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Incorporating Stochastic Weather Generators into Studies on Climate Impacts: Methods and Uncertainties①

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ABSTRACT

By adopting various stochastic weather generators, different research groups in their recent studies have realized the importance of the effects of climatic variability on crop growth and development. The conventional assessments derived climate change scenarios from General Circulation Models (GCMs) experiments, however, are incapable of helping to understand this importance. The particular interest here is to review the general methodological scheme to incorporate stochastic weather generator into climate impact studies and the specific approaches in our studies, and put forward uncertainties that still exist.

A variety of approaches have been taken to develop the parameterization program and stochastic experiment, and adjust the parameters of a typical stochastic weather generator called WGEN. Usually, the changes in monthly means and variances of weather variables between controlled and changed climate are used to perturb the parameters to generate the intended daily climate scenarios. We establish a parameterization program and methods for stochastic experiment of WGEN in the light of outputs of short-term climate prediction models, and evaluate its simulations on both temporal and spatial scales. Also, we manipulated parameters in relation to the changes in precipitation to produce the intended types and qualitative magnitudes of climatic variability. These adjustments yield various changes in climatic variability for sensitivity analyses. The impacts of changes in climatic variability on maize growth, final yield, and agro-climatic resources in Northeast China are assessed and presented as the case studies through the above methods.

However, this corporation is still equivocal due to deficiencies of the generator and unsophisticated manipulation of parameters. To detect and simulate the changes in climatic variability is one of the indispensable ways to reduce the uncertainties in this aspect.

Key words: Stochastic weather generator, Climate impacts, Climatic variability

1. Introduction

Although there are many apparent deficiencies in General Circulation Models (GCMs), including lower temporal and spatial resolution and disagreement between its controlled integration and the climate base, etc., it must be admitted that climate models are so far the only available source of climate change scenarios based on atmospheric mechanism processes. Thus, the methods of linking GCMs' outputs with inputs of climate impact models, such as crop growth simulation models together have been the best choice in the studies on the impacts of climate change.

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Conventional assessments on the possible impacts of climate change have a hypothesis of keeping climatic variability in accord ance with that of present climate due to limited available information about changes in climatic variability. More attention has been paid to the effects of changes in climatic means on crop production. For instance, how might an increase in annual average temperature or monthly average temperature affect average grain yield? What could be the effects of an increase or decrease in average precipitation? Fixed temperature change and a fixed precipitation adjusting factor assumed or derived from GCMs′ simulation is added to observed daily temperature or is multiplied by historical daily precipitation respectively in these studies (Smith et al., 1989).

Variability in changing climate, however, is more important than averages. IPCC confirmed in its Second Assessment (Houghton et al., 1996) that the frequency and severity of climatic extreme events and climatic variability have reliably changed in some regions during the past years, although there are no sufficient evidences to affirm this consistent change on global scale. It was indicated in a number of studies that the variation of climatic variability is closely related to the changes in climatic means. Moreover, the former is far more complicated than the latter. Unfortunately, the reliable information of this particular parameter is not yet available in GCMs′ simulation.

The importance of emphasizing the effects of climatic variability on crop growth and development arose from the studies of the effects of climatic variability, and has been realized by different research groups in their recent studies. Extreme events which are particularly sensitive to changes in climatic variability are most likely to influence crop growth and development and have severe consequences (Katz and Brown, 1992). Negative impacts could derive from more subtle influence on various plant physiological processes (Wilks and Riha, 1996). The importance of daily weather variability to crop simulation was elaborated by Katz and Brown (1992), Semenov and Porter (1995), Riha et al. (1996), Mearns et al. (1997), and Wu and Wang (2000a).

Changes in climatic variability, however, were not considered in most studies due to limited knowledge and related skills. The hypothesis which keeps climatic variability constant in the traditional research imposes restriction on the overall investigation of the impacts of climate change on crop production, and disaster mitigation activities which need a better understanding of the data on climate extremes.

