GLOBAL COMPARISON OF THREE GREENHOUSE CLIMATE MODELS

C.H.M. van Bavel
Soil and Crop Sciences
Texas A&M University
College Station, TX
U.S.A.

T. Takakura
Agricultural Engineering
University of Tokyo
Tokyo
Japan

G.P.A. Bot
Physics and Meteorology
Agricultural University
Wageningen
The Netherlands

Abstract

Three dynamic simulation models for calculating the greenhouse climate and its energy requirements for both heating and cooling were compared by making detailed computations for each of seven sets of data. The data sets ranged from a cold winter day, requiring heating, to a hot summer day, requiring cooling. On the whole, the models agreed in regard to calculated air temperature, humidity, and heating requirements. Significant differences were found between the estimates of fan-and-pad (evaporative) cooling, and the estimated daily amounts of transpiration. These differences appear to be related to the manner in which each model simulated the internal air exchange and the stomatal conductance for transpiration. This report is the conclusion of an effort by a working party consisting of the authors, assisted by advice and comments of other ISHS members.

1. Introduction

The necessity of efficient energy use in protected cultivation has given rise to detailed studies of the many processes involved in the transfer and utilization of energy in greenhouses. For engineering purposes, both in construction design and in operational control, it is desirable to have adequate and yet practical methods for predicting the greenhouse climate from given external conditions, from construction and control parameters, and from crop characteristics. Consequently, there has been a world-wide activity in the formulation and testing of greenhouse climate models, many designed as computer simulation programs.

In a review report presented to the 1985 Wageningen Symposium, it was shown by Bailey how the growing complexity of the interaction between the outdoor and the greenhouse climate and of the climate control measures can be dealt with only by mechanistic simulation, if science and engineering are to keep pace with the expectations that growers have of modern technology. In another review paper at the same Symposium, Takakura has argued that climate models, to be useful, should be dynamic (i.e. capable of simulating energy storage and of keeping up with short-time changes, in the order of minutes), modular so as to be easily understood and modifiable, and flexible, that is, suitable for different greenhouse types and control methods.

The afore-mentioned considerations are particularly important when one considers the critical role that the greenhouse crop itself has in the flow and storage of mechanical and biological energy. Fortunately, the simultaneous solution and integration of the corresponding differential equations is no longer a problem, even if it needs to be done thousands of times. The result has been a proliferation of greenhouse climate models that may well confuse those that wish to solve practical problems by the simplest means possible.

At the 1983 Symposium in Columbus, Ohio, the senior author proposed that a working party should conduct a comparative study of some available models and present a report in 1985. This proposal was supported by Dr. G. Germing, the convener of the Wageningen Symposium and the effort was underway.

2. Methodology

The general approach to answering the question, whether different models give different answers in terms of predicting the greenhouse climate from a known set of environmental and greenhouse parameters, was as follows. A limited, but representative set of models of widely different origin was to be selected from those that had been described and tested in the literature. Each model was then to be used to calculate energy requirements and the greenhouse climate, defined in standard terms, for a set of weather conditions. This set, again, was to represent a global spectrum of the conditions under which protected cultivation can realistically take place, defined in terms of hourly (or more frequent) values of solar radiation, air temperature and humidity, and windspeed. A standard type greenhouse was to be chosen, but without specifying the climate control methods too closely.

The end result would then be a permutation of all models and climate sets, allowing an intercomparison over a wide range of conditions. We realized that the procedure was not perfect, in as much as the control action, rather than the control method, ought to be a boundary value or specification. However, documented data sets of simultaneously observed external and internal boundary values are virtually not available.

Originally, the plan called for five different models and five data sets. This schedule had to be reduced for practical reasons to three models, but the number of data sets was increased to seven, so as to include partially cloudy as well as clear days, ranging from quite cold to quite hot weather. Locations were Lubbock, Texas, Tokyo, Japan, and Wageningen, The Netherlands.

The models were chosen because of their availability and documentation, and of the need to fit the project in the available time. We recognize the existence of other work in the area, recent summaries having been given by Bot (1982) and, in this Symposium, by Takakura. The models used were:

(TX): SG79, a general simulation model using CSMP language, originally conceived for solar and fluid-roof greenhouse design. (Van Bavel, Damagnez, and Sadler, 1981).

