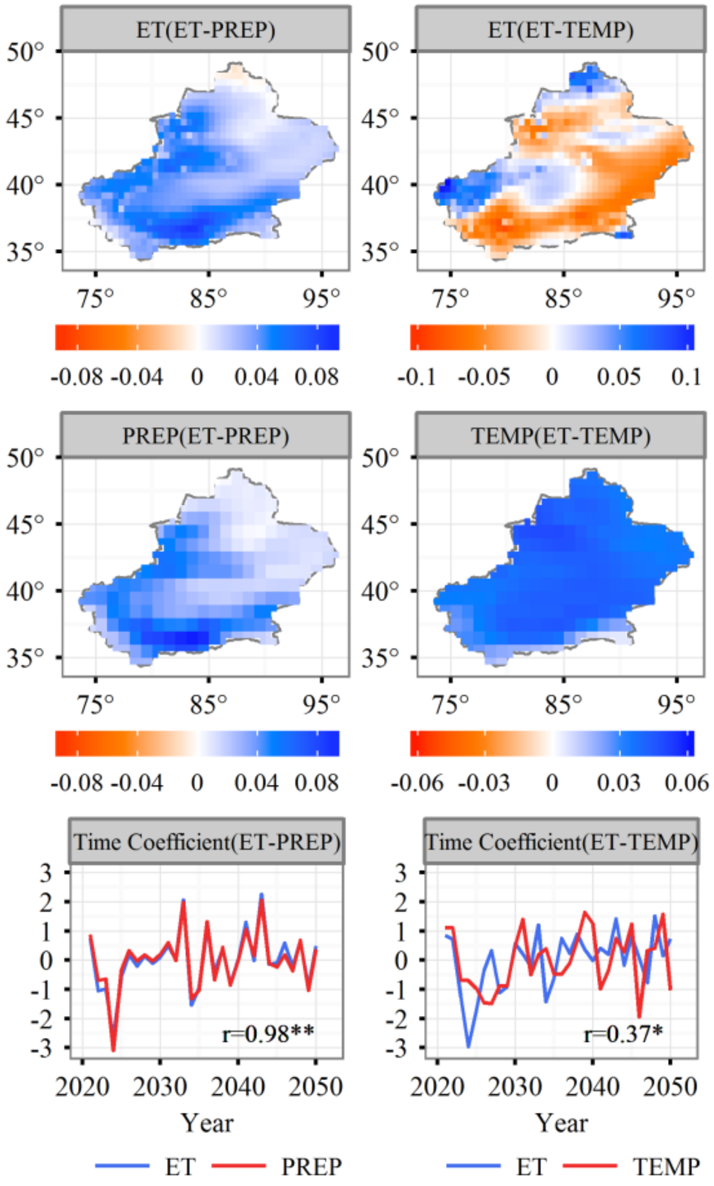

Figure 4.6 The first leading pair of spatial mode and associated time coefficients of EvapoTranspiration (ET) under RCP4.5 scenario obtained from SVD analyses.

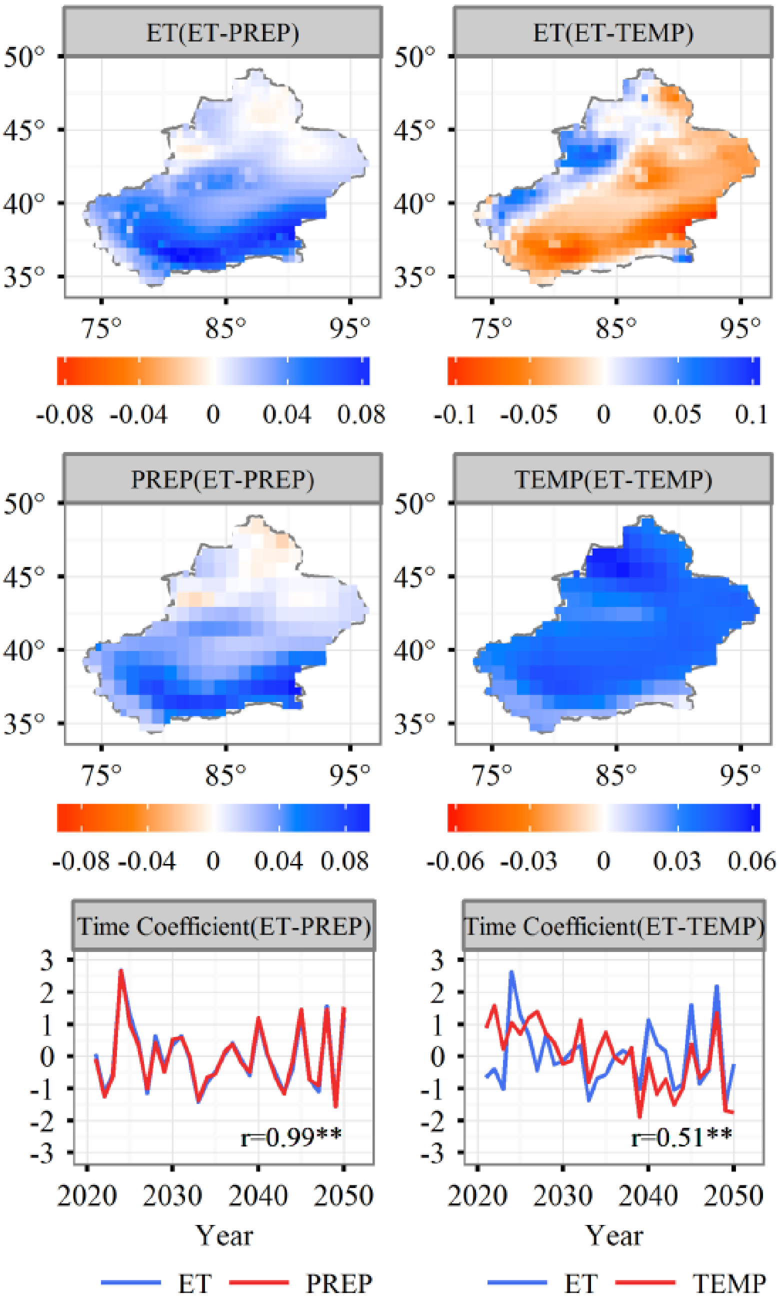

Figure 4.7 The first leading pair of spatial mode and associated time coefficients of evapotranspiration under RCP8.5 scenario obtained from SVD analyses.

The spatial patterns of evapotranspiration-precipitation and evapotranspiration-temperature under the RCP8.5 scenario were similar to those under RCP4.5 (Figure 4.7). The first spatial mode can explain about 67.7% of covariability for evapotranspiration-precipitation and 81.3% for evapotranspiration-temperature. The correlation between the two time series of coefficients was 0.99 for evapotranspiration-precipitation and 0.51 for evapotranspiration-temperature, respectively. Overall, the SVD analyses under both scenarios suggested that the changes in evapotranspiration were more closely associated with the local precipitation variability than with local temperature variability.

