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Comparing Maize Potential yields Predicted using Actual and Interpolated Weather data in Uganda

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Abstract

Acquisition of measured weather data in Uganda for crop growth modeling is a challenge due to the low number of weather stations. Often, rainfall, maximum and minimum temperatures are measured. Total solar radiation is only measured at few weather stations due to shortage of sunshine duration recorders, the time graded paper strips or the newer automated weather stations (AWOS). A number of agencies do fill this void and provide on-line interpolated daily weather data to enable long-term simulations. A dynamic crop growth model CERES within the DSSAT modeling suite was used in order to evaluate simulation results obtained using actual and interpolated weather data from Kawanda, Central and Mbarara, south-western Uganda. Generic coefficients for very short, short, medium and long season maize varieties with in DSSAT were used. Farmer planting dates for the two cropping seasons were used to start the simulation. Results showed that at Kawanda, the average actual and interpolated maximum temperature were comparable, while at Mbarara, maximum temperatures were underestimated with a deviation of −3°C. At both sites, actual and interpolated minimum temperatures were comparable. The average actual total solar radiation at Kawanda was lower, probably indicating a shift in the AWOS radiation sensors. At Mbarara, the interpolated and measured values are comparable, indicating that the solarimeter method is still very reliable. RMSEs between actual and predicted potential yields at Kawanda were larger; very short (942 kg ha^{-1}), short (1176 kg ha^{-1}), medium (1864 kg ha^{-1}) and long season maize (3055 kg ha^{-1}). Actual radiation measurements at this site were lower, which emphasizes the importance of re-calibrating radiation sensors at least every two years. At Mbarara, the RMSEs for very short (418 kg ha^{-1}), short (618 kg ha^{-1}), medium (1056 kg ha^{-1}) and long season (1896 kg ha^{-1}) were low and acceptable. Interpolated data from the NASA can be used to predict potential yields and for long-term simulations in absence of measured weather data.

Keywords: Potential yields, interpolated, weather data, radiation, modeling

Introduction

Solar radiation, minimum and maximum temperature data are crucial for the simulation of potential crop production[1]. Potential yield is determined by radiation, temperature, crop physiology and canopy characteristics, with water and nutrients not limiting, and in absence of diseases, pests and weeds[2]. This value indicates the maximum possible dry matter production and will vary with the same variety at different locations due to temperature and total solar radiation variations. The yield level may indicate the suitability of the crop to a location. Temperature determines the development rate, with higher temperature implying a faster development rate, provided it is still within the plant's optimum temperature range. The total incoming radiation (MJ m^{-2} d^{-1}), the radiation use efficiency (RUE; g DM MJ^{-1}) and the leaf area index (ha leaf ha^{-1} soil) determine the radiation intercepted and the amount of dry matter produced on particular day.

Climate change is likely to adversely affect communities whose livelihoods entirely depend on crop production[3]. This is likely to result from increases in temperature above the physiological optimum for the affected crops, making the areas unsuitable and hence a production shift to new areas. According to the predictions, average rainfall in Uganda will increase with uneven distribution over the country and average temperatures are estimated to increase by 1.5ºC in the next 20 years[4]. Coffee a major cash crop is sensitive to temperature and banana a staple food is also sensitive to drought stress and temperature[5]. Research in the developing countries shows that the impacts of climate change on annual crop production can be reduced by adopting short and medium season varieties[6]. However, due to the reduced growing cycle, the yields tend to be lower. In order to carry out climate change assessments, accurate weather data is required for the base year.

In Uganda, it is often difficult to obtain long-term weather data to run crop growth models[7]. This is attributed to obsolete equipment, the past political instability and the poor coverage of the weather stations. At some stations, rainfall, maximum and minimum temperatures are measured but total solar radiation is only measured at few weather stations using the traditional solarimeters. The conventional gauging is good, but is labour intensive. For solar radiation, the time graded paper stripshave to be inserted each morning, the total sunshine hours calculated from the burnt sections and converted to daily total radiation (DTR,MJ $m^{-2}d^{-1}$). Automatic weather observation systems (AWOS) though convenient are still few due to the cost. As a country where agriculture supports over 70% of the population, accurate and timely high quality weather data must be collected and passed onto farmers to allow rational production decision making.

