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METEOROLOGICAL EFFECTS ON SOIL MOISTURE AND CROP YIELD AS DETERMINED FROM THE SOYBEAN CROP SIMULATOR: GLYCIM

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METEOROLOGICAL EFFECTS ON SOIL MOISTURE AND CROP YIELD AS DETERMINED FROM THE SOYBEAN CROP SIMULATOR: GLYCIM

A Thesis in

Meteorology

by

Stephen N. Di Rienzo

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Abstract

Estimation of near surface soil moisture availability is of great importance to meteorologists and agriculturists. Potential benefits from knowing the soil volumetric water content include healthier crops, savings in water and money, and reduced leaching of hazardous chemicals into groundwater supplies. Many methods of estimating soil moisture have been developed. Devices to measure volumetric water content include tensiometers, porous electrical resistance blocks, neutron scatterers, Time Domain Reflectors (TDRs), and capacitance probes. Meteorologically driven computer models have also been constructed to estimate the soil volumetric water content. Computer crop simulators must also estimate soil moisture for the plants themselves as well as the nutrient content and flow in the soil.

This thesis discusses some problems in the soil moisture module of the soybean crop simulator: GLYCIM. Initial model calculations are compared to a proven soil hydrology model. Improvements were made to the soil moisture module of GLYCIM so a more accurate estimation of soil volumetric water content and nutrients in the soil are calculated and available to plants in the model. Soil volumetric water content was then compared to the soil hydrology model for verification and differences were explained. Sensitivity tests were then carried out on GLYCIM to see which meteorological conditions are most important to soil volumetric water content as calculated by the model and also to crop yield as forecast by GLYCIM. Maximum probable error for soil volumetric water content and crop yield were calculated.

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Finally, I would like to thank my family for their patience and acceptance of my long hours needed to complete this project.

Chapter 1.

Introduction

1.1 Motivations

Estimation of near surface (1-2m) soil moisture availability is of great importance to meteorologists and agriculturists. Soil moisture is often considered the most important variable in partitioning the available net radiation at the surface between latent and sensible heat fluxes. It has been shown that soil moisture significantly affects atmospheric circulations both on local and regional scales (Yeh et al., 1984; Avissar and Pielke, 1989), and soil moisture distribution can have an important effect on outbreaks of severe weather (Lanicci, et al., 1987; Chang and Wetzel, 1991). For the agriculturist a knowledge of atmospheric circulations and associated weather is important because meteorological variables are prime determinant of soil moisture and crop yield. To the agriculturist, monitoring and measurement of soil moisture under crops, especially irrigated crops, is part of an integrated management scheme that helps avoid: (1) the negative effects on crops associated with under and over irrigation, and (2) the environmentally costly effects of over irrigation which include wasted water and energy, the leaching of nutrients and agricultural chemicals into groundwater supplies, and degradation of surface water supplies by sediment-laden irrigation water runoff (Ley, 1994).

As stated above, meteorological variables and surface soil moisture are linked to one another. This thesis explores the link between meteorological variables, surface soil moisture, and crop yield by showing how meteorological variables determine surface soil moisture and crop yield. In a practical sense, if agriculturists had continuous measurement of atmospheric variables, an estimate of surface soil volumetric water content at all depths in the surface layer could be made. They would then use that estimate to irrigate only when necessary (if irrigation was available). Better forecasts of crop yields based on soil moisture could be made. Application of pesticides for controlling underground pests could be better regulated, and, finally, less soil would be lost from fields due to runoff, if a good estimate of soil moisture was available.

1.2 Soil Moisture Measurement

Soil sampling is the only direct method for measuring soil water content, and is often used for calibration of other techniques. Soil sampling involves taking soil samples from each desired depth in the soil and temporarily storing them in waterproof containers. The samples are then weighed and the open containers oven-dried. The dry samples are then weighed again and the volumetric soil water content can be computed from the weight of water removed, the sample dry weight, the volume of soil, and the soil bulk density. Many samples from a given field should be taken to reduce the inherent sampling variability (Bell et al.,1980).

As one can see, soil sampling is a tedious, labor intensive, and expensive way to measure soil moisture, and therefore, its use is limited. However, the management of soil moisture has great cost and environmental impact to agriculturists. Because of this necessity to measure soil moisture, and the work involved in sampling soil moisture, many other devices to quantify or estimate soil moisture in the field have been developed. These include tensiometers, porous electrical resistance blocks, neutron scatterers, Time Domain Reflectors (TDRs), and capacitance probes.

Computer modelers have developed meteorologically driven soil moisture models to calculate soil moisture (Abramopoulos et al., 1988; Groves, 1989; Capehart, 1992; Capehart and Carlson, 1994), and at least one of these soil moisture models is being used to initialize regional scale atmospheric prediction models (Smith, et al., 1994). These models require initial conditions of moisture availability plus weather data of the type taken at class-A reporting stations with the addition of net radiation. Commercial soil moisture models that run on personal computers and ingest weather data from field weather stations are available to farmers and agricultural consultants. Computer crop simulators have been developed to forecast crop yields. Because soil moisture plays an important role in plant growth and maintenance, it must be modeled in crop simulators.

1.3 Research Objectives

The need to know the surface soil moisture profile leads to three research objectives. The first is to compare the soil volumetric water content for a given soil as calculated by two separate models driven by the same set of meteorological data. The first model is GLYCIM which is a soybean crop simulator developed by Acock and Trent (1991), and the second is the Soil Hydrology Model (SHM) developed by Capehart (1992). The SHM has been tested against neutron probe measurements under a wide variety of conditions and found to be quite accurate. On the other hand, the soil water content as calculated by GLYCIM is believed to be a weak point in the simulator (personal communication with Dr. Basil Acock).

Should large differences occur in the calculations of volumetric soil water content between the models, a modification of the soil moisture module in GLYCIM would be developed to improve its ability to calculate soil water profiles. This will be done by altering the computer code in the soil moisture module and running simulations with the original weather data again. Final results of calculations of volumetric soil water content will be compared to output from the SHM for verification.

The second objective is to see if any further improvements can made to the SHM. Vegetation parameters such as root zone depth and crop height are set in the SHM under the generic vegetative type "agriculture". Any improvement to the SHM leading to the parameterization of a specific crop such as soybeans would be welcome.

The third objective is to determine what effect weather data measurement errors have on the soil volumetric water content, and soybean crop yield as determined from GLYCIM. In order to explore model response to the input parameters, sensitivity tests will be conducted in which input parameters are individually varied from a set of baseline values. From these tests, the most significant input parameters will be determined as well as the maximum probable error in soil volumetric water content and crop yield as determined from the soybean crop simulator, GLYCIM.

Chapter 2.

Description of GLYCIM

2.1 General Description of Model

GLYCIM is a simulator (a means for making predictions) of the soybean crop developed in cooperation with the United States Department of Agriculture at the University of Idaho College of Agriculture. GLYCIM consists of a set of mathematical equations written in FORTRAN 77, such that the calculations can be done quickly and accurately by a computer. These equations describe many of the mechanisms involved in the physical and physiological processes taking place in the plant and its environment. The processes of light interception, carbon and nitrogen fixation, growth and death, flows of water, nutrients, heat and oxygen in the soil, and more are included (See table 2.1).

GLYCIM was designed to make predictions and to test hypotheses. It includes mechanisms to simulate the growth of soybeans from any maturity group, on any soil, at any location and time of year. It has the potential for enabling farmers to optimize the use of their resources, to help government agencies to make better yield predictions, including the prediction of yields in a world with different CO_2 concentration and climate, and to help teachers instruct students in a new way.

GLYCIM is not a finished product, but a vehicle that other scientists may use to test their own modules and thus improve the main model (Acock and Trent, 1991). GLYCIM has a modular structure. A model with this structure has the following benefits: (1) it is easier to validate the individual modules; (2) it is thus easier to find faults in the computer code; (3) specialists can modify just those modules which deal with their own areas of expertise without knowing how the rest of the model worked; (4) it is easier to interchange code between models; (5) the model and modules could be useful teaching

Table 2.1. List of GLYCIM modules (subroutines) and when they are used.

Module Name	Purpose	Frequency of Use
COMMON	Sets variable types, dimensions arrays, holds common variables.	Each Run
MAIN	Controls when modules are called	Each Run
RSTATE	Reads stored variables from a manually stopped run.	Called Once Each Run
WSTATE	Writes stored variables to a manually stopped run.	Called Once Each Run
SOILIN	Reads soil characteristics and initial volumetric water content for each soil layer.	Called Once Each Run
OUTPUT	Outputs model generated data.	Called Daily
WEATHER	Calculates daylength, effective photo period, cloud cover, mean day and night air temperature, hourly air temperature and hourly vapor pressure deficit.	Called Daily

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Table 2.1. (continued)

Module Name	Purpose	Frequency of Use
LYTINT	Calculates hourly values of total and photosynthetically-active radiation that would be intercepted by crop canopy.	Called Daily
SOILEN	Updates volumetric water content, water potential, hydraulic conductivity, oxygen, ammonium, and nitrogen concentration, and temperature for each cell.	Called Hourly
PNET	Uses single-leaf photosynthetic characteristics to calculate crop canopy characteristics.	Called Hourly
PHEN	Calculates the vegetative and reproductive stages of growth and limits the growth of determinate plants.	Called Hourly

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Table 2.1. (continued)

POTGRO	Calculates potential rates of growth for all organs on the plant at the given air temperature.	Called Hourly
PARTIT	Calculates an initial partitioning of carbon to various plant organs.	Called Hourly
WATERS	Maintains a functional balance between root and shoot by growing root as necessary to meet transpiration demand.	Called Hourly
NUTRTS	Calculates a supply and demand for nitrogen in the whole plant, and calculates nitrogen fixing activity.	Called Hourly
ACTGRO	Calculates the actual growth in size and dry weight of all organs on the plant.	Called Hourly

aids. The goal here, as stated earlier, is to improve on the soil moisture flow scheme in GLYCIM and determine meteorological effects on soil moisture and crop yield as predicted by GLYCIM.

2.2 Required Data

Data is input into GLYCIM from four files: (1) Weather file; includes daily total solar radiation (Wm^{-2}), maximum and minimum temperatures (°F), rainfall/irrigation (mm day^{-1}), mean daily wind speed (km hr^{-1}), daily mean wet bulb temperature (°F), and daily mean temperature (°F). Meteorological data collection is discussed in Appendix B. (2) Plant file; includes maturity group number (00-VIII), whether determinate (0) or indeterminate (1) variety, latitude of planting (deg), Julian date of emergence, Julian date of first frost, row spacing (cm), plant population within the row (plants per meter), row orientation (deg from true north), operator's desired output frequency, time of day of output (hrs local time), seed fill rate at 24 °C (mg $seed^{-1}$ day^{-1}), atmospheric CO_2 concentration (ppmv), number of seeds per pound weight typical for cultivar, residual nitrogen as nitrate in soil at beginning of season (lb. $acre^{-1}$), residual nitrogen as ammonium in soil at beginning of season (lb. $acre^{-1}$), fertilizer nitrogen applied (lb $acre^{-1}$), fraction of fertilizer nitrogen which is nitrate, fraction of fertilizer nitrogen which is ammonium, organic matter added to the plow zone at beginning of season (lb $acre^{-1}$), the number of operator specified layers in soil profile (max. = 20), the number of columns in the soil profile (max. = 20), the depth of each soil cell (cm), Depth to which soil is cultivated (cm), the depth to a gas-impermeable layer from the soil surface (cm), temperature of the soil below the test volume (°C), a number to indicate whether initial values of volumetric soil water content are available for each soil layer (=1 if they are), depth of roots at date of emergence (# of cells), width of roots at date of emergence (# of cells), and percentage of roots in top 10 layers of soil. These Table variables as used in this study are summarized in table 2.2. (3) Cultivar dependent file; includes 15 parameters which are cultivar specific. (4) Soil file; includes soil type, description of site and location, number of layers in soil profile, saturated hydraulic matric potential (m) after Cosby, et al., (1984), and then for each layer soil depth (cm), hydraulic diffusivity at a soil water potential of -15 bars, volumetric water content of soil at a soil water potential of -15 bars ($cm^3 cm^{-3}$), slope of log (hydraulic conductivity vs. volumetric water content) , volumetric water content of soil at saturation ($cm^3 cm^{-3}$), field capacity of soil ($cm^3 cm^{-3}$), volumetric water content of air dry soil ($cm^3 cm^{-3}$), bulk density of soil ($g\ cm^{-3}$), soil characteristic parameter relating volumetric water content to water potential, saturated hydraulic conductivity [(cm^3 H_2O) (cm moved)$^{-1}$(cm soil water potential gradient)$^{-1}$day^{-1}], the soil percentage of sand , the soil percentage that is clay, saturated hydraulic conductivity (ms^{-1}) of the soil (Cosby et al., 1984), scaling function (Cosby et al., 1984), and initial soil layer volumetric water contents ($cm^{-3} cm^{-3}$). These are for a sandy loam type soil and are from the United States Department of Agriculture after Whisler (1976) except where noted and are summarized as used in this study in table 2.3.

The meteorological variables used in this study were obtained according to the methods described in Appendix B. All other variables used in this study were obtained as data files for GLYCIM from the United States Department of Agriculture. Plant variables in these data files were checked and modified for the proper soybean varieties grown at the average latitude for Pennsylvania according to Scott and Aldrich (1970).

Table 2.2. Plant file variables as used in this study.

Plant File Variable	Value as Used in This Study
Maturity Group Number	1
Indeterminate Variety	1
Latitude of Planting	40.20 deg N
Julian Date of Emergence	121
Julian Date of First Frost	308
Row Spacing	96.520 cm
Plant Population Within The Row	number of plants per meter
Orientation of Row From True North	135.0 deg
Output Frequency	once per day
Time of Day of Output	0800 Local
Seed Fill Rate at 24°C	7.50 mg $seed^{-1}$ day^{-1}
Atmospheric CO_2 Concentration	350 ppmv
Number of Seeds Per Pound Weight	2500
Residual Nitrogen as Nitrate in Soil at Beginning of season	35.0 lb $acre^{-1}$
Residual Nitrogen as Ammonium in Soil at Beginning of Season	3.5 lb $acre^{-1}$
Nitrogen Fertilizer Applied	0.0 lb $acre^{-1}$

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Table 2.2. (continued)

Fraction of Nitrogen Fertilizer Which is Nitrate	0.0 lb $acre^{-1}$
Fraction of Nitrogen Fertilizer Which is Ammonium	0.0 lb $acre^{-1}$
Organic Matter Added to Plow Zone at Beginning of Season	22,000.00 lb $acre^{-1}$
Number of Soil Profile Layers	20
Number of Soil Columns	4
Depth of Each Soil Cell	10 cm
Depth to Which Soil is Cultivated	18 cm
The Depth to Gas Impermeable Layer From the Soil Surface	200 cm
Temperature of Soil Below Test Volume	10°C
Initial Volumetric Soil Water Content Available (1=yes)	1
Depth of Roots on Date of Emergence	1 cell
Width of Roots on Date of Emergence	1 cell

Table 2.3. Variables used in the calculation of sandy loam soil volumetric water content according to equations in Appendix A plus additional soil file variables.

