Revista Brasileira de Agrometeorologia, Santa Maria, v. 9, n. 2, p. 357-376, 2001
Recebido para publicação em 22/02/2001. Aprovado em 22/11/2001.

ISSN 0104-1347

Evaluation of the WGEN and SIMMETEO weather generators for the brazilian tropics and subtropics, using crop simulation models

Avaliação dos geradores de dados meteorológicos WGEN e SIMMETEO, nas condições tropicais e subtropicais brasileiras, usando modelos de simulação de culturas

Paulo Cesar Sentelhas[1], Rogério Teixeira de Faria[2], Matheus Oliveira Chaves[1] and Gerrit Hoogenboom[3]

Abstract - *Daily weather data are normally required as an input for crop simulation models. However, raw data collected by weather stations frequently contain errors. Sometimes the available weather series is too short for long-term analyses, which normally require at least 20 to 30 years of daily weather data. For these cases, weather generators can be used to generate daily weather data, based on long-term climate data. The objective of this study was to evaluate the performance of two weather generators, WGEN and SIMMETEO, for Brazilian tropical and subtropical weather conditions using data from five different weather stations, representing four climate zones in Brazil. Two different methods were used to evaluate the performance of both weather generators. In the first analysis the averages and frequency distribution functions of generated and observed values were compared. In second analysis comparisons were made for irrigated and rainfed grain yield of maize and dry-bean crops simulated with the CERES-Maize and CROPGRO-Dry Bean models, using as input generated and observed weather data. It was verified that in most of the simulations (72.5%), the crop yield simulated with generated weather data from both generators did not differ significantly at the 5% level from yield simulated with observed weather data. Based on the results of this study, it can be concluded that both weather generators can be used to generate long-term weather data for the Brazilian tropics and subtropics for application in strategic analyses with crop simulation models. However, there were significant differences in the distributions of observed and generated data for solar radiation and air temperature.*

Key words: *solar radiation, temperature, rainfall, crop simulation model, maize, dry bean, decision support system.*

Resumo - *Modelos de simulação de culturas normalmente exigem o emprego de dados meteorológicos diários. No entanto, os dados provenientes de estações meteorológicas normalmente apresentam problemas ou as séries históricas não são longas suficientes para seu emprego em análises de longo período. Nesses casos, pode-se lançar mão dos geradores de dados meteorológicos. Neste estudo foram avaliados dois geradores de dados meteorológicos, WGEN e SIMMETEO, nas condições tropicais e subtropicais do Brasil. Foram utilizadas, para tanto, séries históricas de dados meteorológicos de cinco localidades, duas no Estado do Paraná e três no Estado de São Paulo. Os resultados foram avaliados de duas formas: comparando-se as médias e as distribuições de frequência dos dados meteorológicos gerados e observados, e comparando-se as médias e as distibuições de frequência dos dados de produtividade potencial e real das culturas do milho e do feijão, estimadas respectivamente pelos modelos CERES-Maize e CROPGRO-Dry Bean, utilizando-se séries de dados meteorológicos gerados e observados. Comparando-se as distribuições de frequência das produtividades potencial e real das culturas do milho e do feijão, simuladas com dados gerados e observados, foi verificado que na maioria das simulações (72,5%) não houve diferença significativa, o que permite concluir que, apesar das diferenças observadas entre os dados observados e gerados, ambos os geradores podem ser usados para gerar ou expandir séries históricas de dados meteorológicos para as condições tropicais e subtropicais brasileiras, quando o objetivo é se conduzir análises de longo período com modelos de simulação de culturas.*

Palabras-chave: *radiação solar, temperatura, chuva, modelos de simulação de culturas, milho, feijão, sistema de suporte à decisão.*

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Introduction

Crop simulation models have become an increasingly valuable tool in agricultural science, research, and extension for assisting with decision making both at a farm level as well as at a regional level (RITCHIE et al., 1990; TSUJI et al., 1998). The models can be used to simulate growth of individual crops or management of whole farming systems (MEINKE et al., 1995; BOOTE et al., 1996). They can also be used for improvement of genotypes and cultivars (WHITE, 1998), water management of irrigated crops (MACROBERT & SAVAGE, 1998), and crop risk assessment and food security (THORNTON & WILKENS, 1998).

The development of crop models and decision support tools, such as the Decision Support System for Agrotechnology Transfer (DSSAT), to aid research and development in agriculture was the focus of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project (UEHARA & TSUJI, 1998; HOOGENBOOM et al., 1999). Access to reliable historical weather data is essential for obtaining accurate simulations of crop growth, development and yield. This is especially important for rainfed production systems where weather variability is responsible for almost 80% of the variability of agricultural production (HOOGENBOOM, 2000).

One of the main limitations for a wide use and application of crop simulation models is the lack of accurate data that describe both the spatial and temporal variability of the main input factors needed to predict crop performance (RITCHIE et al., 1990). Some of the common weather data problems include: data format errors, missing data, data suspect to be erroneous, and data in an inconvenient format (PICKERING et al., 1994). Another problem is that in many cases weather data are available but incomplete (MEINKE et al., 1995) or the available climate series is too short (LEENHARDT, 1999).

Weather generators are frequently used when there are insufficient weather data available for a location or when there are problems with the quality of the weather data. Synthetically generated weather data based on climatological inputs can be a substitute for observed weather and can be used to simulate the impact of weather variability on management decisions (HAYHOE, 1998; HOOGENBOOM, 2000).

There have been several recent efforts to develop weather generators that can generate daily data for rainfall, maximum and minimum air temperature, and solar radiation (LARSEN & PENSE, 1982; BRISTOW & CAMPBELL, 1984; RICHARDSON & WRIGHT, 1984; GENG et al., 1986; MCCASKILL, 1990; JONES & THORNTON, 1999; DONATELLI & CAMPBELL, 1999; DUBROVSKY, 1999). Several of these weather generators have been evaluated for many regions across the world representing different climatic conditions. For instance, MEINKE et al. (1995) evaluated the performance of three weather generators, i.e., TAMSIM; WGEN; and the Bristow and Campbell's method, for estimating air temperature and solar radiation in the Australian tropics and subtropics. They concluded that there were significant differences between the observed and generated data. However when both the generated and observed weather data were used as input in crop simulation models, only 20% of simulations showed significant differences for the estimation of biomass, specially for the data generated by WGEN. Similar results were found by SOLTANI et al. (2000) for semiarid climatic conditions in Iran. They found that chickpea yields estimated with WGEN-generated weather data differed significantly in only 8% of the years under rainfed conditions from simulations with observed data. HARTKAMP et al. (2001) evaluated the WGEN, SIMMETEO and TAMSIM weather generators for different climatic conditions in Mexico. For these conditions, the use of SIMMETEO is currently prefered considering that only monthly means are needed as input for the weather generator and that there is little or no difference between crop simulations based on generated and observed data.

In the DSSAT system (TSUJI et al., 1994; HOOGENBOOM et al., 1999), weather data are managed and generated by WeatherMan, a utility program for both importing, analyzing and generating weather data (PICKERING et al., 1994). WeatherMan includes two methods for stochastically generating sequences of daily weather data: WGEN (RICHARDSON & WRIGHT, 1984) and SIMMETEO (GENG et al., 1986). Both methods can be parameterized from daily data, and SIMMETEO can also use monthly averages from any secondary climate data source. These weather generators provide daily values for solar radiation, maximum and minimum temperatures and precipitation for a n-year period. A second-order Markov chain model is used to simulate the occurrence of wet or dry day and the probability of rain on a given day is conditioned on the previous day. If a wet day is generated, the amount of precipitation will be generated from the two-parameter gamma distribution. Solar radiation and maximum and minimum temperatures are generated depending on the precipitation, or the occurrence of wet or dry days. The values of these three variables are obtained from the residual elements, which are generated using a multivariate normal generation procedure that maintains the relationship between variables (serial correlation and cross correlation), in addition to the seasonal averages and standard deviations.

The use of crop simulation models and the DSSAT system for long-term studies in Brazil has increased during the last few years (FARIA et al., 1997; SOLER, 2000; CARDOSO, 2001; HEINEMANN et al., 2001; MEIRELES et al., 2001; ROLIM et al., 2001). However, for many locations in Brazil historical series of weather data of 30 years or longer are not available. There is therefore a need to use a weather generator for these types of simulation studies, but the performance of the weather generators for the Brazilian tropics and subtropics is unknown. The objective of this study was to evaluate the performance of the WGEN and SIMMETEO weather generators, as distributed with the DSSAT system Version 3.5 for tropical and subtropical conditions in Brazil, by comparing observed and generated data, and the impact of the weather generator simulation of crop yield.

Material and methods

The WeatherMan (Weather data Manager) program was designed to simplify or automate many of the repetitive tasks associated with preparing raw weather data for use or application by crop or other simulation models. One of its important features is quality control of the weather data (PICKERING et al., 1994). WeatherMan is part of the DSSAT Version 3.5 system (TSUJI et al., 1994; HOOGENBOOM et al., 1999) and it has the capability to import and export different file formats, to convert the units of individual variables, to check for errors on import, to fill in missing and to replace suspicious values on export. In addition, it can generate complete sets of daily weather data comprising of solar radiation, maximum and minimum air temperature and rainfall.