4.4 Discussion

Evapotranspiration is the highest outgoing water flux in the hydrological cycle and is of vital importance in assessing the effects of climate change in water availability in Xinjiang. Based on the simulation of global evapotranspiration, Pan et al. (2015) reported that decreased evapotranspiration would mainly take place in regions in central and western Asia for the 2090s. This simulation is close to our study that the annual mean evapotranspiration during 2041-2050 will decrease by 0.3 mm under RCP4.5 scenario and by 0.4 mm under RCP8.5 scenario respectively, relative to 1996-2005. However, the predictive values of evapotranspiration decrease are small and did not show significant trends, which may be the result of the relatively short study period. As a consequence of global warming, the enhanced water cycles have been reported at regional and global scales, and the intensification of water cycles has been expected to continue for the rest of 21st century (Betts et al., 2007; Durack et al., 2012). Under the warming trend, the proportion of glacial melt water enhanced, associated with the increase of runoff from 41.5% to 46.5% over the past 50 years (Chen et al., 2015; Gao et al., 2010), which will exert impacts on hydrology and water resources. Due to the less water dissipated and more water recharged by glacial melt water, the water resource will become more availability for the agriculture development.

Experimental and model-based studies have shown that Xinjiang has been experiencing a transition from a warm-dry to a warm-wet climate (Mannig et al., 2013;

Shi et al., 2007b). It has been verified partly in our study that the temperature will continue to increase before the middle of 21st century. However, the precipitation did not show significant trend under both scenarios. The spatial patterns of precipitation changes showed an obvious geographical feature which was characterized by a wet trend that in eastern and southern areas and a dry trend in western areas in Xinjiang. The CCSM-based spatial changes of precipitation in this study are in concordance with previous studies that the precipitation will increase in eastern Tianshan Mountain regions, and will reduce in western Tianshan Mountain and Taklimakan desert regions (Li et al., 2012c; Mannig et al., 2013). Such changes in climate would exert a profound effect on evapotranspiration, which is demonstrated in our study. Similar to previous studies in this region that the evapotranspiration to a large extent is influenced by precipitation (Liu et al., 2008a; Yuan et al., 2017). Our results show that the changes in evapotranspiration were closely linked to local precipitation changes based on SVD analysis. In terms of spatial structure of evapotranspiration changes, strong variations of evapotranspiration occurred in Tianshan and Kunlun Mountain areas and weak variations distributed in Taklimakan desert and Junggar basin areas, which is similar to the spatial structures of precipitation rather than the temperature, implying that precipitation plays a dominant role in determining the spatial changes of evapotranspiration.

Model structures and special representations of hydrological processes may cause different results compared with other land surface models. Kingston et al. (2009) has indicated that differences in evapotranspiration change signal of over 100% are found, and the choice of evapotranspiration method can actually determine the direction of projections of future water resources. Other factors such as carbon dioxide, nitrogen deposition, ozone pollution, and nitrogen fertilizer application may affect the evapotranspiration, which are not involved in this study. However, previous studies have indicated that such factors may not be as important as climate variability in regional scale simulations (Liu et al., 2012; Yang et al., 2015). Besides, the high percentage of captured covariance between evapotranspiration and precipitation suggest that the climate forcing dataset, particularly for the precipitation, is a primary factor in controlling evapotranspiration estimates. Although precipitation in this region under different scenarios presents distinct changing patterns, the low resolution of climate projections from one global climate model in this study (1.25° ×0.9°) may not reveal the most details, topography related effects clearly. Shi et al. (2007b) has reported that due to various uncertainties such as man-made increase of greenhouse gases, the non-human or natural factors (e.g., solar activity change) also may have contributed to the recent climate change, the results of numerical climate simulations could be very variable. Therefore, further work is required to detect, assess and understand multi-model ensembles of projections of future climate datasets to reduce uncertainties.

4.5 Conclusions

In this study, the CoLM was used to characterize the temporal and spatial patterns of evapotranspiration in Xinjiang, China in the future period 2021-2050 under two scenarios, and further examined how changes of climate parameters (e.g., precipitation and temperature) are interrelated with the evapotranspiration changes using the SVD analysis. Our results suggest that the simulated mean regional evapotranspiration were comparable under two scenarios with the value of 127 (±11.9) mm/year under the RCP4.5 scenario and 124 (±11.1) mm/year under the RCP8.5 scenario, respectively. Compared to a historical period (1996–2005), the annual mean evapotranspiration during 2041-2050 will marginally decrease by 0.3 mm under the RCP4.5 scenario and by 0.4 mm under the RCP8.5 scenario respectively. The differences of the spatial change of evapotranspiration suggest that the increased evapotranspiration appeared in eastern and southern areas and decreased evapotranspiration mainly occurred in western areas. Strong variations of evapotranspiration occurred in relative high altitudes areas such as Tianshan and Kunlun Mountain areas and slight variations of evapotranspiration mainly distributed in Taklimakan desert and Junggar basin areas as shown by EOF analysis.

By assessing effects of the possible influences of precipitation and temperature changes on such evapotranspiration variations by using the SVD technique, this study revealed that the high percentage of captured covariance between evapotranspiration and precipitation and the strong correlation between them found in the time series strongly suggest that the precipitation would be the most important factor for affecting the NDVI trend. Therefore, assessing and understanding multi-model ensembles of projections of future climate datasets is of vital importance in determining the reasonable and precious simulation of evapotranspiration in the future.

CHAPTER 5

General discussion

This section summarizes and discusses the results presented in the previous chapters. First, the four scientific questions were reviewed and answered (Section 5.1). Then, the critical reflections on the methodologies, and the limitations and uncertainties found in the study will be also addressed (Section 5.2). Finally, recommendations and suggestions are being proposed (Section 5.3).

5.1 Summary and discussion of the research question

Water resources are an important factor for restricting the economic development and ecological stability in arid and semi-arid areas. Evapotranspiration is an important type of flux between the land and atmosphere, and it is also an important outgoing flux from land to atmosphere under the form of vapour flux. Therefore, an accurate simulation of evapotranspiration is of great significance to objectively understand the status of water resources in Xinjiang, and also to formulate a reasonable scheme for managing water resources. However, due to the special geographical conditions, the special physiological and ecological processes of vegetation and the manner in which farmlands are managed in the region, some uncertainties still exist when simulating evapotranspiration by using LSMs.

Most global LSMs underestimate the ET within arid/semi-arid regions (Jing et al., 2014; Li et al., 2013b; Zheng and Wang, 2007). A possible reason for this phenomenon is that most current LSMs cannot capture special vegetation structures and their related functioning for shrubland. In addition, the population in Xinjiang has been constantly expanding during recent years, leading to the continuous expansion of cultivated land. At the same time, the demand for water resources has also been growing. The contradiction between the limited water resources and the demand for water resources for the expansion of farmland has become increasingly prominent, which lead to the innovation of agricultural management. Drip irrigation under plastic mulch has become a common practice to support agricultural production in the oasis agro-ecosystems (Du et al., 2006; Zhao et al., 2010) and has also exerted impacts on the land surface fluxes by changing physical processes and characteristics on the earth surface (Fan et al., 2015; Yang et al., 2012). The first theme of this dissertation covers the improvement of the CoLM for simulating evapotranspiration in the oasis agro-ecosystems and shrubland.

During recent decades, the climate in Xinjiang also has been undergoing significant changes. Climate change can directly affect the evapotranspiration by controlling both water vapour demand and moisture supply. For example, air temperature can affect the evapotranspiration by regulating the moisture holding capacity and determining the potential water fluxes from the soil to the atmosphere. Besides, precipitation can affect the evapotranspiration by providing moisture sources. Also, the land cover change can exert an impact on the evapotranspiration. Therefore, the second theme of this dissertation is to investigate the impact of climate and land cover change on the evapotranspiration in Xinjiang.

