Prediction of the Natural Environmental High Temperature Influences on Mid-Season Rice Seed Setting Rate in the Middle-Lower Yangtze River Valley

Shouli Xuan, Chunlin Shi, Yang Liu, Yanhua Zhao, Wenyu Zhang, Hongxin Cao, Changying Xue

Prediction of the Natural Environmental High Temperature Influences on Mid-Season Rice Seed Setting Rate in the Middle-Lower Yangtze River Valley

Shouli Xuan[2,a], Chunlin Shi[2,b,*], Yang Liu[2,c], Yanhua Zhao[3,d], Wenyu Zhang[2,e], Hongxin Cao[2,f], Changying Xue [1,g]

[1] CMA·Henan Key Laboratory of Agrometeorological Support and Applied Technique, Zhengzhou 450003, China; [2] Institute of Agricultural Economics and Information, Jiangsu Academy of Agricultural Sciences, Nanjing 210014, China; [3]Suqian Meteorological Bureau, Suqian 223800, China

[a]shirleyxuan2008@hotmail.com, [b]shicl@jaas.ac.cn, [c]senslover@yeah.net, [d]664552404@qq.com, [e]research@wwery.cn, [f]caohongxin2003@yahoo.com.cn, [g]xuecy9@163.com

Abstract. The impact of high temperature on rice yield has been evaluated by using simulation models or conducting experiments with controlled high temperature and sowing times. In this paper, observed daily maximum temperature data at 6 representative stations in the Middle-Lower Yangtze River Valley (MLYRV) from 1984 to 2013 was analyzed to examine the daily relationship between rice seed setting rate (RSSR) and the maximum temperature by using data from the mid-season late-maturing indica rice variety regional experiments conducted in field conditions at the same representative stations from 2004 to 2011 (totally using 615 samples and 69 rice varieties). The results indicated that RSSR appears to be sensitive to high temperature from 36 days before full heading to 4 days before full heading (with the significance of the negative correlation between RSSR and maximum temperature in this period above 99% confidence level) and the most sensitive at about 14 days before full heading (near the meiosis phase), indicating that for the mid-season late-maturing indica rice variety in the MLYRV, more attention should be paid to the high temperature damage at the meiosis stage. According to the extracted high temperature sensitive period, statistical forecast models were established to predict the regional rice high temperature damage in the MLYRV by using atmospheric circulation indices in preceding 12 months with a correlation coefficient between the predicted and observed heat stress index of 0.95 and a normalized root mean square error (*NRMSE*) of 28.4%. In addition, a high temperature-induced rice sterility simulation model was also used to quantitatively forecast the meiosis phase high temperature influence on rice at the site scale. The *NRMSE* of the simulated and forecasted relative seed setting rate was 4.74% and 2.84%, respectively. In conclusion, the presented prediction models were useful to improve the rice high temperature damage forecast and were expected to be helpful to rice high temperature disaster prevention and reduction in the MLYRV.

Keywords: Middle-Lower Yangtze River Valley; mid-season rice; high temperature; seed setting rate; statistical forecast model

1 Introduction

Global average temperature has increased by 0.74℃ in 1906-2005 and is projected to continue to increase [1]. The projected climate change is recognized to increase extremely high temperatures events [2-5]. China is one of the world's most productive rice regions, contributing ~27.5% of the world rice production [6]. The Middle-Lower Yangtze River Valley (MLYRV) is an important rice producing areas in China. Under the background of climate warming, high temperature stress imposes an increasing risk to rice production and becomes one of the major constrains in increasing productivity of rice in the MLYRV [7-11].

High temperature influence on rice has been studied in many researches [12-15]. It has been pointed out that the heat stress damage mainly occurs in the reproductive period of rice. In previous studies, high temperature effect on rice yields were mainly investigated by using model simulations or control experiments [16-21]. Several studies have paid attention to effects of observed climate on rice [22-24]. For example, Zhao et al. analyzed the effects of observed mean maximum temperature at the stages of flowering and pre-milk on rice components in 1981-2003 [25]. These studies mainly concentrated on the growing-season mean or development stage mean (mostly flowering stage and filling stage) influence of high temperature on rice. Actually, the impact of high temperature largely differed with the local climate, land suitability, cultivated rice variety and time of sowing and harvesting et al. However, the critical period of rice damage caused by natural environmental high temperature in actual rice production is still not clear.