WeatherMan uses adaptations of WGEN (RICHARDSON & WRIGHT, 1984) and SIMMETEO (GENG et al., 1986) to generate weather data. The SIMMETEO generator is embodied in the WGEN generator, but uses a different input section. The DSSAT Version 3.5 modification of SIMMETEO can use monthly weather data to determine its input variables, while WGEN is based on daily weather data. Daily values are computed internally, using linear interpolation and regression equations based on monthly climate averages (PICKERING et al., 1994).

The weather generators WGEN/SIMMETEO predict solar radiation and maximum and minimum temperature as a continuous multivariate stochastic process, with daily averages and standard deviations varying depending on wet and dry days. The wet and dry days are generated using a second order Markov chain. A random number generator is used in conjunction with the probability models to generate a random series. When a wet day is generated, the precipitation amount may be generated according to a two-parameter gamma distribution. The program calculates smoothly varying daily average variable values by fitting single sine curves to monthly parameter value which need to be supplied for each site. More details of both weather generators can be found in the original publications that describe these generators (GENG & AUBURN, 1987; GENG et al., 1986; RICHARDSON, 1981, 1985; RICHARDSON AND WRIGHT, 1984).

Five Brazilian climate stations with long-term measured weather data that are reliable were used for this study. The stations include Manduri, Ribeirão Preto and Piracicaba in the state of São Paulo (SP) and Paranavaí and Ponta Grossa in the state of Paraná (PR) (Table 1). The sites were selected to cover a different geographical area and several climatic sub-zones in these two states. According to Köppen's climatic classification the climate for Manduri is Cfa (Subtropical, without dry season and average temperature of the hottest month greater than 22°C), for Ponta Grossa is Cfb (Subtropical, without dry season and average temperature of the hottest month lower than 22°C), for Piracicaba and Paranavaí is Cwa (Tropical, with dry season during the winter and average temperature of the hottest month greater than 22°C), and for Ribeirão Preto is Aw (Tropical, with dry season during the winter and average temperature of the coolest month greater than 18°C).

The weather data used were daily maximum (TMAX) and minimum (TMIN) air temperature,

Table 1. Geographic location of sites, annual climatic averages for maximum (TMAX) and minimum (TMIN) air temperature, solar radiation (SRAD), rainfall (R), and number of wet days (NDR); starting year of the weather data, total number of years for which complete records are available, and the source of the data.

	Manduri (SP)	Piracicaba (SP)	Ribeirão Preto (SP)	Paranavaí (PR)	Ponta Grossa (PR)
Latitude, °S	23.16	22.70	21.18	23.08	25.22
Longitude, °W	49.33	47.63	47.80	52.43	50.02
Altitude, m	589	546	621	480	880
TMAX, °C	27.3	28.2	28.9	28.3	24.0
TMIN, °C	14.9	14.8	16.1	17.7	13.5
SRAD, $MJm^{-2}d^{-1}$	17.6	16.9	18.5	18.5	15.9
RF, mm	1451	1262	1531	1506	1542
NDR, days	118	109	122	117	129
Starting year	1962	1917	1965	1974	1966
Number of years	37	82	34	25	33
Source	IAC[1]	ESALQ[2]	IAC[1]	IAPAR[3]	IAPAR[3]

[1] IAC - Agronomic Institute of Campinas, [2] ESALQ - Agricultural College "Luiz de Queiroz"; [3] IAPAR - Agronomic Institute of Paraná.

hours of sunshine (n), and daily total rainfall (RF). Solar radiation (SRAD) was estimated with WeatherMan, using hours of sunshine duration and the Angström-Prescott's equation:

$$SRAD = SRAD_o \, [a + b \, (n/N)] \qquad (1)$$

where $SRAD_o$ is the solar radiation above the atmosphere, and N is the maximum number of sunshine hours. The coefficients α and β are location dependent and are affected by such factors as latitude, altitude, and atmospheric qualities (RITCHIE et al., 1990). For the sites utilized in this study, α and β were estimated with WeatherMan utilizing the method presented by RIETVELD (1978), in which α and β have a linear relationship with n/N.

Two different crop models were used to evaluate the sensitivity of crop simulation to recorded versus generated weather data. These included the generic grain legume model CROPGRO for dry bean (HOOGENBOOM et al., 1992, 1994; BOOTE et al., 1998), and the generic cereal model CERES for maize (JONES & KINIRY, 1986; RITCHIE et al., 1998). Both are included in the DSSAT program (Version 3.5) (TSUJI et al., 1994; HOOGENBOOM et al., 1999).

These crop models were used to simulate irrigated (60% of available water) and rainfed grain yield for all sites. The maize cultivar Pioneer 3382 and dry-bean cultivar IAPAR14 were selected for simulations. The individual growth and development characteristics of these cultivars are listed in Table 2. Two sowing dates were evaluated for each crop and site: 1st February, called dry season yield for the remainder of this study, and 1st October, called wet season yield, for a total of 20 years to provide for a uniform the series length. The plant densities used were 71,000 plants per ha for maize and 240,000 plants per ha for dry-bean.

The selected sowing dates reflect common management practices adopted in these regions. No effects of pests or diseases were considered and the nutrients were considered non-limiting for plant growth. Soil data were obtained from previous studies by LIMA (1995) for Piracicaba, by FARIA et al. (1997) for Paranavaí and Ponta Grossa, and by SOLER (2000) for Mandurí and Ribeirão Preto.

Tukey's test was used to compare averages of generated and observed weather data, averages of the number of days with rainfall, TMAX > 35°C and TMIN < 5°C, and averages of yields simulated using observed and generated data. To compare distribuitions of each estimated climate variable with recorded data, the *Kolmogorov-Smirnov* (KS) test was applied to determine if there were significant differences between the distributions (ASSIS et al., 1996). The same test was used to analyze grain yield estimated by the crop models using both observed and genereted weather data (MEINKE et al., 1995; SOLTANI et al., 2000). The advantage of the KS test is that it analyses the difference between two distributions functions.

Table 2. Cultivar characteristics and genetic coefficients for the maize and dry bean cultivars used in this study.

Maize - Pioneer 3382

Coefficient	P1	P2	P5	G2	G3	PHINT
Value	200	0.7	800	715	8.5	38.9

Dry-bean – IAPAR 14

Coefficient	CSDL	PPSEN	EM-FL(R1)	FL-SH(R3)	FL-SD(R5)
Value	12.17	0	27.0	5.0	11.0
Coefficient	SD-PM(R7)	FL-LF	LFMAX	SLAVR	SIZLF
Value	30.0	20.0	0.9	295	133
Coefficient	XFRT	WTPSD	SFDUR	SDPDV	PODUR
Value	1	0.2	15.0	3.5	6.5

P1 = thermal time from seedling emergence to the end of juvenile phase (Tb = 8°C), P2 = extent to which development (expressed as days) is delayed for each hour increase in photoperiod above 12,5h, P5 = thermal time from silking to physiological maturity (Tb = 8°C), G2 = maximum possible number of kernels per plant, G3 = kernel filling rate during the linear grain filling stage and optimum conditions (md/day), PHINT = phylochron interval, CSDL = critical daylength, PPSEN = sensitivity to photoperiod (1/h), EM-FL = the time from end of juvenile phase to first flower in photothermal days, FL-SH = the time from first flower to first pod greather than 0.5cm in photothermal days, FL-SD = the time from first flower to first seed in photothermal days, SD-PM = the time from first seed to physiological maturity in photothermal days, FL-LF = the time from first flower to end of leaf growth in photothermal days, LFMAX = maximum leaf photosynthesis rate at saturated light level, optimal temperature (µmol CO$_2$/m^{2}s), SLAVR = specific leaf area (SLA) for new leaves during peak vegetative growth (cm^2/g), SIZLF = maximum size of fully expanded leaf on the plant under standard growing conditions (3 leaflets) (cm^2), XFRT = maximum fraction of daily available gross photosynthesis (PG) which is allowed to go to seeds plus shells, WTPSD = maximum weight per seed under non-limiting substrate (g), SFDUR = seed filling duration for a cohort of seed (photothermal days), SDPDV = average seed per pod under standard growing concitions, PODUR = photothermal days for cultivar to add full pod load under optimal conditions, used to compute rate of pod and flower addition.

Results and discussion

The monthly averages were evaluated for each site; the data generated by WGEN showed a good agreement when compared with observed monthly averages and did not differ significantly from observed data. However, the data generated with SIMMETEO showed a significant difference for SRAD and TMAX (Table 3). This can be seen analyzing the mean absolute error (MAE) for all sites. For SRAD generated by WGEN, MAE was 0.24 MJ.m^{2}.d^{-1} and by SIMMETEO 1.07 MJ.m^{-2}.d^{-1}. For TMAX the MAE was 0.22ºC when WGEN was used and 0.60ºC when data were generated by SIMMETEO. For TMIN and RF the values of MAE were similar when data were generated by both weather generators.