The study was based on observational data and climate model simulations show that the climate in Xinjiang is transiting from a warm-dry type to a warm-wet type, and this transition will remain unchanged for a long period in the future (Shi et al, 2007). Future climate change will inevitably have an impact on the evapotranspiration in this region. Therefore, the third theme of this dissertation is to investigate the future changes of evapotranspiration in Xinjiang.

From the general goals above, four scientific questions were distilled in the following order:

- ***Q1: Can it improve the accuracy in simulating evapotranspiration in oasis agro-ecosystems after adding irrigation and plastic mulch modules into CoLM?***
- ***Q2: Can it improve the accuracy for simulating evapotranspiration after the integration of the latest root functions into CoLM for desert ecosystems?***
- ***Q3: Which are the responses of evapotranspiration to climate and land cover change in Xinjiang?***
- ***Q4: How will the evapotranspiration change in the future in Xinjiang?***

The four research questions were answered in the Chapters 2-4. An overview of the main research topic and the corresponding results of each chapter is summarized in Table 5.1. This table is helpful in order to understand the links between the research objectives and the scientific questions, and how they were organized in each chapter.

RQ1: Can it improve the accuracy for simulating evapotranspiration in oasis agro-ecosystems after adding irrigation and plastic mulch modules in CoLM?

Drip irrigation under plastic mulch has become an important way of oasis farmland management in Xinjiang. It allows an efficient use of water resources. Because of limitations to understanding the processes induced by above agricultural management, the associated module has not been built in CoLM.

Table 5.1 Overview of the main methodology and the results of each chapter

Chapter	Q	Topics and methodology	Main result
Ch2 Modification of CoLM in oasis agro-ecosystem	Q1	■ Incorporation of the module of drip irrigation under plastic mulch ■ Energy balance equations	■ Model-simulated evapotranspiration has a strong sensitivity to the irrigation parameters ■ The addition of an irrigation module only failed to capture the seasonal patterns of evapotranspiration ■ The addition of a plastic film module reduced the variability of the diurnal variation of evapotranspiration
Ch3 The estimation of evapotranspiration and in response to climate factors and land cover change	Q2 and Q3	■ Integration of the latest root functions ■ Scenario experiments	■ The latest root functions improved the accuracy of CoLM ■ The evapotranspiration fluctuated largely and did not show a significant trend ■ The interannual variation of evapotranspiration in Xinjiang is mainly affected by climate change ■ Land cover change increased the evapotranspiration
Ch4 Future projected changes in local evapotranspiration coupled with temperature and precipitation variation	Q4	■ Projections of future evapotranspiration	■ The mean regional evapotranspiration is comparable under two scenarios ■ The evapotranspiration reduced in the central and northern parts of Xinjiang and increased in the south-eastern parts.

Moreover, the underestimation of evapotranspiration exists when we use the default CoLM. The possible reason is that the impact of drip irrigation under plastic mulch on evapotranspiration was not considered. Therefore, the integration of above mentioned module is expected to enhance the accuracy of simulating the evapotranspiration by using CoLM. Therefore, so as to answer the RQ1, experiments were designed in order to simulate the impact of drip irrigation and the use of plastic mulch on evapotranspiration in Chapter 2. After, the observations, WLWS was used to validate the simulations.

First, we evaluated the simulations of the default CoLM with observations. We used two important parameters (i.e., irritation start time, and irrigation water demand) in the irrigation process to control the irrigation. Our results show that the CoLM simulated evapotranspiration with no irrigation module was significantly lower than the measured values and did not show any seasonal patterns during the growing season. After the incorporation of the irrigation module, the simulated evapotranspiration was raised, but large uncertainties still existed so that the fluctuation in simulated evapotranspiration was substantial and could not capture the seasonal patterns of evapotranspiration, without considering the impact of plastic mulch. The peak values of the simulated evapotranspiration occurred after precipitation or irrigation. The possible reason can be attributed to the lack of plastic mulch. When irrigation or precipitation occurs, the transpiration of vegetation and the evaporation of soil surface increased, resulting in a peak of evapotranspiration. With the decrease of soil water, the evapotranspiration decreases rapidly. This dramatic fluctuation of evapotranspiration results in the simulation of evapotranspiration which cannot be improved without the addition of irrigation modules only.

After the incorporation of the plastic mulch module, the simulation of evapotranspiration generally well matched with the observations. The use of plastic mulch allows the soil to maintain a relatively high water content by inhibiting the evaporation of soil moisture. When irrigation occurs, the water in the soil slows down as there is no water evaporation from the soil. As expected, the fluctuations of the simulated evapotranspiration will not be compared with the simulations incorporated with the irrigation module.

Overall, the addition of drip irrigation and plastic mulch modules improved the accuracy of simulated evapotranspiration in CoLM, compared with the default CoLM. The modified CoLM therefore could be more appropriate for oasis agro-ecosystems in arid and semi-arid regions.

RQ2: Can it improve the accuracy for simulating evapotranspiration after the integration of the latest root functions into CoLM for desert ecosystems?

At present, most LSMs usually encounter the problem of underestimating latent heat when applied in arid regions. The primary reason is that most LSMs cannot capture the physiological and morphological features of desert vegetation, and the related functions. Arid vegetation has a deep root system and a high ratio of root/shoot. To date, the most widely used nonlinear model for interpolations of root distributions was a logistic dose-response curve (Schenk and Jackson, 2002), that was based on global sample data (960 samples). However, most of the samples are distributed in humid and semi-humid regions, and the proportion of arid vegetation is less than 5%. Moreover, these samples are not evenly distributed in the arid region. Besides, because of the harsh environment in an arid area, sampling is a very difficult task. Therefore, the fitted logistic dose-response curve based on the limited or possibly biased samples is not enough to factually and objectively describe the root distribution in arid and semi-arid regions.

The deep root system of the arid vegetation can absorb moisture from the deeper soil for vegetation to transpiration. Besides, many scientists have proposed that a non-linear root water uptake function may be more suitable for arid vegetation. This function is generally based on the assumption that local water stress does not necessarily mean water stress on the whole plant level, as the reduced water uptake from the stressed portion of the root zone can be compensated by the enhanced water uptake over portions of the root zone where water is more freely available (Zheng and Wang, 2007). Hydraulic redistribution is also an important function of arid vegetation roots, which has been found in the Tarim river basin in Xinjiang (Hao et al., 2010). In particular, during the drought period, desert vegetation uses its roots at night in order to lift moisture from the deep soil layers to the upper layers for transpiration at daytime, and, it also transports moisture from the upper layers to the deeper soils to reduce surface evaporation and runoff after rainfall. The transported moisture in deeper soils is reused by vegetation when it encounters drought or water stress (Domec et al., 2010; Lee et al., 2005; Ryel et al., 2003). To overcome the problem of underestimating evapotranspiration for desert vegetation in default CoLM and to answer the RQ2, the above mentioned latest root function were jointly applied in CoLM.

First, we modified the two parameters of the logistic dose-response curve (i.e., the modified D_{50} and D_{95} default values of 170 cm and 240 cm to 47 cm and 302 cm) according to our observed vertical root distribution for a typical desert plant (*Tamarix*) (Jing et al., 2014). Then, we designed four simulations to validate the performance of the improved CoLM in shrubland at the FK station in Chapter 2. Our results show that the default simulations were distinctly lower than the observations, and could not capture the seasonal patterns of evapotranspiration. Both the non-linear root water uptake function and the hydraulic redistribution function can improve the accuracy of CoLM simulated evapotranspiration, and the model simulation results were in good accordance with the observed values. However, the hydraulic redistribution process only slightly improves the accuracy. In contrast, the non-linear root absorption process can greatly improve the model accuracy.

