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Applicability of Simultaneous Heat and Water Model for Monitoring Late Frost Injury of Winter Wheat

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Abstract: The late frost injury of winter wheat usually occurs during the jointing-heading stage and may result in severe yield loss in large areas, thus it is of significant importance to monitor and assess late frost injury of winter wheat real-timely and accurately. The simultaneous heat and water (SHAW) model is a detailed process model of heat and water movement in plant-snow-residue-soil system, and it has the capability to simulate heat and water transfer within the canopy. The SHAW model was applied to simulate air temperature within winter wheat young ear layer at the sensitive period after jointing stage in Shangqiu City on the basis of field experiment in 2015, and it was also adopted to monitor occurrence and damage level of late frost injury combining with the days after jointing stage. The results indicated that the air temperature within young ear layer (20 ~ 60 cm) was accurately simulated as a whole, in which about 44.7% and 72.5% of the absolute errors of simulated value were less than 1℃ and 2℃, respectively, and the simulated air temperature at night was better than that in the daytime. Compared with the minimum air temperature measured at the height of 1.5 m at the meteorological station, the simulated minimum air temperature within the young ear layer of winter wheat and the low temperature duration can well express the low temperature environment of young ear when late frost injury was occurred. There were large differences among the minimum air temperature measured at the meteorological station, the minimum air temperature measured at 2 m height in the winter wheat fields and within the young ear layer because of the influence of field microclimate. The method which transformed air temperature data from the meteorological station into air temperature data at 2 m height in the winter wheat fields was better than the method which used air temperature data from the meteorological station as driving data of SHAW model directly, the minimum air temperature simulated by the former method was close to the measured one, and the late frost injury level evaluated by using the former method was in good agreement with the field surveyed one. Therefore, using SHAW model to monitor late frost injury of winter wheat is feasible and applicable, and compared with the traditional monitoring index of air temperature data from the meteorological station it can enhance the accuracy for monitoring the occurrence and damage level of late frost injury.

Key words: SHAW model; winter wheat; late frost injury; applicability; air temperature simulation

0 Introduction

As a kind of sudden harm encountered by low temperature causing water to freeze inside the plant issue after the spring thaw, late frost injury usually occurs after the jointing stage of winter wheat. During this period, the wheat growth flourishes, the height of growth cone or young ear from the ground rise constantly, breaks away from the leaf sheath protection and thus leads to decreased cold resistance. In this case, impacts in varying degrees may be caused on the yield once the young ear suffers from frost injury[1-2]. In the current study of late frost injury, the commonly-used monitoring indicators comprise the land surface temperature, air temperature and leaf temperature. The large-range land surface temperature can be obtained by means of remote sensing. However, studies have shown that the land surface temperature is not in close relationship with the occurrence of late frost injury[3-4]. Meanwhile, its representativeness is often limited by the influence of physical features at different landmasses. Some scholars analyzed the relationship between late frost injury and leaf temperature and believed that the leaf temperature is

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the true reflection of plant temperature and the most ideal monitoring indicator. However, the difficulty in obtaining the leaf temperature data has restricted its wide application in the actual production[5]. The temperature data acquisition at meteorological stations may be relatively simple and convenient. Thus, many scholars have chosen the daily minimum temperature and the number of days away from the jointing stage as monitoring indicators for late frost injury[6-7]. However, the problem is that the air temperature observed at meteorological station is the temperature inside 1.5m thermometer screen and it tends to be quite different from the air temperature of the environment in which the wheat land young ear lives. Due to the combined influence from environmental change of macroclimate and crop activities, the wheat field may create a unique microclimate environment and frequent changes occur inside the wheat canopy by reason of influences from solar radiation, turbulent exchange, canopy group structure characteristics, wind speed and crop growth period and so on. Thus, there is a certain difficulty in the understanding and simulation of it[8-9]. In contrast with the air temperature at meteorological stations, the air temperature inside wheat canopy is more correlated with the physiological process and growth condition of crop. The air temperature at the height where young ear is located can further reflect the true situation of ambient air temperature in which young ear lives when the low temperature comes.

As one of the representative modes with strong mechanism in SVAT (Soil-vegetation-atmosphere transfer), SHAW model is not analogous to crop growth models such as WOFOST and CERES which focuses on the simulation and prediction of crop growth, development and yield. With outstanding performances in the simulation of energy flow and material cycle process in the soil-vegetation-atmosphere system, SHAW model divides the system into multiple layers by taking the atmosphere as upper surface and a certain soil depth as underlying surface, so as to calculate the water, heat and solute flux at each layer. SHAW model has many applications in meteorology, hydrology, ecology, plant and soil & water conservation [10-15]. In this paper, with the research subject focused on the late frost injury prone to occur after the jointing stage of winter wheat, comparisons were made with respect to the advantages and disadvantages of respectively taking the temperature at meteorological stations and the model-simulated young ear layer temperature as monitoring indicators for the late frost injury of winter wheat through the adoption of SHAW model in simulating the temperature along vertical direction with a span of 10 cm in the winter wheat crop of Shangqiu, through the utilization of simulated performance of data validation model based on continuous observation within the sensitive period of late frost and low temperature period during the field experiment in 2015 and in combination with meteorological data and field cold injury research data at 8 sites of research area during 2013, a typical year for the occurrence of late frost injury of winter wheat. Furthermore, the applicability of SHAW model in monitoring the late frost injury of winter was also analyzed.

1 Materials and methods

1.1 Study area

As a major wheat production area, Huang – Huai – Hai wheat zone is the region where suffers from the most serious late frost injury in China and the annual incidence of frost injury is more than 30% [16]. Located in the hinterland of Huang – Huai – Hai Plain, Shangqiu is one of the main plant areas and high yield areas in Huang – Huai – Hai wheat zone. However, it is also the region with the maximum frequency of late frost injury. The climate of Shangqiu belongs to the warm temperate semi-humid continental monsoon climate and years of meteorological statistical data show that the annual average sunshine hours is 2 148.6 h, annual average temperature is around 14℃, annual average rainfall is 623 mm and annual average frost-free period is 211 d. In recent years, during the period from jointing stage until heading stage (March and April) of winter wheat, there is a growing tendency in the occurrence frequency of extreme low temperature, causing the emergence of late frost injury of winter wheat to become obvious. The study area is as shown in Fig. 1.

1.2 Field experiment and data collection

The field experiment was conducted at Shuangba Experimental Station of Shangqiu Academy of

Fig. 1 Map of study area

Agriculture and Forestry Sciences. The geographical location is as follows: north latitude 34°31′55″, east longitude 115°42′37″ and altitude above sea level 50.1 m. The scope of experimental field effectively covered the aerodynamic wind area. The variety planted of winter wheat was Yumai 18, the sowing date was October 15, 2014 and the entry of jointing stage was on March 25 of the next year. From April 3—29, 2015, three samples were set in the experiment field for site-specific observation. ① Temperature observations per hour within the wheat canopy: the experimental observation period coincides with the rapid growth period of winter wheat and the young ear height constantly ascends. For the real-time monitoring of the temperature at the height where young ear is located, temperature-record sensors were installed at the heights of 20 cm, 30 cm, 40 cm, 50 cm and 60 cm. ② Meteorological data observation of upper surface: temperature, humidity, wind speed and solar radiation intensity were determined every other hour at the height 2m above the soil surface of wheat field. The hourly rainfall data was downloaded from China Weather Network (http://www.weather.com.cn/). ③ Soil temperature and soil moisture observation: the buried depths of sensors were 0, 5 cm, 10 cm, 20 cm, 30 cm, 40 cm in downward sequence. ④ Biomarker observation: determinations were made every 5 d with respect to the plant height, leaf width, root depth, proportion of root system within each layer at different depths, height of young ear and dry biomass of aboveground part. In addition, determinations were made every 7 d with respect to the leaf area index (LAL) through the application of specific leaf weight (SLW). ⑤ Definition of growth duration: the time periods for winter wheat to enter into stamen and pistil differentiation phase, initial stage of connectivum formation, last stage of connectivum formation, tetrad stage and heading stage were obtained through the field observation and in combination with the microscopic observation of morphological changes in young ear. ⑥ Determination of soil physical & chemical parameters: the soil profile texture of experiment field was relatively uniform. 50 cm profile was excavated within the sample area, so as to determine the soil mechanical composition, bulk density and other parameters. ⑦ Survey of late frost injury: after the arrival of low temperature, sampling survey of the frost injury condition in the field was timely conducted, while frost injury survey & yield survey were finalized at the late harvest. The data items of frost injury survey mainly comprised the residual ear counts and absent wheat grain counts, etc.

The temperature data at Shangqiu Meteorological Station within the observation time of field experiment and the meteorological data from the jointing stage until heading stage of winter wheat at relevant meteorological stations (including Shangqiu National Meteorological Station and meteorological stations distributing throughout Minquan, Ningling, Suixian, Xiayi, Yongcheng, Yucheng and Zhecheng) in 2013, a typical year for the occurrence of late frost injury of winter wheat, together with the field survey data of late frost injury were accumulated. The meteorological data included temperature per hour, humidity, wind speed, precipitation and solar radiation intensity data. The data of late frost injury included field survey data from 50 ground sites at the time of wheat harvest. The survey points uniformly distributed in each county or district with an average of 6 ~ 7 sampling points and comprehensively reflected the overall situation of frost injury of corresponding county or district. The data items of survey included total ear counts & actual yield within the scope of 1 m^2, residual ear count, immature ear count, average ear-grain count and average ear-grain count of residual ear, etc.

1.3 SHAW model description and localized calibration

As a model of coupled heat-fluid transport established by FLERCHINGER et al from Northwest Watershed Research Center, USDA, SHAW model provides clear mathematical expression for the material-energy transfer process in atmosphere - vegetation - soil system which can be used to simulate the transmission and exchange of moisture, heat and solute flux in each layer of system[17-20]. The water & heat fluxes in system are determined by the meteorological condition of upper surface and soil condition of underlying surface. The simulation of vegetation layer is based on K theory. Water & heat fluxes make vertical movement in each layer and influence with each other. Temperature and humidity profile within plant layer can be simultaneously solved[21-23]. Each node of the plant layer is required to meet the leaf energy-balance equation.

$$S_n + L_n = L_{AI}\rho_a c_a \frac{T_l - T_a}{r_h} + L_{AI}L_v \frac{\rho_{va} - \rho_{vs}}{r_v + r_s} + m_c c_c \frac{\delta T_l}{\delta t} \tag{1}$$

Where S_n is short-wave net radiation absorbed by the plant layer, W/m^2; L_n is long-wave net radiation absorbed by the plant layer, W/m^2; L_{AI} is leaf area index; ρ_a is air density, kg/m^3; c_a is air specific heat, J/(kg · K); T_l is leaf temperature, ℃; T_a is air temperature, ℃; ρ_{va} is vapor density of air, kg/m^3; ρ_{vs} is vapor density inside leaf stomatal cavity, kg/m^3; r_h is heat transfer resistance, s/m; r_v is water vapor transmission resistance, s/m; r_s is stomatal resistance, s/m; L_v is latent heat of vaporization, J/kg; t is time, s; m_c is leaf or stem mass, kg/m^2; c_c is specific heat capacity of leaf or stem, J/(kg·K).

The left side of equation represents the full-wave net radiation absorbed by the plant layer, while the left side of equation represents the sensible heat flux between plant layer and air, the latent heat flux between plant layer and air and the heat transfer flux inside the plant.

