*Pak. J. Bot.*, 48(6): 2359-2366, 2016.

# RELATIONSHIPS BETWEEN THE CLIMATE CHANGE AND THE GRAIN FILLING OF WINTER WHEAT

ZHAOTANG SHANG[1,2], SHUN SHANG[3], JIAN YU[4], JING WU[5] AND DONG JIANG[1*]

[1]*College of Agriculture, Nanjing Agricultural University, Nanjing 210095, China*
[2]*Jiangsu Meteorological Bureau, Nanjing 210009, China*
[3]*National Marine Environment Forecasting Center, Beijing100081, China*
[4]*Haian county Meteorological Bureau, Haian 226600, China*
[5]*College of marinesclences, Shanghai Ocean University, Shanghai 201300, China*
[*]*Corresponding author's email: dongjiangdc@163.com; Tel./Fax：+86 25 86452323*

**Abstract**

The present study is based on the material in a grain filling rate experiment of winter wheat and hourly weather data organised by Xinghua city of Jiangsu Province. The aims are to objectively evaluate the possible influences of the temperature, precipitation, sunshine at the different time of the same day on the grain filling rate of winter wheat. The grain filling rate evaluation model of climate change is firstly developed, and then, the model calculation results are compared with the observed data. The along the changes of the microclimate, changes of the grain filling rate of winter wheat, which is not same in the gradual, rapid and slow increase stages. The changes in grain filling rate of winter wheat, which were caused by variations of temperature, precipitation and sunshine duration, showed periodic fluctuation. Variation in temperature resulted in 1.36 $g{\cdot}d^{-1}{\cdot}(10a)^{-1}$ of grain filling rate change; variation in precipitation resulted in −1.35 $g{\cdot}d^{-1}{\cdot}(10a)^{-1}$ of grain filling rate change; and variation in sunshine duration resulted in 0.07 $g{\cdot}d^{-1}{\cdot}(10a)^{-1}$ of grain filling rate change. Three samples showed a grain filling rate change of 0.08 $g{\cdot}d^{-1}{\cdot}(10a)^{-1}$. These findings indicate that the increase in temperature and sunshine duration caused the elevation of grain filling rate, whereas the increase in precipitation decreased the grain filling rate. Therefore, monitoring and predication capability of Meteorological disasters, such as drought caused by high temperature, should be strengthened to ensure the favourable weather condition and improve the grain filling rate through scientific methods such as artificial precipitation.

**Key words:** Microclimate; Grain filling rate; Precipitation; Sunshine duration.

## Introduction

Climate change has caused the attention of people from all over the world (the National Science Board, 2016; Gallup, 2016; European themselves, 2016), the climate warming to make the effect of drought and other weather disasters on agricultural production more complex (Neelin *et al*., 2006; Lu *et al*., 2007; Sheffield *et al*., 2008), causes some key reproductive period of winter wheat growth and development of severe weather is much enhanced (Guo, 2015), cause increased vulnerability to wheat production (Wilkens *et al*., 2001; Lobell *et al*., 2010), easy to form the production (Wilkens *et al*., 2001; Lobell *et al*., 2007), cause increase wheat yield difference between annual, winter wheat yield affected by climate change degree to be one of the hot topics of attention (Song *et al.*, 2016).Filling stage is to determine the effective panicles, per panicle and grain of the important stage, decided to production elements directly, affect the yield and quality (Asseng *et al*., 2004; Chen *et al*., 2014).Winter wheat grouting rate with the highest temperature, daily range, sunshine time and total radiation were positively correlated, and negatively correlated with precipitation and relative humidity. Filling stage high temperature make wheat physiological activity is restrained, winter wheat grouting rate and filling duration so that the grain weight decreased, weak light stress influence on dry matter production of wheat, the drought affected wheat grouting rate. Therefore, study the effect of agricultural climate resources change on grouting rate become people to study agricultural climate resources change one of the important content of the effect on winter wheat growth and development.

The grain filling would affect the yield and quality of winter wheat, therefore, the effects of the climate change on the grain filling rate is becoming a hot research topic. The increasing related research about the influence of climate change on winter wheat production has attracted social attention that the climate of the microchange in a day would affect the important development process of winter wheat. The gain filling stage is the key one of winter wheat yield and quality formation (Dai *et al.*, 2016; Dong *et al.*, 2015), and the developmental process of grain filling mainly includes, heredity, environment and cultural practices (Motzot *et al.,* 2010; Cossani *et al.,* 2011; Pireivatlou *et al.,* 2011). The variation of the interannual growth of winter wheat is mainly determined by the environmental conditions, especially the meteorological conditions (Zhang *et al.*, 2015; Wu *et al.*, 2016).

The weather conditions changes to incur changes of the grain filling rate are shown in the following aspects. (1) The possible effect of grain filling rate caused by climate change on temperature change. Zhou *et al.* (2014) analysed the influence of meteorological conditions on the winter wheat grain filling rate; as a result, changes of the winter wheat grain filling rate is correlated with changes of the daily highest temperature, daily range, sunshine duration, total radiation and precipitation. Wheeler *et al.* (1996), Dias & Lidon (2009) and Aochen & Prakash (2011) concluded that changes temperature significantly influences the grain filling rate. Wiejand & Caellar (1981) speculated that the changes of temperature gap significantly influences the grain filling speed. Tan *et al.* (2015) and Fu *et al.* (2015) mentioned in their research that high temperature rises to inhibit wheat physiological activity in the filling stage, whereas the decline of winter wheat grain filling rate and shortening of filling duration reduce grain weight. Stone & Nicolas (1996) found that high temperature rises, that is not only influences grain filling rate but also affects the quality of seeds. (2) The possible effect of grain filling rate caused by climate change on precipitation. Zhang *et al.* (2016) believed that the change on grain filling rate through the adjustment of humidity in the field would cause yield changes on winter wheat. Mouna *et al.* (2012) suggested changes of that precipitation also exerts a certain effect on grain filling speed. Papakosta *et al.* (1991) argued that Precipitation anomalies caused by water logging certainly influences wheat grain filling. Fang *et al.* (2006) analysed the conditions of precipitation, soil moisture and field investigation data in Zhumadian from 1990 to 2005 and found that changes of the wheat drought significantly affects the gain filling rate and shortens the wheat grain filling time. (3) The possible effect of grain filling rate caused by climate change on sunshine. Gu *et al.* (2013) combined the net photosynthetic rate of leaf under weak light and impact factors of leaf area index with general SUCROS model and then calculated the influence of weak-light stress on dry matter production of wheat; they found that during the wheat-filling stage, the total photosynthetic active radiation is below 3.71 MJ $m^{-2}$ and persists for more than 2 days, whereas the net photosynthetic rate of leaf decreases significantly. Yan *et al.* (2011) concluded that the average filling rate is reduced after low-light processing, and the grain filling effect of sunshine duration decreases.

