Temperature integration and process-based humidity control in chrysanthemum

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Abstract

Simulations in the authors’ previous studies have shown that a modified temperature integration regime with a 6-day averaging period and increased set-point flexibility was able to reduce annual energy consumption by up to 9% as compared to a regular temperature integration regime. The commonly applied fixed set-point for relative humidity (RH) of 80–85% strongly reduced the potential for energy saving with this regime. Therefore, a more flexible humidity control regime was developed. Simulations indicated that yearly energy consumption could be reduced by 18% as compared to a fixed set-point of 80% RH. By combining the two regimes (temperature integration and humidity control), it was predicted that the energy saving would be even greater. To test this prediction, the combined regimes were applied in two experiments with cut-flower chrysanthemum crops investigating the effect on plant development and growth. Different temperature bandwidths for temperature integration (±2, ±4, ±6 and ±8 °C) were also compared within the joint regime.

Crop development was only delayed with the ±8 °C temperature bandwidth. The best regime with respect to plant development, growth, quality and energy saving (±6 °C temperature bandwidth) was compared in a spring experiment with a climate regime used in commercial practice. Energy consumption was 23.5% less with the joint regime. No negative consequences of high humidity were observed, but there was a strong increase in the dry weight of all plant organs. Total plant dry weight was 39% higher than in the regular regime. It can be concluded that energy saving and crop yield increase can be achieved simultaneously, although the dynamic temperature control has to be adjusted.

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1 Deceased.
to the chrysanthemum developmental stage. The combined dynamic climate regime forms a promising basis for future climate controllers and is easily extendable to other greenhouse crops.

Keywords: Chrysanthemum grandiflorum; Cut-flower chrysanthemum; Climate regime; Energy saving; Greenhouse climate control

1. Introduction

In The Netherlands, agreements were made to increase energy efficiency in greenhouse horticulture by 50% between 1980 and 2000 and by 65% by 2010 (Van der Knijff et al., 2001). The target for the year 2000, however, was missed by 6% (Bakker et al., 2001). Therefore, more energy must be saved in the future. Modern greenhouses and equipment such as climate computers, energy screens and condensers with heat storage facilities have already contributed an energy saving of 3.7% between 1991 and 2000 (Bakker et al., 2001). New techniques will probably be able to increase energy saving yet further, but if all greenhouses were replaced to the average estimated standard by the year 2010, 14.6% energy would be saved in comparison to 1995 (Bakker, 1999). This alone, however, would not be enough to reach the aimed energy saving and efficiency target. Instead of applying more expensive technical solutions, intelligent energy-efficient control regimes should be applied in combination with modern greenhouse design.

Temperature integration (TI) could be used. TI in its simplest form controls the 24 h average temperature, rather than the instantaneous temperature using fixed set-points for heating and ventilation (Cockshull et al., 1981; Seginer, 1981; Hurd and Graves, 1984; Rijsdijk and Vogelezang, 2000). Because many greenhouse crops are able to integrate temperature over longer periods than 24 h, more energy would be saved if the averaging period was extended over several days (De Koning, 1990; Buwalda et al., 1999a). However, TI in this form could be optimised further (Körner and Challa, 2003b), because at present fast (minutes) and slowly responding (days) plant processes are not considered separately. Controlling greenhouse climate with independent long- and short-term processes has been suggested (Challa and Van Straten, 1993; Van Straten et al., 2000). Processes with a slow response time (e.g. plant development) respond primarily to average temperatures over prolonged periods and processes with a quick response (e.g. photosynthesis) may allow more extreme temperatures to be used over short periods of time without losses in quality and growth (Rietze and Wiebe, 1989; Sato et al., 2000). TI has therefore been refined to a nested short- and long-term integration interval system by Körner and Challa (2003b). A decrease in yearly energy consumption of up to 9% was predicted with tomato compared to regular TI (Körner and Challa, 2003b).

The potential for energy saving with TI is limited by humidity control if the usual fixed set-points are maintained, because it counteracts TI. Vents open at lower temperatures and heating is switched on at higher temperatures than required for the optimal effects of TI. A humidity regime with flexible set-points, e.g. with maximum leaf wetness duration, minimum transpiration and transpiration integral (Hand, 1988; Challa and Van Straten, 1993) has been designed for cut-flower chrysanthemum crops (Körner and Challa, 2003a).
Simulations showed that yearly energy consumption could be reduced by 19% with this humidity regime as compared to a fixed set-point of 80% relative humidity (RH).

When these two climate control principles, modified TI and process-based humidity control were merged, energy use was further reduced (Körner and Challa, 2003c). For three separate 12-week cut-flower chrysanthemum crops with planting dates of 1 January, 1 February or 1 March, simulations indicated 12, 30 or 40% energy saving. In these simulations, an optimal heating/screen combination (Bailey and Seginer, 1989) was not applied. Estimate of energy consumption obtained from simulation studies need confirmation in greenhouse experiments where plant responses can also be taken into account. The aim of the present research therefore was to verify the simulations and evaluate the crop responses with the joint climate regime in greenhouse experiments. In two experiments with cut-flower chrysanthemum crops (spring and autumn), different temperature bandwidths with the modified TI (±2, ±4, ±6 and ±8 °C) were compared using the joint regime and the best of these was compared with a regime with rigid set-points.