Recently, stochastic weather generators are widely used to produce various types of climate change scenarios on a site basis. They link information derived from GCMs to local weather characteristics and provide flexibility in the construction of climate change scenarios with climatic variability. Possible climatic variability was comprised in these scenarios by manipulating the parameters of the time–domain models. Here, we will briefly present a typical stochastic weather generator which has received much attention, and discuss the methods of incorporating it into studies on climatic impacts and the uncertainties that still exist.

2. Stochastic weather generator (WGEN)

Numerous stochastic weather generators exist in recent climatic impact studies. The stochastic weather generator WGEN, prevalent in volumes of references, was suggested by Richardson and Wright (1984) on the foundation of stochastic processes of variables′ time series. It can be used to simulate time series of maximum and minimum temperature, solar radiation, and precipitation, etc. on a daily basis.

2.1 *Precipitation*

The simulation of WGEN is based on the distribution of dry and wet days. Daily precipitation occurrence is represented as a two–state first–order Markov chain. It accounts for the stochastic dependence of the series of wet and dry days.

$$\{J_t:\ t=1,2,\cdots\}. \tag{2.1}$$

The state of day t is determined by $J_t=1$ for wet days and $J_t=0$ for dry days. Parameters estimated are unconditional probability of a wet day, π, and the persistence parameter (lag–1 autocorrelation coefficient) of precipitation occurrence, d.

$$\pi = \mathrm{P_r}(J_t=1), \tag{2.2}$$

$$d=\mathrm{Corr}(J_t, J_{t-1}). \tag{2.3}$$

Rainfall amounts (x) are simulated for wet days using the gamma distribution:

$$f(x)=x^{\alpha-1}e^{-x/\beta}/\beta^{\alpha}\Gamma(\alpha), \tag{2.4}$$

$$x \geqslant 0,\quad 0<\alpha<1,\quad \beta>1,$$

where α, β represent the shape parameter and the scale parameter, respectively. $\Gamma(\alpha)$ is the gamma function of α. The mean μ of the distribution is $\alpha\beta$ and the variance σ^2 is $\alpha\beta^2$. Based on the precipitation occurrence and intensity, the variance of the monthly total precipitation is closely related to the characteristics of daily precipitation according to the following equation:

$$\mathrm{Var}(P_k)\approx N_k\pi_k\alpha_k\beta_k^2\left[1+\alpha_k(1-\pi_k)\frac{1+d_k}{1-d_k}\right], \tag{2.5}$$

where $\mathrm{Var}(P_k)$ is the year to year variance of monthly precipitation P_k; N_k is the number of days in the time series; $\pi_k, d_k, \alpha_k, \beta_k$ are relevant parameters in (2.1)–(2.4) for month k.

2.2 *Temperature and radiation*

The maximum and minimum temperature and solar radiation ($X_t(j)$) are modeled as a multivariate first–order autoregressive process in line with the simulation of precipitation.

$$\{X_t(j,k)|J_t=i:\ t=1,2,\cdots\}, \tag{2.6}$$

$$Z_t(j,k)=[A]Z_{t-1}(j,k)+[B]\varepsilon_t(j,k), \tag{2.7}$$

where $i=0,1$ stands for dry and wet days separately. Daily variable $Z_t(j,k)$ is the normalized values of $X_t(j,k)$ and a vector for day t for three elements. $j=1,2,3$ indicates the maximum temperature, the minimum temperature and solar radiation, respectively. $\varepsilon_t(j,k)$ is a vector at day t for the above three elements of independent random normal components. $[A]$ and $[B]$ are 3×3 matrices constructed from the matrices of lag–0 for time dependence and lag–1 for simultaneous correlation among the three j elements, reflecting their time correlation and cross correlation. For each of the j variables, separate means and standard deviations are used for dry and wet days except for the minimum temperature ($j=2$).