Sun *et al.* (2015) found that the change in climate resources, such as light temperature against the background of climate warming, the changes of the microclimate lead to significantly influences crop growth and production. Shang *et al.* (2015) systematically analysed the variation in meteorological elements over time of winter wheat growth at each stage in Jiangsu province and concluded that the degree of climate change in terms of climate factors can be described as wind>temperature>sunshine duration>rainfall. Climate change mainly occurs during the vegetative period, with relatively small changes, which caused the increase of vulnerability for winter wheat production.

Grain filling period is crucial to winter wheat production and development. Many scholars have conducted numerous studies on grain filling process, grain filling features, adversity and planting methods; and they found that the grain filling process is featured by a ‘slow−rapid−slow’ procedure. Lydat & Bawn (1997) speculated that logistic and Richards equations or ternary orthogonal polynomial can be adopted to fit the grain filling changes over time. For instance, Peng & Xiao (2012) compared the cubic polynomial of wheat grain grain filling process with logistic and Richards equations and found that the simulation effect of Richards equation is relatively ideal. Xue *et al.* (2006) fitted the grain-filling process of wheat dwarf 58 with three equations: logistic, polynomial regression and Richards; they found that Richards equation presents the highest precision, but it is not convenient. Zhao *et al.* (2006) fitted the rhythm of weight change of grain after flowering with logistic equation and found that the grain weight of different winter wheat increases by ‘s’ growth curve: slow growth in the beginning followed by rapid growth and ended with slow increase. Zhu *et al.* (2014) selected 11 representative samples from wheat produced in Henan Province which was updated for 9 times as the test material and found that the wheat grain filling is featured by the ‘s’ growth cure in spite of the wheat varieties at different times. Moreover, the grain-filling speed shows a ‘slow–rapid–slow’ process, and the rapid growth period is crucial to the growth of grain filling.

Li *et al.* (2016) proposed that the key to deal with climate change is to assess the degree of the effects of climate change. Therefore, it is very important to objectively evaluate the variation in meteorological elements caused by climate change which might affect the winter wheat grain filling. So far, the related microclimate studies have been scarcely reported, however, the work should be conducted to deal with the climate changes scientifically. In present study, we conducted numerous tests on field planting grain filling rate in winter wheat planting area of Jiangsu (Lixia river area) in Xinghua agricultural meteorological stations from 1996 to 2014 and emphasised the changes of the microclimate influence on winter wheat grain filling rate, to provide data to establish evaluation model. We also analysed the trend variation caused by climate change to strengthen the cultivation techniques of winter wheat research and provide reference to respond actively toward climate change.

## Material and Methods

**Measuring methods:** The China Meteorological Administration (1993) determined grain filling rate by measuring the grain formation in the mature period of dry matter of grain growth in unit time, and the specific measurement methods are described as follows:

(1) Setting the ear. Flowering period was in section four. Up to 200 ears with similar size and same blossom day were selected and set as the sample for measuring grain filling rate. Each of them was recorded for the date.

(2) Sampling. Samples were collected every 5 days since 10 days after flowering (such as 1, 6 and 11) until maturity. For every collection, 20 ears (5 in each section) were selected as test samples from the strain of stem.

(3) Drying. The sample bag was placed in an oven with a constant temperature. The temperature during the first hour was controlled at 100°C to 105°C and maintained at 70°C to 80°C within 6 h to 12 h of ventilation. The sample bag was turned every 0.5 h to 1 h at the beginning and 1 h to 2 h later to discharge the water in the container.
(4) Weighing. Samples were removed and weighed in a dryer after cooling. Balances of a sensitivity of 0.01 g was used with the unit of g. Average weight values were presented in two decimal places.

**Selection of location for observation:** The test experiment was conducted on the farmer field near the agricultural meteorological station of Xinghua, Jiangsu province from 1996 to 2014. It covers an area of 1.2 $hm^2$ (Unit of hectare). An area of 20 m (Length) × 5 m (Width) with four sections was selected as the experimental observation location in the farmland. The soil fertility was averagely compared with that of the local farmland, and the winter wheat was called Yangfu wheat No. 4, the agricultural technical personnel is responsible for the specific observations to collect the data, which is a local winter wheat breed. Its annual yield was normally 6900 $kg/hm^2$.

**Meteorological data sources:** The hourly temperature, precipitation and sunshine duration data at the same period of time were collected and sorted by the technical staff of national fundamental weather stations in Xinghua City of Jiangsu province in accordance with the relevant technical regulations of surface meteorological observation of the China Meteorological Administration.

