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Future Thermal Assessment for the Phenological Development of Potato [*Solanum tuberosum* (L.)] in Cuba †

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Abstract: Current changes in climate conditions due to global warming affect the phenological behavior of economically important cultivable plant species, with consequences for the food security of many countries, particularly in small vulnerable islands. Thus, the objective of this study was to evaluate the thermal viability of *Solanum tuberosum* (L.) through the behavior of the Thermal Index of Biological Development (ITDB) of two cultivation areas in Cuba under different climate change scenarios. For the analysis, we elaborated bioclimatic scenarios by calculating the ITDB through a grounded and parameterized stochastic function based on the thermal values established for the phenological development of the species. We used the mean temperature values from the period 1980 to 2010 (historical reference period) of the Meteorological Stations: 78320 "Güira de Melena" and 78346 "Venezuela", located at the western and central of Cuba respectively. We also used modeled data from RCP 2.6 scenarios; 4.5 and 8.5 from the PRECIS-CARIBE Regional Climate Model, which used global outputs from the ECHAM5 MCG for the period 2010 to 2100. As result, the scenarios showed that the annual average ITDB ranges from 0.7 to 0.8, which indicates that until 2010 there were temporary spaces with favorable thermal conditions for the species, but not for the period from 2010 to 2100 in RCP 4.5 and 8.5. In these scenarios, there was a progressive decrease in the indicator that warned of a marked loss of Viability of S. tuberosum, reduction of the time-space to cultivate this species (particularly the month of April is the most inappropriate for the ripening of the tuber). These results showed that Cuba requires the establishment of an adaptation program with adjustments in the sowing and production calendar, the use of short-cycle varieties of less than 120 days, the management of genotypes adaptable to high temperatures, and the application of "Agriculture Climate Smart", to reduce risks in food safety.

Keywords: climate change; potato phenology; *Solanum tuberosum* L.

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1. Introduction

The current behavior of climatic processes compromises world food security. The effects of the increase in temperature in many areas of the world are the cause of the decrease in the production yields of crops. The increased vulnerability of the agri-food sector to climate change and global warming is evident [1], providing a reason to establish forms of adaptation that minimize damage and provide resilience in agricultural production systems [2,3].

The increase or decreases in temperature can cause stress in plants, and these are the cause of marked anatomical, morphological, and functional changes in plant species. Such changes include a reduction in cell size, reduced stomatal conductance, and closure of stomata, changes in membrane permeability, increases in stomata and trichome density, and larger xylem vessels [4]. The decrease in photosynthesis and the thermo-stability of the cell membrane are also reported. It is known that temperatures above 40 °C can cause burns in leaves and young shoots, foliar senescence and abscission, inhibition of shoots and root growth, as well as discoloration of the fruits. It can be summarized that high-temperature stress disturbs the cellular ultrastructure, especially the membrane. Plant cells exposed to these conditions lose the ability to maintain the concentration gradient of these structures [5]. Therefore, it is a fact that stress acts negatively on the normal development of plants, with a direct impact on the decrease in crop yield [6].

The potato [*Solamun tuberosum* (L.)] is a food of world importance [7]. In Cuba, the production of this tuber constitutes a contribution to food security and sovereignty. In recent years, their yields have shown a decrease in production figures [8], a situation that some specialists and experts in the country attribute to the negative effect of climate variability and the incidence of pests.

These arguments make it necessary to carry out research to clarify the possible alterations in the viability and development of crop plant species in future thermal scenarios under the effect of climate change, mainly for those agricultural regions with weight for food security. Therefore, the objective is to evaluates the thermal viability of *Solanum tuberosum* (L.) through the behavior of the Thermal Index of Biological Development (ITDB) in two cultivation areas in Cuba under different climate change scenarios.

2. Material and Methods

The work was carried out at the Center of Atmospheric Sciences of the National Autonomous University of Mexico from March–August 2019.

2.1. Bioclimatic Scenarios and Methodological Elements

The bioclimatic scenarios were performed for two agroclimatic zones of Cuba characterized by high tuber production (the Western Various Crops Enterprise "Güira de Melena" in the Artemisa province (located at 22° N and 82.3° W) and for the central of Various Crops Enterprise "La Cuba" in Ciego de Ávila (located at 22° N and 78.5° W).

