



Article Climate Change Impacts on Temperature and Chill Unit Trends for Apple (*Malus domestica*) Production in Ceres, South Africa

Phumudzo Charles Tharaga *, Abraham Stephanus Steyn 🖻 and Gesine Maria Coetzer

Department of Soil, Crop and Climate Sciences, The University of the Free State, Bloemfontein 9301, South Africa; steynas@ufs.ac.za (A.S.S.); EngelbGM@ufs.ac.za (G.M.C.)

* Correspondence: tharagapc@ufs.ac.za; Tel.: +27-514012882

Abstract: Climate is an essential part of crop production, determining the suitability of a given region for deciduous fruit products such as apples (Malus domestica). It influences the yield and quality of fruits. There is strong evidence of global and regional-scale climate change since the advent of the industrial era. In South Africa, mean surface temperatures have revealed a warming trend over the last century. This study aimed to assess the impact of climate change on temperature and chill unit trends for apple production in Ceres, South Africa. The daily positive Utah chill units (DPCU) model was used as frequent high temperatures can lead to a high negation volume. Historically observed (1981–2010) and future projected (2011–2100) temperatures were obtained from the South African Weather Service (SAWS) and three ensemble members of the Cubic-Conformal Atmospheric Model (CCAM), respectively. The latter employed the RCP8.5 pathway. Linear trends were calculated for temperature and accumulated PCUs for the historical base period. The probability of accumulating specific threshold PCU values for both historical and future periods was assessed from cumulative distribution functions (CDFs). The historical change in minimum temperatures showed no significant trend. Ceres revealed a warming trend in maximum temperatures over the historical period. By the 2080s, the probability of not exceeding a threshold of 1600 PCUs was exceptionally high for all ensemble members. Future projections showed a decline in the accumulated PCUs of 2-5% by the 2020s, 7–17% by the 2050s, and 20–34% towards the end of the 20th century. Based on these results, it is clear that winter chill units are negatively influenced by climate change. The loss in yield and fruit quality of apples due to climate change can negatively impact the export market, leading to significant economic losses for apple production in the Ceres area.

Keywords: climate model; daily positive; Utah chill unit model; temperature trends; apple (*Malus domestica*)

1. Introduction

Climate change is a reality as evidenced by the increase of average temperatures, melting of snow or ice, rising sea levels and changes in other climate metrics such as chill and heat units [1,2]. It is widely recognised that there has been a noticeable rise in global mean surface temperatures during the last century and that this rise cannot be explained unless human activities are accounted for [2,3]. The rate of this increase in the global mean surface temperature also increased during the second half of the 20th century [2,4]. This is emphasised by the fact that the six warmest years on record have occurred since 2015 [5].

There is strong evidence, based on analysis of mean temperature anomalies, of this warming on a regional scale in South Africa, with the most significant changes observed over the interior continental regions [6]. The annual mean temperature anomalies for 2013 from the preliminary data of 21 climate stations across South Africa were on average about 0.3 °C above the reference period (1961–1990). An average warming trend of 0.13 °C per decade was indicated by these particular climate stations and was statistically significant at 5% level. The anomalies are also larger in more recent years, suggesting that the rate of



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). increase in minimum and maximum temperatures is increasing. This is consistent with findings from [7,8].

Global mean temperatures are expected to continue to rise over the 21st century under persistent greenhouse gas emissions. It is further predicted that by the end of the century, temperatures will be 1.5 to 4.8 °C above pre-industrial levels [2]. It is also anticipated that the mean temperatures for the southwestern fruit production areas of South Africa will increase by 1 to 2 °C [1]. These conditions may also be accompanied by lower autumn and winter rainfall and a much shorter winter season in terms of temperature [9].

The coldness of winter has a major influence on deciduous crops' bud break, fruit set, yield and quality [10]. Successful cultivation of many deciduous fruits depends on fulfilling the winter chilling requirement, which is cultivar specific [11]. Deciduous fruit trees need to be exposed to a certain amount of chilling temperatures for a sufficient period of time during the rest period to break dormancy and to begin flowering [12].