**Establishment of evaluation model for the effects of climate change:** Winter wheat growth speed is simulated by logistic equation. Given the days after flowering were represented by *t*, and the thousand-grain weight was TGW, the following equation can be calculated:

$$\mathrm{TWG}(t) = \frac{k}{1 + ae^{-bt}} \quad (1)$$

Creech & McArdle (1996) concluded that a four-point method can solve the value of k by using the logistic curve and linear regression method to calculate the parameters *a* and *b*. In this paper, equation parameters are identified by this method. Nass & Reiser (1975) found that the logistic curve equation can be adopted to calculate the grain filling parameters, such as grain filling rate and grain filling time. On this basis, we set the first day of grain filling peak as $t_1$, the last two days of grain filling peak as $t_2$ and $t_3$, flowering date as $TD_0$, grain filling peak starting date as $TD_1$, grain filling peak ending date as $TD_2$ and grain filling ending date as $t_3$. T is the grain filling time, duration of grain filling increase stage for $T_1$, duration of rapid increase stage for $T_2$ and duration of the slight increase stage for $T_3$. The turning points of the function by TWG (t) were calculated as follows:

$$t_1 = \frac{\ln a - \ln(2 + \sqrt{3})}{b} \quad (2)$$

$$t_2 = \frac{lna - \ln(2 - \sqrt{3})}{b} \quad (3)$$

$$T_1 = t_1 \quad (4)$$

$$T_2 = t_2 - t_1 \quad (5)$$

$$T_3 = T - t_2 \quad (6)$$

Considering the average grain filling as YFR(t), on the basis of the China Meteorological Administration (1993) the grain filling rate were calculated method as follows:

$$\mathrm{YFR}(t) = \frac{TWG(t+5) - TWG(t)}{5} \quad (7)$$

Shang *et al.* (2012) suggested that adopting an integral regression method is reasonable to determine the effect of meteorological conditions. Therefore, considering the average grain filling rate in the i (i = 1, 2, 3, refers to gradual increase, rapid increase and slight increase stages, respectively) filling stage in the year t was YFRi (t), and the hourly average value of corresponding meteorological factors was Xijk (t) (j = 1, 2, 3, correspondingly refer to temperature, precipitation and sunshine duration, k = 1, 2,..., 24 stands for 1 to 24 times), the following equation can be employed:

$$YFR_i(t) = a_0 + \sum_{j=1}^{3}\sum_{k=1}^{24} a_{ijk} X_{ijk}(t) \quad (8)$$

Formula (8) also can be written as follows:

$$YFR_i(t) = a_0 + \sum_{k=1}^{24}\sum_{j=1}^{3} a_{ijk} X_{ijk}(t) \quad (9)$$

For example, $YFRT_{ij}(t) = \sum_{k=1}^{24} a_{ijk} X_{ijk}(t)$

Formulas (8) and (9) can also be written as

$$YFRD_{ik}(t) = \sum_{j=1}^{3} a_{ijk} X_{ijk}(t)$$

$$YFR_i(t) = a_0 + \sum_{j=1}^{3} YFRT_{ij}(t) \quad (10)$$

$$YFR_i(t) = a_0 + \sum_{k=1}^{24} YFRD_{ik}(t) \quad (11)$$

Formula (10) shows that the effect of meteorological conditions on the winter wheat grain filling rate is equal to the sum of the influence of various meteorological elements. Formula (11) indicates that the effect of meteorological conditions on the winter wheat grain filling rate is equal to the sum of the influence of each stage.

**Impact analysis of climate change:** Considering the change in meteorological conditions caused by climate change was $\Delta X_{ijk}$, the change in grain filling rate caused by climate change can be calculated as follows:

$$\Delta YFR_i(t) = \sum_{j=1}^{3}\sum_{k=1}^{24} a_{ijk} \Delta X_{ijk}(t) \quad (11)$$

The $a_{ijk}$ in the formulas (11) are used with the regression method to determine parameters by the test data.

Guo and Ding (2014) found that the variation in the meteorological conditions caused by the change in grain filling rate is often indicated by climate trend rate (CTR):

$$X_{ijk}(t) = a_{ijk} + b_{ijk} \times t \quad (12)$$

$$CTR_{ijk} = 10 \times b_{ijk} \quad (13)$$

The CTR was calculated by the data in in Xinghua agricultural meteorological stations from 1966 to 2014. If $CTR_{ijk}$ was integrated into Formulas (8) to (11) as a representation of $\Delta X_{ijk}$, the amount of change in grain filling rate caused by climate change can be calculated.

## Results and Analysis

**Three phases for grain filling rate:** The data obtained through yearly observation were calculated using formulas (1) to (6), in which the normal flowering period every year was around April 25. The duration of gradual increase stage was 8.1 days, which ended on May 3. The duration of rapid increase stage was 22 days, which ended on May 25. The slight increase stage lasted for 4.5 days and ended on May 30th. In brief, the gradual increase stage accounted for 23.4%, the rapid increase stage accounted for 63.6%, and the rapid increase stage accounted for 13.0% (Table 1).

**Impact analysis of climate change:** The change in grain filling rate caused by climate change is calculated through Formula (11). According to the experimental data, we can obtain the following results through calculation and analysis:

(1) Table 2 shows that the changes of the microclimate is good for improving the winter wheat grain filling rate in Jiangsu province, with the growing rate of up to 0.08 $g \cdot d^{-1} \cdot (10a)^{-1}$. The influence of different meteorological elements is different, and climate change trend of temperature is highly advantageous to improve the winter wheat grain filling rate up to 1.36 $g \cdot d^{-1} \cdot (10a)^{-1}$. Sunshine duration was the second most significant factor, with the rate of 0.07 $g \cdot d^{-1} \cdot (10a)^{-1}$. Precipitation led to a significant decline of winter wheat grain filling rate at −1.35 $g \cdot d^{-1} \cdot (10a)^{-1}$.

(2) As shown in Table 2, temperature, precipitation and sunshine duration presented different impact degrees on the filling rate in winter wheat grain filling period (growing period, fast increase stage and slow increase stage), and the rank of influence degree was slow increase stage > fast increase stage > growing period. In brief, the influence increased as the grain filling process advanced.

(3) As shown in Table 2, the comprehensive impact of temperature, precipitation and sunshine duration was to increase the grain filling rate by 0.02 $g \cdot d^{-1} \cdot (10a)^{-1}$. Different factors demonstrated various impacts. The temperature was changed by −0.49 $g \cdot d^{-1} \cdot (10a)^{-1}$. The precipitation was changed by 0.75 $g \cdot d^{-1} \cdot (10a)^{-1}$, and the sunshine duration was altered by −0.24 $g \cdot d^{-1} \cdot (10a)^{-1}$.

