Effects of crop growth and development on regional climate: a case study over East Asian monsoon area

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Abstract In this study, the CERES phenological growth and development functions were implemented into the regional climate model, RegCM3 to give a model denoted as RegCM3_CERES. This model was used to represent interactions between regional climate and crop growth processes. The effects of crop growth and development processes on regional climate were then studied based on two 20-year simulations over the East Asian monsoon area conducted using the original regional climate model RegCM3, and the coupled RegCM3_CERES model. The numerical experiments revealed that incorporating the crop growth and development processes into the regional climate model reduced the root mean squared error of the simulated precipitation by 2.2–10.7% over north China, and the simulated temperature by 5.5–30.9% over the monsoon region in eastern China. Comparison of the simulated results obtained using RegCM3_CERES and RegCM3 showed that the most significant changes associated with crop modeling were the changes in leaf area index which in turn modify the aspects of surface energy and water partitions and lead to moderate changes in surface temperature and, to some extent, rainfall. Further analysis revealed that a robust representation of seasonal changes in plant growth and developmental processes in the regional climate model changed the surface heat and moisture fluxes by modifying

the vegetation characteristics, and that these differences in simulated surface fluxes resulted in different structures of the boundary layer and ultimately affected the convection. The variations in leaf area index and fractional vegetation cover changed the distribution of evapotranspiration and heat fluxes, which could potentially lead to anomalies in geopotential height, and consequently influenced the overlying atmospheric circulation. These changes would result in redistribution of the water and energy through advection. Nevertheless, there are significant uncertainties in modeling how monsoon dynamics responds to crop modeling and more research is needed.

Keywords Crop growth and development · Regional climate · East Asian monsoon area

1 Introduction

Agricultural crop growth and development processes play a significant role in defining local, regional, and global climate (Tsvetsinskaya et al. 2001a, b; Lu et al. 2001), which is primarily achieved through their effects on precipitation interception, runoff, and soil moisture removal via transpiration and evaporation, as well as the partitioning of net radiation into latent and sensible heat fluxes. Agricultural crops are a special class of vegetation that include a variety of forms and physiological characteristics of crops, and also are affected by human activities such as planting, harvesting, etc. As a result, the growth and development processes of crops have a significant effect on regional climate and should be included in regional climate models.

A regional climate model depends on its land surface model for simulation of surface fluxes of heat, soil moisture, and momentum to be used as a lower boundary

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condition for the atmosphere. These surface schemes are differentiated between various land cover types, but their treatment of a particular land cover type of interest, e.g., agricultural crops, is rather crude. One problem is that they do not distinguish between different crops and agricultural practices, such as planting and harvesting schedules, fertilizer application and tillage practices. Another problem is that they do not address crop phenological development within a given crop type. Most models assume that crop phenology is predefined according to existing climatologies and time of year. The crop-related parameters are usually assigned as constant values of crop type or vary in accordance with simple climatologically prescribed functions (e.g., in BATS, LAI is determined solely by the subsoil temperature with no regard for soil moisture status). This means that these parameters are relatively independent of the climate inputs and that the crop has no response to the crop varieties, genotype parameters, and climate environment. In contrast to these assumptions, crop growth actually responds strongly to crop varieties, atmospheric radiation, temperature, precipitation, and soil moisture.

Recently, dynamic representations by climate models have provided important insights (Claussen 1995; Betts et al. 1997; Foley et al. 1998; Dickinson et al. 1998; Lu et al. 2001; Dan et al. 2005). Indeed, these studies have enabled progress in understanding the vegetation-atmosphere interaction, but none of these studies explicitly addressed the issue of detailed representations of agroecosystems. For agroecosystems, the crop model CERES was introduced into the regional climate model RegCM2 to investigate the effect of seasonal crop growth and development on surface fluxes and regional climate (Tsvetsinskaya et al. 2001a, b), while the interactions between crops and atmosphere in Huang-Huai-Hai Plain in China were simulated using RegCM2 coupled to the crop growth model SUCROS (Song et al. 2003). However, these studies only focused on one crop type, and lacked long-term continuous simulations. Furthermore, the treatment of the agroecosystems in the climate model was rather crude.

In the present study, we focused explicitly on agroecosystem simulations representing the actual cropping system in China. In addition, we introduced the seasonal crop growth and development into the land surface model and climate model, and thus investigated the effect of crop growth and development on surface fluxes and regional climate. In a previous study (Chen and Xie 2011), a two-way interaction model was developed by coupling a crop growth model (Crop Estimation through Resource and Environment Synthesis version 3.0, CERES v3.0) with the biosphere-atmosphere transfer scheme (BATS), which is the land surface component of the ICTP Regional Climate Model version 3 (RegCM3). The results of several

numerical experiments showed that the coupled model could capture the responses of crop growth and development of environmental conditions, as well as the feedback of crop growth and development on land surface processes. Introducing interactive crop growth and development functions into BATS resulted in significant changes in the land surface fluxes (e.g., latent heat flux, sensible heat flux, etc.). In this study, we examined the effect of those changes in surface fluxes on the regional climate simulated by RegCM3.