Insufficient buildup of chilling during the dormant period (winter months) will result in delayed budbreak, even though temperatures are suitable for growth. There was a study conducted by [13] on Golden Delicious and Granny Smith, which are high and medium chill requiring cultivars. In this study, it was found that both cultivars reached dormancy in the Bokkeveld area in Ceres earlier than expected. The accumulation of chill units, irrespective of the model used, will differ depending on the climate of the area where the orchard is situated. A study conducted by [13–15] indicated that chill units still accumulate in different areas around the Western Cape, even though it has a Mediterranean climate with warm winter temperatures. Temperature plays a major role in the accumulation of chill units during dormancy and therefore understanding the range of temperatures that impact the hourly chill units is crucial [14–16]. A similar study was conducted on apricots to determine the chill unit fulfilment in South Africa and Spain in areas under different climatic conditions for two consecutive seasons (2007 and 2008). The study was carried out in areas ranging from low- to high-chill, on several apricot cultivars with a range of chilling requirements in both countries [17]. Though the chilling requirement of a cultivar is determined genetically, other factors such as latitude, elevation and climatic conditions during dormancy can also influence it. Accumulated chilling is affected by local geography, especially the altitude in tropical and subtropical regions, and therefore there is a positive relationship between chilling accumulation and the altitude of different areas [18].

The chilling requirement of deciduous fruit is typically measured in terms of chill units, chill hours and chill portions, and estimation of all these depends on the model used to simulate the chilling requirement [19,20]. Chill requirements are genetically determined, but differences also exist between buds, with flower buds having a lower chilling requirement than vegetative buds [21]. Deciduous fruits, such as apples produced under conditions of inadequate winter chill, require artificial rest-breaking treatments to achieve satisfactory bud break, fruit set, yield and fruit quality [22]. The accumulation of chill metrics (such as chill hours and chill units) is expected to decrease due to climate warming and may eventually reach a critical threshold at which apple production will no longer be sustainable commercially in current marginal areas. The rate at which chill metrics (chill hours and/or chill units) decrease varies per season, with different phenological results, and between colder and warmer production areas [23].

Apples grow and produce better fruits in regions where the trees experience uninterrupted rest in winter and abundant sunshine in spring for good flower development [24]. Apples can be grown at an altitude of 200–2700 m above sea level. Well-distributed rainfall of 1000–1250 mm throughout the growing season is most favourable for optimum growth and yields [25], while the average summer temperature for growth should be between 21 and 24 °C [26]. Apple cultivars with a high chilling requirement also have a high heat requirement, which may be advantageous in avoiding late frost damage after bud break in spring [27]. Chilling requirements (Table 1) differ between different cultivars [28], but they also vary significantly between cultivars originating in different parts of the world [20]. Therefore, the climate conditions of a specific planned commercial production site are of utmost importance when selecting temperate tree cultivars.

Apple Cultivar	Chilling Requirement	Accumulated Positive Chill Units (PCUs)			
Braeburn	High	800-1000+			
Pink Lady	Medium	450-800			
Fuji	High	800-1000+			
Golden Delicious	High	800-1000+			
Granny Smith	Medium to low	<800			
Royal Gala	Medium to low	500-800			
Star King	High	800-1000+			

Table 1. Chilling requirements of selected apple cultivars [28].

Since apple orchards often remain in production for about 25 years, consideration of future expected winter chill is necessary in times of threatening climatic changes [12,20]. Many fruit-producing areas might receive inadequate chilling due to climate change by the time deciduous trees reach physiological maturity [29]. In some areas, trees are hardly fulfilling their chilling requirements under the current climate conditions, and production might become less viable in the near future due to increased temperatures [30]. Since the markets for deciduous fruit are becoming more and more competitive, especially in areas with marginal apple production, producers will need to adapt to changes in climate [7]. A number of studies demonstrate that there is evidence of climate warming and of winters that have become warmer, reducing the accumulation of chilling. Results from these studies indicated that insufficient chilling is already visible in several global locations [30].

The monitoring of chill unit accumulation by fruit growers in South Africa helps to minimize loss and contributes towards yield forecasting. Since climate plays an essential role in deciduous fruit production, it is essential to determine and understand the effects of climate change in deciduous fruit production and adapt orchard practices accordingly. The aim of this study was to determine the effect of climate change on winter chill units for the largest apple production area in South Africa, namely Ceres.