The poor performance of CoLM with the addition of hydraulic redistribution was in line with the study from Tang et al. (2015), which also reported poorer predictions in the tropics after incorporating the root hydraulic redistribution in CLM4.5. This uncertainty maybe attributed to a few sources, including an insufficient soil characterization, and the lack of groundwater module in CoLM. In CoLM, the hydraulic properties of the soil are determined by the combination of three variables, the percent of the total masses of clay and silt and sand of soil (Dai et al., 2003). The absorbed soil moisture was, to a large extent, determined by the soil matrix potential, which is affected by the soil parameterization. Besides, the deep root of desert vegetation can also absorb water from groundwater to maintain the transpiration. Therefore, the lack of groundwater in CoLM also affects the performance of the hydraulic redistribution. In this dissertation, the value of m in the root water uptake function was calibrated based on the field measurements at the FK station. The soil water uptake efficiency was thus higher than with a default value, especially for the low soil water conditions (the low soil water matrix potential). Therefore, more soil water in modified CoLM will be absorbed than that in the default CoLM. Overall, the accuracy for simulating evapotranspiration was improved after the integration of the latest root functioning into CoLM for the desert ecosystems.

RQ3: What are the responses of climate and land cover change on evapotranspiration in Xinjiang?

As described in the previous analyses, both the climate and land cover change can impact the evapotranspiration in Xinjiang. Indeed, this region is unique and, over the years, has experienced a dynamic land-use history and climate change (Hu et al., 2014; Lioubimtseva and Henebry, 2009; Yuan et al., 2015a). The LSMs provide an efficient way to investigate the response of the evapotranspiration to environmental factors, because they can quantify the contributions of various environmental factors on ET by designing different experiments.

Liu et al. (2008a) used another process-based model (CLM 2.0) driven by Qian meteorological data from Qian et al. (2006). Since each model has its own unique characteristics and respective applications, the previous study on the estimation of evapotranspiration in Xinjiang is still insufficient. Particularly, when the special physiological and ecological processes of vegetation and the manners of managing farmland in this region were considered, the simulations from Liu et al. (2008a) may carry a lot of uncertainties. In order to answer the RQ3, the improved CoLM was used to investigate the responses of climate and land cover change on the evapotranspiration in Xinjiang.

Our results show that changes in land cover caused an increase of evapotranspiration in Xinjiang by 1.11 mm. Moreover, the area of increased evapotranspiration mainly appears in the area where the farmland has been expanding. However, the changes of evapotranspiration induced by land cover change were smaller than that induced by climate change, which decreased evapotranspiration by 21.9 mm during the study period 2001 - 2012. The above findings are basically consistent with the conclusions of other scholars, namely that climate change plays a major role in the evapotranspiration on large regional scales. However, on smaller scales, such as on basin level, the areas where land use is relatively intense, the change of the land cover may cause drastic changes in the evapotranspiration (Yang et al., 2015). Luo et al. (2010) pointed out that cultivated land in Xinjiang is mainly reclaimed from natural vegetation such as shrubs, grasslands and deserts, and that irrigation is the main water source for cultivated land. Since the irrigation and crop planting density are higher relative to natural vegetation (shrubs, grasslands, etc.), their leaf area for transpiration is also relatively high, resulting in higher evapotranspiration for the croplands. Therefore, the increase of croplands will inevitably lead to the increase of evapotranspiration. Tao et al. (2011) pointed out that due to human activities such as irrigation, the amount of water entering the main tributaries of the Tarim River has been reduced, resulting in a decrease of available water in the downstream watershed. Therefore, the reasonable control of cropland area, especially in arid and semi-arid regions, is of great significance to the rational distribution of water resources.

RQ4: How will the evapotranspiration change in the future in Xinjiang?

According to the report of the 5th Intergovernmental Panel on Climate Change (IPCC), based on the scenarios of the four types of greenhouse gas emissions in the future, the increase of the global average temperature will be 0.3 °C to 4.8 °C at the end of this century (1980-2099) relative to the end of the last century and the beginning of this century (1986-2005) (Stocker, 2014). Li et al. (2012c) argued that, Xinjiang will experience long-term precipitation increase till the end of this century. Therefore, in order to accurately predict temporal and spatial variation of evapotranspiration in Xinjiang in the future and its response to climatic factors are of great guiding significance to understand Xinjiang's future water cycle and water resources management. To answer the RQ4, the modified CoLM was driven by the future climate data generated by CCSM4 in two different scenarios (i.e., RCP4.5 and RCP 8.5). The tempo-spatial changes of evapotranspiration were analyzed in Chapter 4.

Our simulation shows that in the RCP4.5 scenario, the annual average of evapotranspiration in Xinjiang during the period between 2021 and 2050 is about 127 (± 11.9) mm/year, and the average annual evapotranspiration is about 124 (± 11.1) mm/year under RCP8.5 scenario. In both scenarios, the evapotranspiration decreased. Compared with the reference year (1996-2005), the average annual evapotranspiration decreases about 0.3 mm from 2041 to 2050 under the RCP4.5 scenario. Under the RCP8.5 scenario, the average annual evapotranspiration will decrease by about 0.4 mm.

The spatial patterns of the future evapotranspiration changes are similar, meaning that the evapotranspiration will reduce in central and northern Xinjiang, while the evapotranspiration will increase in the southeast parts.

Because of different structures and algorithms, as well as different parameterizations in different climate models, though an overall decreasing tendency of evapotranspiration is obvious, considerable uncertainties still exist in not only the magnitude but also in the direction of change. This dissertation only used the climate data from the CCSM climate model of the National Center for Atmospheric Research of the United States to drive CoLM. Therefore, the model-simulated evapotranspiration driven by multi-model ensembles of projections of future climate datasets needs further investigations.

5.2 Critical reflections

This dissertation wanted first to improve CoLM at site scale, and then used the improved CoLM to simulate evapotranspiration on a regional scale. Some critical aspects are presented and summarized in this section, regarding the employed methodology and the presented results in each chapter.

Chapter 2: In this chapter, we used two parameters (i.e., irrigation starting time, and irrigation amount). Both of the parameters are determined by sensitivity analysis, and calibrated by comparing with observations of evapotranspiration, which means that the irrigation starting time may not be a real time that happened in real life, as well as the irrigation amount is not the real irrigation amount used. In another words, the parameters are based on experiment ideally. Therefore, mismatch between the observations of evapotranspiration and the simulations from the modified CoLM still existed. In addition, there are many methods of using plastic mulch in Xinjiang. For example, some regions use white plastic mulch, and some others use black plastic mulch. Also, the distance between soil surface and plastic mulch is different for some methods. However, all the processes follow the law of energy balance. And all the processes can be accomplished by adjusting some parameters (e.g., albedo, transmittance, absorptivity). Nevertheless, it's difficult for us to get the data where and how large the different methods used at regional level. In this manuscript, we only assume the soil is covered white plastic mulch partly (~80%) according to the observations from WLWS station at the whole Xinjiang region.

