Impact Evaluation of Crop Yield with Simulated Occurrence of Temperature and Rainfall
— Simulation with SWAP Model —

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1. Introduction

The global warming due to rise of CO_2 concentration will lead to crop productivity increase in many of the cold latitudes but decrease in many of arid land area due to high temperature stress or drought. Not only temperature rise but also rainfall pattern changes accompanying the global warming. That is, it is considered that drought will progress further in arid land area and heavy rain will occur frequently in wet zone.

In this report, distribution property of rainfall and temperature were obtained from time series data in Saga. Then, we simulated daily rainfall and temperature using the Monte Carlo method and investigated the impact of crop yield with simulated occurrences of temperature and rainfall using the SWAP model.

2. Change of temperature and rainfall in Saga city

Fig.1 and 2 show the change of annual mean temperature and annual rainfall in Saga city for 1961-1999, respectively. As shown in Fig.1, annual mean temperature tends to increase. On the other hand, though annual rainfall changes greatly at each year, it does not tend to increase as a whole.

Fig.3 shows the variation of day number of daily rainfall greater than 20mm and 50mm. Both day numbers increase gradually since 1980. Thus, it is considered that rainfall property of Saga in recent years is characterized by an increase in rainfall intensity.

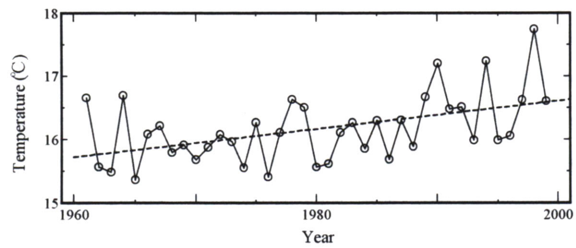

Fig.1 Variation of temperature in Saga (1961-1999)

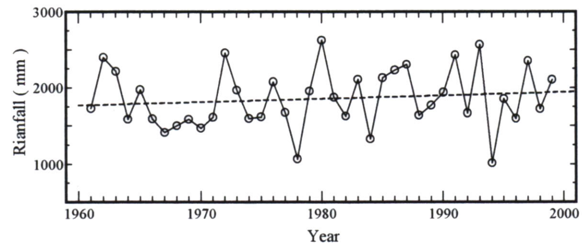

Fig.2 Variation of rainfall in Saga (1961-1999)

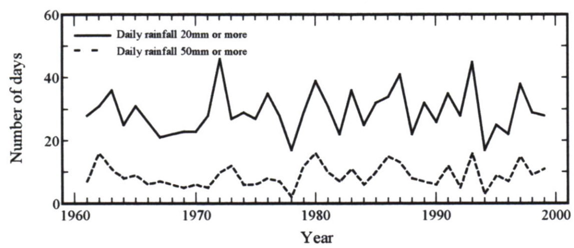

Fig.3 Day number of daily rainfall 20mm and 50mm over in Saga (1961-1999)

3. Simulation of rainfall

The amount of water supply, which is made available for plant, has a significant effect on the crop yield. Moreover, the interval of water supply may also have an effect on the crop yield, because the development stage that crop yield decrease owing to water stress is present in crop growth. Thus, in order to investigate the relationship between rainfall pattern and crop yield, rainfall pattern is analyzed by the probabilistic approach and rainfall is simulated.

Rainfall is characterized statistically by the occurrence probability of rainfall phenomenon and the probability distribution of rainfall. Rainfall records for 39 years are used to derive rainfall model parameters. It is necessary to consider the previous time period in calculating the probability of rain for a given day, the Markov Chain phenomenon. A day is defined as wet if 0.25mm or more rainfall occurred on that day. The conditional probabilities of rainfall P(W/D) and P(W/W) are obtained from the measured meteorological data for 1961- 1999. P(W/D) is the conditional probability that any day during W^{th} week will be wet, given that the previous day was dry. P(W/W) is the conditional probability that any day during i-th week will be wet, given that the previous day was wet. Fig.4 shows P(W/D) and P(W/W) in Saga.