(TO): M280H, a general simulation model also using CSMP language, based on early work by Takakura (1971), but in updated form by Takakura.

(WA): VENTWE, a general simulation model, originally oriented toward design of ventilation and heating controls in a Venlo type house, written as a CSMP program (Bot, 1983).

It should be stated here that any of these models could be translated in FORTRAN, PASCAL, or other languages, suitable for small computers, but at the expense of more programming and execution time.

The seven sets of climate data are identified in Table 1, with the required control action. More specific information is given in Table 2. In the cases of the four Lubbock sets and the two for Tokyo, the data were averages, typical for the time of year. Two cloudy periods of one hour (10-11, 13-14) were inserted to form a 'partly cloudy' variation. The Wageningen data are actual measurements every 3 min. averaged every 15 min., and show a clear morning, followed by a partly cloudy afternoon (Figure 2). The last three sets enable one to determine the short-term response and stability of each of the models.

In each case, the annual average soil temperature at the location and at 2 m depth was assigned at the beginning of the simulation (0 hours) to all soil layers. Initial air temperature and humidity in the greenhouse was set equal to the outside value at 0 hours.

The common greenhouse type was a glasshouse, of the gutter- connected Venlo design. Heating was accomplished by a pipe heating system controlled by an air thermostat. The detailed simulation of the heating system varied between models. Ventilation was controlled by an air thermostat and was accomplished either by opening ridge windows or the activation of exhaust ventilators. Again, the simulation details differed between models. Summer cooling was done by a fan/pad evaporative cooling system, operating at 80% of the theoretical efficiency and at 100 AC (air changes) per hour, controlled by an air thermostat. The leakage rate (infiltration) was set at 1 AC/hr. The operational characteristics are summarized in Table 3.

A detailed review of the three models cannot be given here. Suffice it to say that they are similar in respect to the following:

1. all boundary values are identical, except long-wave sky radiance.
2. all are continuous (time step 1 minute or less), modular, and flexible in being adaptable to all common types of greenhouses.
3. all use a multilayered soil compartment.
4. all are based on conservation of energy and mass, and are defined mathematically by a set of difference equations.

Important differences exist between the models with regard to:

1. the simulation of the penetration and absorption of solar radiation.
2. the equations of two parameters describing heat and mass transfer between the greenhouse air and the greenhouse crop.
3. the control functions for heating, ventilation and cooling.
4. the crop function describing stomatal action in regulating transpiration.
5. the method of estimating long-wave sky radiance.

All three models are capable of giving detailed and summarized information on the common climate characteristics: radiance inside the greenhouse, air temperature and humidity, as well as energy related variables: heating and cooling power, ventilation rates, and rates of water vapor loss. Many other variables can be obtained as well, such as roof (glass) temperature, crop temperature, soil temperature, pipe temperature, soil heat flux, transpiration rate, rate of condensation of water on the inside of the roof, stomatal resistance, among others.

3. Results

The data obtained in the first round of calculations were circulated and a review took place at a work group conference prior to the 1985 Symposium in Wageningen. Some errors and misunderstandings were noted and corrected, followed by a second round of calculations which are the basis of the present report. This report focuses on the principal greenhouse climate and control elements, with a few secondary results as well.

No details are presented on the results of the 'partly cloudy' sets for Lubbock and Tokyo. These simply showed that the models were all capable of responding to a sudden change in solar radiation, as produced by a cloud obscuring the sun and reducing the shortwave radiance by as much as 80% in a minute or less, as well as the inverse process. During such events no excessive cooling or heating was the result, as evidenced from the calculated air or crop temperatures, that remained stable and under control.

In Table 4, the calculated 24-hour heating or cooling requirements are given, showing that, for the winter and fall weather, the agreement is reasonable and adequate for engineering purposes. When the heating is marginal, as in the spring weather, or when cooling is required there are differences that cannot be ignored. We will comment on these later. A graphical comparison of the heating and cooling action for the winter, spring and summer data sets is given in Figures 1, 2, and 3.