Chapter 3: Although a comparative analysis between other evapotranspiration products and our simulations, we did not validate the evapotranspiration on a regional scale. The water-balance method on basin level seems to be an appropriate way to assess the CoLM-simulated ET. However, it also has many limitations. Concerning this issue, The Tarim River Basin in Xinjiang was selected to make a comparison between the CoLM-simulated and the water-balance ET (Fig. 5.1), and we also made some analyses about the comparison between them. Fig. 5.1 shows that the CoLM-estimated ET was larger than the water-balance ET. It comes to our concern that the glacier change has a significant impact on hydrology process in the Tarim River Basin, and that the glacial melting water possesses about 50% the portion of water supplies for the Tarim River Basin (Li et al., 2012a). Under the warming trend in spring and winter, the proportion of glacial melting water runoff has increased from 41.5% to 46.5% over the past 50 years (Chen et al., 2015; Gao et al., 2010). The large recharge runoff from glacial melting water possibly resulted in the overestimated ET when using the water-balance method. Besides, extensive artificial water-transfer also occurred in the Tarim River Basin, due to the ecological water conveyance project (Ye et al., 2009). Such uncertainties in the runoff data mentioned above may therefore result in the large discrepancy between the CoLM-simulated and the water-balance ET. As a result, we discarded the section about the comparison between the CoLM-estimated and the water-balance ET.

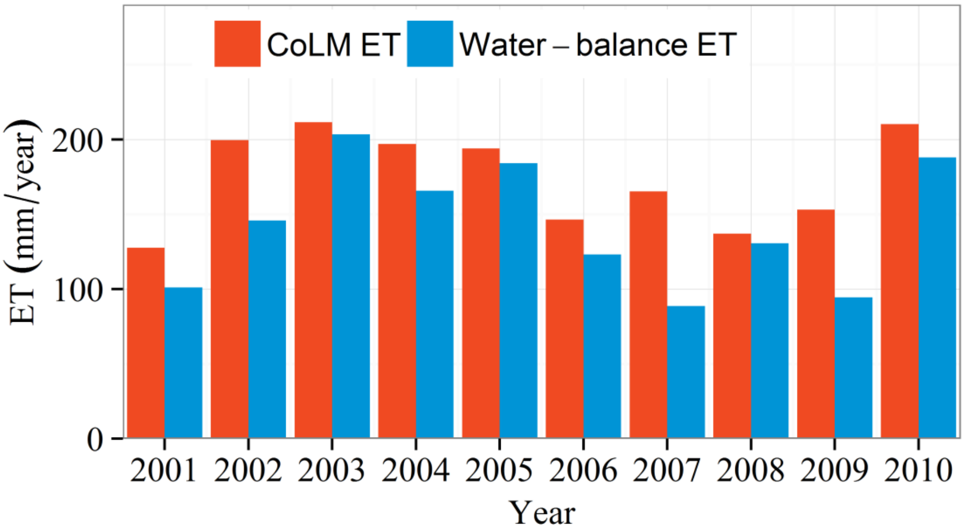

Figure 5.1 Comparisons of evapotranspiration between CoLM and water-balance estimations

Besides, the climate forcing data set is the primary factor controlling evapotranspiration estimates. The spatial resolution of PRINCETON forcing data (1°×1°) used in this study could not capture the characteristics of precipitation in mountain areas, which will lead to underestimate the evapotranspiration in these areas. The different spatial resolution between our result and previous studies could also bring some mismatch. Moreover, two parameters in our dissertation were defined to simulate irrigation process, irrigation start time and irrigation amount. Because all kinds of irrigation process have two components, we can simulate different kinds of drip irrigation by adjusting these two components. However, at the regional scale, there were no observations for to calibrate these two parameters, and all the cropland in our dissertation was treated to be as same as WLWS.

Chapter 4: The modified CoLM was used to simulate future evapotranspiration in this chapter. Some critical aspects also exist. Firstly, we only selected two emission scenarios (i.e., RCP4.5 and RCP8.5) as the “low” and “high” signals for future climate change. However, the other scenarios (RCP2.6 and RCP6.0) were ignored. Secondly, the resolutions of CCSM (1.25° ×0.9°) are too low to represent the complex mountain topography.

5.3 Some recommendations and suggestions for future work

5.3.1 Future work on CoLM improvement

Concerning the special morphological characteristics of the desert vegetation with deep root distribution, the desert vegetation can uptake groundwater to maintain transpiration soil water is limiting. The module of groundwater should be incorporated into CoLM to further validate its performance in simulating evapotranspiration. Besides, other factors such as carbon dioxide, nitrogen deposition, ozone pollution, and nitrogen fertilizer application may affect the ET, which is not involved in CoLM. Therefore, all these modules should been considered in CoLM to understand the responses of evapotranspiration to environmental factors more factually.

5.3.2 Future work on model validation

The performance of CoLM has not been validated yet except for cropland, grassland, and shrubland. Because of the land cover types are being complex and diverse in Xinjiang, different underlying surface types will exert different impact on evapotranspiration simulated by CoLM. Also, the observations in forests and urban areas are not available in this dissertation, and the work of validation concerning such land cover types should be carried out in the following research. Moreover, a relatively closed basin without the effects of glacier and snow melting should be selected to further validate the CoLM on regional scale.

5.3.3 Future work on evapotranspiration simulation at regional scale

Uncertainties usually existed between reanalysed datasets, particularly in arid/semi-arid areas, because reanalysis datasets have different accuracies in capturing terrain- and long-term drought-induced effects (Hu et al., 2016). Therefore, assessments of different forcing data set impacts on ET estimates should be made and more accurate climate datasets at regional scales should be investigated in future research. For future climate data, there are huge uncertainties due to different models or downscaling methods. Multi-model ensemble is recommended to reduce the uncertainties of the climate driving data.

CHAPTER 6

General conclusion

The main findings of this dissertation on the modification of the CoLM, the regional evapotranspiration simulation, as well as the future evapotranspiration projection are concluded in this chapter.

This dissertation discussed the evapotranspiration in Xinjiang, China. In order to simulate the evapotranspiration more reasonably and factually, the CoLM was firstly modified and then validated for cropland and shrubland. Through all chapters, a comprehensive evaluation of the modified model, the analyses of the climate and land cover change impact on evapotranspiration and the projection of evapotranspiration has been concluded.

The model-simulated evapotranspiration shows a strong sensitivity to the irrigation parameters (i.e. the irrigation starting time and irrigation water requirements). Without considering the plastic mulch module, the addition of irrigation modules increased the total amount of evapotranspiration. However, the simulated diurnal variation of evapotranspiration fluctuated largely, without showing an obvious seasonal variation and resulted thus in a poor performance in simulating evapotranspiration. The reason is the following: when irrigation occurs, the evaporation of the soil surface is rising , resulting in a sharp increase of evapotranspiration. Afterwards, evapotranspiration rapidly decreases as the soil water was dissipated. The dramatic fluctuation of evapotranspiration results in the fact that the evapotranspiration simulation cannot be improved only by the addition of irrigation modules. The supplement of the plastic mulch module is improving the accuracy of the simulated evapotranspiration with a reduction of the diurnal variation and is showing obvious seasonal patterns, as well as in (good) accordance with the observed values.

Regarding desert vegetations, we can conclude that both the non-linear root water uptake and the hydraulic redistribution processes improved the accuracy of CoLM for simulating evapotranspiration and that the modified model simulation results were in accordance with the observed values. However, the hydraulic redistribution process improves the precision (of the CoLM model) only slightly. In comparison, the non-linear root water uptake process is able to improve the model’s accuracy substantially.