2. Materials and methods

2.1. Plants and climate conditions

Two experiments (experiments 1 and 2) were performed in four almost identical greenhouse compartments (12.8 m × 12.0 m) within a multi-span Venlo-type greenhouse at Wageningen University, The Netherlands (latitude 52°N). The four compartments A–D were neighbouring each other in an ascending row from A (west) to D (east). Greenhouse compartments A–C consisted of one outside wall (south) and greenhouse compartment D of two outside (east and south) and two inside walls. The east wall of compartment D was whitened for experiment 2 and had a normal light transmittance in experiment 1.

About 24,000 block-rooted chrysanthemum cuttings ‘Reagan improved’ obtained from a commercial propagator (Fides Goldstock Breeding, Maasland, The Netherlands) were transplanted to the greenhouse compartment on 24 August 2001 (experiment 1) and 6 February 2002 (experiment 2) at a density of 64 plants m⁻². In each greenhouse compartment, there were eight parallel soil beds (each 1.13 m × 10.25 m). Compartments were heated with upper and lower heating circuits as is common in Dutch commercial practice for cut-flower chrysanthemum (Kempkes and Van de Braak, 2000). The lower heating circuit was located on the grid that was lifted when appropriate to support the plants as they grew. To prevent plant damage, the maximum pipe temperature of the lower circuit was set to 38 °C. The upper circuit (located on the side walls and overhead below the screen) was the main heating system with a maximum temperature of 80 °C. Air samples were taken continuously from above the crop canopy for measuring CO₂ concentration with an infrared gas analyser (Advance Optima Uras 14, ABB, Hartmann & Braun, Frankfurt, Germany). Pure CO₂ was supplied when the measured concentration was below the set-point. Air temperature and relative humidity (RH) were measured just above the crop canopy (10–20 cm) with dry and wet bulb PT-500 temperature sensors. Data were automatically recorded every five minutes by a commercial climate control system (VitaCo, Hoogendoorn, Vlaardingen, The Netherlands).
The RH within the compartment was controlled by heating and ventilation in experiment 1 and by ventilation only in experiment 2. Heating of the lower circuit was used in the first 2 hours after the blackout screens were withdrawn in the morning when RH exceeded the set-point (experiment 1). For RH control lee-side vents opened in proportion to the difference between the measured RH and the set-point to a maximum of 10% (experiments 1 and 2).

Four tensiometers were distributed in each compartment. Water was supplied according to demand. A sprinkler system located under the screens was used until flowers started to show colour. After that, irrigation pipes placed on each soil bed were used. The plants were treated with 18 h long day (LD) until the 16th leaf on the plants was unfolded followed by short day (SD) of 11 h using blackout screens. Blackout screens were drawn over the crop for the whole night irrespective of the greenhouse climate. In experiment 2, assimilation lighting (SON-T AGRO, Philips, Eindhoven, The Netherlands) providing 9.6 W m\(^{-2}\) photosynthetically active radiation (PAR) was used throughout the light period when outside global radiation fell below 150 W m\(^{-2}\) and was switched off again at 200 W m\(^{-2}\). No assimilation lighting was used in experiment 1, instead incandescent lamps were used for day-length control. As is common practice in Dutch cut-flower chrysanthemum cultivation, the top flower of each stem was removed.

Leaf temperature of sunlit and shaded leaves in the canopy was continuously measured in the two middle greenhouse compartments by 10 evenly distributed K-type thermocouples (Ø 0.025 mm), averaged over 5 min and stored on a data logger (DT 600, Esis, Roseville, NSW, Australia). Thermocouples were attached to the lower surface of the leaves with tension and glue (Tarnopolsky and Seginer, 1999). Energy consumption of the two middle greenhouse compartments (B and C) was calculated from the water flux in the heating pipes, as measured with electromagnetic flowmeters (MagMaster, ABB Kent-Taylor Ltd., Cambridgeshire, UK), and the difference between the in- and out-flux temperature to the greenhouse compartments (measured with isolated PT-100 thermometers mounted on the heating-pipes with thermo-conductive gel). Measurements were performed every 10 s, averaged over 5 min and stored on a datalogger (Hewlett-Packard, Palo Alto, CA, USA) between days of year 261–311 and 38–108 for experiments 1 and 2, respectively.