The result of Figure 1 clearly shows essential agreement between models. In Figure 2, we see agreement during the morning hours, but not for the evening. This is caused by the fact that models TX and TO assumed clear sky conditions for calculating long-wave radiant exchange. When this condition is changed to the cloudiness of record, there is no evening heating, and there is agreement, as Table 4 shows. Figure 3 shows qualitative agreement, but a greater cooling requirement predicted by model TX, as compared to the other two. The former has a smaller mass transfer coefficient inside the greenhouse, resulting in lower transpiration, higher crop and air temperatures and, consequently, greater cooling requirements.

A comparison of calculated temperature extremes is given in Table 5, which shows essential agreement between the three models. Such differences as exist are likely caused by a somewhat different simulation of thermostat and heating/ventilation action. A single example of the concordance of temperature control between three models, on an hourly basis, is shown in Figure 4. Likewise, the maximum relative humidity during the morning hours, when this parameter is of the most practical interest, demonstrates fair agreement between models, as shown in Table 6.

A parameter of general interest is the amount of shortwave radiation actually absorbed by the crop or the soil (floor), as it indicates both the solar heating and the available light, as estimated by each model. Table 7 gives the daily total of shortwave radiation collected, of which about 50% is in the form of photosynthetically active radiation. Despite different approaches to the calculation, there is essential agreement, though the TX model probably overestimates at low sun angles and vice-versa. We may note that there is a significant difference between roof transmittance, as usually defined, and actual collection efficiency, as calculated.

All three models calculate the crop temperature, basically as the temperature of horizontal, transpiring leaves. The energy balance and resulting temperature of the foliage is a result, in actuality and in computation, of a complex set of equations that have parameters about which there is uncertainty and controversy. Table 8 shows significant differences between the predictions of the three models. Likewise, an other element of the foliage energy balance, the evaporation from the crop, shows differences of note, as may be seen in Table 9. In general, the TX model calculates lower evaporation rates and higher crop temperatures than the TO and WA models.

4. Discussion

In terms of climate parameters that are of greatest interest to greenhouse design engineers, extension horticulturists and growers, the three different models produce essentially the same results. It is reasonable to assume that other models, based on similar principles, will not be different either, though the actual methods of computation may vary widely. Therefore, we suggest that the first order of business should be reconciliation or codification of such remaining problem areas as have been noted, in contrast to the writing of entirely new programs and the construction of new models.

Another priority that our work seems to indicate is the potential for simplification of existing models, and the development of clear and concise user guides, preferably oriented toward the use of small (personal) computers and in a machine-independent language.

Our experience, nevertheless, indicates some problem areas. These appear to relate foremost to the current lack of knowledge about the convective exchange processes inside the greenhouse and the role that is played by ventilation, greenhouse shape and size, method of heating, and crop arrangement. Another area in which an inadequate data base or understanding prevents realistic modeling, is the role of stomatal regulation in gas exchange between the leaf interior and the greenhouse air.

Models such as the ones used in this report, are quite capable of calculating carbon dioxide depletion and the carbon dioxide requirements for enrichment. However, such estimates are bound to be sensitive to the manner in which stomatal action is simulated, as well as to the internal convection mechanism.

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Table 1. Description of the seven data sets used to compare three different greenhouse climate models.

Location	Season	Sky Condition	Heating	Cooling	Vent.
Lubbock	Winter	Clear	Yes	No	No
Lubbock	Winter	2 overcast hours	Yes	No	No
Tokyo	Fall	Clear	Yes	No	Yes
Tokyo	Fall	2 overcast hours	Yes	No	Yes
Wageningen	Spring	Partly overcast	Yes	No	Yes
Lubbock	Summer	Clear	No	Yes	No
Lubbock	Summer	2 overcast hours	No	Yes	No

Table 2. Details of weather conditions comprising the seven data sets used to compare three different greenhouse climate models.

	Date	Solar Rad.	Min/Max	Min/Max	Wind Speed
Location	day/mo.	MJ/m^2	°C	°C	m/s
Lubbock	15/12	9.8	-2/12	-7/1	3.0
Lubbock	15/12	7.7	-2/12	-7/1	3.0
Tokyo	27/11	11.0	5/13	-2/1	3.0
Tokyo	27/11	8.7	5/13	-2/1	3.0
Wageningen	15/05	12.0	6/16	3/10	0.6-3.0
Lubbock	15/06	30.0	18/32	14/17	3.0
Lubbock	15/06	25.0	18/32	14/17	3.0

Table 3. Specification of the glasshouse and its climate controls as used in the calculation of the climate by three different models.