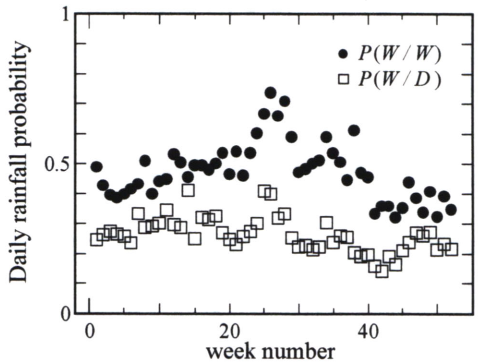

Fig.4 Rainfall probabilities for rainfall greater than 0.25mm at Saga

Next, Markov model is used for daily rainfall occurrences. The persistency of rainfall is represented by a Markov process[1], and the probability distribution of rainfall is taken as log-normal distribution. Then, daily rainfall is simulated using the Monte Carlo method[2].

4. Simulation of temperature

The probability distribution of temperature is represented as the normal distribution. From the measured temperature, the averages and standard deviations of temperature are computed for each day of the year for dry days and for wet days. These values are shown in Figs.6-9, and are expressed as the following polynomial equations (1)-(8). Then, daily maximum and daily minimum temperatures are simulated based on the normal curve combined with the Monte Carlo method.

$$MDT_{\max} = 11.3275 - 1.3370W + 0.2615W^2 - 0.0134W^3 + 3.8830 \times 10^{-4} W^4 - 6.5960 \times 10^{-6} W^5 + 4.6362 \times 10^{-8} W^6 \quad (1)$$

$$MDT_{\min} = 0.5043 + 0.2674W - 0.0850W^2 + 0.0120W^3 - 4.419 \times 10^{-4} W^4 + 5.9000 \times 10^{-6} W^5 - 2.4326 \times 10^{-8} W^6 \quad (2)$$

$$SDT_{\max} = 2.9502 + 0.0223W + 0.0081W^2 - 1.0446 \times 10^{-3} W^3 + 3.5491 \times 10^{-5} W^4 - 4.4428 \times 10^{-7} W^5 + 1.6961 \times 10^{-9} W^6 \quad (3)$$

$$SDT_{\min} = 2.8842 - 0.4071W + 0.0950W^2 - 7.4070 \times 10^{-3} W^3 + 2.4955 \times 10^{-4} W^4 - 3.79027 \times 10^{-6} W^5 + 2.13268 \times 10^{-8} W^6 \quad (4)$$

$$MWT_{\max} = 9.7973 - 0.48222W + 0.1288W^2 - 5.9298 \times 10^{-3} W^3 + 1.7980 \times 10^{-4} W^4 - 3.6376 \times 10^{-6} W^5 + 2.9356 \times 10^{-8} W^6 \quad (5)$$

$$MWT_{\min} = 3.3698 - 0.5736W + 0.1142W^2 - 3.8957 \times 10^{-3} W^3 + 1.0458 \times 10^{-4} W^4 - 2.5720 \times 10^{-6} W^5 + 2.4426 \times 10^{-8} W^6 \quad (6)$$

$$SWT_{\max} = 2.9054 + 0.4903W - 0.0791W^2 + 4.9285 \times 10^{-3} W^3 - 1.5093 \times 10^{-4} W^4 + 2.2661 \times 10^{-6} W^5 - 1.3259 \times 10^{-8} W^6 \quad (7)$$

$$SWT_{\min} = 3.2383 + 0.2955W - 0.04669W^2 + 2.7295 \times 10^{-3} W^3 - 9.2008 \times 10^{-4} W^4 + 1.6995 \times 10^{-6} W^5 - 1.2476 \times 10^{-8} W^6 \quad (8)$$

where W is week number, MDT_{max} and MDT_{min} are the average daily maximum and daily minimum temperature for dry days of the W^{th} week, SDT_{max} and SDT_{min} are the standard deviation of maximum and minimum temperature for dry days of the W^{th} week, MWT_{max} and MWT_{min} are the average daily maximum and daily minimum temperature for wet days of the W^{th} week and SWT_{max} and SWT_{min} are the standard deviation of maximum and minimum temperature for wet days of the W^{th} week.