A number of sites or agencies such as the National Aeronautics and Space Administration (NASA) do provide long-term interpolated data to allow long-term simulations. However, there have been issues related to the accuracy of the interpolated valuesas compared with the measured or observed values. The inaccuracies in weather data may result in overestimations of yield of over 35%[8]. The objectives of the study were to; i. compare the radiation, minimum and maximum temperatures measured from the sites and interpolated data for two sites in Uganda ii. compare the simulated potential yields and crop cycle durations using actual and interpolated weather data from NASA.

Material and Methods

Weather data: Actual weather data was obtained at Kawanda Research station, central Uganda (0°25'N, 32°30'E, 1147 meters above sea level) and Mbarara experimental farm weather station, southwest Uganda (0°61'S, 30°65'E, 1405 meters above sea level). At Kawanda, measured weather data (daily total radiation - MJ m^{-2} d^{-1}, rainfall – mmd^{-1}, minimum and maximum temperature -°C) were obtained for the years 2000–2006 and at Mbarara data was obtained for years 1993–1999. At Mbarara, measured daily sunshine hours were converted to daily total radiation using the Angstrom formula[9], which relates solar radiation to extraterrestrial radiation and relative sunshine duration.

$$R_S = \left(a_s + b_s \frac{n}{N} \right) R_a$$

Where R_S is the daily total solar radiation (MJ m^{-2} d^{-1}), $a_s + b_s$is the fraction of extraterrestrial radiation reaching the earth on clear days (n=N),n is the actual sunshine duration (sunshine hours), N is the maximum possible duration of sunshine or daylight hours (sunshine hours), n/N is the relative sunshine duration, $R_a$is the extraterrestrial radiation (MJ m^{-2} d^{-1}) and a_s is the regression constant, expressing the proportion of extraterrestrial radiation reaching the earth on overcast days (n=0). Since no actual direct solar radiation data are available for Mbarara and no calibration has been carried out for improved a_s and b_s parameters, the values of 0.25 and 0.50 respectively are recommended by the Food Agricultural Organisation (FAO) and were used. For this location close to the equator, the maximum number of sunshine hours (N) is 12.

Interpolated weather data were obtained from the NASA Climatology Resource for Agroclimatology Daily Averaged http://power.larc.nasa.gov/cgibin/cgiwrap/solar/agro.cgi?email= agroclim@larc.nasa.gov. For the NASA site, the GPS coordinates of each location were used to obtain the interpolated data. All weather files were formulated in Microsoft Excel and weather stations were created using the weatherman tool in DSSAT[10]. In order to complete the standard format of weather files in Weatherman, rainfall was also added but it is not required in simulating potential production.The potential yields and the crop cycle durations obtained using actual and interpolated weather data were compared using the root mean square error (RMSE).

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(a_i - p_i)^2}{n}}$$

Where n is the number of observations, a_i is the potential yield value obtained using actual data and p_i is the potential yield value obtained using interpolated weather data.

The DSSAT modeling suite: The CERES-Maize model was first introduced without N-supply subroutines with N assumed to be non-limiting[11]. It has been improved over the years and included in the Decision Support System for Agrotechnology Transfer– Crop Simulation Model - DSSAT-CSM, a collection of models that simulate growth of over 15 crops[10]. CERES maize simulates growth on a daily time step in response to soil, weather, environmental conditions, fertilizer rates / timing / placement, and other field management strategies. It simulates plant phenological development (emergence, end of juvenile stage, silking and physiological maturity), biomass accumulation (radiation use efficiency approach) and partitioning as a function of the development stage and final dry matter (grain yield and stovers). The CSM-CERES-Maize has been used to predict potential yields[12] and study effects of climate change[13].

