Numerical Simulation of the Climatic Effects of Plastic Film Mulched Cropland Underlying Surface in Arid Regions on East Asia: A Postprint

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Abstract

Plastic film mulching in farmland is currently a widely adopted cultivation practice in arid and semi-arid regions of China. To investigate the climatic effects of large-scale plastic film mulching on the East Asian region, a land-atmosphere water-heat transfer process model for plastic film mulching was established based on experimental observations and theoretical studies, and the plastic film mulched farmland underlying surface module was introduced into the regional climate models RegCM4 and WRF to conduct simulation experiments on summer climate over 17 years. Parameters such as precipitation, soil temperature, soil moisture, sensible heat flux, and latent heat flux output from the RegCM4 model were compared with experimental observations and theoretical values, and validated through output results from the WRF model. The results indicate that the regional climate model incorporating the plastic film mulched farmland underlying surface module can realistically characterize the features of its underlying surface. Further analysis of the simulation results reveals that by affecting near-surface water-heat transfer through plastic film mulching and acting on the regional geopotential height field and wind field, which in turn influences large-scale water vapor transport, ultimately leading to reduced precipitation in Northwest and South China, and increased precipitation in Southwest China and the Huai River basin.

Full Text

Numerical Simulation of Climate Effects of Plastic Film Mulching Farmland in Arid Regions of East Asia

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Abstract

As an effective agricultural practice, plastic film mulching is widely used on farmland in arid and semi-arid regions of China. To investigate the climate effects of plastic film mulching on farmland in East Asia, this study developed a heat-water transfer process model for mulched farmland based on experimental observations and theoretical research. The mulched farmland module was introduced into RegCM4 and WRF models to conduct a 17-year summer climate simulation experiment. Output parameters such as precipitation, soil moisture content, surface soil temperature, sensible heat flux, and latent heat flux were compared between the RegCM4 model and experimental observations/theoretical values, and the parameters were verified against the WRF model output results. The results showed that after mulching with plastic film, the regional climate model can accurately describe the characteristics of the farmland underlying surface. Further comparison revealed that the potential field and wind field could be altered through the influence of plastic film mulching on near-surface heat and water transfer processes. Water vapor transmission was affected, resulting in reduced precipitation in northwestern and southwestern parts of China, but increased precipitation in southwestern China and the Huai River Basin.

Keywords: plastic film mulching; RegCM4.3; WRFV3.6; numerical simulation; climate effect; arid land

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1. Model Development

A heat-water transfer model for mulched farmland was developed based on experimental observations and theoretical research. The model introduces a mulched farmland module into RegCM4 and WRFV3.6, incorporating the BATS (Biosphere-Atmosphere Transfer Scheme) land surface scheme. The fundamental equations governing the heat and water transfer processes are:

$$H_f = H_{g1} + H_{f0}$$

$$E_f = E_{g1} + E_{f0}$$

where the detailed flux components are calculated as:

$$H_f = \rho_a \delta_f C_p C_D V_a (T_{af} - T_a)$$

$$H_{g1} = \rho_a C_p [C_{SOIL} C \delta_f U_{af}] (T_{g1} - T_{af})$$

$$E_f = \rho_a c_a (q_{af} - q_a)$$

$$E_{g1} = \rho_a C_G f_g (1 - \phi)(q_{gs} - q_{af})$$

Table 1. Physical meanings of parameters in the model

Parameter	Description
H_f	Sensible heat flux from the mulched surface
H_{g1}	Sensible heat flux from the soil beneath the mulch
H_{f0}	Background sensible heat flux
E_f	Latent heat flux from the mulched surface
E_{g1}	Latent heat flux from the soil beneath the mulch
E_{f0}	Background latent heat flux
ρ_a	Air density
δ_f	Mulch coverage fraction
C_p	Specific heat capacity of air at constant pressure
C_D	Drag coefficient
V_a	Wind speed
T_{af}	Air temperature at the mulch surface
T_a	Reference air temperature
C_{SOIL}	Soil heat transfer coefficient
U_{af}	Wind speed at the mulch surface
T_{g1}	Soil surface temperature
c_a	Atmospheric water vapor transfer coefficient
q_{af}	Specific humidity at the mulch surface
q_a	Reference specific humidity
C_G	Soil moisture transfer coefficient
f_g	Soil moisture availability factor
ϕ	Mulch porosity
q_{gs}	Saturated specific humidity at the soil surface

The model employs a spin-up period of 6-8 months to ensure stable initial conditions for the land surface parameters. The RegCM4 simulation uses a horizontal resolution of 20 km with 166$\times$79 grid points, while the WRF simulation employs a nested configuration with 60 km and 20 km resolution grids.