The main parameters required to be inputted in SHAW model lie in three aspects:

(1) Location information: latitude of experimental site is 34°32′, slope and exposure is 0.

(2) Biophysical characteristics parameters: calibration parameters are shown in Tab. 1. Leaf angle orientation describes the morphological structure of plant leaves, represents the leaf area ratio between horizontal projection plane and vertical projection plane. The model is adopted when setting the recommended value of leaf angle orientation (0.96). The albedo of plant determines the shortwave radiation budget inside vegetation layer and its evaluation refers to literature [24], calibrated as 0.2. The minimum temperature of plant transpiration is 7℃ and it is the air temperature representing the winter wheat transpiration in the early spring of study area. There are three key parameters for the calculation of stomatal resistance r_s in transpiration, i. e. stomatal resistance r_{so} without water stress, empirical exponent relating actual stomatal resistance to leaf water potential n, and critical leaf water potential ψ_c. Among them, critical leaf water potential ψ_c refers to the leaf water potential when the stomatal resistance is 2 times of the minimum value. The stomatal resistance r_s has direct influence on the water flux and transpiration. The empirical equation[25] suggested by CAMPBELL is adopted in the model to express the relationship between these three factors. The formula is listed as below:

$$r_s = r_{so}[1 + (\psi_l/\psi_c)^n] \tag{2}$$

Where ψ_l is leaf water potential of vegetation layer at a certain node, m.

Height difference is adopted in the model to represent the water potential of different exchange surfaces, 1 MPa equals to 100 m water column. For the evaluation of r_{so}, ψ_c and n, the parameters obtained by YU et al[26] in the related research of winter wheat at Yucheng Experimental Station within North China Plain. The resistance of roots and resistance of leaves are respectively the root-to-stem and stem-to-leaf transmission resistances of liquid water in the plant body. The built-in parameters of SHAW model that correspond to winter wheat are adopted as the initial values.

Tab. 1 Biophysical characteristics parameters of winter wheat

Parameter	Value
Leaf angle orientation	0.96
Albedo of plant	0.2
Minimum temperature of plant transpiration/℃	7
Stomatal resistance without water stress/(s · m^{-1})	100
Empirical exponent relating actual stomatal resistance to leaf water potential	5
Critical leaf water potential/m	-200
Resistance of leaves for plant/(m^3·s·kg^{-1})	1.5×10^5
Resistance of roots for plant/(m^3·s·kg^{-1})	3.0×10^5

(3) Soil physical and chemical parameters and

hydraulic characteristic parameters: such physical and chemical parameters as soil particle size composition, volume weight and saturation moisture content were obtained by the field actual measurement. Moisture soil serves as the soil type at the observation site. Sand grain mass fraction is 30.3%, powder particle is 40.5%, clay particle is 29.2%, organic matter mass fraction is 0.5%, average volume weight is 1.42 kg/m^3, and saturation moisture content is 0.49 m^3/m^3. Saturated hydraulic conductivity (0.298 cm/h), air entry potential (−0.1 m) and gap size distribution index (3) were calculated and obtained via the empirical equation [25] proposed by CAMPBELL and established by soil structure, volume weight, particle and other basic characteristics.

1.4 Simulation mode of model

The driving data of SHAW model comprises meteorological data (including temperature, humidity, wind speed, solar radiation and amount of precipitation), soil temperature and humidity data, plant population structure data, and so on. For the meteorological data measurement of upper surface, it is required to measure at a certain height above the wheat field (typical value: 2 m). Simulation can be made by taking day or hour as the step length. In consideration of the suddenness of late frost injury, the air temperature simulation of winter wheat canopy was conducted by taking hour as the step length.

Based on the localized calibration of model and through the utilization of field observation data in 2015, the air temperature inside wheat canopy along the vertical direction was simulated, the simulation step length was set as hour and the simulated air temperature performance of SHAW model during the sensitive period of late frost injury was analyzed.

Further application analysis of SHAW model was made through the application of relevantmetrological station data and field frost injury data at Shangqiu in 2013. Due to the lack of metrological data actually measured above the wheat field in 2013, the observation data of meteorological stations were directly substituted into SHAW model to function. Next, relevant equation was established on the basis of metrological station data and field measured data in 2015, the metrological station data in 2013 was converted into the metrological station data (2m above the wheat field) and substituted into the model to function. The simulated step length was set as hour and the applicability of SHAW model in the monitoring of late frost injury was further analyzed in combination with the field frost data.

2 Results and analysis

2.1 Air temperature simulation of SHAW model during the sensitive period of late frost injury

2.1.1 Air temperature simulation of young ear layer

SHAW model was applied to simulate the air temperature of winter wheat every 10cm along the vertical direction of plant height within April 3 − 29, 2015 (JD 93 − 119) and comparisons were also made with the measured values. The observation session covered stamen and pistil differentiation phase, connectivum formation stage, tetrad formation stage and heading to flowering stage. Among them, the period from stamen and pistil differentiation phase until connectivum formation stage (JD 93 − 109) was considered as the most low temperature sensitive period for winter wheat[27]. During the observation period, winter wheat grew rapidly, the average plant heights increased from 50 cm to 75 cm and the average heights of growth cone or young ear grow from 15 cm to 50 cm. However, due to the difference in the growth process of axis and tiller, the heights of young ears in a strain of wheat were not identical. As indicated in the existing studies, the reasons why young ears are more sensitive to low temperature if compared with steam leaves lie in the fact that stem leaves can restore voluntarily within a short period of time if the frost is not serious. In contrast, young ears have irreversibility after frost injury. Meanwhile, due to the dense stem leaves at the height of young ears, cold air at night is easy to converge and the daily minimum temperature also frequently appears at this height[28]. Therefore, the research emphasis was laid on the young ear layer within the height of 20 ~ 60 cm.

The simulated and measured air temperatures within young ear layers (20 cm, 30 cm, 40 cm, 50 cm, 60 cm) were made and the results showed that the efficiency coefficient of Nash − Sutcliffe model at different heights were greater than 0.9, the mean absolute errors (MAE) were 1.50℃, 1.32℃, 1.69℃, 1.67℃ and 1.70℃, respectively. About 44.7% of the absolute error of simulated value was less than 1℃ and 72.5% was less than 2℃. By taking the height of 40cm as an example, Fig. 2 is the comparison diagram of simulated and measured air temperature. It is clear that the simulated values can better reflect the variation tendency of measured values and both have better degree of fitting.

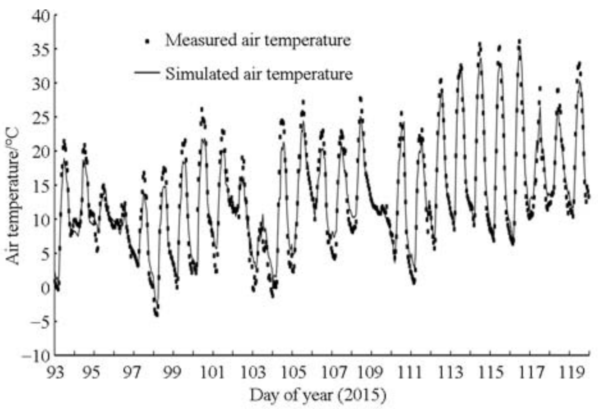

Fig. 2 Comparsion of simulated and measured air temperature within winter wheat young ear layer

2.1.2 Simulation effects along the vertical direction and low air temperature duration

Fig. 3 and Fig. 4 arevertical profile diagram of air temperature and low temperature duration diagram respectively simulated by SHAW model in the experimental field on April 8, 2015. The air temperature was the minimum at 5:00. and the air temperature reached the maximum value at 14:00. Thus, solid lines were used in Fig. 3 to represent the air temperature within 05:00 – 14:00, while the temperatures of remaining time are represented by dash lines.

On April 8 in the morning, low temperature below zero was observed in the wheat field and the average plant height was about 55 cm at this time. As shown in Fig. 3, the maximum air temperature appeared at 14:00, the minimum air temperature at 05:00 and both the maximum and minimum air temperature appeared at the height of 40 cm and 50 cm where there were dense stem leaves. The main reasons lied in the facts that more quantity of radiation can be obtained during the day due to the impact of radiation budget, high temperature layer may form at the height where weak turbulence exchange and transpiration are weak, air temperature decreased progressively either upwardly or downwardly at this place. The temperature difference was unobvious at different heights in the night. However, most of low temperature layers developed at the place where stem leaves were concentrated.

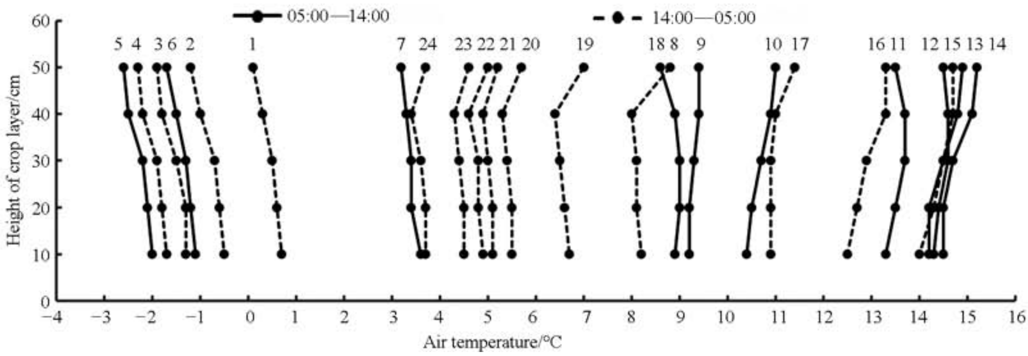

Fig. 3 Air temperature profiles within winter wheat canopy

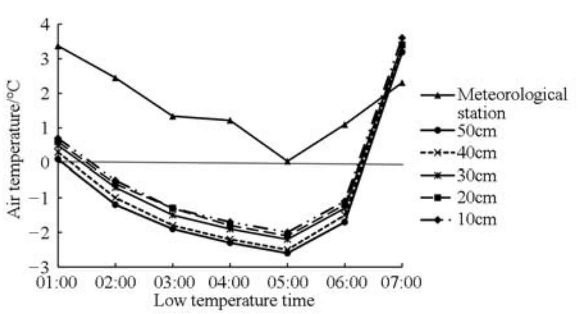

Fig. 4 Simulation results of low air tempeature within winter wheat canopy

As indicated in Fig. 4, the sub-zero low temperature process within winter wheat canopy lasted about 6h, the air temperature constantly dropped since 01:00 and reached the minimum at 05:00. At 06:00 – 07:00, due to the solar radiation within winter wheat canopy, the air temperature quickly rose from the sub-zero low temperature. Among them, the trend of temperature change at different heights was identical, the air temperature dropped along with the increase of height at the same time and the temperature values were the minimum and closer at the heights of 40 cm and 50 cm. In contrast with the data at metrological stations, the information (air temperature dropped to 0℃ only at

05:00, while the remaining air temperatures were all higher than 0℃) was displayed only at 05:00. As discovered, the advantages of applying SHAW model in monitoring the late frost injury lie in the fact that the model can not only simulate the air temperatures at different time and different heights within crop layer, but also reflect the sub-zero low temperature duration.

2.1.3 Simulation effects at day and night

As late frost injury often occurs at night with low temperature, the simulation performance of model during the day (07:00 – 18:00) and night (19:00 — 06:00 of next day).