The statistical analysis of the frequency distribution showed that there was a significant difference from distributions of recorded data for SRAD and air temperature generated by WGEN and SIMMETEO (Figs. 1, 2 and 3, Table 4). These observations are similar to the weather generator evaluations conducted in Australia (MEINKE et al., 1995) and Iran (SOLTANI et al., 2000). The WGEN-generated data had lower maximum difference values than the SIMMETEO-generated data. MEINKE et al. (1995) found the same tendency. Based on this analysis it can be concluded that WGEN provides a more realistic representation than SIMMETEO in generating weather data.

A detailed analysis of SRAD for both generators showed that the worst fit between distributions of observed and generated data was for values between 5 and 20 MJ.m^{-2}.day^{-1}. For values of SRAD between 25 and 35 MJ.m^{-2}.day^{-1}, the fit was almost perfect (Fig.1). The poor performance of SIMMETEO could be caused by the simplifying assumptions on which some of the weather generators that use only monthly averages as input data are based (ACCUTIS et al., 1999). For TMIN and TMAX, in general, the worst fit was also found for the most frequent values, between 20 and 29ºC for TMAX (Fig.2) and between 13 and 19ºC for TMIN (Fig.3).

Both WGEN and SIMMETEO were capable to generate extremes values for TMIN and TMAX

Table 3. Comparison of average monthly observed and generated weather data in Ribeirão Preto (SP), Brazil. O - observed; W - WGEN; and S - SIMMETEO.

Month	SRAD (MJ.m^{-2}day^{-1})			TMAX (ºC)			TMIN (ºC)			RF (mm)		
	O	W	S	O	W	S	O	W	S	O	W	S
1	20.5	20.6	17.9*	29.7	29.5	29.9	18.7	18.8	18.6	257	249	259
2	20.2	20.0	17.2*	30.2	30.1	29.4*	18.7	18.7	18.7	218	219	227
3	19.8	19.9	16.9*	30.0	30.4	28.6*	18.1	18.3	18.3	164	169	156
4	18.7	18.9	17.8*	28.9	28.9	27.9*	16.3	16.2	16.1	86	86	78
5	15.4	15.1	16.4*	26.9	26.8	27.6	13.9	13.8	13.8	58	58	53
6	14.3	14.0	15.8*	26.2	26.0	27.6*	12.4	12.3	12.4	34	34	32
7	15.3	15.1	16.8*	26.7	26.3	28.1*	12.1	11.8	12.2	24	27	22
8	17.5	17.6	18.3*	28.9	29.1	28.4	13.6	13.4	13.5	24	23	23
9	18.4	18.3	19.1	29.8	29.7	29.2	15.5	15.5	15.7	62	63	74*
10	20.9	21.3	19.7	30.3	30.7	29.6	17.0	17.1	17.1	133	157*	119
11	21.5	22.0	20.1*	29.9	29.8	30.5	18.0	17.9	18.2	176	171	150
12	19.8	19.8	18.3*	29.3	29.1	30.4*	18.6	18.6	18.7	294	314	292
Annual	18.5	18.6	17.9*	28.9	28.9	28.9	16.1	16.0	16.1	1531	1570	1486

* The observed average and the generated average are significantly different at the 1% level.

that were similar to the extreme values of the observed data (Fig. 2 and 3). Extreme values are important particularly when using models to predict potential frost and heat damage to crops. A recent study by HAYHOE (1998) verified that the modified WGEN model (WXGEN) used in EPIC (Erosion/Productivity Impact Calculator) is a poor tool to generate realistic extremes for weather variables because it uses fixed values to account for the effect of wet and dry days on temperature and solar radiation. In contrast to WXGEN, the original model (WGEN), utilized in this paper, uses observed wet and dry day monthly averages and standard deviations.

A statistical comparison of observed and generated RF showed that both the monthly averages and frequency distributions of generated data did not differ significantly from those of observed data for most of the sites (Fig.4, Table 4). LARSEN & PENSE (1982) obtained the same results when using a two-parameter gamma distribution to generate RF amount, similar to the process used in WGEN and SIMMETEO. Only for the generator WGEN in Piracicaba and Ponta Grossa and SIMMETEO in Ponta Grossa the frequency distributions of generated RF data differed significantly from observed data. However, the differences between calculated and critical KS values were very low showing the potential application of both methods to generate rainfall data for these locations (Table 4). Similar results for rainfall were found by SOLTANI et al. (2000). However, one should be carefull about the interpretation of the performance of the generator, as it is highly dependent upon the length of the observed data series used to calculate the parameters of the models.

The analyses of the number of days with extreme values for temperature and rainfall are presented in Table 5. Both weather generators presented a tendency to overestimate the number of days with TMAX > 35ºC and to underestimate the number of days with TMIN < 5ºC. For the number of days with rainfall or wet days, both weather generators showed a very good performance for all locations of this study.

An analysis of the impact of using either simulated or observed weather data on the simulation of crop growth, development and yield showed that average yield estimated using data generated by WGEN and SIMMETEO did not differ significantly from yields simulated with observed data (Table 6 and 7). However, the overall performance of simulated maize yield based on the generator WGEN was better than maize yield based on the generator SIMMETEO. Significant differences were found in 20% of the simulations when WGEN was used and in 40% of the simulations when SIMMETEO was used. For dry bean, there were no significant differences between the yield simulated by the both generators and the yield based on observed data. This is partially due to the shorter cycle of dry bean in comparison to maize.

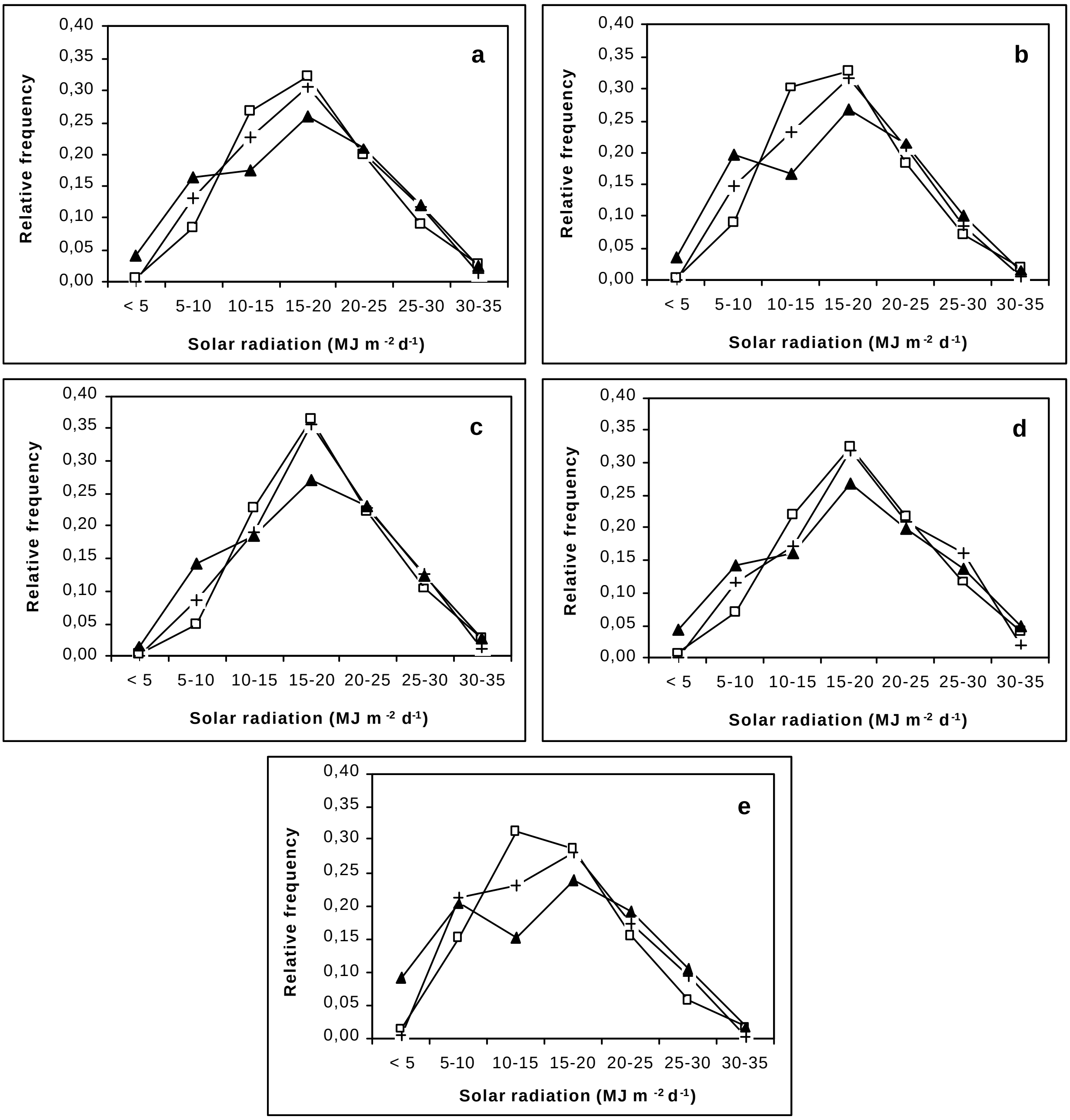

Figure 1. Comparison of solar radiation distrubutions generated using WGEN (□) and SIMMETEO (▲) with distributions calculated from observed data (+) in (a) Mandurí, SP, (b) Piracicaba, SP, (c) Ribeirão Preto, SP, (d) Paranavaí, PR, and (e) Ponta Grossa, PR, Brazil.

