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Article

Future Emission Scenario Effects on Melon Cultivars (*Cucumis melo* L.) in the Brazilian Semi-Arid Region

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Abstract: Future emission scenarios can interfere with the yield of major crops. In this study, we investigated the future impact of increased air temperature and relative humidity on melon phenology and water demand in the Brazilian semi-arid region. We applied the PRECIS (Providing Regional Climates for Impact Studies) climatological model to develop the Intergovernmental Panel on Climate Change emission scenarios—B2 optimistic emission scenario and A2 pessimistic emission scenario—and we assessed the climate change effects on the phenology and water demand of two melon cultivars. The "Orange County" hybrid, the Honeydew melon, grew from 2006–2007, and the "Néctar" hybrid, the Galia melon, grew in 2008. These cultivars were also considered using the actual emission scenario. We found that the B2 and A2 emission scenarios will cause a cycle decrease of 15.49 and 25.35% for the "Orange County" hybrid and a 9.84 and 18.03% decrease for the "Néctar" hybrid. Future changes to the climate will increase the melon crop coefficient and daily rate of evapotranspiration. Regarding the "Orange County" hybrid, the cycle shortening overcomes the daily water demand increases, decreasing water demand by 13.7–18.3%. Regarding the "Néctar" hybrid, cycle shortening will be proportional to the increase in water demand. The Honeydew melon will be more sensitive to air temperature and relative humidity increases than the Galia melon.

Keywords: evapotranspiration; phenology; PRECIS climatological model; relative humidity; temperature

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1. Introduction

Melon (*Cucumis melo* L.) is a cucurbit that is cultivated in various regions of the world, and it has significant economic importance, mainly in Brazil [1]. Melon cultivation in Brazil prevails in the northeastern region; in 2021, 22,044 ha of the area was planted with the crop, and 584,484 t of the crop was produced, which corresponded to 92.1 and 96.3% of the planted area and national output, respectively [2].

The semi-arid region of Brazil stands out for being a significant producer of this fruit. Nevertheless, drought periods directly affect crop production since rain is the primary water source used by small and medium-sized producers [3]. The intense temporal and spatial variability of rainfall in the Brazilian semi-arid region makes it difficult to identify changes in the hydrological cycle [4]. Regarding the hydrological cycle, evapotranspiration is most affected by increases in air temperature and relative humidity. Negative impacts on crop development and productivity occur due to air temperature, relative humidity, and evapotranspiration changes [5,6]. The edaphoclimatic conditions of the cultivation area influence the productivity of a species or the production of a cultivar. Different physiological and morphological responses within the same variety or genotype occur due to environmental influences or genetic components [7].

In an overall evaluation of the simulations and mathematical projections of the effects of climate change on agricultural production, [8] points out that the effects of climate change on agricultural production vary according to the type of greenhouse gas emission, the analyzed period, the actual climate, and the management practices that are adopted in different regions. According to [9], this regional information is essential for assisting farmers and decision-makers when they adopt adaptation and mitigation measures that aim to ensure agricultural production is not negatively affected and can meet future demand for food. This information also helps to predict any increase in the price of food, which is expected in the near future [10].

Assuming that climate change directly influences the economic scenario in the northeastern region, it is possible to infer that the production of the main cultivated crops will suffer. They will be significantly impacted by extreme climatic events in the states of this region, such as long periods of drought, increases in temperature, and a reduction in relative humidity [11]. Using simulation models on a computer, calculating the future responses of the main crops in this region saves time, work, and resources for planning and managing the agricultural sector in the long term [12]. Ref. [5] used air temperature and relative humidity projections from the PRECIS climatological model to assess climate change impact on the watermelon (*Citrullus lanatus* Schrad) cultivars in the Brazilian semi-arid region for the year 2100. When compared with the actual emission scenario, the authors found increases of 3.0 and 5.2 °C in terms of mean temperature and decreases of 4.8 and 8.3% in terms of the mean relative humidity for the optimistic and pessimistic emission scenarios, respectively. These changes will cause the watermelon vegetative cycle to decrease and the crop coefficient to increase, thus increasing the watermelon crop's daily and total evapotranspiration; this may also change the manner in which irrigation management is conducted.

We hypothesized that the air temperature and relative humidity changes could impact melon phenology and water consumption. Changes in melon cycle duration, the crop coefficient (Kc), and evapotranspiration may cause changes to melon field management. In this study, we investigate the future impacts of increased air temperature and relative humidity on melon phenology and evapotranspiration in the Brazilian semi-arid region.