As indicated in Tab. 2 and Fig. 5, MAE at night was less than MAE during the day at all heights, the average was lower than 0.70℃ and the aggregation extent of scattered points at night was apparently higher than that of the daytime around the 1∶1 scale line. The reason is mainly listed as below, as there is no solar radiation at night, the error that air temperature changes within canopy caused by the calculation of shortwave radiation can be reduced in the energy balance equation of model. Furthermore, the humidity inside crop layer at night was relatively high and the variation range of air temperature was far less than that during the day. Therefore, the simulation effects at night were better.

Tab. 2 Comparison of mean absolute error of simulated and measured air temperatures in the daytime and at night within winter wheatyoung ear layer ℃

	Height of young ear layer/cm				
	20	30	40	50	60
MAE of day	1.69	1.74	2.05	2.05	2.06
MAE of night	1.31	0.87	1.32	1.28	1.33

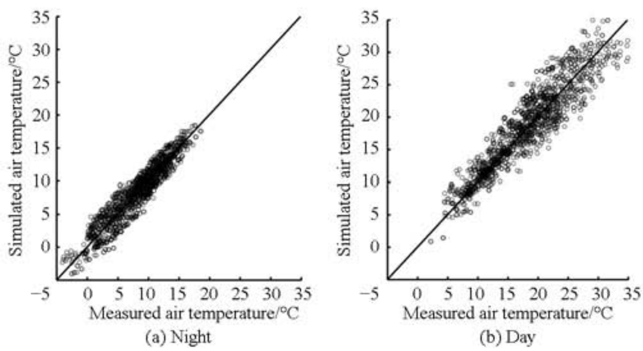

Fig. 5 Comparison of simulated and measured air temperatures at 20 ~ 60 cm height of young ear layer at night and in the daytime at sensitive peroid of late frost injury of winter wheat

2.1.4 Comparisons between observation data at metrological stations and simulated data

Extreme low temperature serves as the key disaster-deducing factor in the occurrence of late frost injury of winter wheat. Difference value treatment was implemented between metrological stations, wheat fields above 2m height and daily minimum air temperature within young ear layer. The differentiation results between above parameter difference values are as shown in Tab. 3.

Tab. 3 Descriptive statistics of differences among daily minimum air temperature of meteorological station, wheat fields at 2 m height, and measured and simulated values within young ear layer

Statistical quantity	Minimum value/℃	Maximum value/℃	Average value/℃	Sample variance/℃	Standard Deviation/℃	Coefficient of variation/%
$A-B$	0.33	4.67	2.08	1.30	1.14	54.81
$A-C$	1.50	7.95	4.75	2.05	1.43	30.11
$B-C$	0.68	4.42	2.67	0.90	0.95	35.58

Note: A is minimum air temperature of meteorological station, ℃; B is daily minimum air temperature at the height of 2 m above wheat field, ℃; C is minimum air temperature at young ear layer, ℃.

As indicated in Tab. 3, the average air temperature of meteorological station was 2.08℃ higher than the daily minimum air temperature; the average daily minimum air temperature at the height of 2 m above wheat field is 2.67℃ higher than the minimum air temperature at young ear layer and the average air temperature of meteorological station was 4.75℃ higher than the minimum air temperature at young ear layer. In addition, the maximum difference value reached 7.95℃. The difference between the maximum value and minimum value ranges 5.3 ~ 14.2 times. The sample variance and standard deviation of the difference value between minimum air temperature of metrological station and minimum air temperature of young ear layer is the highest, indicating that the diversity between these two is the greatest. The coefficient of variation of parameter difference values are more than 30%, representing greater dispersion degree. Thus, obvious difference exists between the minimum air temperatures of meteorological station, the height of 2 m above wheat field and young ear layer. Its difference value is not a fixed value due to the fact that significant difference exists between the geographical position of metrological station and that of wheat field. Furthermore, the urban heat island effect has caused the minimum air temperatures of meteorological station to be generally higher than that of the height of 2 m above wheat field and young ear layer. Meanwhile, different microclimate environments were thus formed due to the differences in terms of daily humidity, wind speed & direction, cloud amount, soil temperature & humidity, etc. For this reason, the amount of difference values of daily minimum air temperature in above three parameters was not fixed and the diversity was greater.

The measured and simulated values of daily minimum air temperatures of meteorological station, the height of 2 m above wheat field and young ear layer 20 ~ 60 cm were extracted and the results were as shown in Fig. 6.

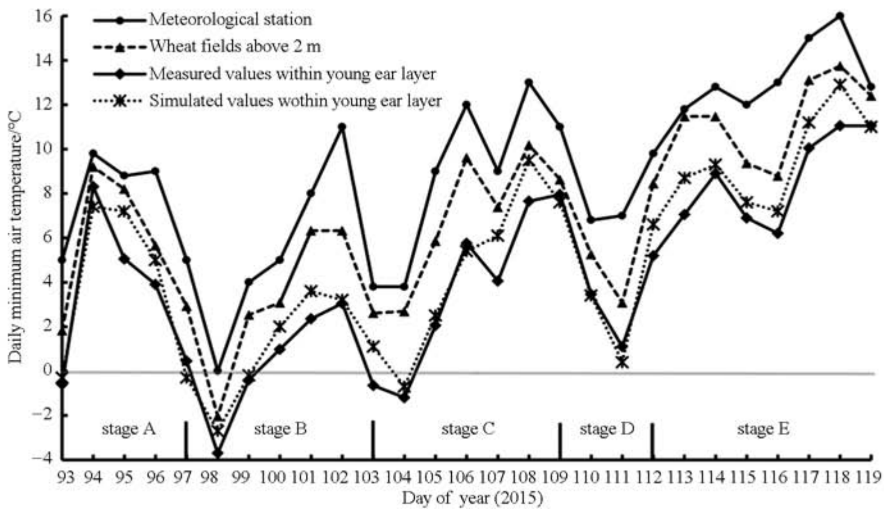

Fig. 6 Comparison of daily minimum temperature of meteorological station, wheat fields above 2 m, measured and simulated values within young ear layer

Note: stage A is stamen and pistil differentiation phase; stage B is initial stage of connectivum; stage C is last stage of connectivum; stage D is tetrad stage; stage E is blooming & heading stage.

As shown in Fig. 6, the minimum air temperature of metrological station (0℃) appeared only on the 98 th day (April 8). In contrast, the minimum values of young ear layer appeared on the 93 rd day (April 3), the 103 rd (April 13) and the 104 th (April 14) were all below 0℃. During the 4 days after the occurrence of sub-zero low temperature, the model accurately simulated the sub-zero low temperatures on the 93 rd, 94 th and 104 th day. However, the simulated value was 1.3℃ when the air temperature dropped to −0.65℃ on the 103 rd day. The reasons for major error in simulation may be like this, 4-northerly wind appeared at the night of the 103 rd day and the exponential decay law presented in the simulation of wind speed profile in the model. When the wind speed was excessively strong, this law may not conform to the actual situation. The minimum air temperature of young ear layer on the 93 rd day was −0.6℃ and in stamen and pistil differentiation phase, −3.7℃ on the 98 th day and in the initial stage of connectivum formation and the sub-zero low temperature lasted 6 h. On the 103 rd and 104 th day, the minimum air temperature was −0.65℃ and −1.2℃, respectively and was in the last stage of connectivum formation. In summary, stamen and pistil differentiation phase and connectivum formation stage are the low temperature sensitive period for winter wheat to suffer from late front injury. Frost injury can be judged from three occasions of temperature drops. If the minimum air temperature of metrological station was directly taken as monitoring indicator, it would be difficult to judge whether frost injury occurred only from the 0℃ low temperature occurred on the 93 rd day. From the survey at the late stage frost injury, the late frost injury occurred in winter wheat, causing sterility of 2.4 ears, 4 absent grains and 14.9% grain absence rate. It is evident that the direct application of meteorological information into the monitoring of frost injury may cause apparent error. In contrast, the utilization of SHAW model can enhance the accuracy rate in the monitoring of late frost injury.

2.2 Application analysis of SHAW model in the monitoring of late frost injury

The year of 2013 was a typical year when the late frost injury of winter wheat occurred in Shangqiu. Among them, three temperature-fall periods (April 7, 10 and 21) caused great damages to the local winter wheat until the period when the winter wheat grew to booting stage and heading stage[29]. In combination with the meteorological data at 8 metrological stations and basic soil data, the feasibility and effectiveness of SHAW model in the monitoring of late frost injury were further validated. Due to the lack of measured meteorological data at the height of 2 m above wheat field in 2013, the relevant equation was established in accordance with the measured air temperature data at the height of 2 m above wheat field in 2015 and the air temperature data of meteorological stations, as shown in Fig. 7.

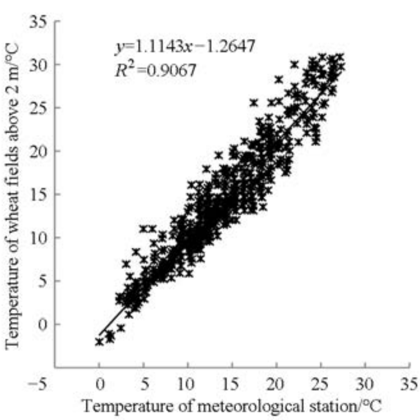

Fig. 7 Correlation analysis of air temperatures from meteorological station and wheat fields at 2 m height

The meteorological data in 2013 was used to drive the model and denoted it as SHAW I simulation. The meteorological data in 2013 was transformed, via the above related equation $y = 1.1143x - 1.2647$ (x stands for the air temperature per hour at metrological station, ℃) into the model driven by meteorological data at the height of 2 m above wheat field and denoted it as SHAW Ⅱ simulation.

The comparisons of daily minimum air temperatures between metrological stations at all counties & districts of Shangqiu and two kinds of SHAW simulation effects during three low temperature frost dates were shown in Tab. 4. As displayed in metrological stations, only the air temperature of Yucheng was below 0℃ on April 7 and 10. The air temperatures of Suixian, Xiayi and Yucheng were below 0℃ on April 21. The air temperatures of remaining counties and districts were all greater than 0℃. In SHAW I simulation, the air temperatures of Xiayi and Yucheng were below 0℃ on April 7. The air temperature of Yucheng was below 0℃ on April 10. The air temperatures of crop layers of 8 counties and districts were all below 0℃ on April 21. In SHAW II simulation, the air temperatures of Ningling, Xiayi, Yongcheng and Yucheng were below 0℃ on April 7. Sub-zero low temperature appeared in Minquan, Xiayi, Yucheng and Zhecheng on April 10. On April 21, the minimum air temperatures of crop layer within 8 counties and districts were all below 0℃. Compared with SHAW I simulation, the minimum air temperature of SHAW II simulation was even lower.

For the winter wheat of Shangqiu, the average date of jointing stage is around March 20. After the jointing stage, the cold resistance of wheat drops continuously along with the advancement of growth process. For this reason, based on the existing research results, the daily minimum air temperature and the number of days after jointing stage are selected as the monitoring indicators to judge the degree of frost injury of winter wheat, as shown in Tab. 5[30].