Important external quality parameters for cut-flower chrysanthemum are the lengths of stems and internodes, leaf number per plant and leaf size, flower number and size (Carvalho and Heuvelink, 2001). To evaluate the effect of the climate regimes on external quality, 24 or 12 plants (experiments 1 and 2, respectively) were harvested weekly per greenhouse compartment. Harvest was done from randomly selected areas of the inner six soil beds (the two border soil beds and a 2 m wide strip at each end of a bed were not used for sampling). Areas clearly influenced by non-uniformity of soil structure or water and nutrient supply were not used either. Sampled areas were not used later on. In that way, influences of non-uniformity of the canopy on crop growth were minimised. From each plant, fresh and dry weights (drying oven at 105°C for two cycles of 16 h) of leaves, stems, and flowers, stem length, and numbers of leaves and flowers were measured. Leaf area of each plant was determined with a leaf area meter (LI 3100, LI-COR, Lincoln, NE, USA). Plants were checked for fungal diseases and humidity related disorders twice a week.
Table 1
Climate treatments applied in two greenhouse experiments (experiments 1 and 2) in four greenhouse compartments (GH) each with 6-day temperature integration (TI) with long-term temperature bandwidths (b), process-based humidity regime (PB) and blueprint regime (BP)

<table>
<thead>
<tr>
<th>GH</th>
<th>Experiment 1</th>
<th>Experiment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature</td>
<td>RH</td>
</tr>
<tr>
<td>A</td>
<td>TI ± 4°C</td>
<td>PB</td>
</tr>
<tr>
<td>B</td>
<td>TI ± 2°C</td>
<td>PB</td>
</tr>
<tr>
<td>C</td>
<td>TI ± 8°C</td>
<td>PB</td>
</tr>
<tr>
<td>D</td>
<td>TI ± 6°C</td>
<td>PB</td>
</tr>
</tbody>
</table>

2.2. Climate control and treatments

During the first 5 days after transplanting in experiment 2, heating and ventilation temperatures were set to 18.5 and 19.5, and 19.5 and 20.5°C for day and night, respectively; RH was set to a maximum of 80%. In experiment 1, treatments started the second day after transplanting. During treatments, climate was controlled either with the joint regime (JT) or with a blueprint regime according to commercial practice (BP) (Table 1).

BP was controlled with heating and ventilation set-points of 18.5 and 19.5, and 19.5 and 20.5°C for day and night, respectively. Daytime ventilation set-points were increased by 0.5 K per additional 100 W m\(^{-2}\) between 600 and 1000 W m\(^{-2}\) outside global radiation. Night-time heating and ventilation set-points were increased by 0.5 K per additional 1 MJ m\(^{-2}\) per day global daily radiation sum between 7 and 12 MJ m\(^{-2}\) per day in the preceding light period.

2.2.1. Temperature

In JT, TI with an integration interval of 6 days was applied. Each 24 h period was treated independently and nested within the 6-day averaging period. A target 24 h temperature window rather than a fixed target temperature as in regular TI was used as the control criterion (Körner and Challa, 2003b). Maximum ventilation and minimum heating set-points were applied (34 and 10°C). Extreme temperatures were avoided by using soft boundaries (flexible temperature thresholds) that were created using temperature–time dose responses. Two types of thresholds (absolute and relative) represented the limits and an exponential response was assumed between them. Either of the two was used for control depending on the time–dose response (Körner and Challa, 2003b). The absolute boundaries were set as default and a maximum duration (30 min) at those thresholds (maximum and minimum set-points) was set, too. Temperature was recorded for dose response after passing a relative boundary (14 and 30°C for heating and ventilation, respectively). The heating and ventilation temperatures for the dose response were initially set to the absolute thresholds and adjusted after dosage was completed. The relative boundary was then held for the duration of a refresh time of 6 h before it was reset. Temperature was allowed to fluctuate within this range provided that the 24 h average temperature remained within the 6-day boundaries. For that, greenhouse temperature during the next 24 h was simulated with forecast weather and a simple static greenhouse model as used by Körner and Challa (2003a). The weather
The forecast was supplied by a meteorological company (Meteo Consult, Wageningen, The Netherlands) using the Dutch software package Weerbeeld (version 6.4.1, Meteo Consult) through an internet connection. The mean forecast temperature was updated with the actual temperature every 5 min and used as the control criterion.

The 6-day boundaries were calculated from the targeted 6-day mean temperature ($T_{\text{targ}}$), the allowed long-term temperature bandwidths ($\pm 2, \pm 4, \pm 6$ or $\pm 8^\circ$C) and a proportional back regulation (Körner and Challa, 2003b). A receding horizon of 1 day was used, i.e. the preceding 5-day period was evaluated at the beginning of each new day and compensated at day 6 of the averaging period. Temperature history older than 5 days was not taken into account. $T_{\text{targ}}$ depended on that of a reference regime and was calculated either from the set-points of an imaginary blueprint regime (experiment 1) or from the actual greenhouse temperatures realised in the BP compartments (experiment 2).

Because integration capacity in chrysanthemum depends on plant developmental stage (Cockshull and Kofranek, 1994) and excessive temperature fluctuations during flower initiation can delay flower development (Karlsson et al., 1989; Wilkins et al., 1990), a developmental stage dependent temperature control as suggested by Ludolph and Hendriks (1989) was applied in JT. TI was applied during LD in both experiments with JT. Since time to visible flower bud is particularly sensitive to temperature variation during SD (Wilkins et al., 1990), temperature with JT in experiment 1 was set to be the same as in BP in this period.