2. Materials and Methods

2.1. Experimental Site Details, Experimental Designs, and Climate Change Scenarios

We conducted studies on two crops at the Rafael Fernandes Experimental Farm, which belongs to the Federal Rural University of the Semi-Arid Region, Mossoró, State of Rio Grande do Norte, Brazil (5°03′37″ S; 37°23′50″ W; and altitude of 72 m). Oxisol is the predominant soil-type in the area. According to Köppen's classification, the climatic sort of the municipality is BSh, meaning that it is a dry, semi-arid climate [13]. The region has an average temperature of 27.4 °C, an irregular annual rainfall of 673.9 mm, and a relative humidity of 68.9% [14]. The irrigation water used had an electrical conductivity (EC) of 0.57 dS m^{-1}, which was collected from a well (800 m) that was drilled in the Arenito Açu aquifer. We measured the air temperature, relative humidity, wind speed, global radiation, and precipitation data during this period and determined the crop coefficients (Kc). We applied the PRECIS (Providing Regional Climates for Impact Studies) climatological model for the emission scenarios developed by the Intergovernmental Panel on Climate Change —B2 optimistic emission scenario and A2 pessimistic emission scenario—and we assessed the effects of climate change on the phenology and water demand of two melon cultivars. Honeydew melon (*Cucumis melo* L.), the "Orange County" hybrid, grew from December 2006 to February 2007. Galia melon, the "Néctar" hybrid, grew from October to December 2008.

We analyzed climate change simulations for the year 2100, which included assessing changes in temperature and relative humidity, predicted water consumption, and melon development. We used the PRECIS (Providing Regional Climates for Impact Studies) climatological model, which is based on the third generation of the Hadley Center's regional model (HadRM3), to estimate changes in temperature and relative humidity. The HadRM3 regional model has a horizontal resolution of 50 km, with 19 vertical levels (from the surface to 30 km in the stratosphere), and four levels on the ground. The spatial resolution is 0.44 × 0.44° (latitude x longitude), which corresponds to an approximate grid of 50 × 50 km. Ref. [15] provides more details concerning the PRECIS system.

The B2 (optimistic) and A2 (pessimistic) emission scenarios from the IPCC report were considered. We used the PRECIS climatological model's temperature and relative humidity outputs to simulate future scenarios (B2 and A2). In the A2 scenario, the world operates independently, with self-sufficient nations, a growing population, and region-oriented economic development. In the B2 scenario, the world population increases at a lower rate than in the A2 scenario. The B2 scenario indicates the adoption of local solutions for economic, social, and environmental sustainability.

2.2. Plant Material

The melon hybrids used in the experiment are noble melon cultivars grown in Brazil for export purposes, and they belong to the *inodorus* and *cantalupensis* groups [16,17]. We evaluate the Honeydew melon (*Cucumis melo* L.) in the first experiment. The "Orange County" hybrid belongs to the inodorus Naud botanical variety [16]. It has round fruits with a smooth cream rind and dark orange pulp with a small internal cavity; on average, it weighs between 1.5 and 1.8 kg. We grew the melon on mulch (black–white polyethylene film, with the white face up), which was previously placed on ridges, and it was prepared by harrowing, using 2.0 × 0.3 m spacing between the plants, for a total of 16,667 plants per hectare. The crop cycle lasted 71 days, and harvests were performed at 55, 61, and 71 days after transplantation [18].

In the second experiment, we evaluate the Galia melon. The "Néctar" hybrid belongs to the cantalupensis Naud botanical variety [17]. It has round fruits, netted rind, green pulp, and an average weight of 0.8–1.2 kg. The spacing between plants was 2.0 × 0.4 m, for a total of 12,500 plants per hectare. The crop was grown on mulch (in the same manner as the first experiment), which was previously placed on ridges, and it was then prepared by plowing and harrowing. The crop cycle lasted 61 days, having started on the day of transplantation, and the harvests were carried out 54 and 61 days after transplantation [19,20].

2.3. Irrigation and Crop Evapotranspiration

In the actual emission scenario, the area was irrigated using a localized drop irrigation system, with two lateral lines per plant row and emitters with flow rates of 1.1 and 1.3 L h^{-1}, at a pressure of 100 kPa, per dripper, for experiments 1 and 2, respectively.

