Regional climate effects of plastic film mulch over the cropland of arid and semi-arid regions in Northwest China using a regional climate model

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Abstract

Plastic film mulch, which effectively maintains soil moisture by suppressing soil evaporation, has been widely used in cropland in Northwest China, where water scarcity severely restricts agricultural development. Plastic mulch affects surface albedo and blocks water vapor exchange between soil and atmosphere. Therefore, the large area of cropland covered by plastic film will have serious impacts on regional climate by modifying the surface-atmosphere partitioning of vapor and energy. In this study, a dynamic irrigation scheme was incorporated into the Weather Research and Forecasting model with Noah land surface scheme; two experiments (with and without plastic mulch) were designed to simulate the impacts of plastic mulch over cropland in Northwest China on regional climate. In irrigated cropland, the irrigation amount decreased substantially during the early stage of crop growth (ESCG; from 22 April to 1 July) with plastic mulch, especially in May, indicating that plastic mulch conserved agricultural water. In nonirrigated cropland, soil moisture in cropland with plastic mulch was clearly greater than that without plastic mulch. The influences of plastic mulch on land surface processes were mainly reflected in the ESCG, such that upward shortwave radiation increased and latent heat flux decreased. In cropland during the ESCG, after plastic mulch, the latent heat flux decreased significantly by $12\text{--}30\text{ W m}^{-2}$, the sensible heat flux increased significantly by $8\text{--}16\text{ W m}^{-2}$, and the surface air temperature increased significantly by $0.2\text{--}0.8\text{ }^{\circ}\text{C}$. The plastic mulch reduced water vapor in the lower atmosphere, which might lead to decrease precipitation in Northwest China.

1 Introduction

Oasis cropland, an active component of ecosystems in the extensive arid and semi-arid regions of Northwest China, links the underlying surface and atmosphere by modulating the exchanges of energy and mass across the interface

and has aroused more interest than ever before from researchers (Zhang et al. 2016; Zhang et al. 2017; Yuan et al. 2019). The oasis is the concentrated areas of population in Northwest China, where agricultural activities (e.g., irrigation, plastic film mulch, and tillage) have markedly altered the underlying surface characteristics. The changes in underlying surface property can produce nonnegligible impacts on land surface processes and regional climate (Yang et al. 2012; Yang et al. 2016; Zhang et al. 2017; Wu et al. 2018).

In the irrigated cropland of Northwest China, the scarcity of precipitation inevitably leads to the use of large amounts of irrigation water, but water resources are very scarce here; therefore, saving agricultural water is very important and meaningful. Plastic film mulch can effectively inhibit soil evaporation and maintain soil moisture (Liu et al. 2009; Wang et al. 2009; Yang et al. 2012; Cuello et al. 2015; Yuan et al. 2019), which then saves irrigation water, indicating that plastic film mulch technology has high potential for application in the cropland

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of Northwest China. In fact, this technology has been widely used in some irrigated cropland and its area of use is expected to continue to grow. When compared with cropland in the plains, terraced fields in Eastern Gansu province are more difficult to irrigate, and their water resources are also scarce; thus, farmers in these areas have widely adopted plastic film to cover the cropland to maintain soil moisture (Liu et al. 2016). When compared with ordinary cropland, plastic mulch of cropland not only reduces soil evaporation, but also affects the surface physical parameters such as surface albedo (Yang et al. 2012; Fan et al. 2015); thus, the plastic mulch will affect the land–atmosphere interaction by modifying the exchanges of vapor and energy between the surface and the atmosphere. Some micro-meteorologists have used off-line land surface models to study the impacts of plastic mulch on land surface processes (Ham and Kluitenberg 1994; Wu et al. 2007; Yang et al. 2012; Lu and Zuo 2018; Yuan et al. 2019). In cropland covered with plastic film, experiments considering the plastic mulch scheme showed obvious improvement in simulating several variables such as vapor and energy, indicating that the physical processes of plastic mulch should be implemented into the land surface models for studying vapor and energy in cropland ecosystems with plastic mulch.

The changes in underlying surface have been shown to affect local and regional climate by modifying land surface characteristics. In recent years, there have been many numerical simulation studies that focused on the impacts of land use/cover changes over China on regional climate (Feng et al. 2012; Yu et al. 2013; Cao et al. 2015; Chen et al. 2015; Chen et al. 2017; Yang et al. 2016; Zhang et al. 2017; Wu et al. 2018). These studies involved urbanization, irrigation, and changes in land use types among others, but for the particular case of cropland covered with plastic film, few studies have investigated its regional climate effects. Therefore, it is necessary to consider the physical processes of plastic film mulch in regional climate models coupled with land surface models, and then the coupled model can be adopted to simulate the impacts of plastic mulch on land surface processes and regional climate in arid and semi-arid regions of Northwest China.