This paper is organized as follows. The model development is described in Sect. 2. Section 3 introduces the study domain and the data used in this study. The effects of seasonal crop growth and development on regional climate are discussed in Sect. 4. Finally, the results of the study are concluded and discussed in Sect. 5.

2 Model development

In this study, the regional climate model, RegCM3, was used to evaluate the role of crop growth and development processes, and the CERES phenological growth and development functions were implemented into RegCM3 to represent interactions between regional climate and crop growth processes. Therefore, model development including RegCM3, CERES model and its implementation are described in this section.

2.1 Regional climate model RegCM3

The Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climate Model version 3 (RegCM3), which is based on the model of Giorgi et al. (1993a, b) with the upgrades described by Pal et al. (2007), was employed in this study. RegCM3 is a 3-dimensional, hydrostatic, compressible, primitive equation, σ -vertical coordinate regional climate model. The dynamical core of RegCM3 is based on the hydrostatic version of the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model MM5 (Grell et al. 1994). The model currently employs the radiative transfer package used in the NCAR's Community Climate Model, version 3 (CCM3) (Kiehl et al. 1996). Boundary layer physics are modeled using the nonlocal planetary boundary layer scheme developed by Holtslag et al. (1990), as described in Giorgi et al. (1993a). RegCM3 also employs the bulk aerodynamic ocean flux parameterization described by Zeng et al. (1998), in which sea surface temperatures (SSTs) are prescribed. Three different convection schemes (Kuo, Grell, and Emanuel) are available for the non-resolvable-scale rainfall processes (Giorgi et al. 1993b). In addition, land surface physics are modeled

by the biosphere–atmosphere transfer scheme (BATS) developed by Dickinson et al. (1993). RegCM3 has been validated against observations of modern-day climate in China (Liu et al. 1994; Hirakuchi and Giorgi 1995; Giorgi et al. 1999; Kato et al. 2001; Gao et al. 2004; Zhang et al. 2005, 2007; Yuan et al. 2008; Zheng et al. 2009; Chen and Xie 2010). Additionally, the model has been found to do a good job of simulating spatial and temporal climate features (Bell et al. 2004; Gao et al. 2001, 2002, 2006, 2008; Snyder et al. 2002).

2.2 CERES v3.0 model and its implementation in RegCM3

Crop Estimation through Resource and Environment Synthesis version 3.0 (CERES v3.0, Jones and Kiniry 1986; Tsuji et al. 1994, 1998) is a process oriented dynamic crop growth model that predicts the status of crops on a real time basis as a function of exogenous parameters. The CERES family of models require daily weather data, plant genetic coefficients and soil data and management to simulate crop development, growth, and yield through evaluation of the stage of crop development, the growth rate and the partitioning of biomass into growing organs of crops such as maize, wheat, and rice under a given agroclimatic condition. All of these processes are dynamic and are affected by environmental and cultivar specific factors. In this study, the wheat, maize, and rice models of the CERES family were selected since they are the main crops grown in China. Furthermore, these models have already been validated for a wide range of climates worldwide and operate independently of location and soil type encountered (Kiniry et al. 1997; Pang et al. 1997; Yao et al. 2007).

To represent the crop growth and development processes in RegCM3, the CERES model was synchronously coupled to the biosphere–atmosphere transfer scheme (BATS), which is the land surface component of the RegCM3. In a previous study (Chen and Xie 2011), the CERES formulations of maize, wheat, and rice phenological development and growth were incorporated into BATS. The interface between the two models is connected through the exchange of environmental conditions and crop growth conditions in a daily time step. CERES receives weather conditions (minimum temperature, maximum temperature, radiation, etc.), surface conditions (surface albedo, etc.), and soil conditions (soil moisture, etc.) from BATS, and calculates crop growth and development in a daily time step. BATS takes the output of CERES such as leaf area index, stem area index, and root fraction as input, and uses this daily updated information to simulate the surface fluxes with a time step of 180 s. For ease of description, the new regional climate model coupled with CERES was named RegCM_CERES.