Crop evapotranspiration (ETc), at different stages, was determined by weighing lysimeters with dimensions of 1.5 × 1.8 m (area of 2.70 m^2) and a 0.9 m depth. Each lysimeter was positioned on a precision electronic scale that was connected to a sensitive element (load cell) and coupled to a data acquisition system (datalogger: CR23X model, from Campbell scientific). The ETc of the crops was determined using the methodology recommended by [21]. We collected lysimeter data daily to identify rainfall, irrigation, or soil drainage. These data were disregarded from the ETc calculation. After this procedure, we obtained the mass by converting the electrical signal using the calibration equation. We obtained the evapotranspiration depth by calculating the ratio between the mass and the area of the lysimeter that was being used (1.6 × 2.0 m).

We used the methodology shown in [22] to obtain the average crop coefficients. The melon cycle was divided into four phenological stages: stage I—the initial stage between sowing and 10% soil cover; stage II—the growth stage between 11–80% of total soil cover; stage III—the intermediate stage between 81% of total ground cover and the beginning of fruit maturation; and stage IV—the final phase considering the period of fruit maturation until harvest.

Equation (1) shows the FAO-parameterized Penman–Monteith method used to obtain the reference evapotranspiration (ETo) [23]. Automatic weather stations with a datalogger (CR23X from Campbell Scientific, Garden City, US) were installed in the area to obtain the average, maximum, and minimum temperatures; maximum and minimum relative humidity; and wind speed and global radiation in the area. This was necessary for the determination of ETo. The air temperature and relative humidity projections for 2100, using the optimistic and pessimistic emission scenarios, were applied to obtain the ETo projections.

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T_{mean}+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

ETo—reference evapotranspiration, mm day^{-1};
Δ—the slope of the saturation vapor pressure curve, kPa °C^{-1};
γ—Psychrometric constant, kPa °C^{-1};
Rn—Net radiation, MJ m^{-2} day^{-1};
G—soil heat flux, MJ m^{-2} day^{-1};
T_{mean}—mean daily air temperature at 2 m height, °C;
U_2—wind speed at 2 m height, m s^{-1};
e_a—actual vapor pressure, kPa; and
e_s—saturation vapor pressure, kPa.

2.4. Degree Days

Cumulative degree days were determined using the methodology of [24], which, according to [25], is most often used in simulations, especially in climate change scenarios that predict more significant increments in air temperature; this is because this methodology uses the upper and lower basal temperatures and considers more significant penalties on days when the maximum temperature exceeds the basal temperature. The lower basal temperature used in the model for the melon crop was 16 °C, and the upper basal temperature was 35 °C [26]. With this method, the thermal sum has five conditioning factors, each with a specific equation for calculating the degree days (DD) (Equations (2)–(6)):

(1) TB > TM > Tm > Tb

$$DD = \frac{TM - Tm}{2} + Tm - Tb \quad (2)$$

(2) TB > TM > Tb > Tm

$$DD = \frac{(TM - Tm)^2}{2(TM - Tm)} \quad (3)$$

(3) TB > Tb > TM > Tm

$$DD = 0 \quad (4)$$

(4) TM > TB > Tm > Tb

$$DD = \frac{2(TM - Tm)(Tm - Tb) + (TM - Tm)^2 - (TM - TB)}{2(TM - Tm)} \quad (5)$$

(5) TM > TB > Tb > Tm

$$DD = \frac{1}{2} \cdot \frac{(TM - Tb)^2 - (TM - TB)^2}{TM - Tm} \quad (6)$$

DD—degree days, °C;
TM—maximum temperature of the day, °C;
Tm—minimum temperature of the day, °C;
Tb—lower basal temperature, °C; and
TB—upper basal temperature, °C.

The air temperature data from the current emission scenario and the air temperature projections for 2100, according to the optimistic and pessimistic emission scenarios, were applied to obtain the accumulated degree days. The number of degree days accumulated to complete each phenological stage in the actual emission scenario was used to determine the duration projections for each phenological stage in the optimistic and pessimistic emission scenarios.

2.5. Crop Coefficient

The Kc values obtained for stages 1, 2, 3, and 4 of the "Orange County" hybrid were 0.13, 0.65, 1.09, and 0.79, respectively; for the "Néctar" hybrid, the values were 0.08, 0.44, 1.06, and 0.88, respectively. We compared the Kc values obtained in the experiments (Actual) with those obtained in the climate change scenarios (B2 and A2). We adjusted the Kc values in accordance with climate change conditions using Equation (7) [23].

$$\mathrm{Kc} = \mathrm{Kc}_{\mathrm{actual}} + [0.04(\mathrm{u}_2 - 2) - 0.004(\mathrm{RH}_{\mathrm{min}} - 45)]\left(\frac{\mathrm{h}}{3}\right)^{0.3} \quad (7)$$

Kc—adjusted crop coefficient;
Kc (actual)—crop coefficient (if $\geq$ 0.45);
u_2—average wind speed of the stage at 2 m height, m s^{-1};
RHmin—average minimum relative humidity during the stage, %; and
h—average plant height during the stage, m.

