Relationship between air and media temperature in frequently irrigated containerized nursery plants

M. Gheysari[1*], A. Garcia y Garcia[2,3] and G. Hoogenboom[2,4]

*[1]Water Engineering Department, College of Agriculture, Isfahan University of Technology, 84156-83111, Isfahan, Iran; [2]Department of Biological and Agricultural Engineering, University of Georgia, Griffin, Georgia 30223, USA; [3]Current address: Department of Plant Sciences, College of Agriculture and Natural Resources, The University of Wyoming, Powell, Wyoming 82435, US; and [4]Current address: Washington State University, Prosser, Washington 99350-8694, US. *Email: gheysari@cc.iut.ac.ir*

Gheysari, M., A. Garcia y Garcia and G. Hoogenboom. 2010. **Relationship between air and media temperature in frequently irrigated containerized nursery plants**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. 52: 1.19–1.34.

The media temperature of containerized plants has a distinct impact on crop growth and development, water and nutrient uptake. Ultimately, it influences the marketable quality of the plant. Containerized plants suffer due to a low root zone temperature during the winter and a high root zone temperature during the summer months. Understanding the relationship between media temperature and weather conditions is the first step towards the development of strategies that could reduce crop risks associated with extreme temperatures in the root zone. The objective of this study was to determine the relationship between the media temperature (MT) and the air temperature (AT) of containerized nursery crops subjected to short irrigation intervals.

The study was conducted at Monrovia Growers, located in Cairo, Georgia, USA, during the summer of 2005 and the spring and summer of 2006. Data from 2006 were used to develop various models and the data from 2005 were used for model evaluation. The experiment consisted of a 14.7-L plastic container with five replicates. Media temperature, air temperature and solar radiation were recorded at 15-min intervals. Weather data were obtained from an automated weather station located 20 m from the experimental site. Irrigation was applied six times daily using a micro-irrigation system consisting of micro-sprayers (spitters). The MT gradient (ΔMT) and AT gradient (ΔAT) were determined every 2 h, from 0600 h to 2000 h, in May, June, July, and August. The investigation lasted for 10 d each month.

For all 10-d periods, a significant ($P < 0.05$) correlation between ΔAT and ΔMT was found during the day. The correlation between ΔAT and ΔMT was affected by the time lag between AT and MT. The relationship between ΔAT and ΔMT varied for different time periods during the day and for all 10-d periods that were analyzed. Our results demonstrated that media temperature and air temperature have a significant correlation. However, this correlation seems to be a function of the time of day. Specific equations were, therefore, developed for estimating ΔMT as a function of ΔAT for different time periods of the day and for different months. These equations could successfully predict media temperature as a function of air temperature for time periods of less than an hour. Further work will consider other variables, such as solar radiation, media moisture and the temperature of the irrigation water.

Key words: containerized crops, temperature, moisture, ornamental crops, irrigation, media, pot.

La température du substrat de culture des plantes en contenants a un impact sur leur croissance, leur développement ainsi que sur leur consommation en eau et en nutriments. Par conséquent, celle-ci influence la qualité commerciale des plants. Les plantes cultivées en contenants souffrent en raison de la température inappropriée de leur zone racinaire: faible durant l'hiver et élevée durant les mois d'été. Une compréhension de la relation entre la température du substrat de culture et les conditions météorologiques constitue une première étape vers le développement de stratégies qui pourraient réduire les risques associés aux températures extrêmes dans la zone racinaire des plantes. L'objectif de cette étude était de déterminer la relation entre la température du substrat de culture (MT) et la température de l'air (AT) des cultures de pépinière en contenants fréquemment irriguées.