3 Study domain and experimental design

All of continental China and its surrounding area were selected as the study domain, which was centered at 36.5°N/114.5°E, with a horizontal resolution of 60 km and 120 × 90 grid points (Fig. 1). Two simulations were conducted: (1) a control run (henceforth denoted as CTL), where the standard unmodified Regional Climate Model version 3 (RegCM3) was used; and (2) an interactive run (henceforth denoted as CSM), where CERES phenological growth and development functions were incorporated into the RegCM3/BATS configuration for all grid cells with land cover type agriculture (henceforth denoted as RegCM3_CERES). Each experiment used the ERA40 Reanalysis data (Uppala et al. 2005) and the National Oceanic and Atmospheric Administration Optimally Interpolated Sea Surface Temperatures (Reynolds et al. 2002) as lateral boundary conditions, and the Grell scheme (Grell 1993) with Fritsch and Chappell closure (Fritsch and Chappell 1980) as the convection scheme. Both experiments were conducted from 1982/01/01 to 2001/12/31 with a time step of 180 s. The first year was used for spin-up and the last 19 years were selected for analysis.

4 Model performance and analysis

In this section, we examine the performance of both RegCM3 and RegCM3_CERES, after which the interaction between crop and regional climate was discussed, and the effects of seasonal crop growth and development on regional climate in China were investigated. The observed precipitation dataset developed by Xie et al. (2007) and the CRU TS3.0 monthly temperature dataset (Mitchell and Jones 2005) were chosen to evaluate the model performance. Both datasets have a resolution of 0.5° latitude by 0.5° longitude. For convenience of data reanalysis, the observations were interpolated onto the model output grids. To analyze the effects of crop growth and development on the regional climate over the East Asian monsoon area, we divided the eastern portion of the study domain into five sub-regions (Fig. 1) according to different climatology and crop cultivars. Region NE is located in northeast China (NE), which has a semihumid climate and one crop a year. The primary crops in Region NE are spring maize, winter wheat, and single rice. Region NC is located in north China, which has a semiarid climate and two crops a year. The primary crops in Region NC are winter wheat and summer maize. Region HH is located in Huai River Basin, which is characterized by a humid climate and two crops a year. The primary crops in Region HH are winter wheat and summer maize. Region SE is located in southeast China, which has a humid climate and two or three crops a

Fig. 1 The study domain (*NE* Northeast China Region, *NC* North China Region, *HH* Huai River Basin Region, *SE* Southeast China Region, and *SW* Southwest China Region)

year. The primary crops in Region SE are early rice, later rice, single rice, and spring maize. Region SW is located in southwest China, which is characterized by a humid climate and two crops a year. The primary crops in Region SW are single rice, winter wheat, spring maize, and summer maize.

4.1 Simulation for precipitation

Monsoon is characterized by pronounced seasonality, and the crop development and growth are significant in summer. Therefore, we concentrate on precipitation in summer monsoon season in the analysis below. The mean JJA precipitation simulated by RegCM3 and RegCM3_CERES were compared with the observed values (Xie et al. 2007), and the results are shown in Fig. 2a–c. The spatial distribution of the mean JJA precipitation simulated by RegCM3 and RegCM3_CERES agreed with the observed values to some extent. Both simulated precipitation decreased from south to north, which is consistent with the observations. Although both models overestimated precipitation in northeast China and underestimated it in south China, the RegCM3_CERES alleviated the overestimation in northeast China (especially in sub-region NE and NC). However, the RegCM3_CERES did not show improvements in south China.

To quantify the model performance, the systematic error (ME), root mean squared error (RMSE), and correlation coefficient (CC) were calculated for each grid point. Figure 2d–f shows the spatial distribution of differences in ME, RMSE, and CC for the CSM-run and CTL-run compared with the observed values. The largest improvement of the new model performance appears in sub-region NE

with respect to the RMSE and CC. Table 1 lists the detailed statistics for the JJA precipitation series simulated by the two models. Both models overestimated the precipitation over sub-region NE and NC and underestimated it over sub-region HH, SE, and SW. The systematic error (ME) of the entire domain and five sub-regions NE, NC, HH, SE, and SW for the CTL-run were 0.20 mm/day (5.0%), 0.63 mm/day (15.2%), 0.49 mm/day (15.7%), –1.14 mm/day (–25.6%), –0.52 mm/day (–7.5%), and –1.24 mm/day (–20.4%), respectively, while that for the CSM-run were 0.19 mm/day (4.6%), 0.48 mm/day (11.7%), 0.38 mm/day (12.3%), –1.36 mm/day (–30.7%), –0.53 mm/day (–7.6%), –1.28 mm/day (–21.2%), respectively. These biases are on the same order of magnitude with the biases from Fu et al. (2005), Feng and Fu (2006), and Zhang et al. (2007) (see Fig. 3a). All of the spatial correlation coefficients (CC) between simulations and observations satisfied the 95% confidence level, and the highest CC for the two models occurred in sub-region NC. The RegCM3_CERES showed better performance than RegCM3 over sub-region NE and NC with respect to the root mean squared error (RMSE). The relative variations in RMSE calculated by

$$\frac{|\text{RMSE}_{\text{RegCM3_CERES}}| - |\text{RMSE}_{\text{RegCM3}}|}{|\text{RMSE}_{\text{RegCM3}}|} \times 100\% \quad (1)$$

over the entire domain and five sub-regions NE, NC, HH, SE, and SW were 0.8, –10.7, –2.2, 20.0, –0.4, and 1.4%, respectively (Table 1).