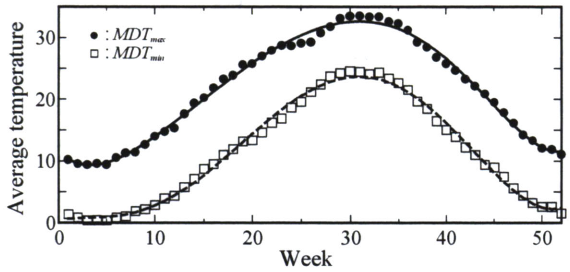

Fig.6 Variation of MDT_{max} and MDT_{min}

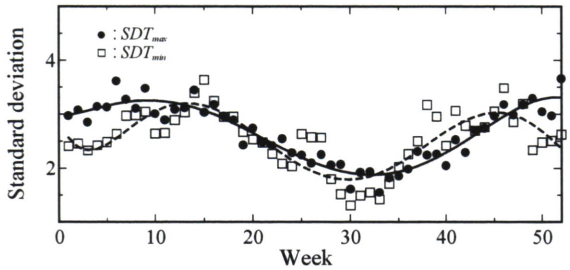

Fig.7 Variation of SDT_{max} and SDT_{min}

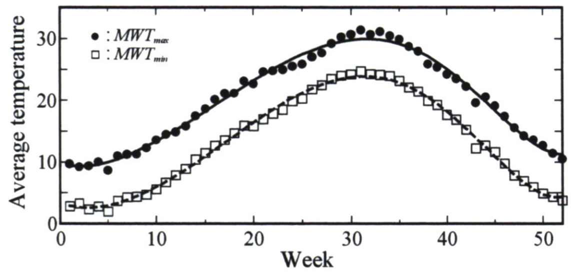

Fig.8 Variation of MWT_{max} and MWT_{min}

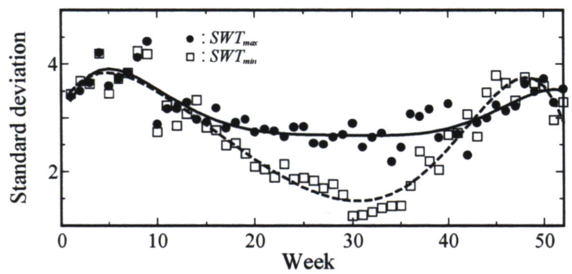

Fig.9 Variation of SWT_{max} and SWT_{min}

5. Simulation of SWAP model

(1) Analytical condition

SWAP [3] is a computer model that simulates water flow, solute transport and crop growth according to current modeling concepts. The program is designed for integrated modeling of the Soil-Atmosphere-Plant System. The input data of SWAP are meteorology, crop, irrigation, soil, drainage and surface water.

Daily meteorological data of Saga City weather station (1999) is used. Masa soil of one-layer is assumed, and it is divided into compartments as shown in Fig.10. The soil hydraulic function of Masa soil is expressed by the Mualem-van Genuchten equation[4] (9)-(11).

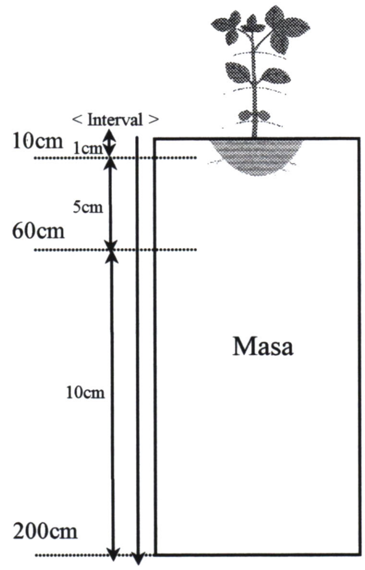

Fig.10 Cross section used in the analysis

Parameter α and n of these equation are obtain by the method of nonlinear least squares of measured data. Figs.11 and 12 show the calculated and measured values of h, θ and K. The field is cultivated with soybean, which emerges 1 August, and is harvested 1 November.

$$\theta = \theta_{res} + \frac{\theta_{sat} - \theta_{res}}{(1 + |\alpha h|^{n})^{m}} \tag{9}$$

$$K = K_{sat} S_e^{\lambda} [1 - (1 - S_e^{1/m})^{m}]^{2} \tag{10}$$

$$S_e = \frac{\theta - \theta_{res}}{\theta_{sat} - \theta_{res}} \tag{11}$$

where θ is the moisture content, θ_{res} is the residual moisture content (=0.125 cm^3/cm^3), θ_{sat} is the saturated moisture content (=0.495 cm^3/cm^3), $\alpha = 0.06182$, h is the soil water pressure head, $n = 1.51465$, $m = 1 - 1/n$, K is the unsaturated hydraulic conductivity, K_{sat} the saturated hydraulic conductivity (=1500cm/day),

S_e is the relative saturation and $\lambda = 0.5$.