In general, when generated data were used to estimate the crop yield, the standard deviation decreased and in some cases the average yield increased. This behaviour is related to the generation of rainfall (VILLALOBOS et al., 1999). In this study, this tendency was not found for either the maize or dry bean crop (Table 6 and 7), due to the very good performance of both generators to generate the RF series (Table 3 and 5).

The simulations conducted for the two crops and five sites showed that for most of the simulations (72.5%), both irrigated (potential) and rainfed grain yield frequency distributions for generate data did not differ significantly from observed weather data (Figs. 5 to 9, Table 8). Only in eleven cases (27.5%), including ten cases for maize yield in which three were simulated with WGEN-generated data and seven

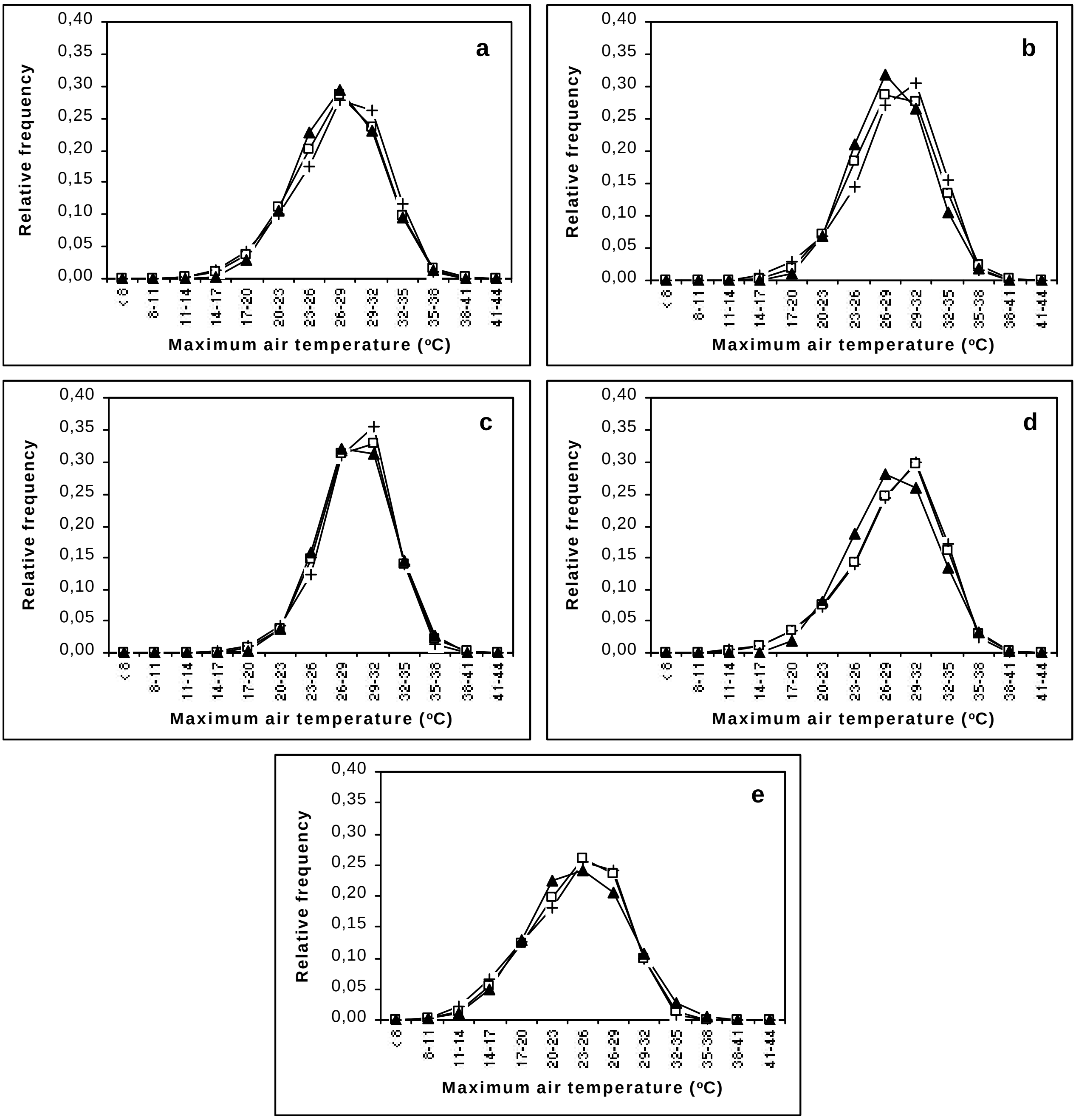

Figure 2. Comparison of maximum air temperature distrubutions generated using WGEN (☐) and SIMMETEO (▲) with distributions calculated from observed data (+) in (a) Mandurí, SP, (b) Piracicaba, SP, (c) Ribeirão Preto, SP, (d) Paranavaí, PR, and (e) Ponta Grossa, PR, Brazil.

were simulated with SIMMETEO-generated data, and one for rainfed dry-bean yield simulated with WGEN-generated data, there were significant differences in frequency distributions (Table 8).

The use of crop simulation models as a sensitivity analysis tool to evaluate the performance of the WGEN and SIMMETEO weather generators showed that both generators can be used to solve problems related to weather data, such as missing data and insufficient length of the data series, as well as mentioned by HARTKAMP et al. (2001). However, when weather generators are used as a tool to generate long series of meteorological data from shorter series of measured data, it is critical that the generated data

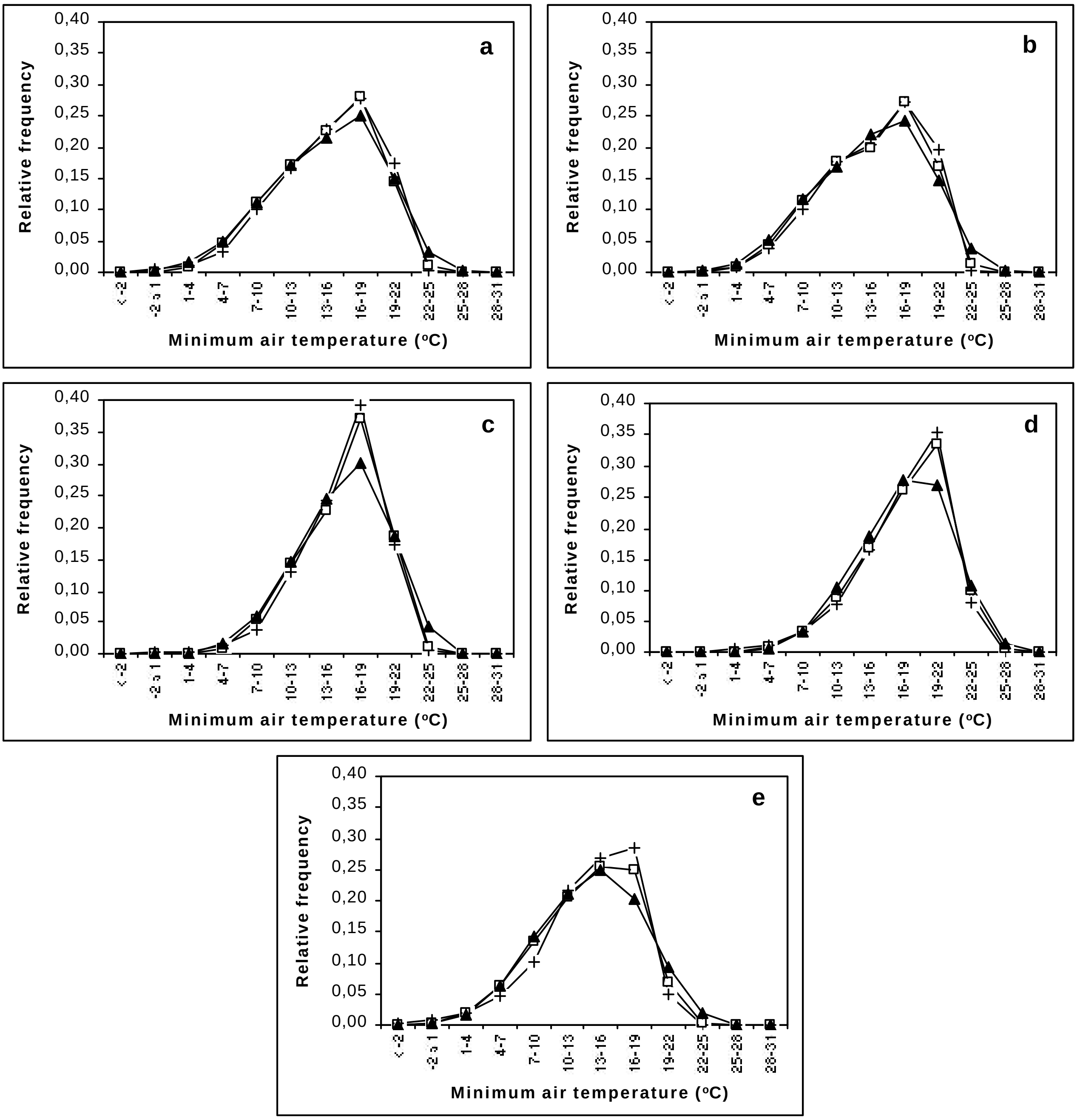

Figure 3. Comparison of minimum air temperature distrubutions generated using WGEN (□) and SIMMETEO (▲) with distributions calculated from observed data (+) in (a) Mandurí, SP, (b) Piracicaba, SP, (c) Ribeirão Preto, SP, (d) Paranavaí, PR, and (e) Ponta Grossa, PR, Brazil.