Figure 4 shows the simulated and observed mean annual monthly precipitation for the sub-regions. The largest differences between the simulations appeared during summer. Based on comparison with the observed values, the

Fig. 2 The mean precipitation and its error over East Asian monsoon area in JJA: **a–c** mean precipitation for CTL-run, CSM-run, and observation; **d** the differences between CSM-run and CTL-run; **e** the differences in root mean square error for the CSM-run and CTL-run compared with the observed values; **f** the differences in correlation coefficient for the CSM-run and CTL-run compared with the observed values

RegCM3_CERES showed an obvious improvement over RegCM3 for sub-region NE and NC between April and August. Although the RegCM3_CERES did not provide a better annual precipitation simulation over sub-region HH, SE, and SW than the RegCM3, it did show slight improvements during some months (such as April and May for sub-region HH, June and July over sub-region SE, and March and April for sub-region SW).

4.2 Simulation for temperature

We concentrate on temperature in summer monsoon season. Figure 5a–c shows the mean JJA temperature simulated by RegCM3 and RegCM3_CERES compared with the observed values (Mitchell and Jones 2005). Both models captured the spatial distribution of the mean JJA temperature. The spatial correlation coefficients of the mean JJA temperature simulated by the two models over the entire domain both reached 0.94 (see Table 1). Although both models underestimated the mean JJA temperature in some regions of China, which is consistent with

the results described by Fu et al. (2005) and Zhang et al. (2007) (see Fig. 3b), the RegCM3_CERES obviously alleviated the underestimation, especially in the cropland areas of east China.

Similar to precipitation, the systematic error, root mean squared error, and correlation coefficient were calculated for each grid point, and the spatial distribution of these errors between the simulated and observed mean JJA temperature are shown in Fig. 5d–f. Although both models underestimated the temperature in China by 1–3°C, the RegCM3_CERES obviously alleviated this underestimation, especially in northeast China and the Sichuan Basin. Table 1 shows the detailed statistics for the JJA temperature series simulated by the two models. Both models underestimated the mean JJA temperature over the entire domain and five sub-regions, especially sub-region SW. All of the spatial correlation coefficients (CC) between the simulations and observations satisfied the 95% confidence level, and the highest CC for the two models occurred in sub-region SW. Among the five sub-regions, the RegCM3_CERES performed better than the RegCM3,

Table 1 Statistics of mean precipitation and 2 m mean temperature simulated by the two models in JJA

Run	Error type	TPR						T2M					
		DOMAIN	NE	NC	HH	SE	SW	DOMAIN	NE	NC	HH	SE	SW
CTL	ME ^a	0.20 (5.0%)	0.63 (15.2%)	0.49 (15.7%)	-1.14 (-25.6%)	-0.52 (-7.5%)	-1.24 (-20.4%)	-3.73	-1.25	-2.15	-1.33	-2.64	-3.47
	RMSE ^b	2.56	1.22	0.91	1.30	2.34	2.20	4.59	1.65	2.30	1.45	2.96	3.79
	CC ^c	0.75	0.21	0.73	0.71	0.57	0.47	0.94	0.87	0.96	0.94	0.55	0.97
CSM	ME	0.19 (4.6%)	0.48 (11.7%)	0.38 (12.3%)	-1.36 (-30.7%)	-0.53 (-7.6%)	-1.28 (-21.2%)	-3.58	-0.68	-1.50	-0.83	-2.39	-3.20
	RMSE	2.58	1.09	0.89	1.56	2.33	2.23	4.51	1.14	1.71	1.07	2.70	3.58
	CC	0.75	0.29	0.70	0.59	0.56	0.46	0.94	0.90	0.96	0.92	0.59	0.97

^a Systematic error: $ME = \frac{1}{n} \sum_{i=1}^n (x_{mi} - x_{oi})$, x_{mi} and x_{oi} is the simulated and observed mean JJA precipitation/temperature of grid i respectively, n is the grid number of the region; the percentage data in the parentheses means the relative bias

^b Root mean square error: $RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_{mi} - x_{oi})^2}$

^c Correlation coefficient: $CC = \frac{\sum_{i=1}^n (x_{mi} - \bar{x}_m)(x_{oi} - \bar{x}_o)}{\sqrt{\sum_{i=1}^n (x_{mi} - \bar{x}_m)^2 \cdot \sum_{i=1}^n (x_{oi} - \bar{x}_o)^2}}$

Fig. 3 The mean precipitation and 2 m temperature bias over China in JJA: **a** Precipitation bias (%); **b** 2 m temperature bias (°C)

especially over sub-region NE, which showed a decrease of 0.57, 0.49, and 0.51°C in the systematic error, mean absolute error, and root mean squared error, respectively, and an increase of 0.03 for the spatial correlation coefficient. The relative variations in RMSE by formula (1) over the entire domain and five sub-regions NE, NC, HH, SE, and SW were -1.7, -30.9, -25.7, -26.2, -8.8, and -5.5%, respectively (Table 1).

