ON THE WEATHER-YIELD SIMULATION AND MODELS IN CHINA

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Received June 15, 1989

ABSTRACT

In this paper, the development of the studies on the weather-yield simulation and forecasting model in China is briefly reviewed, and the main features of the current development stage are presented. Moreover, through examples the technical characters, approaches and experimental results are detailedly described and discussed of several major statistical forecasting models, dynamic crop growth simulation and the satellite remote sensing methods to estimate crop yield. Finally, the line of further development and the applied field are pointed out. At the present time, in particular, using the above-mentioned modelling techniques to simulate and evaluate the possible impact of climatic variation on agricultural production and further on man's survival and activities are of a very practical significance as well as socioeconomic benefits.

I. INTRODUCTION

Food production is one of the basic conditions for the survival and development of human beings. However, the growth and development of crops and their ultimate yield are affected by both the natural environment and social conditions and, especially are closely related to the variation of meteorological conditions. In addition, since the 1970s climatic anomalies on a global scale has caused great perturbations in food production. It would directly affect china's stability and the life of the public. Therefore, analysing and understanding the relationship between crop growth and yield and variation of synoptic climate, studying and developing weather-yield simulative models, and applying the results of such studies to the monitoring, forecast and management of food production are extremely important not only to gaining advantages and preventing disasters in agricultural practives for stable and high yields, but also to the economic development, food supply and storage as well as trade planning both at home and abroad. Nowadays, with the rapid development of science and technology in the world the anthropogenic impact on environment and climate is getting more and more serious. Therefore, the studies on the problems are of a far more profound significance.

II. A BRIEF REVIEW

The study on the simulation and model of weather-yield relations in China began in the mid-70s. Before 1980, it had been at the stage of exploration and investigation (Wang et al., 1980; Baier, 1977; Coop. Group, 1980). After 1980, it entered the stage of applied research (Wang, 1982, 1983; Lan, 1982; Zhao, 1982; Wan, 1984; Gao, 1984). To date, a set of weather-yield models (mainly statistical models) of different time-space scales are developed and could be applied to yield prediction (Edit. Group, 1983; Wang, 1989b; Wan, 1988). Operational yield predictions and their services conducted at different levels of provinces, cities as well as some counties are warmly welcomed by departments concerned and have gained better socioeconomic benefits.

Since 1986, the weather-yield simulation and model have stepped into the new stage of application and service as well as of thorough studies. Their features can be summarized as follows:

(1) To popularize and apply the scientific achievements of simulation and models and to establish gradually an operational system of application, presently, with emphasis on prediction application (Wang, 1986a, 1986b, 1989b; Wan, 1988);

(2) To further advance the study of simulation and model, to develop dynamic simulation models for the growth of various crops, and to conduct modelling experiments of the relationship between climate variation and food production and corresponding analysis and assessment (Wang et al., 1989d; Li, 1986; Feng, 1987; Penning de Vries, 1982);

(3) To introduce satellite remote sensing techniques for yield estimation and to develop yield-prediction models and methods which take measurements of NOAA satellites as major data source (Coop. Group, 1987; Wang et al., 1989b; Xiao, 1986; Li, 1990; Tian et al., 1989; Zhu et al., 1989).

III. THE RESEARCH ON SIMULATION AND MODELS OF THE RELATIONSHIP BETWEEN WEATHER-CLIMATE AND FOOD PRODUCTION

In general, the present models for weather-yield simulation developed and used in China could mainly be classified into 3 types and 9 subtypes as shown in Table 1.

Table 1. Types of Models for Weather-Yield Simulation

Statistic models	Decomposition model Structure model Regression model
Dynamic growth simulation models	Model of main physiological processes Model for accumulation and distribution of assimilate products Model of yield formation
Remote sensing synthetic estimation models	Area estimation model Crop growth vigor model Greenness index-yield model

1. *Statistical Model*

As described above, various kinds of statistical models have been developed not only on different time-space scales, but also in different technical approaches, such as simple regression, multivariable regression, multiple regression, piecewise regression, stepwise regression, regression integral, principal component analysis and ridge regression. Also, they may use different predictors, including ground meteorological elements, characteristics of atmospheric circulation and SST (sea surface temperature), etc. In this paper, only some examples are given for illustration, and more details can be referred to the relevant literatures (Edit. Group, 1983; Wang et al., 1989b).

