Crop transpiration and top-leaf temperature

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Abstract
Growers try to achieve favourable growing conditions with their cultivation practices and climate control. Especially in warm and cold periods of the year this requires steering skills and in horticultural skills. Training and education provide handles and insights for this.
One of the recently developed tools to support this is Kassim, an application with a dedicated interface to show simulation results of the extensive dynamic greenhouse climate simulation model Kaspro. When launched, back in 2018, this tool gave realistic results for the winter situation, but too high crop temperatures were calculated for summer situations. This detracts from the trust and usability of this tool.
Therefore, in this project the simulation model has been improved. This resulted in a proper matching computation of crop temperature and transpiration of Tomato, Cucumber, Gerbera and Anthurium when compared with measurements.
The realistic calculations, based on sound physical explanatory modelling and parametrizing, allows for all kind of scenarios to be analysed. The report shows a number of examples to explain which type of insights can be obtained and how this helps growers to make better informed decisions about climate control.
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Summary

With their cultivation practices and climate control, growers aim to create favourable growing conditions for their crops. In terms of climate control, temperature and light regime are the most important factors, but humidity, crop evaporation and CO_2 regime are also important. Under favourable conditions (fresh, sunny spring conditions) there are hardly limitations for get optimal growing conditions, but in cold or warm periods of the year, growers encounter the limitations of the greenhouse. In winter, energy consumption can be very high and in summer it can become much too hot or the CO_2 loss (when dosing supplementary CO_2) can become very high.

Especially in those periods of the year, it comes down to the horticultural skills and in horticultural education and courses handles and insights need to be provided which helps to make the proper choices.

In 'Het Nieuwe Telen' (best translated as: 'Novel Cultivation Practice'), the insights and strategies are approached via balancing the balances. The energy and mass balance around the plant is one of the most important.

Greenhouse crops have a small het capacity in comparison to their surface area, which means that the crop temperature changes rapidly in response to changing environmental conditions. As a result, the crop can be assumed to be practically always in equilibrium with its environment.

This crop temperature (actually the leaf temperatures) at this equilibrium point is determined by physical processes around energy gain and loss. This is predominantly a passive physical process with unambiguous fixed parameters, such as absorption and extinction coefficient for light and the long wave optical parameters. However, there is one important parameter that is difficult to capture in a mechanistic description and that is the stomatal resistance. It definitely varies during the 24 hours, possibly during the season and certainly also per crop.

The combination of environmental conditions, the fixed physical crop parameters and the variable stomatal resistance determine the excess temperature of the leaves compared to its environment. At night, the leaves are colder than the surrounding air and at high solar irradiation they are warmer.

The educational tool Kassim has been developed to provide insight in these processes. When Kassim was launched in 2018, it gave a realistic view on the energy balance under low-light conditions, but for summer conditions the crop temperature was calculated too high. This hampered the usability of the tool.

In order to fix this shortcoming, the current project looked in detail at crop temperatures and evaporation processes under summer conditions in order to be able to update the core-model used by Kassim, which is the simulation model Kaspro. Kaspro is a dynamic greenhouse climate simulation model which is developed and constantly validated by the Business Unit Greehouse Horticultere of Wageningen UR.

Due to the central role of the energy balance in the calculations, the first chapter of this report is devoted to the components in that balance and the structure of the model that describes the stomatal and evaporation behaviour of the crop.

It follows from this explanation that a correct balance calculation starts with a correctly calculated absorption of sunlight by the crop. Based on measurements with an upwards and downwards 'looking' light sensor above and below the crop, the crop absorption of four crops (tomato, cucumber, Gerbera and Anthurium) could be determined. With the data, the model could be adjusted in such a way that observed and calculated crop absorption was similar.

In the equilibrium situation, during day time the absorbed light energy is dissipated in the form of latent heat (evaporation), convective heat and radiation. At night there is no energy supply from light, but energy is still extracted through evaporation and long wave radiation, which must be supplied to the crop via convective heat supply. Therefore, the leaf has to be colder than the environment.

From these three components, the latent heat loss is relatively easy to determine in the form of the water uptake of the crop. For crops with a weighing gutter this can be done on a small time scale (quarterly values), but for most greenhouses there is no more accurate determination of water consumption than the difference between supply and drain. Of course, in both cases the water uptake for crop growth has also to be taken into account as it is taken up, but not transpired.

After applying suitable model parameters, the developed simulation model appears to calculate not only the light absorption (energy input), but also the most important energy removal (latent heat via crop evaporation) realistically. Daily evaporation sums are in good agreement with observations and for the data on Cucumber cultivation, where a weighing gutter was present, the diurnal course could also be simulated well.

However, correctly calculated radiation absorption and evaporation do not automatically imply that the energy balance is correctly computed. A certain evaporation rate can be achieved with a large stomatal resistance combined with a large temperature difference between crop and greenhouse air, but also with a small stomatal resistance and consequently a small temperature difference.
Therefore, crop temperature measurements were also used in this project. As in an energy balance the crop temperature only has meaning in relation to the surrounding greenhouse air, these crop temperatures are expressed in temperature-difference.
After the suitable parameters for the different crops were determined, the model showed that the overtemperatures (during the day) and undertemperatures (at night) were calculated in the same range and with a comparable profile as the measured values.

Since the comparison between measurements and calculations show good agreement, the newly developed and parameterized model around the crop in this project waws connected to the on-line running Kassim program. To illustrate the use and insights provided by Kassim, chapter 3 discusses the output produced for different conditions for the four crops. The results clearly show the effect of changing conditions in crop absorption, the radiation balance and evaporation. Also the interaction between crop, climate conditions and the effect of shadow screens can be nicely illustrated, together with the effect of misting. The CO_2 balance is another topic that can be studied with the tool.
Although the focus in this project was on crop temperatures under high summer conditions, chapter 3 also discusses the energy balance on a cold winter night. Also for such completely different outdoor and greenhouse climate conditions, the model provides realistic outputs and relevant insights .

The theoretical description of the physical processes and their detailed evaluation on the basis of measurements resulted in well-founded, quantitative insights in the energy balance around the crop and the role of crop evaporation. For growers and other users, this offers the helpful background for setting out an energy-efficient control strategy which is also favourable for the crop.

Introduction

Growers try to get the crop to perform in an optimal way by choosing the best possible greenhouse climate and cultivation strategy. For greenhouse crops, this means that sunlight, often supplemented with artificial light, must be converted as efficient as possible by the plant into marketable products. This requires knowledge, insight and experience from the grower and it requires that the grower is provided with relevant and sufficiently accurate information about the status of the crop.
The major factors that determine growth like air temperature, humidity, CO_2 concentration, and light are available as continuous measured data but the crop evaporation is usually unknown. And that while crop evaporation is one of the most important processes in plant growth. The evaporation ensures water transport, with which the nutrients are transported from the root to the growing parts. In addition, the evaporation cools the leaves. The evaporation of water from the leaves removes latent heat from the leaf, so that it hardly becomes more than a few degrees warmer than the ambient temperature, even in full sun.

Most growers have a general idea of the crop transpiration. When growing plants on a gutter system, the water uptake can be determined by comparing the amount of drain water that returns with the amount irrigated. Part of the water taken up goes to growth, but most of it evaporates. The difference between application and drain therefore gives a good value of the evaporation per day.
However, detailed information about evaporation during the day is generally lacking. Only growers with a weighing gutter know the crop evaporation in a small time interval. However, a weighing gutter is a maintenance-sensitive and expensive measuring instrument and is therefore not commonplace.
The consequence is that there is still little knowledge about how the evaporation process exactly takes place and therefore little knowledge about which water uptake profile over the day can be called 'normal' or 'optimal'. In addition, the growers ability to influence evaporation is quite limited. Evaporation can be adjusted to some extent by manipulating the humidity in the greenhouse but is strongly influenced by the amount of light to which the crop is exposed.

Another way to estimate instantaneous crop evaporation is to use the plant temperature as a derived quantity. The plant temperature in itself says nothing about evaporation, but the temperature difference between crop and greenhouse air, in combination with other greenhouse climate factors such as air humidity and especially the light intensity, can be translated into an estimate of evaporation via a model. This approach has been applied in a former project called ‘top-of-crop evaporation'. Not only the temperature difference between crop and greenhouse air, humidity and light intensity were used, but also the screen and greenhouse cover temperatures. In that project, which was completed in 2017, it turned out that this approach works in principle, but that very accurate measurements are needed to be able to calculate the temperature difference with sufficient precision. The cheaper IR cameras are not suitable for this and when more expensive IR cameras have to be used, this method no longer offers any advantage over the use of a weighing gutter (unless one is interested in the evaporation of a specific part of the crop, a question that cannot be answered with a weighing gutter as it weighs a number of complete plants).

In the top-of-crop evaporation' project, the interpretation of the measured temperatures was carried out using the 'radiation monitor' that had just been developed at the time. In that application, the energy balance of the leaf formed the basis for calculating the leaf temperature. And since evaporation from the leaf plays a very prominent role in that energy balance, accurate calculation of crop temperature and accurate calculation of crop evaporation are almost synonymous.

When comparing results from the radiation monitor with weighing gutter data, it appeared that the radiation monitor was able to determine the evaporation process, and therefore also the crop temperatures, under low-light conditions (up to about 300 μmol/(m² s)) with good accuracy.
When using the same model for crop temperatures and evaporation under summer conditions, the total transpiration rates calculated were still quite nice, but the deviations between observed and calculated crop temperatures became very large.

For sunny conditions, the radiation monitor calculates temperatures for the top of the crop that are as much as 5 to 6 °C above the greenhouse air temperature.

The educational program **Kassim**, developed shortly afterwards as a follow up of the radiation monitor, also showed very high crop temperatures under sunny conditions. Although the model computations for night time and dull days were correct (crop temperatures no more than half a degree different from measurements), this obvious deviation during sunny periods undermined the acceptance of the model results.

This led to this follow-up project at hand. This follow-up project aims to measure instantaneous crop water uptake over a wide range of environmental conditions and in different crops. Based on these measurements, the model used by Kassim should be adjusted in such a way that the results are correct for that much wider range.
This makes the model more suitable for use in horticultural education and courses. In these courses, moisture control, evaporation and latent heat are key concepts so the educational software used in these courses should calculate these quantities in a clear and realistic way.

This report first describes the theory behind the crop evapotranspiration process and how this has been incorporated into the simulation model (chapter 1).
Then, for four crops, it is described how the typical properties of these crops are processed by the model. The model quality is judged by showing the correspondence between observations and simulations (Chapter 2).

Chapter 3 shows how the general principles of evaporation and moisture control are reflected in the calculation results using the program Kassim. These calculations nicely show what effects can be expected from interventions in the moisture balance in the greenhouse. This gives growers insight into their span of control to get the moisture and heat balance to a desired level.

In chapter 4 the conclusions from this research are drawn and it is indicated in which application areas the developed simulation technique can be used.

1 Theoretical background

1.1 Introduction

Plants have all kinds of mechanisms that allow to adapt to the environment. These are largely genetically defined processes through which clear patterns can be discovered when carefully studying the crop's response to environmental factors. When such patterns are known, models can be used to predict how a plant will react under certain circumstances.
Such models can be very general, such as a relationship that indicates from coarse production records that a crop needs, for example, 90 mol PAR to produce 1 kg fresh weight of tomatoes.
Models can also be more detailed, by including the description of the underlying processes that result in that average of 90 mol PAR per 1 kg. After all, to realize this conversion from light to fresh product, the plant had to produce leaves and trusses. It is known that the production speed is strongly dependent on the temperature. And the growth rate of those leaves and fruits in turn depends on the amount of assimilates (sugars) available to the plant. This sugar production depends on the availability of light and CO_2, whereby the conversion of CO_2 to sugars under the influence of light again depends on the crop temperature and the CO_2 concentration in the leaf. And finally, the CO_2 concentration in the leaf in turn depends on the CO_2 concentration of the greenhouse air and on the resistance that the CO_2 experiences to diffuse from the greenhouse air to the core of the leaf. Biochemical models go even further and describe how proteins and enzymes convert the light photons into chemical intermediates and how these ultimately result in sugar production and further processing.

When growers have more knowledge about the underlying mechanisms by which plants convert light into marketable fresh weight, they might be better capable in increasing the efficiency of plant production, so that more marketable product can be produced with the same resources (in particular light), or the same amount of product with less resources, so less electricity, water and/or heating.
Efficiency improvement can take place at various points in the growth process. This may involve improved varieties, better greenhouses, better cultivation management, reduced losses due to pests and diseases and improved coordination of the underlying growth processes. The latter is nowadays often referred to as ‘maintaining the correct plant balance’.
A correct plant balance means that the crop is brought (or kept) as much as possible at the temperature that matches the growth potential of the growing environment. Growth potential of the environment means predominantly light and can be increased with an elevated CO_2 concentration, or will be reduced when the CO_2 concentration drops. On a longer time scale, also temperature plays a role as it affects the crop architecture.

In modern greenhouses, the grower can get the crop temperature to the desired level under most circumstances by heating (ideally in combination with screens) when it gets too cold or venting when it gets too warm. Only when it is very cold or very warm outside, the greenhouse will run outside its control range and the grower has no other choice than to accept the detrimental temperatures.
However, the control of the greenhouse air temperature has also implications for the air humidity and the CO_2 concentration. Especially under summer conditions when the vents are fully opened (or fans are running at maximum speed) the humidity can drop to low levels. Also, in those conditions, greenhouses that apply CO_2 dosing cannot reach substantially elevated CO_2 concentrations anymore. At such times, growers can use misting to cool the greenhouse and/or limit ventilation, but it is difficult to gain a good insight into how moisture, temperature and CO_2 concentration affect crop temperature, transpiration and photosynthesis in a dynamic equilibrium.

In order to provide insight in these dynamic equilibria, all kinds of calculation tools have become available in recent years. First there were the ‘Calculation Tools' created by Letsgrow (www.Letsgrow.com). These are small calculation programs that calculate the energy consumption and CO_2 loss under certain greenhouse and outdoor air conditions, given the properties of the greenhouse and the installations used. These are straightforward calculations that don’t take the feedback interaction between crop and environment into account.
This was followed by 'the Radiation Monitor', with which similar effects could be calculated, but it included interactions between moisture and heat transport, and in which a clear distinction is made between convective and radiative heat exchange (www.glastuinbouwmodellen.wur.nl/radiationmonitor/?user=Grt_p_ENC_ext).

In addition, the radiation monitor presented the effect of screens and greenhouse covers on the vertical temperature profile in the crop.
The Radiation Monitor calculated the temperature balance for low-light and relatively cold outdoor conditions with good accuracy, but had an incomplete moisture balance. It calculated evaporation, but no condensation on screens and greenhouse roofs and no interaction between crop transpiration and the humidity control actions. The Radiation Monitor also lacked a CO_2 balance.

Subsequently, in 2018, the program 'Kassim' became available. Kassim is a further development of the Radiation Monitor and does calculate a full moisture and CO_2 balance in addition to a full energy balance. For example, if in the Kassim-program the amount of sunlight is increased while having a certain CO_2 dosing capacity and setpoint for the greenhouse air temperature, on a warm day the ventilation will be computed to increase. As a consequence, the CO2 concentration in the greenhouse will drop (assuming that the dosing rate is at its maximum). Taking this interaction between light and ventilation into account makes that the extra photosynthesis due to the increased amount of light will be smaller than when the computation would only calculate with the increased light. As another example, Kassim calculates that if the humidity setpoint is lowered, the ventilation rate will have to be increased more to achieve that setpoint than maybe expected. Increased ventilation is namely not only caused by the lower difference of the absolute humidity between inside and outside at lower greenhouse humidities, but also because a plant in a drier greenhouse will evaporate more.

Kassim has been developed as a calculation tool in teaching packages and courses on greenhouse climate in horticulture. When the tool was introduced to teachers and extension workers (at the end of 2019), the realistic interaction between the various balances in the greenhouse was very much appreciated. The only point where Kassim did not show realistic calculations was the too high calculated crop temperature at the top of the crop under full summer conditions. Apparently, during high radiation conditions, the energy balance over the leaves at the top of the crop was not calculated according to reality. This resulted in the too high calculated top-of-crop temperatures.
In order to improve the calculations on this point, in this project the crop temperatures and evaporation have been measured again in order to obtain data for a re-parameterisation.
This chapter first explains the background of the model used in Kassim (§ 1.2). With this background, it is clear that the measured crop temperature is necessarily determined by the ratio of dissipation of heat from the leaf through sensible and latent heat and that this ratio is influenced by the stomatal resistance. Apparently this stomatal behaviour and/or the absorption of solar radiation was not sufficiently accurate implemented in the original version of the model behind Kassim. The choices made to fix this issue are discussed in § 1.3.

1.2 Kassim, Kaspro and energy and mass balances

Kassim is a user interface that provides online access to the very extensive greenhouse climate simulation model Kaspro. Kaspro is a dynamic greenhouse climate simulation model, including a close-to-practice greenhouse climate controller. As Kassim was designed to offer an interface that is close to horticultural practice, the input parameters are comparable to what growers set in their greenhouse climate computers. This means that greenhouse air temperature or humidity are not an input, but a result of the user defined heating temperature, ventilation temperature, humidity setpoint and CO2 setpoint. Just like in a real greenhouse, the realised greenhouse climate conditions are often close to the set points, but not necessarily the same. This is because in practice there are often limits to the controllability of the greenhouse climate. In Kassim, for example, the greenhouse air temperature will never reach 20 °C under sunny, summery conditions, even though the heating setpoint is set at e.g. 16 °C and the ventilation line at e.g.18 °C. After all, an ordinary greenhouse has no other way of lowering the greenhouse air temperature than opening the vents and, if available, to apply misting. Given a standard vent-configuration on a sunny Dutch summer day (25 °C, 60% RH, 800 W/m² radiation, 5 m/s wind) a greenhouse with and a full grown tomato crop without misting will have around 27°C as minimum reachable inside temperature.
In this case, this 27 °C is the equilibrium temperature at which the heat loss through the windows and from the glass to the environment is equal to the amount of energy that the greenhouse absorbs from the sunlight.

Together with the 27 °C for the greenhouse air temperature, the simulation model has also calculated that in these conditions the crop is on average half a degree warmer. The temperatures of the greenhouse roof, the floor surface and the construction parts were also calculated. This is required because all these surfaces absorb sunlight and transfer that heat to the greenhouse air (via convection) and to the other surfaces (via radiation) and therefore influence the equilibrium values.
The figure below shows a schematic representation of all temperatures calculated in the simulation model.

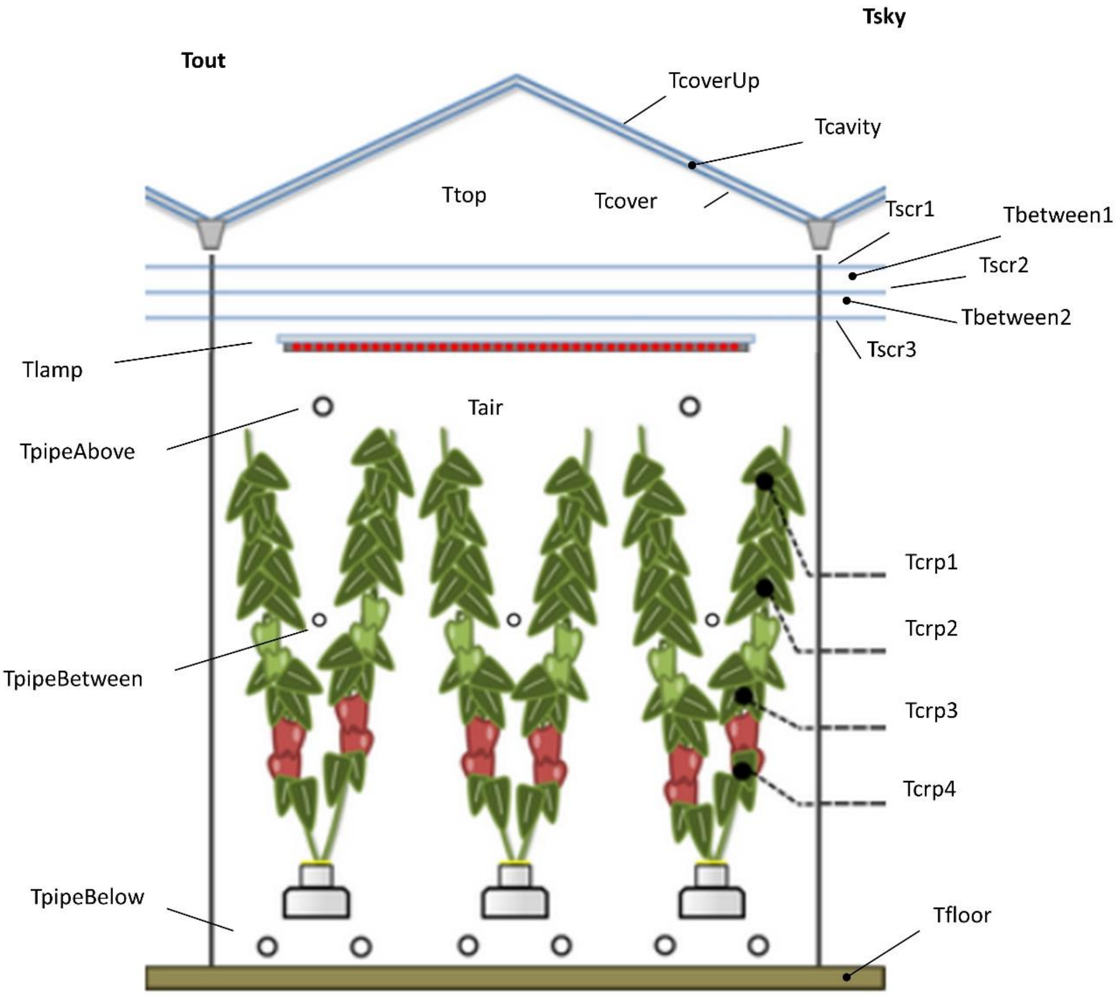

Figure 1 *De most important temperature-states of the Kaspro simulation model.*

This figure shows the maximum number of calculated temperatures. If less surfaces are selected, e.g. only one screen or only one heating system, the model shrinks and becomes faster.

All surfaces can intercept light (and when using lighting, the lamps can make light) and therefore heat up. A surface that is warmer than the air around it will lose heat through convection. The amount of heat released depends on the heat transfer coefficient and the temperature difference.
In addition to convective heat transfer, also the transfer by radiation is calculated. Since in principle any surface can exchange radiation with any other surface (unless a surface is completely out of 'sight'), the number of radiation exchanges increases almost quadratically with the number of surfaces that play a role in the simulation. The model therefore clearly becomes more computationally intensive as more installations are present in the simulated greenhouse. This is very noticeable when the model is used to simulate an entire growing season. However, when used by Kassim, only an equilibrium situation is calculated. This is a relatively short calculation so that the difference in computation time is too small to be noticed.

In an average situatuation, the Kaspro simulation model consists of about 10 to 20 states, each with its own temperature, and about 50 to 200 energy exchange processes that connect those temperature states. When this simulation model is used by Kassim, an iterative process is used to find that temperature distribution in which all processes are in equilibrium. This is the stationary equilibrium and each model part then loses as much energy to its surroundings as it receives.

In addition to energy exchange between the various components of the simulation model, also processes of energy conversion are included. The most important conversion is from light to heat when light is absorbed by a surface. The model uses an extensive set of formulas that calculate how light penetrates the greenhouse and the crop, whereby part of the light is absorbed and converted into heat along the way.
The second important conversion process is the conversion of heat into water vapor (evaporation) or, conversely, the conversion of water vapor into liquid water (condensation).
The evaporation process requires the availability of water in the first place, and a driving force in the second place. Water is supplied to a greenhouse system via the roots of the crop or via the high-pressure misting system (when marked to be present in the greenhouse). The driving force for evaporation is a vapor pressure that is higher on the evaporating surface than the vapor pressure of the air around it. Condensation occurs when the vapor pressure above a surface is lower than that of the air around it.

The vapor pressure (just above) a surface is a physical parmeter and is described by the saturated vapor pressure curve. The saturated vapor pressure curve for air at standard air pressure (100 kPa, or 1 bar) is shown in the graph below.