Hydraulic Coefficients	Variable	Value as Used in This Study
Saturated Soil Matric Potential (Cosby et al., 1984)	ψ_s	-0.0316 m
Hydraulic Diffusivity at a Soil Water Potential of -15 bars	D_o	.80610E-04
Volumetric Water Content of Soil at -15 bars	θ_o	.005 cm^3cm^{-3}
Slope of Log(hydraulic conductivity vs. volumetric water content)	β	43.36
Volumetric Water Content of Soil at Saturation (Cosby et al., 1984)	θ_s	.434 cm^3cm^{-3}
Field Capacity of Soil	θ_{fc}	.3255 cm^3cm^{-3}
Volumetric Water Content of Air Dry Soil	θ_r	.001 cm^3cm^{-3}
Bulk Density of Soil	*n/a*	1.159 g cm^{-3}

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Table 2.3. (continued)

Soil Characteristic Parameter Relating Volumetric Water Content to Water Potential	η	3.64
Saturated Hydraulic Conductivity	k_s	6.909 [(cm^3 H_2O) (cm moved)$^{-1}$ (cm soil water potential gradient)$^{-1}$ day^{-1}]
Percentage of Soil That is Sand	*n/a*	46
Percentage of Soil That is Clay	*n/a*	10
Saturated Hydraulic Conductivity (Cosby et al., 1984)	k_s	6.19E-06 ms^{-1}
Scaling Function (Cosby et al., 1984)	b	4.74
Initial Soil Volumetric Water Content For All Layers (50% of Saturation)	θ_i	.217 cm^3cm^{-3}

2.3 Description of GLYCIM Soil Moisture Module

The GLYCIM soil moisture module is a 2-dimensional model. Fluxes of materials between cells are calculated in the vertical and in one horizontal direction. These cells are rectangular blocks of soil with a thickness of one centimeter in the direction of the plant row and a width that is a sub-multiple of the spacing between plant rows. The vertical depth of each cell is user specified and was set at 10 cm for this study. Root activity and soil processes are assumed to be symmetrical about the plant row, so fluxes are calculated only for cells from the plant row to the mid-row and to the user specified depth (see figure 2.1).

The vertical planes below the plant row and the mid-row are assumed to be planes of symmetry and they are modeled as impervious boundaries to all materials so there is no horizontal flow across these planes. The treatment of upper and lower boundaries depends on the material considered. For water, the lower boundary is a sieve; water lost from the bottom of the profile is never recovered. This can be changed to fit other known local bottom boundary conditions such as a water table. Fluxes are first calculated in the vertical and then in the horizontal. Vertical fluxes from top to bottom in column 1 are computed then column 2, etc. After the vertical fluxes are calculated horizontal fluxes are calculated. Soil characteristics for each layer are required.

The flow of water in GLYCIM was calculated using a form of the Richard's equation (Richard's, 1931) as shown by Whisler (1976) and shown in appendix A except that the gravitational flow was not modeled according to the gravitational equation given in appendix A. Instead, water that entered the soil through the top layer was transported downward through all lower layers by filling each layer to field capacity in turn. This is not physically or observationally proper, and was probably the biggest cause of error in the volumetric soil moisture calculations (figure 2.2). The vertical transport equations

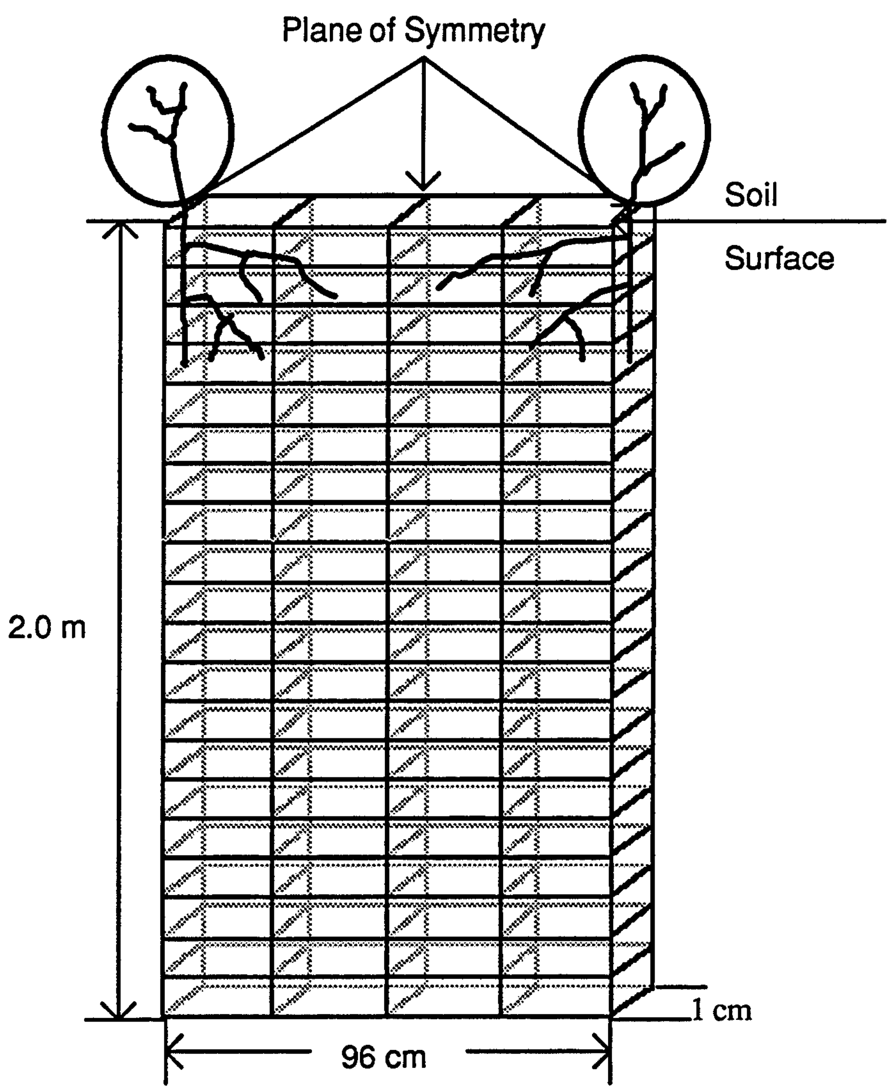

Figure 2.1. Schematic showing the soil profile between plant rows in GLYCIM. The soil profile is divided into a grid of rectangular cells each 1 cm thick in the direction of plant rows. Height and width of the cells are user specified and are as used for this study.

have been modified and are now analogous to those of Richard's (1931). The horizontal diffusion equation is according to Whisler (1976) and is a form of the Richard's equation and was not modified. A complete discussion of both GLYCIM and SHM soil moisture physics is given in Appendix A.

2.4 Model Comparisons

Comparisons between model output from the SHM and the modified GLYCIM are discussed in this section. Note that the modified GLYCIM is the new version that was modified to incorporate Richard's (1931) soil moisture physics. Figure 2.2 shows that although there are some differences, the soil volumetric water content for the top 40 cm of soil output by the modified GLYCIM compares much more favorably to the volumetric water content output by the SHM. The original GLYCIM obviously overestimated the soil volumetric water content, and kept the soil moisture at near field capacity. The modified GLYCIM still appears too high with values at the start of the period but I believe this is a problem with the way the SHM initializes on the first day of a run, and not a problem with the modified GLYCIM. On the first day of this run (1 May 1994), it rained nearly 4 cm. The SHM shows a drying of the soil from day 1 to day 2. This is probably not correct, and it appears in fact that the SHM fails to account for precipitation that falls on the first day of a run. Bill Capehart (personal communication) confirmed that the SHM does not account for precipitation on the initialization day. Initializing the SHM at 00Z on 30 April 1994 as opposed to 00Z on 1 May 1994 gives better results (figures 2.3-2.4). There was no precipitation on 30 April 1994.

The modified GLYCIM also is dryer at the end of the comparison period. This is probably due mainly to root depth. The SHM uses a root function which allows the roots to grow to a depth of 1/3 the vegetation height. Vegetation height for this case is about

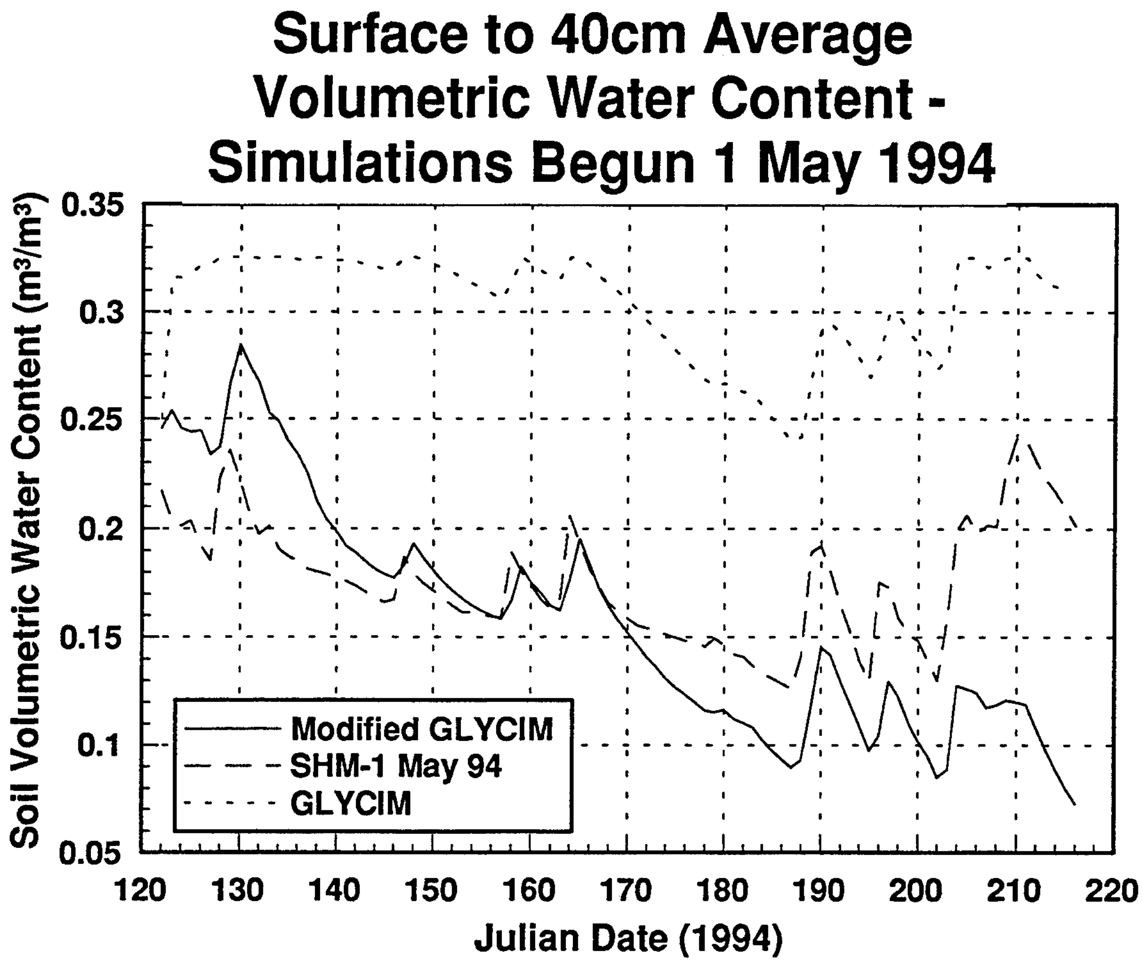

Figure 2.2. Surface to 40 cm average volumetric water content for simulations from GLYCIM, the SHM, and the modified GLYCIM all started on 1 May 1994 using data from Harrisburg, PA. Starting soil profile volumetric water content is uniform in all layers at 50% of sandy loam soil saturation.

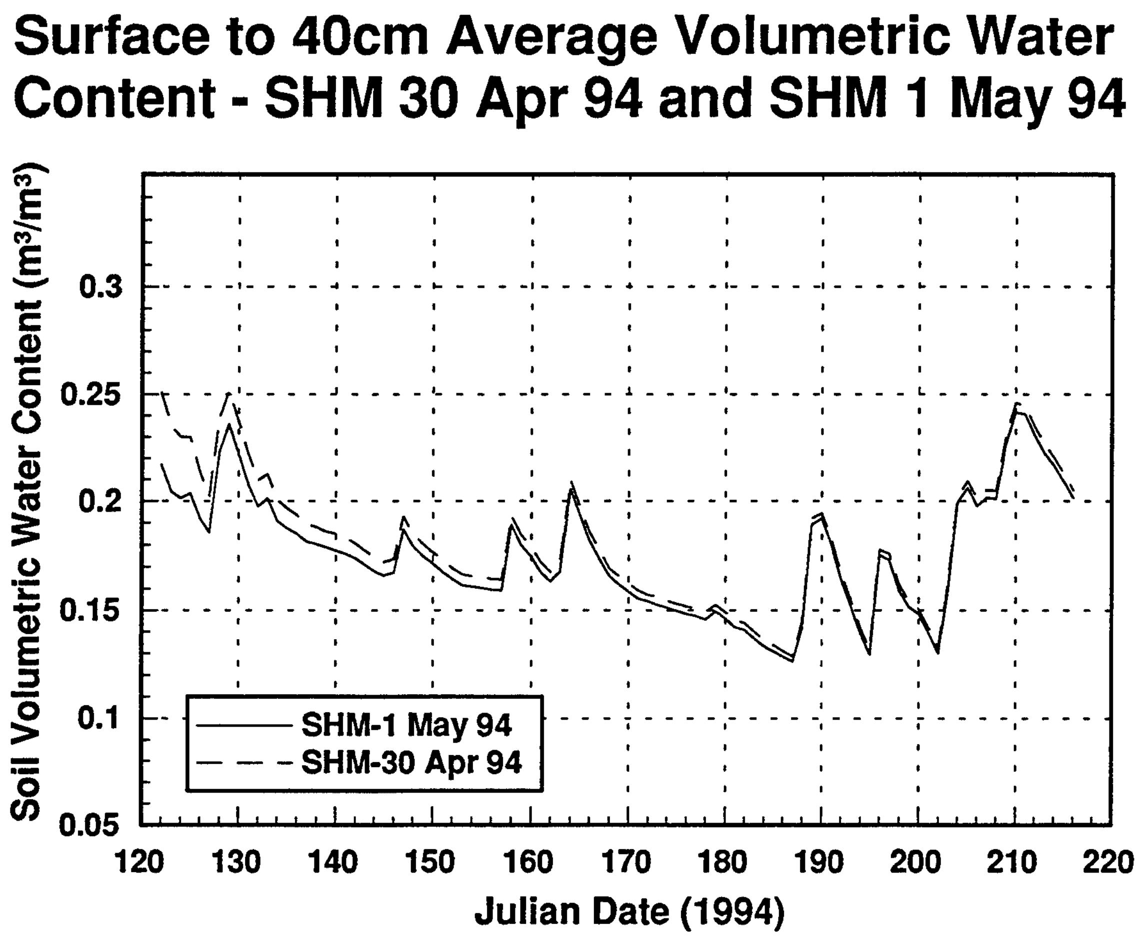

Figure 2.3. Surface to 40 cm average volumetric water content for simulations from the SHM started on 1 May 1994 and 30 April 1994. There was no precipitation recorded at Harrisburg, PA on 30 April 1994, but there was precipitation recorded on 1 May 1994. Starting soil volumetric water content is uniform in all layers at 50% of sandy loam soil saturation.