(1) *Statistical model for wheat yield all over China*

The master model is written as

$$Y = Y_t + Y_w + \Delta Y, \tag{1}$$

where Y is wheat yield per unit area; Y_t is tendency yield, also called the time-technological trend contribution of yield; Y_w is the meteorological contribution, simply named the meteorological yield; and ΔY is the "random noise". Y_t is calculated with the piecewise linear regression. The second order nonlinear models of temperature and precipitation at the representative stations were developed to estimate Y_w. They are a kind of typical decomposition model. The simulated values ($\hat{Y}$) fit well with the actual values (Y) for historical yields (shown in Figs. 1 and 2). The difference ($\Delta Y = Y - \hat{Y}$) is smaller, and most of the relative errors are within 10% (Wang, 1982, 1983a, 1989b; Edit. Group, 1983).

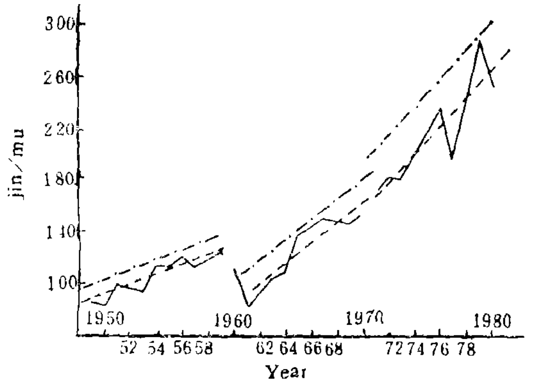

Fig. 1. Actual wheat yield (solid line) in China, 1949—1980; dashed line for trend yield and dot-dashed line for trend yield under the ideal meteorological conditions. 1 Jin = 0.5 kg, 1 mu = 666.7 m² = 0.06667 ha.

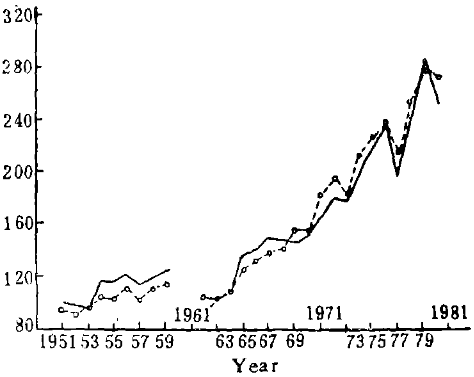

Fig. 2. The comparison of simulated (dashed) and actual (solid) yield of wheat in China.

(2) *Statistical structure model for rice yield*

As is known to all, rice yield consists of the three main components, i.e., the number of effective ears per unit area, the average number of grains per ear and the kilograin weight. However, these three components are formed under different environmental meteorological conditions in the corresponding periods of growth. Thus in terms of the key meteorological factors in the different periods of growth, the dynamic-statistical model could be constructed (stage by stage). It has the form:

$$Y_i = f(X_i), \tag{2}$$

where $i = 1, 2, \ldots, n$, is the number of development stages. Consequently, the final yield (Y) can be written as

$$Y = K \times Y_1 \times Y_2 \times Y_3 \cdots Y_n = K \prod^{n} f(X_i), \tag{3}$$

where Y_i can be the number of effective ears per unit area, the average number of grains per ear or kilograin weight etc. X_i are the critical meteorological factors, corresponding to the relevant development stages of crops, such as temperature, sunshine, precipitation, etc. Each component is related to the critical meteorological factors in the corresponding development stages of crops so as to establish component-submodels at first, and then, all submodels are combined to set up a structure model by "factorial" techniques. All experimental simulation and predictive application obtain better results, and most of the relative errors are no more than 5—10% (Wang, 1983; Jiang, 1983; Wang, 1986a).