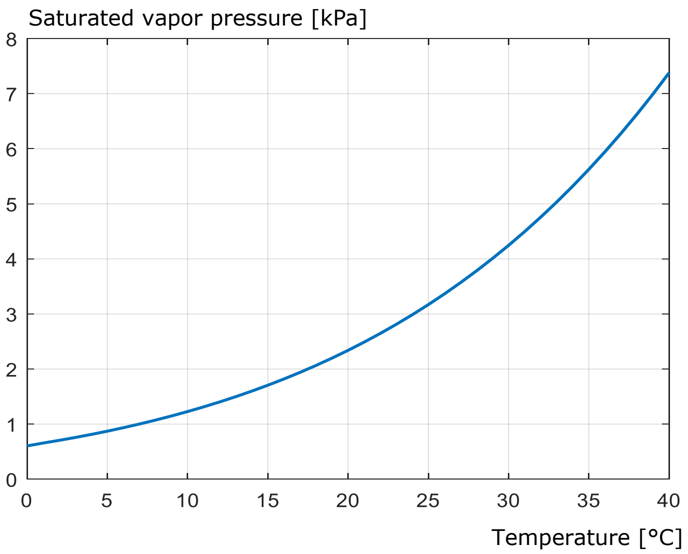

Figure 2 *Saturated vapor pressure in standard air conditions (100 kPa)*

If a surface is wet, and has a higher saturated vapor pressure than the vapor pressure of the surrounding air, this surface will release water vapor to the air. This process requires energy (latent heat), which is extracted from the (water layer on the) surface.
In case the wet surface and the air form an enclosed space, which is completely isolated from the environment, this evaporation process will continue until the vapor pressure of the air is equal to the saturated vapor pressure of the surface as at that point there is no longer a driving force for the evaporation. In that equilibrium situation, the air will have 100% relative humidity and the surface will have the same temperature as the (slightly cooled) air.

In a greenhouse, however, the greenhouse air is never an enclosed space. There is leak, as a result of which humid greenhouse air escapes, and when the cover is cold, moisture is withdrawn from the envelope by condensation on the greenhouse roof. As a result, the humidity practically always remains below 100%.
Usually, however, the humidity is significantly below 100% RH because the grower stimulates the removal of moisture through ventilation. The equilibrium level reached by the humidity depends on the one hand on the

speed at which the crop can evaporate water and on the other hand on the speed at which the greenhouse loses the water vapour.
For the evaporation rate of the crop, the driving force behind evaporation (the vapor pressure difference between the leaf and the air) is one of the two determining factors. This driving force increases as the greenhouse air dries. The other factor is resistance to moisture exchange. This will be discussed later.
Moisture loss to the outside is also determined by two factors. Also here there is a driving force, namely the difference between the humidity inside the greenhouse and outside the greenhouse. This difference in humidity becomes smaller as the humidity in the greenhouse decreases. The other factor for the moisture discharge is the ventilation flow rate. When using mechanical ventilation, the ventilation flow rate is a clear setting, but when using vents, the flow rate is determined by temperature differences, vent aperture and wind speed. All these processes are part of the simulation program, but are not discussed further in this project.
Because the driving force behind the evaporation works in the opposite direction to the driving force for the moisture discharge, in a greenhouse (and in the model) an equilibrium situation for the air humidity will be reached. This is sketched below.

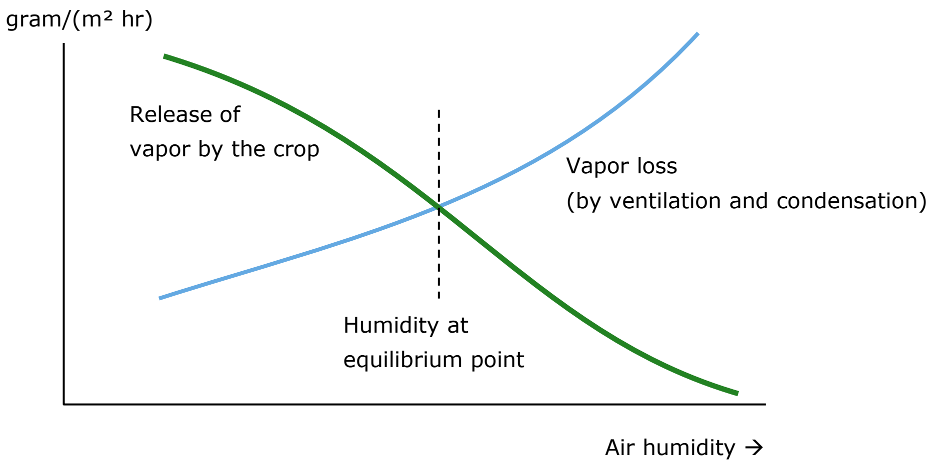

Figure 3 *Schematic drawing of the equilibrium humidity where vapor production equals vapor loss.*

In the picture, the moisture loss to the outside is shown as a line that gets steeper as the humidity in the greenhouse increases. This is due to the combination of the linear relationship between moisture discharge and humidity difference, and on top of that an increasing air exchange because the greenhouse climate controller will ventilate more as the greenhouse air is more humid (the P-band on humidity). The discharge via condensation will also increase as the greenhouse air is more humid.
The moisture production by transpiration from the crop is also a non-linear relationship. This is because in a greenhouse, when the moisture production from the crop changes, the temperature of the crop also changes (more about this later). This changes the vapor pressure just above the leaves (which is the driving force for evaporation) more than just the change in the vapor pressure of the greenhouse air. At very low air humidity, the moisture production of the crop can decrease again because the water supply from the roots can become restrictive, or the crop closes the stomata due to stress.

Because the direction of the processes with increasing humidity is opposite, an equilibrium point can be calculated. Such an equilibrium point is what Kassim calculates as a result of the (constant) settings provided by the user. The equilibrium point in the air humidity (but a similar mechanism also occurs for the temperatures in the greenhouse) shifts to the left or to the right depending on the environmental factors. But even if they were constant, the equilibrium point shifts to the left or to the right when the greenhouse or crop characteristics change. In a well-sealed greenhouse, the leakage loss is small and the blue line in Figure 3 will be somewhat lower and the point of intersection of the lines (the equilibrium humidity) will shift to the right. The greenhouse air is then more humid.

If the crop is larger in size, or if it evaporates more easily, the green line will move upwards and the equilibrium point will also move to the right. Conversely, in the case of a low evaporating crop, the green line shifts downwards and the equilibrium point moves to the left.
The humidity in a greenhouse is therefore determined on the one hand by physical and technical factors on the moisture removal capacity of the greenhouse and on the other hand by the physical and biological factors that determine evaporation from the crop. Technical and physical factors can be calculated with well-known standard formulas, but for crop evaporation this is much more difficult. In principle, evaporation from the plant is also a straight-forward physical process, but with an important biological component, namely the opening of the stomata. When the stomata are open, water vapor can easily be released from the leaf to the surrounding air (provided, of course, there is a certain vapor pressure difference) and a relatively large amount of water will be converted from the liquid to the gaseous phase. This produces a lot of evaporation and a lot of latent heat extraction from the leaf.
However, if the stomata are closed, little water vapor will be released from the leaf to the environment and the plant will evaporate little and extract little latent heat.
The physical process here is clear. Moisture is released to the greenhouse air via the resistance of the stomata and the boundary layer resistance of the leaf. However, the biological process behind this stomatal resistance means that the behaviour of the stomata cannot be described with generally valid relationships. Stomata properties can vary greatly from one crop to another. The stomata behaviour of one crop can also vary over time. Plants can adapt to their environment and therefore create more or fewer stomata per unit of leaf surface in new leaves. It is also known in Rose, for example, that when roses are grown under continuously high humidity conditions, the leaves are much less able to adapt the stomata resistance than a crop that is more hardened by the humidity being low (not under humidity conditions) at least some of the time. keep the 80%).
Due to this large variability between varieties and crops and within a crop, and possibly also variability during the growing season, a simulation model needs several parameters to be able to calculate at least the basic behaviour of the stomatal resistance.
In the next section, the theory behind stomatal behaviour, evaporation and crop temperature is first discussed in more detail. Then, in the next chapter, the results of the model in the simulation of evaporation and temperature of the crop will be shown based on measuring data in four different crops.

1.3 Stomatal aperture, transpiration and crop temperature

The previous section explained in general terms how the stomatal resistance influences evaporation from the leaf and thereby the latent heat that extracted from the leaf. This latent heat extracted is one of the components that ultimately determine the equilibrium temperature of the leaf. The other components are the energy that is absorbed by the crop from sunlight (or other light sources), the convective heat exchange between the leaf and the air around it and the energy that the leaf exchanges with the surrounding surfaces via radiation. As with the explanation of the equilibrium point for the humidity in the moisture balance (Figure 3), the energy flows around the temperature balance of the leaf have an equilibrium point where the input of energy from the sun is equal to the energy losses by evaporation, convection and radiation. It will be clear that we are talking about the daytime situation here. At night there is no absorption of sunlight and the balance looks different, which will be discussed later.

The balance during daytime is visualized in the drawing below.

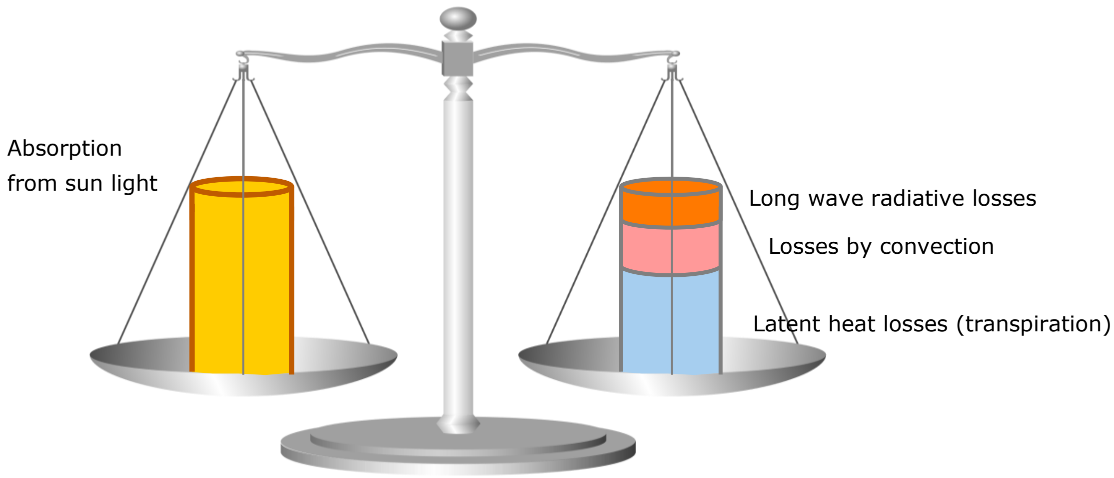

Figure 4 *Sketch showing the energy balance on the during day time.*

In this balance, with a given amount of sunlight and transmission from the greenhouse, the energy input to the leaf is constant and the simulation model will calculate that temperature at which the three losses together equal the energy input from the sun. If the leaf is calculated to be too cold, then the loss is less than the absorption and the leaf will become warmer. If the leaf is calculated to be too warm, the loss will be greater than the energy from the absorption of sunlight and the leaf will cool down.
It is evident that the energy loss due to (long wave) radiation depends on the temperature of the leaf. A warmer leaf will radiate more energy to a (colder) greenhouse cover than a colder leaf. And also for the convective heat it is clear that a leaf will release more energy to the greenhouse air as that leaf gets warmer.
But the energy loss through evaporation also depends on the temperature. With an increasing temperature of the leaf, a higher (saturated) vapor pressure is created in the wet cavities in the leaf (Figure 2). As a result, the driving force for evaporation increases and therefore also evaporation. With a decreasing temperature, evaporation decreases via the same mechanism.
When all three of these relations are known as a function of leaf temperature, the temperature at which the total energy loss equals the energy input can be found.
For radiation and convection, these relations follow directly from the heat transfer theory. The evaporation from the leaf cavities also follows standard heat transfer theory. The temperature of the leaf determines the vapor pressure difference between the leaf cavities and the greenhouse air and the actual moisture exchange then follows from this vapor pressure difference and the resistance for that exchange.
However, that resistance only partly follows the standard transfer theory, namely the part that describes the convection from a surface to the surrounding air. The other part is determined by the stomatal resistance.

This stomatal resistance is a biologically determined resistance and is subject to change via biochemical processes in the crop. The picture below shows schematically how the stomata open or close under the influence of the cell pressure.

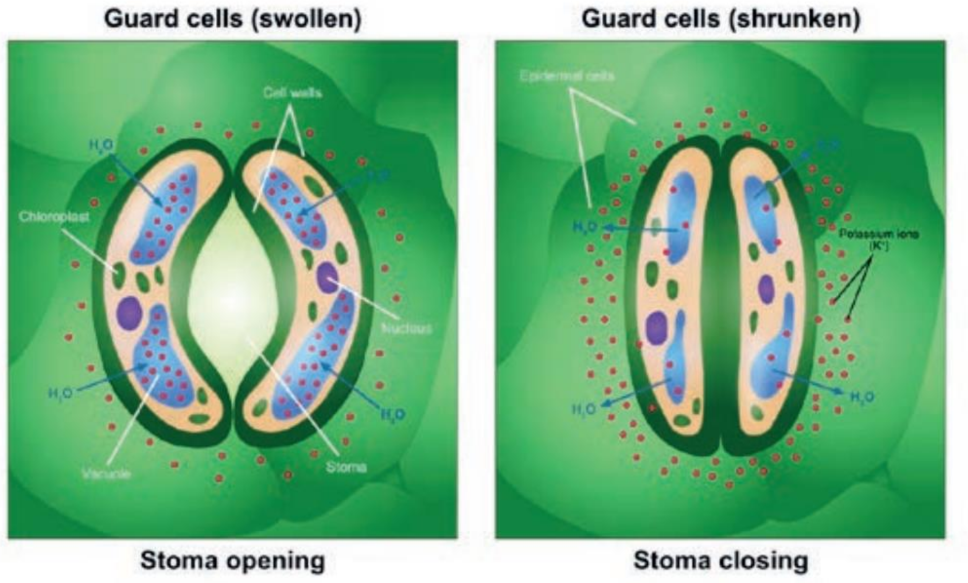

Figure 5 *Stomata. The guard cells contain Chloroplasts. Driven by radiation these chloroplasts provide the energy for K-ions (red dots) to be imported from the neighbouring cells. Because of this the Turgor of the guard cells increases and the stomata opens.*

Biologically, the opening of the stomata is determined by the osmotic value of the guard cells relative to the osmotic value of the surrounding cells. This osmotic value is regulated by the selective passage or blocking of ions and that process is influenced by numerous factors and forms the field of work for biochemists. However, this process can also be viewed at a higher level of abstraction to conclude that the stomatal opening can largely be correlated to the amount of light. Physiologically, this is because the guard cells also have chloroplasts that provide the energy to actively lower the osmotic value of the guard cells, causing them to swell.
Indeed, during the development of the Radiation Monitor, it turned out that for the simulation of evaporation, a relation that determines the stomatal resistance as a function of light intensity alone yielded good results.
The formula for the Radiation Monitor that was used in that tool showed to be sufficient to calculate the stomata behaviour under light-poor conditions (see https://www.glastuinbouwmodellen.wur.nl/radiationmonitor/Content/HlpEN.pdf page 7). However, at higher light intensities (summer conditions), the stomatal resistance appeared to be too large, resulting in insufficient transpiration and a too high a leaf temperature. Therefore, the formula for the calculation of stomatal resistance was adjusted in for the current project, while sticking to a simple type of equation. The core of the parameterisation of the stomatal resistance is that a maximum and a minimum stomatal resistance are defined for each crop, plus a parameter that indicates how the stomatal resistance is reduced under the influence of light to which the crop is exposed.
Because the reasoning is along the line that it is photosynthesis that drives the osmotic properties of the guard cells, the stomatal resistance is made dependent on the PAR-level to which a leaf is exposed. This led to the formula:

$$R_{stomata} = R_{stomata,min} + (R_{stomata,max} - R_{sotmata,min}) *(\exp(-PAR / (PAR90percent/2.4)));$$

The three parameters are the minimum stomatal resistance ($R_{stomata,min}$), the maximal stomatal resistance ($R_{stomata,max}$) and a parameter determining how strong the stomata respond to exposure to light (PAR90percent). The maximum stomatal resistance is the resistance of the stomata when closed, i.e. the value used in dark conditions. The minimum stomatal resistance is the value that the stomata provide when they are fully open, i.e. during the day. The PAR90percent parameter indicates the intensity of PAR radiation at which the stomata are

already 90% open, *i.e.* almost at their minimum resistance. If that value is high, for example 300 μmol/(m² s), then the crop apparently reacts very passively to an increasing light intensity and there must be quite a lot of light before the stomata open properly. If that value is low, for example 100 μmol/(m² s), this means that the stomata react very quickly to light. The number '2.4' shown in the function is just a fitting parameter.
In this calculation, 'the intensity of the PAR radiation' refers to the intensity of the light that falls on the top side of a leaf layer. In a way this is strange, as stomata are mainly located on the bottom side of the leaf, where the light intensity is significantly lower. The fact that this definition has been chosen is because: 1) the light intensity on a horizontal plane in a leaf layer is in line with the intuitive feeling of light intensity and, 2) the light intensity at the bottom is quite correlated with the light intensity at the top of a leaf layer and it therefore makes no difference for the determination of a regression parameter which light intensity is used.
As long as it is clear how the light intensity is defined, the model can be used to determine the stomatal resistance.
Please note that, 'stomata resistance' does not refer to the resistance of an individual stoma. It is the resistance of the total leaf surface, composed from stomata, but also from other tissue.
The model through which the transport of moisture from the leaves to the greenhouse air takes place in the model is outlined in the figure below.

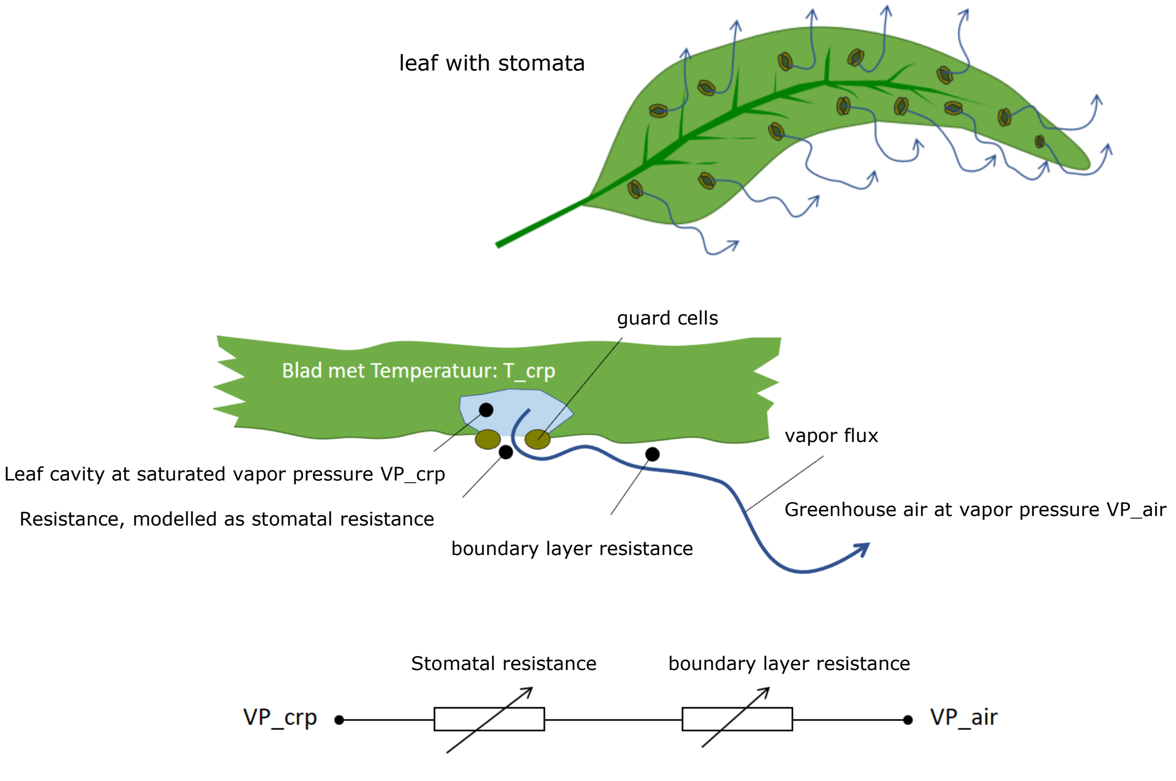

Figure 6 *Schematic representation of the transpiration process from the leaf cavity to the greenhouse air, both as a drawaing and as a representation as a series of two variable resistances.*

The starting point in the model calculation of the evaporation from leaves is that there is a certain vapor pressure in the leaf cavities (the saturated vapor pressure associated with the temperature of that leaf) that is higher than the vapor pressure of the greenhouse air. Due to this vapor pressure difference, water vapor will flow from the leaf cavity to the greenhouse air. That flow rate (the evaporation) depends on the pressure difference and the resistance, and that resistance consists of two components. The first component is the already discussed stomatal resistance, which is determined by a biochemical process. The second resistance is the boundary layer resistance. This boundary layer resistance determines the 'ease' with which air that is close to the leaf can be exchanged with the greenhouse air. This is a convective exchange process in which energy (heat) and mass (water vapor, CO2) are exchanged.

Because the exchange of heat and mass in a boundary layer follows the same principle, namely the exchange of the air from which the water vapor and CO2 are part, the boundary layer resistance for water vapor can be calculated from the boundary layer resistance for heat exchange. The general formula for this is:

$$\text{BoundaryLayer\_vapor} = Le^{2/3}\ \text{BoundaryLayer\_heat} \qquad [\text{s m}^{-1}]$$

where Le denotes the Lewis-number. For water vapour in air the Lewis-number is 0.89. With this, the boundary layer resistance for vapour can be calculated by:

$$\text{BoundaryLayer\_vapor} = 0.93\ \text{BoundaryLayer\_heat} \qquad [\text{s m}^{-1}]$$

The boundary layer resistance to heat can be determined experimentally using artificial leaves. By incorporating resistance wire into this and thus releasing a known amount of heat in the artificial leaf and then measuring how much warmer the artificial leaf becomes compared to its surroundings, the heat transfer coefficient can be calculated. In her PhD research, Stanghellini conducted various experiments with such artificial leaves and came to the conclusion that the (single-sided) heat transfer coefficient of tomato leaves that are two degrees warmer than the environment is around 5 W/(m² K). The heat transfer theory indicates that such a heat transfer coefficient increases with the temperature difference between leaf and air (more turbulence). For free convection with a turbulent character, a factor $dT^{0.33}$ is used, where dT is the temperature difference between the heat-emitting surface and the air.
Therefore, when simulating a tomato crop, the heat transfer coefficient between leaf and air is calculated in the simulation model by

$$\alpha_{LeafAir,singleside} = 4 * |T_{leaf} - T_{air}|^{0.33} \qquad [W/(m^2_{singleSideLeaf}\ K)]$$

Since a leaf can exchange heat on both sides, the heat exchange of a leaf is twice as large, so $\alpha_{LeafAir} = 2\ \alpha_{LeafAir,singleside}$. A cucumber crop, which has significantly larger leaves, will have a somewhat smaller heat transfer coefficient, so in that case calculations are made with $\alpha_{LeafAir} = 2 * 3 * |T_{leaf} - T_{air}|^{0.33}$ $W/(m^2_{leaf}\ K)$.
The boundary layer resistance to heat then follows from

$$\text{BoundaryLayer\_heat} = 1200 / \alpha_{LeafAir} \qquad [\text{s m}^{-1}]$$

where 1200 is the volumetric heat capacity of air (1.2 kg/m³ x 1.0e3 J/(kg K)).
Given that the boundary resistance to moisture is equal to 0.93 times the boundary layer resistance for heat, the evaporation from a leaf can now be calculated with:

$$\text{Transpiration}_{leaf} = \frac{\rho\ c_p\ \text{surface}}{\Delta H\ \gamma\ (r_{b,V} + r_{s,V})} \qquad [\text{kg/(s Pa)}]$$

Where ρ is the density of air (1.2 kg/m³), c_p the heat capacity of air (1.0e3 J/(kg K)), A the surface of the leaf, ΔH the latent heat of evaporation (2.45e6 J/kg (@ 20 °C)), γ psychrometric constant (65.8 Pa/K) and $r_{b,V}$ and $r_{s,V}$ the boundary layer and stomatal resistance for vapor.
In principle, this formula applies to every leaf, but in the simulation model the existing leaf is divided in 3 layers. The surface on which the balance is calculated therefore covers 1/3 of the leaf surface per m² present in the greenhouse, *i.e.* 1/3 of the LAI.
The model then calculates that average temperature for each layer at which the energy loss through radiation, convection and evaporation is equal to the absorption of energy from the sunlight.
The picture below shows an example of such a calculated temperature distribution over a cucumber crop that is exposed to 600 W/m² of radiation (measured just above the crop) in a greenhouse with a greenhouse air temperature of 26 °C and a humidity of 80%.