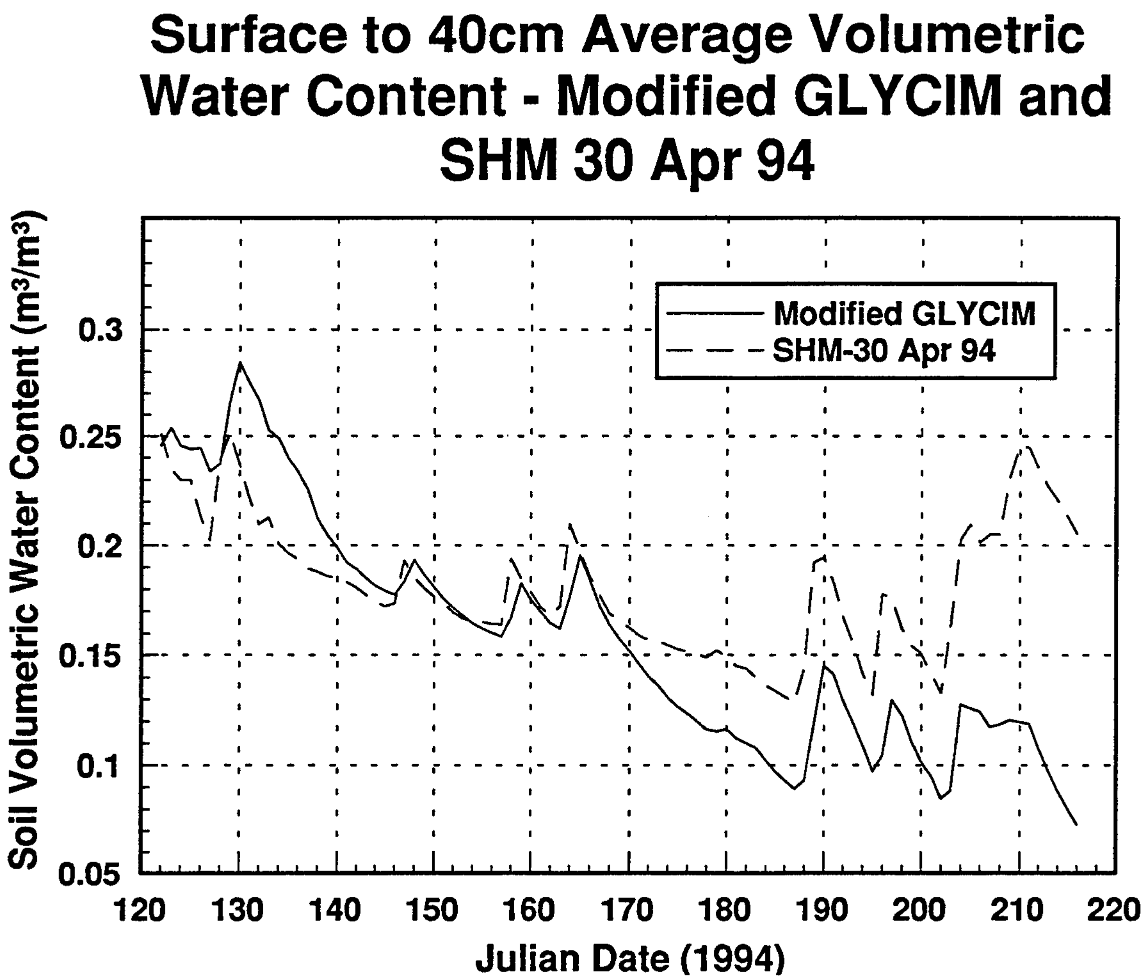

Figure 2.4. Surface to 40 cm average volumetric water content for simulations from the SHM started 30 April 1994 and GLYCIM started 1 May 1994. Starting soil profile volumetric water content is uniform in all layers at 50% of sandy loam soil saturation.

48 cm (as determined by the modified GLYCIM). Therefore, the SHM root depth is only 16 cm while GLYCIM shows a root depth of 40 cm. In this case, this lack of root depth in the SHM causes water extraction to be from the upper two layers of soil. Once these two layers of soil dry, the SHM modeled plants wilt and extraction of water from the soil is limited. The plants in GLYCIM continue to extract water from deeper layers as the roots grow, and therefore the average volumetric water content is lower for the top 40 cm of soil. Figure 2.5 shows a comparison of the modified GLYCIM and SHM average surface to 40 cm volumetric water content output when both "grew" roots to equal depths during the simulation period. Figure 2.6 shows a comparison of root depth between the models as a function of time. The greatest difference in surface to 40 cm average volumetric water content when both models had similar root depths was .04 m^3m^{-3}. This difference was .12 m^3m^{-3} when the root depths were dissimilar. Table 2.4 details model comparisons. Actual weather data is given in figures 2.7-2.10. A complete discussion of plant growth functions and water extraction is given in Appendix A.

Table 2.4. Initial model comparisons and results.

Model	Crop Height	Root Depth	Date of Maturity	Crop Yield at Maturity
GLYCIM	64 cm	30 cm	1 Aug 1994	39.7 Bushels per Acre
Modified GLYCIM	48 cm	40 cm	5 Aug 1994	42.9 Bushels per Acre
SHM	48 cm	16 cm	n/a	n/a

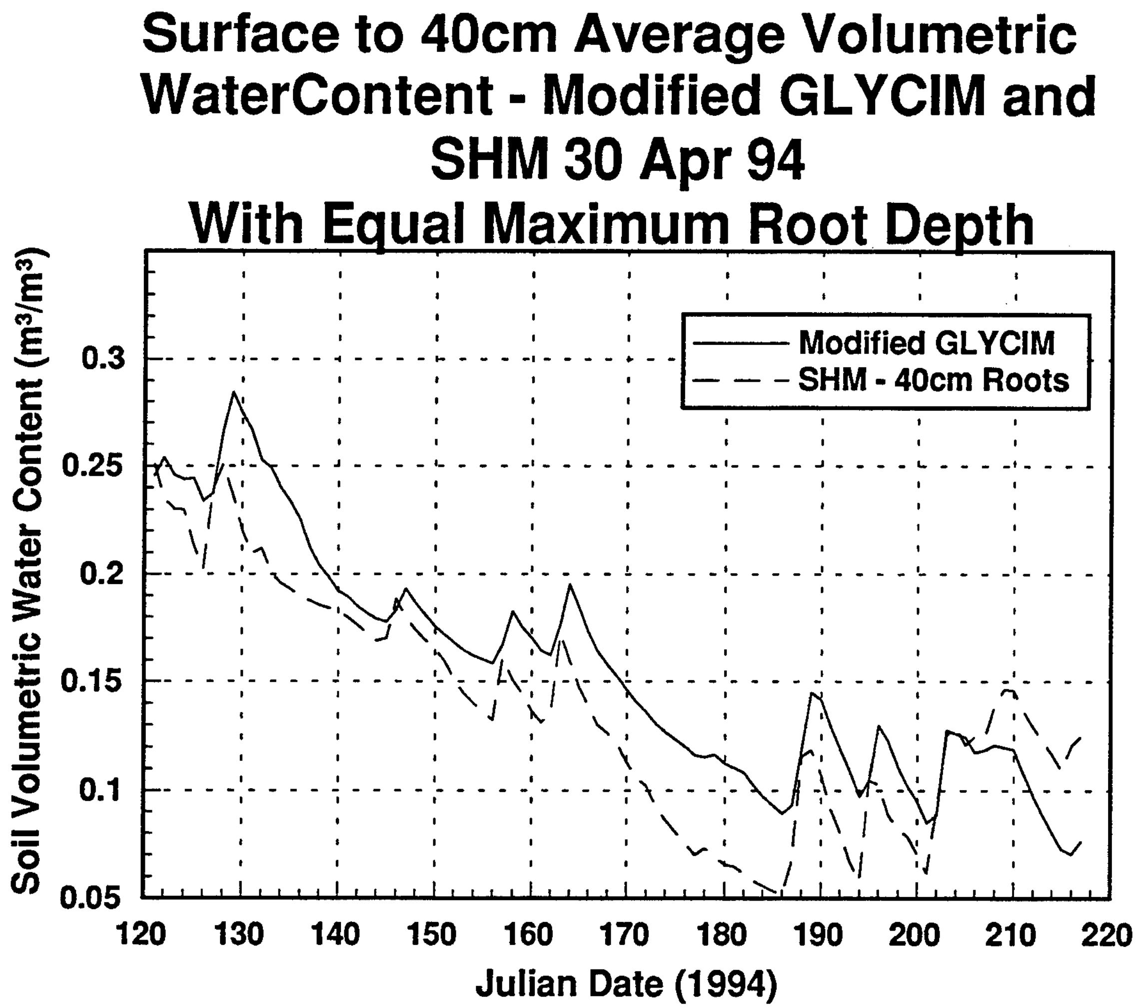

Figure 2.5. Surface to 40 cm average volumetric water content for simulations from the SHM started 30 April 1994 and GLYCIM started 1 May 1994 when root depth is a maximum at about 40 cm. Starting soil profile volumetric water content is uniform in all layers at 50% of sandy loam soil saturation.

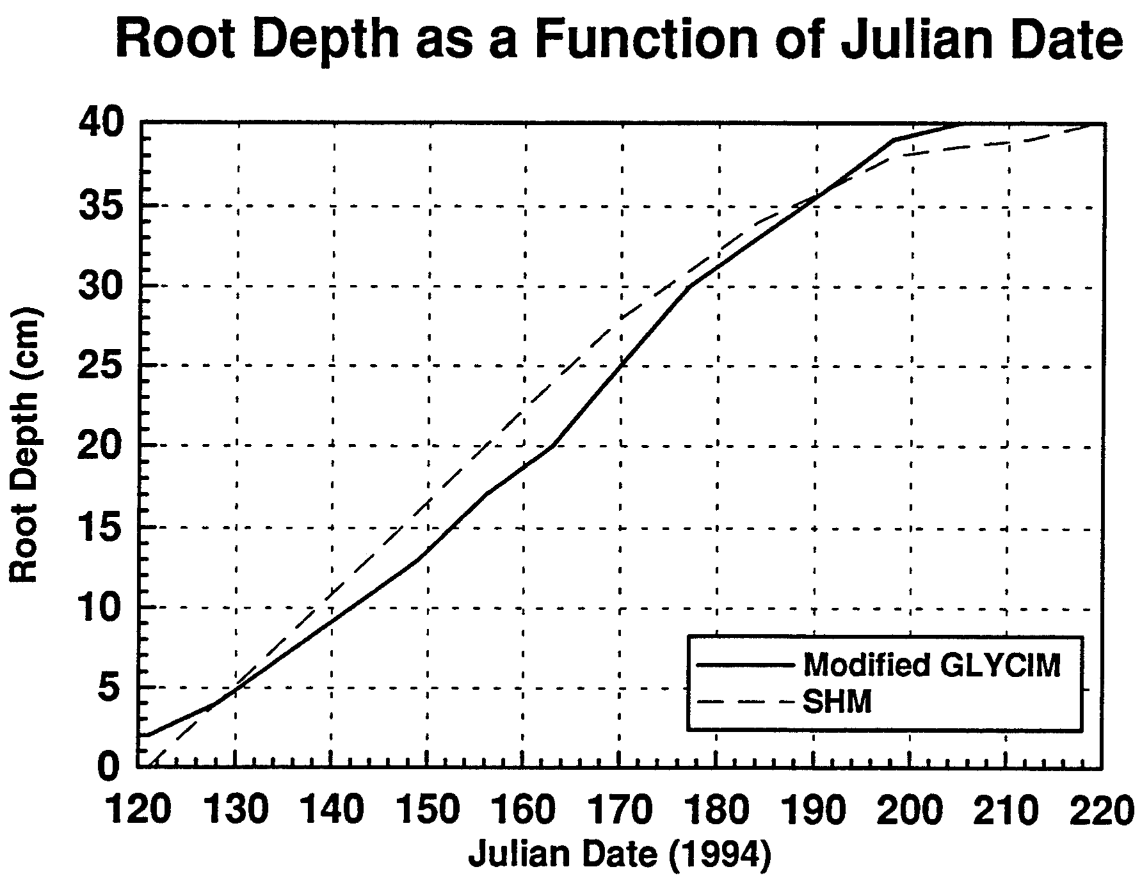

Figure 2.6. Root depth as a function of Julian date for the SHM and the modified GLYCIM.

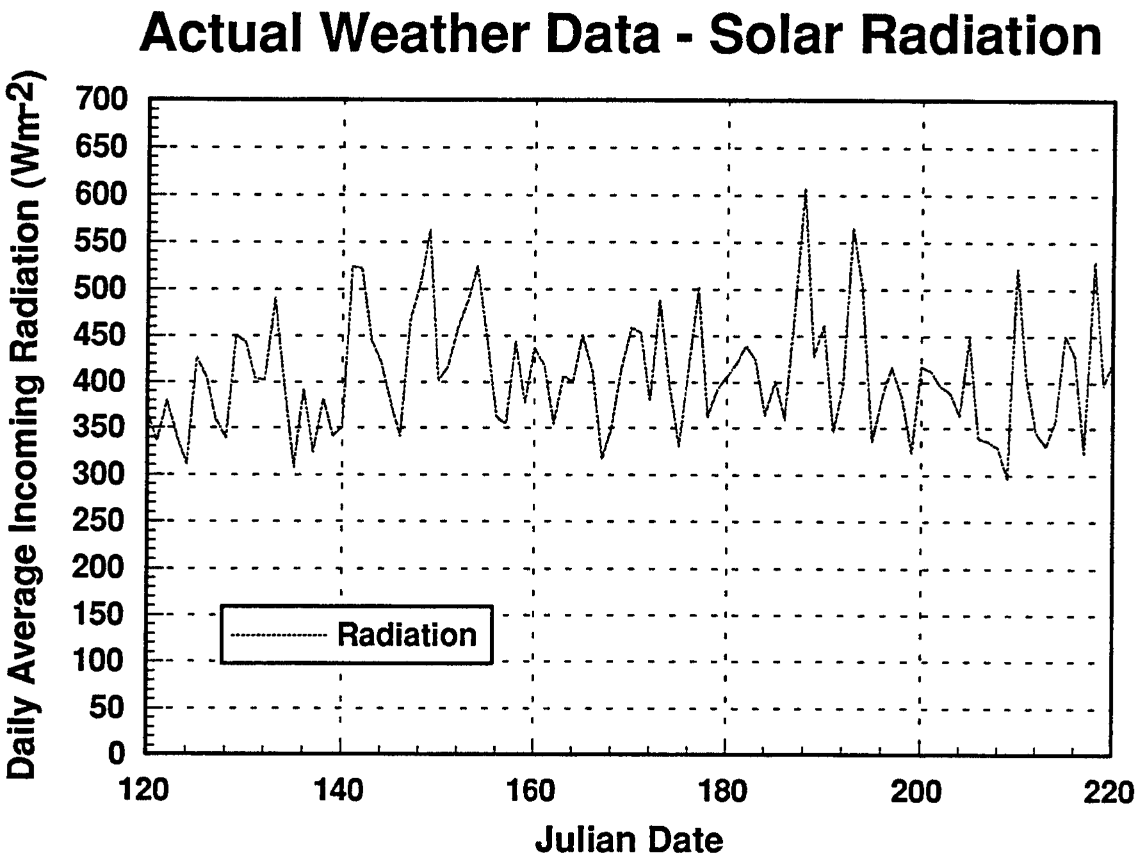

Figure 2.7. Actual daily average incoming radiation as a function of Julian date as estimated for days during this study.