Because the first stages in chrysanthemum flower development are already complete when the first flower bud is visible (Adams et al., 1998) and flower development is probably not sensitive to temperature variations, the procedure was changed for experiment 2. The time to initiate the first flower primordium on pinched chrysanthemum plants was determined to be 8.7 days with a regression model using the prevailing temperatures (Adams et al., 1998). This agrees well with the 8–10 days reported by Van Ruiten and De Jong (1984). Although, cut-flower chrysanthemum plants are not pinched before short days are applied, vegetative growth is still going on for 6–8 days before flower initiation starts (Cockshull, 1979). Because flower initiation is an ongoing process, we assumed the processes occurring in the first 14 SD were sensitive to temperature variations. During this period, temperature fluctuation was restricted by a 6-day temperature bandwidth of $\pm 1^\circ$C but temperature could still fluctuate in the short-term. However, its magnitude was restricted in the long-term (Körner and Challa, 2003b). Particular care was taken with night temperature during SD. Although flower development depends on 24 h mean temperature (Cockshull et al., 1981), flower initiation was reportedly delayed with night temperatures lower than $16^\circ$C or higher than $24^\circ$C (Cockshull et al., 1995). Therefore, short-term fluctuations were restricted also during the night while flowers initiated. The heating set-point was restricted to $>18^\circ$C and a fixed margin of $1^\circ$C was set between the heating and ventilation temperatures.

### 2.2.2. Relative humidity

The RH was controlled with a process-based humidity regime (PB) within JT (Körner and Challa, 2003a), i.e. set-points were calculated according to their likely effect upon various plant-affecting processes such as Ca-deficiency, plant water stress, crop growth, crop development and airborne fungal diseases (e.g. powdery mildew, chrysanthemum white rust and grey mould). Decisions on climate control to avoid fungal diseases were mainly...
based on calculated leaf wetness duration (LWD, i.e. time integral of leaf condensation) (Huber and Gillespie, 1992). Leaf wetness was determined from predicted crop temperature (Stanghellini, 1987) and measured RH. Leaves were assumed to be wet when the difference between the predicted dew point and crop temperature was less than 1.5 °C (Avissar and Mahrer, 1982; Zhang et al., 1997).

2.2.3. CO₂
The CO₂ concentration set-point was 1000 μmol mol⁻¹ when the greenhouse vents were closed and 350 mol mol⁻¹ when they were open or when the outside global radiation was below 40 W m⁻². The temperature giving rise to maximum crop gross photosynthesis (P_{gc}) at 1000 μmol mol⁻¹ (under prevailing light conditions) was used as a secondary set-point for ventilation with JT (Körner and Challa, 2003b), hence the ventilation set-point was recalculated when the vents opened. Leaf photosynthesis was calculated as described by Körner et al. (2003) according to equations derived by Farquhar et al. (1980) including stomatal resistance as a function of radiation absorbed by the canopy, leaf temperature and vapour pressure deficit (Stanghellini, 1987). Leaf photosynthesis was scaled up to P_{gc} according to Goudriaan and Van Laar (1994) based on radiation distribution within the canopy.

![Network Diagram](image)

Fig. 1. Network system at Wageningen University to control greenhouse climate with a commercial VitaCo climate computer connected via RsImport, version 1.0 with the set-point generator programmed in the control software MATLAB® with direct computer to computer connections (-----) and network connections (——).
2.3. Climate control implementation

The climate regimes JT and BP were implemented in the technical software environment MATLAB® (version 6.0, MathWorks Inc., Natick, MA, USA). The control programme was used as the set-point generator and it was coupled to a commercial greenhouse climate computer (VitaCo) via the internal computer network of Wageningen University (Fig. 1). The greenhouse climate computer controlled climate by heating and ventilation. It further recorded temperature, RH and CO₂ concentration every 5 min. Climate data were supplied by the climate computer to a shared computer network drive and read by the set-point generator programme. Set-points were then sent to an intermediate computer. The connection to the climate computer was done by exclusively designed software (RsImport, version 1.0, Hoogendoorn, Vlaardingen, The Netherlands). Set-points were used by the climate computer for climate control in the same way as set-points that are input to the system.

3. Results

3.1. General regime behaviour and greenhouse climate

Temperature with BP was rigidly controlled with a small margin between the heating and ventilation temperatures (Fig. 2). This was in strong contrast to JT. With JT, fluctuations

![Figure 2](image-url)
Fig. 3. Twenty-four hours averages of greenhouse temperature (—), heating set-point (—−−) and ventilation set-point (- - -) for the joint climate regime (JT) with four different temperature bandwidths (±2, ±4, ±6 and ±8 °C) in cut chrysanthemum cultivation (experiment 1).