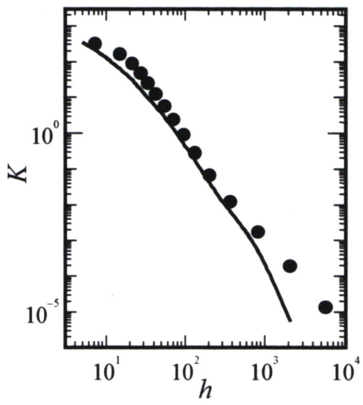

Fig.11 Relationship between h and K
(● : measured, —— : calculated)

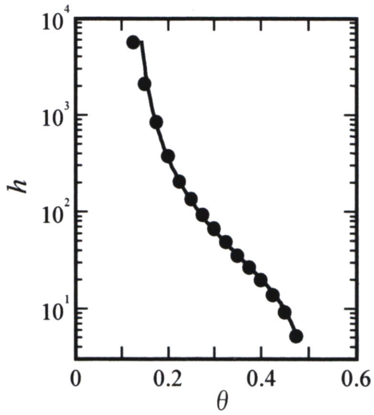

Fig.12 Relationship between θ and h
(● : measured, —— : calculated)

(2) Results and Discussion

The yearly average of simulated rainfall is 1664.0mm compared to an actual average of 1856.4mm computed from 1961 to 1999 for Saga City. The simulated yearly total rainfall ranges from 1000.0mm to 2768.3mm, while observed yearly total ranges from 1013.5mm to 2627.5mm. Therefore, on a yearly basis, simulated rainfall values are close to observed values.

Another important consideration in comparing simulated rainfall data with observed rainfall data is the frequency of occurrences of wet days, or the distribution of the number of consecutive dry days, referred to as dry runs. The number of times that only one day separated rainy days is counted for the simulated data for 39 years of observed data. This process is repeated for 2 days, 3 days and so on until the longest dry run is counted. The results of this comparison are shown in Fig.13. As shown from this figure, the simulated data are in good agreement with the observed data. Based on these comparisons, it is shown that the Markov Chain model can be effectively used to simulate rainfall data using the Monte Carlo method of simulation.

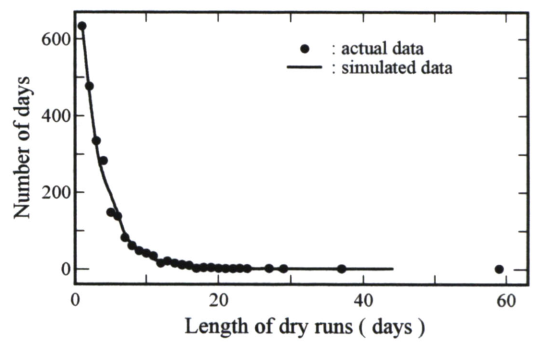

Fig.13 Comparison of dry sequence lengths from actual data and simulated data.

Figs.14 and 15 show the average daily maximum and daily minimum temperatures for both simulated data and observed data for wet days and for dry days, respectively. These figures indicate that the simulated temperatures follow the actual data the entire year for both wet days and dry days. Therefore, it is shown that the normal curve combined with the Monte Carlo method of simulation can be used to generate daily temperature data.

Daily rainfall, daily maximum and daily minimum temperature in 2003-2103 are simulated 30 times. In simulating daily temperature, average temperature is projected to increase by 2.2℃ over the period 2003 to 2103. Using these simulated data, yields of soybean in 2003-2103 are calculated by the SWAP model. Here, other daily meteorological data are used from measured data of Saga City weather station in 1999.

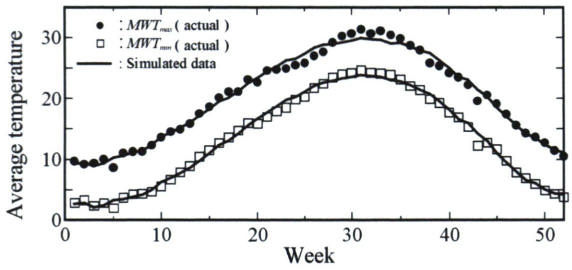

Fig.14 Comparison of actual data and simulated data for wet days.