The relationship between interannual and daily variance of temperature is approximated by:

$$\mathrm{Var}(T_{j,k}) \approx \frac{\sigma^2_{d(j,k)}}{N_k}\frac{1+\rho_1(j)}{1-\rho_1(j)}, \tag{2.8}$$

where $\mathrm{Var}(T_{j,k})$ is the interannual variance of monthly temperature $T_{j,k}$; $\sigma_d^2(j,k)$ is the variance of daily temperature; $\rho_1(j)$ shows the first order autocorrelation coefficient of daily temperature. Here $j=1,2$ corresponds to maximum temperature and minimum temperature respectively.

3. Methods

Nonlinear relationships between crop and weather must be considered in the integration of weather data with the crop–climate model. Therefore, it is essential to provide daily climatic data as well as its variability for improving crop models' simulation. On the other hand, because of the large uncertainty in the variability of a greenhouse climate, usually, a series of sensitivity analyses of these models are performed to assess the impacts of changes in variability of temperature and precipitation. Both of these objectives involve the combination of GCMs experimental outputs and stochastic weather generators, and can be attained through a large number of different combinations of parameters in WGEN.

3.1 *General methods*

For comparison, the corresponding Mean Changes only daily climate scenario (MC) is produced by classic climate scenarios forming techniques: Differences between 2 $\times$ CO_2 and controlled monthly mean maximum and minimum temperatures, and ratios of $2\times CO_2$ to controlled monthly mean precipitation from the outputs of GCMs are calculated firstly. Then monthly mean differences are added to the daily time series of maximum and minimum temperatures for the 30 years (e.g. 1961–1990) of observed data, and the observed daily precipitation values are multiplied by these monthly ratios. These procedures are incapable of depicting changes in climatic variability, and result in a change only in the means of temperature and precipitation, because their variabilities remain the same as for the observations.

Usually, the available information derived from GCMs is monthly or yearly values. The following figure illustrates the methodological scheme to incorporate stochastic weather generator into climate impact studies. Before generation, the simulations of WGEN for present climate consistent with the observed monthly statistics should be tested and validated to ensure that the sampling distributions exhibit observations' variability. Observed daily data or monthly statistics are used to fit the parameters of WGEN. The changes in monthly means and variances of weather variables between controlled and changed GCMs experiment are used to perturb these parameters to generate the intended daily climate scenarios. On the assumption that surface solar radiation is changing very slowly or is questionable in current GCMs, only changes in temperature and precipitation are to be treated here.

3.1.1 *Temperature parameter adjustments*

For the temperatures (maximum and minimum), adjusting the means and variances is easily achieved by changing the variance of daily temperature $\sigma_d(j,k)$ and its mean values $\mu_t(j,k)$. The alteration can be conducted for each month separately according to (2.8), and the algorithm in (3.2).

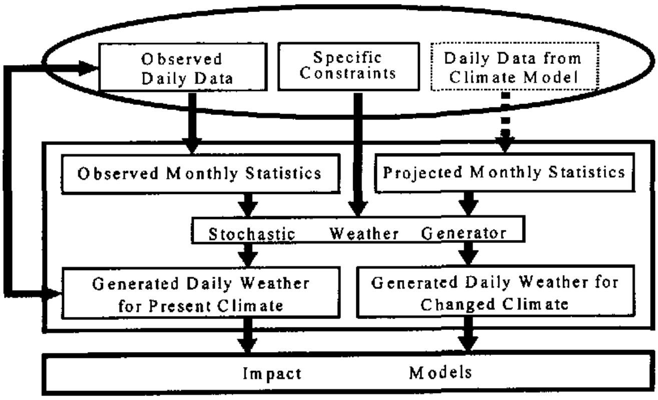

Fig. 1. Methodological scheme to incorporate stochastic weather generator into climate impact studies. The simulations for present climate consistent with observed monthly statistics are evaluated to ensure that the sampling distributions exhibit observations' variability. The changes in monthly means and variances of weather variables between controlled and changed GCMs experiments, and specific constraints are used to perturb parameters to generate the intended daily climate scenarios.