During the study period between 2001 and 2012, the annual average amount of evapotranspiration fluctuated largely with a mean value of about 131.22 (± 21.78) mm/year in Xinjiang The total evapotranspiration decreased but the trend was not significant ($p = 0.12$).

The inter-annual variation of evapotranspiration in Xinjiang was mainly affected by climate change, while the land cover change has little impact on the evapotranspiration. Climate change led to the reduction of evapotranspiration in Xinjiang. In contrast, land cover changes caused an increase in evapotranspiration in Xinjiang.

In view of the projection of evapotranspiration in Xinjiang, the mean regional evapotranspiration is comparable in two scenarios (RCP4.5 and RCP8.5) during 2021-2050. Compared to the historical period (1996–2005), the mean annual evapotranspiration will marginally decrease in both scenarios during 2041-2050. The spatial variation characteristics of evapotranspiration in Xinjiang are similar in the way that evapotranspiration reduced in the central and northern parts of Xinjiang and the evapotranspiration in the south-eastern parts.

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Summary

The Xinjiang Uyghur Autonomous Region of China is located deep inside the Eurasian continent, and is one of the typical arid and semi-arid regions in the world. Water resources are the most important factor that restricts the development of local economy and ecological stability. Evapotranspiration is an important water vapor flux connecting the land and the atmosphere, and is also the main way of water dissipation in the water cycle in the region. In recent decades, human activities with the expansion of cultivated land, as well as the drastically changed climate, affected significantly the temporal and spatial variation of evapotranspiration in the region. Therefore, accurately estimating evapotranspiration in Xinjiang and exploring its response to climate and land cover change have an active role in objectively understanding the status of water resources and formulating a reasonable water resource allocation strategy. The process-based land surface model is an effective tool to solve above issues. However, due to the lack of land-surface processes that reflect the hydrothermal transfer induced by the use of drip irrigation under plastic mulch, and the lack of modules that reflect special ecological process for desert vegetations, there is still a great deal of uncertainty in estimating evapotranspiration by using land surface models.

Based the above background, in this dissertation, we selected the Common Land Model (CoLM) as a platform, and we first modified CoLM. Then, we analyzed the response of evapotranspiration to climate and land cover change, and projected the future changes of evapotranspiration, combining with reanalysis climate data. The main results are presented as follows:

1) Firstly, for the oasis agro-ecosystem, based on the theory of energy balance, the surface water heat transfer process induced by using drip irrigation under plastic mulch is incorporated into the CoLM. Combining with the eddy covariance observations of Wulanwusu agricultural station, the validation of CoLM and sensitivity analysis of key parameters were carried out to improve the performance of CoLM for simulatingwater vapor flux. Our results show that the model-simulated

evapotranspiration has strong sensitivity to irrigation parameters (irrigation start time and irrigation demand water). Without considering plastic mulch effects, the addition of irrigation module increased the total amount of evapotranspiration whereas the simulated diurnal variation of evapotranspiration was poor, and failed to capture seasonal patterns of evapotranspiration: the root mean square error increased from 76 W m^{-2} to 87 W m^{-2}; the slope of the linear fit increased from 0.04 to 0.72; and the correlation coefficient increased from 0.2 to 0.4. The addition of plastic mulch increased the accuracy of simulated evapotranspiration: the root mean square error decreased from 87 W m^{-2} to 44 W m^{-2}; the slope of the linear fit increased from 0.72 to 0.92; and the correlation coefficient increased from 0.4 to 0.75. Moreover, the addition of plastic film module reduced the variability of diurnal variation of evapotranspiration and showed obvious seasonal characteristics, which was in good agreement with the observed values.

2) For desert vegetation, the latest functional functions (root water uptack function and hydraulic redistribution function) are integrated into CoLM. Combining with the eddy covariance observations Fukang Desert Station, the performance of CoLM in simulating the evapotranspiration was validated. Our results show that non-linear root water uptake function and hydraulic redistribution process both improved the accuracy of CoLM simulated evapotranspiration, and the model simulation results were in good agreement with the observed values. However, the hydraulic redistribution process only slightly improves the model accuracy. In contrast, the non-linear root absorption function can greatly improve the model accuracy.

3) We analyzed the spatio-temporal changes of evapotranspiration in Xinjiang from 2001 to 2012, using PRINCETON meteorological data as the driven data and MODIS IGBP vegetation type data as the surface parametric data. Our results show that the annual average evapotranspiration in Xinjiang is about 131.22 (± 21.78) mm/year. During the study period, the evapotranspiration fluctuated largely. The evapotranspiration decreased overall, but it did not pass the significancy test ($p = 0.12$). Spatially, the magnitude of evapotranspiration change is quite different in

different regions, and evapotranspiration is reduced in most regions (about 86.5% of pixels). The areas with reduced evapotranspiration mostly occur in the eastern and northwestern regions with a reduction rate of up to 8 mm/year. About 13.5% of the area shows that evapotranspiration increased. The area where evapotranspiration increased mainly occurred in the marginal area of southwestern Xinjiang. Based on scenario experiments, our results show that the interannual variation of evapotranspiration in Xinjiang is mainly affected by climate change, while the change of land cover has less influence on evapotranspiration. Between 2001 and 2012, climate change lead to a decrease of 21.90 mm in evapotranspiration and a 1.11 mm increase in evapotranspiration affected by land cover change in Xinjiang.

4) Based on the CoLM and the CCSM4 meteorological data under two greenhouse gas emission scenarios (RCP4.5 and RCP8.5), the spatial and temporal variations of evapotranspiration from 2021 to 2050 in Xinjiang were simulated. Our results show that the mean regional evapotranspiration is comparable under two scenarios during 2021-2050 with the value of 127 (±11.9) mm/year under RCP4.5 scenario and 124 (±11.1) mm/year under RCP8.5 scenario, respectively. Compared to the historical period (1996–2005), the annual mean evapotranspiration during 2041-2050 will marginally decrease by 0.3 mm under RCP4.5 scenario and by 0.4 mm under RCP8.5 scenario respectively. Under both scenarios, the spatial variation characteristics of evapotranspiration in Xinjiang are similar: the evapotranspiration is reduced in the central and northern parts of Xinjiang and the evapotranspiration in the southeast parts.

This dissertation improved CoLM in simulating the water vapor fluxes in oasis agro-ecosystem. For the desert vegetations, the latest root function mechanisms are integrated into CoLM, and further validated its performance in simulating the water vapor flux. The improved part of CoLM in this study will provide important reference for the research work in arid and semi-arid region. In addition, the study of the response of evapotranspiration to climate and land cover change will provide scientific support for exploring the role of evapotranspiration in regional water cycle and for maintaining the sustainable development of Xinjiang water resources.