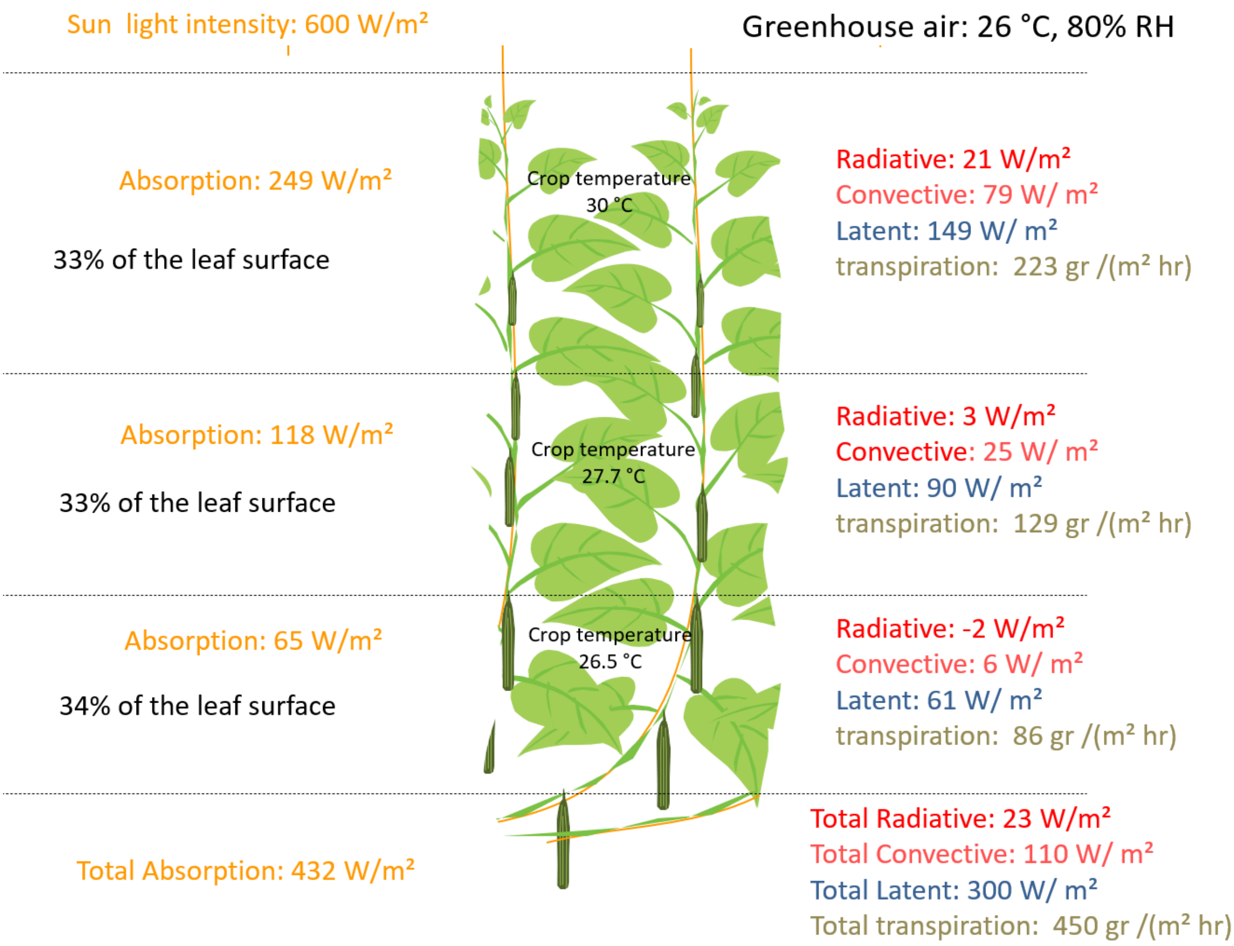

Figure 7 *Result of the calculation of crop temperatures in a cucumber crop with the simulation model. For this figure the parameterization of the crop properties as described in the next chapter is used.*

The Figure shows that in sunny conditions, most of the energy absorbed by the crop is lost via latent heat, *i.e.* is removed via evaporation (300 W/m² of the 432 W/m² = 69%). The picture also shows that not all light to which a crop is exposed is absorbed by the crop. An important part, mainly from the Near Infra Red part of the solar spectrum, is reflected.

With the model described above, the energy balance across the crop can be calculated for all conditions when the crop parameters for the various crops have been determined properly.
The next chapter explains how that proper parameterization was performed.

2 Determination of modelparameters

From the theory of the energy balance of the crop, it appears that the most important factors that play a role in this are the radiation absorption of the crop and the resistance of the stomata. Radiation absorption is the engine for the energy supply to the crop and the stomata then determine the distribution of that energy between sensible and latent heat dissipation.
Because strain absorption forms the basis of the energy balance, it is discussed first in this chapter (§ 2.1). Subsequently, we zoom in on the evaporation behavior and, with that, on the crop temperature (§ 2.2). In both cases, the four crops that have been studied in more detail in this project are examined, namely tomato, cucumber, Gerbera and Anthurium.

2.1 Absorbtion of radiation in tomato, cucumber, Gerbera en Anthurium

In recent years, various experiments at the Bleiswijk test site have used a net radiation meter that separately outputs the four components of this radiation measurement.
The photos below show the 4 sensors that are incorporated herein and their function.

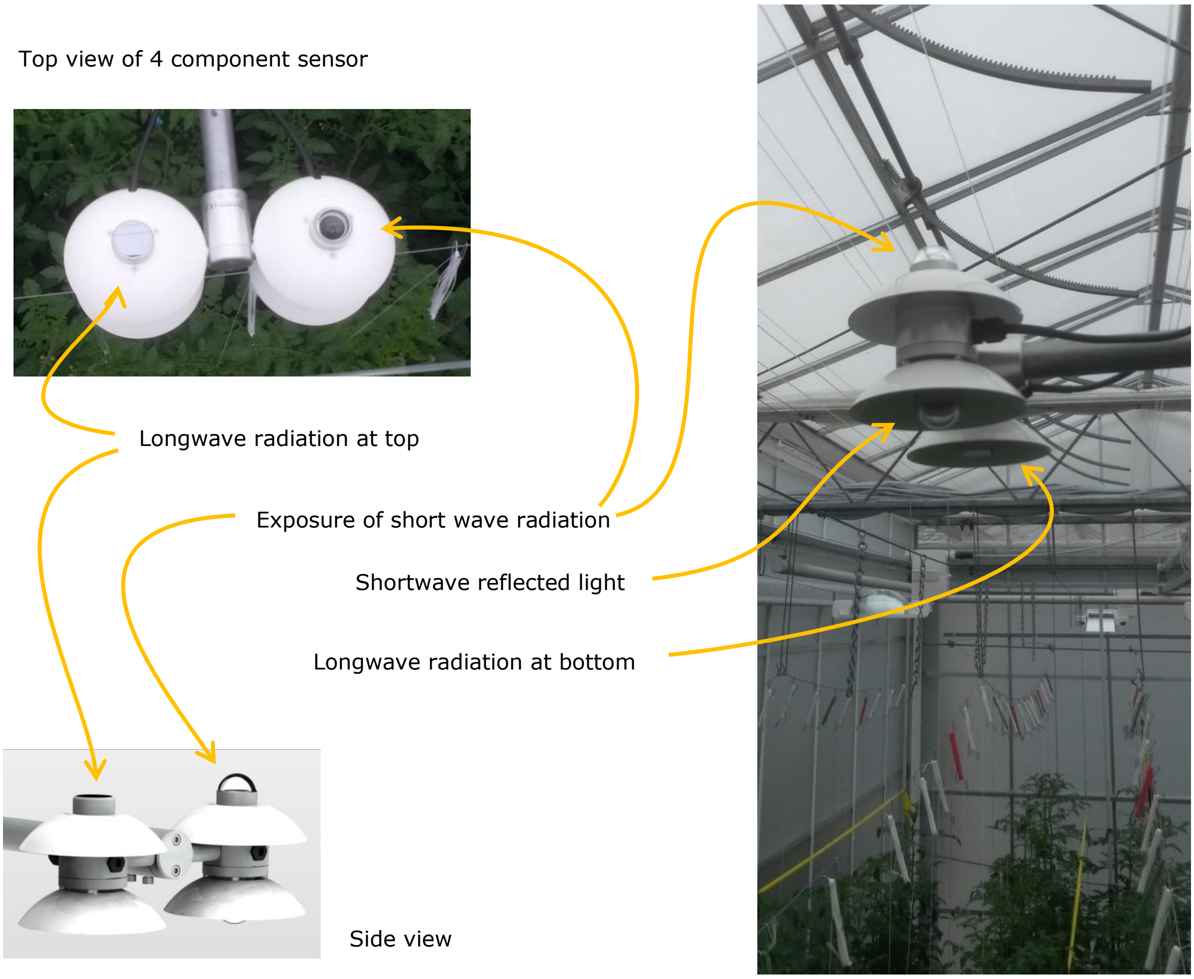

Figure 8 *Net radiation meter measuring 4 channels individually.*

At the top are a pyranometer that measures the incident sunlight (PAR + NIR) and a pyrgeometer that measures the long-wave radiation exchange upwards. The pyranometer measures values up to about 700 W/m² during the day and of course 0 W/m² at night, except when the lighting is on and some short-wave light will also be measured due to reflections. The upper pyrgeometer almost always gives a negative value (radiation loss) because the sensor will generally be warmer than the surfaces in the sensor's 'field of view'.
The lower short-wave radiation sensor (also a pyranometer) measures the light reflected from the crop and the floor surface of the greenhouse. In a fully grown tomato crop, the intensity of the upward short-wave radiation is around 13% compared to the downward short-wave radiation, but in other crops it is clearly higher and sometimes even considerably higher. Such a higher value can be caused by a higher reflection in the PAR region, but also by a higher reflection in the NIR region.
The lower pyrgeometer measures the radiation exchange between the sensor and anything below it. At night the sensor is sometimes a bit colder than the surfaces under the sensor and will therefore give a positive value. Net radiation is then delivered to the sensor. However, if the crop evaporates considerably, or if the crop radiates strongly towards the greenhouse roof, the crop surface will be colder than the sensor housing and the lower pyrgeometer will also give a negative value.
The Figure below shows the course of the 4 signals from which the net radiation is built up over 2 days in a tomato crop (Figure from report 'De Uitstralingsmonitor', de Zwart et.al., 2017)

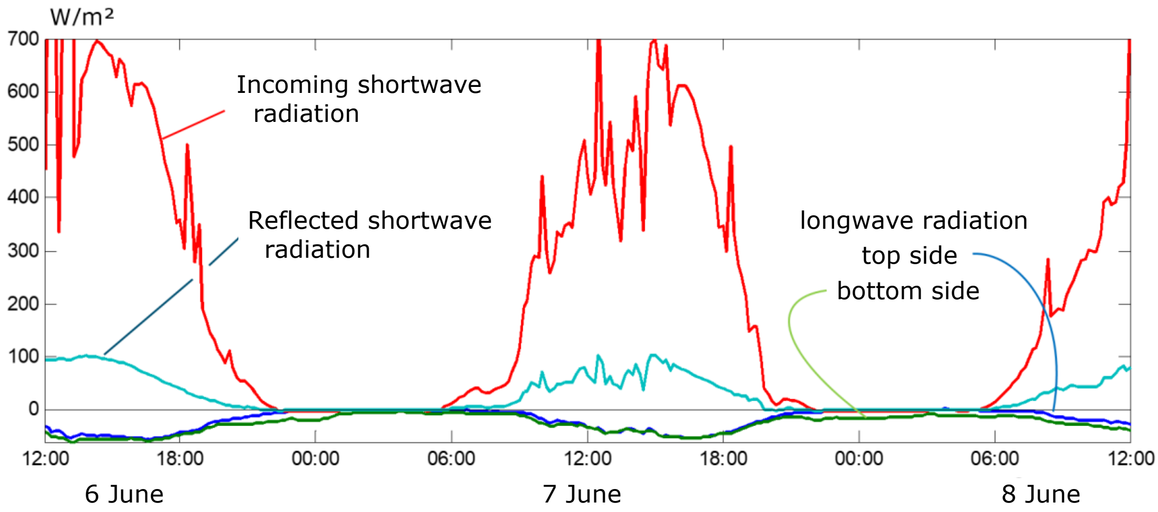

Figure 9 *The 4 radiation components for 48 hours in a greenhouse with a fully grown tomato crop without using an energy or shade screen.*

The 2 pyranometers of the 4-component net radiation meter can be used to determine the crop's short-wave radiation absorption. After all, the difference between the short-wave light at the top and bottom of the sensor is absorbed by the crop and the floor surface.
The figure below shows hourly average values of the measured downward radiation on the x-axis and the thereby measured upward radiation on the y-axis in the 4 crops in which this 4-component net radiation meter has been used in recent years in various test departments in the test location. Bleiswijk has been used. In all cases it concerns mature crops..

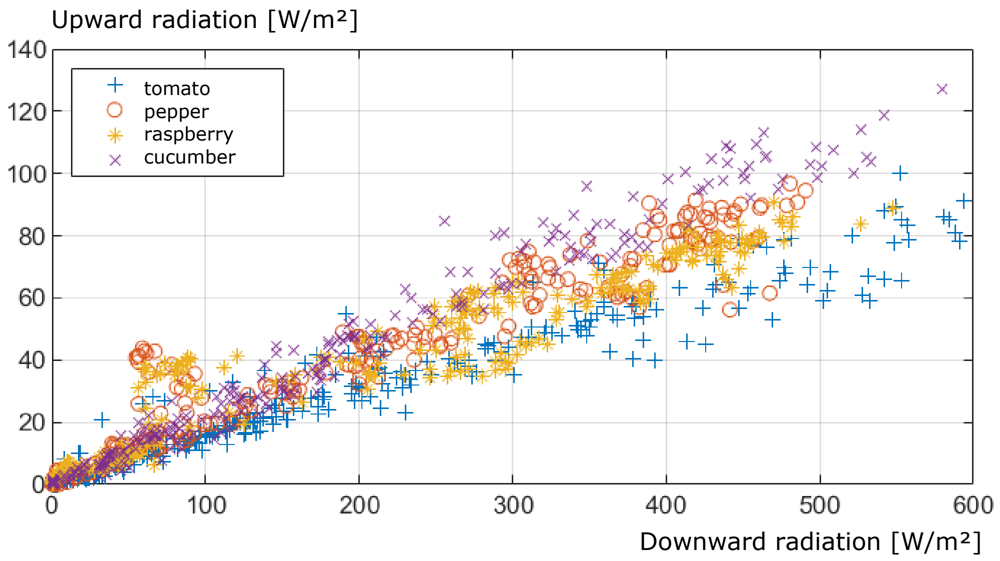

Figure 10. *Hourly average values of the measured downward short-wave radiation and upward short-wave radiation in 4 crops, all fully grown.*

The data are all obtained under summer conditions (May and June) and it is clear that the ratio between upward and downward radiation is quite constant. All points are reasonably close to an average line. The fraction of reflected light from the combination of crop and soil apparently depends only slightly on light intensity.
The slope of the line that can be drawn through the point cloud for the 4 crops gives the average reflection of crop + floor surface, which is smallest for tomato (14%) and highest for cucumber (19%). Bell pepper is close to cucumber with 18% reflection and raspberry is between the other crops with 17% reflection..

The Kaspro simulation model also includes a 4-component net radiation meter that simulates the measured values of such a net radiation meter. For the four crops mentioned, the model calculates the values below for the downward and upward short-wave radiation under summer conditions in a fully grown crop (LAI=3 (and 4 for Sweet pepper)).

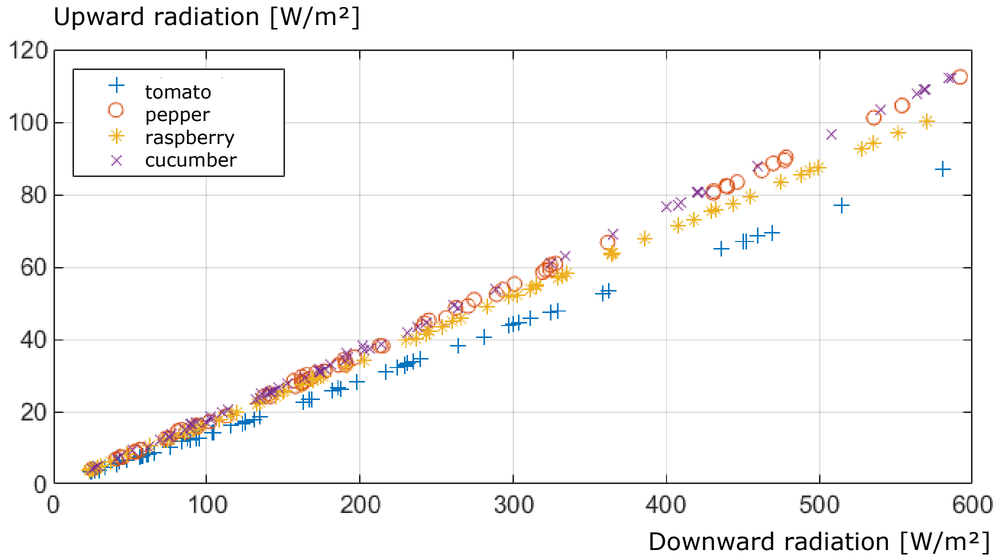

Figure 11 *Downward and upward short-wave radiation as stimulated by the simulation model for a tomato crop, a cucumber crop, a pepper crop and a raspberry.*

It is clear that in the model the relationship between downward and upward radiation is almost linear, where a clear spread can be seen in measurements. All kinds of effects of temporary shading of the sensors by construction parts, differences because the crop is moved with the 'lowering', differences because the sun shines exactly in the path or because reflections of the sun fall exactly on sensors are not included in the model. The model does take into account the differences between one or the other crop. This clearly shows that, just like in the measurements, a tomato crop absorbs the most light, while a cucumber crop absorbs the least.
No measurements with a 4-component pyranometer were available for the Gerbera and the Anthurium. In those two crops, the ratio between upward and downward short-wave radiation was determined by having a pyranometer alternately measure upwards and downwards.

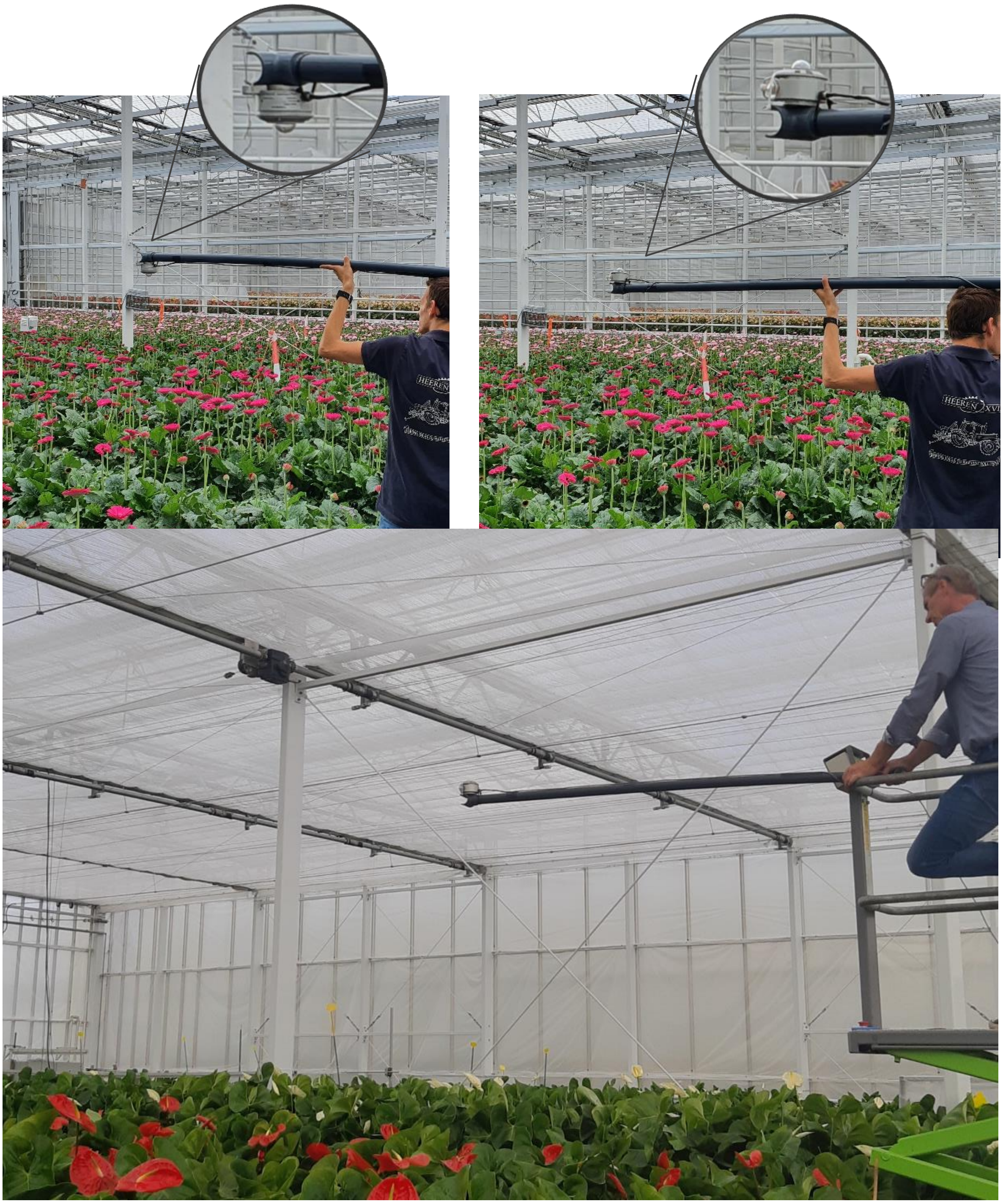

Figure 12 *Manual determination of light absorption by crop+floor by measuring the downward and upward short-wave radiation.*

To compare the results of the manual measurement with the results of the 4-component radiation meter, the measurement method shown above was also carried out in a tomato and cucumber crop. The results are shown in the table below.

Table 2.1
Op going intensity of the sunlight above the crop, measured manually, as a percentage of the downward radiation above the crop for 4 crops. All crops are fully grown..

	Gerbera	Anthurium	Tomato	Cucumber
Downward radiation	100%	100%	100%	100%
Upward radiation (manual)	16%	35%	12%	18%
Upward radiation (automatic)	N/A	N/A	14%	18%

The table shows the same value for cucumber. For tomato, the manual measurement gave even greater crop absorption than what was measured with the 4-component radiation meter, but the results do show that in the absence of a series of automatically generated radiation data, manual measurement is a useful alternative.

The difference between the amount of sunlight that is emitted upwards at crop height and the amount of light that enters from above gives the absorption of sunlight by all surfaces below the sensor. The crop is the largest surface in this area, but not the only one. The gutters and the floor also absorb sunlight and part of the non-returning sunlight is therefore absorbed under the crop and not by the crop.
To determine this quantity, the pyranometer also measured up and down alternately at gutter height. The difference between the measurement signal when the pyranometer is looking upwards and when it is pointing downwards is due to the absorption of light under the crop.
The table below shows the complete overview of the measured radiation intensity, all expressed as a fraction of the downward radiation intensity at the top of the crop.

Table 2.2
Upward reflections of the sunlight above the crop and downward and upward radiation intensities at the bottom of the crop as a percentage of the downward radiation at the top of the crop. All values were measured manually by turning a pyranometer up and down alternately. In all cases the crops are fully grown.

	Gerbera	Anthurium	Tomato	Cucumber	
Downward radiation at top of crop	100%	100%	100%	100%	A
Upward radiation from top of crop	16%	35%	12%-14%	18%	B
Downward radiation at bottom of crop	10%	5%	12%	15%	C
Upward radiation at bottom of crop	4%	2%	4%	6%	D
Absorption by the ‘floor’	6%	3%	8%	9%	E
Crop absorption (a-b-(c-d))	78%	58%	78%-80%	73%	F

Table 2.2 shows that the 'floor', meaning all surfaces below the lowest crop layers, absorbs on average about 60% of the sunlight that still falls on the underside of the crop. 40% is reflected and therefore has a second chance to be absorbed by the crop. The simulation model not only calculates the energy input from light coming from above, but also from light coming from below, but the percentages shown in Table 2.2 show that the contribution of that light coming from the floor has a second chance gets small to very small. However, the table also shows that for vegetable crops, for example, the absorption of light by the soil is not insignificant. The absorption of light under the crop (row E = row C – row D) amounts to 8 to 9% of the incident light. Neglecting the absorption by the floor would then give a considerable overestimation of the absorption by the crop.