$$Z_t(j,k) = (X_t(j,k) - \mu_t(j,k)) / \sigma_d(j,k), \tag{3.1}$$

$$V_t(j,k) = \mathrm{Var}(T'_{j,k}) / \mathrm{Var}(T_{j,k}) = \sigma'^2_d(j,k) / \sigma^2_d(j,k), \tag{3.2}$$

where $\mu_t(j,k)$ is the mean of the time series; $\sigma_d(j,k)$ is the standard variance of the base climate; $V_t(j,k)$ is the ratio of the changed to the original variances of the changed and base climate. All the symbols pertaining to the changed climate are denoted with primes. The parameter $V_t(j,k)$ specifies relative temperature variability: for $V_t(j,k) > 1$ or < 1, the temperatures are more variable or less variable than in the base climate; for $V_t(j,k) = 1$, the variability in changed temperature is kept constant.

3.1.2 *Precipitation parameter adjustments*

Parameter adjustments for precipitation are more complex. The mean monthly total precipitation $\mu_p(k)$ can be expressed in terms of daily precipitation parameters as:

$$\mu_p(k) = N_k \pi_k \alpha_k \beta_k. \tag{3.3}$$

Another equation for the parameter alteration can be deduced from (2.5) as:

$$V_p(k) = \mathrm{Var}(P'_k) / \mathrm{Var}(P_k), \tag{3.4}$$

where the relative precipitation variability $V_p(k)$ bears the analogous meaning, i.e. for $V_p(k) > 1$ or < 1, the synthetic precipitation series exhibit more or less variability than in the base climate case; for $V_p(k) = 1$, the variability in changed precipitation remains constant.

There are four parameters α, β, π, d in (3.3) and (3.4) to determine the changed precipitation scenario. Therefore, two additional constraints or equations are required to fix them. These constraints depend on other available information or the objectives of a particular climate impact study. In general, they are varied to conduct a series of sensitivity analyses (Riha et al., 1996; Wu and Wang, 1999). There are a number of ways to adjust these four parameters to achieve the intended changes in precipitation variability while preserving the monthly means. In our consideration aiming at physical consistency among the variables, at least 28 combinations of the parameters can be used as constraints in which some parameters may remain constant.

Because WGEN can generate values of daily climate factors, it is also used in analyzing the possible variations of climatic extremes, such as the extreme maximum and minimum temperatures, annual maximum daily precipitation, maximum length of dry spell and the number of days with precipitation exceeding specified thresholds, etc. (Wu et al., 2000b).

3.2 *Specific methods used in our study*

3.2.1 *Parameterization program and stochastic experiment of WGEN, and its simulations evaluation*

Several statistic techniques (such as parametric analysis of dynamic data, etc.) and GCMs′ outputs with low temporal resolution (monthly and yearly) were adopted in this study to develop a parameter program for WGEN (Wu and Wang, 2000c). All parameters in WGEN can be assessed through commonly available information from GCMs (based on spatial regression downscaling to translate the coarse resolution GCMs grid–box predictions of climate change to site–specific values). Also, a stochastic experiment of WGEN was presented and carried out on the basis of the principles of Monte–Carlo numerical calculation.

Proceeding from the comprehensive analyses of temporal and spatial statistic characteristics, we evaluated the simulations of present climate in Northeast China. Here, several examples are given for the evaluation. Daily observations for 30 years(1961–1990) are adopted as the climate base while WGEN simulation series with the same length are used for comparison. Observed and simulated monthly distributions of the wet days′ number and their standard deviations at Shenyang location are illustrated in Fig. 2. It is clear that the simulated wet days in nine months are exactly the same as those observed. The other three months only

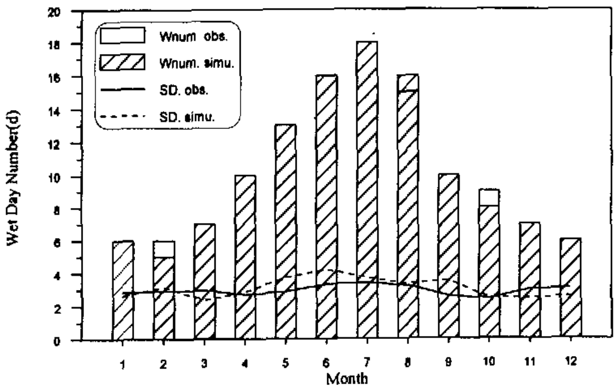

Fig. 2. Monthly distributions of the observed and simulated wet days′ number (Wnum) and its standard deviation (SD) (Shenyang). Observations for 30 years (1961–1990) are adopted as the climate base. Simulations for 30 years are also used for comparison.