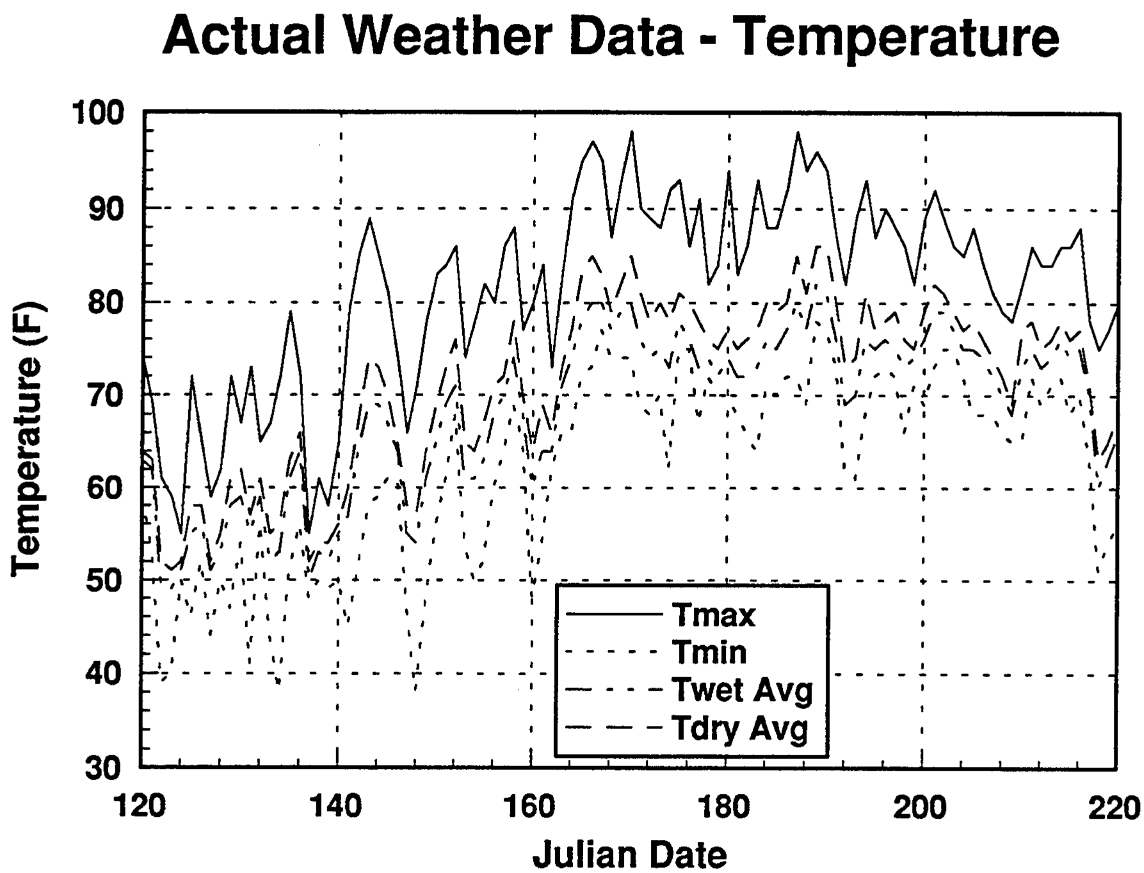

Figure 2.8. Actual daily maximum, minimum, daily average wet bulb, and daily average dry bulb temperatures observed during this study.

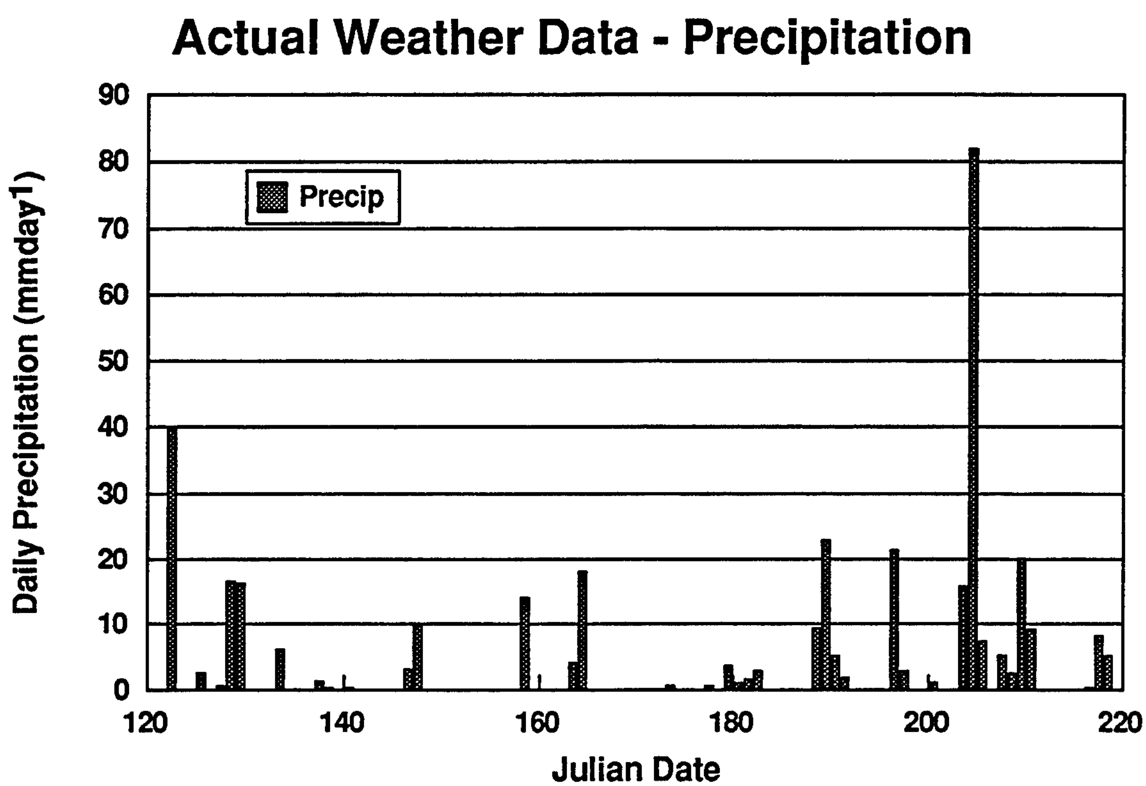

Figure 2.9. Actual observed daily precipitation for days during this study.

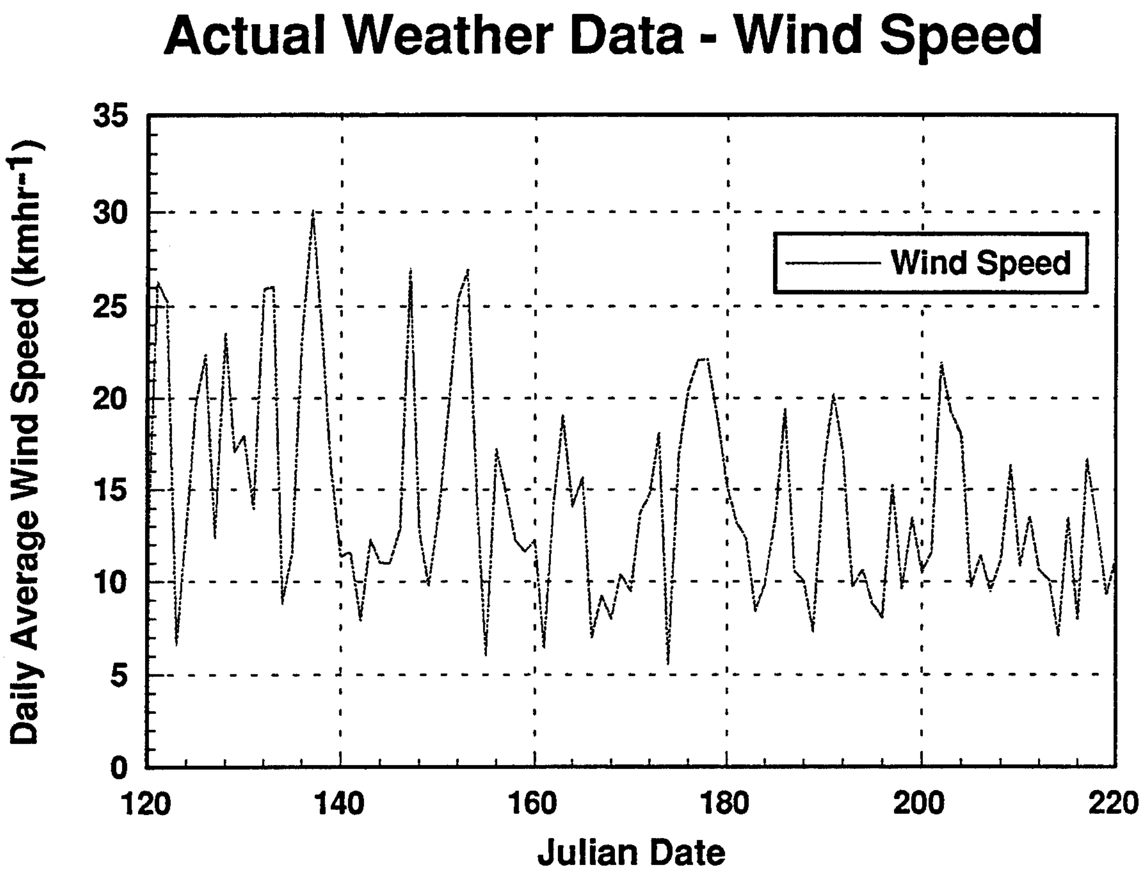

Figure 2.10. Actual daily average observed wind speed as a function of Julian date.

Chapter 3

Sensitivity Tests on The Modified GLYCIM

3.1 Description of Tests

Chapter 3 discusses the GLYCIM sensitivity to meteorological variables. Sensitivity of soil volumetric water content and crop yield as output by GLYCIM are shown. Meteorological variables that were used for the sensitivity tests are daily average incoming radiation, daily maximum, minimum, and average temperature, daily rainfall, daily average wind speed, and daily average wet bulb temperature (see table B.1). Individual tests were run for each meteorological variable to determine model sensitivity, and compared to the model run using actual data from Harrisburg, Pennsylvania. Dry bulb temperature values were varied in unison. Variables were adjusted according to table 3.1.

The adjustment to meteorological variables was done to simulate differences in weather which can occur between a measuring location such as Harrisburg and a field site which may be 30 or 40 miles away, or errors which are inherent in measurement of weather data. Intermediate adjustments were made to the data to see if the model had a linear response to the perturbations.

3.2 GLYCIM Soil Moisture Sensitivity Tests

GLYCIM soil moisture sensitivity test results are represented graphically in figures 3.1- 3.5. Tests are listed in order of sensitivity. GLYCIM soil moisture changes are most sensitive to temperature variations and least sensitive to wind speed variations.

Table 3.1. Meteorological data adjustment for sensitivity tests.

Variable	Minimum	Minus	Control	Plus	Maximum
Daily Average Incoming Radiation	Actual -20%	Actual -10%	Actual Data	Actual +10%	Actual +20%
Dry Bulb Temperature (Max, Min, Avg)	Actual -5°F	Actual -2.5°F	Actual Data	Actual +2.5°F	Actual +5°F
Daily Rainfall	Actual -20%	Actual -10%	Actual Data	Actual +10%	Actual +20%
Daily Average Wind Speed	Actual -20%	Actual -10%	Actual Data	Actual +10%	Actual +20%
Daily Average Wet Bulb Temperature	Actual -5°F	Actual -2.5°F	Actual Data	Actual +2.5°F	Actual +5°F

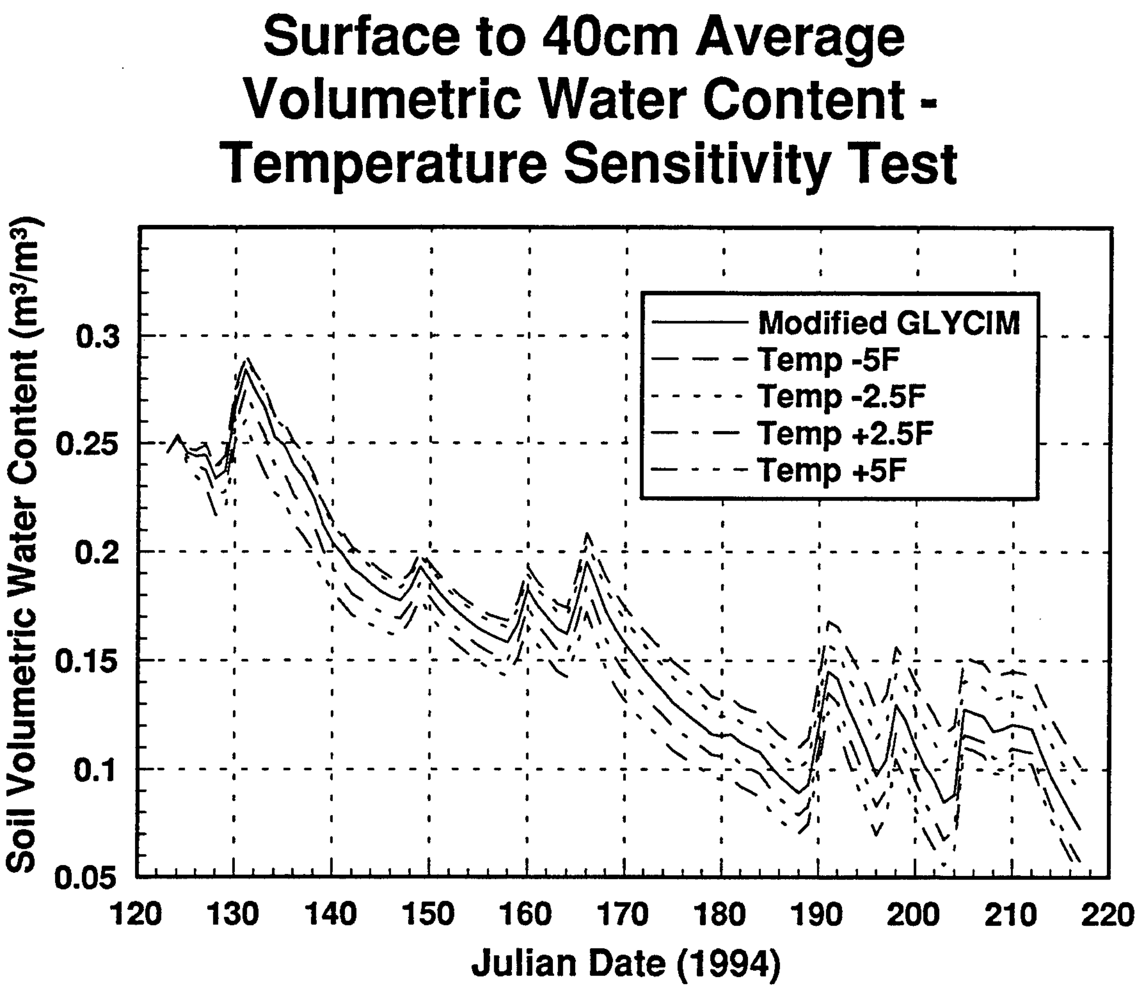

Figure 3.1. Surface to 40 cm average volumetric water content for temperature sensitivity test. Temperature was varied by ±5°F from actual.