Based on the daily minimum air temperature and the number of days after jointing stage, the grades of late frost injury during three frost dates of 2013 were determined (Fig. 8), the daily minimum air temperature of metrological stations was adopted as the indicator, medium frost and light frost only occurred at Yucheng during April 7 – 10, light frost occurred at Minquan, Ningling, Shangqiu and Zhecheng on April 21, medium frost occurred at Suixian and Xiayi, heavy

Tab. 4 Daily minimum air temperature from meteorological station and two SHAW simulation results in three frost dates of Shangqiu ℃

Date		Minquan	Ningling	Shangqiu	Suixian	Xiayi	Yongcheng	Yucheng	Zhecheng
April 7	Meteorological station	4.2	5.2	4.7	3.7	1.5	4.7	-0.1	5.1
	SHAW Ⅰ simulation	2.1	1.5	3.5	2.1	-0.6	1.9	-1.4	2.6
	SHAW Ⅱ simulation	0.2	-0.5	1.5	0.2	-2.5	-0.1	-3.2	0.6
April 10	Meteorological station	5.3	5.7	6.2	4.7	3.2	5.4	0	3.4
	SHAW Ⅰ simulation	1.8	3.2	3.5	3.3	0.6	2.2	-1.6	1.4
	SHAW Ⅱ simulation	-0.2	1.2	1.5	1.3	-1.3	0.2	-3.4	-0.5
April 21	Meteorological station	0.7	1.0	0.3	-0.5	-0.4	4.8	-0.7	0.7
	SHAW Ⅰ simulation	-2.9	-2.8	-3.0	-3.7	-3.7	-0.2	-3.8	-2.9
	SHAW Ⅱ simulation	-4.7	-4.6	-4.8	-5.5	-5.5	-2.2	-5.6	-4.7

Tab. 5 Meteorological assessment indicator of late frost injury level of winter wheat ℃

Degree of frost	Indictor of frost	The number of days after Jointing stage			
		1 ~ 5 d	6 ~ 11 d	11 ~ 15 d	After 16 d
Light frost	Daily minimum air temperature	-2.0 ~ -1.0	-1.0 ~ 0	-0.5 ~ 0.5	0 ~ 1.0
Medium frost	Daily minimum air temperature	-4.0 ~ -2.0	-1.0 ~ -2.5	0.5 ~ -1.0	0 ~ -0.5
Heavy frost	Daily minimum air temperature	-5.0 ~ -4.0	-3.5 ~ -2.5	-1.0 ~ -2.0	-0.5 ~ -1.0

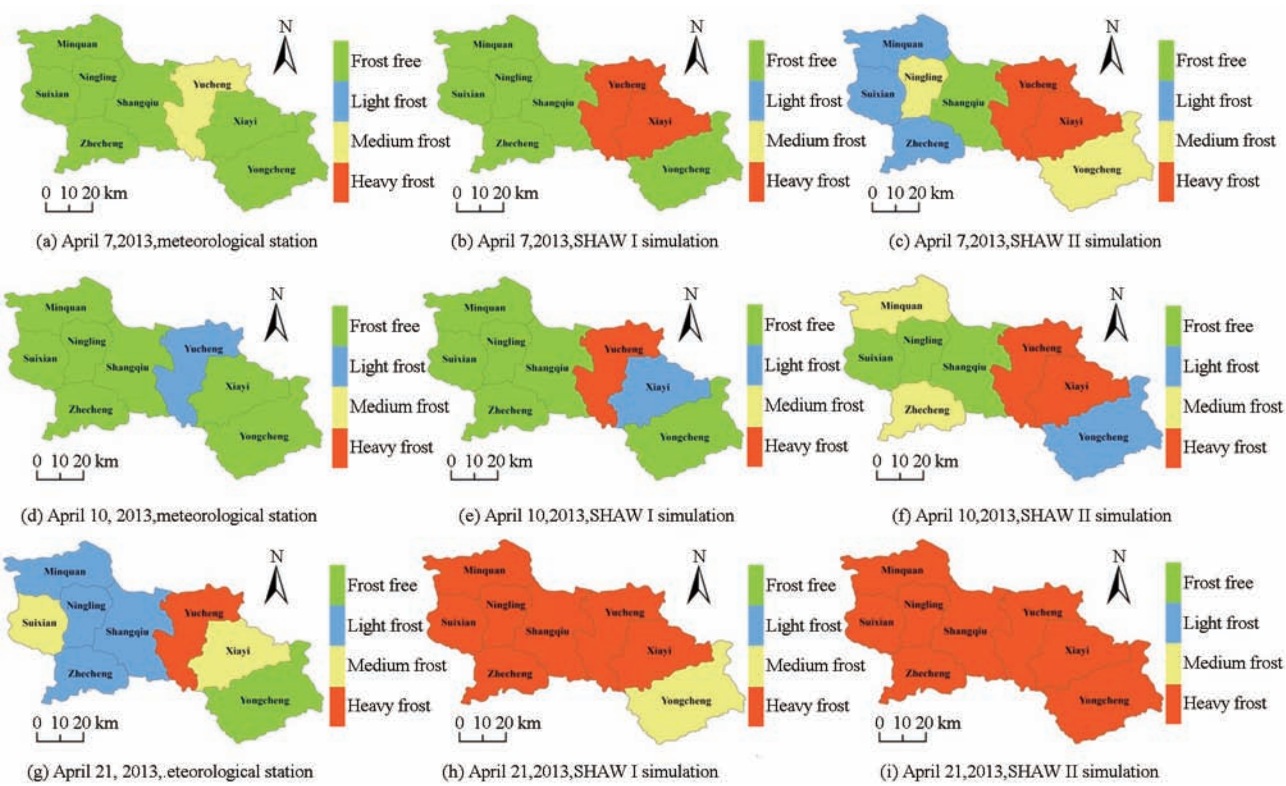

Fig. 8 Late frost injury level maps of Shangqiu City

frost occurred at Yucheng and no frost occurred in Yongcheng. The frost injury results simulated by SHAW Ⅰ: heavy frost and light frost occurred at Xiayi, heavy frost occurred at Yucheng during April 7 - 10, heavy frost occurred in remaining counties and districts except for medium frost at Yongcheng on April 21. The frost grade obtained by SHAW Ⅱ simulation was generally higher than that of SHAW Ⅰ simulation. On April 7, frost injury at various degrees occurred at the remaining counties except for Shangqiu. On April 10, frost injury occurred at the remaining five counties and districts except for Ningling, Shangqiu and Suixian. On April 21, heavy frost occurred at 8 counties and districts.

As winter wheat was in the stage of connectivum or tetrad stage during April 4 - 7, the later stage of immature ear rate and residual ear rate can be used to express its frost degree during this stage. Immature ear is small tillering generated after the cold exposure of wheat. The number of immature ear is in direction proportion to the number of ears or stems died of frost killing. Residual ears refer to those ones died of frost killing and can not be recovered. On April 21, winter wheat was in the critical period for grain formation and apparent absence of grain caused by frost injury of wheat. In this case, average decrease rate of ear-grain count can be used to express the frost degree during this stage. As indicated in the field survey of late frost injury at 50 sample sites of Shangqiu in 2013, serious late frost injury appeared in all counties and districts in the same year, frost symptoms at various degrees occurred in the ears of wheat and the proportion of frost population was relatively large. The temperature drop during April 7 – 10 caused the immature ear rate in Xiayi, Yucheng and Zhecheng to reach 25%, 28% and 20%, respectively. Despite that the immature ear rate in Ningling, Shangqiu, Suixian and Yongcheng was relatively low, yet the residual ear rate reached 40.6%, 27.2%, 17.7% and 28.6%, respectively. The temperature drop on April 21 led to obvious phenomenon of absent grains in ear of wheat. The average decrease rates of ear-grain counts in Ningling, Shangqiu, Suixian, Xiayi, Yongcheng, Yucheng and Zhecheng district were 44.0%, 39.6%, 48.6%, 40.6%, 19.4%, 50.8% and 38.9%, respectively.

Based on the survey results of field late frost and in combination with Fig. 8, it is clear that the frost grades obtained via these three methods are not uniform. Among them, the frost grade obtained by taking the air temperature of metrological station as indictor was too light. The accuracy of frost grade determined by SHAW Ⅱ simulation method was superior to that of SHAW Ⅰ simulation method. Obviously, under the condition that there are inadequate measured 2 m height metrological data which can be substituted into SHAW model, the late frost grade as determined by utilizing SHAW Ⅱ simulation method in the acquisition of ambient air temperature of young ear will be more tally with the actual situation and prove to be more accurate and effective in the monitoring of late frost injury and frost degree, if compared with the results simulated at metrological stations and SHAW Ⅰ.

3 Discussion

Among the existing monitoring methods for late frost injury of winter wheat, the minimum air temperature of metrological station is often used to judge whether the late frost injury has happened and the occurrence indicator due to its easy access. However, this indictor also has certain limits. Firstly, the air temperature measured at metrological station is often greater than the environmental temperature of young ear. When the frost injury has occurred in wheat field, the air temperature measured at metrological station may still remain above 0℃. Secondly, even if the air temperature at metrological station has dropped below 0℃, it is difficult to accurately deduce the environmental temperature of young ear due to the diversified field microclimate. Furthermore, when the temperature has dropped below 0℃, the cytosol of plant body may not freeze at once. Instead, it keeps the under-cooling state and start to freeze when the temperature has constantly dropped and reached a certain value. In this paper, mechanism-based SHAW model was introduced to simulate the ambient air temperature of young ear as the monitoring indicator for late frost injury. The reason why it can enhance the accuracy of monitoring the occurrence and degree of frost injury lies in the fact that the air temperature inside crop layer is not only influenced by the macroclimate but also correlated with the crop population structure, light energy distribution among plants, air temperature and humidity, wind speed and soil temperature & humidity. The above various kinds of impact factors have explicit mathematical expressions in the model. In addition, hour-based step length was applied in this model, which can not only simulate the extreme low temperature of environment in which the young ear lives but also obtain the duration of low temperature. It is of great significance to the monitoring of late frost injury just because the occurrence of late frost injury can either be caused by extreme low temperature or constant low temperature. Therefore, it is feasible to apply SHAW model into the monitoring of winter wheat late frost injury.

When the late frost injury occurs, air temperature is the most important disaster-causing factor, while humidity also has a great influence on the disaster-causing degree. If the air humidity is relatively high, the water vapor will present the saturation state, condense into ice crystal and produce white frost. If the humidity is relatively low, water vapor can not saturate or condense for latent heat release. In this case, the frost injury of wheat may be aggravated, hence the name of black frost[31]. In this study, the applicability of SHAW model in the monitoring of late frost injury of winter wheat was discussed from the perspective of air temperature. In the follow-up studies, air humidity factor may be supplemented to better reflect the frost injury degree of winter wheat. Single point simulation was applied in SHAW model. In the follow-up studies, considerations may be made to regionalize driving data and input parameters and expand them as regionalized simulation, interpolate the routine observation data of metrological station on the basis of GIS' spatial interpolation algorithm or obtain the driving data required by surface model on the basis of inverse method for remote sensing observation data and apply SHAW model into the area monitoring of late frost injury of winter wheat.

4 Conclusions

(1) During the late frost sensitive period of winter wheat, SHAW presented better overall effect in the air temperature simulation of young ear layer. To be specific, the simulated young ear layer has a height of 20 ~ 60 cm, an average of 44.7% simulation error is within 1℃, 72.5% simulation error is controlled within 2℃ and the simulation effect at night is better than that of daytime. The air temperature of young ear layer simulated by SHAW model in combination with the frost injury survey data of experimental field in 2015 was more suitable to be taken as the monitoring indicator of late frost injury. As a result, the monitoring accuracy of the occurrence of late frost injury was improved.