In this study, we tried to identify the most sensitive stage of mid-season RSSR to high temperature in the MLYRV in field conditions. Based on the extracted key sensitive period, the influence of high temperature on rice in the MLYRV was predicted by using the statistical forecast models and the high temperature-induced rice sterility simulation model.

2 Data and Methods

2.1 Data

This study was based on the rice data (including growth period and seed setting rate) at 6 stations (Yichang, Yueyang, Hefei, Nanchang, Hangzhou, Yangzhou) in the MLYRV from 2004 to 2011, which were obtained from the national regional yield trial of southern China (totally using 615 samples and 69 mid-season late-maturing indica rice varieties). The daily maximum temperature data and the monthly 74 circulation indices in 1984-2013 from the Chinese Meteorological Administration were also used.

2.2 Methods

2.2.1 Definition of the heat stress index

In previous studies, the high temperature effects on rice were often investigated by using meteorological indices which were usually defined as the days of daily mean temperature > 30℃ or days of daily maximum temperature > 35℃ [26-28]. In the present study, the heat stress index (I_{hs}) calculated for the high temperature influence assessment was based on the work of Teixeira et al. [29]. It was assumed that (1) rice crop are only sensitive to high temperature during thermal sensitive period (*TSP*, days); (2) heat damage occurs when maximum temperature (T_{max}) exceeds the critical temperature threshold (T_{crit}); and maximum effect occurs when T_{max} exceeds the limit temperature threshold (T_{lim}). To calculate I_{hs}, "daily" high temperature stress intensity (I_{hsd}) is firstly estimated as a function of T_{max} (Eq.(1)).

$$I_{hsd} = \begin{cases} 0.0 & T_{\max} < T_{crit} \\ \dfrac{T_{\max} - T_{crit}}{T_{\lim} - T_{crit}} & T_{crit} \le T_{\max} < T_{\lim} \\ 1.0 & T_{\max} \ge T_{\lim} \end{cases} \quad (1)$$

The value of T_{crit} and T_{lim} used in this study is 35℃ and 45℃ respectively. The daily values of I_{hsd} are then accumulated and averaged throughout the *TSP* (Eq.(2)).

$$I_{hs} = \frac{\sum_{i=1}^{TSP} I_{hsd}}{TSP} \quad (2)$$

The period from July 11 to August 12 is chosen as the thermal-sensitive period in this paper.

2.2.2 Validation of the forecast model

The normalized root mean square error (*NRMSE*) was used to evaluate the predictive ability of the statistical forecast models.

$$NRMSE = \frac{\sqrt{\sum_{i=1}^{n} (Y_i - X_i)^2 / n}}{\overline{X}} \times 100\% \quad (3)$$

where Y_i is the forecasted value, X_i the observed value, n the number of observations, and $\overline{X}$ is the mean of all observed values.

3 Results

3.1 Daily Variation Characteristics of the Maximum Temperature

In order to investigate the daily variation characteristic of the maximum temperature in significant growth stages of rice, averaged daily maximum temperatures (mean of 615 samples) were calculated near the full heading phase. For example, for the full heading day, the averaged maximum temperature was calculated as the mean of maximum temperatures in all the full heading days in 615 samples. As shown in Fig.1, for the mid-season rice variety in MLYRV, persistent high temperature mainly occurred in the month before full heading (according to the standard of 33℃). After the full heading stage, there was a consistent decrease in the averaged maximum temperature. Thus, the persistent high temperature occurred concomitantly with the booting and heading stages, resulting in serious loss and harm to rice production in this region.

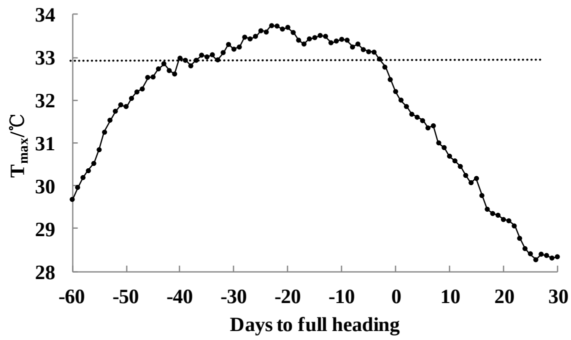

Fig.1. Daily variation of the T_{max}

3.2 High Temperature Effects on RSSR

To indentify the sensitive stage of RSSR to high temperature in the MLYRV, daily relationships between maximum temperature (5-day running means) and RSSR before and after full heading day were calculated. As shown in Fig.2, the RSSR is sensitive to T_{max} in the period of 4-36 days before full heading, corresponding to the averaged date from July 11 to August 12. Obviously, the high temperature at about 14 days before full heading had the most significant impact on RSSR. However, the RSSR seemed to be not closely related to the high temperature at the full heading day. A possible reason might be due to the lower maximum temperature at the full heading day (32.2℃， see Fig.1). After the full heading day, the maximum temperature did not have any influence on RSSR. Therefore, for the mid-season rice variety in MLYRV, more attention should be paid to the heat damage around 2 weeks before full heading.