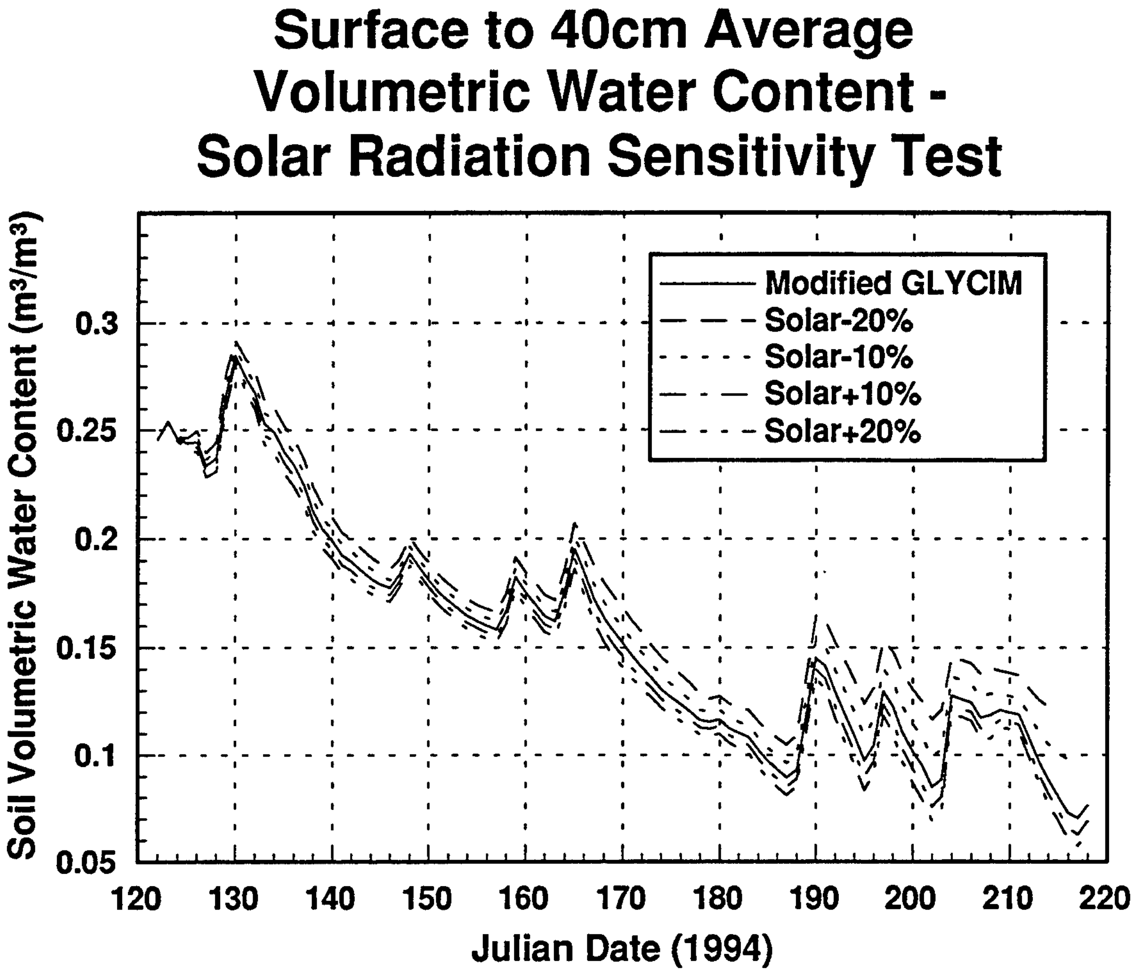

Figure 3.2. Surface to 40 cm average volumetric water content for solar radiation sensitivity test. Solar radiation was varied by ±20% from actual.

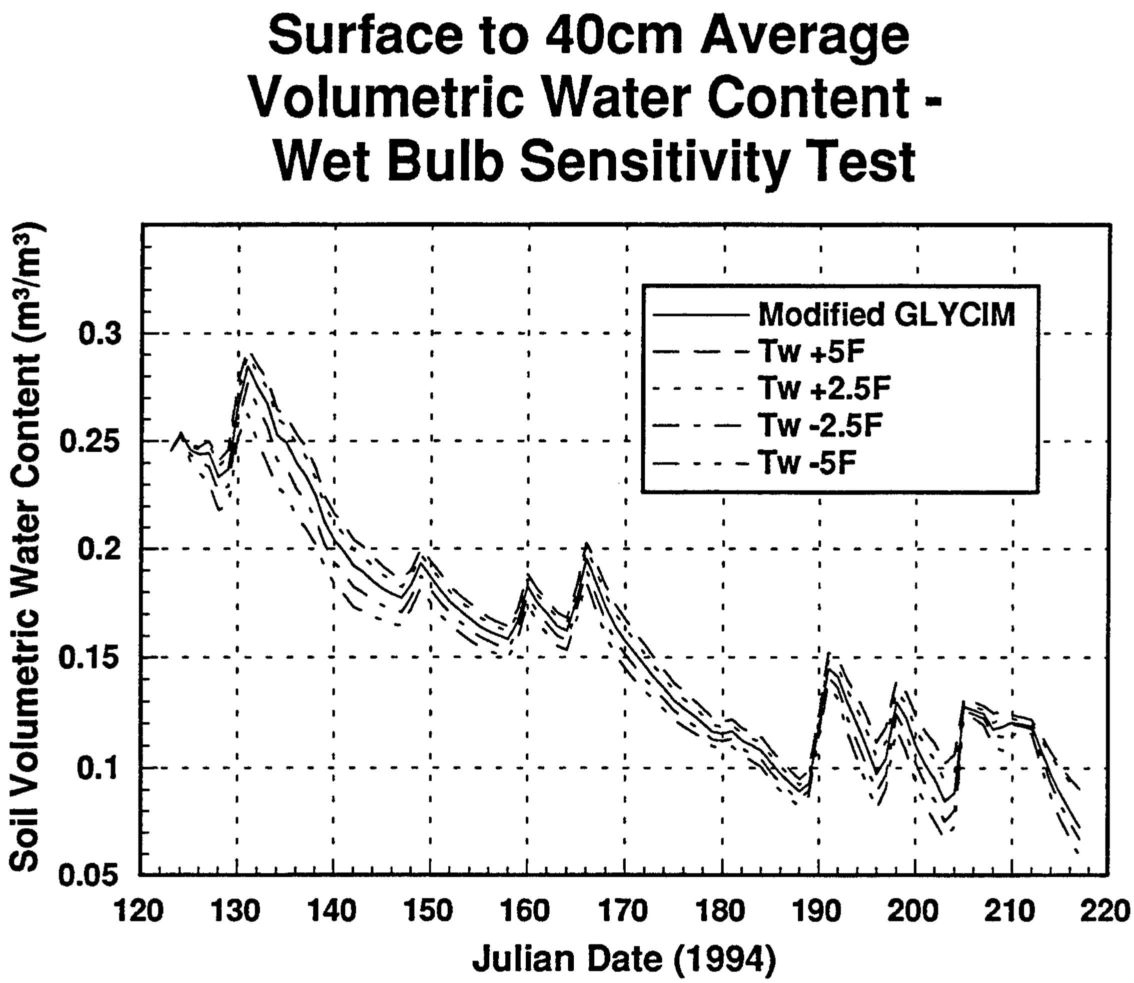

Figure 3.3. Surface to 40 cm average volumetric water content for daily average wet bulb sensitivity test. Wet bulb temperature was varied by ±5°F from actual.

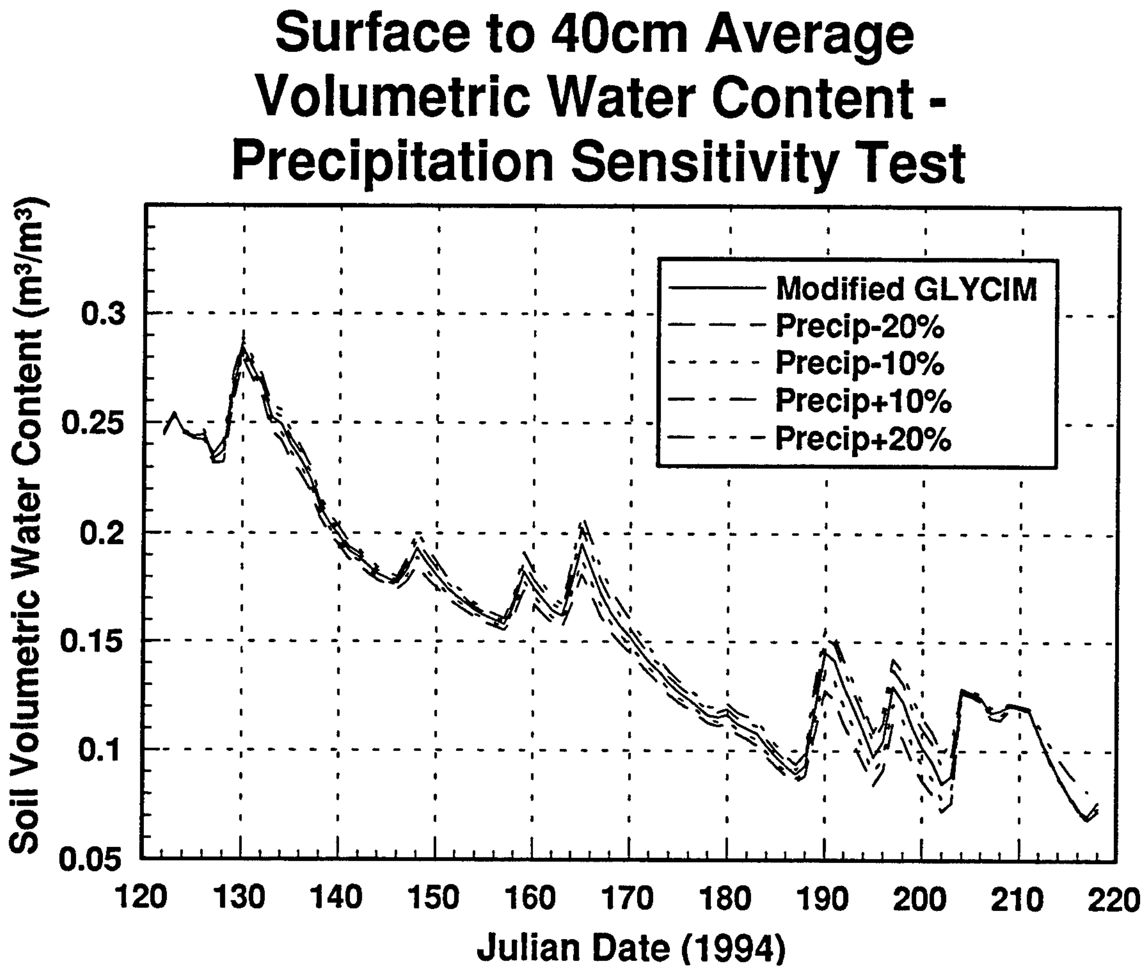

Figure 3.4. Surface to 40 cm average volumetric water content for daily precipitation sensitivity test. Incoming radiation was varied by ±20%.

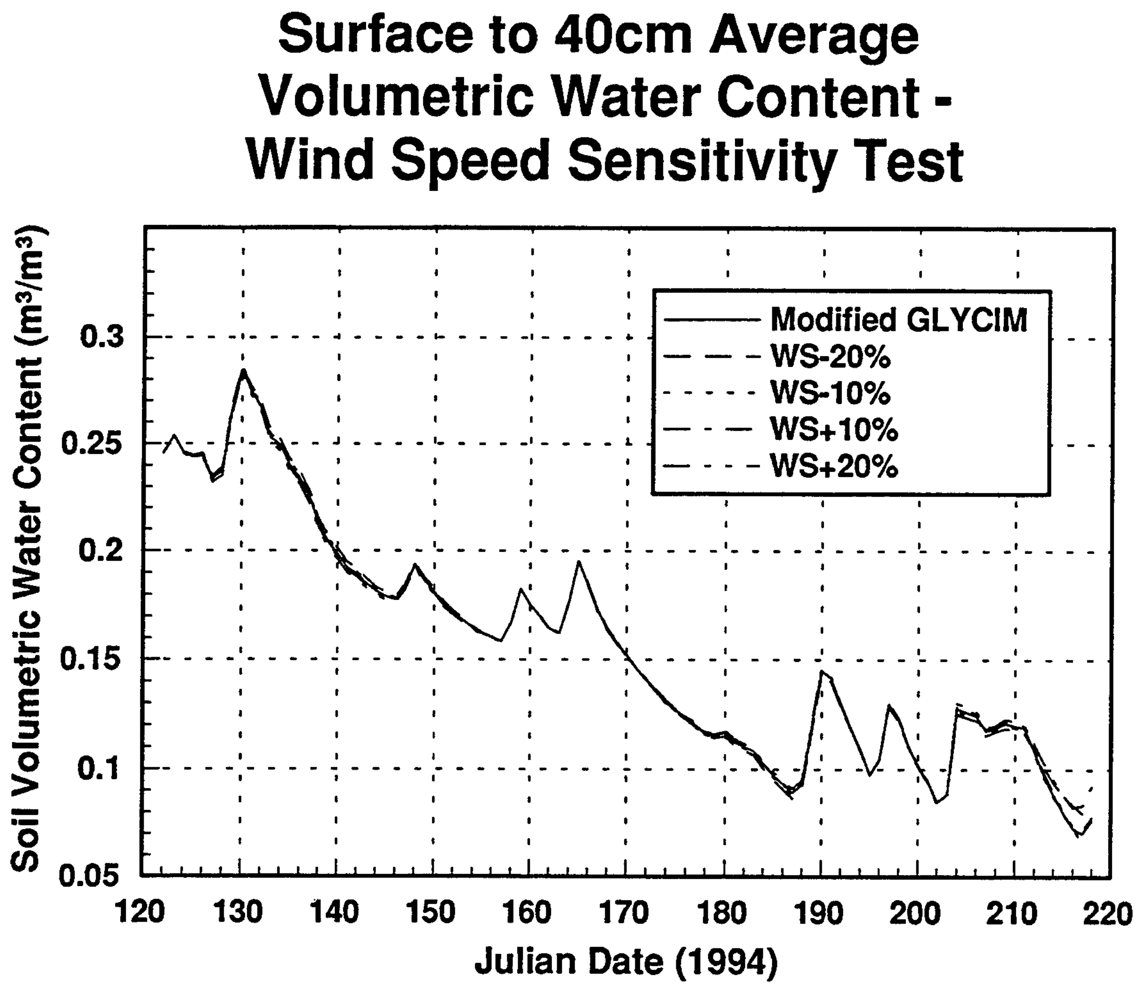

Figure 3.5. Surface to 40 cm average volumetric water content for daily average wind speed sensitivity test. Wind speed was varied ±20% from actual.

Figure 3.1 shows the surface to 40 cm average soil volumetric water content output by GLYCIM varying with time for the five temperature sensitivity comparison runs. Maximum, minimum, and average dry bulb temperature were all varied in unison. The solid line represents the control run using actual data from the summer of 1994. Temperature was varied by ±5°F to determine sensitivity of soil volumetric water content to temperature. Decreasing the temperature led to higher values of soil moisture while increasing the temperature led to lower values of soil moisture.

Figure 3.2 shows the surface to 40 cm average soil volumetric water content output by GLYCIM varying with time for the five daily average incoming radiation sensitivity comparison runs. The solid line represents the control run using actual data from the summer of 1994. Daily average incoming radiation was varied by ±20% to determine sensitivity of soil volumetric water content to solar radiation. Decreasing the solar radiation led to higher values of soil moisture while increasing the solar radiation led to lower values of soil moisture.

Figure 3.3 shows the surface to 40 cm average soil volumetric water content output by GLYCIM varying with time for the five daily average wet bulb temperature sensitivity comparison runs. The solid line represents the control run using actual data from the summer of 1994. Daily average wet bulb temperature was varied by ±5°F to determine sensitivity of soil volumetric water content to daily average wet bulb temperature. Increasing the wet bulb temperature led to higher values of soil moisture while decreasing the wet bulb temperature led to lower values of soil moisture.

Figure 3.4 shows the surface to 40 cm average soil volumetric water content output by GLYCIM varying with time for the five daily precipitation sensitivity comparison runs. The solid line represents the control run using actual data from the summer of 1994. Daily precipitation was varied by ±20% to determine sensitivity of soil volumetric water content to precipitation. Decreasing the precipitation led to lower values of soil moisture while increasing the precipitation led to higher values of soil moisture. One might expect precipitation to have a greater effect on the soil moisture than what is shown. However, almost all of the precipitation at Harrisburg this summer fell as convective precipitation. The precipitation was of high intensity and short duration. The soil volumetric water content in the top 10 cm layer quickly reached field capacity at which time infiltration approached zero. Excess water then flowed out of the model domain according to model physics. This excess water is not specifically calculated by the models, but can be thought of as runoff. Reducing the precipitation by 50% (figure 3.6) led to reduction of calculated soil volumetric water content in both the modified and original GLYCIM, but the effect was greatest in the original GLYCIM again illustrating how it overestimated soil volumetric water content.