Table 4 Kolmogorov-Smirnov statistic test for the comparison of the frequency distributions of observed and generated data of solar radiation (SRAD), maximum (TMAX) and minimum (TMIN) air temperature, and rainfall (RF), at five sites in the tropical and subtropical conditions of Brazil.

Site	SRAD		TMAX		TMIN		RF	
	WGEN	SIM	WGEN	SIM	WGEN	SIM	WGEN	SIM
Manduri (SP)	0.042*	0.076*	0.039*	0.051*	0.023*	0.036*	0.007	0.002
Piracicaba (SP)	0.055*	0.086*	0.043*	0.087*	0.021*	0.042*	0.029*	0.012
Rib.Preto (SP)	0.034*	0.074*	0.014	0.024*	0.022*	0.050*	0.010	0.008
Paranavaí (PR)	0.038*	0.071*	0.008	0.066*	0.023*	0.044*	0.007	0.005
Pta Grossa (PR)	0.050*	0.086*	0.024*	0.033*	0.039*	0.064*	0.016*	0.017*

Values followed by * have distributions differing significantly from observed data at P <0.05. SIM is abreviation of SIMMETEO.

reproduce the variability of the measured meteorological data, without introducing unrealistic extreme values. In this context, the number of available years for which measured data are available becomes very important. According to ACUTIS et al. (1999) and SOLTANI et al. (2000), the quality of climatic simulations increases in proportion to the length of available data that are used to develop the inputs for the weather generators. Temperature series based on climate data with a duration of seven years or less can create unrealistic values for extreme temperature conditions, whereas rainfall data are only adequately simulated when the climate data are based on a series of 10 years or longer.

Conclusions

Based on the results from this study, it can be concluded that the weather generators WGEN and SIMMETEO performed adequately when they were used to generate weather for simulating growth, development and yield for maize and dry bean for the tropical and subtropical climatic conditions of Brazil. The weather generators can be used to generate long-term weather data sets or to fill missing data when existing weather data are of poor quality or of short duration. They provide the capability for conducting strategic simulation analyses and climatic risk assessment for many sites in this region where the period of record for measured weather data is too short or many data are missing. However, there were significant differences in the averages and distributions of observed and generated data for solar radiation and air temperature, mainly when SIMMETEO was used.

Acknowledgements

The authors wish to thank “Instituto Agronômico de Campinas” and “Instituto Agronômico do Paraná” for the weather data used in this project.

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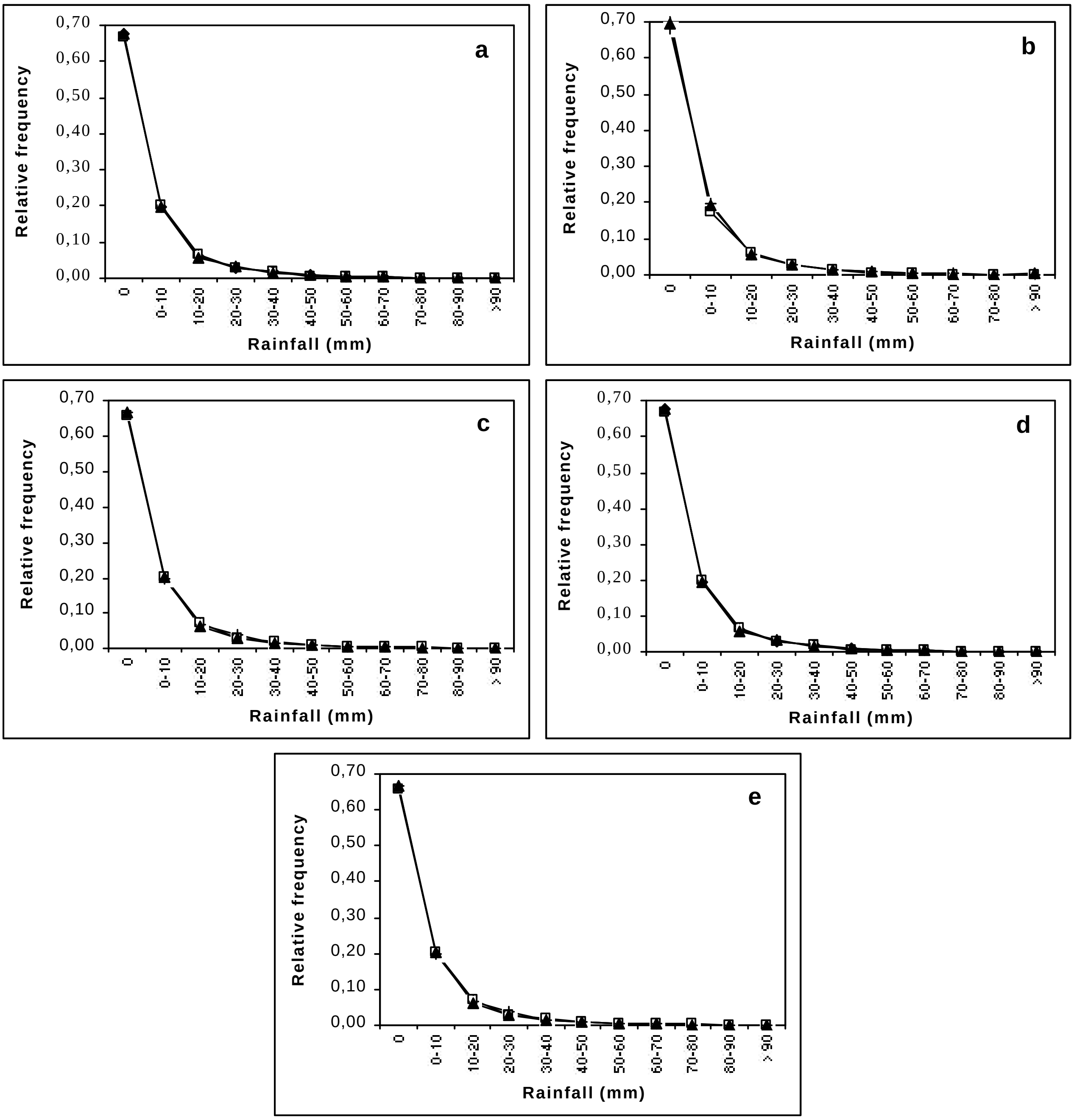

Figure 4. Comparison of rainfall distrubutions generated using WGEN (☐) and SIMMETEO (▲) with distributions calculated from observed data (+) in (a) Mandurí, SP, (b) Piracicaba, SP, (c) Ribeirão Preto, SP, (d) Paranavaí, PR, and (e) Ponta Grossa, PR, Brazil.

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Table 5. Comparison of average annual number of days with TMAX > 35°C, TMIN < 5°C and rainfall for observed and generated data with the WGEN and SIMMETEO generators in tropical and subtropical climatic conditions in Brazil.

Variable	Places	Observed	WGEN	SIMMETEO
TMAX>35°C	Paranavaí, PR	0.05	0.00	0.55*
	Ponta Grossa, PR	9.25	8.80	15.55*
	Mandurí, SP	3.05	8.35*	5.35
	Piracicaba, SP	6.30	9.40	9.50
	Ribeirão Preto, SP	4.85	7.30	9.25*
TMIN < 5°C	Paranavaí, PR	15.15	10.30*	11.25
	Ponta Grossa, PR	3.40	0.90*	0.30*
	Mandurí, SP	8.80	7.85	6.95
	Piracicaba, SP	7.15	6.50	12.20*
	Ribeirão Preto, SP	1.95	0.60*	1.50*
Rainfall > 0	Paranavaí, PR	130.50	135.00	131.05
	Ponta Grossa, PR	116.15	111.10	119.75
	Mandurí, SP	119.80	120.95	123.80
	Piracicaba, SP	108.50	107.00	102.95
	Ribeirão Preto, SP	123.30	126.05	126.65

* The observed average and the generated average are significantly different at the 1% level.

Table 6. Average and standard deviation (SD) for maize yield (kg ha^{-1}), estimated with the CERES-Maize model using observed and generated weather data.