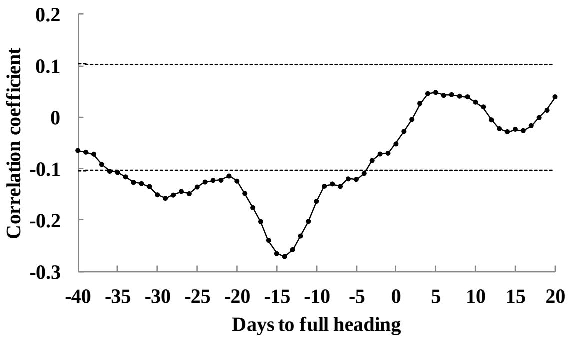

Fig.2. Daily correlation between RSSR and T_{max} (5-day running means)（dashed indicate significance at 99% confidence level）

The relationship between RSSR and averaged maximum temperature in 4-36 days before full heading in 2004-2011 was further investigated in Fig.3. The results indicated that RSSR was decreased significantly with increasing maximum temperature in the sensitive period (4-36 days before full heading). The correlation coefficient between regional averaged RSSR and averaged maximum temperature in 4-36 days before full heading during 2004-2011 was -0.9 (significance above 99.9% confidence level). It was found that all the years with the averaged T_{max} larger (less) 33℃ exhibited below (above) 80% RSSR in the MLYRV. Especially for the year 2004, the MLYRV suffered from a severe heat wave in summer. In this year, the averaged maximum temperature in 4-36 days before full heading day reached above 34℃ with the RSSR of 76%.

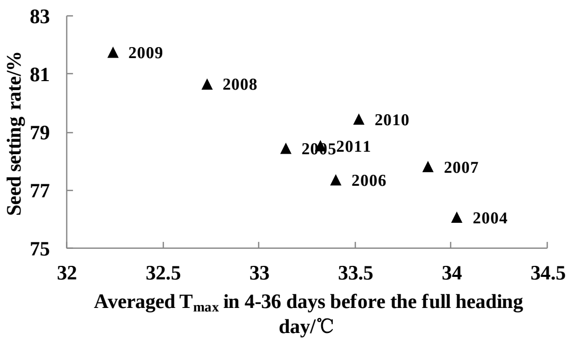

Fig.3. The relationship between RSSR and averaged T_{max} in 4-36 days before full heading

3.3 Statistical Forecast Models of I_{hs}

As discussed above, the prediction of high temperature influence on rice with several months lead time is valuable to the rice production in the MLYRV, where the higher than normal summertime temperature will directly cause decreases in rice yield. To further predict the impacts of high temperature on mid-season rice in MLYRV, a rice heat stress index (I_{hs}) was calculated by using *TSP* as the extracted sensitive period (from July 11 to August 12) and statistical models were presented for predicting the high temperature stress on rice in this section.

Presented in Fig.4 was the inter-annual variation of the I_{hs} in the extracted sensitive period of the mid-season rice in the MLYRV (solid line). It can be seen that the I_{hs} showed a significant ability to describe the rice heat-stress events occurred in the MLYRV (such as the year 2003 and 2013). As is known, local climate variability mainly depends on the large scale atmospheric circulations. Therefore, the correlation coefficients between the rice heat stress index in the MLYRV and 74 circulation indices in preceding 12 months (January to June in current year and July to December in last year) was examined to identify key preceding predictors of the I_{hs}. Statistical prediction models for the I_{hs} in the MLYRV were then constructed by using a multi-linear stepwise regression method based on the extracted predictors. We applied year-by-year validation to further verify the prediction models. The year-by-year validation was applied by establishing prediction models using circulation indices in preceding 20 years to forecast the I_{hs} in the following year (for example, using circulation indices in 1984-2003 to establish the forecast model and predict the I_{hs} in 2004; using circulation indices in 1985-2004 to establish the forecast model and predict the I_{hs} in 2005; ……; using circulation indices in 1993-2012 to establish the forecast model and predict the I_{hs} in 2013). The year-by-year validation method was used because it was closer to the approach in actual forecasting. Results of the year-by-year validation test during 2004-2013 (Fig.4) demonstrated that the constructed prediction models shown good predictive abilities for forecasting the I_{hs} in the MLYRV with the correlation between the predicted and observed I_{hs} of 0.95 (significance above 99.9% confidence level) and the *NRMSE* of 28.4%.