Finally, figure 3.5 shows the surface to 40 cm average soil volumetric water content output by GLYCIM varying with time for the five daily average wind speed sensitivity comparison runs. The solid line represents the control run using actual data from the summer of 1994. Daily average wind speed was varied by ±20% to determine sensitivity of soil volumetric water content to wind speed. Decreasing the wind speed led to higher values of soil moisture while increasing the wind speed led to lower values of soil moisture, but the changes are very small as shown by the graph.

3.3 Crop Yield Sensitivity

Crop yield, date of maturity, root depth, and height were specified to be output by GLYCIM. Their sensitivity to the weather input variables are described in the following tables. Crop sensitivity to temperature is shown in table 3.2. Crop yield at 13% moisture,

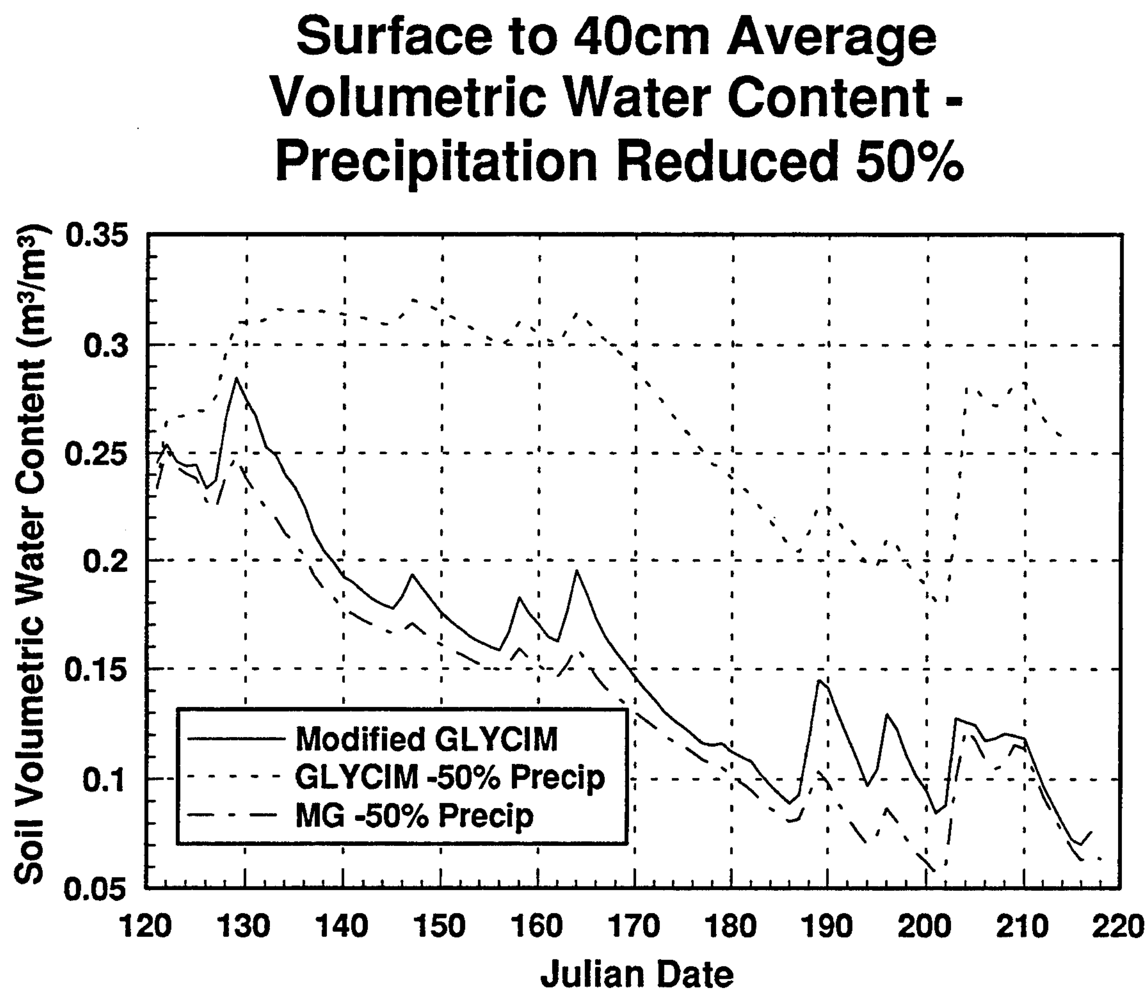

Figure 3.6. Surface to 40 cm average volumetric water content for simulations from the modified GLYCIM as compared to runs of the modified GLYCIM and the original GLYCIM where actual observed precipitation was reduced by 50%. Starting soil profile volumetric water content is uniform in all layers at 50% of sandy loam soil saturation.

Table 3.2 Soybean crop sensitivity to temperature. B/A = Bushels per Acre.

Variable	Crop Height	Root Depth	Date Mature	Crop Yield
Temp +5°F	47.7 cm	40 cm	6 Aug 94	46.5 B/A
Temp +2.5F	47.5 cm	40 cm	6 Aug 94	42.7 B/A
Temperature	48.1 cm	40 cm	5 Aug 94	42.9 B/A
Temp -2.5°F	42.5 cm	30 cm	5 Aug 94	39.0 B/A
Temp -5°F	40.1 cm	30 cm	5 Aug 94	38.6 B/A

assuming no loss at harvest, decreases when the temperature decreases. However, an increase of 2.5°F produces a slight decrease in yield while a 5°F increase in temperature produces an increase in yield.

Crop sensitivity to Daily average incoming radiation is shown in table 3.3. Crop yield decreases with decreasing daily incoming average radiation. A 10% increase in radiation does not increase crop yield. However, a 20% increase in incoming radiation does increase crop yield.

Crop sensitivity to Daily average wet bulb temperature is shown in table 3.4. Changing wet bulb temperatures effectively changes the relative humidity as calculated by the model as well as net radiation and soil moisture. Crop yield decreased most when increasing daily average wet bulb temperature by 5°F. Decreasing daily average wet bulb temperature

has little effect on crop yield. Crop sensitivity to Daily precipitation is shown in table 3.5. Changing precipitation by ±20% appears to have a random effect on crop yield although its effect was not random on soil moisture.

Table 3.3. Soybean crop sensitivity to daily average incoming radiation. B/A = Bushels per Acre.

Variable	Crop Height	Root Depth	Date Mature	Crop Yield
Radiation +20%	44.4 cm	40 cm	6 Aug 94	45.0 B/A
Radiation +10%	45.4 cm	40 cm	5 Aug 94	42.9 B/A
Radiation	48.1 cm	40 cm	5 Aug 94	42.9 B/A
Radiation -10%	50.9 cm	30 cm	3 Aug 94	36.3 B/A
Radiation -20%	50.7 cm	30 cm	1 Aug 94	32.6 B/A

Table 3.4. Soybean crop sensitivity to daily average wet bulb temperature. B/A = Bushels per Acre.

Variable	Crop Height	Root Depth	Date Mature	Crop Yield
T_w +5°F	56.5 cm	40 cm	5 Aug 94	38.6 B/A
T_w +2.5°F	49.9 cm	40 cm	4 Aug 94	41.8 B/A
Wet Bulb Temperature T_w	48.1 cm	40 cm	5 Aug 94	42.9 B/A
T_w -2.5°F	42.3 cm	40 cm	5 Aug 94	41.5 B/A
T_w -5°F	39.9 cm	40 cm	7 Aug 94	41.9 B/A

Table 3.5. Soybean crop sensitivity to daily precipitation. B/A = Bushels per Acre.

Variable	Crop Height	Root Depth	Date Mature	Crop Yield
Precip +20%	49.4 cm	40 cm	4 Aug 94	37.7 B/A
Precip +10%	46.5 cm	40 cm	4 Aug 94	42.4 B/A
Precipitation	48.1 cm	40 cm	5 Aug 94	42.9 B/A
Precip -10%	47.2 cm	40 cm	5 Aug 94	39.5 B/A
Precip -20%	46.7 cm	40 cm	5 Aug 94	41.3 B/A

Table 3.6. Soybean crop sensitivity to daily average wind speed. B/A = Bushels per Acre.

Variable	Crop Height	Root Depth	Date Mature	Crop Yield
WS +20%	44.0 cm	40 cm	5 Aug 94	40.5 B/A
WS +10%	51.5 cm	40 cm	5 Aug 94	40.2 B/A
Wind Speed	48.1 cm	40 cm	5 Aug 94	42.9 B/A
WS -10%	46.8 cm	40 cm	4 Aug 94	42.1 B/A
WS -20%	48.4 cm	40 cm	4 Aug 94	41.0 B/A

3.4 Model Sensitivity to Uncertainties in Determining Input Parameters

An attempt was made to estimate the uncertainties in calculating average surface to 40 cm soil volumetric water content and crop yield as determined by the modified GLYCIM model that would result from an inability to correctly measure or estimate an input value.

One can determine the error in calculating soil volumetric water content or crop yield using the following equation provided that these errors are mutually uncorrelated.

$$\hat{\delta}Q = \left[\left(\frac{\partial Q}{\partial x_1}\right)^2 \hat{\delta}x_1{}^2 + \left(\frac{\partial Q}{\partial x_2}\right)^2 \hat{\delta}x_2{}^2 + \left(\frac{\partial Q}{\partial x_3}\right)^2 \hat{\delta}x_3{}^2 + \ldots \right]^{\frac{1}{2}} \quad (3.1)$$

The partials are taken only with respect to one of the five input variables x_1, x_2, x_3, etc., and $\hat{\delta}Q$ represents a maximum probable error in $\hat{Q}$ symbolizing that for soil volumetric water content θ or crop yield. Generally,

$$\left|\hat{\delta}Q\right| = \left[\hat{S}_1{}^2 + \hat{S}_2^2 + \hat{S}_3^2 + \hat{S}_4^2 + \hat{S}_5^2\right]^{\frac{1}{2}} \quad (3.2)$$

where $\hat{S}_i$ is the greatest error due to each individual variable separately, and $\hat{\delta}Q$ is the square root of the sum the squares of the greatest errors due to an error in each variable separately.

Table 3.7 shows the maximum daily error associated with each input variable, and probable maximum daily error in surface to 40 cm average soil volumetric water content for the sensitivity tests. Maximum probable error for surface to 40 cm average soil volumetric water content is .04 m^3m^{-3} which is about 12% of field capacity.

Table 3.8 shows the maximum error associated with each input variable, and probable maximum error in crop yield for the sensitivity tests. Maximum probable error for crop yield is 13.3 bushels per acre which is about 31% of the control run yield. This maximum error may be so large because the adjustments to meteorological variables individually take the form of a systematic error in the measurements over the entire simulation period. This systematic bias shows up in the surface to 40 cm average volumetric water content but the errors are much smaller.

Table 3.7. Maximum probable error in average surface to 40 cm soil volumetric water content from sensitivity tests and maximum error associated with each input variable.

Variable	$\hat{\delta}x$	$\hat{S}$
Temperature	±5°F	.02 m^3m^{-3}
Daily Average Incoming Radiation	±120 Wm^{-2}	.02 m^3m^{-3}
Daily Average Wet Bulb Temperature	±5°F	.02 m^3m^{-3}
Daily Precipitation	±1.6 cm	.02 m^3m^{-3}
Daily Average Wind Speed	±6 $kmhr^{-1}$	.01 m^3m^{-3}
$\hat{\delta}\overline{\theta}_{40cm}$	n/a	.04 m^3m^{-3}

Table 3.8. Maximum probable error in crop yield from sensitivity tests and maximum error associated with each input variable. B/A = Bushels per acre.

Variable	$\hat{\delta}x$	$\hat{S}$
Temperature	±5°F	4.3 B/A
Daily Average Incoming Radiation	±120 Wm^{-2}	10.3 B/A
Daily Average Wet Bulb Temperature	±5°F	4.3 B/A
Daily Precipitation	±1.6 cm	5.2 B/A
Daily Average Wind Speed	±6 $kmhr^{-1}$	2.7 B/A
$\hat{\delta}$ *Crop Yield*	n/a	13.3 B/A

Chapter 4

Summary and Conclusions

4.1. Summary

This study has explored the link between meteorological variables and their relationship to soil volumetric water content and crop yield. Surface to 40 cm average volumetric water content as calculated by the SHM and the original GLYCIM were compared. It was shown that the original GLYCIM significantly overestimated soil volumetric water content. Modifications to the soil moisture physics in the soil moisture module of GLYCIM were made. Surface to 40 cm average volumetric water content as calculated by the SHM and the modified GLYCIM were compared. It is shown that the modified GLYCIM now calculates a reasonable soil water profile. This change in soil moisture led to a positive eight percent change in the resulting crop yield forecast.

Sensitivity tests were run on GLYCIM to determine maximum probable error in the modified GLYCIM's calculation of daily volumetric water content and crop yield at the date of maturity, both as a function of possible meteorological differences which may occur over spatial distances. Adjustments to meteorological variables were made to reflect differences that may occur over the length of a growing season between a weather observation site and a field site 30 or 40 miles away. Maximum probable error in the calculation of volumetric water content was found to be small as compared to maximum probable error in crop yield.

4.2. Conclusions

The results of this study indicate that output of soil volumetric water content based an local data may be applicable to field sites within a 30 or 40 mile radius. Daily precipitation may vary by more than twenty percent over this distance, temperature by more than ±5°F, etc., but over the course of a growing season a twenty percent or ±5°F average difference is reasonable. These differences led to small daily and long term differences in soil volumetric water content. It is feasible that individual National Weather Service offices could run crop models, or even generic soil hydrology models such as the SHM, set up with the proper parameterizations for crops, to provide agriculturists a better estimate of soil moisture. Agriculturists could then use irrigation and pesticides more efficiently. These soil moisture values could also be used as input for atmospheric prediction models.

This study also indicates that modified GLYCIM crop yields are largely affected by systematic biases in the input variables. In some cases, the systematic effect on crop yield is predictable such as for temperature and solar radiation. If the temperature or radiation was increased, yield went up, and if the temperature or radiation was decreased, yield went down. In other cases the systematic effect appears to be almost random such as is the case for daily average wet bulb temperature and daily precipitation.

This bias might be removed if a random number generator were used to calculate daily errors as opposed to using a constant adjustment to input variables for each day. Because this bias is large and applied over a long time period, it probably led to greater error in yield forecasts than would be expected from random temperature, solar radiation, or wet bulb, etc. fluctuations that would normally be attributed to measurement error or distance from observing site. However, this bias may be similar to an actual bias between other sites due to elevation differences or proximity to water differences. Over the length of a growing season differences may be found in crop yield over a 30 or 40 mile radius from the observing site.

Appendix A

Soil Moisture Physics

A.1 Introduction.

The net soil moisture content can be expressed as a budget equation where

$$\frac{\partial\theta(z,t)}{\partial t}=\frac{\partial q(z,t)}{\partial z}+S(z,t) \qquad (A.1)$$

where θ is the volumetric water content, and t is time (s), z is depth (m), and q is the vertical moisture flux within the soil (ms^{-1}). The term S represents a source/sink term which accounts for the rate of input and output of moisture into a column of soil. How GLYCIM and the SHM handle the individual components of this equation determines how much water is in the soil. Because of the differences in the way the three components are calculated, there are differences in the water storage as output by the models. The SHM has been tested and produced a representative profile of soil moisture when supplied with good initial conditions. As mentioned earlier, GLYCIM had known weaknesses in its soil moisture module and produced an unrepresentative soil moisture profile when driven by actual meteorological data so it was modified to contain the equations in the next section.