Site	Sowing Date	Water Management	Observed		WGEN		SIMMETEO	
			Yield (kg/ha)	SD (kg/ha)	Yield (kg/ha)	SD (kg/ha)	Yield (kg/ha)	SD (kg/ha)
PRV	1st Oct	Rainfed	6,893	2,623	6,412	2,865	5,355	2,323
	1st Oct	Irrigated	11,195	1,410	11,184	1,573	10,162*	1,139
	1st Feb	Rainfed	7,968	2,870	8,064	2,364	8,087	1,947
	1st Feb	Irrigated	11,098	853	10,623	994	9,729*	1,224
PTG	1st Oct	Rainfed	5,530	2,978	7,938*	2,403	5,355	2,384
	1st Oct	Irrigated	11,125	1,264	10,340	1,379	10,162	1,516
	1st Feb	Rainfed	5,019	2,351	9,648*	1,868	8,087*	2,268
	1st Feb	Irrigated	10,821	667	11,483	1,663	9,729	1,820
MAN	1st Oct	Rainfed	9,991	1,392	7,926*	2,762	8,522*	1,351
	1st Oct	Irrigated	11,334	1,374	10,692	1,161	10,247*	1,487
	1st Feb	Rainfed	9,518	2,087	9,958	1,956	8,963	1,505
	1st Feb	Irrigated	11,308	872	11,295	654	10,022*	1,343
PIR	1st Oct	Rainfed	7,884	2,387	8,539	2,585	6,764	3,134
	1st Oct	Irrigated	10,592	1,536	11,143	1,296	9,744	1,577
	1st Feb	Rainfed	8,231	2,283	6,956	3,138	7,200	2,061
	1st Feb	Irrigated	10,208	866	10,635	1,001	9,976	1,192
RPT	1st Oct	Rainfed	9,790	1,616	9,790	1,291	8,873	1,792
	1st Oct	Irrigated	12,158	984	11,365	1,261	9,690*	949
	1st Feb	Rainfed	8,951	2,187	9,811*	1,504	8,133	1,861
	1st Feb	Irrigated	10,988	699	10,897	1,301	9,294*	1,497

Values followed by * differ significantly from yield averages estimated using observed data at 5% level. PRV = Paranavaí, PTG = Ponta Grossa, MAN = Mandurí, PIR = Piracicaba, RPT = Ribeirão Preto.

Table 7. Average and standard deviation (SD) of dry bean yield (kg ha^{-1}), estimated with the CROPGRO-Dry Bean model, using observed and generated weather data.

Site	Sowing Date	Water Management	Observed		WGEN		SIMMETEO	
			Yield (kg/ha)	SD (kg/ha)	Yield (kg/ha)	SD (kg/ha)	Yield (kg/ha)	SD (kg/ha)
PRV	1st Oct	Rainfed	1,417	510	1,137	375	1,371	354
	1st Oct	Irrigated	1,649	337	1,717	440	1,517	332
	1st Feb	Rainfed	1,378	410	1,139	532	1,330	521
	1st Feb	Irrigated	1,956	309	1,985	409	1,870	333
PTG	1st Oct	Rainfed	942	279	977	386	987	287
	1st Oct	Irrigated	1,467	401	1,415	345	1,461	421
	1st Feb	Rainfed	1,144	452	977	398	1,027	382
	1st Feb	Irrigated	1,913	412	2,130	276	2,010	302
MAN	1st Oct	Rainfed	965	238	994	338	961	260
	1st Oct	Irrigated	1,607	286	1,520	315	1,475	323
	1st Feb	Rainfed	993	403	938	362	744	331
	1st Feb	Irrigated	1,812	308	1,899	327	1,884	342
PIR	1st Oct	Rainfed	977	491	937	416	871	402
	1st Oct	Irrigated	1,965	325	1,836	251	2,108*	255
	1st Feb	Rainfed	769	418	804	486	688	449
	1st Feb	Irrigated	2,073	377	1,985	326	2,003	620
RPT	1st Oct	Rainfed	676	300	615	235	630	315
	1st Oct	Irrigated	1,774	311	1,640	289	1,833	301
	1st Feb	Rainfed	437	260	520	267	499	304
	1st Feb	Irrigated	1,684	268	1,773	417	1,736	299

Values followed by * differ significantly from yield averages estimated using actual data at 5% level. PRV = Paranavaí, PTG = Ponta Grossa, MAN = Mandurí, PIR = Piracicaba, RPT = Ribeirão Preto.

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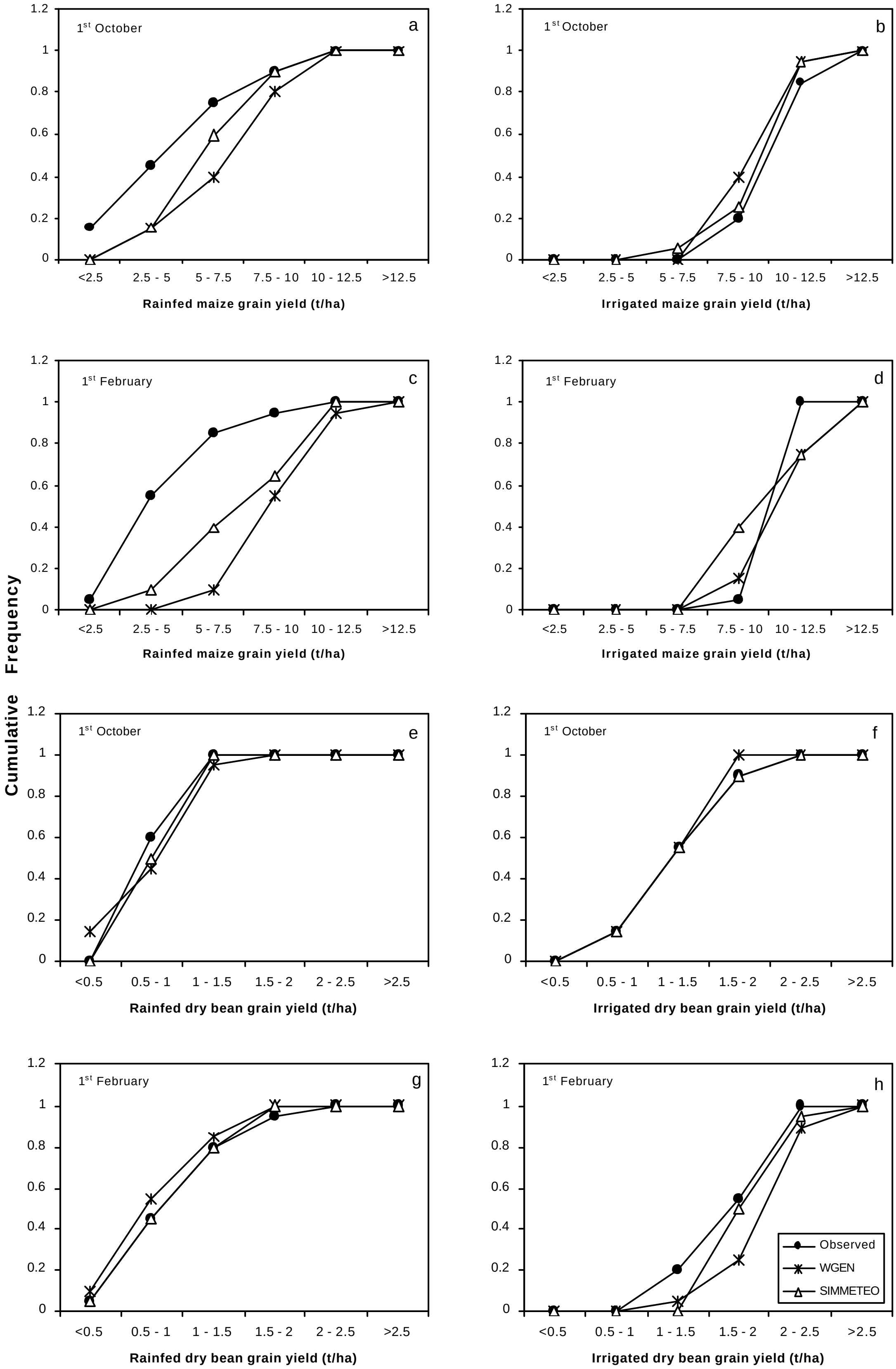

Figure 5. Cumulative frequency distributions for simulated yield of rainfed and irrigated maize and dry bean, using the CERES-Maize and CROPGRO-Dry bean models, based on observed and generated weather data with WGEN and SIMMETEO in Ponta Grossa, PR, Brazil.