2.1.1. Bioclimatic Scenarios. General Considerations

Values of the mean temperature (Tm) and the Thermal Index of Biological Development (ITDB) of S. tuberosum were used, after the determination through the creation of a stochastic linear function created for this purpose, which is detailed in Section 2.1.2.

For the design of the scenarios, the considerations and technical elements that appear in the technical instructions for potato production in Cuba [9] were also used. These instructions establish the annual period of cultivation, the breakdown, and the duration in days of the phenological stages (phases) and other agrotechnical aspects that are applied and that allow to single out the similarity of the agronomic conditions of the areas under analysis and that give the opportunity to independently assess the thermal conditions.

Baseline or reference line bioclimatic scenarios:

Daily values of Tm were used and monitored during the period from November to April from 1980 to 2010, belonging to the Meteorological Stations "Güira de Melena" (78 320) and "Venezuela" (78 346) both from the Institute of Meteorology of Cuba.

Future bioclimatic scenarios modeled for climate change conditions:

Values of Tm were used for each zone. It was obtained from the PRECIS—CARIBE Regional Climate Model [10], generated by the ECHAM5 Global Climate Model (MCG), and its different Representative Emission Paths (RCP) 2.6; 4.5 and 8.5; from the Center for Atmospheric Physics of the Institute of Meteorology of Cuba.

2.1.2. Average Annual Bioclimatic Scenario of the ITDB for *S. tuberosum*

This was developed with the annual average ITDB values obtained in the historical reference line (period 1980–2010) and each of the RCP 2.6 scenarios; 4.5 and 8.5. (period 2010 to 2100). This scenario allowed the comparison of the behavior of the historical thermal conditions that maintained the development of the species in past and future periods, facilitating the assessment of the viability of the species based on the thermal requirements that demand its phenological development.

2.1.3. Determination of the Thermal Index of Biological Development (ITDB)

Its determination was based on the threshold of thermal development of S. tuberosum, demarcated by the limiting indices of the minimum temperature of 7 °C; a minimum optimal temperature of 17 °C; an average optimum temperature of 21 °C; a maximum optimal temperature of 25 °C, and upper extreme temperature of inhibition 30 °C [11–15].

From these parameters, a linear function was determined that allows determining the ITDB by considering that values of 7 and 30 °C inhibit development and lead to estimate a value of zero for this index. Meanwhile, the temperature value of 21 °C implies a value of one, as maximum development.

The proposed function was based on the daily mean temperature values (Tt) with an expression where FDt = f(Tt). FDt can take values in the interval {0, …, 1}, values close to 1 for temperature close to the optimum, and close to zero for unfavorable situations. For the application of FDt, we considered that:

$$FD_t = \begin{cases} 0 & si T_t \leq a \\ \alpha_1 + \beta_1 T_t & si\, a < T_t \leq b \\ \alpha_2 + \beta_2 T_t & si\, b < T_t < c \\ 0 & si T_t \geq c \end{cases} \quad (1)$$

where a = 7 °C and c = 30 °C represent the lower and upper thermal limits, respectively, for potato development and b = 21 °C is the optimal value, with a range of 17 °C to 25 °C. The intercepts and slopes of *FDt* were calculated according to the following:

$$\beta_1 = \frac{1}{b-a} \;\; \beta_2 = -\frac{1}{c-b}$$

$$\alpha_1 = \beta_1 * a \;\; \alpha_2 = -\beta_2 * b + 1$$

The associated uncertainty and variability in the effects of *Tt* on potato development, parameters a, b, and c were modeled as random variables defined as:

$$a = 6.5 + \varepsilon_1 \qquad \varepsilon_1 \sim U(0,1)$$

$$b = 17 + 8 * \varepsilon_2 \qquad \varepsilon_2 \sim U(0,1)$$

$$c = 29.5 + \varepsilon_3 \qquad \varepsilon_3 \sim U(0,1)$$

where $U(0,1)$ represents the continuous standard uniform distribution. The random component in the optimal values and of the limits a and c allows incorporating in the analysis not only the fact that such values are uncertain, but also the function parameters of β_1, β_2, and $\alpha 1$, $\alpha 2$. Therefore, *FDt* is a stochastic developmental function and the biological response of the species to a given value of daily temperature is represented by a probability distribution.