The purpose of this appendix is to outline the processes which govern the value for volumetric water content as output by the two models. There are differences in the governing equations for each model, but the basic ideas behind the equations are nearly the same.

A.2 Darcy Motion

The flow of water in the soil which is known as Darcy Flow is governed by the Richard's equation (Richard's, 1931). This is written as

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(D(\theta)\frac{\partial\theta}{\partial z}\right) + G(\theta)\frac{\partial\theta}{\partial z} \tag{A.2}$$

where θ is equal to the volumetric water content (m^3m^{-3}) of the soil , $D(\theta)$ is the diffusion coefficient (m^2s^{-1}), $G(\theta)$ is the gravitation coefficient (ms^{-1}), t is time (s), and z is depth (m). The diffusion coefficient can be written as

$$D(\theta) = k(\theta)\frac{\partial\psi}{\partial\theta} \tag{A.3}$$

where ψ is hydraulic matric potential (m) and k is the hydraulic conductivity (ms^{-1}) of the soil. $G(\theta)$ is given as

$$G(\theta) = \frac{\partial k}{\partial\theta} \tag{A.4}$$

where k the hydraulic conductivity and ψ the matric potential are defined several ways in the literature. These definitions are derived from mathematical and statistical regressions of field data. Clapp and Hornberger (1978) and Cosby et al. (1984) defined hydraulic conductivity as

$$k(\theta) = k_s\left(\frac{\theta}{\theta_s}\right)^{2b+3} \tag{A.5}$$

and matric potential as

$$\psi(\theta) = \psi_s\left(\frac{\theta}{\theta_s}\right)^{-b} \tag{A.6}$$

where b is a scaling coefficient and $\theta_s$is the volumetric water content (m^3m^{-3}) of the soil at saturation. Whisler (1976) defined the diffusion coefficient as

$$D(\theta) = D_o \exp\beta(\theta_i - \theta_o) \tag{A.7}$$

where D_o is the diffusion coefficient at some very low volumetric water content θ_o, β is the slope of graph of log (hydraulic conductivity) vs. volumetric water content for a given soil, and θ_i is the actual volumetric water content of the soil. He defined the gravitational coefficient as above where k the hydraulic conductivity is given as

$$k = k_S \left[\frac{(\theta - \theta_r)}{\theta_S - \theta_r} \right]^{\left(\frac{3\eta}{\eta - 2} \right)} \tag{A.8}$$

where k_S is the saturated hydraulic conductivity, θ_S is the volumetric water content of the given soil at saturation, θ_r is θ_o slightly reduced (used in GLYCIM to avoid problems with dividing by zero), and η is a soil characteristic parameter relating volumetric water content to water potential for a given soil. Table 2.3 lists hydraulic coefficients as used in this study.

A.3 Precipitation (Irrigation) and Infiltration

Precipitation and infiltration are handled by GLYCIM and the SHM in different ways. GLYCIM first takes the 24 hour total rainfall (irrigation) and divides it into 24 equal amounts. The precipitation intensity is then equal for all 24 one hour periods. Water infiltrates into the top layer at the precipitation rate but only until field capacity of the given soil is reached (field capacity = 75% of the value of soil volumetric water content at saturation). GLYCIM code then invokes a limiter which maximizes the volumetric soil water content in the top layer at the field capacity. Water was then transported downward in the soil via gravitational effects and by diffusion. Upward and horizontal diffusion were also allowed according to equation A.7. Gravitational flow as given by Acock and Trent (1991) was represented by the following equation

$$\theta_z^{\tau} = \theta_z^{\tau-1} + \left(\frac{I_z^{\tau} - I_{z+1}^{\tau}}{d} \right) \tag{A.9}$$

where θ is the volumetric water content of a given layer z (maximized at field capacity), τ is the current time step, I is the water infiltrating into a given layer, and d is the depth between layers which for this study is 10 cm. The water infiltrating into a given layer (I) is equal to the precipitation rate (cms^{-1}) for the top layer and is given by the following equation for the remaining layers

$$I = AMAX\left[0.0, H_2O - (\theta_{fc}d)\right] \tag{A.10}$$

where H_2O is given as

$$H_2O = I^{\tau}_{z-1} + (\theta^{\tau}_{z-1}d) \tag{A.11}$$

and where θ_{fc} is the volumetric water content of the soil at field capacity and the intrinsic FORTRAN function *AMAX* finds the maximum of the absolute values of the arguments. The original GLYCIM equations for gravitational flow were found to overestimate the soil volumetric water content and were replaced by the gravitation term of equation A.2.

For the SHM water enters the model domain through precipitation, but before it can be incorporated into the soil layers it must be partitioned into three categories: (1) Precipitation falling on the vegetation canopy rather than the ground is leaf interception; (2) The rainfall that reaches the ground is infiltrated into the soil's topmost layer at a rate dependent on the soil's hydraulic properties; (3) If the soil cannot accept the precipitation, the water ponds on the surface where it is allowed to flow out of the model domain. (Capehart, 1992).

In the SHM, leaf interception of precipitation by the vegetation canopy is a function of the leaf area index, *LAI*, which is proportional to the canopy's foliage density and the precipitation intensity. The total precipitation intercepted per unit area, P_{leaf}, is equal to

$$P_{leaf} = W_{leaf} LAI \tag{A.12}$$

and W_{leaf} is an intensity coefficient equal to 0.2 $KgH_2O\ m^{-2}$. Intercepted rainfall remains on the canopy until evaporated. This intercepted precipitation is set at 1mm of precipitation in the SHM. Canopy interception of precipitation is ignored in GLYCIM.

In order to calculate the infiltration, the precipitation intensity must be known. For the SHM, precipitation is partitioned into to 12 hour groups in the input data file. An intensity curve that is similar to actual rainfall intensity curves is then used to simulate the amount of rainfall as a function of time. The function chosen to simulate the precipitation intensity (i) is

$$i \equiv \frac{\partial P}{\partial t} = I_x \sec h\left(\frac{t-R}{C}\right) \tag{A.13}$$

where P is the amount of rainfall as a function of time, I_x is the maximum precipitation intensity calculated from a 12 hour rainfall total, R is equal to one half the time step (s), and C is equal to 5.43×10^4 s.

In the SHM, as precipitation falls on the soil, it infiltrates at a rate equal to the precipitation intensity until the top soil layer reaches field capacity and water ponds on the surface. The ponding time (t_p) is calculated as

$$t_p = \frac{k_{fc}\Psi_{fc}\Delta\theta}{i(i-k_{fc})} \tag{A.14}$$

where $\Delta\theta$ is the difference between the topmost layer's volumetric water content and field capacity. k_{fc} and ψ_{fc} are the soil's hydraulic conductivity and matric potential at field capacity, respectively. Once ponding occurs, the top layer of soil accepts water at a rate less than that of the precipitation intensity. From this point, the total amount of precipitation infiltrated into the top layer is solved iteratively using the Green-Ampt infiltration method (Green and Ampt, 1911; Chow et al., 1988). Once water enters the soil's top layer, it is then distributed throughout the porous environment through diffusion and gravitation processes listed as equations A.2-A.6.

A.4 Evapotranspiration From Bare Soil and Vegetation

Both GLYCIM and SHM use a version of the Penman equation to solve for evaporation from bare soil. GLYCIM uses an equation according to Penman (1963), while the SHM uses an equation after Monteith (1981). The Penman equation in both models is of the form

$$\lambda E = \frac{M}{\gamma + \Delta M}\left[(R_n - G)\Delta + \frac{\rho C_p(e_s - e)}{r_{atm}}\right] \tag{A.15}$$

where λE is the latent heat flux into the atmosphere, λ is the psychrometric constant, Δ is the derivative of the saturation vapor pressure with respect to temperature, (e_s-e) is the vapor pressure deficit between the vapor pressure of a saturated surface at the air temperature (e_s) and the actual vapor pressure of the atmosphere (e), ρ is the atmospheric density, C_p is the specific heat capacity at constant pressure, and (R_n-G) is the net radiation minus the ground flux.

The moisture availability (M) is modeled differently by the two models, but is similar. In both cases it acts as to limit Evapotranspiration as the soil becomes drier. In GLYCIM the moisture availability of bare soil (M_{soil}) is a function of the soil diffusivity, the soil volumetric water content, and the depth of calculated layer of dry soil at the surface. This layer of dry soil is found as

$$d_{dry} = 2\left[1 - \left(\frac{\theta - \theta_o}{\theta_s - \theta_o}\right)^{0.1}\right] \tag{A.16}$$

where d_{dry} is the depth of the surface dry layer in cm, θ is the surface layer volumetric water content of the surface layer, θ_s is the volumetric water content of the soil at saturation, and θ_o is the volumetric water content of the soil at -15 bars. The depth of this layer of dry soil has a maximum limit of 2 cm at absolutely dry soil. Next, the hydraulic diffusivity of the surface layer is calculated as

$$D_{sfc} = D_o \exp[\beta(\theta - \theta_o)] \tag{A.17}$$

(Whisler, 1976) where D_o is the hydraulic diffusivity of the surface layer at -15 bars, and β is the slope of the graph of the log (hydraulic conductivity vs. volumetric water content). Next, a hydraulic diffusivity accounting for the layer of air dry soil at the surface is calculated as

$$D_{dry} = \frac{D_{sfc}}{\left(D_{sfc} d_{dry}\right) + \left(1.0 - d_{dry}\right)} \tag{A.18}$$

Finally, the rate at which water can move to the surface to be evaporated (E_p) is given as

$$E_p = \frac{D_{dry}(\theta - \theta_o)10000.0}{12.0d} \tag{A.19}$$

where this potential moisture for evaporation has the units of g m^{-2} hr^{-1}. This potential is then related to soil moisture availability (M_{soil}). If atmospheric potential evaporation exceeds this soil moisture availability then evaporation from the soil is limited to what is available (E_p). The original GLYCIM equations of limiting water movement to the surface have been replaced because they were found to almost completely limit evaporation from bare soil, no matter what the moisture availability. Equations A.16-A.19 have been replaced with equations A.21a-A.21b which limit evaporation from the top layer of soil as a whole, and are used in the SHM. In GLYCIM, atmospheric resistance (r_{atm}) is equal to

$$r_{atm} = \frac{1}{1+.149u(2.0-2.0veg)} \tag{A.20}$$

where *u* is the wind speed and *veg* is the percent of the soil covered by vegetation.

In GLYCIM the moisture available to the vegetation canopy is limited by the soil moisture and atmospheric resistance and is a function of canopy roughness height. Uptake by plants from the soil is limited only after root growth is maximized (Figure A.1). First, the average soil water potential weighted by the rate at which water is being extracted from each soil cell is calculated. Next, the water uptake for existing roots is calculated at the leaf water potential found in the previous period of the day (point B). The change in leaf water potential necessary to prevent all shoot growth fixes point C. As leaf water potential decreases, shoot turgor decreases, carbon is diverted to the roots and root growth occurs. The plant can then meet a higher transpiration demand. Moisture is drawn out of the ground under the plant canopy by root/plant uptake only.

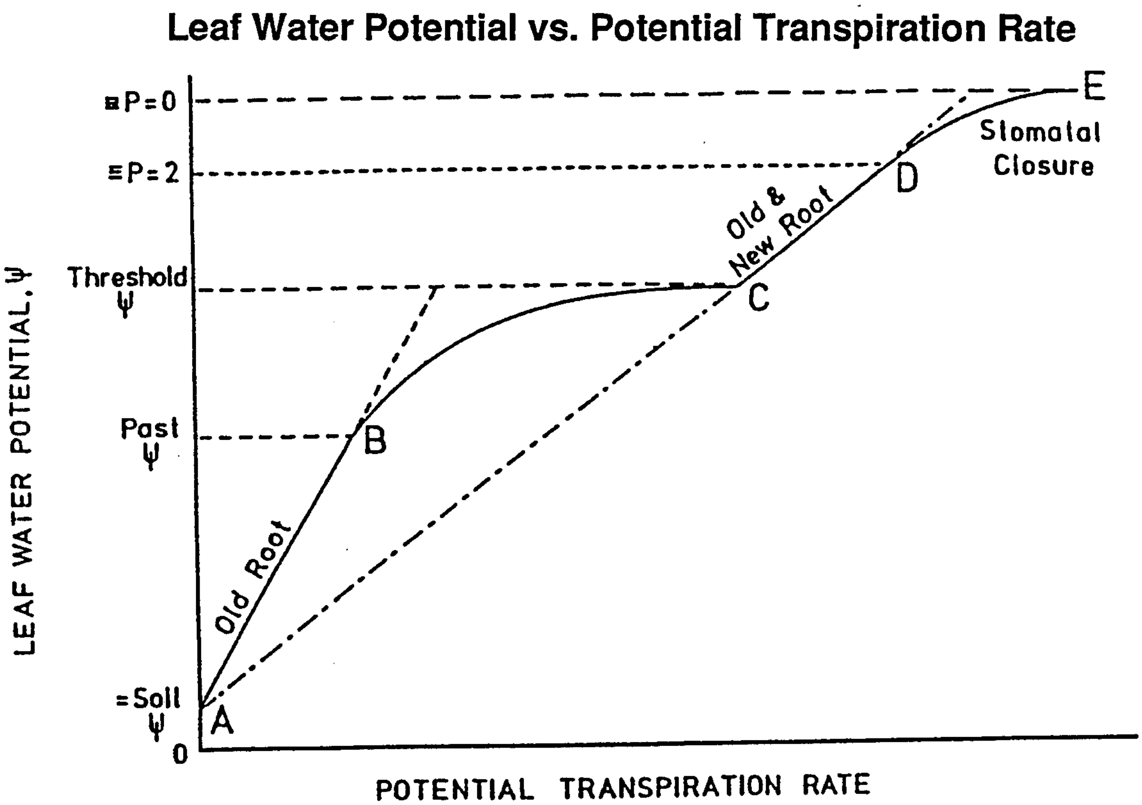

Figure A.1. Relationship of leaf water potential and root growth to potential transpiration rate (Acock and Trent, 1991).

In the SHM the moisture availability (M_{soil}) over bare soil is a function of the volumetric water content and is obtained through a formula by Lee and Pielke (1992). It is given as

$$M_{soil} = \frac{1}{2}\left[1-\cos\left(\frac{\theta_{10cm}}{\theta_{fc}}\pi\right)\right] \quad \text{if } \theta_{10cm} < \theta_{fc} \qquad \text{(A.21a)}$$

$$M_{soil} = \qquad 1 \qquad \text{if } \theta_{10cm} \geq \theta_{fc} \qquad \text{(A.21b)}$$

where θ_{10cm} is the volumetric water content of the top layer of soil and θ_{fc} the volumetric water content at field capacity. In the SHM moisture availability over vegetation (M_{veg}) is a function of both bulk stomatal resistance of the canopy, and atmospheric resistance (r_{atm}) and is given as

$$M_{veg} = \frac{r_{atm}}{r_{atm} + r_{st}} \qquad \text{(A.22)}$$

where r_{atm} is given as

$$r_{atm} = \kappa\left\{u_{inst}\left[k \ln\left(\frac{z_{inst} - d}{z_o}\right)\right]^2\right\}^{-1} \qquad \text{(A.23)}$$

and k is the von Kármán constant (0.40), u_{inst} is the wind velocity at instrument height z_{inst}, d is the canopy displacement height (2/3 vegetation height), z_o is the roughness length (.13 vegetation height), and κ is an empirical constant (0.85). The bulk stomatal resistance is calculated as

$$r_{st} = r_{st\,\min}\left[\frac{R_{sclr}}{1+R_s}\left(\frac{1.2\theta_w}{0.9\theta_{root} + 0.1\theta_{10cm}}\right)^2\right]\left(\frac{1.2 + 0.3LAI}{LAI}\right) \qquad \text{(A.24)}$$

(Mascart et al., 1991) where R_s and R_{sclr} are the incoming solar radiation for ambient and clear sky conditions, respectively, r_{stmin} is the minimum stomatal resistance for a given vegetation type, LAI is the leaf area index over the vegetation canopy, θ_{10cm} and θ_{root} are the volumetric water contents for the top 10 cm and the root zone, respectively, and θ_w is the volumetric water content at the plant's wilting point (-153m).