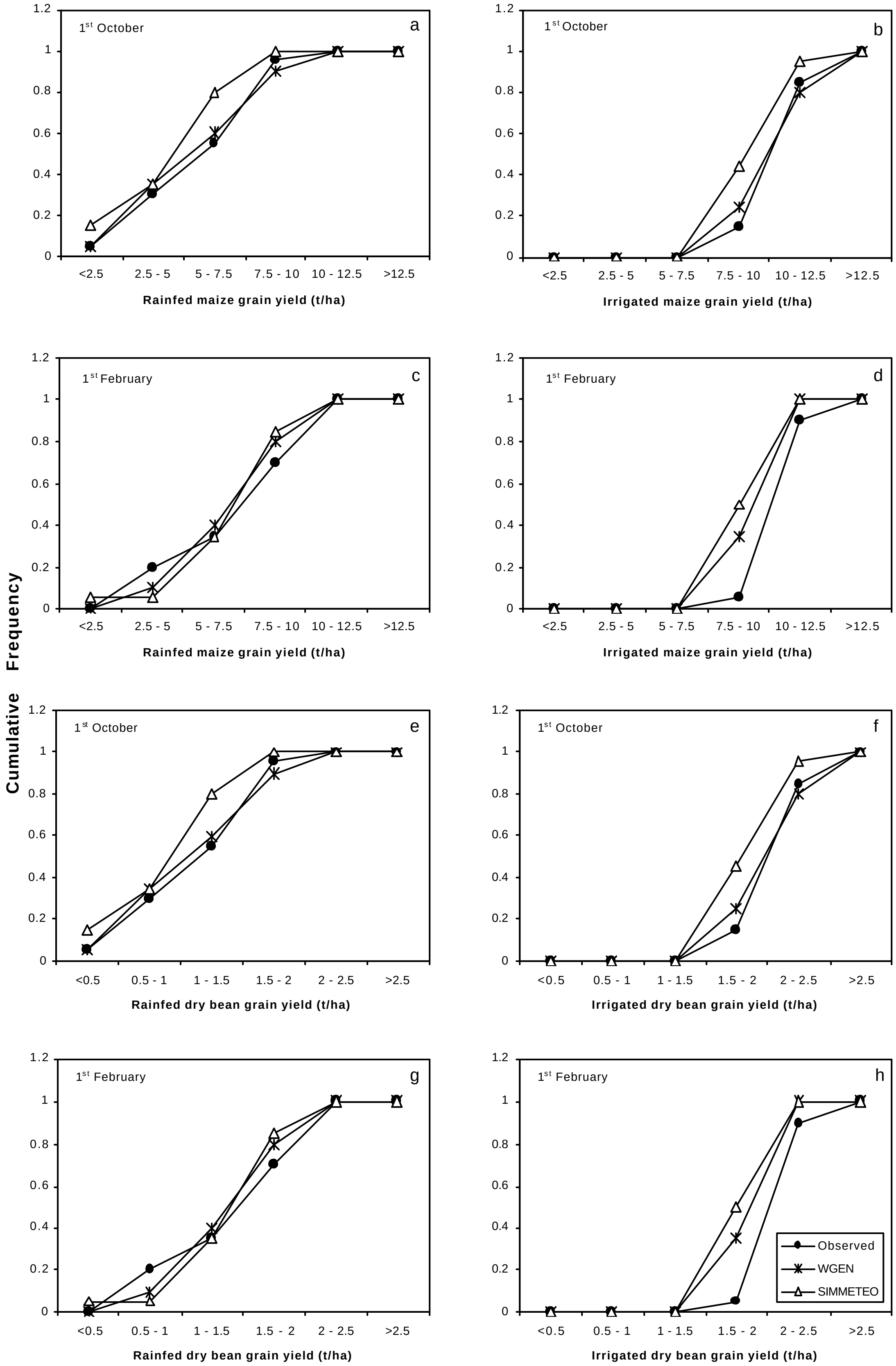

Figure 6. Cumulative frequency distributions for simulated yield of rainfed and irrigated maize and dry bean, using the CERES-Maize and CROPGRO-Dry bean models, based on observed and generated weather data with WGEN and SIMMETEO in Paranavaí, PR, Brazil.

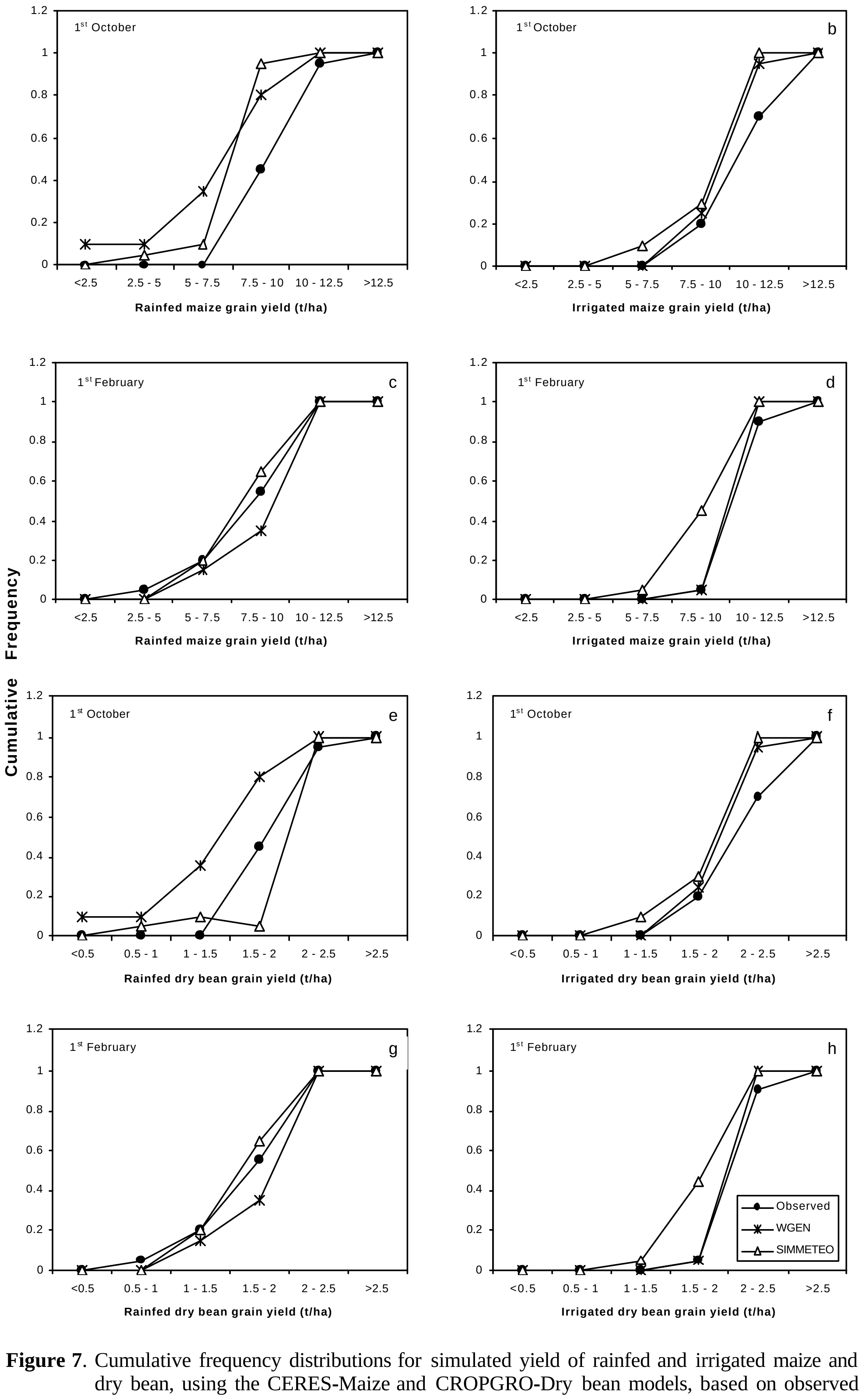

Figure 7. Cumulative frequency distributions for simulated yield of rainfed and irrigated maize and dry bean, using the CERES-Maize and CROPGRO-Dry bean models, based on observed and generated weather data with WGEN and SIMMETEO in Manduri, SP, Brazil.