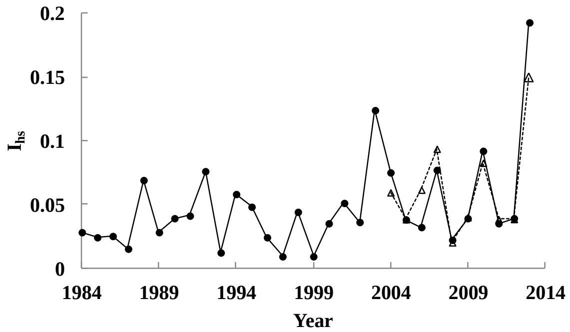

Fig.4. The observed (solid) and forecasted (dashed) I_{hs} values in the MLYRV

3.4 Quantitative Forecast Model of High Temperature Effects on Rice

The heat stress in the MLYRV could be well forecasted with several months lead time by using the presented statistical models. However, the application of large area averaged prediction information was quite limited in production decisions. Therefore, a simulation model of high temperature induced rice sterility at a meiosis phase was used to predict the relative RSSR in MLYRV at the site scale.

According to the research of Shi et al. [30], the daily RSSR could be expressed in terms of temperature in meiosis phase with a quadratic equation:

$$Y_i = 1 - c \cdot (T_i - T_C)^2 \quad (4)$$

where Y_i is the daily relative RSSR, T_i is the daily T_{max}, c and T_C are variety parameters. The relative RSSR decreases when the maximum temperature in the meiosis stage is higher than T_C. Because of the varied daily maximum temperature in actual production, the total influence of high temperature on relative RSSR is expressed in the product of daily relative RSSR:

$$Y = \prod_{i=t0}^{t1} Y_i \quad (5)$$

where Y is the total influence of high temperature during meiosis phase on relative RSSR, *t0* and *t1* is the starting and ending time of the meiosis phase, respectively.

In the present study, the year 2009 without heat stress was set as the CK year. The observed rice relative RSSR was defined as rRSSR(i)/rRSSR(2009) ×100%, where rRSSR(i) and rRSSR(2009) is the relative RSSR in forecast year and in 2009, respectively. As shown in Fig.3, the MLYRV experienced significantly high temperature stress in the year 2004 and 2007. Therefore, the rice data in 2004 and 2007 was used to calibrate and validate the model, respectively. The daily T_{max} in crucial high temperature sensitive stage (7-19 days before full heading, see Fig.2) were used to run the high temperature-induced rice sterility simulation model and trail-and-error method was adopted to calibrate the parameters. The result of calibration showed that for the mid-season rice in the MLYRV, the value of parameter c and T_C is 0.000246 and 30.6℃, respectively. Fig.5 presented the simulation and prediction results of the high temperature-induced rice sterility simulation model (observed RSSR is the average of 69 rice varieties). Because of the missing data in Nanchang (2004 and 2009) and Yangzhou (2007), we actually used 5 samples in 2004 and 4 samples in 2007. The results shown that the high temperature-induced rice sterility simulation model accurately simulated the relative RSSR in 2004 with a NRMSE of 4.74% and forecasted the relative RSSR in 2007 with a NRMSE of 2.84% (the correlation coefficient between the predicted and observed relative RSSR in 2007 reached 0.96 with the significance above 95% confidence level), indicating the good predictive skill of the high temperature-induced rice sterility simulation model in the MLYRV.