L'étude a été réalisée à Monrovia Growers, situé à Cairo, Georgie, États-Unis durant l'été 2005 et le printemps et l'été 2006. Les données de 2006 ont été utilisées pour développer plusieurs modèles et les données de 2005 ont été utilisées pour l'évaluation de ces modèles. L'expérience a été réalisée avec un contenant de plastique de 14,7 L et cinq réplicats. La température du substrat de culture, la température de l'air et la radiation solaire ont été enregistrées à des intervalles de 15 minutes. Les données météorologiques ont été obtenues d'une station météorologique automatisée située à 20 m du site expérimental. Les plants étaient irrigués six fois par jour en utilisant un système de micro irrigation muni de mini-diffuseur (spitters). Les valeurs des gradients MT (ΔMT) et AT (ΔAT) étaient déterminées à toutes les deux heures entre 6h00 et 20h00 durant les mois de mai, juin, juillet et août. Les expériences ont été conduites durant une période de dix jours par mois.

Pour toutes ces périodes de 10 jours, une corrélation significative ($P < 0,05$) entre ΔAT et ΔMT a été observée durant la journée. La corrélation entre ΔAT et ΔMT était influencée par le délais entre AT et MT. La relation entre ΔAT et ΔMT variait pour différentes périodes de temps durant le jour et pour toutes les périodes de 10 jours qui ont été analysées. Nos résultats démontraient que la température du substrat de culture et la température de l'air sont corrélées de manière significative. Cependant, cette corrélation semble être fonction de l'heure de la journée. Par conséquent, des équations spécifiques ont été développées pour estimer ΔMT en fonction de ΔAT pour différentes périodes de la journée et pour différents mois. Ces équations peuvent prédire avec succès la température du média en fonction de la température de l'air pour des périodes de temps de moins d'une heure. Des études supplémentaires considéreront d'autres variables comme la radiation solaire, la teneur en eau du substrat et la température de l'eau d'irrigation. **Mots clés:** cultures en contenants, température, teneur en eau, plantes ornementales, irrigation, substrat, pot.

INTRODUCTION

Several studies have determined the effect of temperature on nursery crops (Niu et al. 2001; Wolukau et al. 2004). The conditions of containerized crops are different from the conditions of field crops. Some of the most important differences are soil structure, e.g., containers filled with artificial substrates called media; irrigation scheduling, e.g., containers irrigated at short intervals; drainage, e.g., drainage in containers is very rapid; and the effect of air temperature in the root zone, e.g., the air temperature affects containerized crops more than it affects field crops. Containerized plants suffer due to a decrease of the root zone temperature during the winter and due to an increase in root zone temperature during the summer months (Mathers 2003).

Containerized crops are generally more productive than field nurseries because plants can grow faster and are grown at higher densities (Mathers 2003). However, several studies have shown that a media temperature higher than 40°C can significantly reduce plant growth and cause root death or injury (Johnson and Ingram 1984; Martin et al. 1991; Irmak et al. 2004). The temporal variation in the media of containerized crops has been studied as a function of the position inside the container, e.g., the container walls versus the center of the container (Martin and Ingram 1993), container size (Martin and Ingram 1993; Stapleton et al. 2002), container color (Irmak et al. 2004), and container material (Tsakaldimi et al. 2005). Other studies have also determined the effect of the media temperature on nitrogen loss (Azam et al. 2003).

Watts (1975) studied the air and soil temperature of containers in controlled environments and determined that when there was no surface insulation or shading on the sides of the plastic container, the soil temperature at 0.01 m below the soil surface equilibrated at 7.5°C above AT. A reflective surface that covered or provided a shade for the sides of the container reduced this difference to 2.4°C. Martin and Ingram (1992) developed a three-dimensional equation to estimate the root system temperature for polyethylene containers. Their equation used an energy balance approach and required thermal conductivity, bulk density, and specific heat capacity of the substrate as well as solar radiation, wind speed, relative humidity, and minimum and maximum air temperature as input variables. Irmak et al. (2005) improved a practical equation for estimating the minimum and maximum root zone temperature of white and black colored containers by using minimum and maximum air temperature and solar radiation. Garcia y Garcia et al. (2004) found that a functional relationship between containerized media temperature and moisture and air temperature was a promising tool for estimating water use by nursery crops.