(3) *SST-yield regression model*

It is assumed that SST is one of the important physical factors of long-term synoptic processes, and its variation would directly affect the atmospheric circulation in the Pacific Ocean and East Asia, thus causing perturbation of food production in this area. Therefore, the SST-yield regression models are developed on different geographic scales. The basic clue of these models is first to find the high correlation regions of ocean, then to analyse and test the differences in SST features among various production years and finally to construct prediction models by use of stepwise regression. The results show that the correlationship between SST and yield is stabler, the valid time of forecasting can be extented obviously and the prediction can also be improved due to reduction of indirect errors. Moreover, the larger the space scales, the better the forecasting (Zhao, 1982; Wang, 1984a; Wang et al., 1989b). It is a typical regression model with the fully physical and ecological significance.

Similar to techniques mentioned above, many researchers have also established the general circulation-yield regression models and other mixed regression models with circulation, SST and weather factors (Ji et al., 1989; Wang et al., 1989b; Wang et al., 1983; Wang, 1984b). In addition, the techniques of the principal component analysis, empirical orthogonal functions and field analysis are also applied to develop weather-yield models, and significant results are obtained (Yu et al., 1985; Shi et al., 1989; Wang et al., 1989b; Yang et al., 1989).

2. *Crop Growth Simulation Model*

This is a simulation model with well-defined mechanism, which considers the formation of crop yield as the processes of accumulation, distribution and transformation of net photosynthetic products during the crop growth, i.e., the processes of energy transformation and matter conservation. It is also named as dynamic growth simulation model. A quite number of investigations in this field have already been conducted in Holland, USA and USSR. However, in China the study is just in its infancy. Since the 1980s, a few case studies have been carried out on major crops, such as rice and wheat. For convenience of practical application, attemps have been made on restrictions that only those easily accessible observations are to be included in the model and efforts are directed to simplifying those complicated calculations.

(1) *The growth model of early rice*

It can be simply expressed by the following submodels(Feng et al., 1987;Exp. Group,1984).

1) Submodel of photosynthesis is given by

$$\frac{dP}{dt}=\frac{\mu_{CH2O}}{\mu_{CO2}}\,\frac{a}{1000}\int_0^s\int_0^F P\,dt\,ds, \qquad (4)$$

where dP is the photosynthetic product per unit leaf area (a) per unit time (dt), P is the photosynthetic intensity of rice, s is sunshine duration, F is a coefficient of green leaf area and μ is gram-molecular weight, a constant. The photosynthetic intensity is associated with sunshine intensity, furthermore, the latter is subject to the leaf temperature in relation to air temperature. Therefore, after the correction and calculation of canopy extinction coefficient, plant height and vertical distribution density of leaf area, the above-mentioned submodel can be transformed into a concrete running model.

2) Respiration (R) provides energy needed for maintaining the life and growth of plants. In the process the maintenance respiration is related to the mass and temperature of plants. On the other hand, the growth respiration is related to photosynthesis. Therefore, the submodel of respiration can be written as

$$\frac{dR}{dt} = B_0 \frac{dP}{dt} + (b_1 W_1 + b_2 W_2) Q_{10}^{\frac{T-T_1}{10}} + b_3 W_3, \tag{5}$$

where T_1 is the most desirable temperature for respiration, Q_{10} is the temperature coefficient of respiration. B_0, b_1, b_2, b_3 are the functions concerning properties of the crop, W_1, W_2 and W_3 are the dry weight of leaf, stem and root, respectively.

3) The accumulation of dry matter of rice (W) can be represented by the following formula:

$$W = \alpha(P - R), \tag{6}$$

where α stands for the efficiency of transforming net assimilation product into dry weight, and is usually called growth function.

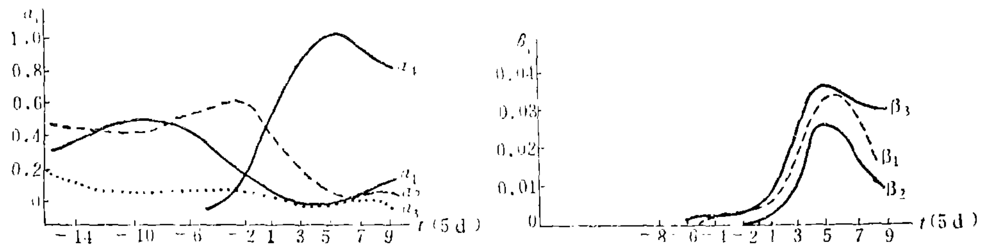

Fig. 3. The evolution of rice growth function with development range t.