(4) Table 2 shows that the comprehensive impact of temperature, precipitation and sunshine duration was lower in terms of filling rate in fast increase period, with a value of −0.04 $g \cdot d^{-1} \cdot (10a)^{-1}$. The different meteorological elements displayed significant disparities, with the temperature by 2.02 $g \cdot d^{-1} \cdot (10a)^{-1}$, precipitation by −1.82 $g \cdot d^{-1} \cdot (10a)^{-1}$ and sunshine duration by −0.24 $g \cdot d^{-1} \cdot (10a)^{-1}$.

(5) As shown in Table 2, in the slow increase stage, the comprehensive impact of temperature, precipitation and sunshine duration evidently increased the grain filling rate up to 0.1 $g \cdot d^{-1} \cdot (10a)^{-1}$. Temperature and precipitation caused the reduction by −0.17 and −0.28 $g \cdot d^{-1} \cdot (10a)^{-1}$, respectively, whereas the sunshine duration increased by 0.55 $g \cdot d^{-1} \cdot (10a)^{-1}$.

**Table 1. Time from blossom day to the end of grain filling day in each year by be calculated Observation data.**

| Year | $TD_0$ mm／d d | $t_1$ d | $T_1$ d | $TD_1$ mm／d d | $t_2$ d | $T_2$ d | $TD_2$ mm／d d | $t_3$ d | $T_3$ d | $TD_3$ mm／d d |
|---|---|---|---|---|---|---|---|---|---|---|
| 1996 | 5/2 | 7 | 7 | 5/9 | 29 | 22 | 5/31 | 35 | 6 | 6/10 |
| 1997 | 4/27 | 3 | 3 | 4/30 | 23 | 20 | 5/20 | 31 | 8 | 5/28 |
| 1998 | 4/23 | 2 | 2 | 4/25 | 27 | 25 | 5/20 | 35 | 8 | 5/30 |
| 1999 | 4/24 | 9 | 9 | 5/3 | 29 | 20 | 5/23 | 33 | 4 | 5/27 |
| 2000 | 4/26 | 4 | 4 | 4/30 | 26 | 22 | 5/22 | 36 | 10 | 6/1 |
| 2001 | 4/21 | 11 | 11 | 5/2 | 30 | 19 | 5/21 | 37 | 7 | 5/28 |
| 2002 | 4/12 | 8 | 8 | 4/20 | 33 | 25 | 5/15 | 39 | 6 | 5/21 |
| 2003 | 4/29 | 7 | 7 | 5/6 | 29 | 22 | 5/28 | 34 | 5 | 6/2 |
| 2004 | 4/22 | 11 | 11 | 5/3 | 33 | 22 | 5/25 | 39 | 6 | 5/31 |
| 2005 | 4/26 | 7 | 7 | 5/3 | 31 | 24 | 5/27 | 33 | 2 | 5/29 |
| 2006 | 4/21 | 11 | 11 | 5/2 | 33 | 22 | 5/24 | 35 | 2 | 5/26 |
| 2007 | 4/21 | 12 | 12 | 5/3 | 34 | 22 | 5/25 | 36 | 2 | 5/27 |
| 2008 | 4/26 | 6 | 6 | 5/2 | 32 | 26 | 5/28 | 34 | 2 | 5/31 |
| 2009 | 4/25 | 10 | 10 | 5/5 | 27 | 17 | 5/22 | 32 | 5 | 5/27 |
| 2010 | 5/5 | 12 | 12 | 5/17 | 32 | 20 | 6/6 | 34 | 2 | 6/9 |
| 2011 | 5/2 | 5 | 5 | 5/7 | 29 | 24 | 5/31 | 31 | 2 | 6/2 |
| 2012 | 5/2 | 2 | 2 | 5/4 | 22 | 20 | 5/24 | 26 | 4 | 5/28 |
| 2013 | 4/26 | 13 | 13 | 5/9 | 36 | 23 | 6/1 | 39 | 3 | 6/4 |
| 2014 | 4/20 | 13 | 13 | 5/3 | 36 | 23 | 5/26 | 38 | 2 | 5/30 |
| Average | 4/25 | 8.1 | 8.1 | 5/3 | 30.1 | 22 | 5/25 | 34.6 | 4.5 | 5/30 |

**Table 2. Amount of change on grain filling rate of winter wheat in Jiangsu Province caused by climate change by be calculated on the evaluation model.**

| Items | Gradual increase stage $g\cdot d^{-1}\cdot(10a)^{-1}$ | Rapid increase stage $g\cdot d^{-1}\cdot(10a)^{-1}$ | Slight increase stage $g\cdot d^{-1}\cdot(10a)^{-1}$ | Sum $g\cdot d^{-1}\cdot(10a)^{-1}$ |
|---|---|---|---|---|
| Temperature | -0.49 | 2.02 | -0.17 | 1.36 |
| Precipitation | 0.75 | -1.82 | -0.28 | -1.35 |
| Sunshine | -0.24 | -0.24 | 0.55 | 0.07 |
| Sum | 0.02 | -0.04 | 0.1 | 0.08 |

(6) Fig. 1 shows that at different phases of variations in temperature, precipitation and sunshine duration, climate change caused a significant modification in grain filling rate at different times of the day, and the rank according to the degree of influence was fast increase period > growing stage > cache gain stage. The effects of temperature, precipitation and sunshine on grain filling rate showed periodic fluctuation featured by ‘increase/decrease.’ The periodic frequency was 1 h to 5 h and dominated by 1 h to 2 h. Amplitude: −13.98 to 11.98 $g\cdot d^{-1}\cdot(10a)^{-1}$ in growing period, −27.72 $g\cdot d^{-1}\cdot(10a)^{-1}$ to 17.46 $g\cdot d^{-1}\cdot(10a)^{-1}$ in fast increase period, and −3.50 $g\cdot d^{-1}\cdot(10a)^{-1}$ to 6.12 $g\cdot d^{-1}\cdot(10a)^{-1}$ in fast increase period.