Media temperature (MT) affects the water status of the crop (Graves et al. 1989), photosynthesis (Ruter and Ingram 1992), crop growth (Mathers 2003; Irmak et al. 2005), and evapotranspiration (Garcia y Garcia et al. 2004). Direct measurement of the MT may be expensive and impractical in containerized nursery crops. However, its indirect determination by means of weather variables, such as air temperature and solar radiation, could be a viable strategy. Although the equation developed by Martin and Ingram (1992) can successfully predict the media temperature, its use is limited due to the large number of inputs that are needed and that are not readily available. Some of the inputs, such as the substrate variables, are not constant during the growing season and also vary among containers. Thus, a simple equation with few input data could be more useful for growers, consultants, extension agents, and technicians who work with nursery crops (Irmak et al. 2005). Irmak et al. (2005) used three input variables, including minimum and maximum air temperature and solar radiation, to predict minimum and maximum media temperature. Although the equation developed by Irmak et al. (2005) is simple, it is unable to predict media temperature for each specific time period during a given day. In addition, irrigation scheduling of the studies conducted by Martin and Ingram (1992) and Irmak et al. (2005) was not the same as the practical schedule that is normally used for containerized crops. While the experiment for obtaining the equation of Martin and Ingram (1992) triggered the irrigation system once a day, the experiment conducted by Irmak et al. (2005) applied water with two different methods: a sprinkler irrigation with daily irrigations and a multi-pot box system with capillary rise. Thus, it is necessary to consider the relationship between media temperature and available environmental data for practical irrigation management of nursery crops. The objective of this study was to determine the correlation between the media temperature and the air temperature for nursery containers that had short irrigation intervals.

MATERIALS and METHODS

Site and experimental description

The experiment was conducted during the summer of 2005 and during the spring and summer of 2006 at Monrovia Growers, located in Cairo, Georgia, USA (lat. 30°86′N, long. 84°2′W, and 81 m above sea level). The experimental setup consisted of five green 14.7-L (container #5 in Monrovia Growers, 0.21, 0.29, and 0.29 m bottom and top diameter and height, respectively) plastic containers that were filled with a substrate composed of 80% pine bark and 20% compost and then planted with *Viburnum nudum* 'Earth Shade'. To avoid border effects, 25 containers of the same size and same type of plant and media were arranged in the experiment. Row distance was 0.8 m and pots distance on the row was 0.7 m.

One soil temperature probe and one soil moisture probe (TDR, time domain reflectometry, Campbell Scientific Inc.) were installed in each of the five containers. The soil temperature probes (Campbell Scientific Inc.) were installed between the center and the edge of each container. The soil moisture probes were installed as close as possible to the temperature probes. Both probes were connected to an automated data logger, which recorded the conditions of each container every 15 min. Weather data were obtained from an automated weather station of the Georgia Automated Environmental Monitoring Network, AEMN (www.GeorgiaWeather.net), located about 20 m from the experiment. All information was retrieved daily via a dedicated telephone line and modem by a computer located in the Department of Biological and Agricultural Engineering at the University of Georgia, Griffin Campus.

The containers were irrigated using a micro-irrigation system consisting of micro-sprayers or "spitters" (Netafim Co.). Irrigation was applied as usually scheduled by the nursery in their production area. The irrigation scheduling consisted of six irrigation applications per day. Irrigation started at 0800 h and was at at 2-h intervals with a duration of 5 min per irrigation event.

Data preparation

A backward moving average (MA) procedure, as described in Eq. 1, was used as a method to smooth the air and media temperature observations. The MA procedure intends to facilitate identifying the direction of a possible trend (Pring 2002; Amberger 2006).

$$X_{MA(t,n)} = \frac{\sum_{k=1}^{n} X_{[t-(k-1)\times\lambda]}}{n} \tag{1}$$

Where $X_{MA(t,n)}$ is the average of the previous n consecutive media or air temperature data at time t, $X_{[t-(k-1)\times\lambda]}$ is the media temperature or air temperature value for the $[t-(k-1)\times\lambda]^{th}$ data, k is a counter ($k = 1, 2, 3 \ldots n$), and λ is the interval time between each data record (h:min).