After correction of the measurements above the crop by the absorption of light below the crop, the absorption by the crop follows. In table 2.2 this is described as row F = row A – row B – row E.
The conclusion of the measurements of the radiation absorption of the various crops is that a tomato crop absorbs 78% to 80% of the sunlight measured at the top of the crop, a gerbera crop 78%, a cucumber crop 73% and an anthurium crop 58 %.

The simulation model, of which we have seen that the calculated ratio between the downward and upward radiation intensity is quite comparable with what the pyranometers of a 4-component net radiation meter measures, also yields values in terms of crop absorption that are close to the values in table 2.2. The measured and calculated radiation absorption for the 4 crops are shown in the table below.

Table 2.3
Crop absorption of sunlight as a fraction of the intensity of the sunlight as measured above the crop. The table shows the measured and calculated value for 4 mature crops.

	Gerbera	Anthurium	Tomato	Cucumber
Downward radiation at top of crop	100%	100%	100%	100%
Measured crop absorption	78%	60%	78%-80%	73%
Calculated crop absorption	79%	61%	79%	72%

The simulation model does not give the exact same value as determined by the manual measurements, but in all cases comes very close. Given that the simulation model can never exactly simulate the variability in those ratios (compare Figure 10 with Figure 11), the results shown in Table 2.3 are assumed to be acceptable.

2.2 Conversion of absorbed radiation on sensible and latent heat

The light that is absorbed by the crop during the day is converted into heat and that heat is dissipated in the form of latent heat (evaporation) and, if the crop is warmer than the environment, also in the form of sensible heat. The distribution of the absorbed energy per leaf layer over radiation, convection and evaporation is determined by the resistance to moisture transport, consisting of a stomata resistance and a boundary layer resistance. If the total resistance to evaporation is small, then evaporation will be 'easy' and the leaf temperature will be close to the greenhouse air temperature. If the stomata resistance is high, then a sufficiently large vapor pressure difference will only arise at a higher leaf temperature to generate substantial evaporation, and thus cooling. The temperature at which the release of energy is in equilibrium with the absorption of sunlight then rises further above the greenhouse air temperature. Typically latent heat loss remains the major component in the heat balance during the day, but in crops with high stomatal resistance the balance will shift towards sensible heat loss as the leaf heats up. At least, as long as the absorption of sunlight by leaves remains unchanged. A crop such as Anthurium, which has difficulty evaporating due to its greasy leaves, has a high reflection so that the temperature does not rise too high despite the limited evaporation.

The above description of the process indicates that three factors must be realistically calculated for a calculation model for the energy balance of a crop. In the first place, the light absorption must be correct, which was discussed in the previous section. Secondly, the evaporation must be right and thirdly, the temperature of the leaves at which that evaporation is realized must match.
A rough comparison between calculated and measured evaporation can be made on the basis of a comparison of irrigation and drainage on a daily basis. The difference between fertilizer and drain gives the total water absorption, of which about 10% is drained off in the form of the harvested product in a fruit crop, but also in a floristry crop. The daily evaporation is therefore about 90% of poison-minus-drain.
A weighing chute was also present in the cucumber crop studied. This makes it possible to study evaporation not only on a daily basis, but also on a quarterly basis. Moreover, with a weighing trough it is possible to distinguish evaporation from water absorption. The difference between the two is the weight gain of the crop. For the cucumber crop, it is therefore possible to zoom in even higher detail on the calculated crop evaporation.

In this section, the evaporation on a daily basis is first examined. Subsequently, for the cucumber crop, the evaporation on an hourly and quarterly basis is examined. And finally, the calculated temperature in the top of the crop is also compared with measurements by an InfraRed camera.

2.2.1 Simulated and measured daily transpiration in tomato

Data on crop water uptake and transpiration of a tomato crop were obtained from a growing cycle of tomato in the Bleiswijk research facility in an experiment on the effect of reduced CO_2 dosing. This was an experiment in 2020 with three 144 m² compartments subject to different CO_2 dosing regimes. One of the three, compartments 6.08 reflected common practice so the data from this compartment was used.
The summer of 2020 had a very warm period around August 11 and the days with the highest daily light integral were in the week around July 14 and the week around July 21.
The graphs below show the daily light sum in the greenhouse and the average 24-hour temperature for a period of more than 3 months. The crop was planted in February, so in this summer period the crop was full grown and productive.

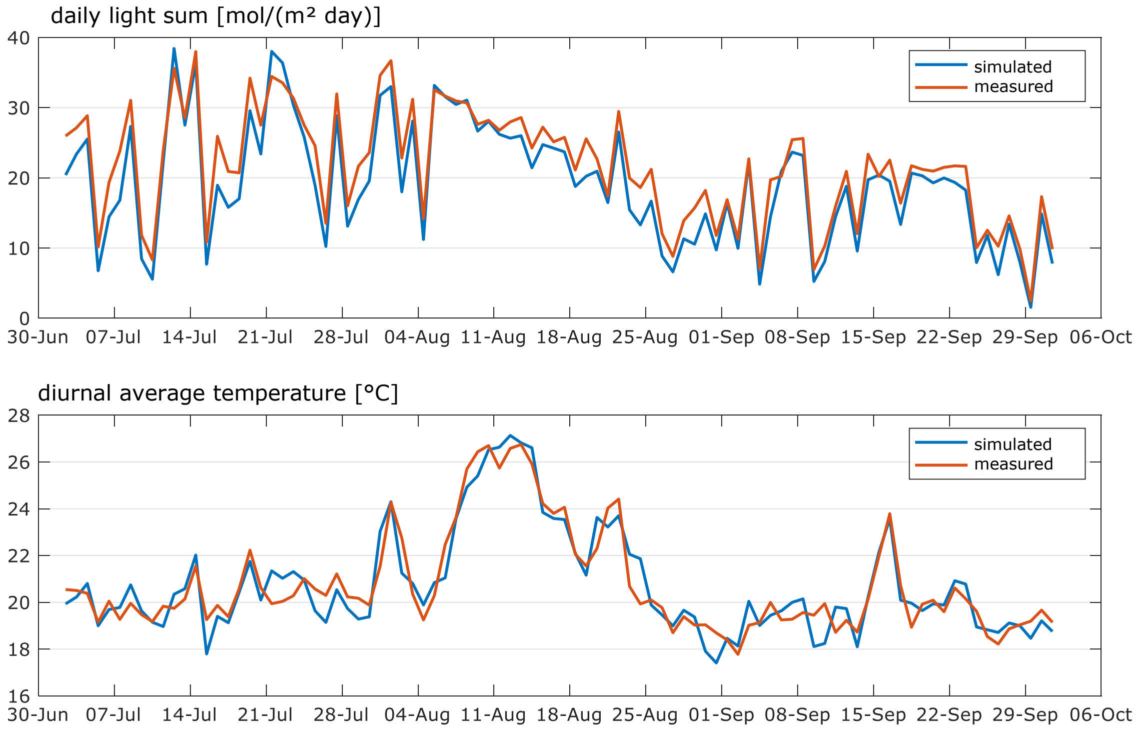

Figure 13 *Daily light integral and diurnal average temperature used for the verification of the crop evaporation and top leaf temperature for tomato.*

The Figure shows that the summer of 2020 had all kinds of different combinations of temperature and radiation and therefore offers a suitable dataset to see how well the model is able to simulate the measured evaporation. The tomato greenhouse did not have a weighing gutter, so the daily water uptake is here derived from the water supply minus drain on a daily basis. The water uptake of the crop is the sum of evaporation and water uptake for crop growth. To determine evaporation, the water intake for crop growth must be subtracted from the daily water intake. This water uptake for crop growth can be estimated by dividing the dry matter production calculated by the model by the average dry matter percentage of the grown crop. The graph below shows the calculated daily water intake for growth.

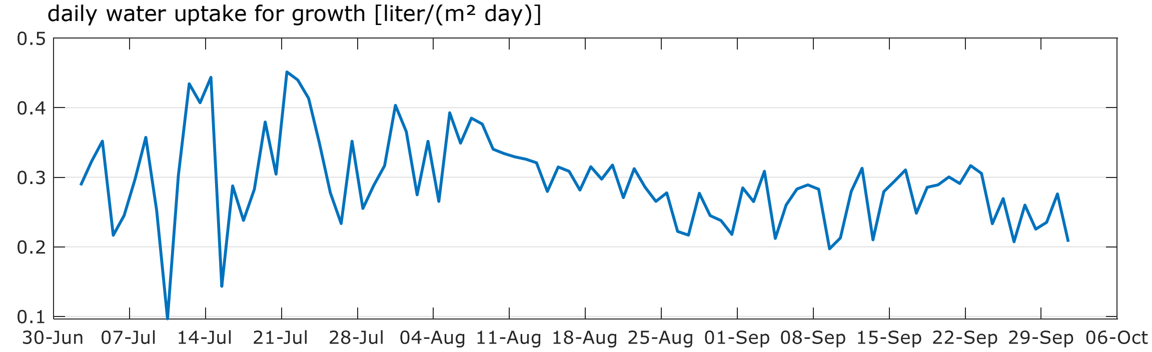

Figure 14 *Calculated water uptake for growth, assuming an average dry matter percentage of 7%.*

After subtracting the shown water uptake for growth, the graph below is obtained, showing the measured daily evaporation. It is placed together with the simulated transpiration.

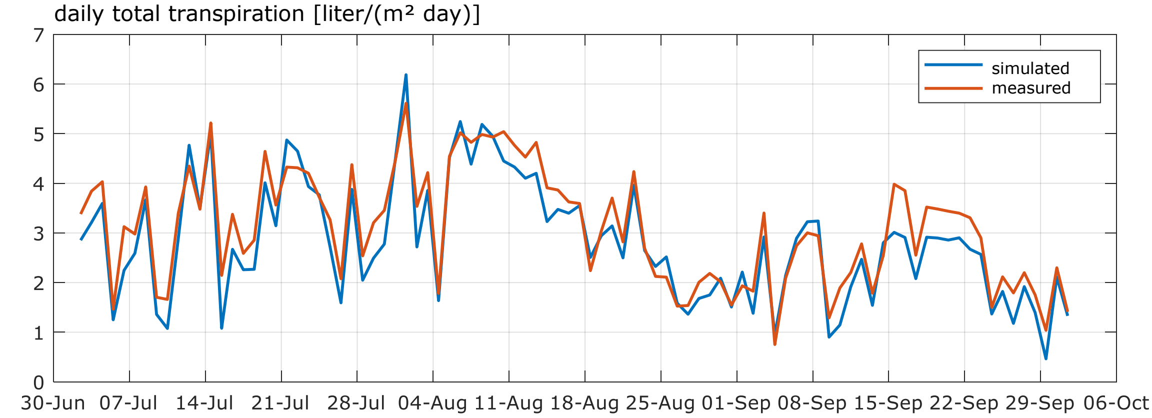

Figure 15 *Daily crop evaporation as simulated by the model and as determined from subtracting the drain and water uptake for growth from the daily irrigation.*

The Figure shows that the simulation model follows the measured evaporation well, but that the two lines are not tightly aligned. One day the model calculates a somewhat higher evaporation than the measured evaporation and the next day a somewhat lower value. This is of course because a model always gives not more than an approximation of reality, but also because the model does not include the exact course of the LAI. At the start of cultivation (in this case in February), the model assumes a small plant that grows into a fully grown crop in the course of 6 to 8 weeks, but then the LAI is assumed to be constant. In reality, the LAI always forms a kind of sawtooth pattern because 2 or 3 leaves are removed from each plant about once a week. Two or three leaves means that the LAI decreases by about 0.5 m^2/m^2 after such a pruning. If the model is used to calculate the effect of this last half m^2 of leaf on the daily evaporation, it turns out that this amounts to an average of 150 cc per m^2 per day of evaporation. This can be seen in Figure 16 where the calculated daily difference in evaporation is shown for a crop with LAI 2.5 and a crop with LAI 3.

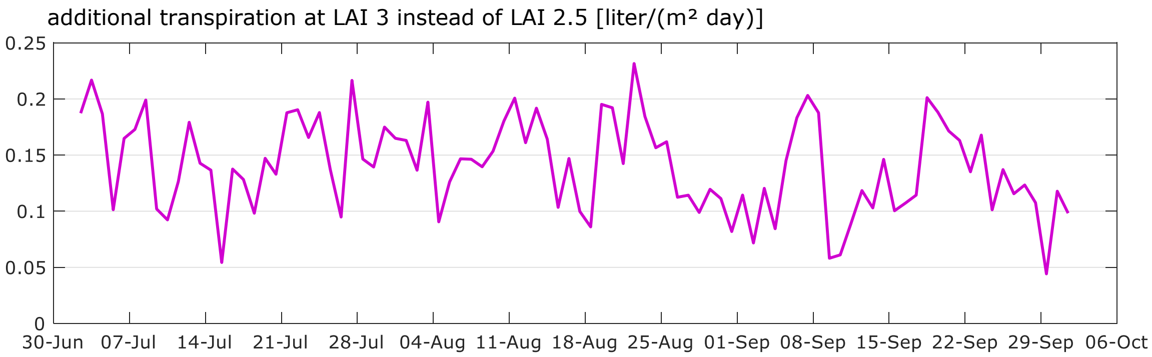

Figure 16 *Computed effect of 0.5 m^2/m^2 change of the LAI on water uptake of a tomato crop.*

In addition to the variation resulting from a changing LAI, there is also the variation due to the inaccuracy in the measured evaporation. Supply minus drain gives a good indication, but every day, the trigger for the last irrigation is uncertain. If the last irrigation turn is given just before 'closing time' of the watering period, the calculated watering for such a day is easily 200 cc more than when just 1 turn less is given. The variation in LAI alone and whether or not an irrigation turn is carried out just before 'closing time' results in an uncertainty of around 300 cc. Considering the above-mentioned uncertainties, the differences between model and 'measurements' shown in Figure 15 can be considered normal. 'Measurements' is placed in quotes here because the measured water intake per day includes a calculated water intake for crop growth and is therefore already partly a calculated value.

2.2.2 Simulated and measured daily transpiration in cucumber

The registrations in the Winterlight greenhouse in the summer of 2020 were used to evaluate the crop evaporation and top temperature in the cucumber. In addition to the standard measurement of supply and drain, the Winterlight greenhouse also has a weighing trough. For the validation of the cucumber transpiration parameters, next to the daily transpiration value, also at the transpiration on a quarter-hour scale can be evaluated.
For the cucumber model validation, data from the period from May 10th to August 10th were used. The Figure below shows the daily light sums and average 24-hour temperature.

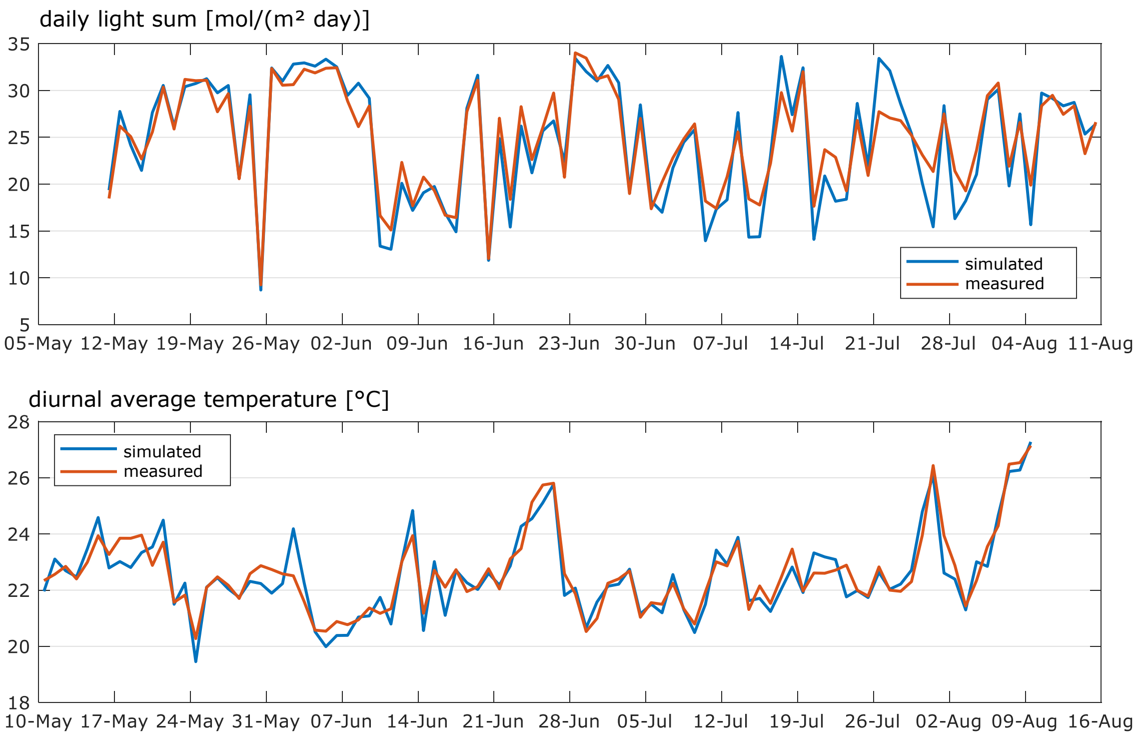

Figure 17 *Daily light integral and diurnal average temperature in the cultivation used for the verification of the crop evaporation and top leaf temperature for cucumber.*

The simulated light sum and 24-hour temperature were obtained using the greenhouse climate controller of the simulation model. This climate controller is comparable to the climate controller of the Winterlight greenhouse, but not exactly the same. In the actual greenhouse, the climate controller settings are changed frequently, sometimes for only half a day. These kinds of details are not included in the simulation model and explains the deviations between simulated and measured climate data. However, the overall picture shows a good match between simulated conditions in the greenhouse and the measured conditions.
It should be expected from the model that if the cultivation conditions are simulated properly, the calculated evaporation will also be in good agreement with the measurements. Again, when looking at the supply and the drain of water on a daily basis, the water that is captured by the crop must be subtracted to get the transpiration. Cucumber has a lower dry matter percentage than tomato, so where in tomato cultivation the water absorption was calculated by dividing the calculated dry matter production by 0.07, an average dry matter percentage of 6% is maintained in the cucumber. The dry matter percentage of cucumber fruits is lower, but the dry matter percentage of the other plant organs is higher so as an average, 6% is fair to use. This results in the below water uptake for crop growth.

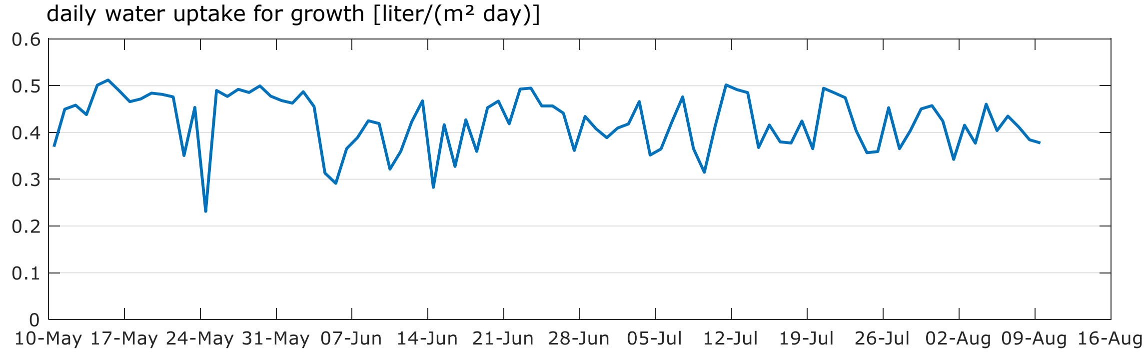

Figure 18 *Calculated water uptake for growth by a mature cucumber crop, assuming an average dry matter percentage of 6%.*

After subtracting the shown water uptake for growth, the graph below for the measured daily evaporation is obtained, which is placed in a figure together with the simulated evapotranspiration.

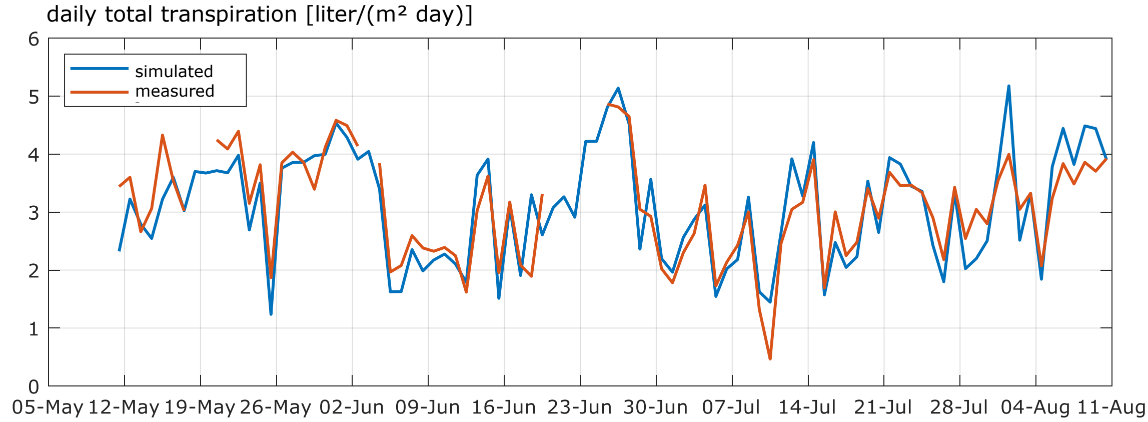

Figure 19 *Calculated crop evaporation of a cucumber crop in the 'Winterlight greenhouse' in summer (2020).*

Again, on a daily basis, the model follows the measured crop evaporation very well.
In addition to using the rough determination of the crop evaporation on a daily basis, based on data from 2020, also weighing gutter data registered in the same greenhouse compartment in 2021 could be used for the model validation. The Figure below shows the hourly evaporation obtained from the weighing gutter data and the calculated Values in June and July of 2021.

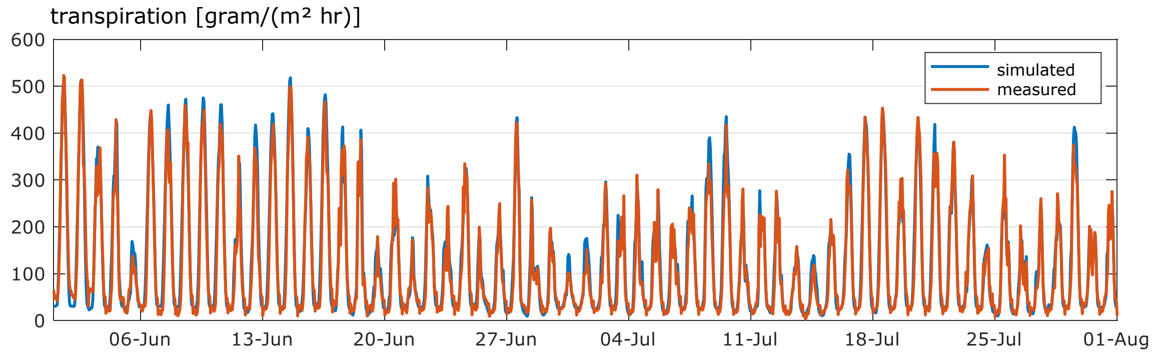

Figure 20 *Impression of the evaporation by a cucumber crop (expressed as an hourly average number) in the three summer months. The measured values come from a weighing gutter.*

The figure shows that not only the daily evaporation is simulated well, but also the hourly course. If zooming in on this figure, for example on the period from 13 to 21 June, it also becomes clearly visible that the model follows the evaporation over sunny days and dark days.