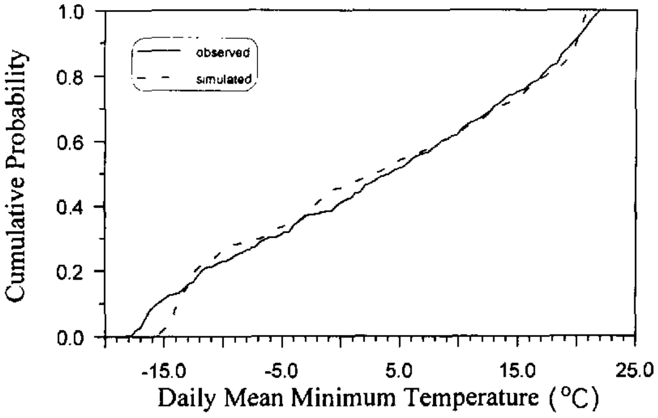

Fig. 3. The observed and simulated cumulative probability functions of daily mean minimum temperature (Shenyang). Observations for 30 years (1961–1990) are adopted as the climate base. Simulations for 30 years are also used for comparison.

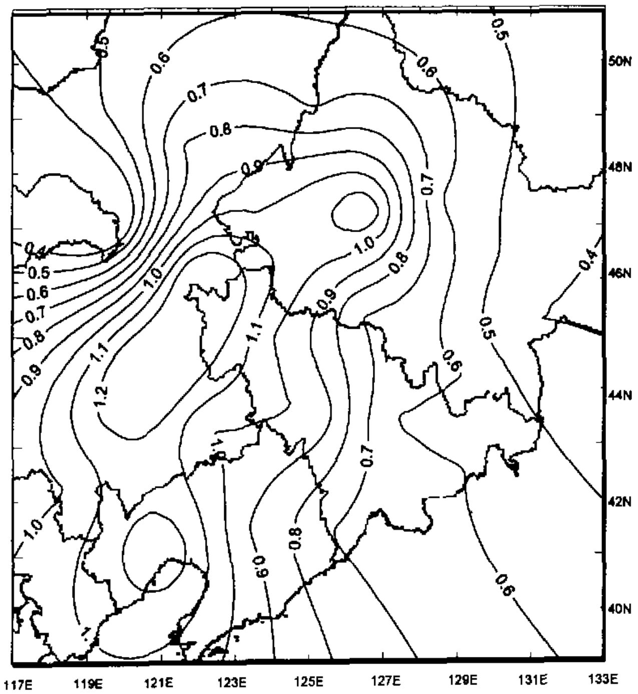

Fig. 4. Comparison of simulated field with observed field for annual mean precipitation per wet day (mm) in Northeast China. Observations for 30 years (1961–1990) are adopted as the climate base. Simulations for 30 years are also used for comparison.

have a deviation of one day. The difference of standard deviation between observations and simulations is less than one day in all the 12 months. We examined the temporal statistical distribution of simulated climatic factors as well. Figure 3 displays the similarity and consistency of observed and simulated cumulative probability functions of daily mean minimum temperature. Also, a series of spatial comparison between simulated and observed values of the maximum and minimum temperatures, solar radiation and precipitation (including wet days' number and precipitation per wet day) are conducted on various temporal scales. Figure 4 demonstrates the departure of simulated annual mean precipitation per wet day based upon observations in Northeast China. The values are varied but they are less than 1.0 mm in most areas of Liaoning, Jilin, and Heilongjiang Provinces.