Figure 6 shows the simulated and observed mean annual monthly temperature for sub-regions. The RegCM3_CERES performed better than the RegCM3 during

most months for all five sub-regions. The largest improvement appeared between May and October over sub-region NE and NC, while it occurred between May and November over sub-region HH, SE, and SW.

4.3 Effects of crop growth and development on regional climate

In this section, we analyze the effects of physical processes involved in crop growth and development on regional climate.

Fig. 4 Simulated and observed mean annual monthly precipitation for sub-regions

4.3.1 Effects of crop growth and development on local land surface conditions

To detect the mechanisms underlying the interactions between crops and the atmosphere, we first evaluated the differences in simulated land surface variables induced by considering crop growth and development. The differences in JJA are chosen for analysis since the differences in land surface water and energy variables primarily appeared during summer (see Table 2), which is the main crop growing season.

The detailed differences in land surface water and energy variables averaged over the sub-regions in JJA are shown in Table 2. Compared with the results from the CSM run and CTL run, decreases of 2.06, 2.54, 3.96, 1.30, and 1.05 m^2/m^2 in the leaf area index were observed over the five sub-regions NE, NC, HH, SE, and SW, respectively, since the CERES phenological growth and development functions were incorporated and the effects of precipitation, radiation, soil moisture, cropping systems and other factors on crop growth and development were

considered. The decrease in leaf area index was accompanied by a decrease in fractional vegetation cover, which led to a decrease in vegetation transpiration and an increase in soil evaporation. Thus, increases of 0.01, 0.03, 0.04, 0.02, and 0.01 mm^3/mm^3 in the root zone soil moisture, and decreases of 0.02, 0.01, 0.02, 0.01, and 0.01 mm^3/mm^3 in top soil moisture were observed as a directly result of the decrease in leaf area index and fractional vegetation cover over the five sub-regions NE, NC, HH, SE, and SW, respectively. These findings are consistent with the results derived from the two off-line experiments conducted by Chen and Xie (2011). Although the top-layer soil moisture is reduced, the sum of top-layer soil moisture and root zone soil moisture is increased, which led to an increase of 0.01, 0.08, 0.08, 0.09, and 0.05 mm/day in surface runoff (In BATS, the surface is related to the sum of top soil moisture and root zone soil moisture rather than top soil moisture.). Besides, a decrease of 0.12, 0.29, 0.30, 0.01, and 0.06 mm/day in evapotranspiration were observed over the five sub-regions NE, NC, HH, SE, and SW, respectively, which was accompanied by a decrease of 3.44, 8.47, 8.61, 0.39, and

Fig. 5 The mean 2 m temperature and its error over East Asian monsoon area in JJA: **a–c** mean 2 m temperature for CTL-run, CSM-run, and observation; **d** the differences between CSM-run and CTL-run; **e** the differences in root mean square error for the CSM-run and CTL-run compared with the observed values; **f** the differences in Correlation Coefficient for the CSM-run and CTL-run compared with the observed values

1.88 W/m² in latent heat flux and cooling of the surface (known as evaporative cooling). Over the five sub-regions NE, NC, HH, SE, and SW, the 2 m mean air temperature increased by 0.59, 0.66, 0.51, 0.29, and 0.27°C, respectively. These increases led to decreases in the surface-atmosphere temperature differences and increases in the mean annual sensible heat flux of 6.42, 6.22, 5.46, 2.50, and 1.95 W/m² over the five sub-regions, respectively. Moreover, these changes in surface condition affected the surface albedo and increased the net absorbed shortwave and net longwave radiation, which also plays an important role in surface energy balance and water balance. Ultimately, the changes in these surface water and energy variables influenced the structure of the boundary layer and led to the decreases of 0.16, 0.12, 0.23, 0.02, and 0.05 mm/day in total precipitation. It should be noted that decreases of 0.10, 0.14, 0.20, 0.01, and 0.07 mm/day in convective precipitation were responsible for the decrease in total precipitation.