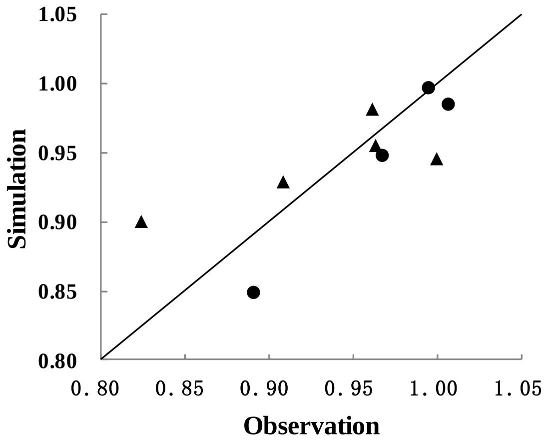

Fig.5. The simulated (2004, triangle) and forecasted (2007, circle) results of the relative RSSR

4 Conclusions

Previous studies have found that rice plant was the most sensitive to high temperature at heading time. In this study, daily relationship between RSSR and temperature was investigated by using observed daily maximum temperature data at 6 representative stations in the MLYRV. Our results indicated that for the mid-season rice in the MLYRV, years with the maximum temperature in meiosis stage of rice above than normal may experience significant yield losses in the MLYRV. The results in the present study reinforced the need to plan adaptive strategies for rice production with regard to heat stress in the meiosis phase of mid-season rice in the MLYRV. Based on the revealed high temperature sensitive period, high temperature-induced rice sterility simulation model and statistical models were established to forecast rice heat stress in MLYRV. The results of validation tests further illustrated the good prediction ability of the constructed forecast models.

Acknowledgment

Funds for this study was provided by the National Natural Science Fund (31401279), the CMA/Henan Key Laboratory of Agro-meteorological Support and Applied Technique (AMF201201), the Jiangsu Agriculture Science and Technology Innovation Fund (CX(12)5059), the China Meteorological Administration Special Public Welfare Research Fund (GYHY201306035), the China Agricultural Administration Special Public Welfare Research Fund (201203032), and the Jiangsu Province Science and Technology Support Program (BE2012391).

References

[1] IPCC. Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change[M]. Cambridge: UK: Cambridge University Press, 2007.

[2] Wheeler T R, Craufurd P Q, Ellis R H et al. Temperature variability and the yield of annual crops[J]. Agriculture, Ecosystems and Environment, 2000, 82: 159-167.

[3] Tao Fulu, Hayashi Yousay, Zhang Zhao et al. Global warming, rice production, and water use in China: developing a probabilistic assessment[J]. Agricultural and Forest Meteorology, 2008, 148(1): 94-110.

[4] Lu Peiling, Yu Qiang, Wang Enli et al. Effects of climatic variation and warming on rice development across South China[J]. Climate Research, 2008, 36: 79-88.

[5] Zhang Tianyi, Zhu Jiang, Wassmann Reiner. Responses of rice yields to recent climate change in China: An empirical assessment based on long-term observations at different spatial scales (1981–2005)[J]. Agricultural and Forest Meteorology, 2010, 150: 1128-1137.

[6] FAO. Food and Agriculture Organization of the United Nations, 2013, http://faostat.fao.org (last visited: 07.07.2015).

[7] Zheng Jianchu, Sheng Jing, Tang Risheng et al. Regularity of high temperature and its effects on pollen vigor and seed setting rate of rice in Nanjing and Anqing[J]. Jiangsu Journal of Agricultural Sciences, 2007, 23(1): 1-4 (in Chinese)

[8] Ma Xiaoqun, Xu Ying, Zhao Haiyan. Impacts of maximum or minimum temperature on yield and yield components of single-season Indica rice in Yangtze-Huaihe area[J]. Geographical Research, 2008, 27(3): 603-612 (in Chinese)

[9] Tian Xiaohai, Luo Haiwei, Zhou Hengduo et al. Research on heat stress of rice in China: progress and prospect[J]. Chinese Agricultural Science Bulletin, 2009, 25(22): 166-168 (in Chinese)

[10] Jiang Min, Jin Zhiqing, Shi Chunlin et al. Occurrence patterns of high temperature at booting and flowering stages of rice in the middle and lower reaches of Yangtze River and their impacts on rice yield[J]. Chinese Journal of Ecology 2010, 29(4): 649-656(in Chinese)

[11] Xie Zhiqing, Du Yin, Gao Ping et al. Impact of high-temperature on single cropping rice over Yangtze-Huaihe river valley and response measures[J]. Meteorological Monthly, 2013, 39(6): 774-781 (in Chinese)

[12] Satake T, Yoshida S. High temperature-induced sterility in Indica Rices at flowering[J]. Japanese Journal of Crop Science, 1978, 47(1): 6-17.