Heating	Thermostat set at	15°C
	Heating capacity	200 W/m^2
	Heating power proportional to deviation	
	Simulation of hot water pipe heating	
Ventilation	Passive (infiltration)	1 AC/h
	Window or fan	10 AC/h
	Thermostat set at 25°C	
Cooling	Forced ventilation	100 AC/h
	Evaporative cooling	80% efficiency
	Thermostat set at	25°C

Table 4. Daily requirement for heating or cooling, as computed for clear days at four different locations and seasons, using three different models.

		Heating or Cooling (MJ/m^2 per day)		
Location	Season	TX	TO	WA
Lubbock	Winter	6.7	7.5	6.1
Tokyo	Fall	4.7	5.7	4.0
Wageningen	Spring	2.3[a/]	1.8[a/]	1.7
Lubbock	Summer	5.6	2.3	3.2

[a/] AM only

Table 5. Daily extreme values of greenhouse air temperature, as *computed for clear days at four different locations and* seasons, using three different models.

		Min/Max Inside Temp (°C)		
Location	Season	TX	TO	WA
Lubbock	Winter	13/20	15/19	13/23
Tokyo	Fall	14/26	15/22	13/25
Wageningen	Spring	14/25	15/25	14/27
Lubbock	Summer	17/25	19/25	17/25

Table 6. Maximum relative humidity during the morning hours (0-12 h), as computed for clear days at four different locations and seasons, using three different models.

		Maximum Rel. Hum. (%)		
Location	Season	TX	TO	WA
Lubbock	Winter	61	67	65
Tokyo	Fall	62	74	70
Wageningen	Spring	79	82	77
Lubbock	Summer	87	95	94

Table 7. Daily amount of solar (shortwave) radiation absorbed inside the greenhouse as computed for clear days at four different locations and seasons, using three different models.

		Solar Radiation Collected (MJ/m^2 per day)		
Location	Season	TX[1/]	TO[2/]	WA[1/]
Lubbock	Winter	4.6 (47%)	5.8 (60%)	4.3 (44%)
Tokyo	Fall	5.2 (47%)	6.5 (60%)	4.6 (44%)
Wageningen	Spring	5.7 (47%)	8.4 (69%)	5.9 (50%)
Lubbock	Summer	14.1 (47%)	19.7 (69%)	15.6 (52%)

[1/] "collected"

[2/] "inside greenhouse"

Table 8. Maximum crop (foliage) temperature as computed for clear days at four different locations and seasons, using three different models.

		Max. Crop Temperature (°C)		
Location	Season	TX	TO	WA
Lubbock	Winter	27	21	25
Tokyo	Fall	30	25	28
Wageningen	Spring	31	30	30
Lubbock	Summer	38	35	31

Table 9. Daily total evaporation as computed for clear days at four different locations and seasons, using three different models.

		Evaporation (mm/day)		
Location	Season	TX	TO	WA
Lubbock	Winter	0.7	1.7	1.5
Tokyo	Fall	1.0	1.6	1.5
Wageningen	Spring	1.1	1.9	1.5
Lubbock	Summer	3.7	4.7	4.6