(2) Due to the differences in daily air humidity, wind speed & direction, cloud cover and crop layer structure, during the observation of daily minimum air temperature, the observed value at metrological station was the highest, followed by the observation value measured at the height of 2 m above wheat field and the observation value of young ear layer. Moreover, there are comparatively large diversities between the above parameter values. The frost injury grade obtained by taking the daily minimum air temperature at metrological stations as monitoring indicator through the combination of SHAW model, metrological station data from 8 counties and districts and filed survey of frost injury in 2013 in Shangqiu was too light and failed to agree with actual situation. Compared with the simulation method of directly substituting the metrological data at metrological stations into SHAW model, the grade of late frost injury determined by the daily minimum air temperature of young ear layer simulated by substituting the metrological data at the height of 2 m above wheat field (transformed from the metrological data at metrological stations) into SHAW model was more tally with the actual situation. For this reason, whenever there is lack of measured air temperature in young ear layer or metrological data at the height of 2 m above wheat field, it may be a kind of better alternative for the acquisition of air temperature in young ear layer by transforming the metrological station data into the metrological data at the height of 2 m above wheat field and substituting into SHAW model.

(3) During the sensitive period of late frost injury of winter wheat and low temperature, the model had better simulation effect of air temperature in young ear layer and it could better simulate the low temperature duration. Furthermore, the grade of late frost determined by taking the daily minimum air temperature as the monitoring indicator of late frost injury was more tally with theactual survey data of frost injury. Consequently, the application of SHAW model in the monitoring of winter wheat frost injury is feasible and applicable. It possesses greater advantage if compared with the traditional monitoring method for late frost injury.

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SHAW 模型在冬小麦晚霜冻害监测中的适用性研究

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摘要： 利用一维多层水热耦合 SHAW(Simultaneous heat and water)模型，在 2015 年商丘田间实验基础上，模拟冬小麦拔节后晚霜冻敏感期幼穗层气温，并结合拔节后天数对晚霜冻害的发生及其程度进行监测，以研究 SHAW 模型在冬小麦晚霜冻害监测中的适用性。结果表明，模型能准确模拟晚霜冻敏感期幼穗层 20 ~ 60 cm 高度垂直方向上的每小时气温变化，模拟值与实测值间的绝对误差低于 1℃ 的占 44.7%，低于 2℃ 的占 72.5%，且夜晚的模拟效果优于白天，相较于气象站日最低气温，SHAW 模型模拟的幼穗层日最低气温和低温持续时间更能反映实际冻害发生时的低温环境。由于农田小气候的影响，气象站、农田上方 2 m 高度和幼穗层气温具有较大差异性，当 SHAW 模型所需的农田上方 2 m 高度气象数据缺乏时，将气象站数据转换为农田 2 m 高度气象数据代入模型的模拟方法优于直接将气象站气象数据代入模型的模拟方法，前者模拟的幼穗层日最低气温与实测值更为接近，所确定的晚霜冻等级与实际情况更加符合。因此，利用 SHAW 模型对冬小麦晚霜冻害进行监测是可行且适用的，相较于传统的气象站日最低气温监测指标，可提高监测晚霜冻害发生情况和冻害程度的准确率。

关键词： SHAW 模型；冬小麦；晚霜冻害；适用性；气温模拟

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Applicability of Simultaneous Heat and Water Model for Monitoring Late Frost Injury of Winter Wheat

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Abstract: The late frost injury of winter wheat usually occurs during the jointing-heading stage and may result in severe yield loss in large areas, thus it is of significant importance to monitor and assess late frost injury of winter wheat real-timely and accurately. The simultaneous heat and water (SHAW) model is a detailed process model of heat and water movement in plant-snow-residue-soil system, and it has the capability to simulate heat and water transfer within the canopy. The SHAW model was applied to simulate air temperature within winter wheat young ear layer at the sensitive period after jointing stage in Shangqiu City on the basis of field experiment in 2015, and it was also adopted to monitor occurrence and damage level of late frost injury combining with the days after jointing stage. The results indicated that the air temperature within young ear layer (20 ~ 60 cm) was accurately simulated as a whole, in which about 44.7% and 72.5% of the absolute errors of simulated value were less than 1℃ and 2℃, respectively, and the simulated air temperature at night was better than that in the daytime. Compared with the minimum air temperature measured at the height of 1.5 m at the meteorological station, the simulated minimum air temperature within the young ear layer of winter wheat and the low temperature duration can well express the low temperature environment of young ear when late frost injury was occurred. There were large differences among the minimum air temperature measured at the meteorological station, the

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minimum air temperature measured at 2 m height in the winter wheat fields and within the young ear layer because of the influence of field microclimate. The method which transformed air temperature data from the meteorological station into air temperature data at 2 m height in the winter wheat fields was better than the method which used air temperature data from the meteorological station as driving data of SHAW model directly, the minimum air temperature simulated by the former method was close to the measured one, and the late frost injury level evaluated by using the former method was in good agreement with the field surveyed one. Therefore, using SHAW model to monitor late frost injury of winter wheat is feasible and applicable, and compared with the traditional monitoring index of air temperature data from the meteorological station it can enhance the accuracy for monitoring the occurrence and damage level of late frost injury.

Key words: SHAW model; winter wheat; late frost injury; applicability; air temperature simulation

引言

冬小麦晚霜冻害是春季回暖后突遇低温而导致组织内水分结冰的突发性伤害,一般发生于冬小麦拔节后,此时小麦长势较旺,生长锥或幼穗距离地面高度不断上升,并脱离了叶鞘的保护,抗寒性下降,一旦幼穗受到冻害,则会对产量造成不同程度的影响[1-2]。目前晚霜冻害研究中常用的监测指标有地表温度、气温和叶温。地表温度可通过遥感手段大范围获取,但也有研究表明地表温度与发生晚霜冻害的关系并不密切[3-4],同时由于受到不同地块物理特性的影响,其代表性往往受到限制。有学者分析了晚霜冻害与叶温之间的关系,认为叶温是植株体温的真实反映,是最为理想的监测指标,然而叶温数据的难获取问题限制了其在实际生产中的广泛应用[5]。气象站气温数据获取较为简单方便,因此较多学者选择日最低气温和该日距离拔节的天数作为晚霜冻监测指标[6-7],但存在的问题是气象站观测的是1.5 m百叶箱内气温,往往与麦田幼穗所处环境气温差异较大。受到外界大气候的环境变化和作物自身活动的综合影响,农田会产生独特的小气候环境,作物层内气温受太阳辐射、湍流交换、群体结构特征、风速和作物发育时期等的影响而频繁变化,使得了解和模拟它具有一定难度[8-9],而相较于气象站气温,作物层内气温与作物生理过程和生长状况联系得更为紧密,幼穗所在高度的气温则更能反映低温来临时幼穗环境气温的真实情况。

SHAW模型是土壤-植被-大气传输SVAT(Soil - vegetation - atmosphere transfer)模型中机理性很强的代表模型之一,相较于作物生长模型WOFOST、CERES等侧重于对作物的生长、发育和产量的模拟与预测,SHAW模型在模拟土壤-植被-大气系统中的能量流动和物质循环过程上有突出表现,它以大气层为上垫面,土壤一定深度处为下垫面,将系统划分多个层次并计算每一层的水、热和溶质通量,在气象、水文、生态、植物和水土保持等学科上均有诸多应用[10-15]。本文针对冬小麦拔节后易发生的晚霜冻害,采用SHAW模型模拟商丘冬小麦作物层每10 cm间隔垂直方向上的气温,利用2015年田间实验的连续观测数据验证模型在晚霜冻敏感期幼穗层和低温时段的模拟表现,并结合冬小麦发生晚霜冻害的典型年份(2013年)的研究区8个站点的气象数据和田间冻害调查数据,比较气象站气温和模型模拟的幼穗层气温分别作为冬小麦晚霜冻害监测指标的优劣,分析SHAW模型在冬小麦晚霜冻害监测中的适用性。

1 材料与方法

1.1 研究区域概况

黄淮麦区是我国重要的小麦生产区,是中国遭受晚霜冻害最严重的地区,霜冻害的年际发生率在30%以上[16]。商丘地处黄淮平原腹地,是黄淮麦区主要种植区和高产区之一,但同时也是遭受晚霜冻害频率最高的地区。商丘属暖温带半湿润大陆性季风气候,据多年气象统计资料,年均日照时数为2 148.6 h,年均温在14℃左右,年均降水量623 mm,年均无霜期为211 d。近年来,该地区在冬小麦拔节期至抽穗期的3、4月份中,极端低温的出现频率有增加趋势,导致冬小麦发生晚霜冻害现象明显。研究区如图1所示。

1.2 田间实验与数据采集

田间实验在商丘农林科学研究所双八实验站进行,地理位置为北纬34°31′55″、东经115°42′37″,海拔高度50.1 m,实验田范围有效覆盖了空气动力风浪区。冬小麦种植品种为豫麦18号,播种日期为2014年10月15日,次年3月25日左右进入拔节期。2015年4月3日—4月29日间于实验田设定3个样点进行定位观测:①作物层内每小时气温观

图 1　研究区域概况

Fig. 1　Map of study area

测。实验观测时段为冬小麦快速生长期，幼穗高度不断升高，为实时监测幼穗所在高度的气温，在 20、30、40、50、60 cm 高度均安装传感器记录气温。②上垫面的气象数据观测。在麦田土壤表面上方 2 m 高度每隔 1 h 测定气温、湿度、风速和太阳辐射强度。每小时降水量数据从中国天气网（http：//www.weather.com.cn/）下载记录。③土壤温度和土壤水分观测。传感器埋藏深度依次向下为 0、5、10、20、30、40 cm。④生物指标观测。每隔 5 d 对株高、叶宽、根系深度及各深度层内根系所占比例、幼穗所在高度、地上部分的干生物量进行测定，利用比叶重法每隔 7 d 对叶面积指数（LAI）进行测定。⑤生育期界定。通过田间观察并结合显微镜观察幼穗的形态特征变化获取冬小麦进入雌雄蕊分化期、药隔形成初期、药隔形成末期、四分体时期、抽穗期的时间。⑥土壤理化参数测定。试验田土壤剖面质地较为均匀，在样地内挖取深度为 50 cm 剖面，测定土壤机械组成、容重等参数。⑦晚霜冻害调查。在低温来临后，及时对田间冻害情况进行采样调查，后期收获时完成冻害调查和测产工作，冻害调查的数据项主要为残穗数、缺粒数等。

收集了田间实验观测时间内商丘气象站的气温数据和发生晚霜冻害典型年份 2013 年商丘有关气象站的冬小麦拔节期至抽穗开花期间气象数据和晚霜冻害田间调查数据，包括商丘国家基准气候站及民权、宁陵、睢县、夏邑、永城、虞城和柘城气象站。气象数据为每小时的气温、湿度、风速、降水量和太阳辐射强度数据。晚霜冻害数据为小麦成熟收获时在 50 个地面点的实地调查数据，调查点均匀分布在各县区，平均每个县区的调查样点为 6 或 7 个，能在一定程度上综合反映该县区的整体冻害情况，调查的数据项包括 1 m^2 范围内的总穗数与实际产量、残穗数、青穗数、正常穗的平均穗粒数、残穗的平均穗粒数等。

1.3　SHAW 模型描述与本地化标定

SHAW 模型是由美国农业部西北流域研究中心 FLERCHINGER 等建立的水热耦合模型，对大气-植被-土壤系统中物质能量传输过程有着清晰的数学表达，可用来模拟系统各层的水分、热量和溶质通量的传输交换[17-20]。上垫面的气象条件和下垫面的土壤条件决定了系统中的水热通量，植被层的模拟基于 K 理论，水热通量在各层垂直移动并相互影响，可同时求解植被层内温湿度廓线[21-23]，植被层每个节点需满足叶能量平衡方程

$$S_n + L_n = L_{AI}\rho_a c_a \frac{T_l - T_a}{r_h} + L_{AI} L_v \frac{\rho_{va} - \rho_{vs}}{r_v + r_s} + m_c c_c \frac{\delta T_l}{\delta t} \tag{1}$$