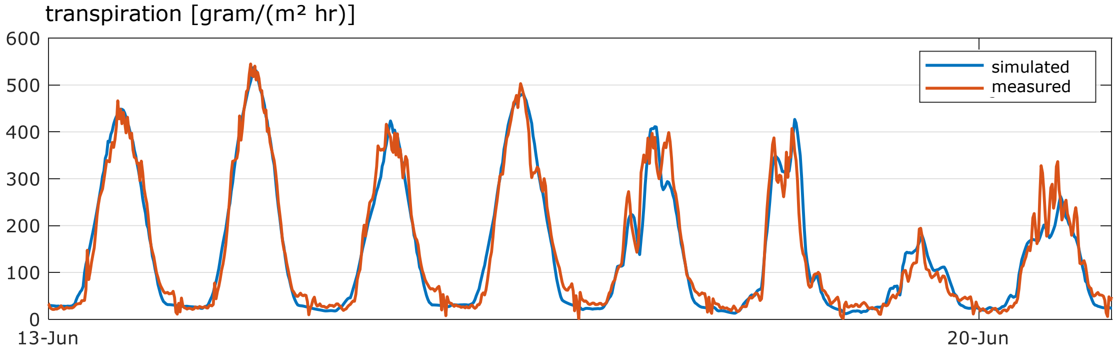

Figure 21 *Detail image of the same data as shown in figure 20. It concerns the evaporation by a cucumber crop on a 15-minutes time scale. The measured values come from a weighing gutter.*

The fact that both daytime evaporation and night-time evaporation are correct means that the chosen model that calculates stomatal resistance works well. This model makes the resistance high at night and low during the day. For the cucumber, the maximum stomatal resistance is set at 1600 s m^{-1}. During the day, the resistance is lowered to 250 s m^{-1}. The reduction from 1600 to 250 follows a smooth line that has already reached 90% of the reduction at a light intensity of 100 μmol/(m² s). The maximum stomatal resistance and the light intensity at which 90% of the resistance reduction is reached is equal to that of the tomato for the cucumber, but the minimum stomatal resistance is higher for the cucumber than for the tomato. This means that the tomato evaporates slightly more than the cucumber under light-rich conditions.
A slight but notable difference between simulation and measurement is that at the end of the day the model underestimates crop evaporation and overestimates it a little at the beginning of the day. This may be caused by some lagging of the stomata behaviour. In the model, the stomatal resistance is immediately adjusted under changing conditions, but it is quite conceivable that there will be some delay in reality.

2.2.3 Simulated and measured daily transpiration in Gerbera

Gerbera is a completely different crop than tomato and cucumber. Both in terms of plant and cultivation. Significantly less of the crop is harvested, the leaves grow more slowly, the day length is kept shorter (in summer) and there is considerable screening. The intensive shading and the shortening of the day length lead to a clearly lower light sum.
The data from compartment 2 of the greenhouse2030 complex of Wageningen UR Greenhouse Horticulture in Bleiswijk was used to validate the evaporation model for Gerbera.
The graph below shows the measured and simulated greenhouse air temperature in this Gerbera greenhouse. Similar lines of the previously discussed tomato cultivation are also drawn in the graph for comparison.

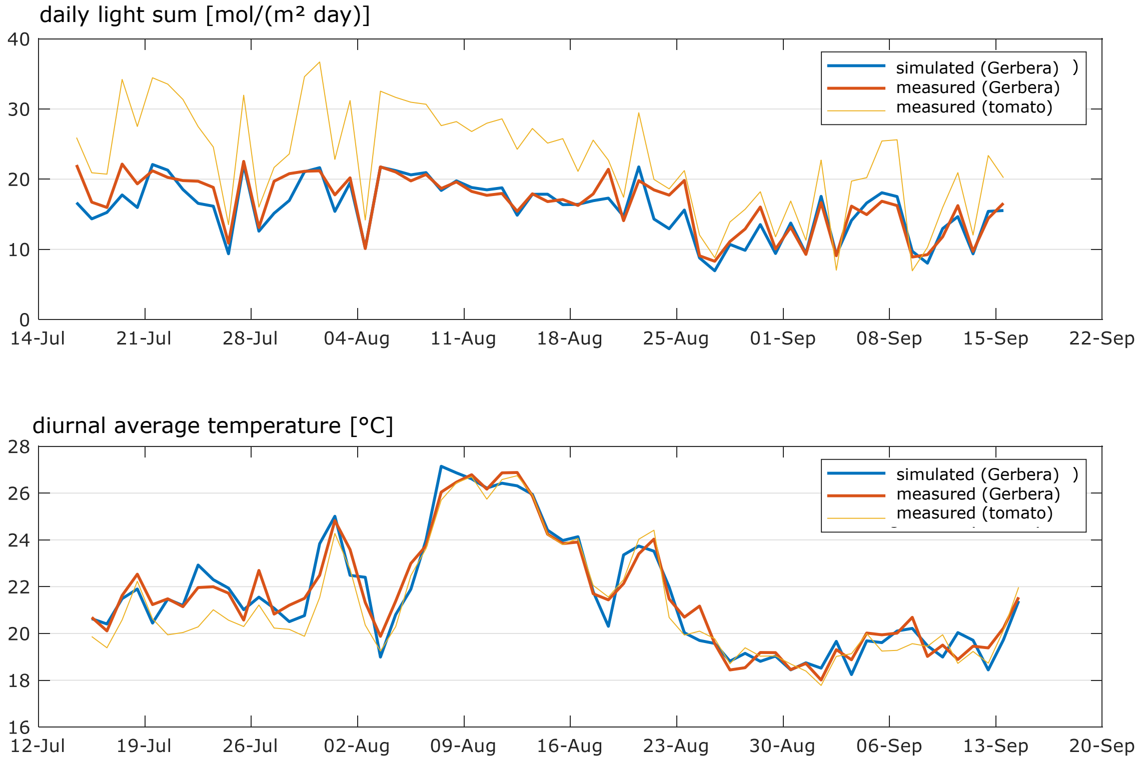

Figure 22 *Daily light integral and diurnal average temperature in the cultivation used for the verification of the crop evaporation and top leaf temperature for Gerbera. As a comparison, also the DLI and average temperature in the tomato-cultivation from the same period are shown.*

On most days the calculated and measured light sum is in line and the temperatures are also in line. There was no weighing system in the greenhouse compartment for the Gerbera, so the daily evaporation can only be deduced from the water supply minus drain minus the amount of water that is captured in the crop. Here too, the water uptake for crop growth is estimated by dividing the dry matter production calculated by the model by the average dry matter percentage of the growing crop. A Gerbera crop has a significantly higher average dry matter content than tomato and cucumber. Assuming 10% dry matter, the graph below is obtained for the water retention by growth per day.

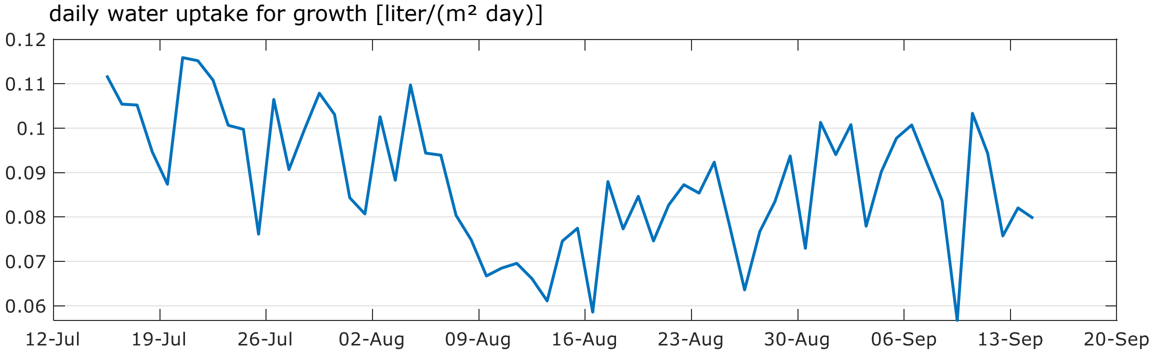

Figure 23 *Calculated water uptake for growth, assuming an average dry matter percentage of 10%.*

After subtracting the shown water uptake for growth (which has hardly any influence given the small amount), the graph below for the measured daily evaporation is obtained, which is placed in a figure with the simulated evaporation.

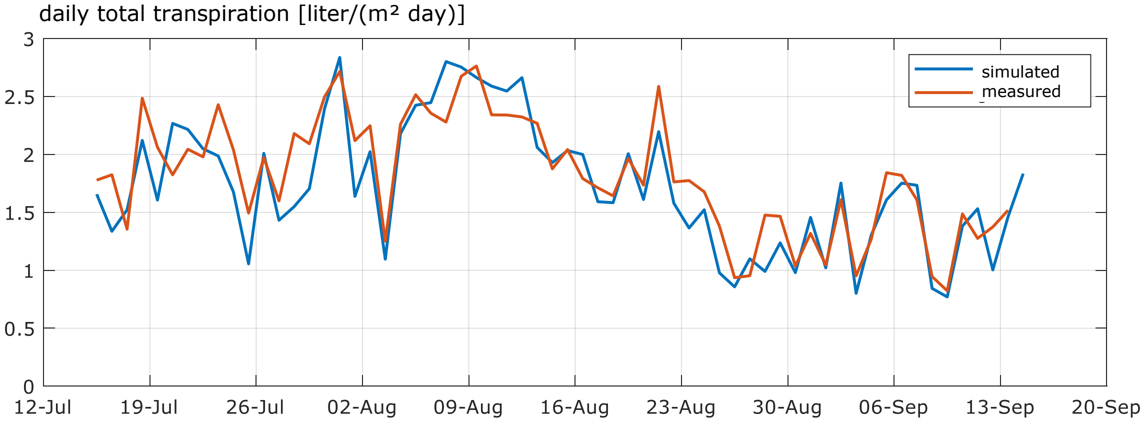

Figure 24 *Calculated and measured crop evaporation of Gerbera per day. The measured evaporation is derived from the difference between irrigation and drain minus the water intake for crop growth.*

As with tomato and cucumber, the calculated evaporation keeps pace with the measured evaporation. To make the calculated evaporation comparable, notably higher stomatal resistances were used for the Gerbera than for the tomato and cucumber.
The minimum stomatal resistance, i.e. the resistance that the crop handles in light-rich conditions, is 1500 $s \cdot m^{-1}$ and the maximum resistance, the Value at night, is 2000 $s \cdot m^{-1}$. Given the small difference between these two values, the value of the parameter that determines the transition from one resistance to the other (the light intensity at which 90% of the difference between the day and night Value is realized) is hardly relevant. Moreover, research by Garcia et al. indicates that a well-functioning Gerbera crop enlarges the stomatal opening even before it gets exposed to light due to a circadian rhythm. Circadian rhythms are not part of the simulation model, but by setting the parameter SWRfor90percentStomatalOpening to 50 μmol/(m² s), the model calculates early in the morning with the day-value for the stomatal resistance.
From the fact that the values proposed for the minimum and maximum stomatal resistance are also very round numbers, it can be concluded that the model used is assumed to be no more than a good approximation of reality.

A real life growing crop has temporal and seasonal variations, periods with thick leaves and thinner leaves, variations in the quality of the root system and possibly a whole host of other factors that influence evaporation. An automated procedure that optimizes the three Values that are adjusted per crop in such a way that measured and simulated evaporation become even closer to each other will yield a better match between measured and calculated evaporation figures with much fewer round numbers. This suggests a very precise determination, but negates the nature of the stomata model applied, which is not more than an approximation of the process of opening and closing the stomata.

2.2.4 Simulated and measured daily transpiration in cut-Anthurium

Where Gerbera is already quite a different crop compared to the vegetable crops, cut Anthurium can hardly be compared with the other crops. Cut Anthurium is a very slow growing crop (average 1.5 flowers per m² per week), and has a greasy leaf with few stomata. Moreover, the Anthurium is known to close its stomata during the day when there is a lot of light. And 'a lot of light' is soon the case with the cut Anthurium. As can be seen in the graph below, there is heavy shade screening

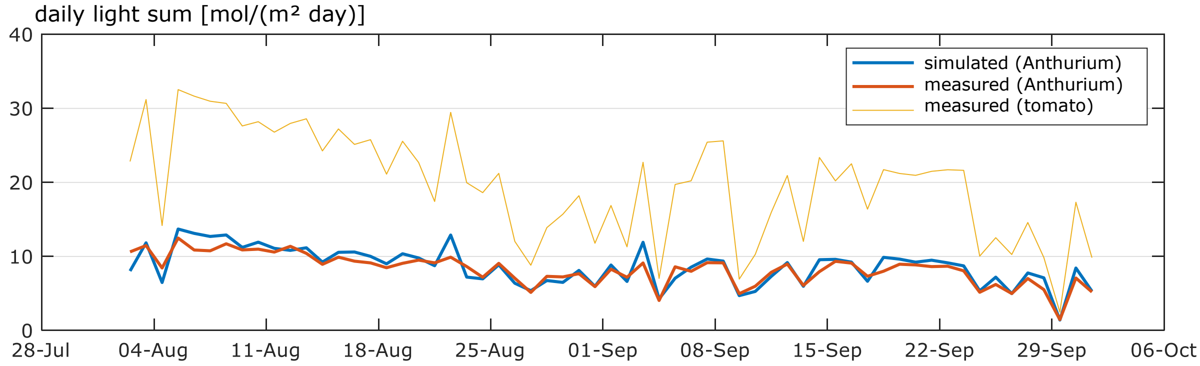

Figure 25 *Daily light integral in the two (late) summer months in the cultivation of cut-Anthurium, used fort he verification of crop transpiration and temperature. As a comparison also the DLI of a tomato cultivation in the same period is shown.*

By starting to deploy screens with a high shading factor at radiation levels above 250 W/m² global radiation, the light sum in an Anthurium greenhouse is kept around 10 mol/(m² day) during the summer period. The maximum radiation intensity in a cut Anthurium greenhouse generally does not exceed 200 µmol/(m² s), barely exceeds 300 µmol/(m² s) and almost never exceeds 400 µmol/(m² s).

The 24-hour temperature is actually significantly higher than in tomato cultivation. This can be seen clearly in the graph in figure 26.

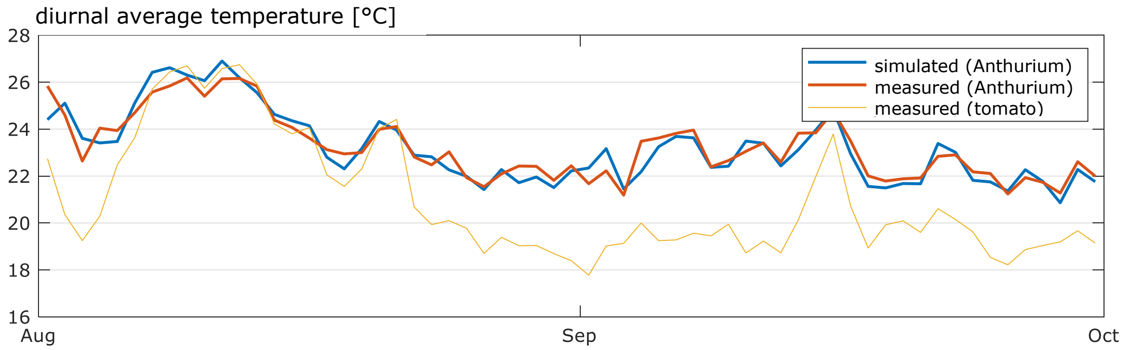

Figure 26 *Diurnal average temperature in the late summer cultivation of cut-Anthurium, used for the verification of crop transpiration and temperature. As a comparison the average temperature in a tomato crop in the same period is shown as well.*

In mid-August, the temperatures in the tomato and Anthurium crops were the same because the outside conditions were such that lower temperatures in the tomato were not possible. Outside of this exceptional period, it can easily be an average of 2-3 °C warmer in an Anthurium greenhouse than in a tomato crop.
The above two graphs show that the calculated 24-hour average temperature and light conditions in the simulation model correspond well with the measured values in the greenhouse.

The greenhouse in which the cut Anthurium was grown also had no weighing system. As a result, no analysis can be made of the hourly pattern in crop evaporation, but only of the evaporation per day. Here too, supply minus drain gives the water uptake of the crop, which is not equal to the crop evaporation. However, the crop growth of cut Anthurium is so small (about 20 grams per m² per day, less than 2% of the water intake) that it is practically negligible. However, the cut Anthurium shows a lot of guttation. Crop specialists estimate this at around 100 grams per m² per day. This is around 10% of the daily water intake and therefore a not negligible factor. Water

released by the plant is a water loss, but not by evaporation and therefore does not extract latent heat from the leaf. Guttation is also not included in the simulation model.
However, for the comparison between the daily measured and calculated water dose, the guttation must be subtracted from the measured water dose.
Anthurium cultivation also has a steady growth of leaves, which are pruned back at an interval of 3 weeks in the summer. In the simulations it has been assumed that the LAI always increases from 3.5 to 4.5 over a period of 4 weeks and that it is then pruned back to 3.5.
With all these assumptions the graph below is obtained.

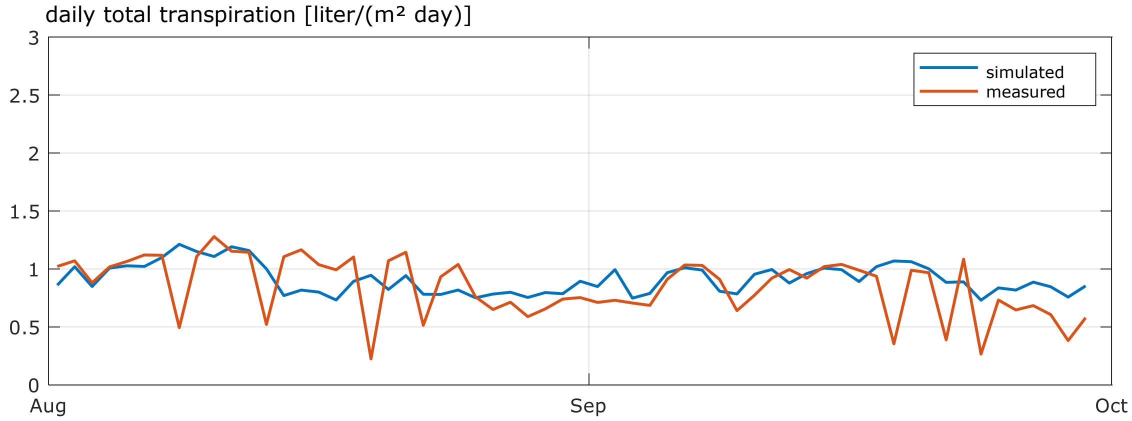

Figure 27 *Measured and computed daily transpiration of cut-Anthurium. The measured data are obtained from subtracting the drain from the irrigation amount and assuming that the crop has 100 cc guttation per m² per day.*

The evaporation is calculated fairly well and is very low compared to the 3 to 5 liters per day measured (and calculated) during this period in the typical vegetable crops. This is of course largely due to the much lower light sum in the greenhouse, but also due to the much higher stomatal resistance used for the Anthurium.
And especially during the day. Anthurium is a CAM plant, which means that CO_2 absorption mainly takes place at night. In the model, Anthurium therefore has a lower stomatal resistance at night than during the day. To get both the calculated daily evapotranspiration and the leaf temperature (see next section) in agreement with measurements, a 6000 s m^{-1} stomata resistance during the day and 400 s m^{-1} at night was used. The transition from day to night value is set around a radiation intensity of 150 μmol/(m² s).

2.3 Crop temperature

When the light absorption is realistically calculated (§ 2.1) and the evaporation agrees with the observations (§ 2.2), the latent heat transfer is known. Then, in the energy balance only one term remains, the sensible heat. During the day, the crop is usually warmer than its surroundings and will therefore give off sensible heat. At night, the crop is usually colder than the environment (especially in the top of the crop) and will therefore absorb sensible heat from the environment. As shown in figure 4, sensible heat is the sum of radiative transfer and convective heat transfer. The model calculates the different types of heat transfer depending on physical parameters. To check this part of the model, the match between the calculated and measured crop temperatures can be examined. With regard to crop absorption and evaporation, it has been shown in previous chapters that these are in good agreement with measurements, and if the calculated crop temperature is now also in accordance with measurements, it can be said that the simulation model in combination with the set parameters has a good representation of the physical processes in the greenhouse.
This chapter first discusses the infrared camera used and the interpretation of the images it supplies. Then the results in the four crops are discussed.

2.3.1 Measurement of crop temperature

The temperature measurements in the four crops were made with a thermal camera (Flir, type A655sc) above the crop. The camera took an image at every 15 minutes.

Figure 28 *Imaging thermal camera. On the left when used in a short-term measurement, on the right built into a housing that protects the camera from overheating by the sun. In this project, the set-up shown in the right image has always been mounted above the 4 crops during a number of summer days.*

There are always different leaves in the image of the camera. In general, and especially on sunny days, it is then clearly visible that a wide range of temperatures can be observed in the camera image. Figure 29 shows one of the images captured with the IR camera. The camera does not capture images in the visible light spectrum. The user must therefore know exactly what the camera is looking at, but in this case a cucumber crop can clearly be distinguished.

Where an Infrared temperature meter gives one vale as a measurement, the image of an IR camera represents as many temperature measurements as there are pixels. In the case of the A655sc, there are more than 300,000 (namely 640 x 480). The average Value of all those pixels was 26.5 °C in the case of the photo shown. This would therefore be the Value that an IR thermometer would give if it were aimed at the crop at the same angle. At the time this photo was taken (June 17, 2020, 3:00 PM), the greenhouse air temperature was 28 °C according to the measuring box.

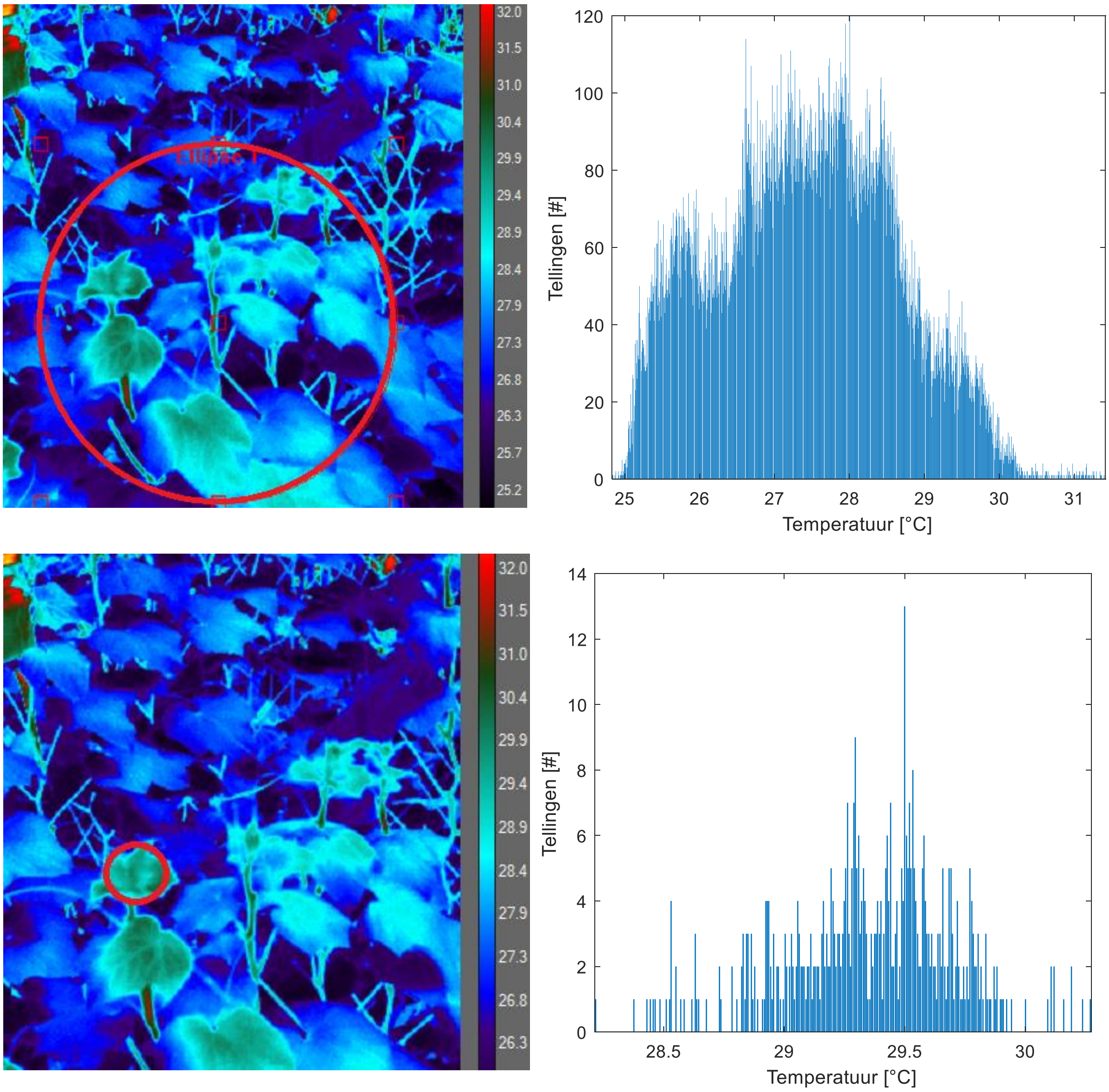

Figure 29 *Result of an infrared image of a cucumber crop in full sun. The average temperature of the entire image is 26.5 °C. The distribution of temperatures in the large circle (top image) is shown in the histogram at the top right. The temperatures in that image range from 25 to 30.5 °C and have an average temperature of 27.8 °C. The even smaller cut-out in the bottom photo concerns an upper leaf and the temperatures of this upper leaf vary from 29 to 29.8 °C, averaging 29.5 °C.*
The greenhouse air temperature measured on the measuring box at the time of this photo was 28 °C and the radiation intensity at crop level was 1020 µmol/(m² s) and the humidity in the greenhouse was 63%.