In the 24h mean temperature increased with increasing long-term temperature bandwidth (Fig. 3) and greenhouse control activities were reduced (Figs. 4 and 5). In periods with relatively high solar radiation in autumn (e.g. days 240–244 of the year), greenhouse temperature in JT was mainly controlled through ventilation. Higher temperature levels were observed when the temperature bandwidth (b) was large. Then, greenhouse temperature could fluctuate almost freely with little control (b = ±6 or ±8 °C; Fig. 4). During a cold period in late October temperature was mainly controlled by heating (Fig. 5), but ventilation

Fig. 4. Actual greenhouse temperature (—), heating set-points (—−−) and ventilation set-point (- - -) for four temperature bandwidths (±2, ±4, ±6 and ±8 °C) with the joint climate regime (JT) in experiment 1 between days of year 240 and 244.
Fig. 5. Actual greenhouse temperature (---), heating set-points (−−−) and ventilation set-point (- - -) for four different temperature bandwidths (±2, ±4, ±6 and ±8°C) with the joint climate regime (JT) in experiment 1 between days of year 302 and 304.

Fig. 6. Twenty-four hours average CO₂ concentration (a) and lee-side ventilation opening (b) for joint regime (JT) (—) and blueprint (BP) (- - -) for experiment 2.
Table 2
Average greenhouse temperature (T) and relative humidity (RH) and average daytime (8 a.m. to 6 p.m.) CO₂ concentration ([CO₂]) for four different temperature bandwidths (b) for the joint climate regime (JT) in experiment 1, and in the blueprint regime (BP) and JT in experiment 2.

<table>
<thead>
<tr>
<th>Experiment 1</th>
<th>Experiment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>JT ± 2°C</td>
<td>JT ± 4°C</td>
</tr>
<tr>
<td>T (°C)</td>
<td>19.68</td>
</tr>
<tr>
<td>RH (%)</td>
<td>86.6</td>
</tr>
<tr>
<td>[CO₂]</td>
<td>646</td>
</tr>
</tbody>
</table>

* LSD: least significant difference for experiment 2 data (Student’s t-test; α = 0.05).

was controlled to maximise $P_{gc}$. RH control was probably the reason the vents were opened in the first place; the secondary control was then continuously calculating the optimum temperature for maximum $P_{gc}$ (Fig. 5, day 302).

Although ventilation was less with the higher temperature bandwidth leading to a higher CO₂ concentration (Fig. 6), mean temperature over the complete cultivation period differed only little within JT (Table 2). The higher mean temperature of $b = ± 4$ °C probably arose because greenhouse compartment A was located next to a tropical experimental compartment. However, this was not the case in experiment 2, but then BP had a 0.7 °C higher average temperature over the complete cultivation period than JT. This was due to the fixed lower heating set-point of 18.5 °C. From mid March the BP greenhouse warmed up to almost 25 °C by day but this could not be compensated for at night as in JT (data not presented). Thus, the 24 h mean temperature was observed to increase gradually over the duration of the experiment (Fig. 2).

When $b$ increased, ventilation was diminished and RH increased (Table 2). Due to the process-based humidity regime this led to ventilation only when absolutely necessary (Fig. 7), e.g. when leaf condensation was predicted to exceed the maximum LWD allowed according to the PB rules (Körner and Challa, 2003a; Table 3). For that purpose, leaf temperature was predicted by a simple model. Little deviation between measured and predicted leaf temperature was observed for shaded leaves, but the variation was greater for sunlit leaves, where the predictions underestimated the measured values at lower temperatures. This led to overestimating of leaf condensation on sunlit leaves during the night (cold period) and humidity control would therefore have acted sooner than it should have.

3.2. Crop performance

When $P_{gc}$ was real-time simulated with the same LAI for both treatments (LAI was a common input to the $P_{gc}$ control module), the high daytime CO₂ concentration observed in the JT controlled climates resulted in a 8.5% higher cumulative $P_{gc}$ as compared to the BP regime (data not presented). Growth analysis, however, showed a stronger increase in dry weight of all plant organs with JT as compared to BP (Fig. 8). After 83 days of cultivation, total plant dry weight was about 39% higher for JT controlled plants. This was probably due to greater light interception by the JT treated plants due to their larger LAI (Fig. 9). Leaf number was only little different throughout the complete cultivation period with JT and BP.
The individual leaves were therefore larger in JT, but specific leaf area was higher with BP than JT (4.3 and 3.7 m\(^{-2}\) g\(^{-1}\), respectively). This difference was only pronounced after 28 March (data not presented). Flower dry weight did not change with \(b\) in experiment 1 but was 25\% higher with JT than with BP in experiment 2 (Fig. 8). Since flower number was

Table 3
Number of hours with leaf wetness (LW) per week (a) and number of times LWD exceeded 3 h (b) for blueprint regime (BP) and joint climate regime (JT) in experiment 2

<table>
<thead>
<tr>
<th>Regime</th>
<th>Week</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP(^a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>0</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>JT(^a)</td>
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<td>0</td>
<td>1</td>
<td>12</td>
<td>18</td>
<td>15</td>
<td>16</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

\(^a\) Leaves were assumed to be wet when the difference between the calculated dew point temperature (Zolnier et al., 2000) and the crop temperature (Stanghellini, 1987) was <1.5 \(^\circ\)C (Avissar and Mahrer, 1982; Zhang et al., 1997) or when the sprinkler was applied for irrigation.
equal with JT and BP individual flowers had 25% more dry weight on average. However, relatively more dry matter was allocated to stems and leaves than flowers.