式中　S_n——作物层吸收的短波净辐射，W/m^2

L_n——作物层吸收的长波净辐射，W/m^2

L_{AI}——叶面积指数

ρ_a——空气密度，kg/m^3

c_a——空气比热容，J/（kg·K）

T_a——气温，℃　　T_l——叶温，℃

ρ_{va}——空气的水汽密度，kg/m^3

ρ_{vs}——叶片气孔腔内水汽密度，kg/m^3

r_h——热量传输阻力，s/m

r_v——水汽传输阻力，s/m

r_s——气孔阻力，s/m

L_v——蒸发潜热，J/kg　　t——时间，s

m_c——叶或茎的质量，kg/m^2

c_c——叶或茎的比热容，J/（kg·K）

等式左侧代表作物层吸收的全波净辐射，等式右侧分别代表作物层与空气间的感热通量、作物层与空气间的潜热通量、作物内的热传导通量。

SHAW 模型所需输入的主要参数有 3 方面：

（1）位置信息：实验地点的纬度为北纬 34°32′，坡度、坡向均为 0。

（2）植物生物物理特征参数：标定参数见表 1。叶向系数描述了植物叶片的形态结构，代表水平投影面与垂直投影面的叶面积比值，采用模型设定的冬小麦叶向系数推荐值 0.96。植物反照率决定着植被层内短波辐射收支，其取值参照文献[24]，标定为 0.2。植物蒸腾的最低温度 7℃ 是研究区早春冬小麦开始进行蒸腾作用的气温。无水分胁迫下的气孔阻力 r_{so}、连接气孔阻力与叶水势的经验指数 n 和临界叶水势 ψ_c 是计算蒸腾作用中气孔阻力 r_s 的 3 个重要参数，其中临界叶水势 ψ_c 指气孔阻力为最小值 2 倍时的叶水势，气孔阻力 r_s 对植被层中水分通量和蒸腾作用有直接影响，模型采用 Campbell 提

出的经验方程[25]来表达三者的关系,其公式为

$$r_s = r_{so}[1 + (\psi_l/\psi_c)^n] \quad (2)$$

式中 ψ_l——植被层某节点处的叶水势,m

模型运用高度差(m)来代表不同交换面的水势差,1 MPa等于100 m水柱。r_{so}、ψ_c和n的取值采用YU等[26]运用SHAW模型在华北平原禹城实验站进行冬小麦相关研究中的参数。根系阻力和叶片阻力分别为植物体中液态水从根至茎、茎至叶的传输阻力,采用SHAW模型自带的与冬小麦对应的参数作为初始值。

表1 冬小麦生物物理特征参数

Tab.1 Biophysical characteristics parameters of winter wheat

参数	数值
叶向系数 XANGLE	0.96
植物反照率 CANALB	0.2
植物蒸腾的最低温度 TCCRIT/℃	7
无水分胁迫下的气孔阻力 RSTOM0/(s·m^{-1})	100
连接气孔阻力与叶水势的经验指数 RSTEXP	5
临界叶水势 PLEAF0/m	−200
植物叶片阻力 RLEAF0/(m^3·s·kg^{-1})	1.5×10^5
植物根系阻力 RROOT0/(m^3·s·kg^{-1})	3.0×10^5

(3)土壤理化参数和水力特性参数:理化参数中土壤粒径组成、容重和饱和含水率由田间实测获得,观测地点的土壤类型为潮土,砂粒质量分数为30.3%,粉粒为40.5%,粘粒为29.2%,有机质质量分数为0.5%,平均容重为1.42 g/cm^3,饱和含水率为0.49 m^3/m^3。饱和导水率K_s、空气进入势ψ_e和空隙大小分布指数b通过CAMPBELL提出的由土壤结构、容重、颗粒组成等基本特性所建立的经验方程[25]计算得到,K_s为0.298 cm/h,ψ_e为−0.1 m,b为3。

1.4 模型模拟方式

SHAW模型的驱动数据包括:气象数据(包括气温、湿度、风速、太阳辐射和降水量),土壤温湿度数据,植物群体结构数据等,其中上垫面气象数据的测定要求在农田上方一定高度(典型值为2 m)。模型可选择以天或小时为步长进行模拟,考虑到晚霜冻害发生的突发性特点,本文以小时为步长对冬小麦作物层气温进行模拟。

在对模型进行本地化标定的基础上,利用2015年田间观测数据,模拟作物层内垂直方向上的气温,模拟步长为1 h,分析SHAW模型在晚霜冻敏感期的气温模拟表现。

利用2013年商丘有关气象站数据和田间冻害数据对SHAW模型做进一步应用分析,由于缺乏2013年农田上方的实测气象数据,首先将气象站观测数据直接代入SHAW模型中运行,然后基于2015年气象站观测数据和田间实测数据建立相关方程,将2013年气象站数据转换为农田2 m高度后的气象数据代入模型运行,模拟步长均为1 h,并结合田间冻害数据进一步分析SHAW模型在晚霜冻害监测上的适用性。

2 结果与分析

2.1 SHAW模型在晚霜冻敏感期气温模拟

2.1.1 幼穗层气温模拟

应用SHAW模型模拟2015年4月3日—4月29日(儒略日93−119)冬小麦株高垂直方向上每10 cm间隔的气温,并与实测值对比。观测时段涵盖了雌雄蕊分化期、药隔形成期、四分体形成期和抽穗开花期,其中,雌雄蕊分化期至药隔形成期(儒略日93−109)是冬小麦对低温最为敏感的时期[27]。观测时段内冬小麦快速生长,平均株高由50 cm增至75 cm,生长锥或幼穗所在平均高度由15 cm增至50 cm,但由于主茎和分蘖的生长进程存在差异,一株小麦的幼穗高度并不一致。已有的研究表明幼穗相较于茎叶对低温更为敏感,主要是因为茎叶受冻不严重时在短期内可自行恢复,而幼穗冻害后具有不可逆性,同时幼穗所在高度层茎叶密集,夜间冷空气易汇集于此,日最低气温也多出现在此高度[28],故本研究重点关注于20~60 cm高度内的幼穗层。

对比幼穗层(20、30、40、50、60 cm)气温模拟值与实测值,结果表明,不同高度的Nash−Sutcliffe模型效率系数均大于0.9,平均绝对误差(MAE)分别为1.50、1.32、1.69、1.67、1.70℃,且气温模拟的绝对误差小于1℃的占44.7%,小于2℃的占72.5%。以40 cm高度为例,图2为气温模拟值与实测值对比图,可以看出,模拟值较好地反映了实测值的变化趋势,两者吻合度较好。

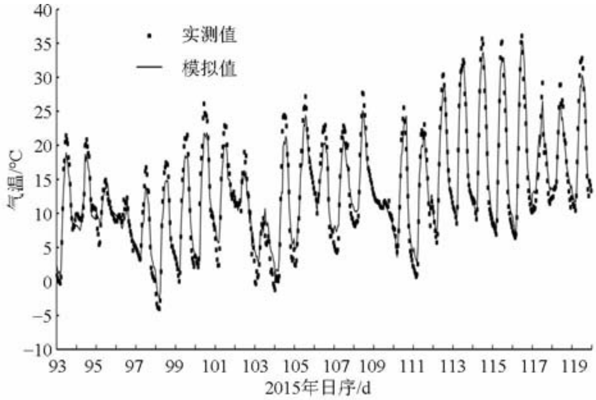

图2 冬小麦幼穗层气温的模拟值与实测值对比

Fig.2 Comparsion of simulated and measured air temperatures within winter wheat young ear layer

2.1.2　垂直方向上和低温持续时间上的模拟效果

图 3 和图 4 分别为 SHAW 模型模拟的实验田间 2015 年 4 月 8 日的气温垂直廓线图和低温持续时间图。当日 05:00 时刻气温最低，14:00 时刻气温达到最大值，因此图 3 中用实线代表 05:00—14:00 时段内气温，其余时刻气温用虚线表示。

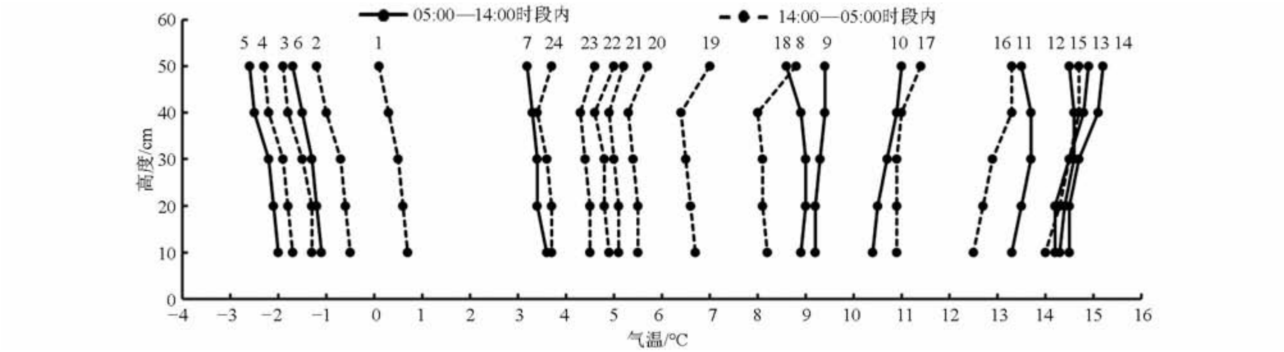

图 3　冬小麦作物层气温垂直廓线

Fig. 3　Air temperature profiles within winter wheat canopy

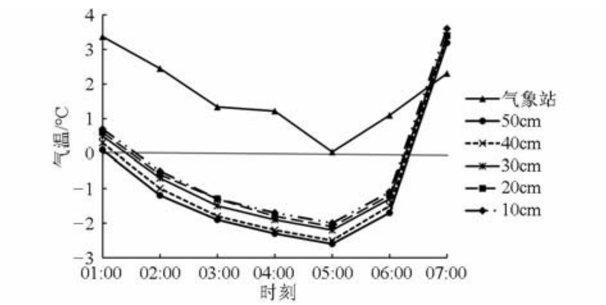

图 4　作物层内低温过程的模拟结果

Fig. 4　Simulation results of low air tempeature within winter wheat canopy

4 月 8 日凌晨观测到麦田内出现零下低温，此时植株平均高约 55 cm，从图 3 可以看出，最高气温在 14:00 出现，最低气温在 05:00 出现，最高气温和最低气温均出现在茎叶密集的 40 cm 和 50 cm 高度处。这主要是因为受辐射收支影响，白天时刻中获得辐射量较多，湍流交换和蒸腾较弱的高度将形成高温层，且气温由此处向上、向下递减，而夜晚不同高度上气温差异不明显，但多在茎叶密集处形成低温层。