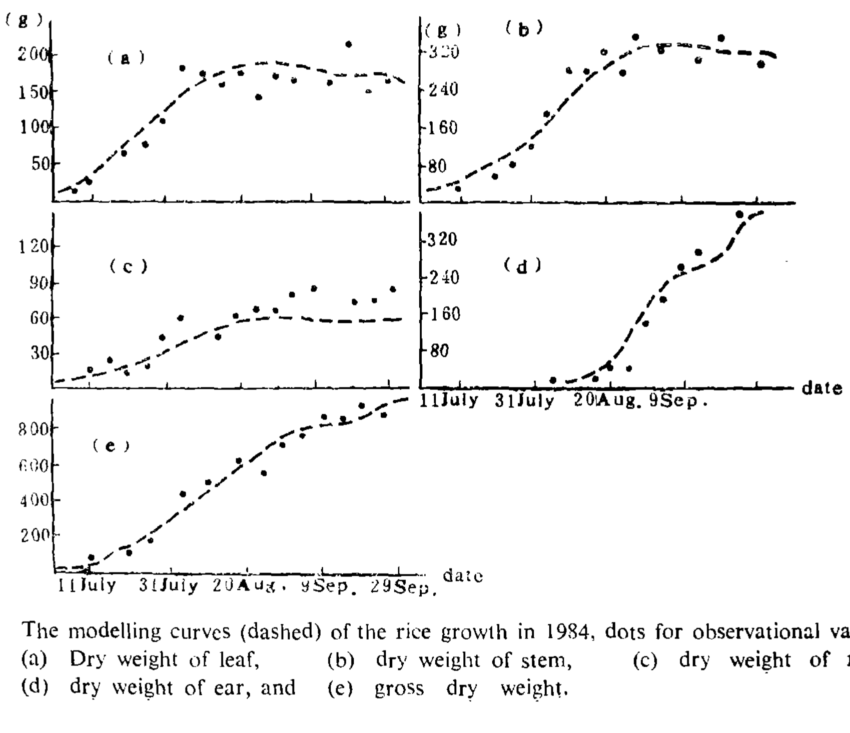

Fig. 4. The modelling curves (dashed) of the rice growth in 1984, dots for observational values. (a) Dry weight of leaf, (b) dry weight of stem, (c) dry weight of root, (d) dry weight of ear, and (e) gross dry weight.

4) The growth model of various organs (leaf, stem, root and ear) may be written as

$$\frac{dW_i}{dt}=\alpha_i(P-R)-\beta_i W_i,\quad i=1,2,3$$
$$\frac{dW_4}{dt}=\alpha_4(P-R)c+\beta_4\sum_{i=1}^{3}\beta_i W_i, \tag{7}$$

where α_i is the distribution coefficient of photosynthetic product, and $\alpha_1+\alpha_2+\alpha_3+\alpha_4=\alpha$; β_i is the diversion coefficient of assimilation product, $\beta_i>0$ indicates the diversion from the organ outwards, whereas $\beta_i<0$ indicates the diversion from other organs to the organ; c is the flow direction control switch of assimilation product (shown in Figs. 3 and 4).

5) The dynamic submodel of leaf area can be written as

$$LAg=\frac{W_1}{H}(1-F_d), \tag{8}$$

where LAg stands for colonial green leaf area, W_1 is the dry weight of colonial leaf, F_d is yellowing leaf rate and H is the ratio of dry weight of leaf sample to its area.

(2) *The simplified growth model of spring wheat* (*Wang et al.*, 1989*d*)

1) According to Penning de Vries et al. (1982), after the correction of radiation, leaf area of canopy and extinction coefficient, the rate of net photosynthetic assimilation can be expressed as

$$P=AF_l P_s, \tag{9}$$

where A is the proportional coefficient of assimilation product to carbon dioxide (CO_2) mole weight, F_l is the weighting coefficient after the correction of actual leaf area of canopy, and P_S is the net photosynthetic assimilation rate after radiation correction.

2) Gross respiration consumption R_t can be written as

$$R_t=P-CVF(P-R_mW), \tag{10}$$

where CVF is the efficiency coefficient of transforming primary photosynthetic product into the structure matter of plant. R_m is the consumption due to maintenance of respiration and W is the dry weight of plant. In calculation R_m must be corrected by the observed temperature.