2. Materials and Methods

2.1. Study Area

The study was conducted for Ceres, which is a major deciduous fruit-producing area situated in the Cape Winelands district of the Western Cape Province, South Africa. Ceres consists of three diverse areas, each with its own unique landscape: the Warm Bokkeveld (a wide fertile valley and the centre of one of the richest agricultural regions of the Western Cape), Bo-Swaarmoed (to the east of Ceres, famous for its cherries), and the Koue Bokkeveld (a mountainous fruit- and vegetable-producing area to the north). Ceres falls under the South-Western Cape climate region characterised by winter rainfall from May to September and a warm to hot and dry summer. The rainfall is profoundly influenced by orographic features. During the season of maximum rainfall, one may normally expect 12 to 15 rain days per month, whilst in the dry season, this region experiences 4 to 5 rainy days per month. The mountains are occasionally snow-capped, but the snow layer never persists throughout the winter. On average, snow occurs on about 5 occasions per year, mainly in winter and early spring [31]. Prevailing winds in summer are from the south-east, and in winter, the north-west, which are frequently strong and may reach gale force. Sunshine duration varies from about 60% of the possible duration in July to over 70% in January [8,31]. A summary of Ceres' climate data is provided in Table 2. Ceres is regarded as a highly susceptible area to changes in climate [32].

Area	Lat (S)	Long (E)	Altitude (m)	Annual Rainfall (mm)	January Average T _{max} (°C)	July Average T _{max} (°C)	January Average T _{min} (°C)	July Average T _{min} (°C)
Ceres	19°12′	33°27′	250	720	30.7	17.9	16.6	6.1

Table 2. Climate summary for Ceres for the period 1981–2010.

2.2. Data Type and Collection

2.2.1. Historical Observed Data

The historically observed climate data used in this study was recorded by an automatic weather station at La Plaisante, located just south of Ceres. The dataset contained daily minimum and maximum temperatures from 1981 to 2010. Seeing as the analysis of winter chill required hourly temperatures, daily values had to be downscaled temporally. This was facilitated by a Temporal Downscaling Model (TDM), which mainly employed idealized mathematical curves [33].

2.2.2. Projected Climate Data

Projections of future climate used in this study were obtained using the conformalcubic atmospheric model (CCAM) described by [34,35]. The CCAM is formulated using a conformal-cubic grid, which covers the globe but can be stretched to provide higher resolution (about 0.5°) over areas of interest. This gives more flexibility to downscaling experiments, allowing the forcing of the CCAM by sea-surface temperatures (SSTs) and from global climate models (GCMs) [36].

A set of three ensemble members was obtained from the Council for Scientific Industrial Research (CSIR), namely EN1 (boundary forcing data provided by GFDL-ESM2M), EN2 (boundary forcing data provided by HadGEM2-CC), and EN3 (boundary forcing data provided by MIROC5) (Table 3). Boundary forcing data included the 1961–2100 simulated (but bias-corrected) sea-surface temperatures (SSTs) and sea-ice fields and topography, vegetation, surface albedo and surface roughness fields. All three ensemble members were obtained for the Representative Concentration Pathways (RCPs), RCP8.5 emission scenario. The RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and GHG emissions in the absence of climate change policies [37,38]. Compared with the complete set of RCPs, RCP8.5 corresponds to the highest greenhouse gas emissions pathway. RCP8.5 is similar to the former A2 scenario [38,39] and matches anthropogenic GHG emission trends over recent decades more closely [40]. It can be thought of as the "business as usual" scenario, representing a future climate state under no mitigation strategies. Thus, the results can be interpreted as the worst-case scenario, without the inclusion of any hypothetical mitigation strategies to curb GHG emissions.

 Table 3. Ensemble members employed.

Ensemble Member	Boundary Forcing Model	Emission Scenario			
EN1	GFDL-ESM2M	RCP8.5			
EN2	HadGEM2-CC	RCP8.5			
EN3	MIROC5	RCP8.5			

The output comprised of gridded minimum and maximum temperatures at daily intervals for the period 1961 to 2100. Only the temperature data associated with the grid box encompassing the study area were extracted. Since the analysis of winter chill required hourly temperatures, it had to be temporally downscaled using the TDM.

2.3. Winter chill models and chilling metrics

Hourly chill units were calculated using the Utah Chill Units Model that records chill in Richardson's units (RCUs). The model takes into account the deterioration in chill accumulation efficiency above and below 7 °C. It also accounts for the negation effects of short periods of warming during winter. Although a few adjusted versions of the weight function exist, the weights from the original publication [41] are used to describe the model that is most widely used. For this study, the threshold values were modified slightly in order to avoid confusion that may have surfaced due to the gaps between them in the original version of Richardson's table (Table 4). Ref. [41] suggests that a full chill unit can be acquired when the temperature is between 2.4 and 9.2 °C for an hour. This model was adopted by the South African deciduous fruit industry in the southern part of the Western Cape [23]. High temperatures \geq 12.5 °C do not contribute to chill accumulation, while temperatures below 1.5 °C are also not considered adequate for chilling. Chilling accumulation always starts when the first positive chill units occur. Chilling negation occurs because of exposure to higher temperatures. Chilling negation does not occur when at least 75% of the chilling requirement has been satisfied before exposure to higher temperatures [42]. Higher temperatures counteract the positive effects of chilling, and negative chill units are applied when temperatures exceed a threshold of 16 °C [23,43].