The Weather Research and Forecasting (WRF) model has been widely used to study regional climate effects of land use/cover changes in recent years (Feng et al. 2012; Yu et al. 2013; Cao et al. 2015; Chen et al. 2017). Since the default WRF model did not consider irrigation processes (Wu et al. 2018), the soil moisture in arid and semi-arid regions cropland is very low in the model and is quite different from the actual values. The Noah scheme in the WRF model is a commonly used land surface module. Therefore, in this study, on the basis of incorporating the dynamic irrigation scheme into the

WRF model coupled with the Noah land surface module (WRF-Noah), two experiments (with and without plastic mulch) were designed to examine the impacts of plastic mulch over cropland in Northwest China on regional climate.

2 Methods

2.1 Model configuration

The WRF model version 3.7.1 with Advanced Research WRF (ARW) dynamic core (Skamarock et al. 2008) was used as a regional climate model in this study. The physical processes parameterization schemes were selected for the simulation experiments as follows: the WRF single-moment six-class (WSM6) graupel microphysics scheme (Hong and Lim 2006), the Rapid Radiative Transfer Model (RRTM) longwave radiation (Mlawer et al. 1997), Dudhia shortwave radiation (Dudhia 1989), the Yonsei University (YSU) planetary boundary layer scheme (Hong et al. 2006), the new Kain-Fritsch cumulus scheme (Kain 2004), and the Noah land surface model (Chen and Dudhia 2001). In the Noah land surface model, the dominant land use types were chosen, and the moderate resolution imaging spectrometer (MODIS) 20-category land use categories were applied.

Two nested model domains were designed (Fig. 1a). The coarse outer domain (d01) was centered at (40° N, 93° E), with 160 (meridional) × 210 (zonal) horizontal grid points and a horizontal resolution of 30 km, and 30 eta levels from the surface to 50 mb were used in the vertical coordinates; the fine inner domain (d02) was centered at (41.25° N, 92.8° E), with 181 (meridional) × 361 (zonal) horizontal grid points and a horizontal resolution of 10 km. d01 covered the whole land region of China, and d02 covered almost all of the arid and semi-arid regions in Northwest China. We adopted one-way nested options without considering the feedback from the nest to its parent domain. The initial and boundary conditions for the simulation were provided by the 6-h intervals and 1° × 1° grid spacing NCEP Final (FNL) operational global analysis data; the lateral boundary-driven fields and sea surface temperature were updated every 6 h, and the latter was also taken from the NCEP-FNL analysis data.

In this study, the leaf area index (LAI) and background surface albedo were no longer calculated through the values in the lookup table. The default green vegetation fraction (GVF), LAI, and background surface albedo in the model were all from static geographical data and were updated every 6 h. The acquisition time of the default land use data in the model was 2001; these data were not only low precision (Gong 2009), but also had poor

Fig. 1 (a) Configuration of nested model domains. (b) Spatial distributions of land use types in the inner domain. In (b), NX, SX, HC, HP, and EG represent Northern Xinjiang, Southern Xinjiang, Hexi Corridor, Hetao Plain, and Eastern Gansu, respectively

timeliness. He et al. (2014) used MODIS data and 1 km digital elevation data of China to update the key land surface parameters such as land use types, GVF, and topography height in the built-in static geographical data. We used the updated land surface parameters. In fact, the variations in LAI should be consistent with the

variations in GVF. Therefore, the LAI was calculated through GVF according to Eq. (1) (Tian et al. 2009), and then the new LAI replaced the default LAI of the simulated areas.

$$GVF = 0.2459 \ln LAI + 0.4666 \quad (1)$$

2.2 Plastic mulch scheme for cropland

2.2.1 Determining the spatial distributions of cropland in Northwest China

Some irrigated cropland exists in arid and semi-arid regions of Northwest China because of the melting water of alpine ice-snow and the rivers formed by them (such as the Heihe River in the Hexi Corridor), the Yellow River flowing through the Hetao Plain, and the exploitation of groundwater in some areas. For the determination of Northwest China cropland in the model, we adopted a semivirtualization method; that is, when grid cells of the simulation areas simultaneously satisfy that the cropland fraction is more than 10% and the topography height is lower than 2500 m, we set these grid cells to be only filled by cropland type and have no other land use type. We can see the spatial distributions of vegetation type No. 20 in Fig. 1b and found that the irrigated cropland was mainly located in the foothills of Tianshan Mountain, the edge of the Tarim and Junggar Basins, the Hexi Corridor, and Hetao Plain. In irrigated cropland with water scarcity in Northwest China, plastic mulch can effectively prevent soil evaporation and conserve irrigation water, so this technology has high application potential. Therefore, the No. 20 vegetation type in Fig. 1b was the irrigated cropland covered with plastic film in this study. In Eastern Gansu where there is a large area of terraced fields, because of the difficulty of irrigation and water shortage, farmers have widely used plastic film to cover cropland because of its effects on soil moisture conservation. In the model, terraces in the Eastern Gansu were set as the nonirrigated cropland covered with plastic film, that is, No. 19 vegetation type in Fig. 1b. It should be noted that there are no No. 19 and No. 20 MODIS vegetation types in the simulated areas; thus, these two serial numbers were set as cropland covered by plastic film and possessed the underlying surface properties of the cropland by modifying the parameter in the lookup table. Among the types of plastic film, the white transparent plastic film was the most commonly used to cover the cropland (Yang et al. 2012; Lu and Zuo 2018). This study also adopted this type of plastic film.