3) The growth of various plant organs can be simply simulated by the following equations:

$$F_i=\frac{\Delta W_i}{\Delta W},\quad i=1,2,3,4,$$
$$FT_i=\frac{\Delta W_i}{W_i},\quad i=2,3 \tag{11}$$

where F_i is distribution function of assimilation product, ΔW_i is the growth increment of a given organ i, ΔW is the increment of gross dry weight of a plant, FT_i is the diversion function of assimilation product, W_i is the known dry weight of a given organ i and subscripts 1, 2, 3, 4 stand for root, leaf, stem and ear, respectively. After flowering, $F_4=1$, F_1, F_2 and F_3 are all zero. It is obvious that for a storing organ, the increasing dry weight of ear is

$$\Delta W_4=F_4\Delta W+\sum_{i=2}^{3}FT_iW_i, \tag{12}$$

4) In this simplified model, the dynamic growth of leaf area is calculated by

$$LAI = W_l SLA, \tag{13}$$

where W_l is the accumulation of dry leaf matter, SLA is specific leaf area and LAI is the leaf area index. It is found that the observational data in the field experiments and yellowing leaf rate can be used to correct and calculate these parameters.

The results of simulation using this simplified model are shown in Figs. 5 and 6.

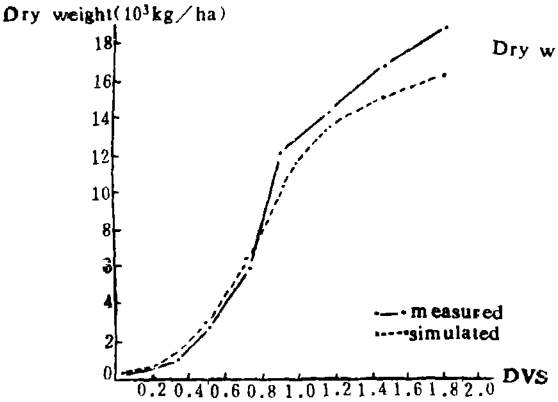

Fig. 5. The modelling curves of gross dry matter weight. DVS: development stage.

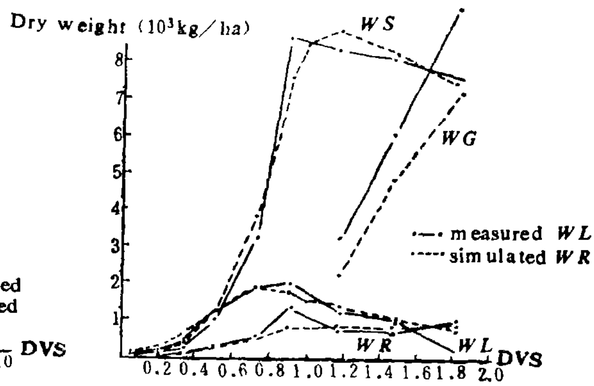

Fig. 6. The modelling curves of dry matter weight for various organs WL—weight of leaf, WR—weight of root, WS—weight of stem, and WG—weight of grain.

A similar modelling technique is used in the experiments on soybean, maize, early rice etc. The simulated values are also in good agreement with the observations (Li, 1986). Some of modelling results are presented in Table 2.

Table 2. The Simulation Results of Various Crops (Nanjing, 1984)

Crop	Calculated and observational values of biological yield of ten-day period		Gross biological weight (kg/mu)		Economic yield (kg/mu)	
	Correlation coefficient (r)	F	M	O	M	O
Soybean	0.9412	62.04	323.1	298.9	126.3	116.0
Maize	0.9757	158.6	892.6	853.1	411.7	374.0
Early rice	0.8663	27.1	781.7	770.6	358.0	356.6
Single cropping of rice	0.8350	23.03	1306.03	1268 24	561.5	546.0

M: Modelling, O: Observational.