It is thus concluded that WGEN has fairly good skills in generating the maximum temperature, the minimum temperature, precipitation and radiation; and the probability property of data sequence observed and simulated is rather identical. We regard WGEN as a promising approach to link climate models with impact models.

3.2.2 *Generation and adjustments of climatic variability*

To explore the impacts of changes in climate variability on various aspects of crop growth, MC climate was constructed according to the general methods mentioned above; and other climate scenarios with changed variability were generated in the following way.

Table 1. Summary of parameter adjustments which produced seven types of climatic variability scenarios

Scenario Type		Parameter adjustment	Description
I	MC	α,β,π,d = constant	Mean change only climate
II	VARPW	α,β = constant	Changes in wet days' number
III	VARAB	π = constant	Changes in precipitation per wet day
IV	VARPWD1	α,β = constant, $d\downarrow$	As II, decrease wet / dry spell
V	VARPWD2	α,β = constant, $d\uparrow$	As II, increase wet / dry spell
VI	VARABD1	π = constant, $d\downarrow$	As III, decrease wet / dry spell
VII	VARABD2	π = constant, $d\uparrow$	As III, increase wet / dry spell

For the complex inter–linkages within the stochastic weather model and unsophisticated manners up to date in adjusting parameters to produce desired changes of climatic variability (Katz, 1996), we manipulated parameters in relation to the changes in precipitation to generate the intended types and qualitative magnitudes of climatic variability. However, the detailed information about changes in precipitation, such as changes of rainfall intensity, wet days' number and the duration, is not clear in GCMs' outputs. So we derived a variety of climatic variability from changes in these variables and conducted a series of sensitivity analyses in our studies(Wu and Wang, 1999). Temperature variability changed simultaneously as precipitation variability was adjusted because temperature is conditioned by precipitation simulation in WGEN.

With the objective of keeping the climatic averages the same as GCMs' simulation, three categories (7 types) of climatic variability scenarios including MC climate were generated in this study. Unconditional probability of a wet day π, the shape parameter α, and the scale parameter β were achieved from (3.5) and (3.6) in separate scenarios.

$$\pi'_k = \Delta P_k \pi_k \ , \qquad (3.5)$$

$$\alpha'_k \beta'_k = \Delta P_k \alpha_k \beta_k \ , \tag{3.6}$$

where ΔP_k is the ratio of $2 \times CO_2$ to controlled monthly mean precipitation. The persistence of precipitation occurrence d decreased or increased by 50 percent referring to Wilks (1992) study. Parameter adjustments, scenario types and their descriptions are summarized in Table 1.

3.2.3 *Assessing the impacts of changes in climatic variability on crop growth, final yield, and agro-climatic resources*

Using the above seven types of scenarios, the impacts of changes in climatic variability on maize growth and development in Northeast China were assessed and compared with the effects of changes in climatic means through Monte Carlo stochastic sampling. Monthly climate change scenarios are derived from a general circulation model called DKRZ OPYC. The analyses were conducted by a dynamic mechanism process–based simulation model for maize growth and development (MZMOD) which has the necessary flexibility to examine the effects of changes in climatic variability on crop production.

Figure 5 illustrates the results from numerical experiments whose parameters are adjusted by Equation (3.5). It is obvious that the responses of maize yield to different changes in climatic variability are quite different. In this case, the changes in precipitation is regulated by wet days' number, while other variables related to precipitation are constant. The results indicate that the yield reduced in SCENARIO–V1 at Shenyang exceeds that in mean change only scenario, which is the focus of traditional researches. When the persistence of precipitation occurrence is decreases by 50% (SCENARIO–V2) or increases by 50% (SCENARIO–V3), and the total rainfall keeps constant, maize yield would be diminished further at various cumulative probabilities in the former case. The reduced yield might be lessened in the later scenario. Therefore, the yield reduction caused by changes in climatic means would be alleviated or aggravated by certain climatic variability scenarios. Moreover, changes in yield variability would be more intricate.