Crop coefficients: Generic parameters from the DSSAT database for the very short, short, medium varieties and a long season hybrid (PIO 3475 original) were used to fully capture the different growth durations and the possible variations in temperature during the growth period. The base or minimum temperature for maize growth is 8°C and the optimum temperature was 34°C, at which maximum development rate occurs during the vegetative and reproductive stages as used in the CERES maize model. The light extinction coefficient (ha soil ha^{-1} leaf) was 0.85 and the radiation use efficiency was 4.2 g DM MJ^{-1}. The planting dates used by the farmers were used to initiate the simulation runs, 3rd March for season 1 and 3rd August for season 2. The planting method used was dry seed at a depth of 5cm. The plant spacing was 0.75×0.25m, giving a plant population of 53,333 plants ha^{-1}. The runs were done for two seasons a year for seven years.

Results and Discussion

Weather data: At Kawanda, the average actual maximum temperature was 27.2°C (17.7–35.7°C), and interpolated average maximum temperature was 25.74°C (19.3‒33.3°C). This indicates a deviation of ‒1.46°C.The average actual minimum temperature was 16°C (6.3‒23.5°C), and interpolated average minimum temperature was 16.72°C (8.7‒21.2°C). The average total solar radiation was 15.10 MJ m^{-2} d^{-1} (1.05‒25.89 MJ m^{-2} d^{-1}), and interpolated total solar radiation was 18.55 MJ m^{-2} d^{-1} (3.7‒28.7 MJ m^{-2} d^{-1}). Figure 1 shows the yearly variations in maximum temperature, minimum temperature and daily total solar radiation at Kawanda, central Uganda.

Table-1
Generic coefficients from the DSSAT v 4.5 shell used to evaluate the weather data sources. P1- Heat sum from seedling emergence to the end of the juvenile phase (°Cd); P2 – Effect of photoperiod on development; P5 – heat sum from silking to physiological maturity (°Cd); G2 - maximum possible number of kernels per plant; G3 - kernel filling rate during the linear grain filling stage and under optimum conditions (mg $kernel^{-1}$ day^{-1}); PHINT - Phylochron interval between successive leaf tip appearances (°Cd)

Season length	P1 (°Cd)	P2	P5 (°Cd)	G2	G3 (mg $kernel^{-1}$ day^{-1})	PHINT (°Cd)
PIO 3475 orginal – Long season hybrid	220	0.70	850	907	9.90	38.90
Medium	200	0.30	800	700	8.50	38.90
Short	110	0.30	680	820	6.60	38.90
Very short	5	0.30	680	820	6.60	38.90