3. *Remote Sensing Yield Estimation Model*

This is a synthetic yield estimation model which is developed on the basis of crop spectral reflectance characteristics and uses various space and ground spectro-radiometric measurements to monitor the growth status of crops and their planting area, and then to process, simulate and calculate these data in computer under the coordination of ground monitoring network. Since the 1970s, the remote-sensing technique has rapidly developed, especially, the LACIE (Large Area Crop Inventory Experiment) and AgRISTARS (Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing) programs implemented by USA have obtained the pioneering results. However, in China it started later. Since 1980, a lot of investigations and experiments have been done in the fields of the spectral response principles of remote sensing (Tian et al., 1989; Zhu et al., 1989), the estimation models and methods (Coop. Group, 1987; Wang et al., 1988; Wang et al., 1989b) and the experimental organization of operational synthetic estimation system by remote sensing of NOAA satellites (Li, 1990). As a results, great progress has been achieved.

(1) *The methods of yield estimation based on spectral data and landsat images*

The study of Tian et al. (1989) shows that the perpendicular vegetation index (PVI) is the best parameter for estimation of rice LAI. By use of the close relationship between LAI and total intercepted photosynthetic active radiation (TIPAR), the rice yield in a large area can be estimated from the photosynthetic transferred rate. Furthermore, Zhu et al. (1989) have considered that the spectral parameter PVI may be related to three components of winter wheat yield. Obviously, under normal conditions, LAI reaches the maximum value in the earing stage, then the stage of flowering can be predicted by extraplating 12—14 days after earing, and the maturing stage is at the time when the obvious dropping of $\sum PVI$ occurs. Therefore, the stages of earing, flowering and maturing can be determined by remotely-sensed spectrum measurements, and thus the complete ground model of remote sensing estimation of crop yield is designed.

(2) *Yield estimation model by remote sensing of NOAA satellite*

The technical approaches to develop remote sensing-statistical estimation model of crop yield can be briefly expressed as follows (Coop. Group, 1987; Li, 1990):

1) To establish a single or multivariate regression model for greenness-yield of winter wheat.

2) To set up greenness-pixel model for area estimation or construct area estimation model by use of the relationship between greenness and wheat-soil ratio.

3) To develop a new regression model to estimate the total production of winter wheat which sometimes is estimated by multiplying the area by yield calculated with the above models.

(3) *Synthetic operational system for yield estimation by remote sensing of NOAA satellite*

In order to rapidly exploit and apply the remote sensing techniques of NOAA satellites, the synthetic operational system for remote sensing yield estimation of NOAA satellites has been developed gradually and preliminarily in China since 1986 (Li, 1990). It consists of the following five subsystems:

1) subsystem of data collection and monitoring;
2) subsystem of data transmission;
3) subsystem of computer's data processing;
4) subsystem of synthetic estimation-prediction;
5) subsystem of service-advisory.

Based on the research described above, a quasi-operational prediction experiment for synthetic winter wheat yield estimation by remote sensing of NOAA satellites started in 1986. The annual harvest tendency, yield trend and yield prediction have been issued correspondingly in March, April and May every year. The results of these experimental predictions show that it is feasible to make the crop output prediction for large areas by the satellite (NOAA) remote sensing.

IV. APPLICATION AND BENEFIT

Meteorological modelling of crop yield has been put into practical services in China, even since they were just established. According to incomplete statistics, from 1982 to 1985, over 60 experimental forecasts, either on nationwide scale or on multi-provincial scale have been provided. The average absolute errors are no more 5% as compared with the results of estimation and survey performed by departments of agriculture and statistics. Although there are 4 or 5 forecasts with the deviation slightly over 10%, the forecasting trend of yield is still generally in good agreement with the changing trend of actual yield. However. the time range of forecasting is usually 1 to 3 months. The satellite remote sensing model for synthetic estimation of winter wheat yield which started later has also achieved the similar results with the deviation less than 5% as compared with the actual yield during the experimental period from 1986 to 1988. As indicated in the above figures and tables, the results of growth simulation models are very encouraging and socioeconomic benefits are satisfactory though the study on these models is still in its initial stage. Therefore, the further study and application of all of these models will draw the attention and win the encouragement from agricultural production departments and government administrations.

V. CONCLUSIONS

From the above discussion, it can be seen that the simulation study on the impacts of climatic variation on food production has begun in China and has achieved some useful results. However, it is still lagging far behind as compared with the current development in the world and many experiments and varifications remain to be done in years to come, especially in the field of the dynamic growth simulation and model.