In addition, the revealment of possible variations of extreme climatic factors in the growing season showed that they would be more acute than climate averages, which adds to the

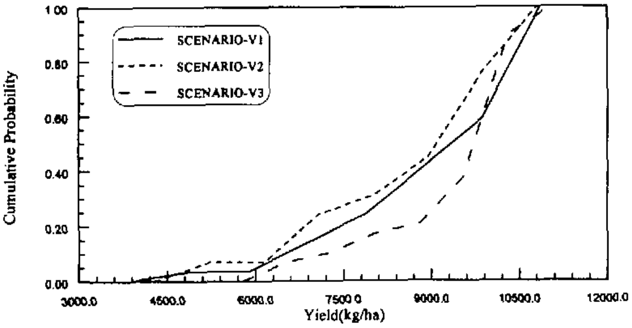

Fig. 5. The cumulative probability functions for maize yield under different climatic variability change scenarios at Shenyang (sowing date: May 6). SCENARIO–V1 is only for wet days' number changes. Wet days' duration is shortened or lengthened in SCENARIO–V2 and SCENARIO–V3 respectively. Yields simulated for 30 years are included for each curve.

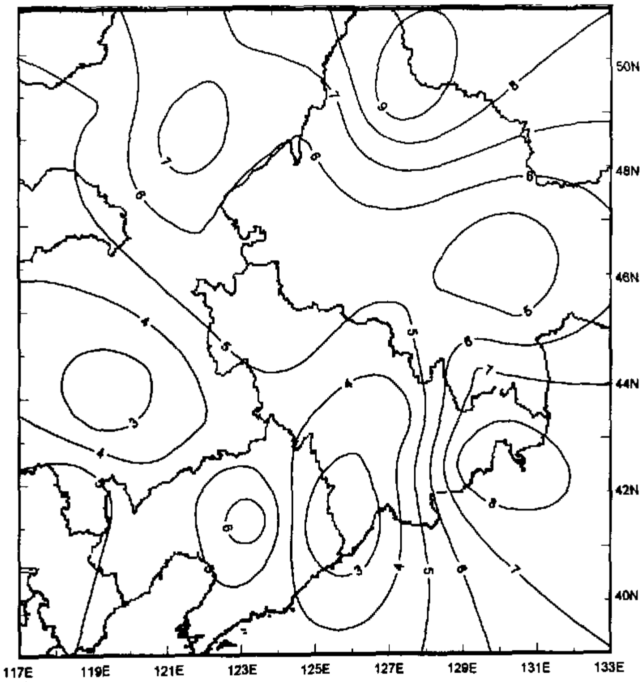

Fig. 6. Delayed days of the initial date with 19°C in Northeast China (days) compared with the normal date under present climate. Observations for 30 years (1961–1990) are adopted as the climate base. Simulations for 30 years are also used for comparison.

possibility of unfavorable impacts of abnormal weather events on the crop growth and development. There are also some favorable changes for crop growth, such as the longer growing season. Here we give an example of the delay in the initial date with 19°C in Northeast China compared with the normal date in present climate (Fig. 6). This index is rather important because it indicates the possibility of cold injuries to crops cultivated in this region. The daily climate scenario generated by WGEN shows that the initial date with 19℃ would be postponed greatly, especially in most areas stricken by cold injuries.

4. Uncertainties

Although this stochastic simulation allows for greater flexibility and physical meaning in making changes in climatic averages and variability than arbitrary adjustments in early studies, uncertainties still exist in most research approaches. Thus far from the final resolutions of the question, we are not yet unequivocal to the future climatic risk to agriculture.

(1) Notwithstanding good agreement of statistic weather generator is demonstrated between the simulation run and observed daily weather at specific site, some of WGEN's statistical characteristics are still unclear. Certain unanticipated effects can be produced when its parameters are adjusted. Especially, it has inadequate capacity to generate extreme

weather variables.

(2) For the unsophisticated approaches in manipulating the parameters of stochastic weather generator, we cannot get the precise changes in the variances of temperature or precipitation and keep its means constant at the same time.