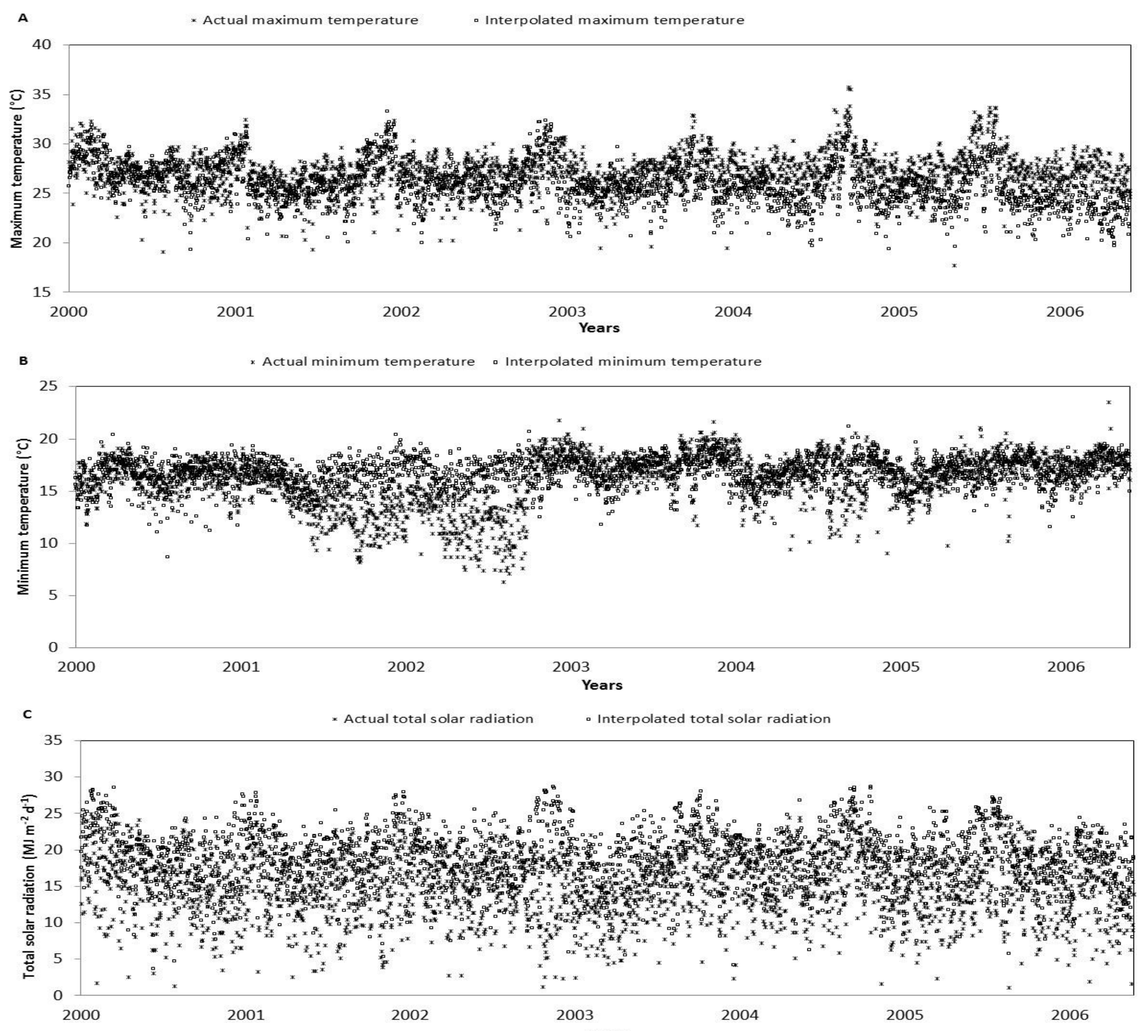

Figure-1
Actual and interpolated maximum temperature (A), actual and interpolated minimum temperature (B), and actual and interpolated total solar radiation (C) at Kawanda, central Uganda

At Mbarara, the average actual maximum temperature was 27°C (18.5−33.2°C), and interpolated average maximum temperature was 24°C (18.4−30.7°C), indicating that maximum temperatures were underestimated with a deviation of −3°C. The average actual minimum temperature was 15°C (10.7−19.9°C), and interpolated average minimum temperature was 16°C (10.3−21.8°C), implying that minimum temperatures were over estimated with a deviation of +1°C. The average actual total solar radiation was 17.28 MJ m^{-2} d^{-1} (8.35−26.87 MJ m^{-2} d^{-1}), and interpolated total solar radiation was 18.47 MJ m^{-2} d^{-1} (5.0−28.2 MJ m^{-2} d^{-1}). Figure 2 shows the yearly variations in maximum temperature, minimum temperature and daily total solar radiation at Mbarara, south-western Uganda.

In comparison, the actual maximum temperatures at Kawanda were higher as compared with Mbarara due to altitude effect, but the averages were comparable. As expected, the minimum temperatures at Mbarara were lower on average as compared with Kawanda. In general, the interpolated maximum temperatures are much lower than the observed values, but the minimum temperatures are comparable. In addition, interpolated solar radiation values are much higher than measured values, especially at Kawanda. At Kawanda, the lower average solar radiation could be attributed to reduced sensitivity or a drift in the sensitivity of the radiation sensors of the AWOS[14]. Often, drifts of 1−5% per annum are observed hence re-calibration of radiation sensors at least every two years. Though sunshine hours were converted to daily total solar radiation, actual and interpolated values were comparable, indicating that solarimeters are still very reliable[15].