It should be noted particularly that with the rapid advance of science and technology in the world the anthropogenic impact on environment and climate has become increasingly serious. For instance, the greenhouse effect, caused by the increasing concentration of CO_2 in the atmosphere may not only have its direct influence on the balance among biosphere, atmosphere and hydrosphere, but also. through the environmental climatic change, have a far more significant impact on the agricultural production upon which man survives. Therefore, many countries are taking measures to mitigate the current impacts of climatic variation on agricultural production and ecological environment. The technique of weather-yield modelling is an effective tool and research approach in simulating and assessing the possible impacts of climatic variation on agricultural production and further on man's survival and activities. Thus, it may be foreseen that a further development and much more socioeconomic benefits must be gainned.

REFERENCES

Baier, W. (1977), Crop-weather models and their use in yield assessments, *Technical Note No* . 151, WMO.

Cooperative Group of the Project of Studies on Agrometeorological Forecasting Methods (1980), *The Selected Papers of Agrometeorological Forecasting Methods*, 151pp. (in Chinese).

Cooperative Group for Synthetic Estimation of Winter Wheat Yield by Using Unified Remote Sensing Network in Beijing-Tianjin-Hebei Area (1987), *Proceedings of Experimental Studies on Estimation of Winter Wheat Yield by Using Remote Sensing in Beijing-Tianjin-Hebei Area*, Beijing Scientific and Technolog. Press, 233pp. (in Chinese).

Editorial Group for the Proceedings of Agrometeorological Forecast (1983), *The Proceedings of Agrometeorological Forecast*, China Meteor. Press, 119pp. (in Chinese).

Experimental Group of Rice Growth Simulation of Nanjing Institute of Meteorology (1984), A preliminary experimental report on the numerical modelling of rice growth and yield formation, *Scientia Meteor. Sinica*, No. 2 (in Chinese).

Feng Dingyuan et al. (1987), Numerical model for the rice growth and yield formation, *J. Nanjing Inst. of Meteor.*, No.2 (in Chinese).

Gao Suhua (1984), An investigation on the method of the crop harvest forecasting by synthetic determination, *Kexue Tongbao*, **29**:184—188 (in Chinese).

Gong Gaofa et al. (1983), A Study of the impacts of precipitation on harvest of winter wheat by the historical harvest records, *Acta Meteor. Sinica*, **41**:444—451 (in Chinese).

Ji Shuqin et al. (1989), The atmospheric circulation model for prediction of the total production in Liaoning Province, In "*The Studies on the Weather-Food Production Prediction in China*", China Meteor. Press, pp.224—230 (in Chinese).

Jiang Delong (1983), *Rice Production and Weather*, China Meteor. Press, 125pp. (in Chinese).

Lan Hongdi et al. (1982), The grain yield forecasting in Northeast China, *Kexue Tongbao*, **27**:383 (in Chinese).

Li Bingbai (1986), The preliminary analysis on the methods for crop's photosynthesis production and actual yield, *Agricultural Meteorology*, **7**: 4,1—8 (in Chinese).

Li Yuzhu (1990), Estimating Production of Winter Wheat by Remote Sensing and Unified Ground Network, II. Nationwide estimation of wheat yields, *Proceedings of* 1989 *Nottingham Easter School.*

Penning de Vries, F.W.T. et al. (1982), *Simulation of Plant Growth and Crop Production*, Pudoc, Wageningen, 320pp.

Shi Dingshan et al. (1987), A study on the dynamic simulation model of winter wheat yield. *Kexue Tongbao*, **32**:63—68 (in Chinese).

Shi Kelin et al. (1989), The study on yield field prediction at provincial level, In "*The Studies on the Weather-Food Production Prediction in China*", China Meteor. Press, 85—91 (in Chinese).

Tian Guoliang et al. (1989), Estimation of rice yield from remotely sensed data-II based on spectral reflectance and landsat images, *J. Remote Sensing of Environment*, **4**:1, 73—80 (in Chinese).

Wan Gongzhan et al. (1984), A preliminary study on yield forecast model of winter wheat in North China, *Acta Meteor. Sinica*, **42**:3, 356—363 (in Chinese).