The PRECIS model only provided data on mean relative humidity; therefore, we applied the same proportion of change, in terms of mean relative humidity, to the maximum and minimum actual values in order to obtain the maximum and minimum relative humidity for the B2 and A2 scenarios. These data were necessary to determine the ETo and to adjust the Kc values of the B2 and A2 scenarios. We used the ETo and Kc data from the actual, B2, and A2 scenarios to determine the melon crop's ETc and water requirement under actual, future optimistic (B2), and future pessimistic (A2) emission conditions.

3. Results

3.1. Scenarios for Temperature and Relative Humidity

In the year 2100, the air temperature (T) for the B2 emission scenario was projected to increase incrementally by 2.5, 2.8, and 2.3 °C for the mean, maximum, and minimum temperatures, respectively (Table 1). The A2 emission scenario also showed incremental increases by 4.5, 5.4, and 3.6 °C for the mean, maximum, and minimum temperatures, respectively (Table 1).

Table 1. Air temperature values (°C) in Mossoró, Rio Grande do Norte state, Brazil, during the melon cultivation period (cultivars Honeydew and Galia), using the PRECIS climatological model, and considering the Intergovernmental Panel on Climate Change's emission scenarios.

Period	Climate Change Scenarios								
	Actual			B2			A2		
	Tmean	Tmax	Tmin	Tmean	Tmax	Tmin	Tmean	Tmax	Tmin
1	27.6	33.6	23.4	30.5	36.4	26.2	32.9	40.0	27.6
2	27.2	34.0	22.0	29.2	36.8	23.7	30.9	38.4	25.0
Mean	27.4	33.8	22.7	29.9	36.6	25.0	31.9	39.2	26.3

Mean temperature (Tmean), Maximum temperature (Tmax), and Minimum temperature (Tmin); 1 = December/2006 to February/2007: Honeydew melon, "Orange County" hybrid; 2 = October to December/2008: Galia, "Néctar" hybrid. Actual: Actual emission scenario. B2: Optimistic emission scenario in the year 2100. A2: Pessimistic emission scenario in the year 2100.

In the year 2100, compared with the actual scenario, the projections of the PRECIS climatological model indicate a decline of 3.2% and 6.0% for the mean, maximum, and minimum relative humidity, respectively, in the optimistic (B2) and pessimistic (A2) emission scenarios, considering the two periods studied (Table 2).

Table 2. Relative humidity values (%) in Mossoró, Rio Grande do Norte state, Brazil, during the melon cultivation period (cultivars Honeydew and Galia), using the PRECIS climatological model, considering the Intergovernmental Panel on Climate Change's emission scenarios.

Period	Climate Change Scenarios								
	Actual			B2			A2		
	RHmean	RHmax	RHmin	RHmean	RHmax	RHmin	RHmean	RHmax	RHmin
1	67.2	84.2	40.1	62.9	79.9	35.7	58.9	75.9	31.8
2	63.1	84.7	33.8	61.1	82.7	31.7	59.4	81.0	30.1
Mean	65.2	84.5	37.0	62.0	81.3	33.7	59.2	78.5	31.0

Mean relative humidity (RHmean), Maximum relative humidity (RHmax), and Minimum relative humidity (RHmin); 1 = December/2006 to February/2007: Honeydew melon, "Orange County" hybrid; 2 = October to December/2008: Galia, "Néctar" hybrid. Actual: Actual emission scenario. B2: Optimistic emission scenario in the year 2100. A2: Pessimistic emission scenario in the year 2100.