Simulated potential yields and days to maturity at Kawanda, central Uganda: The average predicted potential yields over 14 cropping seasons for very short season maize using actual and interpolated data were 2830kg ha^{-1} and 3679kg $ha^{-1}$with a RMSE of 942kg ha^{-1}. Potential yield is under estimated by only 849 kg ha^{-1}. The average days to maturity were 82 and 85, with a RMSE of 6.69 days.

For the short season maize, the average predicted potential yields using actual and interpolated data were 3916kg ha^{-1} and 4950kg ha^{-1} with a RMSE of 1176kg ha^{-1}. Potential yield is under estimated by 1034 kg ha^{-1}. The average days to maturity were 99 and 103, with a RMSE of 9 days. For both the very short and short duration maize varieties, interpolated data can be used with quite acceptable accuracy. The higher RMSE could be attributed to lower measured daily total radiation and increasing variation with increasing crop cycle duration. As compared with Mbarara, actual values tend to under predict yield, probably due to radiation sensor drifts[14].

The average predicted potential yields for medium season maize using actual and interpolated data were 7053kg ha^{-1} and 8384kg $ha^{-1}$with a RMSE of 1864kg ha^{-1}. Potential yield is under estimated by 1331 kg ha^{-1}. The average days to maturity were 122 and 126, with a RMSE of about 10 days. For the long season hybrid maize, the average predicted potential yields using actual and interpolated data were 10730kg ha^{-1} and 13125kg ha^{-1} with a RMSE of 3055kg ha^{-1}. Potential yield is under estimated by 2394 kg ha^{-1}. The average days to maturity were 129 and 133, with a RMSE of about 12 days. For both the medium and long season maize varieties, the increase in crop cycle duration leads to increases in the RMSEs and yield under estimations as a result of lower radiation values. The lower radiation measurements resulted in an 18% under estimation in yield. Although this value is lower than 35% reported[8], it is still large.

Simulated potential yields and days to maturity at Mbarara, southwestern Uganda: The average predicted potential yields for very short season maize over 14 cropping seasons using actual and interpolated data were 3676 kg ha^{-1} and 3865 kg ha^{-1} with a RMSE of 418 kg ha^{-1}. Potential yield is over estimated by only 189 kg ha^{-1}. The average days to maturity were 85 and 87, with a RMSE of 4 days.

For the short season maize, the average predicted potential yields using actual and interpolated data were 4784kg ha^{-1} and 5265kg $ha^{-1}$with a RMSE of 618 kg ha^{-1}. Potential yield is over estimated by 481 kg ha^{-1}. The average days to maturity were 102 and 105, with a RMSE of 4 days. For both the very short and short duration maize varieties, interpolated data can be used with quite acceptable accuracy. The higher predicted potential yield values could be attributed to more solar radiation and lower maximum temperature, hence more radiation intercepted per day and slightly longer growth cycle. Higher predicted potential yields were also report for cereals, using interpolated data from NOAA[16].

The average predicted potential yields for medium season maize using actual and interpolated data were 7933kg ha^{-1} and 8665 kg $ha^{-1}$with a RMSE of 1056kg ha^{-1}. Potential yield is over estimated by 732 kg ha^{-1}. The average days to maturity were 126 and 129, with a RMSE of about 5 days. For the long season hybrid maize, the average predicted potential yields using actual and interpolated data were 12350kg ha^{-1} and 14027kg $ha^{-1}$with a RMSE of 1896kg ha^{-1}. Potential yield is over estimated by 1677 kg ha^{-1}. The average days to maturity were 132 and 136, with a RMSE of about 5 days. For both the medium and long season maize varieties, the increase in crop cycle duration leads to increases in the RMSEs and yield over estimations.