Wan Gongzhan (1988), *Application Package in Basic-Language for PC-*1500 *Pocket Computer*, China Meteor. Press, 309pp. (in Chinese).

Wang Baosheng (1983), A study on the yield forecasting method for the variaty Shanyou No.4, In "*The Proceedings of Agrometeorological Forecast*", China Meteor. Press, pp. 33—36 (in Chinese).

Wang Duo et al. (1983), Analysis on the long-term fluctuation of the large scale circulation and corn yield in North and Southwest China, *Acta Meteor. Sinica*, **41**:4, 460—471 (in Chinese).

Wang Futang et al. (1980), A preliminary investigation on the yield forecasting model of wheat in Jiaxing County, *J. Nanjing Inst. of Meteor.*, No.1, 80—84 (in Chinese).

Wang Futang (1982), A study on yield forecasting method (I), *Collected Papers of Meteorological Science and Technology* (3) *Agrometeorology*, pp.60—69 (in Chinese).

Wang Futang (1983 a), A preliminary study on the agrometeorological forecasting model for national wheat yield in China, *Kexue Tongbao*, **29**: 564—567 (in Chinese).

Wang Futang (1986a), Lecture on methods for agrometeorological forecast (7), *Meteor. Monthly*, No.10, 39—43 (in Chinese).

Wang Futang (1986b), Lecture on methods for agrometeorological forecast (8), *Meteor. Monthly*, No.11, 37—41 (in Chinese).

Wang Futang et al. (1988a), An assumption on the trend of climatic variation and macroprograming of food production in China in 2000, *The Memorial Proceedings for 30th Anniversary of the Foundation of the Chinese Society of Sciences*, 86—92 (in Chinese).

Wang Futang et al. (1989a), A preliminary study on the periodicity of meteorological components related to crop yield, *Meteor. Monthly*, No. 1, 9—14 (in Chinese).

Wang Futang et al. (1989b), *The Studies on the Weather-Food Production Prediction in China*, China Meteor. Press, 272pp. (in Chinese).

Wang Jiasheng et al. (1988), The analysis and application on spectral indices of wheat, *Acta Agricultural Universitatis Pekinensis*, **14**:65—70 (in Chinese).

Wang Shiqi et al. (1979), Statistical analysis on the relationship between winter wheat yield and meteorological factors in Beijing region, *China Agricultural Science*, No. 1, 10—19 (in Chinese).

Wang Shili et al. (1989c), A study on the application of exponential smoothing method to meteorological forecasting of crop yield, *J. Academy of Meteor. Science, SMA*, China, **4**:2, 178—184 (in Chinese).

Wang Shili et al. (1989d), A preliminary study on simplified simulation models of spring wheat, *Annual Report* 1988—1989, China Meteor. Press.

Wang Shuyu et al. (1984a), The statistical forecasting of grain and soybean production in Jilin Province by sea surface temperature, *Agricultural Meteorology*, No. 1, 6—11 (in Chinese).

Wang Shuyu (1984b), A Statistical forecasting method of crop yield, *Acta Meteor. Sinica*, **42**:3, 349—355 (in Chinese).

Xiao Qianguang et al. (1986), Estimation of productivity using meteorological satellite, *J. Remote Sensing of Environment*, **1**:260—269 (in Chinese).

Yang Jiwu et al. (1989), The application of principal component analysis to weather-yield prediction for grain crops in Liaoning Province, In "*The Studies on the Weather-Food Production Prediction in China*", China Meteor. Press, pp. 69—75 (in Chinese).

Yu Ximin et al. (1985), Forecasting of the distribution of meteorological yield using the Chebyshev polynomial, *Agricultural and Forest Meteorology*, **34**:323—332.

Zhao Siqiang (1982), A preliminary investigation on the grain yield forecasting by using sea surface temperature, *Kexue Tongbao*, **27**: 1269—1272 (in Chinese).

Zhou Sisong et al. (1985), Application of AVHRR data to monitoring of crop growth condition, *J. Research of Agricultural Modernization*, No. 6, 51—53 (in Chinese).

Zhu Xiaohong et al. (1989), The structure analysis of winter wheat yield and the principle of remote sensing estimation of winter wheat yield, *J. Remote Sensing of Environment*, **4**:116—127 (in Chinese).