3.2. Scenarios for Cumulative Degree Days

For the actual emission scenario, the degree days required for the melons to complete the cycle were 876.4 °C for the "Orange County" hybrid, which was obtained at 71 days, and 724.6 °C for the "Néctar" hybrid, which was obtained at 61 days (Table 3). Regarding the "Orange County" hybrid, the temperature increases in the B2 emission scenario decreased by 11 days (15.5%) in terms of cycle duration, which corresponds to 1 day in the initial stage, 2 days in the growth stage, 4 days in the intermediate stage, and 4 days in the final stage, as compared with the actual emission scenario. Scenario A2 showed a reduction of 18 days (25.4%) in terms of cycle duration, which corresponds to 4 days in the early stage, 2 days in the growth stage, 6 days in the intermediate stage, and 6 days in the final stage, as compared with the actual emission scenario. The "Nectar" hybrid in the B2 emission scenario showed a reduction of 6 days (9.8%) in terms of cycle duration, which corresponds to 1 day in the initial stage, 3 days in the growth stage, 1 day in the intermediate stage, and 1 day in the final stage, as compared to the actual emission scenario. Scenario A2 showed a reduction of 11 days (18.0%) in terms of cycle duration, which corresponds to 3 days in the early stage, 4 days in the growth stage, 2 days in the intermediate stage, and 2 days in the final stage, as compared with the Actual emission scenario (Table 3).

Table 3. Melon cultivars' cumulative degree days (CDD) and phenological stage durations for the Intergovernmental Panel on Climate Change's emission scenarios.

Melon Cultivars	Honeydew Melon: "Orange County" Hybrid				Galia Melon: "Néctar" Hybrid			
Stages	CDD (°C)	Cycle Duration (days)			CDD (°C)	Cycle Duration (days)		
		Actual	B2	A2		Actual	B2	A2
1—Initial	227.7	18	17	14	199.7	17	16	14
2—Growth	173.1	14	12	12	258.0	22	19	18
3—Intermediate	264.0	21	17	15	181.4	15	14	13
4—Final	211.6	18	14	12	85.5	7	6	5
Total	876.4	71	60	53	724.6	61	55	50

Actual: Actual emission scenario. B2: Optimistic emission scenario in the year 2100. A2: Pessimistic emission scenario in the year 2100.

3.3. Scenarios for Reference Evapotranspiration, Crop Coefficient, and Crop Evapotranspiration

In the year 2100, the increase in air temperature, the decrease in relative humidity, and the decreased length of the melon cycle will change the future emission scenarios for reference evapotranspiration (ETo) (Table 4). The total ETo during the "Orange County" hybrid cycle was 422.01 mm in the actual scenario and 373.51 mm and 345.59 mm in the B2 and A2 emission scenarios (Table 4). With regard to the "Orange County" hybrid, the total ETo decreased by 11.5% in the B2 emission scenario compared with the Actual emission scenario (Table 4). Scenario A2 showed a reduction of 18.1% with regard to the total ETo, compared with the Actual scenario (Table 4). In the B2 scenario, per phenological stage, the ETo showed a decrease of 3.0% in the initial stage, 17.7% in the growth stage, 19.1% in the intermediate stage, and 4.6% in the final stage, compared with the actual emission scenario (Table 4). In the A2 emission scenario, per phenological stage, the ETo showed a reduction of 10.9% in the initial stage, 14.7% in the growth stage, 32.2% in the intermediate stage, and 8.8% in the final stage, compared with the actual emission scenario. The daily ETo showed an increase of 4.7% and 9.7% in the B2 and A2 emission scenarios, compared with the actual emission scenario (5.94 mm) (Table 4).

Table 4. Melon cultivars' crop coefficient values (Kc) and reference evapotranspiration (ETo) for the Intergovernmental Panel on Climate Change's emission scenarios.

Melon Cultivars	**Honeydew Melon: "Orange County" Hybrid**			**Galia Melon: "Néctar" Hybrid**		
Stages	**ETo (mm)**			**ETo (mm)**		
	Actual	**B2**	**A2**	**Actual**	**B2**	**A2**
I—Initial	110.46	107.17	98.45	93.63	115.71	109.67
II—Growth	84.4	69.5	72.02	130.23	126.87	126.55
III—Intermediate	136.78	110.67	92.74	91.57	93.89	94.71
IV—Final	90.37	86.17	82.38	48.4	42.29	38.71
Total	422.01	373.51	345.59	363.82	378.76	369.64
Daily Mean	5.94	6.23	6.52	5.96	6.89	7.39

Actual: Actual emission scenario. B2: Optimistic emission scenario in 2100-year. A2: Pessimistic emission scenario in 2100-year.