In experiment 1, slightly higher flower and leaf numbers were observed with a higher temperature bandwidth in JT (Table 4). The biggest plants with the longest stems and
Table 4
Number of leaves and flowers, leaf area index (LAI) and specific leaf area (SLA, cm² g⁻¹) for chrysanthemums with the joint climate regime (JT) for different temperature bandwidths (b) in experiment 1 at day 77 after transplanting

<table>
<thead>
<tr>
<th>b (°C)</th>
<th>Leaves</th>
<th>Flower</th>
<th>LAI</th>
<th>SLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>±2</td>
<td>30.8 ± 0.3</td>
<td>10.3 ± 0.4</td>
<td>4.6</td>
<td>368</td>
</tr>
<tr>
<td>±4</td>
<td>30.9 ± 0.3</td>
<td>11.3 ± 0.3</td>
<td>4.7</td>
<td>363</td>
</tr>
<tr>
<td>±6</td>
<td>31.6 ± 0.3</td>
<td>11.5 ± 0.3</td>
<td>5.0</td>
<td>374</td>
</tr>
<tr>
<td>±8</td>
<td>31.5 ± 0.3</td>
<td>12.4 ± 0.4</td>
<td>4.6</td>
<td>352</td>
</tr>
</tbody>
</table>

Data are presented with standard error of the mean of 24 plants in each treatment.

The largest leaf area were achieved with a temperature bandwidth of ±6 °C (Fig. 10). With ±8 °C plant development was delayed by 4–5 days (but not at other bandwidths, data not presented). Temperature sums after cultivation with b = ±6 or ±8 °C were only slightly different (Fig. 11). This shows that the overall temperature sum alone did not affect plant development.

However, differences in temperature sum could be observed between the developmental stages. During the vegetative stage, temperature sum had probably little or no influence on leaf unfolding as basically no difference in leaf number was observed between the ±6 and ±8 °C temperature bandwidths (Table 4). The temperature sum was only slightly lower with b = ±8 °C during flower initiation compared to ±2 and ±6 °C. Therefore, the main

Fig. 10. Dry weights of the whole plants (a), stems (b), leaves (c) and flowers (d) at regular harvest at day 77 after transplanting of experiment 1 for four different temperature bandwidths with the joint climate regime. Bars larger than symbols indicate standard error of the mean of two greenhouses.
Fig. 11. Difference in temperature sum (°C days) between the joint climate regime (JT) with 6-day temperature bandwidths of ±8 and ±6 °C (—) and ±8 and ±2 °C (---) during the complete cultivation period with long and short days (LD and SD, respectively) divided into vegetative growth (VG), flower initiation (FI) and flower development (FD) phases.

delay probably occurred during flower development. This stage can be further divided into three phases; ‘visible bud’ to ‘disbud’, ‘disbud’ to ‘colour visible’, and ‘colour visible’ to ‘flower’ (Karlsson et al., 1989). Each phase has a different temperature optimum (Karlsson et al., 1989). Since no detailed investigation for different flower phases was performed here, phases could only be assigned roughly according to the reported average duration for each phase (Karlsson et al., 1989) (Table 5). Temperature was not optimal with any bandwidth, but differences between them were small in the first two phases. Mean temperature decreased with temperature bandwidth during the last two phases and this was probably the reason for the developmental delay of JT with a ±8 °C temperature bandwidth.

Although the difference in temperature sum between BP and JT in experiment 2 increased during SD to 48 °C days (Table 6), no final developmental delay was observed. Also had a difference of 11 °C days at the end of vegetative development (LD + 8) no obvious influence

Table 5
Mean temperatures (°C) during different flower development phases for JT in experiment 1 according to Karlsson et al. (1989)

| °C | Flowering phase
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td>±2</td>
<td>20.25</td>
</tr>
<tr>
<td>±4</td>
<td>20.64</td>
</tr>
<tr>
<td>±6</td>
<td>20.23</td>
</tr>
<tr>
<td>±8</td>
<td>20.30</td>
</tr>
</tbody>
</table>

The phases were: (I) start of short day to visible bud; (II) from visible bud to disbud; (III) from disbud to colour visible and (IV) from colour visible to flower. Average time to complete the phases was assumed to be 40% (I), 35% (II), 10% (III) and 15% (IV) of the total time to flower (Karlsson et al., 1989) resulting in 23.6, 20.7, 5.9 and 8.9 days. Optimum temperature was 21.3, 20.3, 23.1 and 19.1 °C for phases I, II, III and IV, respectively.
Table 6
Temperature sums (°C per day) at the end of the long day period (LD), after the long day period plus 8 days (LD + 8) and after the short day period (SD) for the joint climate regime (JT) and the blueprint regime (BP) in experiment 2

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Period during cultivation</th>
<th>LD</th>
<th>LD + 8</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td></td>
<td>315</td>
<td>466</td>
<td>1590</td>
</tr>
<tr>
<td>JT</td>
<td></td>
<td>304</td>
<td>455</td>
<td>1542</td>
</tr>
<tr>
<td>LSD&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
<td>3.0</td>
<td>2.2</td>
<td>11.0</td>
</tr>
</tbody>
</table>

<sup>a</sup> LSD: least significant difference (Student’s t-test; α = 0.05).