摘要 (Chinese Summary)

新疆深居亚欧大陆内部，是世界上典型的干旱与半干旱区域，水资源是制约当地经济发展与生态稳定的最重要因素。蒸散发作为连接陆地与大气之间的重要水汽通量，也是本地区水循环过程中水分耗散的主要途径。近几十年来，新疆人类活动加剧，耕地面积不断扩张，气候变化剧烈，并显著影响了本地区蒸散发的时空变化特征。因此，准确估算新疆蒸散发，并探究其对气候变化和土地覆被变化的响应机制对于客观认识水资源状况及制定合理的水资源分配方案具有积极的作用。基于机理过程的陆面模式是解决以上问题的一种有效手段，但由于缺乏反映绿洲农田生态系统膜下滴灌改变地表特征及其影响地表水热传输过程的相关模块，以及缺乏反映荒漠植被特殊的生理生态机制的生态过程，关于利用陆面模式模拟新疆蒸散发的研究，仍然存在很大的不确定性。

基于此，本研究以陆面模式 Common Land Model（CoLM）为研究平台，首先对 CoLM 进行改进和完善，并结合气象数据及土地覆被数据，通过情景模拟实验分析不同气候因子和土地覆被变化对实际蒸散发的相对贡献及影响机制；结合未来气候变化数据，预测未来新疆蒸散可能的变化趋势。获得的主要结论如下：

1）首先针对绿洲农田生态系统，基于能量平衡理论，对膜下滴灌的使用所产生的地表水热传输过程嵌入到 CoLM 陆面模式中，并结合乌兰乌苏农业站涡度相关观测数据，开展 CoLM 陆面模式的站点验证及关键参数的敏感性分析研究，旨提高其模拟水汽通量的精度。结果显示，模型模拟的蒸散发对灌溉参数(灌溉发生时间及灌溉用水量）具有很强的敏感性。在未考虑覆膜的情况下，灌溉模块的添加提高了蒸散发的总量，然而其模拟的蒸散发日变化波动剧烈，并未显示

出明显的季节性变化特征，精度未明显提高，均方根误差从 76 W/m^2 增加到了 87 W/m^2，线性拟合的斜率从 0.04 提高到 0.72，相关系数从 0.2 增加到 0.4。地膜模块的添加提高了模型模拟蒸散发的精度，均方根误差从 87 W/m^2 下降到了 44 W/m^2，线性拟合的斜率从 0.72 增加到了 0.92，并相关系数从 0.4 增加到 0.75。并且地膜模块的添加降低了蒸散发日变化的波动性，并表现出明显的季节性特征，与观测值具有很好的吻合性。

2）针对荒漠植被，融合、集成与根系功能相关的功能模块（根分布、根系吸水函数和水利再分配机制）到陆面模式 CoLM 中，并结合阜康荒漠站涡度相关观测数据，进一步检验集成以上所有相关功能后的陆面模式在模拟荒漠生态系统蒸散发时的性能。结果显示：非线性根系吸水过程及水力再分配过程均提高了 CoLM 模拟蒸散发的精度，模型模拟的结果与观测值比较吻合。但是，水力再分配过程仅微弱的提高了模型精度，相比之下，非线性根系吸水过程能极大的提高模型精度。

3）以 PRINCETON 气象数据作为驱动数据，并以 MODIS IGBP 植被类型数据作为地表参数化数据，模拟了 2001 到 2012 年间新疆蒸散的时空变化特征。结果显示：新疆年均蒸散发量大约为 131.22（±321.78）mm/年。研究时段内，蒸散发随时间波动比较大，蒸散发总体上在减少，然而其变化趋势并没有通过显著性检验（$p = 0.12$）。在空间上，蒸散发的变化在不同区域差异比较大，大部分区域蒸散发在减少（约 86.5%的像元）。蒸散发减少的区域主要出现在东部及西北部区域，减少的速率最高达到 8 mm/年。大约有 13.5%的区域显示蒸散发在增加。蒸散发增加的区域主要出现在新疆西南部边缘区域。通过情景模拟实验显示：新疆蒸散发年际变化主要受气候变化的影响，而土地覆被变化对蒸散发影响相对较

小。2001 到 2012 年间，气候变化导致新疆蒸散发减少气候变化导致蒸散发减少了 21.90 mm，土地覆被变化导致新疆蒸散发增加了 1.11 mm。

4）基于 CoLM 陆面模式，并利用 CCSM4 气象数据作为驱动数据，模拟了新疆 2021 到 2050 年未来两种温室气体排放情景下蒸散发时空变化特征。在 RCP4.5 情景下 ,新疆在 2021 到 2050 年间年均蒸散发大约为 127 (±11.9) mm/年，在 RCP8.5 情景下，年均蒸散发大约为 124 (±11.1) mm/年。两种情景下，蒸散发均波动下降，但都没有通过显著性检验。与参考年份 (1996-2005) 相比，RCP4.5 情景下，年均蒸散发在 2041 到 2050 年间减少 0.3 mm 左右。在 RCP8.5 情景下，年均蒸散发减少 0.4 mm 左右。在两种情景下，新疆蒸散发空间变化特征总体上差异不大，即在新疆中部及北部蒸散大在减少，在东南部蒸散发在增加

本研究从陆面模式在干旱区应用过程中出现的问题着手 ,进一步完善了陆面模式在模拟绿洲农田生态系统水汽通量中的相关功能模块，提高了其模拟精度。针对荒漠植被，融合了最新根系功能机制，进一步验证了陆面模式在模拟荒漠植被水汽通量的精度。本研究对陆面模式的完善部分，将为后续陆面模式在干旱区的研究工作提供重要的借鉴意义。另外，对新疆蒸散发模拟工作以及蒸散发对气候变化和土地覆被变化的响应机制的研究 ,将为探究新疆实际蒸散发在区域水循环中的作用，维持新疆水资源的可持续发展提供科学支撑。

Samenvatting

The Xinjiang Uyghur Autonome Regio van China is gelocaliseerd diep in het Euraziatische continent en is één van de typische aride en semi-aride regio's in de wereld. Watervoorziening vormt de meest belangrijke factor die de ontwikkeling van de locale economie en de ecologische stabiliteit inperkt. Evapotranspiratie is een belangrijke waterdampstroom die het land en de atmosfeer verbindt en is ook de belangrijkste wijze van waterverspreiding in de regionale watercyclus. Gedurende recente decennia beïnvloedden menselijke activiteiten op een belangrijke manier de uitbreiding van geteelde grond en het drastisch gewijzigde klimaat tastte eveneens de temporele en ruimtelijke variatie van evapotranspiratie aan in het gebied. Om die reden spelen een accurate schatting van de evapotranspiratie in Xinjiang en het onderzoeken van de respons op de klimaat- en landbedekkingswijziging een actieve rol in het objectieve begrijpen van de waterbronnen en het formuleren van een aannemelijke waterbronbestemmingsstrategie. Het proces-gebaseerde landoppervlaktemodel (*land surface model*) is een effectief middel om de bovenstaande problemen op te lossen. Echter, door een gebrek aan landoppervlakteprocessen die de hydrothermale overdracht weergeven die geïnduceerd werd door het gebruik van druppelirrigatie onder plastic deklaag (*plastic mulch*) en het tekort aan modules die speciale ecologische processen voor woestijnvegetatie weerspiegelen, is er nog steeds een grote onzekerheid in het schatten van de evapotranspiratie door het gebruik van landoppervlaktemodellen.