In the actual scenario, the total ETo during the "Néctar" hybrid cycle was 363.82 mm, and 378.76 mm and 369.64 mm for the B2 and A2 emission scenarios (Table 4). Regarding the "Néctar" hybrid, the total ETo increased by 4.1% and 1.6% in the B2 and A2 emission scenarios, compared with the actual emission scenario (Table 4). In the B2 scenario, per phenological stage, the ETo increased by 23.6% in the initial stage, decreased by 2.6% in the growth stage, increased by 2.5% in the intermediate stage, and decreased by 12.6% in the final stage, compared with the Actual emission scenario (Table 4). In the A2 scenario, per phenological stage, the ETo increased by 23.6% in the initial stage, decreased by 2.6% in the growth stage, increased by 2.5% in the intermediate stage, and decreased by 12.6% in the final stage, compared with the actual emission scenario (Table 4). The daily ETo increased by 15.5% and 24.0% in the B2 and A2 emission scenarios, compared with the actual emission scenario (5.96 mm) (Table 4).

In the year 2100, increases in air temperature and decreases in relative humidity will change the melon crop's coefficient values (Kc) (Table 5). The "Orange County" hybrid Kc values will decrease in the initial stage (−0.01 and −0.02) and growth stage (−0.07 and −0.07), and Kc values will increase in the intermediate stage (+0.03 and +0.01) and final stage (+0.11 and +0.07), in accordance with the B2 and A2 emission scenarios, compared with the actual emission scenario. "Néctar" hybrid Kc values will decrease in the initial stage (−0.01 and −0.02) and growth stage (−0.04 and −0.05), and Kc values will increase for the intermediate stage (+0.01 and +0.01) and final stage (+0.03 and +0.06), in accordance with the B2 and A2 emission scenarios, compared with the actual emission scenarios (Table 5).

Table 5. Melon cultivars' crop coefficient values (Kc) and crop evapotranspiration (ETc) for the Intergovernmental Panel on Climate Change's emission scenarios.

Melon Cultivars	Honeydew Melon: "Orange County" Hybrid			Galia Melon: "Néctar" Hybrid		
Stages	Kc-Values			Kc-Values		
	Actual	B2	A2	Actual	B2	A2
I—Initial	0.13	0.12	0.11	0.08	0.07	0.06
II—Growth	0.65	0.58	0.58	0.44	0.46	0.47
III—Intermediate	1.09	1.11	1.12	1.06	1.07	1.07
IV—Final	0.79	0.86	0.90	0.88	0.91	0.94
Stages	ETc (mm)			ETc (mm)		
	Actual	B2	A2	Actual	B2	A2
I—Initial	14.36	12.86	10.83	7.49	8.10	6.58
II—Growth	54.86	40.31	41.77	57.30	58.36	59.48
III—Intermediate	149.09	122.84	103.87	97.06	100.46	101.34
IV—Final	71.39	74.11	74.14	42.59	38.48	36.39
Total	289.70	250.12	236.70	204.44	205.40	203.80
Daily Mean	4.08	4.43	4.53	3.35	3.73	4.08

Actual: Actual emission scenario. B2: Optimistic emission scenario in the year 2100. A2: Pessimistic emission scenario in the year 2100.

In the year 2100, according to the optimistic (B2) and pessimistic (A2) emission scenarios, the melon "Orange County" hybrid ETc will decrease by 1.50 and 3.53 mm in the initial stage, by 14.55 and 13.09 mm in the growth stage, and by 26.25 and 45.22 mm in the intermediate stage, compared with the actual emission scenario (Table 5); however, the ETc will increase by 2.72 mm in the final stage of the B2 emission scenario, and decrease by 0.25 mm in the A2 emission scenario, compared with the actual emission scenario. According to the B2 emission scenario, the melon "Néctar" hybrid will increase ETc by 0.61 mm in the initial stage, and 3.40 mm in the intermediate stage; ETc will decrease by 6.87 mm in the growth stage and 4.11 mm in the final stage, compared with the actual emission scenario. According to the A2 emission scenario, ETc will only increase in the intermediate stage (4.28 mm) and will decrease in the initial (0.91 mm), growth (7.33 mm), and final (6.20 mm) stages (Table 5).

4. Discussion

Future incremental increases in air temperature and relative humidity will create conditions that are not suited to melon cultivation, thus leading to changes in cultivation practices, such as shading, pest and disease control, and irrigation management. Research to evaluate the effect of climatic factors on the phenological properties of horticulture cultivars is essential. We assessed the impact of future climate change on the development and water demand of melon cultivars in a semi-arid region of Brazil. We estimated future scenarios for factors that are essential to melon development, such as air temperature, relative humidity, and cumulative degree days. We also assessed critical irrigation management factors, such as crop coefficients and evapotranspiration. We found that future climate change could affect the melon's phenological properties, crop coefficient, and evapotranspiration.