Moreover, simulations of the ITDB calculation function were carried out, which allowed us to know the scenarios with possibilities of the viability for the development of the potato under current and future conditions. The uncertainty of the function was assessed using the Monte Carlo simulation process [16]. With a number of repetitions N = 10,000.

3. Results

Figures 1 and 2 show the thermal behavior of RCP 2.6, 4.5, and 8.5 in comparison with the baseline scenario. They show that Tm increases from low to high scenarios. There was a tendency to decrease the temporal space of the crop from November to April, particularly under RCP 4.5 and 8.5 scenarios, and with greater accentuation in the central zone of the country. The ITDB decreased considerably, which showed the probable insufficient viability for the maturation phase.

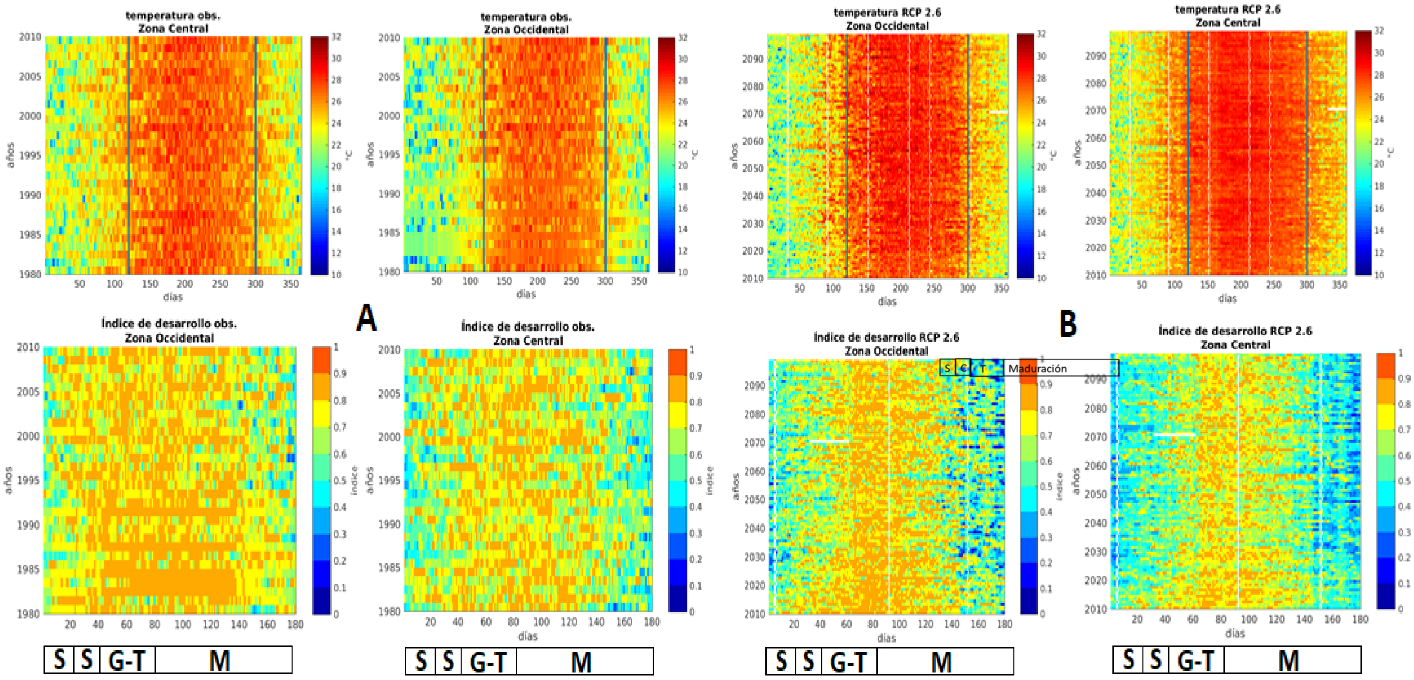

Figure 1. Reference bioclimatic scenario (**A**) and RCP 2.6 (**B**). The behavior of the mean temperature (upper level) and the Thermal Index of Biological Development of *Solanum tuberosum* (L.) according to the phenological phases: sowing (S), sprouting (S), growth and tuberization (G-T) and Maturation (M) in Various Crops Enterprise "Güira de Melena", Artemisa—western region (lower left level), and Various Crops Enterprise "La Cuba", Ciego de Ávila—central region (lower right level). Period 2010 to 2100.