Three gridded weather databases (GWDs), including NASA power were evaluated as compared to actual weather data (CWD) for their ability to predict potential and water limited rice yields in China, maize in USA and wheat in Germany[17]. Results showed that agreement between CWD and GWD results was poor, but when observed weather data from stations in the NOAA database were combined with daily total radiation from the NASA power database, simulated potential and water-limited yields were in agreement with those using CWD data with RMSE 12−19% of the absolute mean. This implies that the radiation data from NASA is quite good as noted from the data at Mbarara. Although, the agreement reported above was poor, we obtained fairly good results in this study. Overall, in absence of actual long-term weather data, interpolated from the NASA power database can be used.

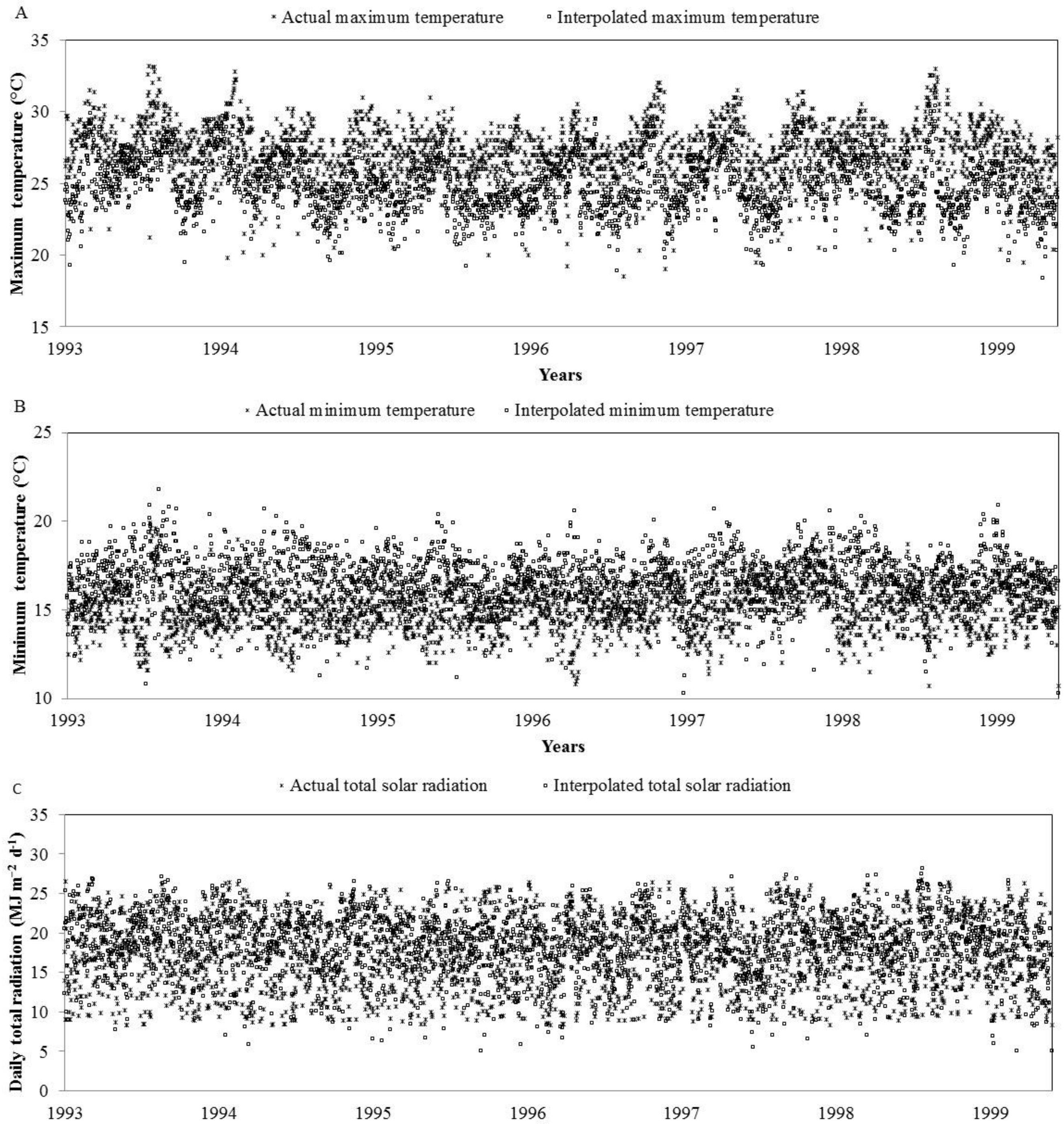

Figure-2

Actual and interpolated maximum temperature (A), actual and interpolated minimum temperature (B), and actual and interpolated total solar radiation (C) at Mbarara, southwestern Uganda

Table-2
Simulated potential yields over two cropping seasons (2000–2008) for very short, short, medium and long season maize varieties at Kawanda using actual and interpolated weather data

Year	Season	Very short season (Grain yield, kg ha^{-1})		Short season (Grain yield, kg ha^{-1})		Medium season (Grain yield, kg ha^{-1})		PIO 3475 original – Long season hybrid (Grain yield, kg ha^{-1})	
		Actual	Interpolated	Actual	Interpolated	Actual	Interpolated	Actual	Interpolated
2000	1	3147	3652	3843	4724	7105	6792	10955	10839
	2	3033	3568	3558	4496	6201	7298	9805	11516
2001	1	3548	4093	4055	5190	8378	8893	10915	14286