2. Experimental Design

The numerical simulation experiment was conducted for summer periods over 17 years using RegCM4 coupled with the mulched farmland module. The model was initialized with NNRPS atmospheric reanalysis data and OISST sea surface temperature data with 6-hourly temporal resolution. The WRF model was configured with ECMWF 1°$×$1° reanalysis data as initial and boundary conditions.

Key parameterizations employed in the simulations include: - RRTM longwave radiation scheme - Goddard shortwave radiation scheme - Monin-Obukhov (Janjić) surface layer scheme - Thompson microphysics scheme - RUC land surface scheme - Mellor-Yamada-Janjic planetary boundary layer scheme - Kain-Fritsch cumulus convection scheme

The time step for integration was set to 30 seconds for computational stability.

3. Results and Analysis

3.1 Wind Field and Potential Field Characteristics Figure 4 shows the 850 hPa wind field and potential field deviations in the simulation. The results indicate that plastic film mulching significantly alters the near-surface atmospheric circulation patterns. In June, the wind field shows enhanced convergence over mulched areas, with potential field deviations creating localized circulation anomalies. By July, these effects intensify, particularly in regions between 30°-40°N where extensive mulching is practiced. The August simulation reveals persistent modifications to the geopotential height gradient, affecting regional wind patterns.

The spatial analysis demonstrates that mulching-induced surface changes create distinct anomalies in the 850 hPa pressure surface, with divergence patterns shifting in response to altered surface energy partitioning. The potential field deviations exhibit a dipole structure, with positive anomalies over mulched areas and negative anomalies in surrounding regions.

3.2 Precipitation Response Figure 5 presents the average total summer precipitation distribution. The simulation reveals that plastic film mulching leads to a complex precipitation response: - Northwestern China experiences a 10-15% reduction in summer precipitation - The Huai River Basin shows a 5-8% increase in rainfall - Southwestern China exhibits mixed signals with localized increases of 8-12%

Figure 6 displays the multi-year average daily precipitation series, showing that mulching affects not only total precipitation amounts but also the frequency and intensity distribution of rainfall events. The reduction in soil evaporation due to mulching decreases atmospheric moisture content in source regions, while enhanced surface temperatures increase convective potential in downwind areas.

The precipitation changes result from two competing mechanisms: (1) reduced surface evaporation limiting moisture supply, and (2) altered surface energy balance enhancing atmospheric instability. The net effect varies regionally depending on background climate conditions and the scale of mulched areas.

3.3 Soil Moisture and Temperature Effects The model simulates significant changes in soil hydrothermal conditions. Surface soil temperature increases by 2-4°C under mulch due to greenhouse effects, while soil moisture content shows less diurnal variation but retains higher mean values. The reduced evaporation leads to improved soil water storage, particularly in the top 20 cm layer.

Sensible heat flux decreases by 30-40% over mulched surfaces, while latent heat flux shows more complex patterns with reductions in dry conditions but potential enhancements when soil moisture is sufficient. These changes alter the Bowen ratio and modify the atmospheric boundary layer development.

4. Discussion and Conclusions

The coupled model successfully captures the essential climate effects of plastic film mulching. Key findings include:

1. **Surface Energy Balance**: Mulching substantially modifies surface radiation balance and heat flux partitioning, with decreased sensible heat flux and altered latent heat flux patterns.
2. **Atmospheric Circulation**: The 850 hPa wind and potential fields respond to mulching through thermal and moisture feedbacks, creating mesoscale circulation anomalies.
3. **Precipitation Patterns**: The simulation reveals a northwest-southeast dipole in precipitation response, with reductions in moisture-source regions and increases in downwind convergence zones.
4. **Model Performance**: Comparison with WRF simulations validates the RegCM4 results, showing consistent patterns of climate response to mulching.

The study demonstrates that large-scale plastic film mulching acts as a significant land-use forcing that can modify regional climate through biophysical feedbacks. The developed model provides a tool for assessing agricultural practice impacts on climate and can inform sustainable intensification strategies in arid regions.

Future work should focus on: - Integrating crop growth dynamics with climate feedbacks - Evaluating long-term climate trends under persistent mulching - Assessing the combined effects of mulching with irrigation practices - Validating model results with extensive field observations

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Note: Figure translations are in progress. See original paper for figures.