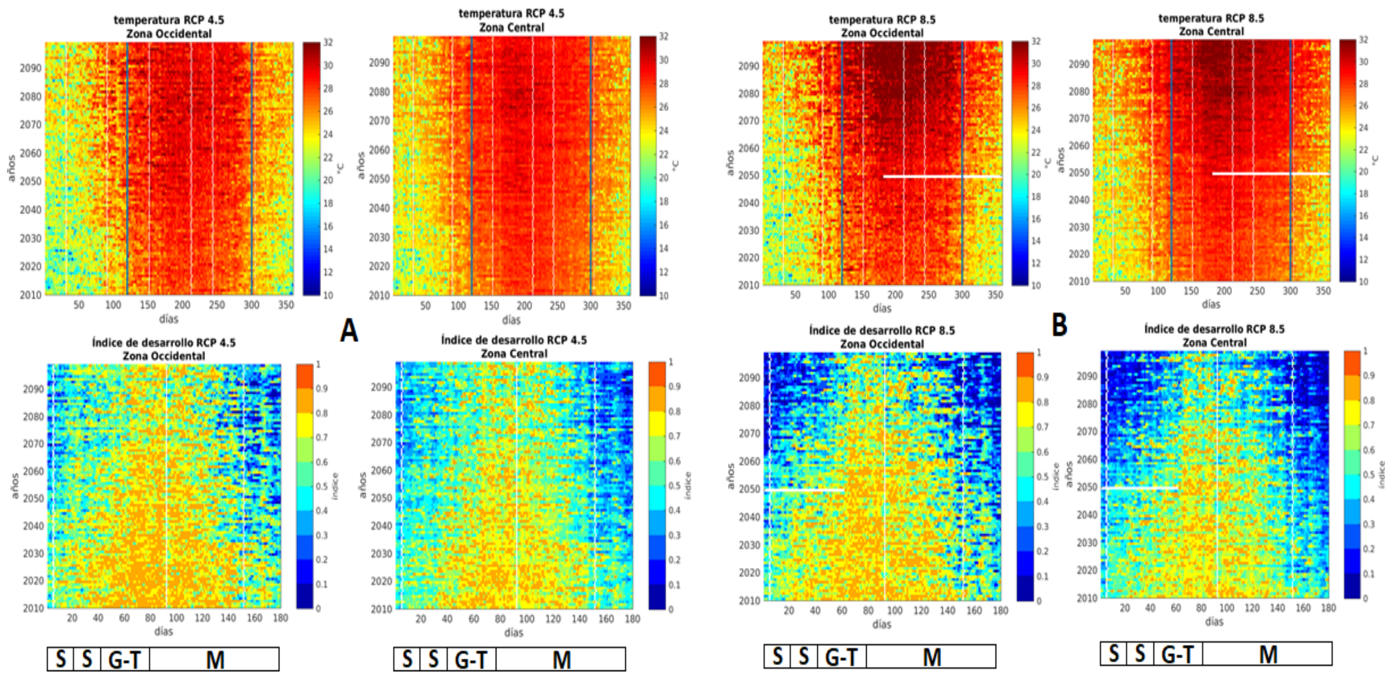

Figure 2. The bioclimatic scenario under RCP 4.5 (**A**) and RCP 8.5 (**B**). The behavior of the mean temperature (upper level) and the Thermal Index of Biological Development of *Solanum tuberosum* (L.) according to the phenological phases: sowing (S), sprouting (S), growth and tuberization (G-T) and Maturation (M) in Various Crops Enterprise "Güira de Melena", Artemisa—western region (lower left level), and Various Crops Enterprise "La Cuba", Ciego de Ávila—central region (lower right level). Period 2010 to 2100.

Figure 3 shows a decrease in the annual average ITDB that indicates a reduction in the feasibility potentials in the RCP 4.5 scenarios with a greater accentuation for conditions expected in an RCP 8.5.