2.2.2 Irrigation scheme

The default coupled model WRF-Noah did not consider irrigation processes, which meant that the simulated soil moisture in the irrigated cropland of arid and semi-arid regions was obviously lower than the actual values; therefore, it was necessary to incorporate the irrigation scheme into the model. In this study, referred to the dynamic irrigation schemes of the previous studies (Qian et al. 2013; Yang et al. 2016; Zhang et al. 2017; Wu et al. 2018), and according to the actual

circumstances of irrigated cropland in Northwest China, we made some improvements and incorporated a realistic dynamic irrigation scheme into the coupled model WRF-Noah. Determining whether irrigation is applied or not is based on the soil water content (the sum of the first layer (0–0.1 m), the second layer (0.1–0.4 m), and the third layer (only taken from 0.4 to 0.6 m) soil water content) and the first layer soil temperature at 08:00 UTC on each day as follows: If the soil water content of the upper 0.6-m layers satisfies Eq. (2), and the first layer soil temperature is greater than 10 °C, the cropland starts irrigation. The irrigation method is flooding, and irrigation continues for 4 h and ends at 12:00 UTC, in which the irrigation rate (I_{RATE} , unit mm s^{-1}) is calculated by Eq. (3). Irrigation water reaches the cropland in the form of effective precipitation.

$$A_{SM} < T_{SMCWLT} + 0.5 \times (T_{SMCREFT} - T_{SMCWLT}) \quad (2)$$

$$I_{RATE} = \left(\sum_{i=1}^3 (S_{MAX} - SM(i)) \times D(i) \times 1000 \right) / (4 \times 3600) \quad (3)$$

$$\text{where } A_{SM} = \sum_{i=1}^3 SM(i)D(i) \times 1000, T_{SMCWLT} = \sum_{i=1}^3 S_{WLT} \times D(i) \times 1000, T_{SMCREFT} = \sum_{i=1}^3 S_{REF} \times D(i) \times 1000$$

where $D(i)$ is the thicknesses of soil layers for layer i : $D(1) = 0.1$ m, $D(2) = 0.3$ m, and $D(3) = 0.2$ m. $SM(i)$ is the soil moisture for layer i ; S_{WLT} , S_{REF} , and S_{MAX} refer to the soil wilting point, field capacity, and saturated value, respectively, their units are $\text{m}^3 \text{m}^{-3}$. A_{SM} is the total soil water content of the three layers of soil thickness (0.6 m); T_{SMCWLT} and $T_{SMCREFT}$ are the total soil water content of 0.6-m soil thickness when soil moisture is at the soil wilting point and field capacity, respectively; their units are mm.

Most of the cropland in Northwest China is planted with single cropping; sowing begins in mid-late April, and harvesting begins in mid-late September. Therefore, irrigation is considered during the period from 20 April to 15 September each year. Because the soil moisture of cropland in April is very low, one irrigation should be considered on 20 April before sowing.

2.2.3 Time series for constructing GVF, LAI, and background surface albedo

The GVF data of Hetao Plain cropland were obtained from the National Oceanic and Atmospheric Administration (NOAA) operational global vegetation index system (Jiang et al. 2010). Based on these data, we made some modifications (for example, the GVF of cropland was set at zero before 20 April, and some smoothing treatment was done in other stages), and

Fig. 2 Time series of (a) GVF and (b) LAI in the Northwest China cropland, (c) background surface albedo in the irrigated cropland with and without plastic mulch, and (d) background surface albedo in the

nonirrigated cropland with and without plastic mulch. GVF green vegetation fraction, LAI leaf area index

constructed the time series of GVF in cropland of Northwest China (Fig. 2a). We also constructed the time series of LAI according to Eq. (1) (Fig. 2b). Yang (2012) analyzed the observed surface albedo data of the cropland covered with transparent plastic film in arid regions and found that the surface albedo was greatly affected by plastic mulch in the initial stage of crop growth, and the mean value was 0.26; the surface albedo was mainly affected by vegetation properties after the GVF reached high values, with the mean value of 0.18; at the other stage of crop growth, the surface albedo decreased with gradual increases in GVF. Yang (2012) also used the land surface model to simulate the variations in surface albedo and found that the plastic mulch of cropland had obvious influences on the surface albedo. From the initial stage of crop growth to before GVF reached high values, the surface albedo of cropland covered with plastic film was greater than that of the cropland without plastic mulch. In this study, the irrigated cropland began to be covered with plastic film and sown on the second day after the first irrigation (22 April), and the terraced fields in Eastern Gansu before sowing were also considered plastic mulched. Based on the observations and simulations of Yang (2012), the background surface albedo time series of the irrigated cropland with and without plastic mulch (Fig. 2c) and the nonirrigated cropland (terraced fields) with and without plastic mulch (Fig. 2d) were constructed.