Table 7
Mean temperatures (°C) of flower development phases for JT and BP in experiment 2 according to Karlsson et al. (1989) (a) and the difference in temperature sum from the optimum temperature (°C per day) (b)

<table>
<thead>
<tr>
<th>Flowering phase</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>20.00 ± 0.02</td>
<td>21.04 ± 0.01</td>
<td>20.65 ± 0.05</td>
<td>20.59 ± 0.06</td>
</tr>
<tr>
<td>b</td>
<td>33.80</td>
<td>16.87</td>
<td>15.93</td>
<td>14.60</td>
</tr>
<tr>
<td>JT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>19.65 ± 0.03</td>
<td>20.22 ± 0.03</td>
<td>20.09 ± 0.04</td>
<td>19.87 ± 0.11</td>
</tr>
<tr>
<td>b</td>
<td>42.90</td>
<td>1.82</td>
<td>19.57</td>
<td>7.6</td>
</tr>
</tbody>
</table>

The phases were: (I) start of short day to visible bud; (II) visible bud to disbud; (III) disbud to colour visible; (IV) colour visible to flower. The average time to complete the phases was assumed to be 40% (I), 35% (II), 10% (III) and 15% (IV) of total time to flower (Karlsson et al., 1989) resulting in 26, 22.8, 6.5 and 9.8 days. Optimum temperature was 21.3, 20.3, 23.1 and 19.1 °C for phase I, II, III and IV, respectively. Data are presented with standard error of the mean of two compartments each.

on leaf unfolding. However, with JT flower development was slightly delayed in the first part of flower development but developmental speed increased later relative to BP (data not presented, but supported by flower dry weight increase in Fig. 9). This was probably due to the more optimal mean temperature with BP until the flower bud was visible and the opposite during the following flower development phase (Table 7).

The PB regime within JT did not cause any fungal disease, visible Ca-deficiency or other problems in any treatment (data not presented).

3.3. Energy consumption

Energy consumption was 23.5% lower with JT (temperature bandwidth of ±6 °C) compared to BP in experiment 2 (Table 8). This was also evident from the temperature sums of the heating pipes of both regimes (Table 9). With a wide temperature bandwidth of ±8 °C, energy consumption was 15.9% less than with ±2 °C (Table 8).
Table 8
Measured energy consumption (MJ m\(^{-2}\)) for the joint climate regime (JT) for two different bandwidths in experiment 1 \((b = \pm 2 \text{ or } \pm 8 ^\circ C)\) and experiment 2 \((b = \pm 6 ^\circ C)\) and the blueprint regime (BP) in experiment 2.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Measuring period (DOY)</th>
<th>Energy consumption (MJ m(^{-2}))</th>
<th>Energy saving (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>244–324</td>
<td>94 (JT ± 2 ^\circ C)</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>79 (JT ± 8 ^\circ C)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>38–108</td>
<td>251 (BP)</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>192 (JT ± 6 ^\circ C)</td>
<td></td>
</tr>
</tbody>
</table>

Table 9
Temperature sums of the upper and lower heating circuits (°C per day) for the joint climate regime (JT, \(b = \pm 6 ^\circ C\)) and the blueprint regime (BP) for cultivation of cut-flower chrysanthemum crops after the fifth day of cultivation in experiment 2.

<table>
<thead>
<tr>
<th>Regime</th>
<th>Lower circuit</th>
<th>Upper circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>JT</td>
<td>824</td>
<td>523</td>
</tr>
<tr>
<td>BP</td>
<td>1589</td>
<td>1052</td>
</tr>
<tr>
<td>LSD(^a)</td>
<td>578</td>
<td>594</td>
</tr>
</tbody>
</table>

Data were used only when the heating was switched on, otherwise the temperature was assumed to be 0 °C.

\(^a\) LSD: least significant difference (Student’s \(t\)-test; \(\alpha = 0.05\)).

4. Discussion

Two experiments showed that the joint climate regime with modified temperature integration and process-based humidity control was able to reduce energy consumption while crop growth was strongly increased as compared to a blueprint regime. Energy saving was as expected with the combined regime during this season (Körner and Challa, 2003c). When the same duration was used for simulations with a reference climate year as in experiment 2, 29% energy was saved (data not presented). The difference from the measured 23.5% can probably be attributed to differences in climates, greenhouse structures, and equipment. This was acceptable for the purpose of proving the regime.