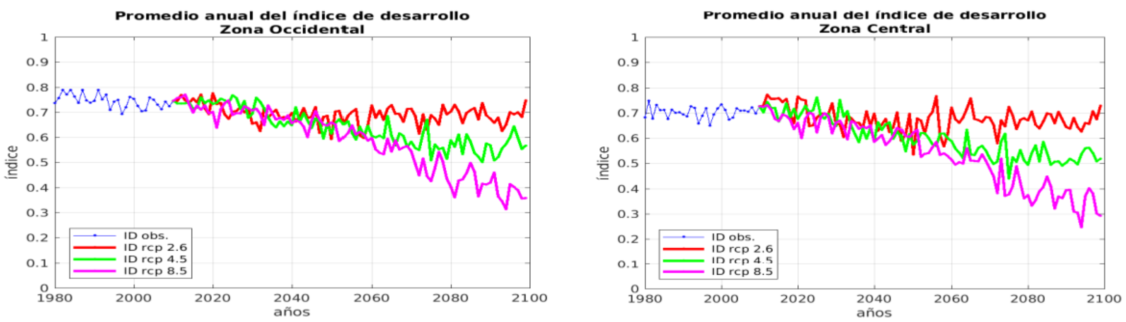

Figure 3. The annual average of the ITDB for *Solanum tuberosum* (L.) according to the historical reference line of the period 1980–2010 and RCP 2.6, 4.5, and 8.5 scenarios. Data from the PRECIS.CARIBE Regional Model (2010).

4. Discussion

The future scenarios under climate change conditions RCP 4.5 and 8.5 (Figures 1 and 2) resulting in this work in comparison with the reference line for each zone show an increase in Tm that in turn conditions a decrease in ITDB, with an alteration in the normal phenological development of the crop. This effect can be seen more clearly in contrast to the average annual ITBD scenario (Figure 3).

The negative effects on productive performance are generated by affecting vital functions associated with plant metabolism. The elevation of the temperature above the biological threshold and in stress levels causes morpho-physiological alterations and affections of the activity of the processes of photosynthesis and respiration. Research has shown that heat stress in potatoes interferes with the energy balance of the cells, inhibits their acquisition, and accelerates their consumption. Therefore, the net photosynthesis/ gross photosynthesis ratio decreases as the temperature increases, and this has an explanation because the carbohydrates produced in the assimilation or photosynthesis process are used in the respiration and growth of leaves, stems, stolons, tubers, and roots. The potato plant with a C3-type photosynthetic system has a certain rate of photorespiration. Therefore, the increase in temperature from 30 °C accelerates the process, resulting in a correlative decrease in net photosynthesis [17]. It is evident that *S. tuberosum* is vulnerable to the increase in temperature; therefore, its production in future years under conditions of climate change implies a climatic risk for Cuba that endangers national food security.

5. Conclusions

The analyses carried out allowed us to confirm that *S. tuberosum* has a high probability of reducing the thermal viability of the species in the temporary spaces in which it is cultivated. This is determined by the decrease in the Thermal Index of Biological Development under conditions of climate change as a cause of the increase in temperature to ranges not favorable. These ranges produce morpho-physiological and metabolic alterations of processes such as photosynthesis and respiration that limit the phenological development accentuated in growth phases. These include tuberization and maturation that increase vulnerability and a climatic risk for crop production and to the detriment of the food security national situation such as rectification of the sowing and harvesting calendar, use of varieties with a short life cycle, management of genotypes adaptable to high temperatures, and "Climate-Smart Agriculture", which become adaptation measures. We also found well-defined differences in the magnitude of vulnerability due to loss of thermal viability at the territorial level. Important areas such as the Various Crops Enterprise "Güira de Melena", show a decrease in the average annual ITDB from 0.75 to 0.37, with a greater accentuation in the Various Crops Enterprise "La Cuba" decreasing from 0.75 to 2.8; for a higher climatic risk under the conditions of RCP 8.5. The elaboration, the analysis of bioclimatic scenarios, and the determination of the ITDB provided the methodological and practical utility to evaluate the probable effects of climate change on plant and animal species.

Author Contributions: A.A.H.-M. conceived the idea of the study. F.E.-P., A.A.H.-M. and G.L.B.d.R. proposed the methodology. O.C.-B. processed the data and created the figures. A.A.H.-M. wrote the manuscript. All authors analyzed the results and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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