The default coupled model WRF-Noah did not consider the influences of soil moisture on surface albedo (Zaitchik et al. 2012), but irrigation could lead to rapid changes in soil moisture, which obviously affected surface albedo. Previous studies have shown that the surface albedo decreased exponentially with the increase of soil moisture (Liu et al. 2008; Roxy et al. 2010) and also decreased exponentially with the increase of GVF (Lu and Zuo 2018). In fact, the influences of soil moisture on surface albedo became small with the increase

of GVF. Therefore, we considered the influences of soil moisture on surface albedo through Eq. (4) in the Northwest China cropland. In Eq. (4), on the basis of background surface albedo, the surface albedo could increase or decrease according to the ranges of soil moisture. When the GVF reached high values in a given year, the surface albedo was less affected by soil moisture, so the applicable periods of Eq. (4) for irrigated cropland and nonirrigated terraced cropland were from 20 April to 1 July and from 1 April to 1 July, respectively. Obviously, this equation only qualitatively analyzed the influences of soil moisture on surface albedo and would need observations to calibrate the parameters in the future studies.

$$ALB_{new} = \begin{cases} ALB_{ori} \times \exp\left(\left(0.32 - SM(1)\right) \times (1 - GVF) \times a\right) & SM(1) \geq 0.32 \\ ALB_{ori} \times \exp\left(\left(0.26 - SM(1)\right) \times (1 - GVF) \times b\right) & SM(1) \leq 0.26 \\ ALB_{ori} & 0.26 \leq SM(1) \leq 0.32 \end{cases} \quad (4)$$

where ALB_{ori} and ALB_{new} denoted the background surface albedo without considering the effects of soil moisture (time series of background albedo constructed in Fig. 2c, d) and considering the effects of soil moisture, respectively. $SM(1)$ (unit $m^3 m^{-3}$) was the first layer soil moisture. The influences of soil moisture on surface albedo in cropland with plastic mulch were less than that in cropland without plastic mulch, which were reflected by setting the values of a and b . In cropland with plastic mulch, $a = 3.0$, $b = 2.0$; in cropland without plastic mulch, $a = 1.5$, $b = 1.0$.

This study mainly focused on the effects of plastic film mulch, but snow had great influences on surface albedo, and some cropland might be covered by snow in April, especially in northern Xinjiang. To eliminate the considerable influences of snow changes on surface albedo, in irrigated cropland, the

influences of snow on surface albedo were not taken into account from 15 April onwards; in nonirrigated terraced fields, the influences of snow on surface albedo were not considered throughout the simulation period.

2.2.4 Decreased soil evaporation

The main function of plastic film mulch in cropland was to effectively inhibit soil evaporation and maintain soil moisture. In the coupled model WRF-Noah, we set the soil evaporation to be decreased by 90%. In irrigated cropland, the applicable time of this setting was from 22 April to the end of the simulation; in nonirrigated cropland, the applicable time of this setting was the whole simulation period. In the actual observations, we found that the arid region cropland was covered with plastic film after the first irrigation, and then irrigation was not required for about 1 month in the early stage of crop growth. The soil moisture of the root zone covered with plastic film acted as the actual irrigation trigger. To approximate the simulation results of the irrigation amount to the actual values, the proportion of the decrease in soil evaporation was set to 90% by a series of calibrated experiments. This proportion was also close to the setting of Zhou et al. (2012).

2.3 Experimental design

Two simulation experiments were conducted in this study: one experiment without considering plastic film mulch (referred to as Nonmulch) and the other experiment with plastic film mulch considered (referred to as Mulch). The consistent settings of the two experiments were as follows: the spatial distributions of irrigated and nonirrigated cropland in Northwest China were identical; irrigation processes were all considered in the determined irrigation cropland; the GVF and LAI of the Northwest China cropland (including irrigated and nonirrigated cropland) were replaced by the time series constructed in advance. The different settings of the two experiments were as follows: The background surface albedo of irrigated cropland with and without plastic film mulch was replaced by the time series in Fig. 2c, and that of nonirrigated cropland with and without plastic film mulch was replaced by the time series in Fig. 2d; the influences of soil moisture on surface albedo in cropland with and without plastic mulch were different according to that of Eq. (4); the soil evaporation was decreased by 90% in the cropland that considered the plastic mulch; and soil evaporation in the cropland without the plastic mulch was not treated. The simulation periods of the two experiments were from 00:00 UTC 1 March to 00:00 UTC 1 October every year, and the simulation results were exported every 6 h. The first month (March) was treated as model spin-up. We piecewise simulated 15 years (2001–2015).

3 Results

3.1 Model evaluation

The simulation results of the inner domain were evaluated against the gridded observation data. The spatial distributions of the observed and simulated (the Nonmulch experiment) surface air temperature (at 2 m) are shown in Fig. 3a, b. The $0.5^\circ \times 0.5^\circ$ monthly gridded surface air temperature observations were provided by the National Meteorological Information Center of China Meteorological Administration. Compared to the observations, although the Nonmulch experiment overestimated the temperature in the lower altitude areas and underestimated the temperature in the higher altitude areas, the experiment essentially reproduced the spatial distributions of the observed 6 months (from April to September) mean surface air temperature; the spatial correlation coefficient between the Nonmulch experiment simulations and observations was about 0.915.