Gezien de bovenstaande achtergrond, selecteerden we in deze PhD het *Common Land Model* (CoLM) als platform en wijzigden het eerst. Daarna analyseerden we de reactie van de evapotranspiratie op de klimaats- (en landbedekkings-)verandering en planden we de toekomstige wijzigingen in evapotranspiratie, gecombineerd met een nieuwe analyse van de klimaatgegevens. De belangrijkste resultaten worden als volgt voorgesteld:

1) Ten eerste, aangaande het oase agro-ecosysteem, gebaseerd op de theorie van de energiebalans, het oppervlaktewater-hitte omzettingsproces uitgelokt door het gebruik

van druppelirrigatie onder *plastic mulch* werd ingebouwd in het CoLM. In combinatie met de eddy-covariantiemetingen van het Wulanwusu landbouwkundig station werden de validatie van het CoLM en de gevoeligheidsanalyse van sleutelparameters uitgevoerd om de prestaties van het CoLM voor de simulatie van de waterdampstroom te verbeteren. Onze resultaten tonen aan dat model-gesimuleerde evapotranspiratie een sterke voeling heeft met de irrigatieparameters (startmoment irrigatie en irrigatievraag voor water). Zonder de *plastic mulch* effecten in overweging te nemen, deed de toevoeging van de irrigatiemodule de totale hoeveelheid evapotranspiratie stijgen terwijl de gesimuleerde dagelijkse variatie in evapotranspiratie klein was en faalde in het vatten van de seizoensgebonden patronen in evapotranspiratie: de gemiddelde kwadratische fout (RMSE) steeg van 76 W m^{-2} tot 87 W m^{-2}; de helling van de *linear fit* nam toe van 0.04 tot 0.72; en de correlatiecoëfficiënt verhoogde van 0.2 tot 0.4. De toevoeging van *plastic mulch* verhoogde de nauwkeurigheid van de gesimuleerde evapotranspiratie: de RMSE daalde van 87 W m^{-2} tot 44 W m^{-2}; de helling van de *linear fit* steeg van 0.72 tot 0.92; de correlatiecoëfficiënt steeg van 0.4 tot 0.75. Bovendien verminderde de toevoeging van de plastic film module de variabiliteit in de dagelijkse variatie evapotranspiratie en demonstreerden ze duidelijke seizoensgebonden eigenschappen, die goed overeenstemden met de waargenomen cijfers.

2) Betreffende de woestijnvegetatie, werden de meest recente functionele taken (wortelwateropname functie en hydraulische redistributiefunctie) geïntegreerd in het CoLM. Samen met de *eddy covariance* metingen in het Fukang Desert Station werd de performantie van het CoLM (in simuleren van de evapotranspiratie) gevalideerd. Onze resultaten bewijzen dat zowel de non-lineaire wortelopname functie als het hydraulische redistributieproces de precisie van de CoLM gesimuleerde evapotranspiratie verbeterden en dat de modelsimulatie resultaten overeenstemden met de geobserveerde waarden. Desalniettemin verbeterde het hydraulische redistributieproces de modelprecisie enkel lichtjes. In contrast hiermee kan de non-lineaire wortelabsorptiefunctie de modelnauwkeurigheid sterk verbeteren.

3) We analyseerden de ruimtelijke temporele veranderingen in de evapotranspiratie in Xinjiang van 2001 tot 2012, door middel van de PRINCETON meteorologische gegevens als bouwsteen en de MODIS IGBP vegetatietype data als de parametrische oppervlaktegegevens. Onze resultaten tonen aan dat het jaarlijks gemiddelde in evapotranspiratie in Xinjiang ongeveer 131.22 (± 21.78) mm/jaar bedraagt. Tijdens de studieperiode fluctueerde de evapotranspiratie grotendeels. De evapotranspiratie daalde in het geheel, maar slaagde niet voor de significantiestest (p = 0.12). In ruimtelijk opzicht is de omvang van de verandering in evapotranspiratie tamelijk verschillend in verscheidene streken en (de evapotranspiratie) verminderde in de meeste gebieden (ongeveer 86.5% van de pixels). De gebieden met een verminderde evapotranspiratie komen meestal voor in het oosten en in de noordwestelijke regio's met een verminderde ratio tot 8 mm/jaar. Ongeveer 13.5% van het gebied bewijst dat de evapotranspiratie steeg. De evapotranspiratie nam vooral toe in het marginaal gebied van het zuidwesten van Xinjiang. Gebaseerd op scenario-experimenten tonen onze resultaten aan dat de interjaarlijkse variatie in evapotranspiratie in Xinjiang voornamelijk wordt beïnvloed door klimaatverandering, terwijl de wijziging in landbedekking minder impact heeft op de evapotranspiratie. Tussen 2001 en 2012 heeft de klimaatverandering geleid tot een daling van 21.90 mm en een stijging van 1.11 mm in evapotranspiratie, beïnvloed door de landbedekkingswijziging in Xinjiang.

4) Steunend op het CoLM en de CCSM4 meteorologische gegevens onder twee *greenhouse gas* emissiescenario's (RCP4.5 en RCP8.5), simuleerde men de ruimtelijke en temporele variaties in evapotranspiratie van 2021 tot 2050 in Xinjiang. Onze resultaten tonen aan dat de gemiddelde regionale evapotranspiratie vergelijkbaar is onder twee scenario's gedurende 2021-2050 met een waarde van 127 (±11.9) mm/jaar onder respectievelijk het RCP45 scenario en 124 (±11.1) mm/jaar onder het RCP85 scenario. Vergeleken met de historische periode (1996–2005), zal de gemiddelde jaarlijkse evapotranspiratie gering dalen tijdens 2041-2050 met 0.3 mm in het RCP45 scenario en met 0.4 mm aangaande het RCP85 scenario. Onder beide

scenario’s zijn de ruimtelijke variatie-eigenschappen van evapotranspiratie in Xinjiang gelijkaardig: de evapotranspiratie verminderde in de centrale, noordelijke delen van Xinjiang en de evapotranspiratie in de zuidoosten gelegen delen van Xinjiang.

Deze PhD verbeterde het CoLM bij het simuleren van de waterdampstromen in het oase agro- ecosysteem. Aangaande de woestijnvegetatie werden de meest recente wortel-functiemechanismen geïntegreerd in het CoLM en het valideerde verder zijn werking in het simuleren van de waterdampstroom. Het verbeterde deel van het CoLM in deze studie zal een belangrijke referentie opleveren voor onderzoekswerk in droge en semi-droge gebieden. Bovendien zal de studie m.b.t. de respons van de evapotranspiratie op de klimaat- en landbedekkingsverandering wetenschappelijke ondersteuning bieden om de rol van evapotranspiratie in de regionale watercyclus na te gaan (en het behoud van de duurzame ontwikkeling van de Xinjiang waterbronnen).

Curriculum Vitae (Biography)

Xiuliang Yuan was born in Jinan (China) on the 12th of March, 1989. In 2012, he graduated at the School of Geography and Planning at Ludong University and started his academic education at the Xinjiang Institute of Ecology and Geography, University of Chinese Academy of Sciences. In 2014, he was recommended to transfer from a master student to a PhD student at the University of Chinese Academy of Sciences.

During his Master's program, his research topic focuses on exploring the effects of climate on vegetation changes, as well as the interaction between vegetation changes and climate change during the master's program. During his PhD program, his work focuses on the Common Land Model (CoLM) improvements and its application on estimating evapotranspiration. In particular, as drip irrigation under plastic mulch is a common agricultural practice in arid region that has not been considered in current LSMs, he focused on developing a module and improving the accuracy of CoLM in simulating evapotranspiration.

His most recent articles are:

Xiuliang Yuan, Jie Bai, Longhui Li, Alishir Kurban, Philippe De Maeyer, 2017. *The dominant role of climate change in determining changes in evapotranspiration in Xinjiang, China from 2001 to 2012,* PLoS ONE; 12(8):e0183071., DOI:10.1371/journal.pone.0183071

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