Temperature (°C)	RCU (per hour)
T < 1.5	0
$1.5 \le T < 2.5$	0.5
$2.5 \le T < 9.2$	1
$9.2 \le T < 12.5$	0.5
$12.5 \le T \le 16.0$	0
$16.0 \le T \le 18.0$	-0.5
T > 18.0	-1

Table 4. Calculation of chill units from hourly temperature data applying the Utah Model [41].

The study conducted by [16] discussed the manner in which chill unit models tend to underestimate the impact of temperatures below 0 °C due to their developmental origin, as most of the models were developed in warm winter areas. Fruit trees grown in temperate regions may exhibit constant below-freezing temperatures, and therefore it becomes difficult for the trees to meet the actual chilling requirements. A study conducted by [44] suggested that slightly negative temperatures of -1.2 °C down to -5.6 °C might have the effect of overcoming dormancy, and this was emphasized by the results of a study that was conducted on fully grown, intact trees, which showed that sub-zero temperatures in the winter may have an effect on chilling and dormancy breaking expectation [16].

Subsequently, positive chill units (PCUs) were calculated according to the Daily Positive Utah Chill Unit Model (DPCU), as proposed by [23]. Chill units for each hour are summed over every 24 h, and if the total for the 24-h period is negative, the total chill unit for that day is counted as zero, but if the total is positive, it is added to the already accumulated chill units. A recent study showed the impacts of temperatures below zero on the accumulation of chill units. Temperatures ranging between 0 °C and -5 °C will result in the accumulation of chill units, though not as effectively as when compared with temperatures ranging from 1.5 °C to 12.5 °C [16], which can lead to over-accumulation of chill units. This model has been found to provide a more accurate estimation of winter chilling in areas with mild to very cold winters [43]. The PCUs were subsequently accumulated in order to determine the seasonal totals.

The historical and future calculated PCUs were subsequently analysed for (linear) trend over each future 30-year period (2011–2040, 2041–2070 and 2071–2100) and compared to the base period (1981–2010). Cumulative Distribution Functions (CDFs) were used to determine the probability of accumulating certain threshold PCU values for all historical

and future periods. The linear trends were also calculated for each 30-year period and for each ensemble member.

3. Results

3.1. Future Temperature Trends

Changes in the future climate were analysed with respect to the CCAM projections from the EN1, EN2 and EN3 ensembles (Table 2), which were all based on RCP8.5. Temperature changes for Ceres are summarised in Table 5, revealing a steady increase in average minimum temperature from the predicted average of 3 °C above the base period to about 4 °C during the 2020s, 5 °C during the 2050s and 6 °C during the 2080s. The average maximum temperature also increased with about 2.5 °C towards 2100.

Table 5. Projected averaged minimum and maximum temperatures (1981–2100).

Variable	Base (1981–2010)			2011–2040			2041-2070			2071–2100		
vallable	EN1	EN2	EN3	EN1	EN2	EN3	EN1	EN2	EN3	EN1	EN2	EN3
T _{min} (°C)	3.6	2.5	3.6	4.6	3.1	4.2	5.6	4.1	4.9	7.0	5.3	6.1
T _{max} (°C)	14.3	13.8	14.3	15.0	14.3	14.6	15.8	15.5	15.2	17.2	16.3	16.9

3.2. Historical Chill Unit Trends

The observed daily minimum and maximum temperatures for Ceres were averaged for each winter season (May–August) and analysed for trend over the climatic base period (1981–2010). There was no significant change in minimum temperature over the base period (Figure 1), while the maximum temperature increased by approximately 0.22 °C per annum (Figure 2).



Figure 1. Observed average daily minimum temperature (May-August) for Ceres for the period 1981-2010.