The spatial distributions of the observed and simulated precipitation of the Nonmulch experiment are shown in Fig. 3c, d. The monthly gridded observation data of precipitation came from the 3B43 precipitation products of the TRMM satellite at $0.25^\circ \times 0.25^\circ$ resolution. Compared to the observed precipitation, the experiment overestimated precipitation in most areas of the inner domain, such as Tianshan Mountain, Qilian Mountain, and the southeastern nested domain; however, there were some areas where the precipitation was underestimated by the model, such as the Junggar Basin and Western Inner Mongolia. Like the temperature simulations, although there were also some deviations in the simulated precipitation, the experiment could well simulate the spatial distributions of the observed 6-months (from April to September) mean precipitation and the spatial correlation coefficient between the simulations and observations was about 0.885.

The main purpose of this study was to examine the influences of plastic film mulch on surface air temperature and precipitation through analyzing the differences between the Mulch and Nonmulch experimental results. Therefore, the bias between the simulated and observed values could be regarded as the systematic error of the WRF model. These errors would basically be offset each other in the processes of differences analysis, which had little influence on the reliability of the conclusions of this study.

3.2 Irrigation amount and soil moisture

The temporal variations of monthly irrigation amount in the cropland of Northern Xinjiang, Southern Xinjiang, Hexi Corridor, and Hetao Plain are shown in Fig. 4a–d, respectively. First, we analyzed the irrigation amount of the irrigated cropland without plastic mulch. The variations in soil

Fig. 3 Spatial distributions of 6 months (from April to September) mean surface air temperature (unit °C) in (a) observation and (b) Nonmulch experiment from 2001 to 2015. Spatial distributions of 6 months (from

April to September) mean precipitation (unit mm day^{-1}) in (c) observation and (d) Nonmulch experiment from 2001 to 2015

moisture before irrigation as shown in Fig. 5b1–d1, b2–d2, and the low soil moisture caused by the drought and small rainfall amounts in the Northwest China cropland cannot guarantee the germination and normal growth of crops. Thus, all irrigated cropland considered one irrigation on 20 April before

sowing. Because of the high soil moisture and low temperature in mid-late April in some cropland areas of Northern Xinjiang, the irrigation amount (67.7 mm) in April in Northern Xinjiang was obviously less than that in other areas (183.9 mm in Southern Xinjiang, 147.7 mm in Hexi Corridor,

Fig. 4 Temporal variations of multi-year (2001–2015) mean monthly irrigation amount averaged over the irrigated cropland in (a) Northern Xinjiang, (b) Southern Xinjiang, (c) Hexi Corridor, and (d) Hetao Plain

Fig. 5 Temporal variations of multi-year (2001–2015) mean soil moisture averaged over the cropland in **(a1, a2)** Northern Xinjiang, **(b1, b2)** Southern Xinjiang, **(c1, c2)** Hexi Corridor, **(d1, d2)** Hetao Plain, and **(e1,**

e2) Eastern Gansu. **a1–e1** and **a2–e2** indicate the first layer (0–10 cm) soil moisture and the second layer (10–40 cm) soil moisture, respectively

135.4 mm in Hetao Plain; Fig. 4). In July, the values of solar radiation, temperature, and LAI were relatively high, causing the evapotranspiration to reach the maximum values, which resulted in the highest irrigation amounts in this month (Fig. 4). The multimean annual irrigation amount was 624.2 mm in Northern Xinjiang, 1141.4 mm in Southern Xinjiang, 839.5 mm in Hexi Corridor, and 684.5 mm in Hetao Plain. The irrigation amount in the different irrigated areas was diverse, indicating that the irrigation amount was closely related to climatic conditions. The annual irrigation amount reached the highest values in Southern Xinjiang where it is the driest in the simulated areas. Cheng et al. (2014) estimated that the annual irrigation amount in the Heihe River Basin was

750–960 mm based on observations, which was close to the simulated annual irrigation amount in Hexi Corridor (839.5 mm).

After the plastic film was applied to cropland, soil moisture was maintained through the inhibition of soil evaporation, which contributed to conserve irrigation water. In the early stage of crop growth (referred to as the period from 22 April to 1 July, the same below), the evapotranspiration was mainly explained by soil evaporation, but the soil evaporation was suppressed by plastic mulch. Therefore, the effects of plastic mulch were mainly reflected in this stage. As shown in Fig. 4, the period in which plastic mulch had the largest influence on the irrigation amount also appeared in the early stage of crop

growth, especially for May, when the decreases in irrigation amount induced by the plastic mulch were the most obvious. The cropland covered with plastic film in Northern Xinjiang, Hexi Corridor, and Hetao Plain basically did not require irrigation in May.