[13] Matsui T, Omasa K, Horie T. High temperature-induced spikelet sterility of japonica rice at flowering in relation to air temperature, humidity and wind velocity conditions[J]. Japanese Journal of Crop Science, 1997, 66(3): 449-455.

[14] Matsui T, Omasa K, Horie T. The difference in sterility due to high temperatures during the flowering period among Janonica-rice varieties[J]. Plant Production Science 2001, 4(2): 90-93.

[15] Kim J, Shon J, Lee C K et al. Relationship between grain filling duration and leaf senescence of temperate rice under high temperature[J]. Field Crops Research, 2011, 122(3): 207-213.

[16] Lin Erda, Xiong Wei, Ju Hui et al. Climate change impacts on crop yield and quality with CO_2 fertilization in China[J]. Philosophical Transactions of the Royal Society of London B, 2005, 360(1463): 2149-2154.

[17] Krishnan P, Swain D K, Bhaskar B C et al. Impact of elevated CO_2 and temperature on rice yield and methods of adaptation as evaluated by crop simulation studies[J]. Agriculture Ecosystems & Environment, 2007, 122(2): 233-242.

[18] Liu Weichang, Zhang Xuefen, Yu Weidong et al. Assessment method study on high temperature damage to rice[J]. Meteorological and Environmental Sciences, 2009, 32(1):

33-38 (in Chinese)
[19] Zhang Qian, Zhao Yanxia, Wang Chunyi. Study on the impact of high temperature damage to rice in the lower and middle reaches of the Yangtze river[J]. Journal of Catastrophology, 2011, 26(4): 57-62(in Chinese)
[20] Jagadish S V K, Craufurd P Q, Wheeler T R. High temperature stress and spikelet fertility in rice[J]. Journal of Experimental Botany, 2007, 58(7): 1627-1635.
[21] Shi Chunlin, Jin Zhiqing, Tang Risheng et al. A model to simulate high temperature-induced sterility of rice[J]. Chinese Journal of Rice Science, 2007, 21(2): 220-222(in Chinese)
[22] Tao Longxing, Tan Huijuan, Wang Xi et al. Effects of high temperature stress on super hybrid rice Guodao 6 during flowering and filling phases[J]. Chinese Journal of Rice Science, 2007, 21(5): 518-524(in Chinese)
[23] Tong Zhiting, Li Shouhua, Duan Weixin et al. Temperature-driven climatic factors and their impact on the fertility of hybrid rice at anthesis[J]. Chinese Journal of Eco-Agriculture, 2008, 16(5): 1163-1166 (in Chinese)
[24] Peng S, Huang J, Sheehy J E et al. Rice yields decline with higher night temperature from global warming[J]. Proceedings of the National Academy of Sciences of the United States of America, 2004, 101(27): 9971-9975.
[25] Zhao Haiyan, Yao Fengmei, Zhang Y et al. Correlation analysis of rice seed setting rate and weight of 1000-Grain and agro-meteorology over the middle and lower reaches of the Yangtze river[J]. Scientia Agricultura Sinica, 2006, 39(9): 1765-1771(in Chinese)
[26] Yao Fengmei, Zhang Jiahua. Change of relative extreme high temperature events and climate risk in rice growing period in China from 1981 to 2000[J]. Journal of Natural Disasters, 2009, 18(4): 37-42 (in Chinese)
[27] Ren Yifang, Gao Ping, Wang Chunyi. High temperature damage to paddy rice in Jiangsu Province and its cause analysis[J]. Journal of Natural Disasters, 2010, 19(5): 101-107(in Chinese)
[28] Xie Xiaojin, Li Bingbai, Wang Lin et al. Spatial and temporal distribution of high temperature and strategies to rice florescence harm in the lower-middle reaches of Yangtze river[J]. Chinese Journal of Agrometeorology, 2010, 31(1): 144-150 (in Chinese)
[29] Teixeira E I, Fischer G, van Velthuizen H et al. Global hot-spots of heat stress on agricultural crops due to climate change[J]. Agricultural and Forest Meteorology, 2013, 170: 206-215.
[30] Shi Chunlin, Jin Zhiqing, Zheng Jianchu et al. Quantitative analysis on the effects of high temperature at meiosis stage on seed-setting rate of rice florets[J]. Acta Agronomica Sinica, 2008, 34(4): 627-631 (in Chinese)