The photo in figure 29 shows that despite the high radiation load, the average temperature observed by an infrared camera is below the greenhouse air temperature measured on the measuring box. The figure also shows that the low observed temperature is certainly also related to the temperature of the non-crop surfaces. The average crop temperature is slightly below the greenhouse air temperature and if we specifically look at the upper leaves, we see a temperature that is 1.5 °C above the greenhouse air temperature.

In the following paragraphs, the temperature calculated for the top of the crop of the four crops is compared with the temperatures observed by the infrared camera. For these temperatures recorded by the IR camera, the images from the IR camera were manually assessed, giving time series with a granularity of a quarter of an hour. The value in the time series was always the camera determined average of two small circles placed over the leaves at the top of the crop (as shown in the bottom photo of Figure 29).
All observations were made in the summer period of 2020, with the camera hanging in a greenhouse for a few days. During the period that the camera was in a greenhouse, days with a high radiation intensity were used because the initial overestimation of the crop temperature under high sun exposure was the reason for this project.

2.3.2 Top of crop temperature in tomato

To compare the measured and calculated temperature of the top leaves in the tomato crop, the IR camera was placed from 16 to 21 September in compartment 6.08 of the test facility in Bleiswijk. The 16th was a less sunny day (1100 J/cm²) but the three following days were pretty sunny with maximum light intensities of 650 W/m². The daily light sum on these days was 1700 J/cm².
Because only the temperature <u>difference</u> between the leaf and the greenhouse air says something about the accuracy with which the energy balance over the leaf is calculated, the greenhouse air temperature has been subtracted from the leaf temperature for both the measurements and the model simulations.
The graph below shows the measured and simulated temperature difference for the upper leaves for these 4 days.

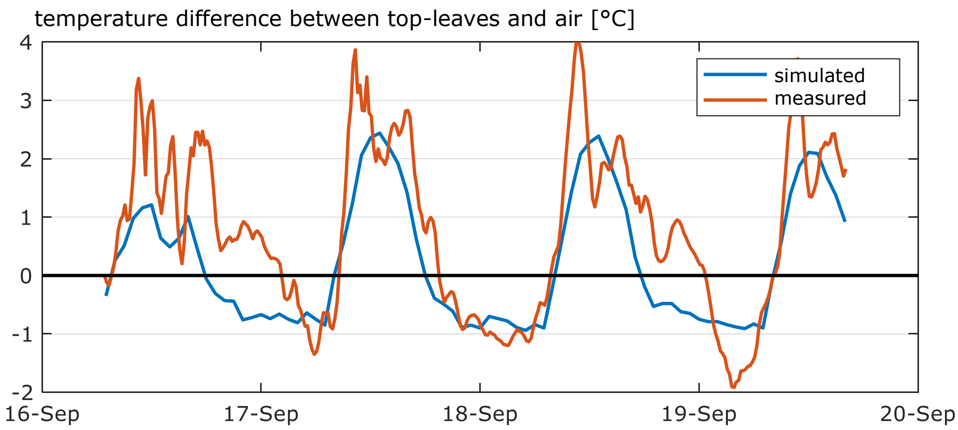

Figure 30 *Measured and calculated temperature difference for the upper leaves in a tomato crop.*

The comparison shows that the calculated difference between leaf temperature and greenhouse air temperature shows a pattern that corresponds to the measured differences. The measurements show larger outliers, both upwards and downwards, but the lines match in terms of trend. The much less smooth course in the measured temperature differences compared to the calculated temperature differences is due to the fact that a point measurement on an arbitrary part of the greenhouse is always influenced by all kinds of local effects (whether or not reflections of sunlight give additional radiation on a specific part, leaf angles that happen to be temporarily more or less perpendicular to the sun, chaotic airflows under the wide-open windows (summer conditions). The simulation model averages out such short-term local effects because it calculates for every moment of the day with the average light transmission of the greenhouse roof, the average orientation of leaves in relation to the sun and the average air exchange through the windows.

The calculated temperature of the upper leaves shown in Figure 30 is therefore assessed against the general trend and therefore qualified as realistic.

This means that the set of model parameters determined for a tomato crop is considered sufficient to be used in simulation calculations. The applied set of parameters is:

Table 2.4

Applied crop parameters for the tomato crop model.

Modelparameter	Value
Extinction coefficient for long wave radiation	0.84
Emission coefficient for long wave radiation	0.85
Reflection coefficient for short wave radiation	0.08 for PAR-light, 0.27 for NIR
Extinction coefficient for diffuse short wave radiation	0.85 for PAR, 0.7 for NIR
Extinction coefficient for direct short wave radiation	0.90 for PAR, 0.75 for NIR
Maximum stomatal resistance (night time)	1600 $s \cdot m^{-1}$
Minimal stomatal resistance (day time)	100 $s \cdot m^{-1}$
Light intensity for a 90% transition from night to day value	120 μmol/(m^2 s) (measured at top)
Characteristic dimension of leaves	7 cm

The model also clearly shows the difference between the crop temperature during the day and the crop temperature at night. During the day, the crop is warmer than the greenhouse air because only the latent heat release is not sufficient to extract all the supplied energy from the sun. At night, the evaporation extracts energy from the leaf, which can only be supplied when the leaf is colder than its surroundings. The figure below shows the energy balances for the day and night situation in a schematic manner. The balance for the day situation is a copy of figure 4 shown earlier.

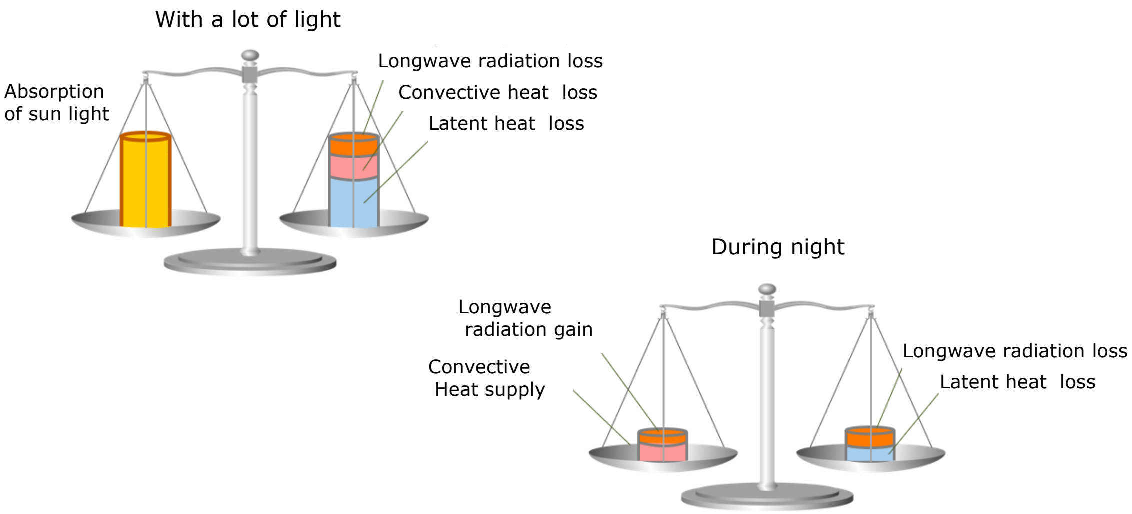

Figure 31 *Schematic representation of the energy balance of leaves during day time and during night time.*

In an equilibrium situation, which is easily reached with leaves of a crop given the limited heat capacity of leaves, the input of energy is equal to the output. Please note that the leaves both receive and lose long-wave radiation energy at night. The upper leaves in particular can lose a relatively large amount of radiant energy when the greenhouse roof is cold and there is no screen. Radiation gain comes from lower-lying leaves that are warmer, or from heating pipes. At the beginning of the night, the floor surface that is still warm from the previous day will also transfer radiant heat to the crop.

Just like during the day, the combination of all those energy exchange processes determines the equilibrium temperature at which the leaf ends up.

2.3.3 Top of crop temperature in cucumber

For the comparison of the measured and calculated temperature of the upper leaves in the cucumber crop, the IR camera shown in figure 28 was placed in the Winterlight Greenhouse of the IDC in Bleiswijk in the first week of May 2020. This was a very sunny period with about 2500 J/m² of radiation daily. The maximum radiation intensity during this period was between 800 and 900 W/m². This is considerably higher than the 650 W/m² to which the tomato crop discussed in the previous section was exposed. The simulation model therefore comes with a significantly higher excess temperature of the upper leaves compared to the greenhouse air temperature. However, the calculated temperature difference is equally higher so still computed excess temperature is well in line with the temperature difference as determined by the IR camera for the upper leaves.
Also striking is the considerably lower temperature of the upper leaves during the night. The larger difference (1 °C or more) is because during this period the screen was not closed at night in order to control the 24-hour temperature.

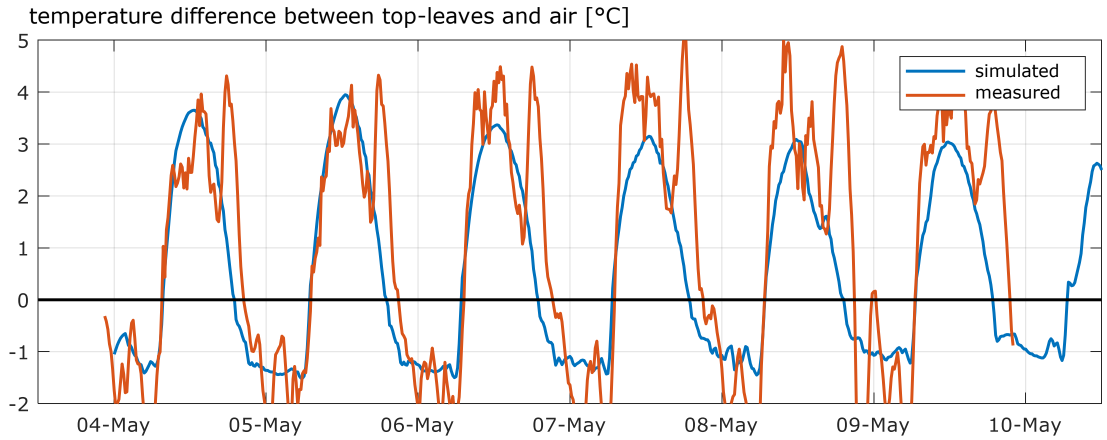

Figure 32 *Measured and calculated temperature difference for the upper leaves in a cucumber crop.*

Again, we see a much larger fluctuation in the measured excess temperature than in the calculated excess temperature. Of course, random local differences also play a role here. The parameters for the energy balance around the leaf used by the simulation model in the calculation of the above result are shown in table 2.5

Table 2.5
Applied crop parameters for the cucumber crop model.

Modelparameter	Value
Extinction coefficient for long wave radiation	0.84
Emission coefficient for long wave radiation	0.8
Reflection coefficient for short wave radiation	0.05 for PAR-light, 0.35 for NIR
Extinction coefficient for diffuse short wave radiation	0.80 for PAR, 0.6 for NIR
Extinction coefficient for direct short wave radiation	0.90 for PAR, 0.65 for NIR
Maximum stomatal resistance (night time)	1600 $s \cdot m^{-1}$
Minimal stomatal resistance (day time)	250 $s \cdot m^{-1}$
Light intensity for a 90% transition from night to day value	100 µmol/(m² s) (measured at top)
Characteristic dimension of leaves	20 cm

If this Table is compared with that of the tomato, the lower reflection and the stronger extinction of short-wave light are the first things that stand out. These parameters ensure the higher absorption of sunlight discussed in section 2.1. The stomatal resistance that is maintained at night is equal to that of the tomato, but during the day a somewhat larger stomatal resistance is used for cucumber. This was necessary to bring the calculated evaporation in accordance with the measured evaporation (Section 2.1.2). The characteristic size of the leaves shows that this is set to a much larger value in cucumber than in tomato (in accordance with the actual situation of the crop) and larger leaves in the model lead to a reduced convective exchange, and therefore also a somewhat larger difference between leaf temperature and greenhouse air temperature. The model does take into account that the leaves in the upper leaf layer are on average half the size of the fully grown leaves, but it nevertheless remains that a cucumber leaf has a somewhat lower convective heat and moisture exchange than the much more fine-meshed tomato crop. The effect of this is clearly visible when the simulation model is used to calculate what temperature of the upper leaves would have had if, in May 2020, not a cucumber crop, but a fully grown tomato crop had been growing in the Winterlight greenhouse.

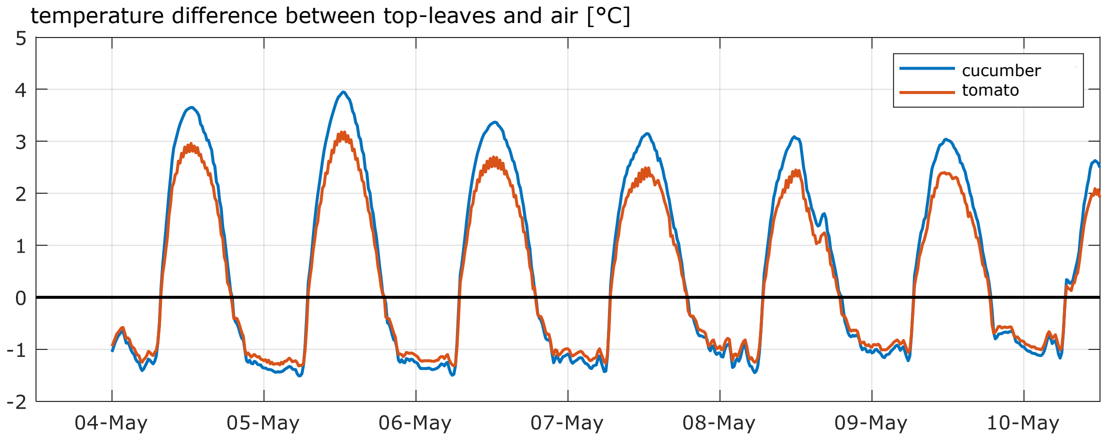

Figure 33 *Calculated excess temperature of the upper leaves in a cucumber crop (a copy from Figure 32) and the upper leaves of a tomato crop in case it wolud have been that crop grown in this first week of May 2020.*

For this calculation, all settings, including the LAI (3) for which the calculations were made, have been kept the same. It is therefore only the leaf size that causes less cooling of the leaf at night. During the day, the differences are caused by the combination of the different light absorption, leaf size and different stomata resistance.

2.3.4 Top of crop temperature in Gerbera

In addition to measurements in the two vegetable crops, the IR camera has also been used to record the temperature of the upper leaves in Gerbera cultivation, as shown in the earlier figure 28. Again, when calculating the energy balance around the leaves, it is best to look at the difference between leaf temperature and greenhouse air temperature as the relevant parameter to obseve. The other components that play a role (light absorption and evaporation) have already been checked in the other parts of this study, so that only the temperature at which the energy balance finds its equilibrium point in relation to the environment is the missing verification. For the Gerbera, the results of this verification are shown below.

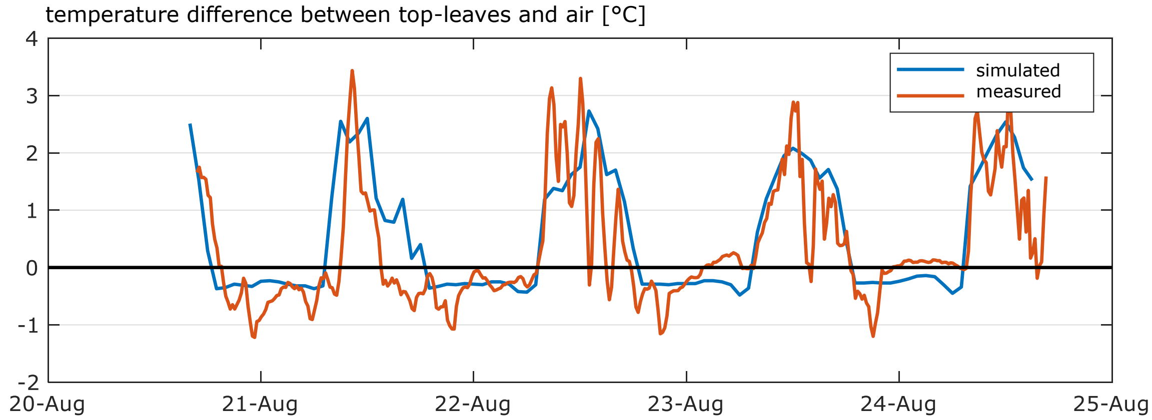

Figure 34 *Measured and simulated temperature difference for the upper leaves in a Gerbera crop.*

In the period shown, August 21 was a sunny day, with a maximum radiation intensity of 800 W/m². Because of that radiation intensity, the shade screen closed halfway through the day, which is reflected in the sudden drop in temperature of the upper leaves on that day. The excess temperature suddenly drops from 2.5 °C to 1 °C above the greenhouse air temperature. The measurements also show a decrease, but a much stronger decrease than what is calculated by the model. Even to below the greenhouse air temperature (a negative excess temperature), which is judged to deviate from all other measurement results obtained in this project in such a way that not too much attention is paid to it.

The other three days were days with varying clouds and a maximum radiation intensity of around 400 W/m². On those days, the observed excess temperature and the calculated excess temperature correspond to an acceptable level.

At night, both the measured and the calculated excess temperature of the upper leaves in the Gerbera crop are close to 0, which is caused by the intensive use of screens in this energy-efficient Gerbera cultivation (cultivation in compartment 2 of the fossil-free greenhouse2030 of the test facility in Bleiswijk).

In terms of crop structure, a gerbera crop is quite different from high-wire vegetable crops because the flowers clearly protrude above the crop and also show only a small amount of evaporation. With an imaging IR camera, the flower temperature can be recorded quite easily separately. The simulation model can also explicitly calculate the flower temperature by assuming the flowers as loose, poorly evaporating surfaces above the top crop layer. The graph below shows that the model calculates the flower temperature realistically with these assumptions.

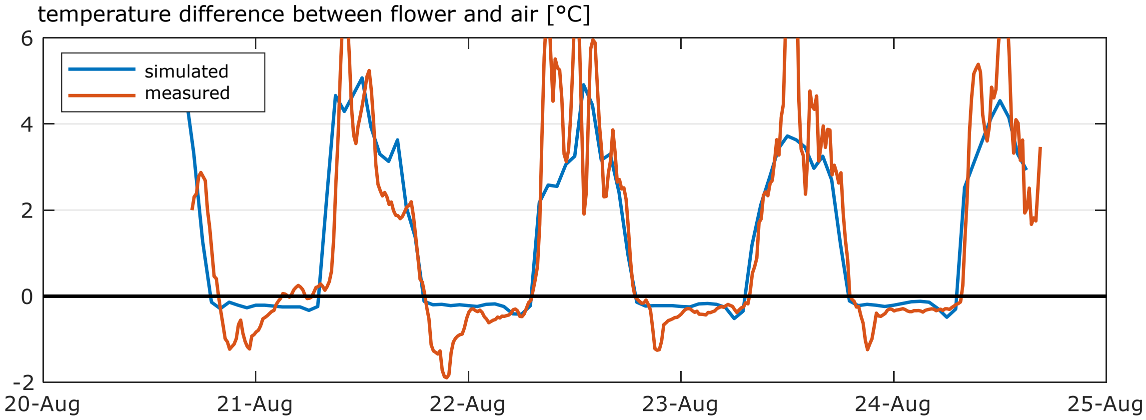

Figure 35 *Measured and calculated excess temperature of the flowers in a Gerbera crop.*

It is clear that the flowers become warmer than the upper leaves during the day and less cold at night. The lower temperature at night is due to the fact that the flowers hardly evaporate and therefore hardly extract any latent heat from the flower surface. For the flowers, it is mainly the radiation loss that causes the lower temperature. With a cultivation strategy that makes intensive use of screens, this radiation loss is very small, which is clearly reflected in the measurements and simulation results.

The parameters related to the energy balance calculations around the leaf used by the simulation model on Gerbera are in table 2.6.

Table 2.6
Applied crop parameters for the Gerbera crop model.

Modelparameter	Value
Extinction coefficient for long wave radiation	0.84
Emission coefficient for long wave radiation	0.85
Reflection coefficient for short wave radiation	0.07 for PAR-light, 0.25 for NIR
Extinction coefficient for diffuse short wave radiation	0.80 for PAR, 0.55 for NIR
Extinction coefficient for direct short wave radiation	0.85 for PAR, 0.70 for NIR
Maximum stomatal resistance (night time)	2000 $s \cdot m^{-1}$
Minimal stomatal resistance (day time)	1500 $s \cdot m^{-1}$
Light intensity for a 90% transition from night to day value	300 µmol/(m^2 s) (measured at top)
Characteristic dimension of leaves	10 cm

When comparing table 2.6 with previous similar tables, it is striking that the stomatal resistance for the Gerbera is set much higher than the values used for the vegetable crops. The measurements of evaporation and excess temperature also showed that the transition from the night to the daytime value for the Gerbera only seems to occur at a higher radiation intensity. Of course, in the search for suitable parameters for the evaporation process, initially the parameters were set close to those for the vegetable crops. In that case, however, the calculated crop evaporation was too high and the excess temperature of the crop was clearly too low.
With the parameterization shown above, the model matched the observed temperature and evaporation behaviour, which is why these values were chosen.

For the calculation of flower temperature, it was assumed that the flowers together account for 1.5% of the total light intercepting surface of the crop and that the evaporation from the flowers takes place via a resistance twice as large as the evaporation from the leaves.
It is also assumed for the Gerbera that the deeper leaves show signs of aging, so that the middle 1/3 of the total leaf package has a 15% reduced evaporation capacity and the bottom 1/3 of the total leaf package has a 30% reduced evaporation capacity .
These reductions in the evaporative capacity of deeper-lying leaves were necessary because otherwise the calculated crop evaporation would be systematically higher than the observed evaporation.

2.3.5 Top of crop temperature in cut-Anthurium

As a final crop, the temperature of the upper leaves and the flower temperature in the cut Anthurium were also examined. Anthurium is very different from the other crops studied in this project. The crop has a greasy leaf, which makes it difficult to evaporate and it is grown in very poor light conditions.
It was previously shown that the model for the anthurium crop calculates the observed reflection and absorption of radiation and the daily crop evaporation with reasonable accuracy. The graph below shows the calculated and measured excess temperature of the upper leaves.

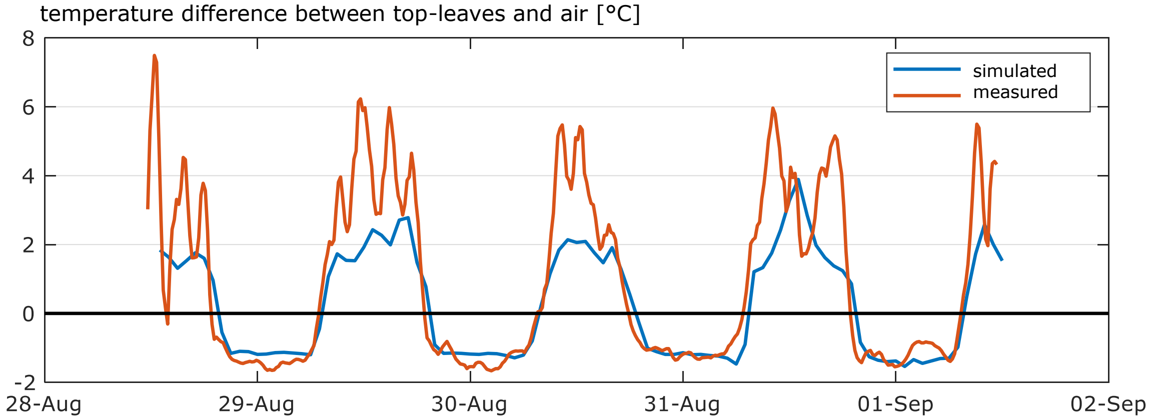

Figure 36 *Measured and calculated temperature excess of the upper leaves in a cut-Anthurium crop.*

Compared to other crops, the temperature in the top of the crop is calculated least accurately in Anthurium cultivation. The model calculates an excess temperature that is roughly comparable to that in gerbera cultivation and tomato cultivation, while the measured crop temperatures are usually higher during the day. Of course, an attempt was made to raise the simulated temperatures even further by reducing the evaporation of the crop. In that case, however, the total evapotranspiration of the crop decreased to such an extent that the agreement between measured and calculated daily evaporation greatly diminished.
The lower temperature of the leaves at night is well described by the model.