A.5 Modeling of Plants

Plant height, ground coverage, and root depth play an important role in determining the water budget in the soil. Differences in the how the models define these variables will undoubtedly lead to differences in the soil moisture profiles. GLYCIM is a soybean plant simulator and it therefore grows an actual plant with time. As the plant grows, the height of the vegetation increases, the ground coverage increases, and roots penetrate deeper into the soil. These variables are intrinsic to the model and are based on nutrients in the soil, soil temperature, solar radiation, soil water content, etc. The modeler has the option to output the values for all these variables and these can then be compared to the same variables as estimated by the SHM.

The SHM user inputs the maximum crop height as part of input. The modeler must run the GLYCIM simulations first to get a plant height to plug into SHM. The SHM uses an Agricultural Growth Function (AGF) to estimate LAI and foliage coverage of the ground (see figure A.2). The LAI for a given date in the SHM is equal to 7.0 times the AGF value for that date. Root depth is a function of the maximum vegetation height and the AGF. In the SHM, moisture uptake is 90% through the plants and 10% from bare soil. Root shape is based on a conical function with amount of roots, and hence extraction, larger near the soil surface. This conical function is also used to obtain a weighted average of θ_{root} in equation A.24. Root depth is assumed to be 1/3 the height of the vegetation.

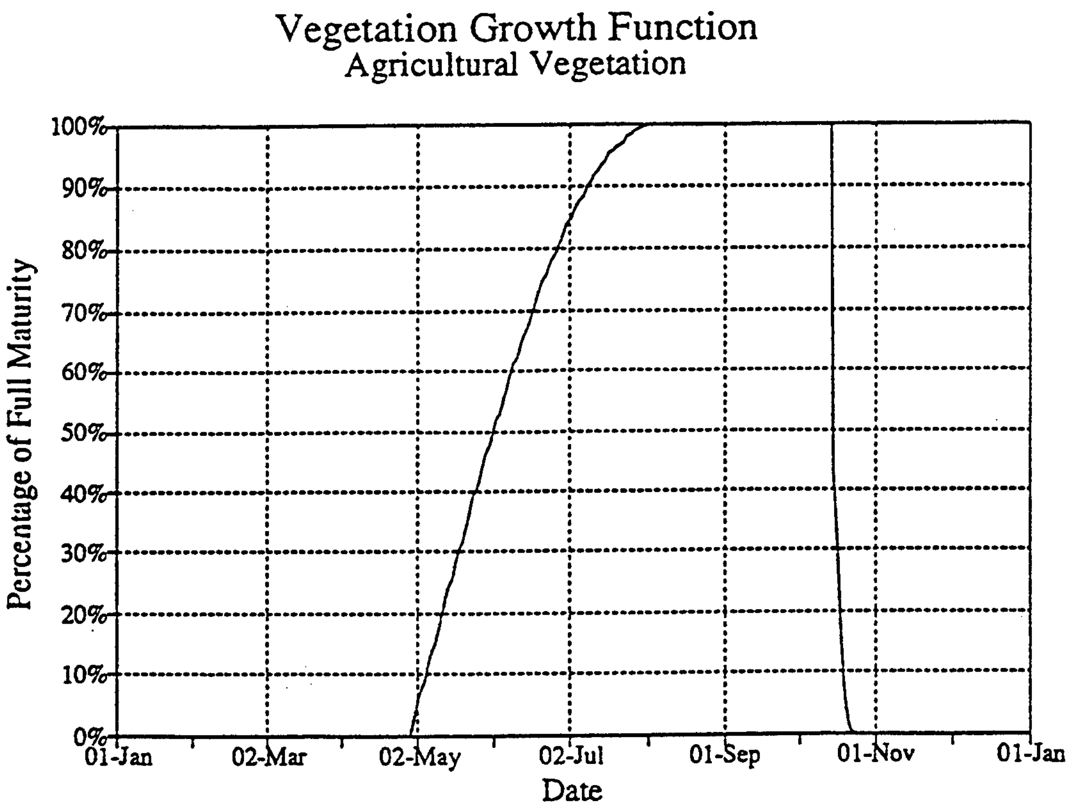

Figure A.2. Agricultural Growth Function (AGF) vs. Julian Date as modeled in the SHM. Leaf area index for a given date in the SHM is equal to 7 times the AGF on that date. Canopy height in the SHM for a given date is equal to maximum crop height (from modified GLYCIM) times the AGF on same date (Capehart, 1992).

Appendix B

Meteorological Data Collection

B.1 Required Meteorological Data

As stated earlier, GLYCIM is a soybean plant simulator. The two environments that the simulated plants grow in are the local soil and atmosphere. Processes in the soil environment include plant uptake, evaporation, and recharge of soil water which are partial functions of meteorological conditions. In the aerial environment, temperature, water vapor pressure and solar and diffuse radiation play important roles in determining plant growth and maintenance. Required data are Julian date, day/month/year, average daily incoming solar + diffuse radiation, maximum air temperature, minimum air temperature, rainfall (irrigation), wind speed, and wet bulb temperature. A summary of required meteorological data for GLYCIM is given in table B.1.

The SHM is also a meteorologically driven model that can produce soil moisture profiles. Therefore, weather data is necessary to accurately model soil moisture changes. Required meteorological data for the SHM are averaged over 2 12-hour periods each day. Required weather data are Julian date (Gregorian calendar), maximum temperature, minimum temperature, water vapor deficit, wind speed, clear/cloudy sky cover ratio, precipitation, month/day/year, and ending time of 12 hour averaging period. These variables are summarized in table B.1.

B.2 Conversion of Raw Meteorological Data to Required Input Data

Most routinely observed and produced worldwide weather data is available and archived on the Pennsylvania State University Meteo VAX/VMS system. Surface

Table B.1 Required Meteorological Data for Model Comparisons

Meteorological Data For GLYCIM	Units
Julian Date	days
Day/Month/Year	N/A
Daily Average Incoming Radiation	W/m^2
Daily Maximum Temperature	°F
Daily Minimum Temperature	°F
Daily Rainfall (Irrigation)	mm/day
Daily Average Wind Speed	km/hr
Daily Average Wet Bulb Temperature	°F
Daily Average Dry Bulb Temperature	°F

Meteorological Data For SHM	Units
Julian Date (Gregorian calendar)	days
Daily Maximum Temperature	°K
Daily Minimum Temperature	°K
12hr Average Water Vapor Pressure Deficit	Pa
12hr Average Wind Speed	m/s
12hr Average Cloud Cover Ratio	N/A
Precipitation	cm/12hr
Month/Day/Year	N/A
Time at End of Averaging Period	hours GMT

meteorological data for a few class-A stations was routinely accessed and saved for the purpose of this experiment. Observations consist of standard surface data as reported by the in-situ observer, and accessed on the VAX by means of a resident meteorology department program called AOBS. This program accesses data at a user specified location for a user specified period of time (usually 01GMT-24GMT) and writes it to a file in the user's directory. For my experiment, I acquired 24 hours of surface data for each site on a daily basis and then copied the information onto a 3.5" floppy disk for future use. An example of a raw surface data file is shown in table B.2. Surface data for each site then had to be converted to units and quantities necessary for model input. Conversion and output into the necessary formats for GLYCIM and the SHM were accomplished by two programs I wrote.

For GLYCIM, maximum and minimum temperatures are simply extracted from the raw surface data file. Rainfall is reported in inches in the data file and is converted to mm/day for use in GLYCIM. Wind speed is reported in knots and is first averaged over a 24 hour

period, and then converted to km/hr. Wet bulb temperature $\mathcal{T}_w$ is calculated according to Rogers and Yau (1991) using the following equations. First, relative humidity (RH) is calculated using the equation

$$\mathcal{RH} = \left[\frac{\left(96.0 - (.056\mathcal{T}) + \left(.56\mathcal{T}_d\right)\right)}{\left(96.0 + (.5\mathcal{T})\right)} \right]^8 \tag{B.1}$$

where $\mathcal{T}$ is the observed temperature in °F and $\mathcal{T}_d$ the observed dew point in °F. Next the saturation water vapor pressure e_s(T) in Pa is calculated using the equation

$$e_s(\mathcal{T}) = 6.112 \exp\left(\frac{17.67\mathcal{T}}{\mathcal{T} + 243.5} \right) \tag{B.2}$$

Table B.2 Example Raw Weather Data File

Data file for AP2794
MDT RS 0050 8 SCT M13 OVC 3R-F 084/49/47/0814/977/RDG TOPS SE-SW OBSCD
MDT RS 0151 8 SCT M14 BKN 20 OVC 2RF 080/49/47/0709/976/RDGS MSTLY OBSCD
MDT SP 0240 M15 OVC 2R-F 0708/974/FEW STFRA 8 HND RDGS MSTLY OBSCD
MDT SA 0251 M15 OVC 2R-F 072/49/47/0707/974/FEW STFRA 6 HND RDGS PLTY OBSCD R- OCNL R/ 72022 15//
MDT SP 0330 M13 OVC 2R-F 0708/974/FEW STFRA 7 HND RDGS PTLY OBSCD R OCNL R
MDT SA 0351 M12 OVC 2R-F 062/49/47/0711/971/ RDGS PTLY OBSCD R
MDT SA 0450 M12 OVC 2R-F 038/49/47/0618/964/PRESFR RDGS PTLY OBSCD
MDT SP 0527 M12 OVC 5F 1011/964/RDGS PTLY OBSCD
MDT SA 0552 M12 BKN 20 OVC 7 037/50/47/0615/964/RE05/ 63431 15// 66
MDT SA 0652 M14 OVC 7 030/50/47/0707/962
MDT SA 0752 M14 BKN 49 OVC 5RW-F 024/49/48/0507/960/RB41
MDT SP 0818 6 SCT M14 OVC 2RW-F 2404/962/RDGS PTLY OBSCD
MDT RS 0851 M6 BKN 14 OVC 3RW-F 032/49/48/0000/962/RDGS PTLY OBSCD/ 60706 17//
MDT SA 0951 6 SCT M13 BKN 30 OVC 5F 028/49/48/0604/961/RE32
MDT SA 1052 5 SCT M13 OVC 3F 035/50/48/0703/963/RDGS PTLY OBSCD
MDT SA 1151 5 SCT M14 BKN 21 OVC 4F 039/51/49/1105/964/RDGS S PTLY OBSCD/ 20706 15// 48 20047
MDT SA 1351 24 SCT M29 BKN 40 OVC 10 047/53/49/2710/966
MDT RS 1451 28 SCT M35 BKN 42 OVC 12 050/54/49/2810/967/ 212 15//
MDT SA 1551 27 SCT E38 BKN 55 BKN 70 OVC 15 054/58/49/2709/968/BINOVC RB07E14
MDT SA 1651 27 SCT M35 BKN 50 OVC 15 057/56/48/2908/969/RB1558E02
MDT SA 1751 M33 BKN 45 BKN 55 OVC 15 057/58/46/3111G16/969/BINOVC/ 10700 15// 48
MDT SA 1851 M33 BKN 40 BKN 50 OVC 15RW- 066/56/44/3113G22/972/RB40
MDT SA 1950 M34 BKN 42 BKN 50 OVC 15 069/56/44/3312/973/RE02
MDT SA 2050 31 SCT M40 OVC 15RW- 076/55/45/3111/975/RB33 / 21900 15//
MDT SA 2150 39 SCT M55 OVC 15 080/56/45/3009/976/RE00 FEW LWR SC SML BINOVC
MDT SA 2250 40 SCT M65 BKN 15 079/57/45/2909/976
MDT SA 2350 48 SCT M75 BKN 15 086/55/46/2809/978/ 21000 1570 59

where $\mathcal{T}$ is the temperature converted to °C . The vapor pressure e (Pa), the partial pressure of the water vapor is found using the following relationship.

$$e \approx e_s(\mathcal{T}) \times \mathcal{RH} \tag{B.3}$$

Next, the saturation mixing ratio w_s and the mixing ratio w are computed from

$$w_s = .0622\left(\frac{e_s}{p - e_s}\right) \tag{B.4a}$$

$$w = .0622\left(\frac{e}{p - e}\right) \tag{B.4b}$$

where p is the observed station pressure in pascals. Finally $\mathcal{T}_w$ is computed from the following equation

$$\mathcal{T}_w = \mathcal{T} - \left(\frac{\mathcal{L}}{C_p}\left(w_s - w\right)\right) \tag{B.5}$$

where $\mathcal{T}_w$ and $\mathcal{T}$ are in °K, $\mathcal{L}$ is the latent heat of vaporization of water in JKg^{-1}, and C_p is the specific heat of air at constant pressure in $JKg^{-1}K^{-1}$. The hourly incoming solar radiation (irradiance) in Wm^{-2} is then estimated according to Iqbal (1983). First, solar declination (δ) for a given day was calculated using the formula

$$\delta = 23.45 \sin\left[\frac{360}{365}\left(d_n + 284\right)\right] \tag{B.6}$$

where d_n is the Julian date and δ is in degrees. Next, the hour angle (ω) is calculated using the following equation

$$\omega = \left(a - (b - \mathcal{L})\right)15.0 \tag{B.7}$$

where a is the offset in hours of the given location from the center of its time zone, b is the hour of solar zenith, and $\mathcal{L}$ is the local time in hours. Finally, the hourly incoming solar radiation at the top of the atmosphere (I_o) is calculated using

$$I_o = I_{sc}\,\mathcal{E}_o(\sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega) \tag{B.8}$$

where I_{sc} is the solar constant with a value of 1369 Wm^{-1}, $\mathcal{E}_o$ is the earth's orbital eccentricity rounded to 1.0, and ϕ is the latitude in degrees of the data collection site. Incoming radiation which falls on a horizontal surface at a given site is then estimated using a scheme developed by Penman (1948). First, cloud cover as reported is converted into a ratio (see table B.3). Then the following regression equation developed by Penman is used to estimate the effect of sky cover.

$$f_{sc} = .8 + \left(.55\frac{n}{\mathcal{N}}\right) \tag{B.9}$$

This value is then used in the final equation to estimate the incoming solar radiation $\mathcal{S}\downarrow$

$$\mathcal{S}\downarrow = .71\, I_0 f_{sc} \tag{B.10}$$

where the average amount of radiation that penetrates the earth's atmosphere is estimated at 71% after Acock and Trent (1991).

For the SHM, any value that was used for GLYCIM and is also used in SHM, is calculated as above. Differences in input variables are mainly in units required for input such as in wind speed, precipitation, temperature and Julian date. SHM uses the vapor pressure deficit (as opposed to the wet bulb temperature in GLYCIM) which is simply given by the difference between e_s and e. The SHM estimates incoming radiation from the cloud cover ratio and a scheme similar to the Penman scheme given above (see table B.3).

Table B.3 Fractional Sky Cover Estimates

Sky Condition	n/N
CLR	1.0
SCT	0.65
BKN	0.30
OVC	0.00

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