(7) As shown in Figs. 2, 3 and 4, the grain filling rate modification caused by climate change was significant, with the temperature change presenting the most obvious impact, which was particularly high at late night (23 ~ 3) and during the middle of day (10 ~ 14). Nevertheless, the impact of precipitation and sunshine was relatively low.

(8) As shown in Figs. 2, 3 and 4, at different growth phases, temperature, precipitation and sunshine duration changed the grain filling rate in various degrees, with the rapid increase period influencing the most, followed by gradual increase period, and the least influence was exerted by the slow increase stage.

(9) As shown in Figs. 2, 3 and 4, temperature, precipitation and sunshine duration changed the grain filling rate by periodic fluctuation featured by ‘increase/decreases.’ The cycle frequency was dominated by 1 h to 2 h.

(10) As shown in Figs. 2, 3 and 4, the amplitude of grain filling rate change caused by temperature was −13.81 $g\cdot d^{-1}\cdot(10a)^{-1}$ to 12.88 $g\cdot d^{-1}\cdot(10a)^{-1}$ in gradual increase period, −3.09 $g\cdot d^{-1}\cdot(10a)^{-1}$ to 1.99 $g\cdot d^{-1}\cdot(10a)^{-1}$ in fast increase period, and −1.59 $g\cdot d^{-1}\cdot(10a)^{-1}$ to 1.24 $g\cdot d^{-1}\cdot(10a)^{-1}$ in slow increase period. Therefore, the grain filling rate instability caused by the temperature climate change was characterised by rapid linear decrease as the grain filling process proceeded.

(11) As shown in Figs 2, 3 and 4, the amplitude of grain filling rate change caused by precipitation was −27.91 $g\cdot d^{-1}\cdot(10a)^{-1}$ to 17.92 $g\cdot d^{-1}\cdot(10a)^{-1}$ in gradual increase period, −1.61 $g\cdot d^{-1}\cdot(10a)^{-1}$ to 0.57 $g\cdot d^{-1}\cdot(10a)^{-1}$ in rapid increase period and −0.5 $g\cdot d^{-1}\cdot(10a)^{-1}$ to 0.3 $g\cdot d^{-1}\cdot(10a)^{-1}$ in slow increase period. These findings indicate that the grain filling rate instability caused by precipitation during climate change showed reduction as the grain filling process advanced, and the decreasing speed was faster than with temperature.

(12) Comparison of Figs. 2, 3 and 4 showed that the amplitude of grain filling rate change caused by sunshine duration was −3.11 $g\cdot d^{-1}\cdot(10a)^{-1}$ to 6.15 $g\cdot d^{-1}\cdot(10a)^{-1}$ in gradual increase period, −0.42 $g\cdot d^{-1}\cdot(10a)^{-1}$ to 0.19 $g\cdot d^{-1}\cdot(10a)^{-1}$ in rapid increase period and −0.94 $g\cdot d^{-1}\cdot(10a)^{-1}$ to 1.23 $g\cdot d^{-1}\cdot(10a)^{-1}$ in slow increase period. These data suggest that the grain filling rate instability caused by sunshine duration during climate change exhibited a different trend from that with temperature and precipitation as the grain filling process advanced and became parabolic.

## Discussions

The climate is always changing. Thus, the climate change has been a major issue for mankind, bringing even the major damage for the human. For example, the abrupt change of climate 4000 years ago caused the breakdown of early human civilisation, reported by Weiss & Bradley (2001). There， it should focus on the influences of climate change on winter wheat production, especially on the grain filling rate.

Although it is a gradual process, it is very urgent to deal with the climate change. For example, Douma *et al.* (2007) proposed that all countries worldwide should actively cope with global climate change and realise the effective governance of climate crisis.

Most scholars speculate that global climate change cannot only cause modifications in winter wheat planting area but can also influence the output of winter wheat. Moreover, the occurrence of disease pest and weed can affect the output of winter wheat. In present study it was found that the impact of climate change on regional winter wheat production is really different. Besides, it was found that the changes of the climate in Jiangsu Province, China is beneficial to improve the winter wheat grouting rate. Therefore, it is important to conduct investigations on climate change according to regional characteristics and the cultivation techniques of wheat should be developed to reduce their influence on grain filling. At the same time, it is important, as our researches suggests, that the major measures to address climate change include the strengthening of the forecast capacity on major natural disasters during the growth and development of winter wheat and conducting disaster prevention measures, such as artificial precipitation, to maintain the stability of weather conditions, promote stable grain filling and realise high output and good quality of winter wheat.

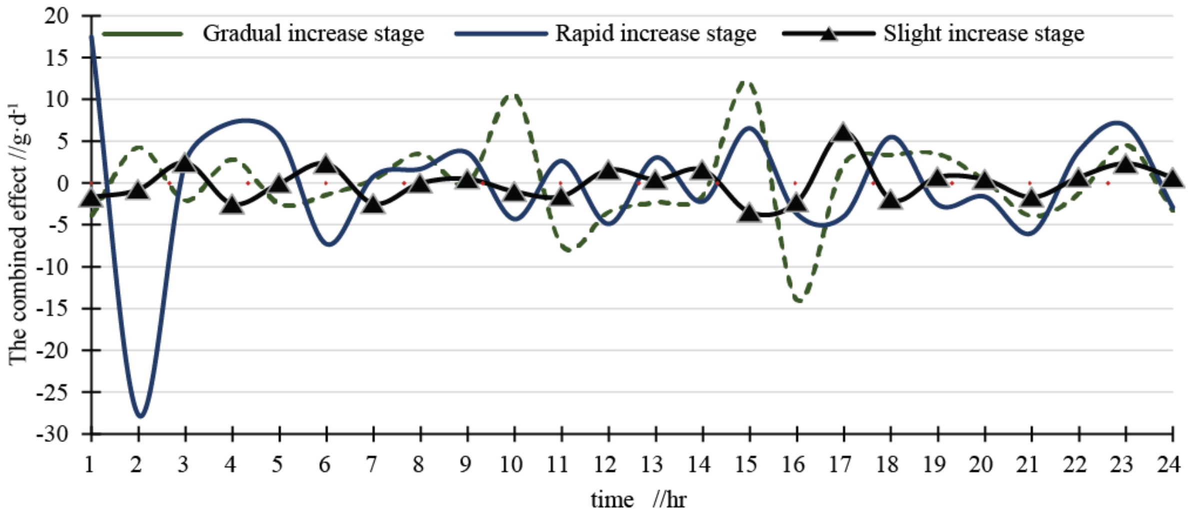


Fig. 1. Comprehensive influence of hourly temperature, cooling and sunshine in different increase phases by evaluation model.