The anthurium crop also has a crop structure with flowers that protrude above the crop and from which the model can provide a calculated temperature. This is shown in Figure 36.
It is clear that the flowers become warmer than the upper leaves during the day and slightly less cold at night. The higher temperatures during the day and the lower temperatures at night are caused by the much smaller evaporation through the leaves of the Anthurium that have transformed into flowers than the regular leaves of the crop. These larger temperature differences between day and night are shown both in the measurements and by the model, although the measurements at night more often show even lower temperatures.

The most prominent effects are however shown realistically by the model.

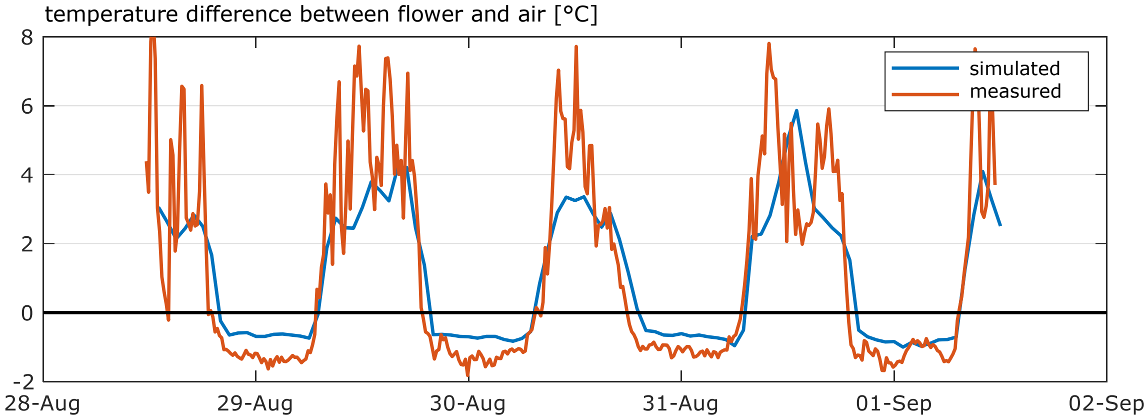

Figure 37 *Measured and calculated temperature excess of the flowers in a cut-Anthurium crop.*

The parameters for the energy balance around the leaf that the simulation model used for the calculations on the Anthurium are in table 2.7

Table 2.7
Applied crop parameters for the Anthurium crop.

Modelparameter	Value
Extinction coefficient for long wave radiation	0.84
Emission coefficient for long wave radiation	0.5
Reflection coefficient for short wave radiation	0.18 for PAR-light, 0.65 for NIR
Extinction coefficient for diffuse short wave radiation	0.80 for PAR, 0.78 for NIR
Extinction coefficient for direct short wave radiation	0.80for PAR, 0.78 for NIR
Maximum stomatal resistance (day time)	6000 $s \cdot m^{-1}$
Minimal stomatal resistance (night time)	400 $s \cdot m^{-1}$
Light intensity for a 90% transition from day to night value	150 µmol/(m^2 s) (measured at top)
Characteristic dimension of leaves	25 cm

When comparing table 2.7 with the previous crop parameter tables, it is clear that the stomatal resistance is high and especially that the high value is used during the day. This parameterizes the fact that the Anthurium is a CAM plant. Unlike most crops, the Anthurium has its stomata mainly closed during the day and open at night.
For the rest, the high reflection coefficient for visible light and especially the very high reflection coefficient for NIR light stand out. This high Value for NIR light was chosen to make the measured and simulated value of the ascending short-wave radiation comparable (see § 2.1). The pyranometer does not distinguish between PAR and NIR, but the high observed reflection of short-wave light must be in the NIR range as it is unlikely that the dark and thick leaves of a cut Anthurium crop will do much more than the 18% reflection of visible light.
It is also assumed for the cut Anthurium that the flowers protruding above the crop together account for 1.5% of the total light-intercepting surface of the crop. For evaporation, it has been assumed that the flowers have only 10% of the evaporative capacity of that of ordinary leaves.

3 Application of the model by Kassim

The Kassim program is a shell around the simulation model that was used in the previous chapter to simulate the crop temperatures and transpiration in a greenhouse. In a real greenhouse there is practically always dynamics. The greenhouse is heating up or cooling down. The humidity is increasing or decreasing. This is largely determined by the outside conditions, which each time produce new combinations of radiation, temperature, humidity and wind speed. In combination with a crop that is a little different every day, it is very difficult to measure the influence of one or two factors on the greenhouse climate. There are always all kinds of interactions involved.
To study the influence of all these factors without being bothered by interactions that obscure the view of the effects, the Kassim program was created. Kassim calculates the equilibrium situation in which a greenhouse would come if the chosen outside conditions remained constant for a long time. It thus provides a view of the energy and mass balance around the crop. Because the crop parameters that were set up in the present project for cucumber, tomato, gerbera and cut Anthurium have now been included in the library with crop properties of the Kassim model, it is possible to look in a very insightful way at how the energy and mass balance for these crops looks like in arbitrary environmental conditions.
As an illustration, a high-summer situation for a tomato greenhouse is shown first.

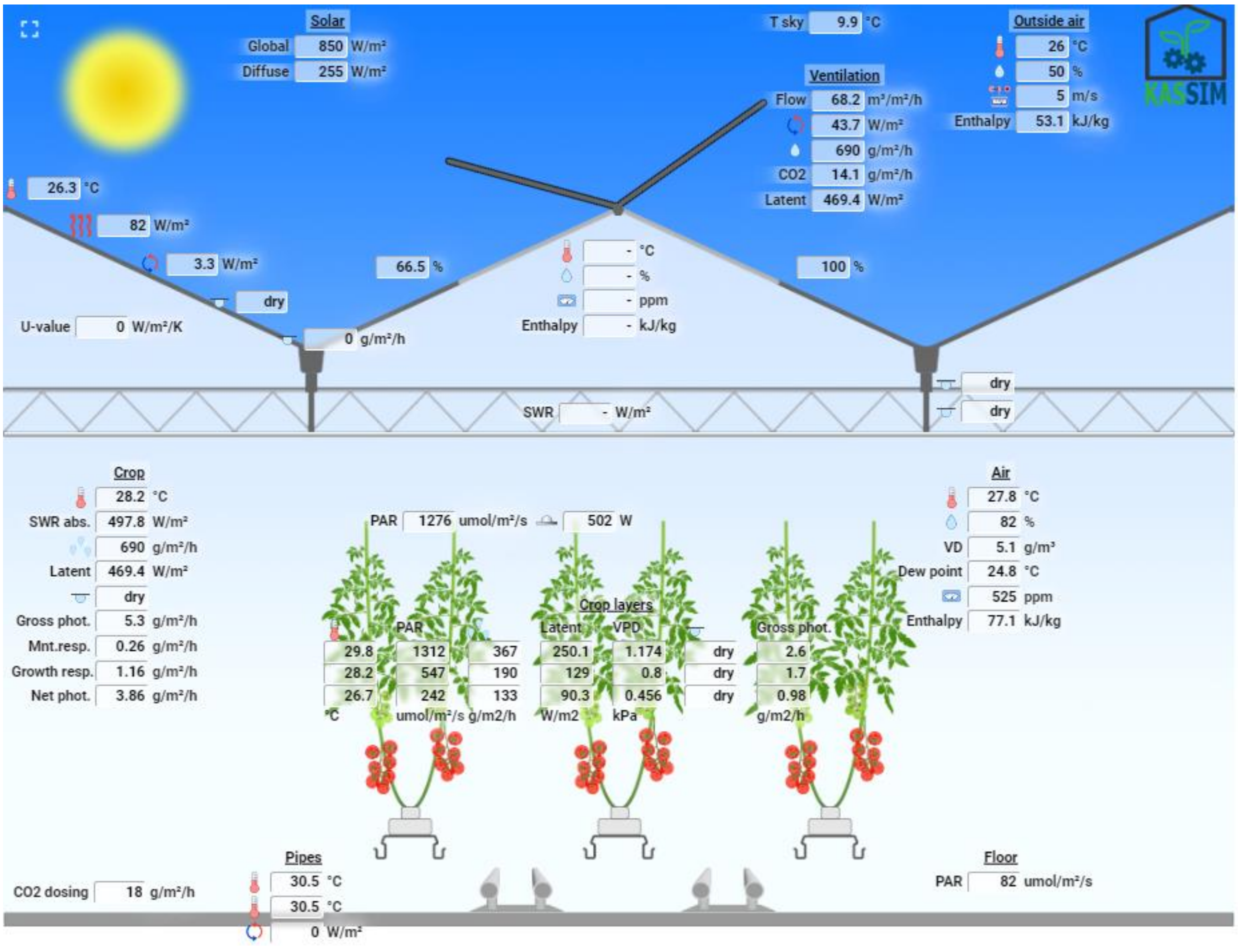

Figure 38 *Result of a Kassim calculation for mid-summer conditions in a tomato crop.*

In terms of solar radiation, for the calculation of the energy balance in figure 38, almost the maximum intensity that can be measured in the Netherlands has been set. On such a bright day, the amount of diffused light in the sunlight is limited. The majority is direct light and due to the favourable angle at which the direct light falls on the greenhouse roof, the transmission is high. The combined transmission of diffuse and direct light results in a PAR intensity of 1276 µmol/(m² s) at crop height. The upper leaves are exposed to even slightly more light (1312 µmol/(m² s)), as there are upward reflections of light in each canopy layer.

The Energy Balance for the entire greenhouse brings the greenhouse air temperature to 27.8 °C, so less than 2 °C above the outside temperature. This only slight increase in temperature is due to the fact that most of the energy is dissipated via evaporation from the crop. The crop evaporating well well (calculated at 690 grams/(m^2 hour)) extracts 469 W/m^2 of latent heat from the greenhouse air and this 469 W/m^2 leaves the greenhouse via ventilation with the wide-open windows. In practice, the tomato crop will not be able to maintain this evaporation rate for a long period of time because it is around the limit of the supply capacity of the root system. Under Dutch conditions, the crop will not have to do this because such high radiation intensities only occur in the middle of the day and the radiation intensity will soon decrease again.
The average crop temperature is 0.4 degree above the greenhouse air temperature, but of course the top crop layer is notably warmer (2 °C above air temperature).
The lowest crop layer is 1.1 °C colder than the greenhouse air, which is caused by the relatively low humidity in the greenhouse. Such a low humidity means that the VPD is still considerable at the bottom of the crop.
There is no heating on such a hot day, but the tube surface does heat up somewhat compared to the greenhouse air temperature because it absorbs sunlight.
The floor surface also absorbs sunlight, but remains just below the greenhouse air temperature because the deeper soil temperature causes the floor temperature to lag behind. For low-light simulations, Kassim maintains a slightly higher floor temperature. Unlike all other temperatures in the greenhouse, which are calculated from an energy balance, the floor temperature is simply assumed to have a value close to the greenhouse air temperature.
In addition to the temperature and humidity balance, Kassim also shows the CO_2 balance. The CO_2 concentration is an equilibrium situation in which the loss through the windows is equal to the dose minus the uptake by the crop. Figure 38 shows that at a concentration of 525 ppm and the calculated air exchange (68.2 m^3/(m^2 hour)) the loss is 14.1 grams per m^2 per hour. This is the difference between the application (18 g/(m^2 hour) = 180 kg/(ha hour)) and the crop intake (3.9 g/(m^2 hour)).
Kassim also shows the net radiation balance of the crop, which is 502 W/m^2 at crop height. A positive number, so there is a large radiation load on the crop.

When the crop is changed from Tomato to Cucumber, we see that the calculated equilibrium greenhouse air temperature is higher (Figure 39). This is mainly because the cucumber has a smaller evaporation capacity than tomato. Also, slightly more heat is coming from the floor because the absorption of sunlight by the floor is somewhat higher due to the smaller light interception in a cucumber crop (assuming an equal LAI).
The lower evaporation capacity of the cucumber crop (the crop evaporates 574 gr/(m² hour)) leads to warmer top leaves leaves (32 °C instead of 29.8 °C for the tomato) and a higher overtemperature (3 °C instead of the 2 °C for tomatoes). This is because the lower transpiration capacity of the top leaves, whereas the energy absorbed is pretty much the same (463 W/m² in the cucumber crop instead of 497 W/m² in the tomato crop).
The higher temperatures in the greenhouse compared to the environment lead to a greater loss of long-wave radiation, as a result of which the net radiation meter shows a lower reading (490 instead of 502 W/m²), despite the fact that the short-wave radiation load from the sun is the same.
The cucumber crop absorbs slightly more CO2 and with almost equal losses the equilibrium CO2 concentration ends up a little lower (505 ppm instead of 525 ppm in the tomato greenhouse).

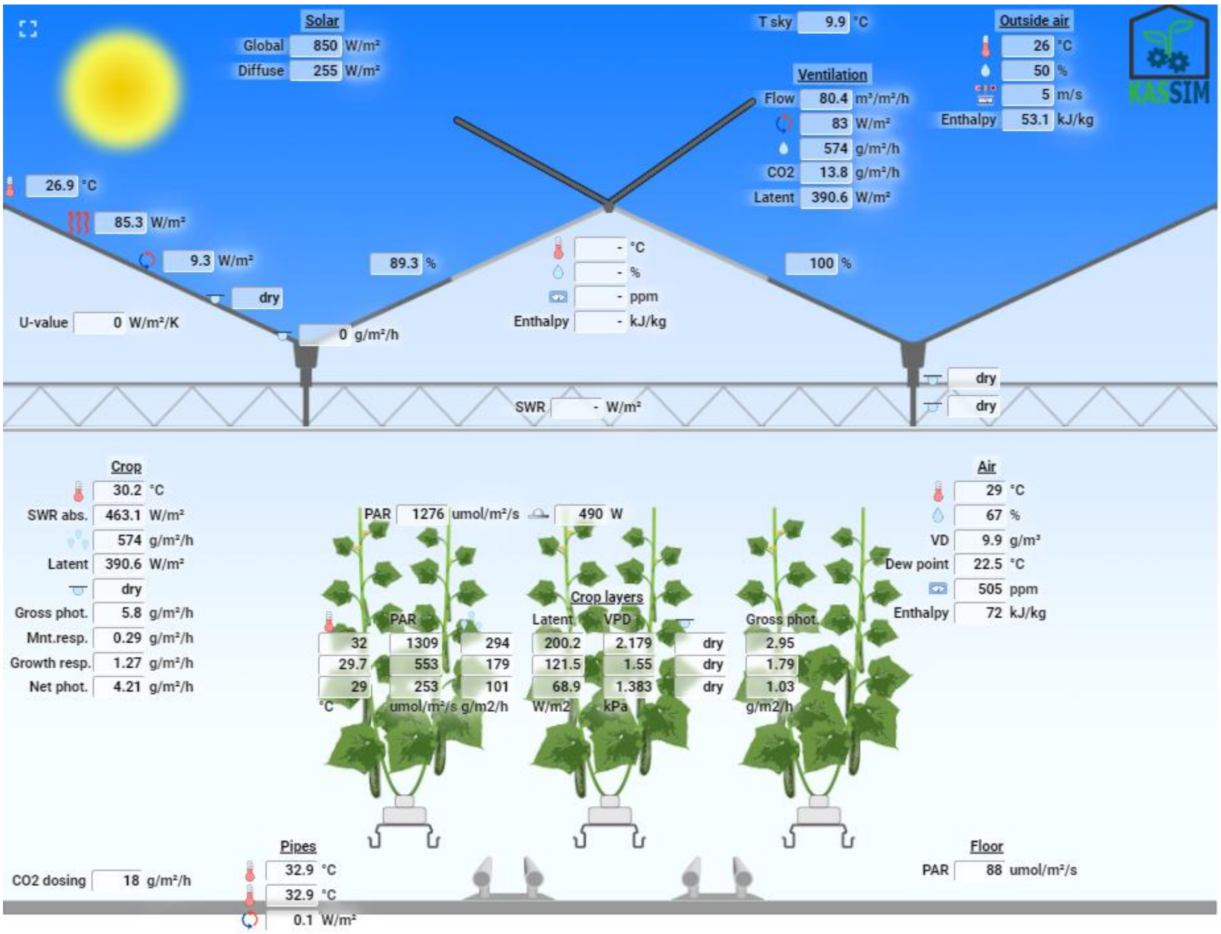

Figure 39 *Result of a Kassim calculation of the same environmental conditions as used for Figure 38, but now with a cucumber crop instead of tomato.*

In the two ornamental crops studied in this project, (heavy) screening will take place under these summer conditions. The figure below shows the calculated situation for a gerbera crop in which the light intensity at crop level has been reduced to 570 μmol/(m²s) by means of a shadow screen.

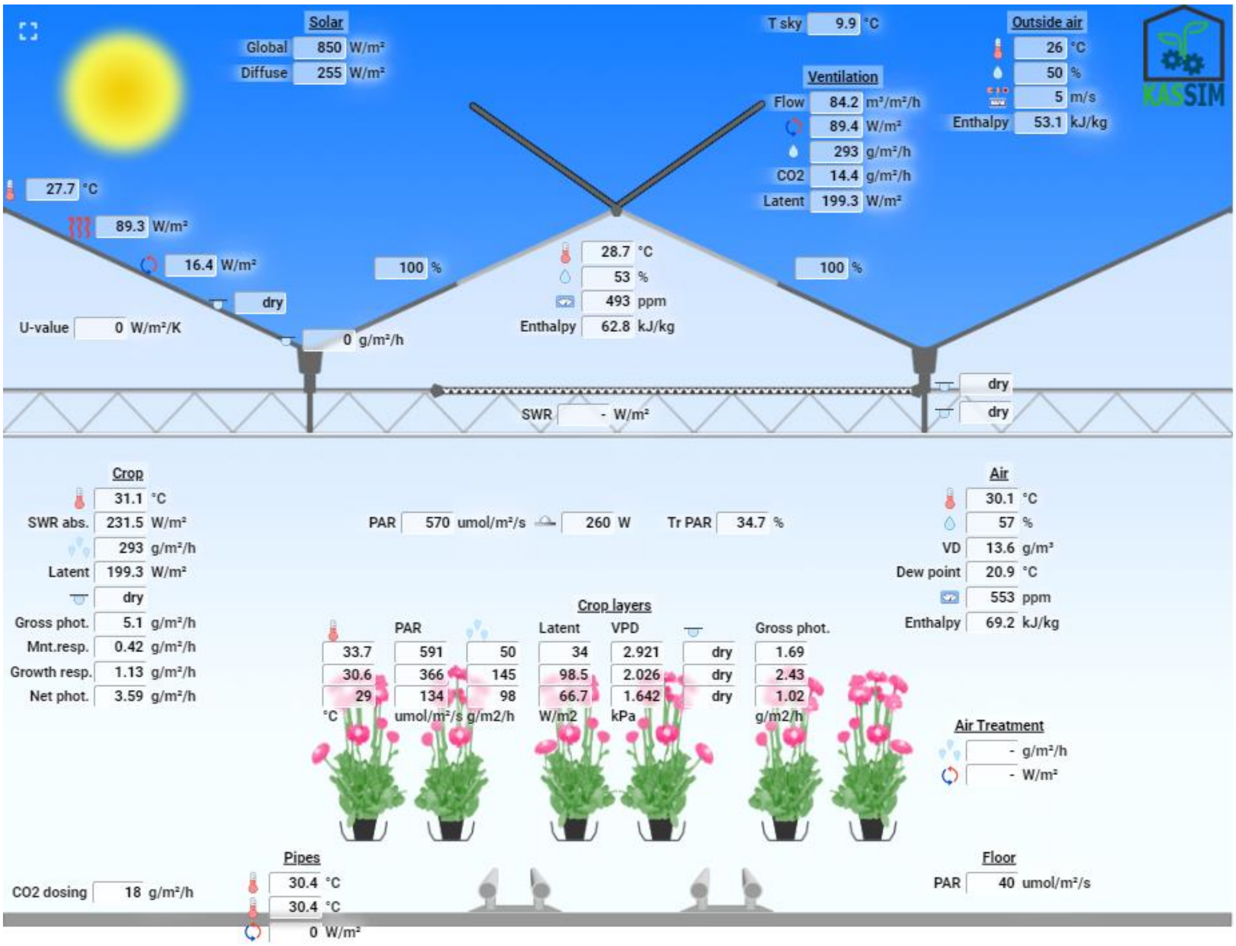

Figure 40 *Result of Kassim calculation for a mid-summer situation in a Gerbera crop. In order to reduce the inside light-intensity, a shade screen is applied, leading to a reduction of light intensity to 570 μmol/(m² s).The LAI of the crop is 4.*

The high outside temperature, the high radiation load and the lower evaporation capacity of the gerbera crop mean that the greenhouse air temperature is even higher than in the cucumber greenhouse.
The transmission of greenhouse + shade screen is 34.7% in this case. for the vegetable greenhouses, the light transmission at crop height was 77%. The light transmission of the partially closed shading screen is therefore 34.7/77 = 45%. The PAR intensity has decreased by the same factor. However, with 260 W/m², the net radiation at crop height is only 53% compared to the net radiation at crop height in a cucumber greenhouse under (unshielded) conditions. The fact that the net radiation has decreased less strongly than the greenhouse transmission is because the warmer surfaces above the crop (warm screen cloth, warm greenhouse roof) which reduce the radiation loss from the crop. The short-wave radiation input is therefore reduced proportionally, but the radiation loss decreases when a screen is used, so that the net radiation decreases less than the light transmission.
The Kassim calculations do not show the flower temperature, by the way.

A striking difference between the situation in the Gerbera greenhouse and the situation in the cucumber greenhouse is also the considerably lower relative humidity (57% instead of 67%). This is due to an added effect of the lower evaporation and the higher air temperature. Given the low RH, the application of misting could lower the greenhouse air temperature. This is shown in Figure 41.
Indeed, with the use of 225 grams of misting per m² per hour, the greenhouse air temperature has decreased to 27.3 °C. A reduction of 2.8 °C. The RH has increased to 81%. The greenhouse air conditions have therefore

become comparable to those of cucumber cultivation, but the lower evaporation capacity of the Gerbera remains undiminished. The overtemperature of the upper leaves remains high at 4.4 °C and is even higher than in Figure 40. Without fogging, the calculated overtemperature was 3.6 °C. The difference is because the misting reduces the vapor pressure difference between leaves and greenhouse air (from 2.9 kPa to 1.8 kPa) and thus reduces the cooling effect of the crop evaporation. Nevertheless, the net effect of misting is that not only the greenhouse air temperature decreases, but also the crop temperature.