The increase in maximum temperatures especially lead to a decrease in optimum temperatures for acquiring chill units (based on the Utah Model). Though not significant, it must also be noted that a decrease in minimum temperatures could have resulted in a decline in winter chill unit accumulation as temperatures below $1.5 \,^{\circ}$ C did not contribute to PCUs (Table 4). A decline in the amount of accumulated PCUs over time is clearly depicted by the linear trend in Figure 3. There was an annual decrease of 4.4 PCUs between 1981 and 2010. Production continued in spite of PCUs dropping below 600 during certain years. Cultivars such as Granny Smith and Pink Lady are better adapted to this area due to their lower chill requirement.



Figure 2. Observed average daily maximum temperature (May–August) for Ceres for the period 1981–2010.



Figure 3. Observed accumulated positive chill units for Ceres for the period 1981–2010.

3.3. Future Chill Unit Trends

The CDFs of accumulated PCUs for Ceres exhibited a shift towards the left of the base. This means the accumulated PCUs are expected to decrease only slightly towards the 2020s (Figure 4a) but more notably by the end of the century (Figure 4c). The decrease in PCUs from the 2020s period was more visible on the EN1 ensemble followed by EN2 (Figure 4a). EN3 during the 2020s showed little significant difference to the base. It can be seen that for EN2, the probability of not exceeding a threshold of 1 200 PCUs in a given season is extremely low during the 2020s (Figure 4a) but increases to about 12% by the 2050s (Figure 4b) and 29% by the 2080s (Figure 4c).

According to the same ensemble, the probability of not exceeding a threshold of 1 600 PCUs is about 73% during the 2020s (Figure 4a) and 91% by the 2050s (Figure 4b). By the 2080s, the probability of not exceeding a threshold of 1 600 PCUs is extremely high for all three ensembles (Figure 4c). During the 2080s period, the area will hardly receive enough chill units to meet the normal number of chill units by more than 700 PCUs. In general, the projections indicate decreases in accumulated PCUs of 2–5% by the 2020s, 7–17% by the 2050s, and 20–34% towards the end of the century (Figure 5). This culminates in a loss of between 320 and 540 PCUs by the 2080s.



Figure 4. Cumulative distribution function of accumulated positive chill units (PCUs) for Ceres for the period (**a**) 2011–2040, (**b**) 2041–2070, and (**c**) 2071–2100.



Figure 5. Projected changes in accumulated positive chill units (PCUs) for Ceres (2011–2100).

4. Discussion

It already became clear from Section 3.2 that high chill requiring cultivars (800–1000+ PCU) will encounter problems under the present conditions, while moderate chill requiring cultivars (400–800) will prosper. Towards the end of the century, the moderate chill requiring cultivars will also start to experience shortages in accumulated PCUs in three out of 10 years.

From the results provided in Section 3.3, it became evident that Ceres exhibited reductions in the future accumulated PCUs. It can be argued that this is a direct result of increasing temperatures. Here, it can be speculated that reductions in accumulated PCUs due to increasing maximum temperatures are offset by chilling gains caused by less frequent frosty conditions. As the century progresses, it is anticipated that moderate chill requiring cultivars will experience winter chilling problems in Ceres towards 2100. It is important to remember that the number of PCUs received is not the only factor involved in bud break in deciduous fruit trees. The reserves in the tree, post-harvest care and fertilisation of the orchard, light interception and temperatures during spring all play an essential role in developing both vegetative and reproductive buds.

5. Conclusions

Based on the overall results of this research, it was clear that climate metrics such as winter chill units are influenced by climate change. Therefore, deciduous fruit production is anticipated to be influenced by potential changes in winter chill units in South Africa's largest apple production area of Ceres. The economic cost of climate change, which is expected to be incurred by apple farmers in Ceres, could be substantial and devastating. Producers may be confronted with the decision either to abandon their production or adapt to altered climatic conditions. This is not good news for local economies, which rely heavily on agriculture, although some services may thrive in the face of adversity (e.g., providers of rest-breaking chemicals). Fortunately, adaptation strategies already exist and are successfully applied in South Africa. However, almost all of the adaptation strategies are relatively expensive and could be economically unviable for some.

The future of the South African deciduous fruit industry will be guided by new plantings that will be more site-specific regarding fruit type, cultivar and rootstock selection, and training systems, because marginal environmental conditions will have a severe impact on profitability. Apple growers must be assisted to better prepare for the potential impacts of climate change. This can only be achieved with the assistance of the Government in the form of well-informed extension personnel who can advise them accordingly. Information can be delivered to extension officers, farmers and other industry stakeholders utilizing so-called "climate field schools", where scholars will have the opportunity to assess farmers' vulnerabilities and convey pertinent information to the target groups concerned.

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