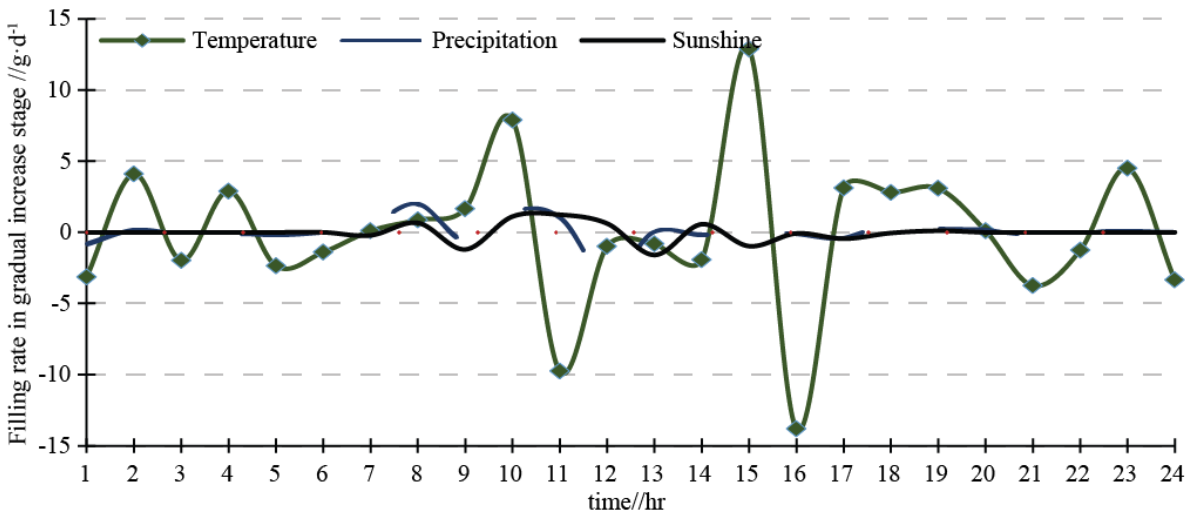


Fig. 2. Hourly effects of climate change in gradual increase period in different stages with different factors by evaluation model.

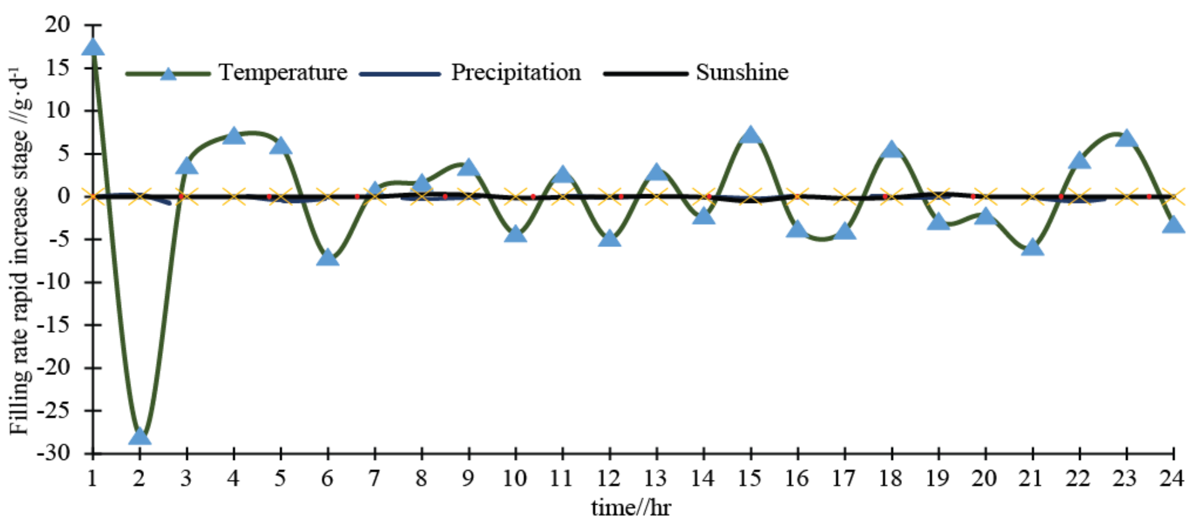


Fig. 3. Hourly effects of climate change in rapid increase period in different stages with different factors by evaluation model.