The response of soil moisture to irrigation was very clear in the irrigated cropland (Fig. 5, except for Fig. 5e1, e2). All the irrigated cropland in the simulated areas that satisfied the irrigation conditions was irrigated once on 20 April, causing the soil moisture to rapidly increase and exceed $0.35 \text{ m}^3 \text{ m}^{-3}$. In other irrigation periods, the irrigation time was not exactly the same every year and Fig. 5 was the multi-year mean results; therefore, the variations in soil moisture were not as rapid as that shown for 20 April. The soil moisture in the irrigation period was obviously higher than that in the non-irrigation period (before 20 April) except for cropland in Northern Xinjiang (Fig. 5), indicating that the increases in soil moisture induced by irrigation would guarantee the crop growth. This also showed that the irrigation processes should be considered in the numerical models when performing relevant regional climate simulations in arid and semi-arid regions including cropland. In the early stage of crop growth, the first layer soil moisture in the cropland without plastic mulch was clearly less than that in the cropland with plastic mulch (Fig. 5a1–d1), for which the reasons were as follows: First, although the cropland without plastic mulch also considered irrigation and the irrigation amount was greater than that in the cropland with plastic mulch, the first layer soil moisture decreased faster after each irrigation than that in the cropland with plastic mulch; second, the variations of the second layer soil moisture in the cropland with and without plastic mulch were not substantially different (Fig. 5a2–d2). Irrigation was determined by the soil water content of the upper 0.6-m layers, so the low soil moisture of the first layer did not necessarily lead to irrigation. After the GVF reached high values, the effects of plastic mulch became smaller, and the variations of the first layer soil moisture in the cropland with and without plastic mulch were basically coincident. The above results indicated that plastic mulch could not only save irrigation water in the early stage of crop growth but also maintain soil moisture in this period.

In the terraced fields of Eastern Gansu, the local precipitation could not completely guarantee the normal growth of crops in cropland without irrigation, which seriously affected agricultural production. The technology of plastic film mulch has been widely used in these terraced fields because of its effects on soil moisture conservation, which reduced the dependence of agricultural production on weather and climate conditions. In this study, because the terraced fields in Eastern Gansu all considered plastic mulch in the whole simulation period, the soil moisture of cropland with plastic mulch was clearly greater than that of cropland without plastic mulch (Fig. 5e1, e2). In nonirrigated cropland where precipitation

was low, the low soil moisture directly threatened the crop growth, and thus, the effective way to increase soil moisture is to reduce soil evaporation. Therefore, the technology of plastic film mulch is of great significance to the development of agriculture in the Loess Plateau.

3.3 Surface energy

In the experimental settings of this study, the different characteristics between cropland with and without plastic mulch were mainly reflected in two aspects: First, the surface albedo was different; second, there was decreased soil evaporation of cropland when covered with the plastic film. Therefore, the greatest influence of plastic mulch on the four components of radiation was the upward shortwave radiation affected by surface albedo, and the most direct influence of plastic mulch on surface energy partitioning was to decrease the surface latent heat flux. In this section, we focused on the analyses of the influences of plastic mulch on the upward shortwave radiation and latent heat flux.

The temporal variations of daily mean surface albedo exported by the model are shown in Fig. 6a1–e1. In Northern Xinjiang, some cropland might be also covered by snow because of the low surface temperature from March to April. Before 15 April, the influence of snow on the surface albedo was considered in irrigated cropland, causing increased surface albedo by approximately 0.5 in the Northern Xinjiang cropland (Fig. 6a1). In this study, the climate conditions of the widely distributed cropland were different; this meant that the actual sowing time of crops was not identical, for example, the actual sowing time was later than the set sowing time of this study in Northern Xinjiang because of the low temperature. Because of the limited information available at present, this study adopted a unified and ideal processing method. From the previous analyses, it can be seen that in the early stage of crop growth, the first layer soil moisture in the cropland without plastic mulch was obviously lower than that in the cropland covered with plastic film (Fig. 5a1–d1). The low soil moisture (< 0.26) meant that the surface albedo of cropland without plastic mulch was greater than the background surface albedo, but it was still less than the surface albedo of cropland with plastic mulch (Fig. 2c and 6a1–d1). In the early stage of crop growth, the higher surface albedo of the cropland with plastic mulch meant that its upward shortwave radiation was greater than that of the cropland without plastic mulch (Fig. 6a2–e2), which resulted in decreases in the surface net radiation in the cropland after plastic mulch. Yang et al. (2012) incorporated a plastic mulch layer model into the two-Big-Leaf-SHAW (TBLSHAW) land surface model and simulated the influences of plastic mulch on the related land surface physical variables, which also concluded that the upward shortwave radiation of cropland with plastic mulch was greater than that of cropland without plastic mulch.