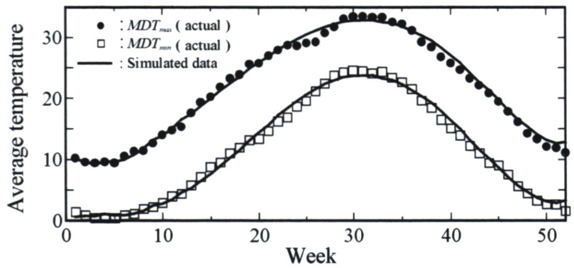

Fig.15 Comparison of actual data and simulated data for dry days.

Fig.16 shows the variation of average yield of soybean in 2003-2103, which average yield is the mean value that we calculated 30 times by the SWAP model at each year. As shown in this figure, average yield of soybean tends to decrease and average yield in 2103 is 13 % reduction as compared with that in 2003.

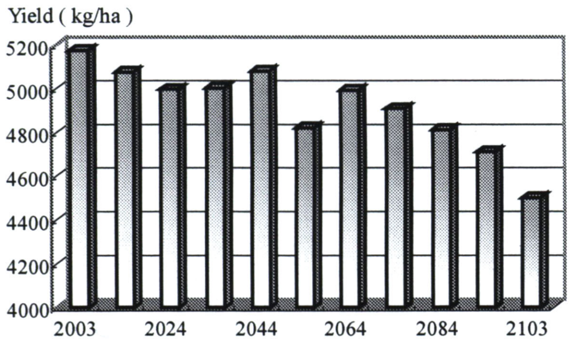

Fig.16 Variation of average yield of soybean.

Fig.17 shows the variation of occurrence probabilities that yields are 10%, 20%, 30% reduction and 10% increase as compared with the average yield of soybean in 2003 (5176 kg/ha). As shown in this figure, occurrence probabilities of yield of 10%, 20% and 30% reduction increase gradually, they are 60%, 27% and 13% in 2103, respectively. On the other hand, occurrence probability of yield of 10% increase drops, it is 6.6% in 2103.

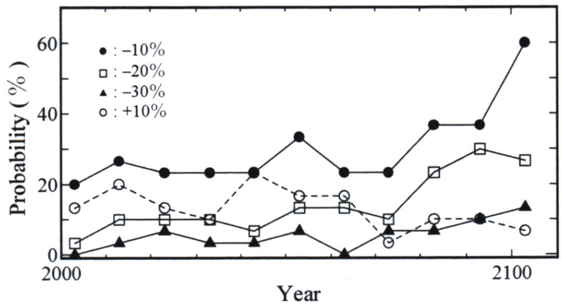

Fig.17 Variation of occurrence probability of yield based on the average yield in 2003.

6. Conclusions

The impact of rainfall and temperature in Saga on crop yield was investigated numerically using the SWAP model. The annual mean temperature in Saga increased for 1961-1999. On the other hand, though annual rainfall changed greatly at each year, it did not tend to increase as a whole. Day number of daily rainfall greater than 20 mm and 50 mm increased gradually since 1980. Therefore, it was considered that rainfall property of Saga in the recent year was characterized by an increase in rainfall intensity. From the probabilistic approach, daily rainfall occurrences were represented by the Markov Chain model, and daily rainfall was simulated by the Monte Carlo method. And, daily maximum and daily minimum temperature were simulated based on the normal curve combined with the Monte Carlo method. Simulated data of rainfall and temperature agreed well with observed data. Change of crop yield (soybean) with simulated daily rainfall and daily temperature was investigated numerically using the SWAP model. As a result, if the present rainfall property was maintained and average temperature was projected to increase by 2.2℃ over the period 2003 to 2103 , it was estimated that crop yield in 2103 would be 10-20% reduction as compared with that in 2003.

In predicting the change of crop yield accompanying the global warming using the SWAP model, it is necessary to obtain the meteorological data from probabilistic approach and investigate the existence of serious decrease in crop yield by repeating simulation using the obtained meteorological data.

In the future, we are planning to predict crop production of wheat and maize as main crops in Turkey using the SWAP model under the various climate scenarios.

References

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