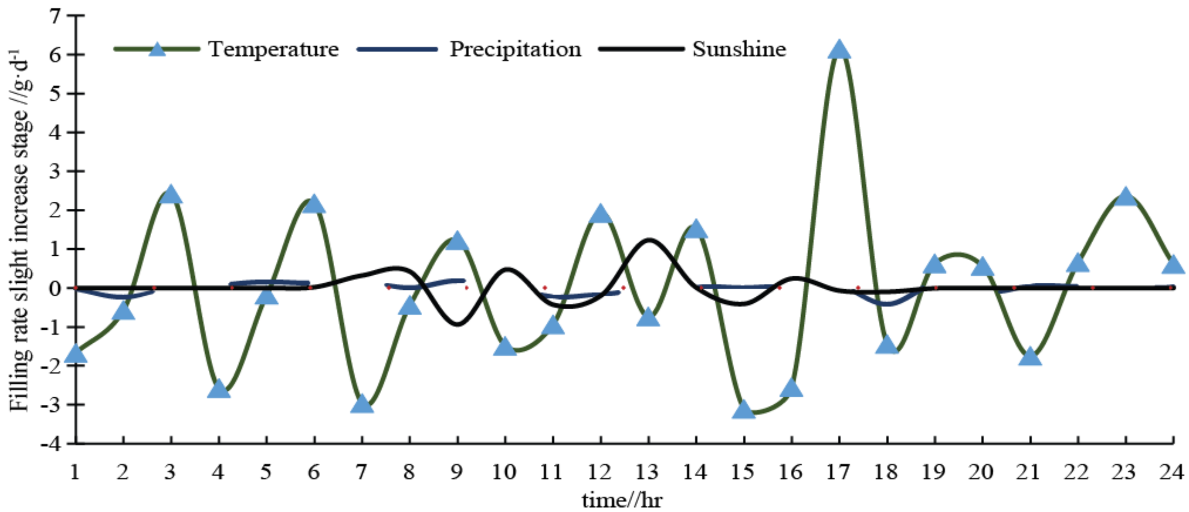


Fig. 4. Hourly effects of climate change in slow increase period in different stages with different factors by evaluation model.

## Conclusion

(1) The temperature, cooling and sunshine will be changed as the climate varied in Jiangsu Province, and this change will be beneficial to improve the grain filling rate and quality and output of winter wheat.

(2) The influence of temperature, precipitation and sunshine on grain filling rate is different during various times of the day. Temperature showed the deepest impact, followed by precipitation, and sunshine demonstrated the slightest impact. Therefore, further research should focus on the effects of temperature on winter wheat grain filling rate. The possibility of the effect of high temperature is greater than that of low temperature in Jiangsu province on the winter wheat grain filling. Consequently, planting technology for anti-high temperature should be studied further to ensure high output and good quality of winter wheat.

## Acknowledgements

This work was funded by the Jiangsu province Meteorological Scientific Research Open Fund (Grant No. 200712: Agricultural meteorological disaster weather pattern library and Grant No. 200807: Research and application with high yield and good quality cultivation techniques on wheat and barley in Lixiahe wetland).

## References

Aochen, C. and P. Prakash. 2011. Responses of wheat (*Triticum aestivum* L.) genotypes to heat stress on account of delayed sowing. *Environ. Ecol.,* 29: 1794-1797.

Asseng, S., I.A.N. Foster and N.C. Turner. The impact of temperature variability on wheat yields. *Glob. Chang. Biol.*,17(2): 997-1012.

Brocklehurst, P.A. 1977. Factors controlling grains weight in wheat. *Nature*, 266: 348-349.

Chen, Q., H. Lu and W. Hou. 2014. Impacts of climate warming on growth development process and yield of winter wheat in Huang-Huai-Hai Region of China. *Journal of Triticeae Crop*, 34(10): 1363-1372.

China, Meteorological Administration. 1993. *Agromteorological specification*. China Meteorological Press, Beijing.

Cossani, C.M., G.A. Slafer and R. Savin. 2011. Do barley and wheat (bread and durum) differ in grain weight stability through seasons and water–nitrogen treatments in a Mediterranean location? *Field Crops Res.,* 121: 240-247.

Creech, R.G. and F.J. Mcardle. 1966. Gene interaction for quantitative changes in carbohydrates in maize kernels. *Crop Sci.,* 6: 192-194.

Dai, T., J. Wang and D. He. 2016. Impact simulation of climate change on potential and rainfed yields of winter wheat in Southwest China from 1961 to 2010. *Chinese J. Eco-Agri.*, 24(3): 293-305.

Dias, A.S. and F.C. Lidon. 2009. Evaluation of grain filling rate and duration in bread and durum wheat, under heat stress after anthesis. *J. Agron. Crop Sci.,* 195: 137-147.

Dong, Z., L. Zhang and L. Lv. 2015. Effects of different irrigation methods on photosynthetic rate and yield of winter wheat. *Agri. Res. in the Arid Areas.*, 33(6): 1-7.

Douma, W.T., L. Massai and M. Montini. 2000. *The Kyoto Protocol and beyond Legal and Policy Challenges of Climate Change*. TMC Asser Press.

Eelin, J.D., M. Munnich and H. Su. 2006. Tropical drying trends in global warming models and observations. *Proc. National Acad. Sci.*, 103(16): 6110-6115.

European, Commission. 2016. *Special Eurobarometer 300: Europeans' Attitudes towards Climate Change*. http://ec.europa.eu/public_opinion/archives/ebs/ebs_300_full_en.pdf.

Fang, W., X. Zhang and Y. Zheng. 2006. Influence of drought on filling velocity of winter wheat during filling period. *Chinese J. Agro-Meteorol.,* 27(2): 98-101.

Fu X., M. He, Z. Shi, Y. Zhao, X. Wang and J. Guo. 2015. Effect of high temperature stress during grain-filling period on wheat grain-filling characteristics and quality. *J. Triticeae Crops.,* 35(6): 867-872.

Gallup. 2016. *Climate Change*：*Environment*. http://www.gallup.com/poll/1615/environment.aspx#.

Gu, Y., X. Liu, W. Zhang, C. Qi, K. Tang, Y. Zhao, Y. Zhang, G. Li, B. Wang, C. Zhao and W. Luo. 2013. The simulation model of the effects of low level of radiation at milk filling stage on wheat growth and yield. *Scientia Agricultura Sinica,* 46(5): 898-908.

Guo, J. 2015. Advances Impacts of Climate change on Agricultural Production in China. *J. Appl. Meteorol. Sci.*, 26(1): 1-11.

Guo, Y. and Y. Ding. 2014. Upper-air specific humidity change over China during 1958–2005. *Chinese J. Atmosph. Sci.*, 38(1): 1-12.

Li K., X. He and Y. Xu. Study on classification of adaptation technologies to climate change in China. China population. *Resources and Environment*, 26(2): 18-26.

Lobell, D.B. and C.B. Field. 2007. Global scale climate crop yield relationships and the impacts of recent warming. *Environ. Res. Lett*., 2(1): 625-630.