Fig. 6 Temporal variations of multi-year (2001–2015) mean (a1–e1) surface albedo and (a2–e2) upward shortwave radiation averaged over the cropland in (a1, a2) Northern Xinjiang, (b1, b2) Southern Xinjiang, (c1, c2) Hexi Corridor, (d1, d2) Hetao Plain, and (e1, e2) Eastern Gansu. The values of surface albedo and upward shortwave radiation were daily means

In the irrigated cropland except Northern Xinjiang, the soil moisture was very low before irrigation, which meant that latent heat flux was also low at approximately 10 W m^{-2} (Fig. 7b–d). The latent heat flux increased rapidly because of the unified irrigation on 20 April (before plastic film covered the cropland). Subsequently, the latent heat flux decreased rapidly in the cropland with plastic mulch because of the inhibition of soil evaporation but decreased slowly in the cropland without plastic mulch. In the early stage of crop growth, the latent heat flux in the cropland with plastic mulch was clearly lower than that in the cropland without plastic mulch (Fig. 7a–d). Like the variations of latent heat flux in the

irrigated cropland, plastic mulch also decreased the latent heat flux in the nonirrigated cropland (Fig. 7e). As shown in Fig. 7, the period, when the latent heat flux of the cropland with plastic mulch was obviously less than that of the cropland without plastic mulch, was mainly in the early stage of crop growth, regardless of the irrigated cropland or the nonirrigated cropland. Yang et al. (2012) used the off-line land surface model to simulate the influences of plastic mulch on latent heat flux and also reached the same conclusion. Moreover, in the early stage of crop growth, the lower latent heat flux of cropland covered with plastic film was consistent with its lower irrigation amount (Fig. 4 and 7a–d).

Fig. 7 Temporal variations of multi-year (2001–2015) mean latent heat flux averaged over the cropland in (a) Northern Xinjiang, (b) Southern Xinjiang, (c) Hexi Corridor, (d) Hetao Plain, and (e) Eastern Gansu. The values of latent heat flux were daily means

3.4 Surface air temperature

The variations of surface energy budget directly affected the surface air temperature. From the previous analyses, it can be seen that the influences of plastic film mulch on the upward shortwave radiation and latent heat flux mainly lay in the early stage of crop growth, and thus, its greater influence on the surface air temperature would also lie in this stage. This section focused on the changes in the surface air temperature affected by plastic mulch during the period from 22 April to 1 July.

After the plastic film covered the cropland, the latent heat flux decreased significantly by $12\text{--}30\text{ W m}^{-2}$ (Fig. 8a). According to the surface energy balance, the sum of latent heat flux and sensible heat flux was roughly equal to the net surface radiation, which led to that the decreases in latent heat flux generally corresponded to the increases in sensible heat flux when the changes in solar radiation absorbed by the surface were not big before and after mulch. The increased upward shortwave radiation led to decreases in net surface radiation in this study. Therefore, the increases in sensible heat flux in cropland ($8\text{--}16\text{ W m}^{-2}$; Fig. 8b) were less than the decreases in latent heat flux and were significant. The increased sensible heat flux led to that surface air temperature in cropland that increased significantly by $0.2\text{--}0.8\text{ }^{\circ}\text{C}$ (Fig. 8c). The decreased soil evaporation led to more surface energy being allocated to sensible heat flux, which favored increases in surface air temperature. However, the higher surface albedo in the cropland with plastic mulch led to decreases in surface

net radiation and the energy allocated to sensible heat flux, which was not conducive to increases in surface air temperature. Obviously, there was a positive and negative feedback mechanism for the influences of plastic mulch on surface air temperature. The inhibition of soil evaporation by plastic film had a positive feedback on the variations of surface air temperature; the higher surface albedo of the covered cropland had a negative feedback on the variations of surface air temperature. The results of this study showed that the positive feedback had greater influence on surface air temperature. Although there are high potential benefits of the use of plastic film in cropland of arid and semiarid regions, it could aggravate climate warming.

3.5 Precipitation

Plastic mulch decreased water vapor content in the atmospheric boundary layer by suppressing soil evaporation in cropland, and the period of the obvious decreases in water vapor was also in the early stage of crop growth. Therefore, this section also only analyzed the changes in precipitation from 22 April to 1 July. As shown in Fig. 9a, the water vapor (specific humidity) at 2 m was significantly decreased in the covered cropland. The decreases of water vapor in irrigated cropland exceeded 0.4 g kg^{-1} , and the decreases of water vapor in nonirrigated cropland were slightly less than that in irrigated cropland. There were also decreases in water vapor around the cropland, such as in the Tarim Basin, Central Inner Mongolia, which was located downwind of the cropland.

Fig. 8 Spatial distributions of differences (Mulch experiment minus Nonmulch experiment) in ESCG mean (a) latent heat flux (unit W m^{-2}), (b) sensible heat flux (unit W m^{-2}), and (c) surface air

temperature at 2 m (unit $^{\circ}\text{C}$) from 2001 to 2015. The black points indicate the statistically significant areas at 95% confidence level. ESCG the early stage of crop growth (from 22 April to 1 July)

Fig. 9 Spatial distributions of differences (Mulch experiment minus Nonmulch experiment) in ESCG mean (a) specific humidity at 2 m (unit g kg^{-1}), (b) total precipitation (unit mm day^{-1}), (c) nonconvective precipitation (unit mm day^{-1}), and (d) convective precipitation (unit

mm day^{-1}) from 2001 to 2015. The black points indicate the statistically significant areas at 90% confidence level. ESCG the early stage of crop growth (from 22 April to 1 July)