Energy saving could be achieved by connecting two sub-regimes for temperature and humidity control. The purpose of the first (TI) is either to shift heating to periods when heat-loss is reduced (Bailey and Seginer, 1989; Lacroix and Kok, 1999) or to use the greenhouse as a solar collector more than is usual with conventional climate regimes by raising the ventilation set-point. Then, one can refrain from heating during colder periods to achieve the targeted mean temperature. In the present case, the temperature rose to 29 °C at the beginning of February and then dropped to 12 °C in the same 24 h period. This led to a 24 h mean temperature of 18.9 °C. With regular temperature integration with the same bandwidth (±6 °C), temperature would have been restricted to a minimum of 14 °C and a maximum of 26 °C. However, maximum energy saving would be achieved if compensation was not necessary. Such a regime was applied in Denmark (Aaslyng et al., 1999), but plant development was delayed in winter (Rosenqvist et al., 2001). In the present regime,
developmental delay was only observed with extreme settings and this was probably due to the non-optimum mean temperature during flower development. The control system was obviously not able to control mean temperature with $b = \pm 8 ^{\circ}C$. A stronger temperature compensation would have been necessary.

With a $\pm 6 ^{\circ}C$ temperature bandwidth, however, no developmental delay was observed and energy was saved while a strong increase in dry matter was achieved. Similar findings with chrysanthemum were reported with a free dynamic climate control system (without temperature compensation) optimising photosynthesis in small acrylic–plastic containers placed in a greenhouse (Hansen et al., 1996; Hansen and Høgh-Schmidt, 1996). Also in roses, a dry matter increase of more than 40% was achieved in late spring with the same control system for greenhouses (Aaslyng et al., 1999). However, energy consumption for heating was then increased as compared to a control (Aaslyng et al., 1999). When the system was applied during winter (January–March), no dry matter increase was found but energy consumption was reduced slightly. This depended on the system settings. Large energy savings were possible but only with a simultaneous decrease in dry matter production (Aaslyng et al., 1999).

A fresh weight increase of 16% and energy saving was reported when temperature integration ($b = \pm 4 ^{\circ}C$) was applied to a chrysanthemum with a constant CO$_2$ set-point of 350 $\mu$mol mol$^{-1}$ (Buwalda et al., 1999b). Since CO$_2$ was kept low in that research and therefore no $P_{gc}$ optimisation was performed, higher photosynthesis levels due to less ventilation and consequently higher CO$_2$ concentration can only partly explain the strong increase in plant weight with the JT climate in the present experiment. Although Peet et al. (1991) reported that CO$_2$ enrichment alone can increase fresh yield of chrysanthemum by up to 37%, greater light interception by the JT treated plants was probably the main reason for more growth. With a higher LAI, light interception was greater and hence photosynthesis and growth. This was only important for the first 30 days or so, because 90% of the available radiation is intercepted at a LAI of 3 (Marcelis et al., 1998) and there is little increase in $P_{gc}$ after that (Gijzen, 1995). Initial plant growth was higher and this partly resulted in the final difference. A positive difference between average day and average night temperature (DIF) was probably the reason for the larger LAI. With positive DIF, internodes elongate and longer stems can be expected (e.g. Bertram, 1992) and leaves are also larger. This was supported by Hendriks et al. (1990), who reported that positive DIF led to taller poinsettia plants with bigger leaves and bracts than combinations with zero or negative DIF. Increase in leaf area may also be promoted through high RH (Gisleørd and Nelson, 1997; Mortensen, 2000).

Dry matter allocation was, however, negatively influenced as the dry matter percentage allocated to flowers was lower with JT than with BP. This was also observed with TI experiments performed by Buwalda et al. (1999b), but in contrast to Cockshull (1982). Cockshull (1982) reported that the proportion of dry matter allocated to chrysanthemum flowers remained constant at a given stage of flower development irrespective of the environmental conditions tested. A positive DIF could have affected the distribution of dry weight as it results in a higher percentage of stem dry matter as compared to negative DIF (Karlsson and Heins, 1992). The observed decrease in flower dry matter percentage was therefore related to the strong increase in stem dry matter with JT (53 and 60% with BP and JT, respectively).
5. Conclusion

When applying the joint climate regime, it is possible to have both a saving of energy and an increase in crop yield and to do so without any delay in plant development. The increase in dry matter was probably a consequence of regular TI behaviour in spring, when greenhouses heat up during day and cool down during night attaining a negative DIF and accordingly larger leaves. At a young stage, this can be very advantageous as compared to a common climate regime with fixed set-points and zero DIF. Unlike existing dynamic regimes for energy saving including $P_{gc}$ maximisation, plant development is also controlled and this is an important economical issue. With chrysanthemum, however, the response of the different developmental stages create bottlenecks for dynamic climate controls. In commercial cut-flower chrysanthemum production, plants at all developmental stages are grown in the same greenhouse and therefore the full application of this dynamic regime may be possible only when also the growing system changes. A different solution would be to select or to breed new genotypes that are more tolerant of temperature fluctuations. A combination of modern greenhouse structures, dynamic climate control regimes and new cultivars will probably be the best solution for environmentally friendly greenhouse production in the future. However, the regimes evaluated here form a promising basis for future climate controllers and can also be extended to other greenhouse crops.

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References