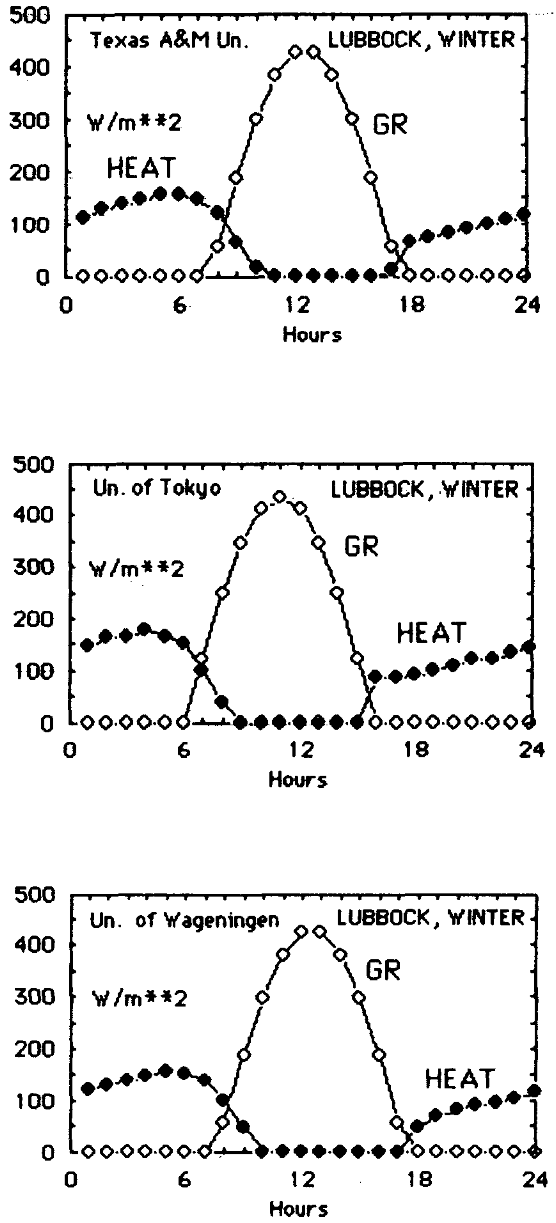

Figure 1. Daily course of incoming solar radiation at Lubbock, Texas on a clear winter day, and heating rate to maintain interior temperature at 15°C, as calculated by 3 models.

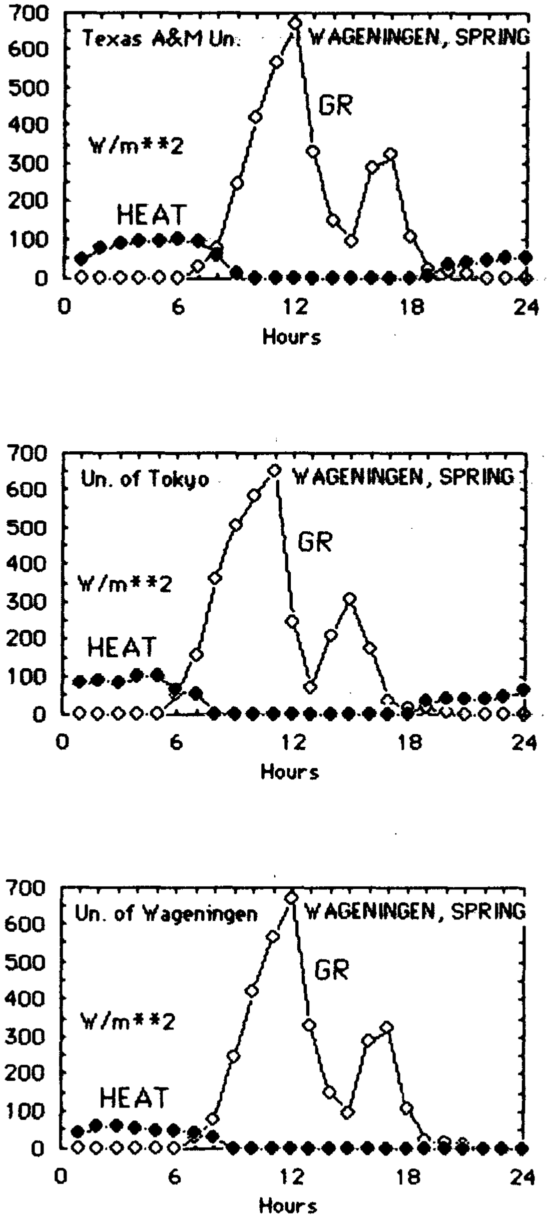

Figure 2. Daily course of incoming solar radiation at Wageningen, The Netherlands on a clear spring day, and heating rate to maintain interior temperature at 15°C, as calculated by 3 models.