Media and air temperature indices

The differences between two consecutive media temperature and two consecutive air temperature observations were determined as follows:

$$\Delta MT_t = (MT_t - MT_{t-1}) \tag{2}$$

$$\Delta AT_t = (AT_t - AT_{t-1}) \tag{3}$$

Where Δ is the difference between two consecutive 15-min values (gradient) (°C per 15 min) and MT_t, MT_{t-1}, AT_t and AT_{t-1} are the actual (t) and previous ($t-1$) media and air temperatures (°C), respectively. ΔMT_t and ΔAT_t can either be positive or negative.

Time lag and time period

A previous study demonstrated that there is a time lag for the media temperature affected by the air temperature (Goswami et al. 2000). Thus, we used 0, 1, 2, 3, 4, 5, 6, 7, and 8 lags between ΔMT and ΔAT, which corresponded to 0, 15, 30, 45, 60, 75, 90, 105, and 120 min, respectively. The media temperature gradient at time t, $\Delta MT_{(t)}$ was associated with the air temperature gradient at time $[t-(m\times\lambda)]$, $\Delta AT_{[t-(m\times\lambda)]}$, where m is the lag number.

In this study, a period of 10 d during each of the four warmest months of 2006 with similar irrigation scheduling was selected for analysis. The 10-d periods included May 22 to May 31, June 15 to June 24, July 11 to July 20, and August 11 to August 20. Then, the MT and AT gradients were determined every 2 h, from 0600 h, for a total of seven 2-h periods. The MT and AT gradient daily variations were large (Fig. 1c), limiting potential relationship between the two variables to intervals shorter than a day. Thus, the day was split into seven 2-h periods. To avoid the effect of irrigation on media temperature, all data recorded during irrigation events were removed from the data series. A period of 10 d from June 19 to June 29 of 2005 was selected for evaluation.

Statistical analysis

The Pearson's coefficient of correlation (r) was used to determine the degree of association between ΔMT and ΔAT at $P = 0.01$, $P = 0.05$ and $P = 0.1$. Regression analyses were performed to determine the relationship between ΔMT and ΔAT, and the relationship between simulated and observed data. Differences between simulated and observed data were assessed by means of the mean squared difference (MSD) as follow:

$$MSD = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2 \tag{4}$$

Where x_i is the simulated value for the ith data ($i = 1, 2, \ldots n$), y_i is the measured, and n is the number of measurements. The lower the MSD, the closer the simulated values to the observed values (Kobayashi and Salam 2000).

RESULTS and DISCUSSION

Air and media temperature patterns

From 0600 h to 0800 h, MT decreased while AT increased, but from 0800 h to 0400 h, both MT and AT increased with different slopes (Fig. 1). The differences between the minimum and maximum MT were lower compared with the differences between minimum and maximum AT for all the four 10-d periods that were studied (Fig. 1, Table 1). The daily average MT was higher than the daily average AT for all four 10-d periods (Figs. 2a, 2b, 2c, and 2d). However, the daytime average of MT and AT did not show any clear relationship between MT and AT (Figs. 2e, 2f, 2g, and 2h). For the four 10-d periods during May, June, July, and August, the differences between average MT and AT were 2.3, 1.6, 1.5, and 2.6°C, respectively. The highest and lowest differences between the minimum and maximum MT were observed during May (13.8°C) and August (10°C), respectively, while the highest and lowest differences between minimum and maximum AT occurred in June (17.7°C) and August (13.4°C), respectively (Table 1). The maximum MT among all four 10-d periods was 36.9°C and occurred in June, while the maximum AT was 35.5°C.