从图 4 可以看出，冬小麦作物层内的零下低温过程持续约 6 h，自 01:00 开始，气温不断下降，于 05:00 降至最低，06:00—07:00 由于作物层内接受到太阳辐射，气温由零下低温迅速升高，其中不同高度的气温变化趋势一致，同一时刻的气温随高度增加而下降，在 40 cm 和 50 cm 高度处气温值最低且较为接近。对比气象站数据仅在 05:00 时显示气温降至 0℃，其余时刻均高于 0℃，可以发现，SHAW 模型运用于冬小麦晚霜冻害监测上的优势在于模型不仅可以模拟出作物层不同时刻和不同高度的气温，同时能反映零下低温的持续时间。

2.1.3　白天和夜晚模拟效果

晚霜冻害多发生于易出现低温的夜间，进一步分析模型在白天（07:00 — 18:00）和夜晚（19:00 — 次日 06:00）的模拟表现。

从表 2 和图 5 可以看出，各高度夜晚的平均绝对误差均小于白天，平均低 0.70℃，夜晚散点在 1∶1 比例线周围的聚集程度明显高于白天。这主要是由于夜间无太阳辐射，在模型能量平衡方程中可减少因计算短波辐射所引起冠层内气温变化这一项的误差，此外夜间作物层内湿度较大，气温的变化幅度远小于白天，致使夜晚模拟效果较好。

表 2　冬小麦幼穗层白天和夜晚的气温平均绝对误差比较

Tab. 2　Comparison of mean absolute error of simulated and measured air temperatures in the daytime and at night within winter wheat young ear layer　℃

类别	幼穗层高度/cm				
	20	30	40	50	60
白天	1.69	1.74	2.05	2.05	2.06
夜晚	1.31	0.87	1.32	1.28	1.33

2.1.4　气象站观测数据与模拟数据对比

冬小麦发生晚霜冻害的关键致灾因子是极端低温。将气象站、农田上方 2 m 高度、幼穗层日最低气温两两之间进行差值处理，上述参量差值之间的差异性结果如表 3 所示。

从表 3 可看出，气象站比农田上方 2 m 高度的日最低气温平均高 2.08℃，农田上方 2 m 高度比幼穗层日最低气温平均高 2.67℃，气象站比幼穗层日最低气温平均高 4.75℃，且差值最大达到 7.95℃；各项差值的最大值与最小值相差在 5.3 ~ 14.2 倍之间；气象站与幼穗层最低气温的差值的样本方差和标准差均为最大，说明两者差异性最大；参量差值的变异系数均在 30% 以上，离散程度较大。可见，气象站、农田上方 2 m 高度、幼穗层日最低气温之间差

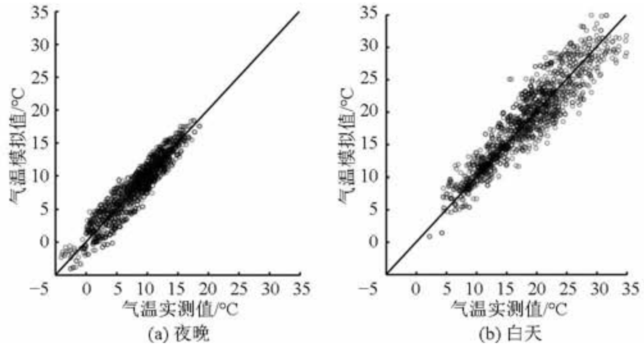

图 5 晚霜冻敏感期夜晚和白天幼穗层 20 ~ 60 cm 气温的模拟值与测量值对比

Fig. 5 Comparison of simulated and measured air temperatures at 20 ~ 60 cm height of young ear layer at night and in the daytime at sensitive peroid of late frost injury of winter wheat

异明显,其差值并非一个定值,这主要是因为气象站的地理位置与农田差异较大,城市热岛效应导致气象站最低气温普遍高于农田上方和幼穗层,同时每日的湿度、风速风向、云量、土壤温湿度等要素的差异形成不同的小气候环境,使得上述 3 个参量关于日最低气温的差值量并不固定,差异性较大。

表 3 气象站、农田上方 2 m 高度、幼穗层日最低气温两两之间差值的描述性统计

Tab. 3 Descriptive statistics of differences among daily minimum air temperature of meteorological station, wheat fields at 2 m height, and measured and simulated values within young ear layer

统计量	最小值/℃	最大值/℃	平均值/℃	样本方差/℃	标准差/℃	变异系数/%
$A-B$	0.33	4.67	2.08	1.30	1.14	54.81
$A-C$	1.50	7.95	4.75	2.05	1.43	30.11
$B-C$	0.68	4.42	2.67	0.90	0.95	35.58

注:A 为气象站日最低气温,℃;B 为农田上方 2 m 高度日最低气温,℃;C 为幼穗层日最低气温,℃。

提取气象站、麦田上方 2 m 高度和幼穗层 20 ~ 60 cm 日最低气温的实测值和模拟值,结果如图 6 所示。

由图 6 可以看出,气象站日最低气温仅在第 98 天(4 月 8 日)出现最低值 0℃,而幼穗层气温在第 93 天(4 月 3 日),第 103 天(4 月 13 日),第 104 天(4 月 14 日)的最低值均下降至 0℃ 以下。在出现零下低温的 4 d 中,模型准确模拟出第 93 天、98 天和 104 天的零下低温,但在第 103 天气温下降至 -0.65℃ 时,模拟值为 1.3℃,模拟出现较大误差的原因可能是:在第 103 天夜间出现 4 级北风,模型中关于风速廓线的模拟呈指数衰减规律,当风速过大时该规律可能与实际情况并不符合。其中第 93 天的幼穗层气温最小值为 -0.6℃,处于雌雄蕊分化期,第 98 天为 -3.7℃,处于药隔初期且零下低温持续时间达到 6 h,第 103 天和 104 天分别为 -0.65℃ 和 -1.2℃,处于药隔后期,雌雄蕊分化期和药隔形成期是冬小麦遭受晚霜冻的低温敏感期,3 次降温可判定冬小麦受到了冻害。若直接使用气象站日最低气温作为监测指标,仅由第 93 天出现的 0℃

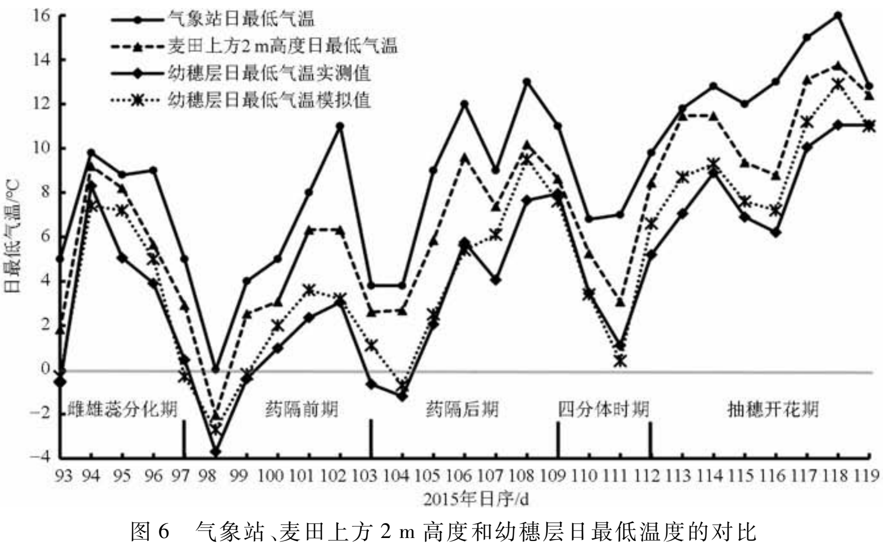

图 6 气象站、麦田上方 2 m 高度和幼穗层日最低温度的对比

Fig. 6 Comparison of daily minimumair temperature of meteorological station, wheat fields at 2 m height, and measured and simulated values within young ear layer

低温则无法判断是否发生霜冻，从后期冻害调查来看，小麦发生了晚霜冻害，单茎中平均有 2.4 个小穗不孕，缺粒数为 4 粒，缺粒率为 14.9%。可见，将气象信息直接用于冻害监测会导致明显误差，而利用 SHAW 模型可提高监测晚霜冻害发生情况的准确率。

2.2　SHAW 模型在晚霜冻害上的应用分析

2013 年是商丘冬小麦发生晚霜冻害的典型年份，其中 4 月 7 日、4 月 10 日和 4 月 21 日的 3 次降温过程对当地冬小麦造成了极大伤害，时至冬小麦发育到孕穗期和抽穗期间[29]。结合 2013 年商丘 8 个气象站的气象数据和基本土壤数据，进一步验证 SHAW 模型在晚霜冻害监测上的可行性和有效性。由于缺乏 2013 年实测的农田 2 m 高度气象数据，因此依据 2015 年农田实测 2 m 气温数据与气象观测站气温数据建立相关方程，结果如图 7 所示。

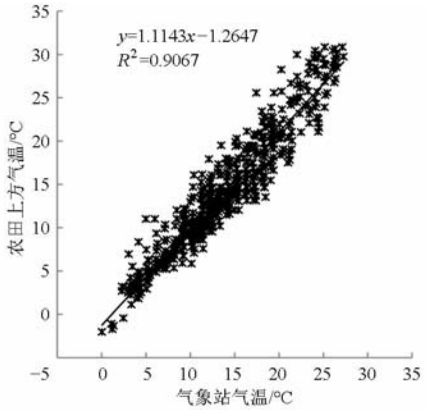

图 7　气象站和农田上方 2 m 高度气温的相关性分析

Fig. 7　Correlation analysis of air temperatures from meteorological station and wheat fields at 2 m height

以 2013 年气象数据驱动模型，记为 SHAW Ⅰ模拟；以 2013 年气象数据经上述相关方程 $y = 1.1143x - 1.2647$（x 代表气象站每小时气温，℃）转换为农田 2 m 高度的气象数据驱动模型，记为 SHAW Ⅱ模拟。

表 4 为商丘各县区气象站和两种 SHAW 模拟结果在 3 次低温霜冻日的日最低气温对比。气象站数据显示 4 月 7 日和 10 日，仅虞城气温低于 0℃，4 月 21 日，睢县、夏邑和虞城气温低于 0℃，其余县区气温均大于 0℃；SHAW Ⅰ模拟中，4 月 7 日气温低于 0℃的有夏邑和虞城，4 月 10 日虞城气温低于 0℃，4 月 21 日 8 个县区作物层内气温均低于 0℃；SHAW Ⅱ模拟中，4 月 7 日，宁陵、夏邑、永城和虞城气温低于 0℃，4 月 10 日，民权、夏邑、虞城和柘城出现零下低温，4 月 21 日，同样在 8 个县区作物层内最低气温均小于 0℃，相较于 SHAW Ⅰ模拟，SHAW Ⅱ模拟的日最低气温更低。

表 4　商丘各县区气象站和两种 SHAW 模拟结果在 3 次低温霜冻日的日最低气温

Tab. 4　Daily minimum air temperature from meteorological station and two SHAW simulation results in three frost dates of Shangqiu City　　℃

日期		民权	宁陵	商丘	睢县	夏邑	永城	虞城	柘城
4 月 7 日	气象站	4.2	5.2	4.7	3.7	1.5	4.7	−0.1	5.1
	SHAW 模拟Ⅰ	2.1	1.5	3.5	2.1	−0.6	1.9	−1.4	2.6
	SHAW 模拟Ⅱ	0.2	−0.5	1.5	0.2	−2.5	−0.1	−3.2	0.6
4 月 10 日	气象站	5.3	5.7	6.2	4.7	3.2	5.4	0	3.4
	SHAW 模拟Ⅰ	1.8	3.2	3.5	3.3	0.6	2.2	−1.6	1.4
	SHAW 模拟Ⅱ	−0.2	1.2	1.5	1.3	−1.3	0.2	−3.4	−0.5
4 月 21 日	气象站	0.7	1.0	0.3	−0.5	−0.4	4.8	−0.7	0.7
	SHAW 模拟Ⅰ	−2.9	−2.8	−3.0	−3.7	−3.7	−0.2	−3.8	−2.9
	SHAW 模拟Ⅱ	−4.7	−4.6	−4.8	−5.5	−5.5	−2.2	−5.6	−4.7