Lobell, D.B. and M.B. Burke. 2010. On the use of statistical modelsto predict crop yield responses to climate change.*Agr. Forest Meteorol.*, 150: 1443-1452.

Lu, J., G.A. Vecchi and T. Reichler. 2007. Expansion of the Hadley cell under global warming. *Geophys. Res. Lett.*, 34: L06805.

Lyda, C. and A. Bawn. 1970. Enzyme of starch metabolism in the developing rice grain. *Plant Physiol.,* 46: 429-434.

Motzo, R., F. Giunta and G. Pruneddu. 2010. The response of rate and duration of grain filling to long-term selection for yield in Italian durum wheats. *Crop Pasture Sci.,* 61: 162-169.

Mouna, E.L.F., M. Said, B. Mounsif and N. Nasserelhaq. 2012. Grain filling and stem accumulation effects on durum wheat (*Triticum durum* Desf.) yield under drought. *Nat. Technol.*, 7: 67-73.

Nass, H.G. and B. Reiser. 1975. Grain filling period and grain yield relationship in spring wheat*. Can. J. Plant Sci.,* 55: 673-678.

National Science Board. 2016. *Science and Engineering Indicators*. National Science Foundation, Arlington VA.

Papakosta, D.K. and A. Gagianas. 1991. Nitrogen and dry matter accumulation, remobilization and losses for Mediterranean wheat during grain filling. *Agron. J.,* 83(5): 864-870.

Peng, H. and L. Xiao. 2012. Analysis of the Grain Filling Traits in Two Wheat Cultivars. *Chinese Agricultural Science Bulletin*, 28(3): 51-54.

Pireivatlou, A.G.S., R.T. Aliyev and B.S. Lalehloo. 2011. Grain filling rate and duration in bread wheat under irrigated and drought stressed conditions. *J. Plant Physiol. Breed.,* 1: 69-86.

Shang, Z., L. He, S. Liu, Z. Lu and L. Cheng. 2012. Effect of climate change on cotton lugus lucorum occurrence degree. *Agri. Sci & Technol.,* 13(4): 784-788.

Shang, Z., L. He, S. Shang, X. Zhang, D. Jiang and W. Ma. 2015. Analysed the climate characteristic during winter wheat seasons in Jiangsu province. *Jiangsu Agri. Sci.,* 43(3): 56-62.

Sheffield, J. and E.F. Wood. 2008. Projected changes in drought occurrence under future global warming from multimodel, multi-scenario, IPCC AR4 simulations. *Clim. Dynam.*, 31(1): 79-105.

Song, D. and L. Ma. 2016. Climate change in Baoji: Its effect on wheat yield. *Chinese Agricultural Science Bulletin*, 32(19): 147-151.

Stone, P. and M. Nicolas. 1996. Effect of timing of heat stress during grain filling on two wheat varieties differing in heat tolerance. II. Fractional protein accumulation. *Funct. Plant Biol.,* 23(6): 739-749.

Sun, S., X. Yang, J. Zhao and F. Chen. 2015. The possible effects of global warming on cropping systems in china Ⅺ. the variation of potential light-temperature suitable cultivation zone of winter wheat in China under climate change. *Scientia Agricultura Sinica,* 48(10): 1926-1941.

Tan, K., X. Yang, S. Ren and S. Fang. 2015. Yield impact of high temperature stress at the grain filling stage of winter wheat. *Acta Ecologica Sinica,* 35(19): 1-10.

Weiss, H. and R.S. Bradley. 2001. What drives societal collapse. *Science*, 291: 609-610.

Wheeler, T.R., T.D. Hong, R.H. Ellis, G.R. Batts, J.I.L. Morison and P. Hadley. 1996. The duration and rate of grain growth and harvest index of wheat (*Triticum aestivum* L.) in response to temperature and $CO_2$. *J. Exp. Bot.,* 47: 623-630.

Wiejand, G.L. and J.A. Caellar. 1981. Duration of grain filling and kernel weight of wheat as affected by temperature. *Crop Sli.,* 21: 95-101.

Wilkens, P. and U.A. Singh. 2001. Code-level analysis for temperature effects in the CERES models. In: White J. *Modeling Temperature Response in Wheat and Maize*. CIMMYT, El Batan, pp.1-7.

Wu, Y., J. Chen and Z. Hu. 2016. Effects of reduced water and diurnal warming on winter-wheat biomass and soil respiration. *Environ. Sci.,* 37(1): 280-287.

Xue, X., Y. Wu, R. Chen, Z. Han and Q. Gao. 2006. Comparison of Different Mathematical Equations for Simulating the Grain Filling Process of Wheat. *J. Triticeae Crops.,* 26(6): 169-171.

Yan, S., W. Li and Z. Yang. 2011. Effects of weak light at grain filling stage on photosynthetic characteristics and grain filling of winter wheat. *J. Triticeae Crops.,* 31(1): 77-81.

Zhang, N., Y. Zhang and W. Xu. 2016. Effect of different drip irrigation amounts on microclimate and yield of winter wheat. *Chinese J. Eco-Agri.*, 24(1): 64-73.

Zhang, Y., Y. Yang and L. Cao. 2015. Effect of high temperature on photosynthetic capability and antioxidant enzyme activity of flag leaf and non-leaf organs in wheat. *Acta Agronomica Sinica*, 41(1): 136-144.

Zhao, H., L. Cai, M. Kun, J. Ling and L. Hou. 2006. Parameter of grain filling of different winter wheat cultivars. *Journal of Anhui Agri. Sci.,* 34(8): 1560-1562.

Zhou, Z., X. Xi, W. Zhao, X. Che, J. Du and M. Zhang. 2014. Influence of meteorological conditions on the grain filling rate of winter wheat in the east of Gansu. *J. Triticeae Crops*, 34(96): 837-841.

Zhu, C., B. Zhang, X. Wang, B. Zhang and Y. Jiang. 2014. Analysis of grain filling characteristics of wheat cultivars from different ages in Henan Province. *J. Hena Agri. Sci.,* 43(94): 32-35.

(Received for publication 10 December 2015)