Figure 7 shows the spatial distribution of JJA differences in leaf area index, root zone soil moisture, latent heat flux, sensible heat flux, total precipitation, and 2 m mean

air temperature between the CSM run and the CTL run. The differences in leaf area index primarily appeared in the monsoon region in eastern China, where there is widely distributed cropland. Corresponding to the decrease in leaf area index, the largest differences in root zone soil moisture, latent heat flux, sensible heat flux, and 2 m mean air temperature also occurred in the monsoon region in eastern China, especially over sub-region HH (Table 2). Most of these differences were statistically significant at the 90% confidence level (*F* test, *n* = 19) in northeast China, north China, and south China (grided in Fig. 7). The total precipitation decreased in the Northeast China Plain, Huai River Basin, and most parts of Sichuan and Guangxi provinces, while it increased in Daxing'anling Mountain, Taihang Mountain, Qinling Mountain, and Fujian and Yunnan provinces. The spatial distribution of the difference in total precipitation was more heterogeneous than that of other variables, and almost no statistically significant differences were shown in the study domain. This was primarily because precipitation is not only affected by the local atmospheric condition, but also by macroscale atmospheric processes.

Fig. 6 Simulated and observed mean annual monthly temperature for sub-regions

To further explore the physical basis for the simulated differences between the CSM run and CTL run, we examined the vertical profiles of state variables that influenced the stability characteristics of the atmospheric boundary layer. Figure 8 shows the vertical profiles of potential temperature, pseudoequivalent potential temperature, actual temperature, and mixing ratio averaged over the NE sub-region for JJA simulated by RegCM3_CERES and RegCM3. For all four variables, the differences between the CSM and CTL runs were primarily located in the lower atmosphere and over several σ throughout the boundary layer. The pseudoequivalent potential temperatures for two runs converged at the top of the boundary layer, at a σ of about 0.67, while both actual and potential temperature for the two runs converged at a σ of about 0.81. The profile of the pseudoequivalent potential temperature can be viewed as the most important aspect of the thermodynamic stratification, and it is directly related to convective instability. The RegCM3_CERES produced a smaller vertical decreasing rate ($\partial\theta_{se}/\partial p$) than the RegCM3

over the five sub-regions, especially sub-region NE, NC, and HH. The CSM run was clearly more stable than the CTL run, which may be one explanation as to why there was less convective precipitation over the five sub-regions in the CSM run than the CTL run.

4.3.2 Effects of crop growth and development on the macroscale atmospheric processes

The differences in land surface variables and boundary structure described above can explain the effects of crop growth and development on regional climate from the local recycling aspect. However, the large-scale variations in crop growth and development will change the spatial distribution of soil moisture and surface fluxes, and consequently influence the overlying atmospheric circulation, which will redistribute the water and energy through advection. Figure 7 shows that the latent heat flux, sensible heat flux, and precipitation changes in Qinling Mountain, although the leaf area index showed no changes. This

Table 2 Differences (RegCM3_CERES Minus RegCM3) in land surface water and energy variables averaged over the sub-regions