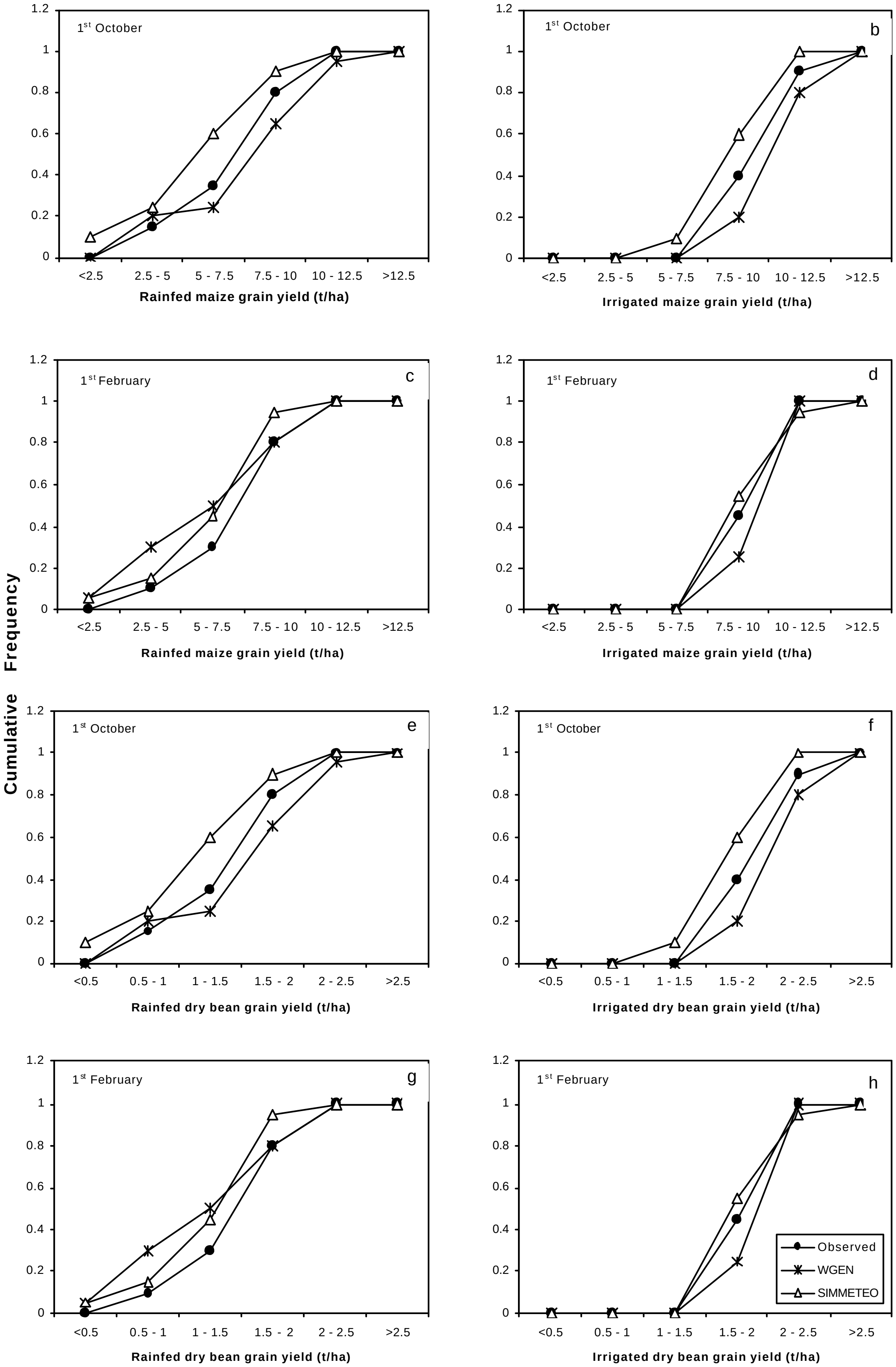

Figure 8. Cumulative frequency distributions for simulated yield of rainfed and irrigated maize and dry bean, using the CERES-Maize and CROPGRO-Dry bean models, based on observed and generated weather data with WGEN and SIMMETEO in Piracicaba, SP, Brazil.

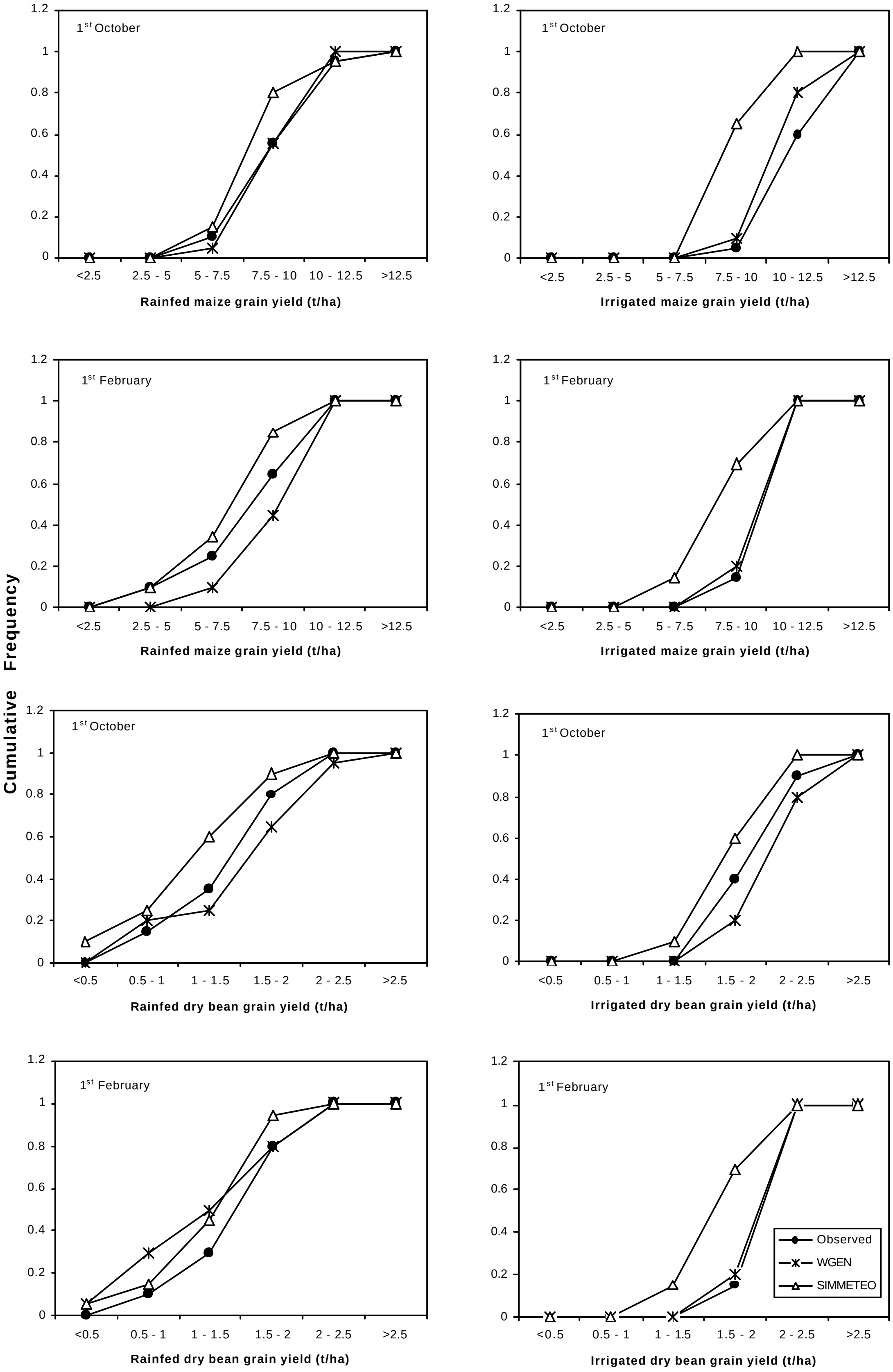

Figure 9. Cumulative frequency distributions for simulated yield of rainfed and irrigated maize and dry bean, using the CERES-Maize and CROPGRO-Dry bean models, based on observed and generated weather data with WGEN and SIMMETEO in Ribeirão Preto, SP, Brazil.

Table 8. Kolmogorov-Smirnov statistic test for the comparison of the frequency distributions of irrigated and rainfed grain yield for maize and dry bean, estimated with observed and generated weather data.

Site	Sowing Date	Water Management	Maize		Dry bean	
			WGEN	SIMMETEO	WGEN	SIMMETEO
PRV	1st Oct	Rainfed	0.333*	0.286	0.143	0.095
	1st Oct	Irrigated	0.190	0.095	0.095	0.000
	1st Feb	Rainfed	0.714*	0.428*	0.095	0.048
	1st Feb	Irrigated	0.238	0.333*	0.238	0.190
PTG	1st Oct	Rainfed	0.048	0.238	0.333*	0.143
	1st Oct	Irrigated	0.095	0.238	0.238	0.238
	1st Feb	Rainfed	0.095	0.143	0.238	0.143
	1st Feb	Irrigated	0.286	0.428*	0.095	0.048
MAN	1st Oct	Rainfed	0.333*	0.476*	0.095	0.048
	1st Oct	Irrigated	0.238	0.286	0.048	0.095
	1st Feb	Rainfed	0.190	0.095	0.095	0.190
	1st Feb	Irrigated	0.095	0.381*	0.048	0.190
PIR	1st Oct	Rainfed	0.143	0.238	0.095	0.143
	1st Oct	Irrigated	0.190	0.190	0.143	0.143
	1st Feb	Rainfed	0.190	0.143	0.143	0.048
	1st Feb	Irrigated	0.190	0.095	0.143	0.048
RPT	1st Oct	Rainfed	0.048	0.238	0.143	0.143
	1st Oct	Irrigated	0.190	0.571*	0.143	0.190
	1st Feb	Rainfed	0.190	0.190	0.095	0.048
	1st Feb	Irrigated	0.048	0.524*	0.143	0.143

Values followed by * have distributions differing significantly from of observed data at $P < 0.05$.

PRV = Paranavaí, PTG = Ponta Grossa, MAN = Mandurí, PIR = Piracicaba, RPT = Ribeirão Preto.

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