In the melon "Néctar" hybrid, climate change affecting the temperature and relative humidity will decrease the length of the crop cycle by 6 days, according to the optimistic emission scenario, compared with the actual emission scenario. According to the pessimistic emission scenario, the crop cycle will be shortened by 11 days, compared with the actual emission scenario. Compared with the actual emission scenario, the melon "Orange County" hybrid cycle will decrease by 18 and 11 days, respectively, according to the pessimistic and optimistic emission scenarios. Thus, a greater decrease occurred in the cycle of the melon "Orange County" hybrid, which was equal to 18 days (25.35%), in the pessimistic emission scenario (A2). This is approximately 63.63% greater than the reduction in the "Néctar" hybrid, which may be related to the longer cycle of the "Orange County" hybrid compared with the "Néctar" hybrid. The greatest decrease in the "Orange County" hybrid cycle occurs during the intermediate and final stages, as the durations decreased by 28.57 and 33.33%, respectively. For the "Néctar" hybrid, the greatest decrease occurred in the initial and growth stages, with reductions of 17.55 and 18.18%, respectively. The greatest decrease in the intermediate and final stages, which was observed for the "Orange County" hybrid, may pose a greater risk to the production and quality of the fruits as this cultivar is more sensitive to future climate scenarios.

The reduced period of time for the melon cycle occurs because future climate projections show higher temperatures [27], with incremental increases of 3 to 5 °C for the optimistic emission scenario B2 and 4 to 8 °C for the pessimistic emission scenario A2, compared with the actual emission scenario. The production cycle of the plants depends on the cumulative degree days [28]; thus, with the increased air temperature, they complete their cycle faster because the air temperature increases incrementally with the speed of the metabolic processes of plants [29]. Ref. [30] assessed climate change influences on soybean crops. They found that the soybean cycle decreased by 8 to 18% in the future emission scenarios (A2 and B2), without the addition of CO_2, for the years 2070 and 2100, compared with actual emission scenarios. Although the future emission scenarios (A2 and B2) show an incremental increase in CO_2, in the years 2070 and 2100, the values ranged between 8 and 21%. For prickly pears, [28] found that the increase in air temperature, as a result of future climate change, decreased the duration of its cycle by 12.03 and 17.89% for scenarios B2 and A2, respectively. Ref. [5] found that the mean temperature increased by 3.0 and 5.2 °C, respectively, and the mean relative humidity decreased by 4.8 and 8.3%, respectively, for the optimistic and pessimistic emission scenarios in the year 2100, compared with the actual emission scenario. According to the optimistic and pessimistic emission scenarios for the year 2100, these changes will cause the vegetative cycle of the watermelon "Mickylee" to decrease by 14.1 and 26.9%, and by 7.9 and 11.1% for the watermelon "Quetzali", compared with the actual emission scenario. As with the melon "Orange County" hybrid, the watermelon "Mickylee", which has the longest cycle, was the most affected by climate change.

Projections for the year 2100 indicate that a 2.5–4.5 °C increase in mean temperature, and a 3.2–6.0% decrease in relative humidity, in the future B2 and A2 emission scenarios, will increase the daily ETo by 4.7–9.7 % for the cultivation period of the "Orange County" hybrid (December–February), and by 15.5–24.0% for the cultivation period of the "Nectar" hybrid (October–December), compared with the actual emission scenario. The October–December period will have a higher water demand than December–February; however, the decline in the "Orange County" hybrid cycle will cause a decrease of 11.5–18.1% in the total ETo, whereas the minor reduction in the "Nectar" hybrid cycle will cause an increase of 1.6–4.1% in the total ETo of the B2 and A2 emission scenarios compared with the actual emission scenario. These changes in temperature and relative humidity will cause changes in the melon hybrids' crop coefficient (Kc). Climate change affected the Kc of the phenological growth and final stages more than the initial and intermediate stages in the two melon hybrids. These changes in Kc values of the different phenological stages occur due to the local evapotranspiration demand and the sensitivity of the stage to the soil–water deficit [31]. These results indicate that the hybrids, "Orange County" and "Néctar", are sensitive to temperature and relative humidity changes at all phenological stages in the optimistic and pessimistic emission scenarios, compared with the actual emission scenario. Regarding the two evaluated hybrids, the growth and final stages are the most sensitive to climate change, with the most significant changes occurring in the Kc of the crop. It is worth pointing out that the changes in Kc were more effective in the "Orange County" hybrid.