The changes in nonconvective precipitation induced by the plastic mulch of cropland were basically consistent with the changes in total precipitation, but the changes in convective precipitation were small (Fig. 9b–d). This was because the precipitation in Northwest China was mainly contributed by nonconvective precipitation, and the response of precipitation to underlying surface changes was also mainly reflected in the influences on nonconvective precipitation. Most of Northwest China is arid and semi-arid regions, where the climate is dry and the water vapor content in the atmosphere is very low. In the case of the cropland covered with plastic film, the surface provided less water vapor to the atmosphere (Fig. 9a), which decreased the water available for precipitation and had a negative effect on the changes in precipitation. As shown in Fig. 9b, the changes in precipitation affected by plastic mulch were mainly decreased and even were significantly decreased in some areas, which might be caused by the decreases in the water vapor in the atmosphere due to the decreased surface evaporation. The arid and semi-arid regions in Northwest China are far away from the ocean and are less affected by the monsoon, where the influences of water vapor transportation from the ocean on precipitation are far weaker than that in the Eastern China monsoon areas. Therefore, surface evapotranspiration provided an important source of

water vapor for precipitation in Northwest China. Zhang and Shi (2002) and Zhao et al. (2012) studied the variations in precipitation in Xinjiang, and they found that the changes in precipitation in Xinjiang were closely related to the changes in evapotranspiration of the underlying surface, which was consistent with the results of this study to a certain extent. Thus, the decreases in water vapor content induced by plastic mulch in Northwest China were the most likely cause of the decreased precipitation.

4 Conclusions and discussion

Given the high potential that cropland in Northwest China was covered with plastic film, we first incorporated the dynamic irrigation scheme into the coupled model WRF-Noah and then constructed the plastic mulch scheme for cropland in the model. Two experiments (with and without plastic mulch) were designed to investigate the regional climate effects of plastic mulch over the cropland in Northwest China. Several conclusions were drawn as follows:

1. In irrigated cropland, after the plastic film covered cropland, the irrigation amount decreased obviously in the

early stage of crop growth (from April 22 to July 1), especially in May, indicating that plastic mulch can save agricultural water. In the early stage of crop growth, the first layer soil moisture in the irrigated cropland without plastic mulch was lower (<0.26), which resulted in surface albedo that was greater than the background surface albedo, but was still less than that in the irrigated cropland with plastic mulch. In nonirrigated cropland, the soil moisture in cropland with plastic mulch was clearly greater than that in cropland without plastic mulch. But, in irrigated cropland, except for the lower first layer soil moisture in cropland without plastic mulch in the early stage of crop growth, the variations of soil moisture in the cropland with and without plastic mulch were basically identical. This was because the two types of irrigated cropland (with and without plastic mulch) were both irrigated.

2. The main influences of plastic mulch on surface energy were during the early stage of crop growth. When compared with the cropland without plastic mulch, the high surface albedo in the cropland with plastic mulch led to increases in upward shortwave radiation, and the inhibition of soil evaporation in the cropland with plastic mulch resulted in decreases in latent heat flux. The latent heat flux in cropland decreased significantly by $12\text{--}30\text{ W m}^{-2}$, which resulted in more surface energy being allocated to sensible heat flux. However, the increased upward shortwave radiation led to decreases in surface net radiation, which resulted in less surface energy being allocated to sensible heat flux. The final results were that sensible heat flux in cropland increased significantly by $8\text{--}16\text{ W m}^{-2}$, and then surface air temperature in cropland increased significantly by $0.2\text{--}0.8\text{ }^{\circ}\text{C}$.
3. Surface evapotranspiration is an important source of water vapor for precipitation in Northwest China, but plastic mulch of cropland decreased the water vapor in the atmosphere through decreasing soil evaporation. This was the most likely reason for the decreases in precipitation induced by plastic mulch in most of Northwest China.

In this study, we investigated the main properties of cropland covered with plastic film and introduced the cropland mulch scheme into the regional climate model on the basis of incorporating the dynamic irrigation scheme into the coupled model WRF-Noah. This study not only revealed the fact that plastic mulch saved agricultural water but also analyzed the impacts of plastic mulch on the regional climate in arid and semi-arid regions in Northwest China. However, the experimental scheme in the model was idealized. Actually, not all cropland in Northwest China was covered with plastic film, and the types, sowing and harvesting times of crops varied in different regions, which was different from the settings of this study. The land use types used in this study were dominant

and did not consider the subgrid-scale heterogeneity, which maximized the cropland area. In addition, the physical processes (such as surface radiation, the exchanges of energy and mass between land and atmosphere) of plastic mulch scheme in some previous studies (Yang et al. 2012; Lu and Zuo 2018; Yuan et al. 2019) were more complex and perfect than that in this study, but these studies were single-point simulations of land surface processes. In future studies, we need to collect detailed agricultural production information in each region in Northwest China and set more reasonable experiments according to the types, sowing and harvesting time of crops and other information; it is also necessary to incorporate more perfect plastic mulch scheme into regional climate model.

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