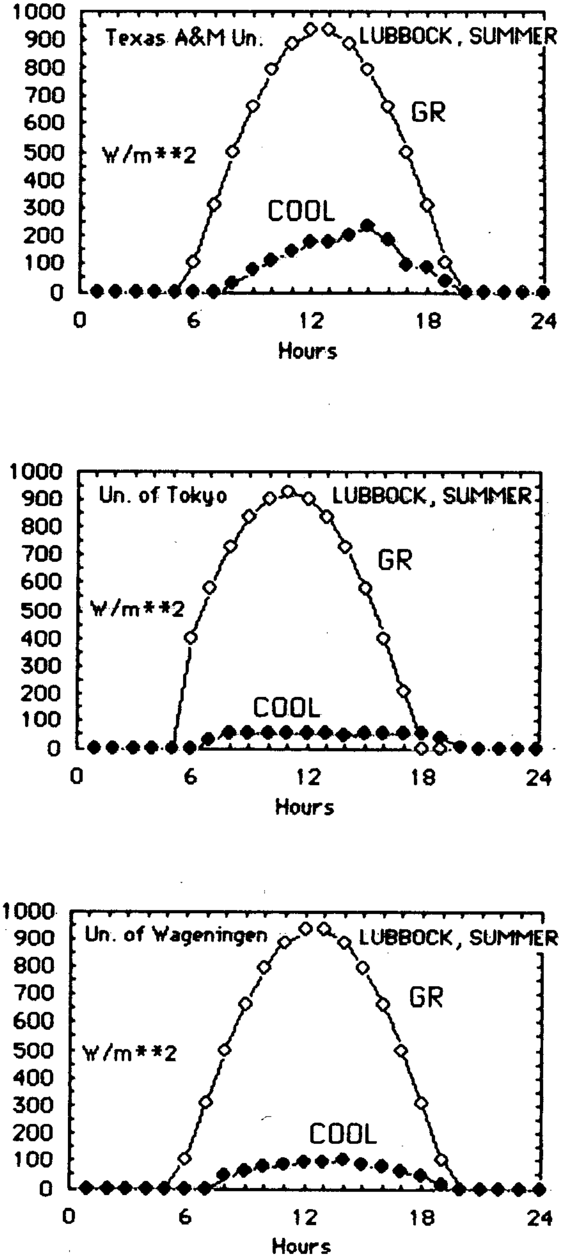

Figure 3. Daily course of incoming solar radiation at Lubbock, Texas on a clear summer day, and cooling rate to maintain interior temperature at 25°C, as calculated by three models.

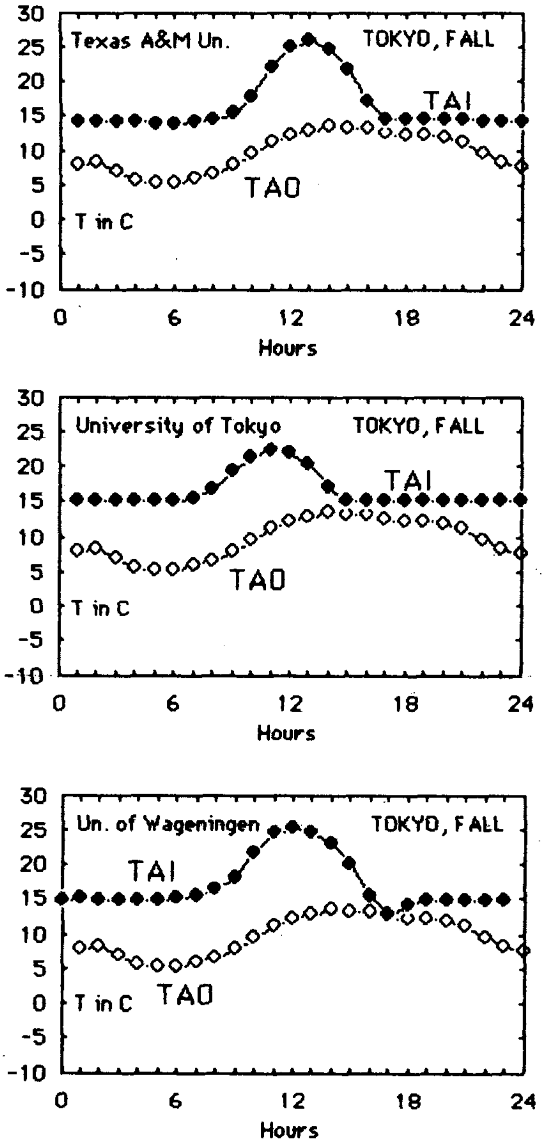

Figure 4. Daily course of outside and inside temperatures at Tokyo, Japan on a clear fall day, with heating at night to maintain 15°C and ventilation during the day to maintain 25°C, as calculated by 3 models.