We found that the melon ETc is more altered in the B2 and A2 emission scenarios due to shortened phenological stages than by increases in ETo and KC. Melon "Orange County" hybrid evapotranspiration (ETc) decreased throughout the crop cycle by about 13.66 and

18.29% in the B2 and A2 emission scenarios, respectively, compared with the actual emission scenario. For the “Néctar” hybrid, the decrease was equal to 3.4 and 4.96%, in the B2 and A2 emission scenarios, respectively, compared with the actual emission scenario. The vapor pressure deficit increase is caused by increases in air temperature, decreases in relative air humidity, as well as an increase in CO_2, and together with the reduced duration of the crop cycle, this will lead to a reduction in the water requirement of crops [28]; thus, the more significant decrease in the ETc of the “Orange County” hybrid corroborates with more variations in its cycle and the crop coefficient compared with the “Néctar” hybrid. This fact is related to the probable temperature increases and relative humidity reduction, which will interfere with the length of the cycles of the melon cultivars. Changes in ETc were noticeable in the “Orange County” hybrid, which has a relatively longer cycle (10 days or 16.39%) compared with the “Néctar” hybrid in both emission scenarios (B2 and A2), thus showing that the variety of longer cycles underwent more significant changes in phenology and gas exchange in comparison to that of the shorter cycle.

The melon crops’ lower and upper basal temperatures are 16 and 35 °C, respectively, which is an acceptable temperature range for its development [26]. Thus, there are abrupt increases in air temperature in the B2 (optimistic) and A2 (pessimistic) emission scenarios; this is especially true of the maximum temperatures in the A2 emission scenario, where the effects of the increase in mean air temperature are more intense than in the B2 emission scenario. Climate change can interfere with the growth and development of crops, thus affecting the phenology, internode elongation, leaf expansion, production, and partitioning of the assimilates in different plant parts, as well as triggering flower abortion, which have direct impacts on production [12].

The ideal relative humidity for melon cultivation is between 65 and 75% [32]. The results obtained in the climate change scenarios showed that the relative air humidity would be less than ideal for the crop, especially in the A2 emission scenario. This condition, associated with high temperatures, is observed mainly in the A2 emission scenario, and the risk of damage to the melon crop is increased because it favors the establishment of the significant fungal disease that affects cucurbits in the northeastern region of Brazil, caused by *Oidium* spp., due to low air humidity and high air temperatures conditions which favor its development [33]. *Oidium* spp. can decrease crop yield due to the decrease in the fruit size, the number of fruits, and the production plant period.

Changes in the water demand of the melon crop indicate the need for adjusting its irrigation management for future scenarios, as they aim to supply the higher daily water requirement; this is because, with the decreased cycle, the recovery from the water deficit is shorter, which may cause a more significant risk to production. Ref. [34] also reported this fact. They observed the need to modify the management of mango cultivation in order to adapt better to scenarios where there is low water availability and the temperature is increased in order to obtain satisfactory production. These changes may also imply the need for changes in the irrigation designs, such as in the reasonable flow rate, which may result in changing the pump and the size of the planted area. Consequently, adjusting an existing project to meet the higher daily water requirement of the crops can result in higher production costs and even lower production if opting for the reduction of the planted area.

5. Conclusions

In the year 2100, incremental increases in air temperature and decreases in relative humidity will cause declines in melon cycle durations, which are approximately 15.49 and 25.35% for the “Orange County” hybrid and 9.84 and 18.03% for the “Néctar” hybrid, respectively, considering the Intergovernmental Panel on Climate Change’s optimistic and pessimistic emission scenarios, compared with the actual emission scenario. The “Orange County” hybrid is more sensitive to climate change in the intermediate and final stages; hence, it is more susceptible to production losses, whereas the “Néctar” hybrid showed no sensitivity. Future climate change will increase the melon crop coefficient and daily evapotranspiration. In the “Orange County” hybrid, the cycle shortening overcomes the daily water demand increases, thus decreasing water demand by 13.7–18.3%. With the "Néctar" hybrid, cycle shortening will be proportional to the increase in water demand. In the year 2100, the daily irrigation volume will be higher in the two hybrids, but the total volume will only be affected in the "Orange County" hybrid. Honeydew melon will be more sensitive to air temperature and relative humidity increases than Galia melon.

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