Variable		NE			NC			HH			SE			SW		
		ANN	DJF	JJA	ANN	DJF	JJA	ANN	DJF	JJA	ANN	DJF	JJA	ANN	DJF	JJA
Differences in water variables																
Leaf area index (LAI)	m ² /m ²	-0.91	-0.01	-2.06	-1.33	-0.08	-2.54	-2.72	-0.74	-3.96	-1.53	-1.47	-1.30	-1.11	-0.80	-1.05
Top layer soil moisture (SSW)	m ³ /m ³	-0.01	0.00	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.01	0.00	-0.01	-0.01	0.00	-0.01
Root zone soil moisture (RSW)	m ³ /m ³	0.01	0.01	0.01	0.03	0.03	0.03	0.04	0.04	0.04	0.02	0.04	0.02	0.02	0.02	0.01
2 m specific humidity (Q2M)	g/kg	-0.06	0.01	-0.15	-0.04	0.02	-0.15	0.10	0.07	0.16	0.04	0.06	0.09	-0.01	0.00	0.06
Surface runoff (RUNOFF)	mm/day	0.01	0.00	0.01	0.03	0.01	0.08	0.05	0.02	0.08	0.05	0.02	0.09	0.03	0.01	0.05
Soil evaporation(ES)	mm/day	0.03	0.00	0.04	0.05	0.03	0.18	0.08	0.08	0.18	0.07	0.02	0.11	0.04	0.02	0.07
Vegetation transpiration(EV)	mm/day	-0.08	0.00	-0.16	-0.15	-0.01	-0.47	-0.20	-0.02	-0.48	-0.17	-0.11	-0.12	-0.12	-0.04	-0.13
Evapotranspiration (EVP)	mm/day	-0.05	0.00	-0.12	-0.10	0.02	-0.29	-0.12	0.06	-0.30	-0.10	-0.09	-0.01	-0.08	-0.02	-0.06
Total precipitation (TPR)	mm/day	-0.05	0.01	-0.16	-0.06	0.01	-0.12	-0.07	0.03	-0.23	0.00	0.00	-0.02	-0.03	0.00	-0.05
Convective precipitation (PRCV)	mm/day	-0.02	0.00	-0.10	-0.05	0.00	-0.14	-0.07	0.00	-0.20	-0.01	0.00	-0.01	-0.03	0.00	-0.07
Differences in energy variables																
Vegetation temperature (TLEF)	°C	0.66	0.06	1.41	0.65	0.04	1.51	0.87	0.14	1.42	0.51	0.34	0.54	0.19	-0.06	0.36
2 m mean temperature (T2M)	°C	0.23	0.04	0.59	0.22	0.03	0.66	0.24	0.00	0.51	0.20	0.12	0.29	0.17	0.10	0.27
2 m maximum temperature (T2MAX)	°C	0.45	0.03	1.12	0.28	-0.05	0.9	-0.11	-0.45	0.46	0.32	0.06	0.61	0.25	0.01	0.40
2 m minimum temperature (T2MIN)	°C	0.12	0.03	0.26	0.23	0.05	0.58	0.49	0.15	0.79	0.21	0.20	0.22	0.18	0.12	0.28
Net absorbed shortwave (FSW)	W/m ²	2.83	-0.21	8.46	0.98	-0.61	3.02	0.35	-0.94	3.50	1.93	-0.23	5.15	1.32	0.31	2.05
Net longwave (FLW)	W/m ²	1.99	-0.05	5.51	1.97	-0.14	5.07	3.10	-0.36	6.37	2.45	1.39	2.86	1.95	1.05	1.98
Latent heat flux (LE)	W/m ²	-1.54	0.13	-3.44	-2.98	0.63	-8.47	-3.62	1.87	-8.61	-2.84	-2.69	-0.39	-2.22	-0.50	-1.88
Sensible heat flux (SENA)	W/m ²	2.40	0.13	6.42	2.17	0.15	6.22	0.95	-1.80	5.46	2.41	1.69	2.50	1.66	0.26	1.95

Fig. 7 Mean differences between the CSM run and CTL run in JJA: **a** LAI leaf area index, **b** RSW root zone soil moisture, **c** LE latent heat flux, **d** SH sensible heat flux, **e** TPR total precipitation, **f** T2M 2 m mean air temperature

phenomenon cannot be explained by the local recycling aspect. Thus, we examined the atmospheric circulations that influence the macroscale water vapor transport.

Figure 9 shows the spatial differences in JJA mean total precipitation, 500 hPa geopotential height and 850 hPa wind between the CSM and CTL run. There were two positive anomaly centers of 500 hPa geopotential height located at Liaoning and Guangxi provinces,

and a negative anomaly center located at Taiwan Province. These anomalies enhanced the southerly wind of Qinling Mountain and brought more water into this region.

To compare the effects of the macroscale atmospheric processes and mesoscale land–atmosphere interactions on the development of precipitation in detail, the atmospheric moisture budgets and two water cycle indices

Fig. 8 Vertical profiles of potential temperature, pseudoequivalent potential temperature, actual temperature, and mixing ratio in JJA simulated by RegCM3_CERES and RegCM3 for the NE sub-region

Fig. 9 Mean differences in total precipitation, 500 hPa geopotential height and 850 hPa wind between the CSM and CTL run in JJA

were analyzed in each sub-region. Based on the definitions in Schär et al. (1999), which has been used in several studies (Yuan et al. 2008; Chen and Xie 2010),

the balance equation for the atmospheric moisture and the definitions of the two water cycle indices can be written as follows:

Table 3 Atmospheric water balance components and two water cycle indices averaged over the sub-regions

Region	Run	P (mm/day)	E (mm/day)	QIN (mm/day)	QOUT (mm/day)	MC (mm/day)	β (%)	χ (%)
NE	CTL	4.72	3.10	14.26	12.64	1.62	17.9	27.2
	CSM	4.59	2.99	14.53	12.93	1.60	17.1	26.2
	CSM-CTL	-0.14	-0.12	0.27	0.29	-0.02	-0.81	-1.02
NC	CTL	3.60	2.83	12.90	12.13	0.77	18.0	22.9
	CSM	3.49	2.55	13.15	12.21	0.94	16.2	22.2
	CSM-CTL	-0.11	-0.28	0.25	0.08	0.17	-1.74	-0.63
HH	CTL	3.29	2.90	8.28	7.89	0.39	26.0	29.4
	CSM	3.07	2.62	7.99	7.55	0.45	24.7	28.9
	CSM-CTL	-0.23	-0.28	-0.29	-0.34	0.06	-1.28	-0.55
SE	CTL	7.05	3.94	17.75	14.64	3.10	18.2	32.5
	CSM	7.06	3.93	17.97	14.84	3.13	17.9	32.2
	CSM-CTL	0.01	-0.02	0.22	0.20	0.02	-0.24	-0.27
SW	CTL	4.82	3.40	7.05	5.63	1.43	32.5	46.1
	CSM	4.78	3.33	6.93	5.48	1.45	32.5	46.5
	CSM-CTL	-0.05	-0.06	-0.13	-0.15	0.02	-0.03	0.41