商丘冬小麦拔节开始日期平均在 3 月 20 日左右，拔节后随着生育进程的推进，小麦的抗寒性不断下降。因此根据已有研究选取日最低气温和拔节后天数作为监测指标判断冬小麦冻害程度，如表 5 所示[30]。

表 5　冬小麦拔节期晚霜冻害气象指标

Tab. 5　Meteorological assessment indicator of late frost injury level of winter wheat　　℃

霜冻程度	霜冻指标	拔节期后天数			
		1～5 d	6～11 d	11～15 d	16 d 以后
轻霜冻	日最低气温	−2.0～−1.0	−1.0～0	−0.5～0.5	0～1.0
中霜冻	日最低气温	−4.0～−2.0	−1.0～−2.5	0.5～−1.0	0～−0.5
重霜冻	日最低气温	−5.0～−4.0	−3.5～−2.5	−1.0～−2.0	−0.5～−1.0

根据日最低气温和拔节后天数确定 2013 年 3 次低温日的晚霜冻害等级（图 8），发现采用气象站日最低气温作为指标，4 月 7 日和 10 日仅虞城发生中霜冻和轻霜冻，4 月 21 日民权、宁陵、商丘和柘城

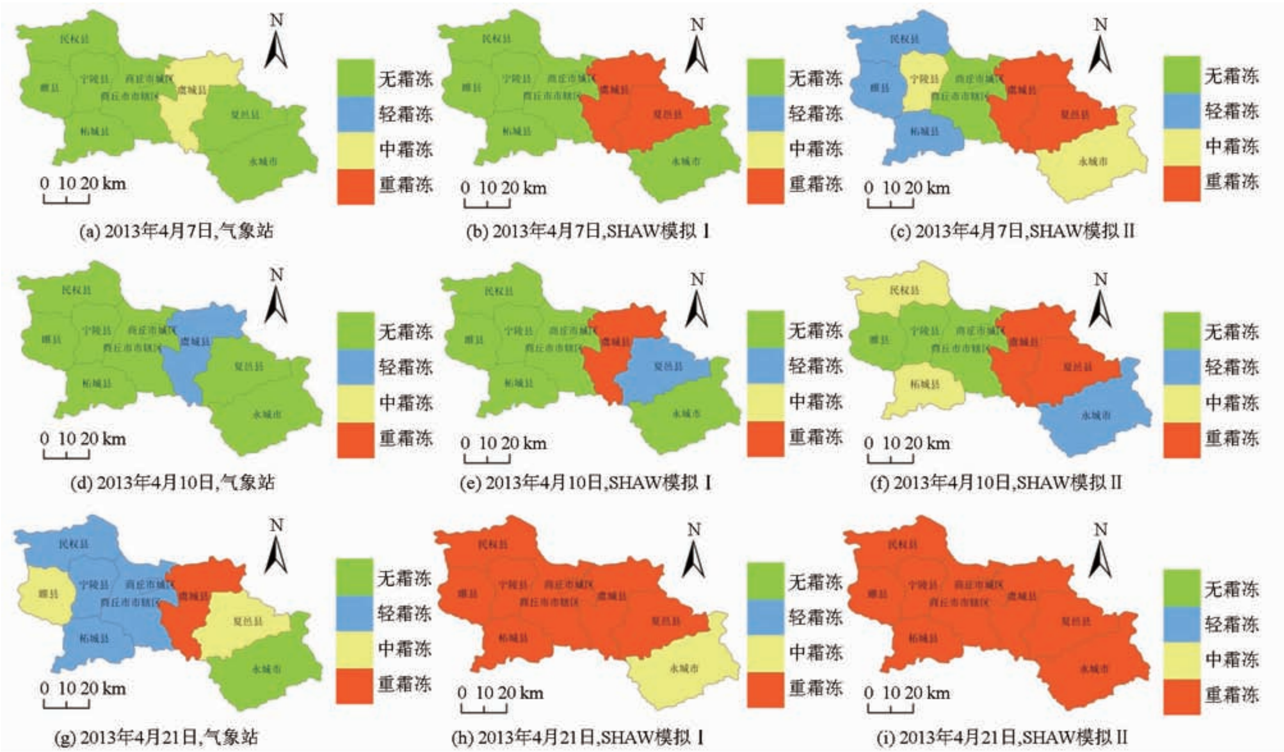

图 8 商丘市各县区冬小麦晚霜冻害等级图

Fig. 8 Late frost injury level maps of Shangqiu City

发生轻霜冻,睢县和夏邑发生中霜冻,虞城发生重霜冻,永城则未发生霜冻。SHAW Ⅰ模拟的冻害结果为:4 月 7 日和 10 日,夏邑发生重霜冻和轻霜冻,虞城均发生重霜冻,4 月 21 日除永城发生中霜冻外,其余县区均为重霜冻。SHAW Ⅱ模拟得出的霜冻等级普遍高于模拟Ⅰ,4 月 7 日除商丘外,其余各县均发生不同程度霜冻害,4 月 10 日,除宁陵、商丘和睢县外,其余 5 县区均发生霜冻害,4 月 21 日,8 个县区均发生重霜冻。

4 月 7 日和 10 日冬小麦处于药隔时期或四分体时期,可以用后期的青穗率和残穗率来表达其在此阶段的受冻程度。青穗是小麦受冻后产生的小分蘖,青穗越多,表明冻死的穗或茎数越多,残穗则是受冻后完全被冻死且不能恢复的穗。4 月 21 日冬小麦处于籽粒形成的关键时期,小麦受冻后会导致明显的缺粒现象,可以用平均穗粒数减少率来表达此阶段的受冻程度。2013 年商丘 50 个样点的田间晚霜冻害调查显示,该年各县区均出现较为严重的晚霜冻害,麦穗出现不同程度的受冻症状,受冻群体比例较大。4 月 7 日和 10 日的降温导致夏邑、虞城、柘城的青穗率分别达到 25%、28%、20%,而宁陵、商丘、睢县、永城的青穗率虽相对较低,但残穗率分别达到 40.6%、27.2%、17.7%、28.6%。4 月 21 日的降温则导致麦穗缺粒现象明显,宁陵、商丘、睢县、夏邑、永城、虞城、柘城地区残穗的平均穗粒数减少率分别为 44.0%、39.6%、48.6%、40.6%、19.4%、50.8%、38.9%。

依据田间晚霜冻调查结果,结合图 8,可以看出,3 种方法得到的霜冻等级并不一致,其中气象站气温作为指标得到的霜冻等级过轻,SHAW Ⅱ模拟方法确定的霜冻等级准确性优于 SHAW Ⅰ模拟方法。可见,在缺乏实测 2 m 高度气象数据代入 SHAW 模型的情况下,相较于气象站和 SHAW Ⅰ模拟的结果,利用 SHAW Ⅱ模拟方法获取幼穗的环境气温所确定的晚霜冻等级与实际情况更加符合,对监测晚霜冻害的发生情况和冻害程度更加准确有效。

3 讨论

在已有的冬小麦晚霜冻害监测方法中,气象站日最低气温由于获取方便,常用做判断晚霜冻害是否发生及其发生程度的指标,然而该指标具有一定的局限性,一是气象站所测气温通常大于幼穗的环境气温,当麦田已经发生冻害时,气象站气温可能还处于 0℃以上;二是即便气象站气温降至 0℃以下,由于农田小气候的差异,幼穗的环境气温无法准确进行推断,且当温度降到 0℃以下时,植物体细胞液并不马上结冰,而是保持过冷却状态,当温度继续下降至某一值时才开始结冰。本文引入机理性 SHAW 模型模拟幼穗的环境气温作为晚霜冻害的监测指标,可提高对霜冻发生情况及程度的监测准确率,主要是因为作物层内气温不仅受到大气候的影响,更

与作物群体结构、植株间的光能分布、空气温湿度、风速、土壤温湿度密切相关，而上述各类影响因子在模型中均有着明确的数学表达，此外模型以小时为步长进行模拟，不仅可以模拟幼穗所处环境的极端低温，同时也可以获取低温的持续时间，这对于晚霜冻害的监测也十分重要，因为晚霜冻害的发生可能由极端低温造成，也可能由持续低温造成。因此，将 SHAW 模型应用于冬小麦晚霜冻害监测中是适用可行的。

晚霜冻害发生时，空气温度是最重要的致灾因子，湿度对致灾程度也有较大影响。若空气湿度较高，水汽呈饱和状态凝结为冰晶，产生白霜；若湿度较低，水汽达不到饱和，无法凝结以潜热释放，但小麦反而受冻更重，称为黑霜[31]。本研究主要从空气温度角度探讨 SHAW 模型在冬小麦晚霜冻害监测上的适用性，在后续研究中，可加入空气湿度因素，以更好地反映冬小麦受冻程度。SHAW 模型为单点模拟，后续研究可考虑将驱动数据和输入参数进行区域化后扩展为区域模拟，基于 GIS 的空间插值算法对气象站常规观测数据进行插值或基于遥感观测数据反演方法获得面上模型所需的驱动数据，将 SHAW 模型应用到冬小麦晚霜冻害的区域监测中。

4　结论

（1）SHAW 模型在冬小麦晚霜冻敏感期幼穗层气温模拟整体效果较好，所模拟幼穗层 20 ~ 60 cm 高度中，平均 44.7% 的模拟误差在 1℃ 以内，72.5% 模拟误差控制在 2℃ 以内，模型在夜晚的模拟情况整体优于白天。结合 2015 年试验田的冻害调查数据，利用 SHAW 模型模拟出的幼穗层气温比气象站气温更适合作为晚霜冻害监测指标，提高了监测晚霜冻害发生情况的准确率。

（2）由于每日的空气湿度、风速风向、云量和作物层结构等的差异，在日最低气温的观测中，气象站观测值最高，农田上方 2 m 高度处观测值次之，幼穗层观测值最低，且上述参量差值间的差异性较大。结合 SHAW 模型、2013 年商丘 8 个县区的气象站气象数据和田间冻害调查数据，气象站日最低气温作为监测指标得到的霜冻等级过轻，与实际情况并不符合，相较于直接将气象站气象数据代入 SHAW 模型的模拟方法，利用气象站气象数据转换为农田 2 m 高度气象数据后代入 SHAW 模型模拟的幼穗层日最低气温所确定的晚霜冻等级与实际情况更加符合。因此，当缺乏实测的幼穗层气温或农田 2 m 高度的气象数据时，选择将气象站数据转换为农田 2 m 高度的气象数据后代入 SHAW 模型获取幼穗层气温是一种较好的替代方法。

（3）模型在冬小麦晚霜冻敏感期和低温时对幼穗层气温模拟较好，且能很好地模拟低温持续时间，模拟的日最低气温作为晚霜冻害监测指标所确定的晚霜冻等级与实际冻害调查数据较为吻合，因此将 SHAW 模型应用于冬小麦晚霜冻害监测是可行且适用的，与传统晚霜冻害监测方法相比具有较大优势。

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