(3) There are many doubts about the structure of stochastic models. For instance, simple first–order Markov Chain process and Gamma distribution seem inadequate to represent the more concentrated rain patterns (Hayhoe, 1998); the matrices [A] and [B] in Equation (2.7) are not constant, but should represent the regional and seasonal values (Wilks, 1999).

(4) Stochastic weather generators developed by these approaches are intended to advance our understanding of the impacts of climate changes in variability, but we are not able to affirm climatic variability in a single future scenario. Therefore, in most sensitivity analyses, few climate change scenarios had reliable and explicit changes in variability due to considerable uncertainties in our knowledge regarding this subject.

(5) Although some consistent and qualitative results have been achieved, there is still much disagreement among these studies: Various climate change scenarios owing to changes in climatic variability appear to yield considerably different changes in crop production. In addition, climate change scenarios derived from one climate model may produce different responses in other crop models.

5. Summary

Progress in this area has been reviewed in context with understanding the uncertainties and challenges. We introduced the general methodological scheme to incorporate stochastic weather generators into climate impact studies as well as the specific ones in this study. Almost all the topics associated with this field such as the parameterization program and stochastic experiment of a typical stochastic weather generator WGEN, and its simulations evaluation, generation and adjustments of climatic variability, assessment of the impacts of changes in climatic variability on crop growth, final yield, and agro–climatic resources were included in the review. The outputs of short–term climate prediction models could be adopted in driving crop growth models to assess the impacts of climatic change in both averages and variability through the adjustment of parameters. Accordingly, we would expect more comprehensive results of climate impact assessment.

Future research should deal with the deficiencies in stochastic weather generators. For instance, in this study, WGEN tends to underestimate and overestimate the observed variance of monthly total precipitation and monthly total solar radiation respectively. Another challenging statistical problem is the development of stochastic models which are used to simulate weather variables simultaneously over both space and time (Hutchinson, 1995) rather than a particular site or range of sites. Definite climate change scenario must be affirmed or the range must be narrowed in climate simulation if we expect to make much progress in such incorporation instead of speculation. All these should be the subjects of further investigation for more robust conclusion.

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在气候影响研究中引入随机天气发生器的方法和不确定性

吴金栋　　王石立

摘　要

通过采用不同的随机天气发生器生成一定气候背景下各种气候变率情景，许多学者在最近的研究中已经认识到气候变率对农作物生长发育影响的重要性．传统的气候影响评估方法直接以大气环流模式的模拟试验结果作为未来气候情景，这样不可能理解如上的重要性．本文着重评述将随机天气发生器应用于气候变化影响研究的一般方法框架，以及作者的具体个例研究方法．文中最后分析了目前该领域研究中还存在的一些不确定性．

在当前的气候变化影响研究中，有不同的方法用来研制一种称为 WGEN 的典型随机天气发生器的参数化方案及其随机试验方法．不同的研究者也有不同的参数调控方法．通常的思

路是通过气候控制试验和 $2 \times CO_2$ 试验之间的气候变量平均值和方差的变化来扰动随机天气发生器的参数,以生成未来逐日气候变化情景。本文作者根据短期气候预测模式的输出产品建立了一套 WGEN 的参数化方案及其随机试验方法,并且在时间和空间两个尺度上检验和评估了此参数化方案下 WGEN 的模拟能力. 另外,作者由未来降水的变化,调试随机天气发生器参数,生成了气候变率变化情景. 这些参数调节可以产生各种不同类型和定性大小的气候变率变化,用于气候影响评估的敏感性分析. 通过如上方法,作为一个个例,文中评估了未来气候变率变化对中国东北地区玉米生长、最终产量和该地区农业气候资源的影响. 然而由于随机天气发生器本身以及参数调控方法的不足,目前将随机天气发生器应用于气候变化影响研究还存在一些不确定性. 检测和模拟气候变率变化信号是减少这种不确定性的必要途径之一.

关键词: 随机天气发生器,气候影响,气候变率