$$\Delta W = q_{\text{in}} - q_{\text{out}} + ET_b - P_b, \quad (2)$$

$$\beta = ET_b / (q_{\text{in}} + ET_b), \quad (3)$$

$$\chi = P_b / (q_{\text{in}} + ET_b), \quad (4)$$

where ΔW (mm/day) denotes the tendency of the atmospheric water content during the integration period; β denotes the recycling rate; χ denotes the precipitation efficiency; q_{in} (mm/day) and q_{out} (mm/day) denote the JJA mean water flux into and out of the domain, respectively; and ET_b (mm/day) and P_b (mm/day) are the JJA mean evapotranspiration and precipitation in the domain, respectively.

Table 3 show the atmospheric water balance components and two water cycle indices averaged over the sub-regions (note that the ET_b and P_b are slightly different from Table 2 due to consideration of ocean grid cells). By comparing the CSM run and CTL run, the moisture convergence ($MC = q_{\text{in}} - q_{\text{out}}$) decreased by 0.02 mm/day over sub-region NE and increased by 0.17, 0.06, 0.02, and 0.02 mm/day over sub-region NC, HH, SE, and SW, respectively. These processes enhanced the precipitation decrease over sub-region NE, while alleviating this decrease over the other sub-regions. As the crop growth and development was considered in the regional climate model, decreases of 4.56, 9.68, 4.93, 1.32, and 0.09% in recycling rate, and 3.74, 2.75, 1.86, 0.83, and -0.89% in precipitation efficiency were observed over the five sub-regions NE, NC, HH, SE, and SW, respectively, indicating a decrease in the water cycle over these sub-regions.

5 Summary and discussion

In this study, we coupled the CERES phenological growth and development functions into the RegCM3/BATS configuration to investigate the effect of crop growth and development on regional climate. By using the new model, we found a 2.2–10.7% decrease in the root mean squared error of precipitation simulation over north China, and a 5.5–30.9% decrease in the root mean squared error of temperature simulation over the monsoon region in eastern China. These findings suggested that it is necessary to incorporate the crop growth and development processes into a regional climate model.

Comparison of simulations conducted using RegCM3_CERES and RegCM3 showed that a robust representation of seasonal changes in plant growth and development in a regional climate model changed the surface heat and moisture fluxes through modifying the vegetation characteristics (e.g., leaf area index, fractional vegetation cover, etc.), and the differences in simulated surface fluxes resulted in different structures of the boundary layer and ultimately affected the convection. The variations in leaf area index and fractional vegetation cover changed the distribution of evapotranspiration and heat fluxes, which led to anomalies in geopotential height, and consequently influenced the overlying atmospheric circulation. These changes would redistribute the water and energy through advection, which implied that interactive parameterizations for crop growth and development resulted in higher temperatures and lower evapotranspiration

and precipitation values compared to the control over the extratropical Northern Hemisphere summer; and that the response of precipitation to LAI was highly nonlinear.

It should be noted that most significant changes associated with crop modeling are the changes in LAI which in turn modify the aspects of surface energy and water partitions and lead to moderate changes in surface temperature, and, to some extent, rainfall. While we have found responses in regional circulation to the changes in surface conditions associated with crop modeling, such changes cannot pass the statistical significance test at 95% confidence level. There are two possible reasons for such results. The first one is that the impacts of crop modeling on the regional circulation are only moderate. The second reason is likely due to the nature of this modeling experiment in which we have used 20-year observed SST forcing. It is well known that the Asian monsoon system is dominated by the SST variations. Land-surface contribution is likely to be secondary comparing to SST forcing so the signals from land-surface can be masked out by significant SST variations in the experiments. We would expect such regional circulation responses to be statistically significant if SST climatology is used in the regional model simulations. Besides, there are some uncertainties regarding the actual magnitude of the effects of crop growth and development on regional climate. These uncertainties include the internal variability of the model which may heavily influence the simulation of precipitation (Giorgi and Bi 2000), the limited skill on regional climate simulation over East Asian monsoon area (Fu et al. 2005; Zhang et al. 2007; Zheng et al. 2009), the lack of description of natural vegetation growth and develop and the simplification of cropping system over the region, and the different time steps between RegCM and CERES. These issues should be addressed in the future.

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