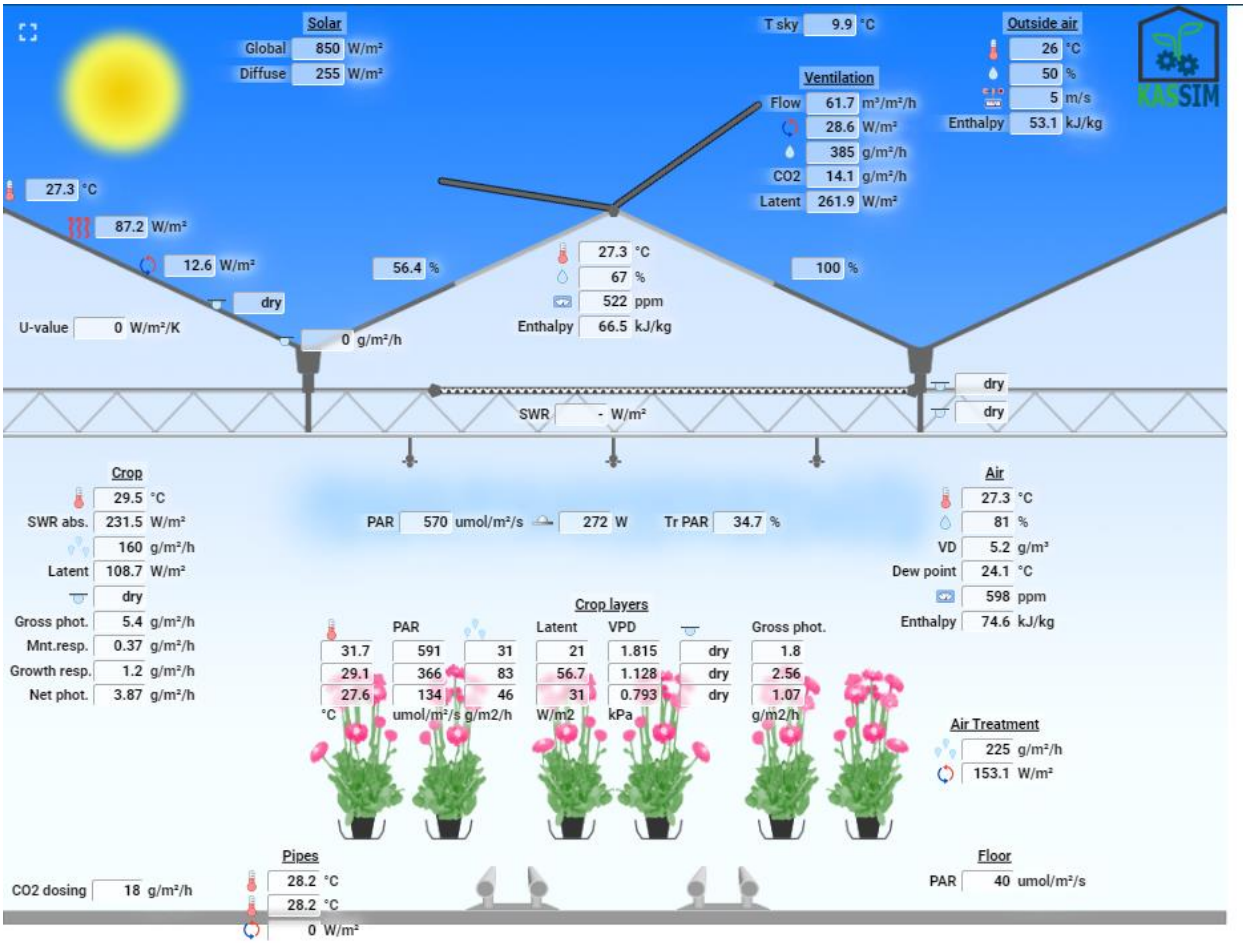

Figure 41 *The Gerbera greenhouse in the same conditions, but with the use of 225 gram misting per m² per hour. Also here, the LAI is 4.*

Finally in the series of results for high-summer conditions, Figures 42 and 43 show the results of two Kassim calculations for the cut Anthurium. The cut Anthurium is screened more than in Gerbera cultivation, which means that the amount of energy absorbed by the crop is lower. However, as also the air exchange through the tighter screen is smaller, the temperature inside the greenhouse is computed to be the same.
The limited evaporation capacity of the Anthurium, especially during the day, in combination with the high temperature ensures a low relative humidity. The evaporation is only 141 gram per m² per hour. Nevertheless, the calculated excess temperature of the top crop layer, at 4.3 °C, is not the highest in the series of calculation results. This is because the radiation load on the crop is small, which is a result of the high shade factor of the screen and because the radiation absorption by the crop is low due to the high reflection in the NIR region. With 101.4 W/m², the total crop absorption is not even half of the crop absorption of the Gerbera and only a 20 to 25% of the absorption of the vegetable crops. Seen in this way, the crop evaporation of 101 grams/(m² hour) is relatively high, which is caused by the large vapor pressure difference between crop and greenhouse air.

Still there is some room for the use of misting in Anthurium cultivation. Figure 43 shows that with the misting of 150 gram/(m² hour) the calculated greenhouse air temperature drops to 26.2 °C. The temperature of the top crop layer drops to 31.5, but, as expected, with 5.3 °C instead of 4.3 °C, the excess temperature is now larger.

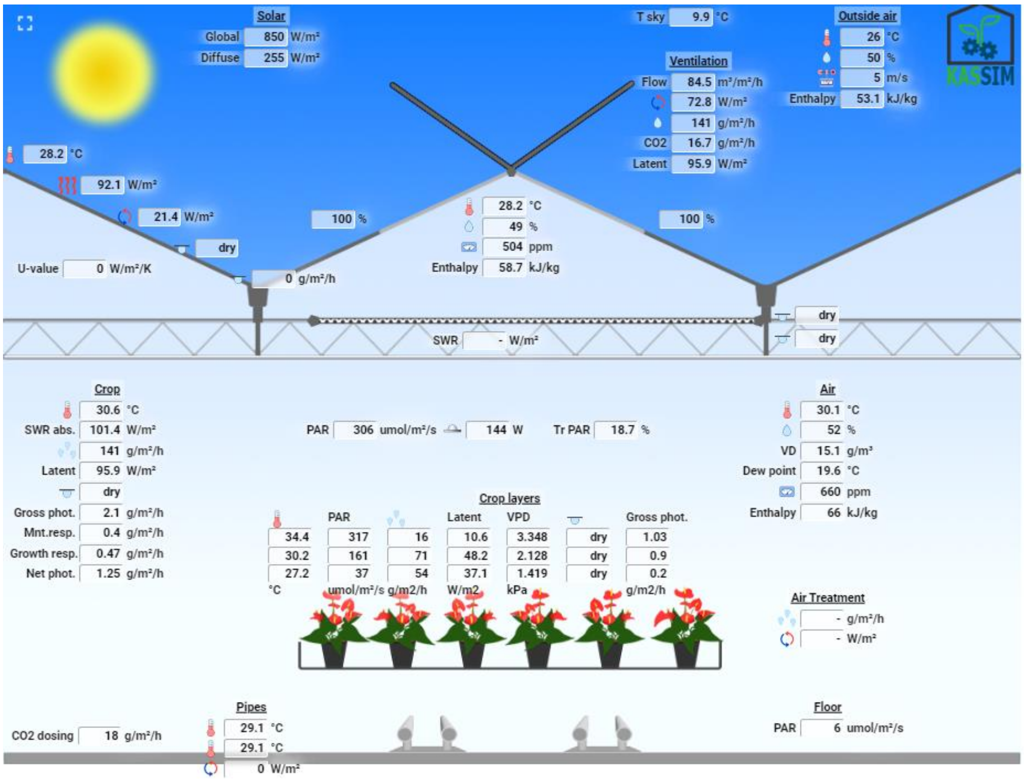

Figure 42 *Result of a Kassim calculation for a mid-summer situation in an Anthurium crop. The graphics show a pot Anthurium, but the parameters, and therefore also the calculation results are set for a cut Anthurium. To lower the light intensity, a heavy shade screen was used, which reduced the light intensity to 306 µmol/(m² s). The LAI of the crop is 4.*

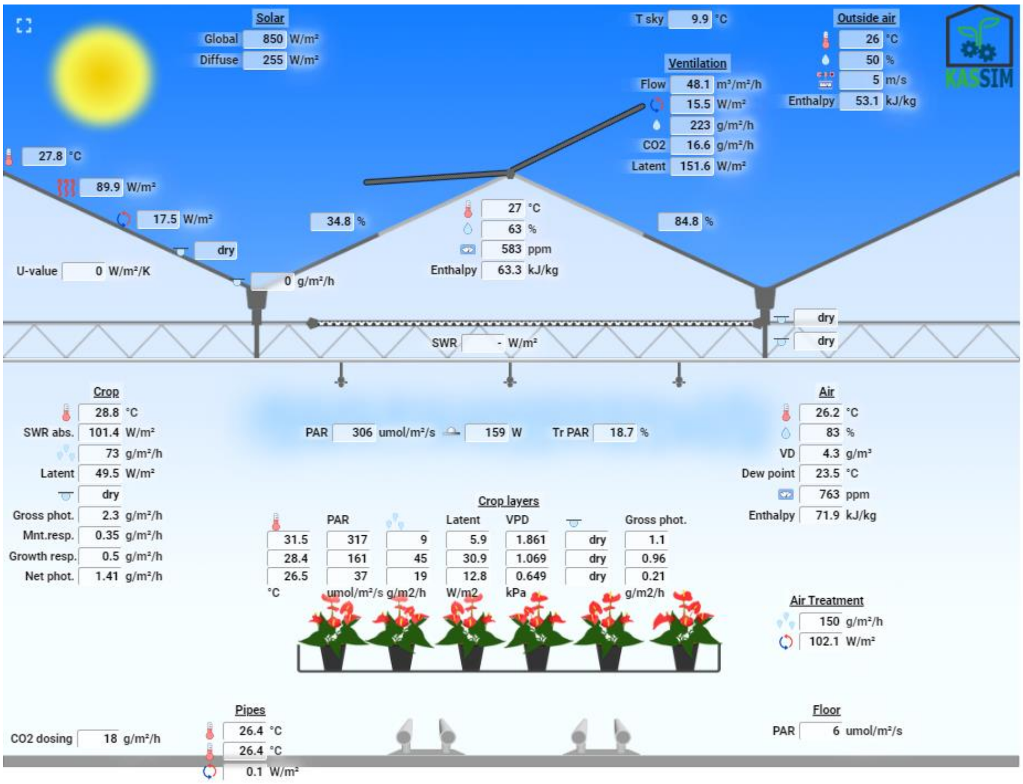

Figure 43 *Result of a Kassim calculation for a mid-summer situation in an Anthurium crop using 150 g/(m² hour) of misting.*

The series of results that Kassim calculates for the high-summer conditions for the 4 crops that have been studied in more detail in this project shows that the re-parameterisation led to the aimed result. The adjustments of the evaporation model, its parameters and the adjustments of the absorption characteristics have ensured that the simulation model calculates realistic values. Both for the dynamic model, the results of which are shown in chapter 2, as for for the derived static Kassim model.
The current model is therefore suitable for use in sunny as well as dark and cold conditions. To illustrate the results in cold and dark conditions, Figure 44 shows the output for a tomato crop during a reasonably cold night (5 °C and a partly cloudy sky, resulting in a sky temperature of -8 °C.

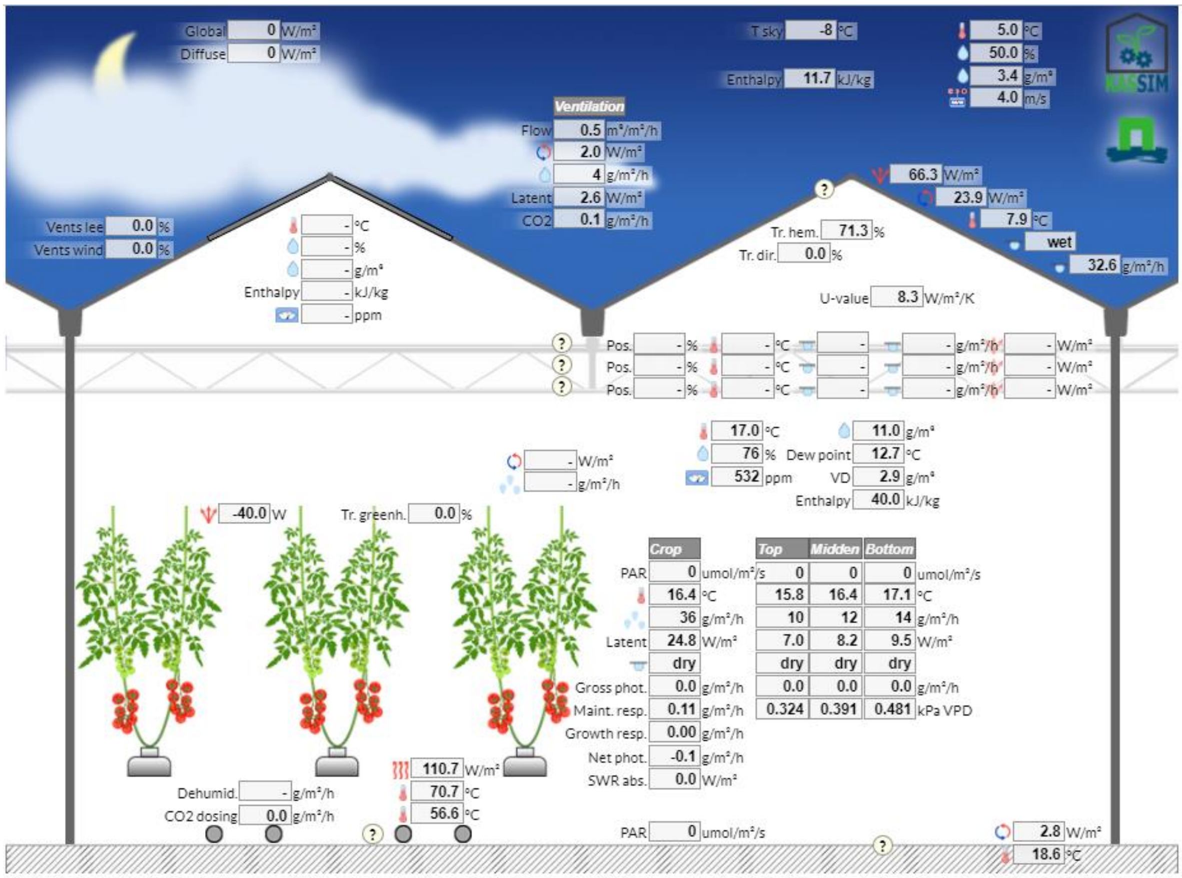

***Figure 44** As an illustration: result of a Kassim calculation for a tomato crop in a greenhouse without a screen during a fairly cold night.*

Because the greenhouse in the case of Figure 44 does not use a screen, the humidity is quite low and a considerable crop evaporation is still calculated (36 g/(m² hour)). As a result, the crop temperature is on average 0.6 °C below the greenhouse air temperature, but the top crop layer is 2.2 °C below the greenhouse air temperature. A considerable heating capacity is required (110.7 W/m²), for which a pipe with a supply temperature of 70.7 °C and a return temperature of 56.6 °C is required (a 51 mm pipe with a circulation speed of 20 minutes is used for the calculations). .
There is no sunlight and the cold greenhouse roof acts as a strong sink for radiative heat, so the simulated net radiation meter shows -40 W/m², meaning a radiative heat loss of 40 W/m² at crop height.
When an energy screen is deployed, the average crop temperature rises, the temperature gradient over the crop becomes smaller, there is less radiation loss and the heating demand decreases. This can be clearly seen in Figure 45 where all model settings are kept the same except for the screen, which is deployed. The crop temperature is now on average 0.3 °C below the greenhouse air temperature, the temperature gradient has decreased from 1.3 °C to 0.7 °C and the net radiation loss at crop height is -15 W/m². The heating power is more than halved.

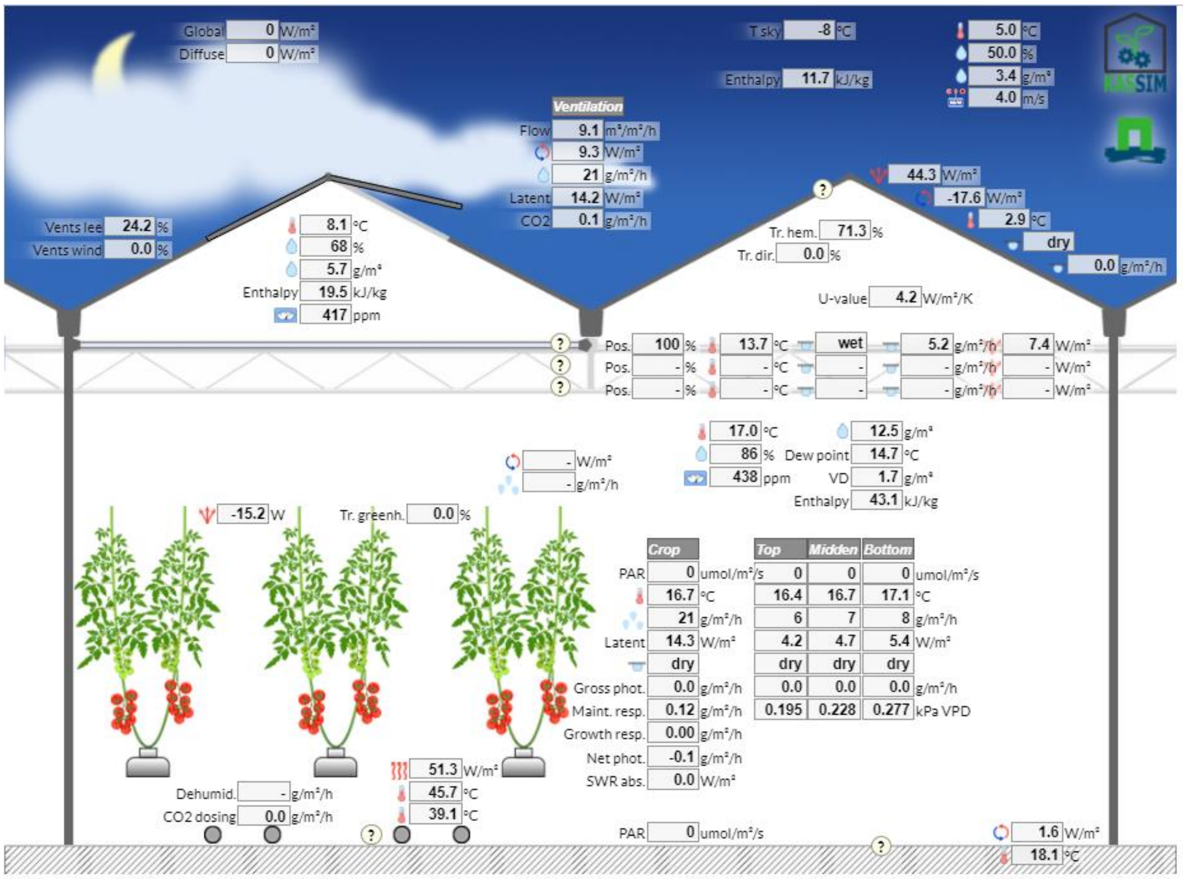

Figure 45 *The same greenhouse and the same environmental conditions as used in the previous figure, but now with a deployed energy screen.*

In addition to the fact that the energy requirement decreases considerably due to the use of a screen, it is also clearly visible that the humidity in the greenhouse increases sharply. The higher humidity lowers the vapor pressure difference between leaves and greenhouse air, which reduces evaporation.

In addition to the direct reduction of the heat demand due to the increased insulation Value, the screen also saves energy through reduced evaporation. In the situation with screen, the crop extracts 14.3 W/m² of latent heat from the greenhouse air, whereas in the situation without screen it extracted 24.8 W/m² of latent heat.

This double effect of a deployed screen occurs especially under very cold conditions. In less cold conditions, where ventilation is needed to remove excess moisture even without a screen, deploying a screen will result in more ventilation above the screen. This effect is already partly visible in Figure 45, where the window has been opened a little to get the RH at the shown 86%. Without that window opening, the humidity would have reached 90%, the crop evaporation would have dropped to 15 grams/(m² hour) and the heating capacity to 40 W/m².

On less cold nights, a screen will therefore not only yield lower savings in absolute terms, but the savings percentage will also be lower.

The Kassim program, which only shows instantaneous effects, calculated from a stationary balance, is therefore mainly intended to show the effect of installations, outside conditions and control actions on the energy and mass balance of the greenhouse + crop. For year-round energy savings calculations, the dynamic version of the model should be used.

In order to accommodate calculations on year round results as well, Wageningen UR has developed other tools as a follow up on this Kassim tool.

4 Conclusions

Greenhouse crops have a relatively small heat capacity (thermal mass) relative to their surface area. The leaf temperature, in particular, therefore changes rapidly with changing environmental conditions. As a result, the crop is always quickly in equilibrium with its environment, which means that the supply of energy and water is almost equal to the ‘outflow’ of heat and vapor. The location of that equilibrium point in terms of crop temperature is determined by physical processes involving energy absorption and heat release. It is therefore a mainly passive process with parameters that are pretty fixed and can be determined physically. The main exception, however, is stomatal resistance. Depending on the growing conditions, and especially depending on the plant species, crops have or get a low or high average resistance. In addition, stomatal resistance varies during the day.
The combination of environmental conditions, the fixed physical crop parameters, such as the absorption coefficient for sunlight and the long wave optical parameters, and the variable stomatal resistance determine the excess temperature of the leaves relative to the environment. At night leaves end up colder than their environment and when there is a lot of (sun)light they are warmer.
The on-line educational tool Kassim has been developed, among other things, to quantify these processes and to provide insight in an easy interpretable way. When Kassim was launched in 2018, the calculated results turned out to be very realistic for winter conditions, but the crop temperature was clearly computed too high for full-summer conditions.
To correct this shortcoming, the present project once again looked in detail at crop temperatures and evaporation processes, with an emphasis on summer conditions.
Reasoning from the energy balance, the starting point for the calculation of crop temperatures is the absorption of sunlight by the crop. This study showed that the crop absorption was not the same for the four crops observed. A fully grown tomato crop absorbs 79% of the amount of sunlight measured just above the crop. The same light absorption was determined for the Gerbera crop, but a Gerbera crop does have a higher LAI (4 instead of 3), so the absorbed energy is divided over a larger leaf surface. Cucumber, having an absorption of 73%, absorbs less than tomato and Gerbera and cut Anthurium absorbs even less, 60%.
After adjustments of the absorption and extinction coefficient for short-wave light in the greenhouse climate simulation model Kaspro, (the model which is used by Kassim to perform the calculations), the simulation model for each of the 4 crops studied in this project came close to the measured light absorption percentages.
In the energy balance calculation, this absorbed light energy is divided over an energy loss in the form of latent heat (evaporation), convective heat and radiation. At night the convective heat exchange is negative, because the leaf is then colder than the greenhouse air.
From these three components, the latent heat loss is relatively easy to determine in the form of the crop's water uptake. After correction for the water used for growth (about 10% of the intake), the amount of evaporated water can be determined and thus the latent heat extraction by the crop. For crops with a weighing gutter this can be done on a narrow time scale (quarterly values), but for most greenhouses there is not a more accurate determination of water uptake than by taking the difference between irrigation and drain.
In §2.2 it is shown that the simulation model parameterized on the measured data shows a realistic daily evaporation. It turned out that one set of parameters per crop could be used to calculate crop evaporation on both sunny and dull days with good accuracy. The results for the simulation of cucumber cultivation, where a weighing gutter was present, show that the calculated evaporation is also correctly calculated throughout the day.
If the calculated and measured radiation absorption and evaporation correspond, then the verification of the crop temperature provides a definite answer about the correctness of the parameters used for the evaporation resistance. After all, if that resistance is assumed to be too great, the crop can evaporate almost the same amount of water, but at a higher leaf temperature. If the evaporation resistance is assumed too small, the leaf temperature during the day will remain closer to the air temperature than measured.
The verification of the simulations on this point (section § 2.3) shows that the parameterization developed in this project indeed leads to realistic overtemperatures (during the day) and undertemperatures (at night). They were in the same range and show a profile comparable to the measured values. It is not likely to be able to use more precise terms than 'range' and 'comparable' because the determination of 'the crop temperature' cannot be done unambiguously. The image of an infrared camera always shows a whole range of temperatures.

The upper leaves are clearly the warmest and the leaves at the bottom of the crop are easily 4 °C colder, but it is hard to say which pixels exactly belong to which leaf layer. The simulation model divides the total leaf mass into three layers and calculates an average temperature for those three layers. The simulation model will therefore not show the extremes that can be seen in infrared images, but must of course remain within the plausible bandwidth.

This project shows that after the adjustments that could be made on the basis of the collected data, the calculated evaporation and crop temperatures correspond well with measurements. As a result, the Kaspro simulation model and its application by Kassim can provide a realistic overview of the energy balance of a greenhouse and the growing crop in a very wide range of outdoor climate parameters, greenhouse equipment and climate control options. To illustrate this, Chapter 3 discusses the key output of Kassim for the four crops under high summer conditions. This clearly shows the influence of crop absorption, the radiation balance, the evaporation and the effect of shadow screens. The CO2 balance is also clearly displayed.
In greenhouses with low evaporating crops and intensive (shade) screen use, it is clear to see that the humidity can drop to very low values. The use of misting then leads to lower greenhouse air and crop temperatures. And to a lower evaporation of the crop.
Although the focus in this project was on crop temperatures under high summer conditions, chapter 3 also discusses the energy balance around greenhouse and crop in a cold winter night. The cold greenhouse roof then causes a lot of condensation and low humidity, which pushes up crop evaporation and thus also the latent heat absorption and energy consumption. In such circumstances, the application of screens leads to a more homogeneous greenhouse climate (lower pipe temperatures, smaller temperature gradient in the crop) and halving of the heat demand.

The examples of the energy balance calculations in chapter 3 are only a small selection of the unlimited number of analyses that can be done with Kassim. This was also possible with its predecessors (Radiation Monitor and earlier versions of Kassim), but the output after the updates on the description of stomatal behaviour and the applied parameters has largely broadened the range of conditions that are simulated realistically.
It provides the users of the model (growers, extension workers, teachers, students) with quantitative insight in the effects of the most important greenhouse climate settings (heating setpoint, ventilation setpoint, misting, screens, illumination, CO2 dosing and venting). With these insights, growers are supported to improve their climate control strategy, leading to a more efficient use of resources for greenhouse horticulture.

To explore the potential of nature to improve the quality of life

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