	2	2584	3375	4266	4779	9019	9202	13642	13508
2002	1	3157	3861	4447	4639	8625	8493	13578	13591
	2	3133	3388	5100	5281	9050	8193	13886	13056
2003	1	2326	4162	2854	4279	6174	7803	8909	12757
	2	2198	3492	3584	4836	6394	8258	10555	13141
2004	1	2611	3304	4179	5264	6334	9572	10263	15825
	2	3315	3726	3889	4914	8311	9318	11322	13643
2005	1	2988	4241	3478	4954	6615	8692	9815	13431
	2	2331	3310	3491	5848	5002	7948	8404	12559
2006	1	2645	3627	4604	5115	5578	7485	8489	12127
	2	2615	3718	3485	4992	5964	9440	9687	13472
Mean		2830	3679	3916	4950	7053	8384	10730	13125
RMSE		942		1176		1864		3055	

Table-3
Simulated days to maturity over two cropping seasons (2000–2008) for very short, short, medium and long season maize varieties at Kawanda using actual and interpolated weather data

Year	Season	Very short season (Days to maturity)		Short season (Days to maturity)		Medium season (Days to maturity)		PIO 3475 original – Long season hybrid (Days to maturity)	
		Actual	Interpolated	Actual	Interpolated	Actual	Interpolated	Actual	Interpolated
2000	1	81	83	94	96	117	118	124	125
	2	82	82	99	101	120	123	128	131
2001	1	85	87	103	106	126	130	134	138
	2	91	86	114	104	139	128	148	133
2002	1	88	85	109	101	136	126	146	132
	2	94	85	119	104	145	126	151	131
2003	1	77	87	91	101	113	122	121	131
	2	82	85	97	101	120	122	126	130
2004	1	78	82	91	103	113	126	119	135
	2	81	89	99	107	120	130	125	138
2005	1	79	86	96	101	118	127	126	134
	2	83	88	99	105	119	128	124	136
2006	1	78	89	95	107	117	132	123	138
	2	78	89	93	107	114	131	123	137
Mean		82	85	100	103	122	126	129	133
RMSE		6.69		9.0		10.8		12	

Table-4
Simulated potential yields over two cropping seasons (1993–1998) for very short, short, medium and long season maize varieties at Mbarara using actual and interpolated weather data

Year	Season	Very short season (Grain yield, kg ha^{-1})		Short season (Grain yield, kg ha^{-1})		Medium season (Grain yield, kg ha^{-1})		PIO 3475 original – Long season hybrid (Grain yield, kg ha^{-1})	
		Actual	Interpolated	Actual	Interpolated	Actual	Interpolated	Actual	Interpolated
1993	1	3660	3475	4790	4851	7365	7683	12178	12416
	2	4272	3973	5621	6248	8034	9663	12662	15441
1994	1	4198	3624	4569	4361	8179	8303	13400	13564
	2	3363	4029	4486	5372	8873	9353	12950	14319
1995	1	3640	3945	4815	5141	8691	9073	11903	14316
	2	3040	3712	5097	5569	7962	9456	12728	15517
1996	1	3427	3397	4926	5050	8830	8138	12049	12697
	2	3903	4414	5137	5807	8050	9270	12894	14583
1997	1	3702	3889	4381	4651	7757	8374	12612	14406
	2	3050	3655	4721	5819	7196	9048	10762	13283
1998	1	4045	4130	4580	4921	6381	6874	10431	12126
	2	3882	3898	4437	5664	8976	8521	13207	14817
1999	1	3692	3815	4749	4972	7014	8662	12103	14897
	2	3589	4154	4673	5291	7757	8897	13027	14006
Mean		3676	3865	4784	5265	7933	8665	12350	14027
RMSE		418		618		1056		1896	

Table-5
Simulated days to maturity over two cropping seasons (1993-1998) for very short, short, medium and long season maize varieties at Mbarara using actual and interpolated weather data

Year	Season	Very short season (Days to maturity)		Short season (Days to maturity)		Medium season (Days to maturity)		PIO 3475 original – Long season hybrid (Days to maturity)	
		Actual	Interpolated	Actual	Interpolated	Actual	Interpolated	Actual	Interpolated
1993	1	84	84	100	100	126	121	132	129
	2	84	79	101	100	123	123	129	132
1994	1	87	86	101	101	126	125	133	133
	2	85	86	105	105	130	131	137	141
1995	1	84	91	104	108	126	132	132	138
	2	84	87	104	106	126	132	134	139
1996	1	86	89	104	108	127	131	133	139
	2	86	91	102	108	128	134	137	141
1997	1	90	93	104	109	127	132	134	139
	2	81	83	97	102	123	129	129	135
1998	1	84	88	96	103	120	122	126	130
	2	89	83	103	104	125	125	130	133
1999	1	83	91	102	109	123	133	129	140
	2	86	90	106	109	129	133	135	142
Mean		85	87	102	105	126	129	132	136
RMSE		4.34		4.06		4.87		5.36	

Conclusion

At Kawanda, the average actual and interpolated maximum temperature were comparable with a deviation of −1.46°C, while at Mbarara, maximum temperatures were underestimated with a deviation of −3°C. At both sites, actual and interpolated minimum temperatures were comparable. This indicates that maximum temperatures were not captured well at Mbarara. The average actual total solar radiation at Kawanda was 15.10 MJ m^{-2} d^{-1} and interpolated total solar radiation was 18.55 MJ m^{-2} d^{-1}, indicating that actual values were lower. At this site, an AWOS was in use, probably the shift in radiation sensors could be the factor. At Mbarara, sunshine hours from the solarimeter were converted to daily total radiation. The interpolated and measured values are comparable, indicating that this old method is still very reliable.

The larger RMSEs between actual and predicted potential yields at Kawanda may be attributed to the lower daily total radiation measurement. This indicates the importance of checking the radiation sensors or sending them back to the manufacturer every two years for re-calibration. At Mbarara, the RMSEs for very short (418 kg ha^{-1}), short (618 kg ha^{-1}), medium (1056 kg ha^{-1}) and long season (1896 kg ha^{-1}) were low and acceptable. We conclude that interpolated data from the NASA Climatology Resource for Agroclimatology Daily Averaged can be used to predict potential yields and for long-term simulations in absence of measured data.

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