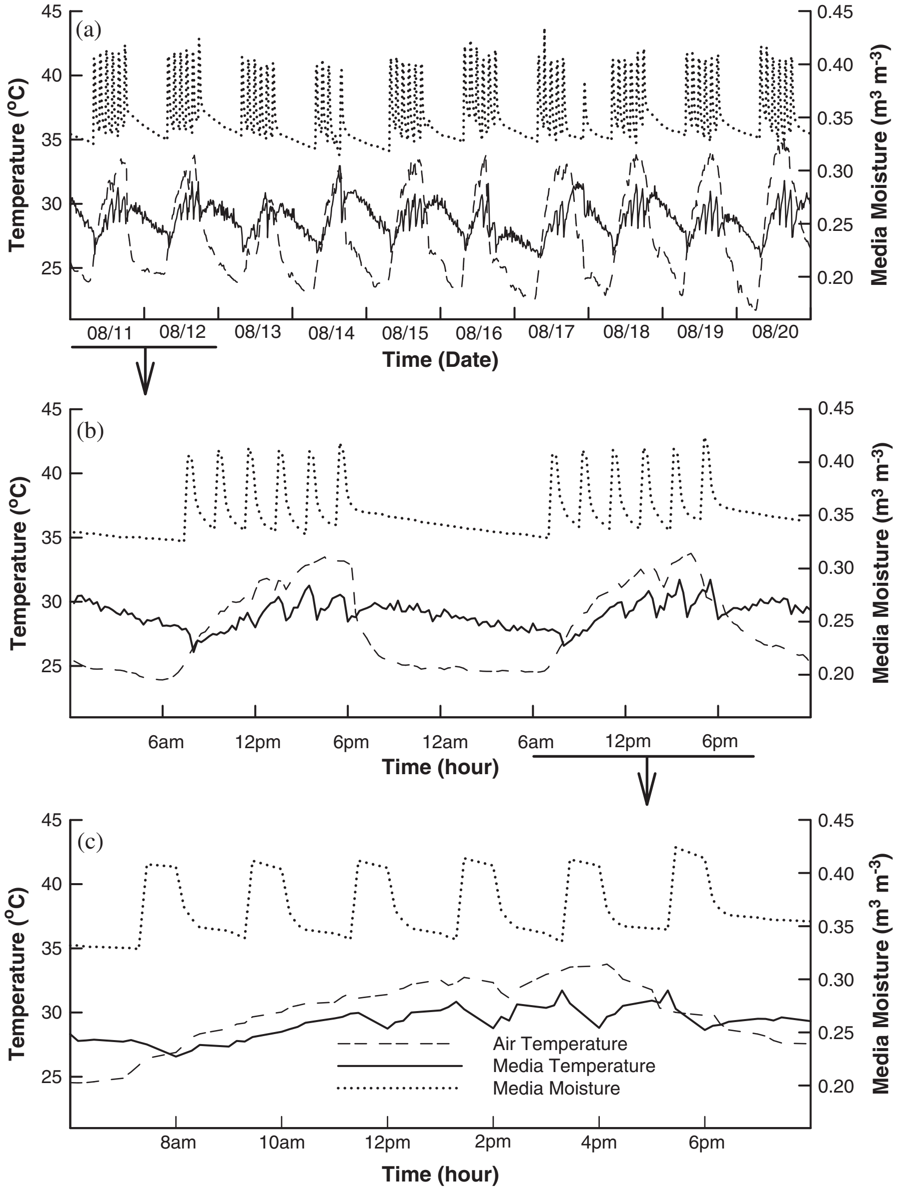

Fig. 1. Temporal variation of air temperature, media temperature, and media moisture for three different time scales: August 11 to August 20 (a), August 11 to August 12 (b), and August 11 (c) in 2006.

Previous studies have reported MT as high as 49.5°C (Fretz 1971) and 58°C (Martin and Ingram 1988) for black polyethylene containers. Irmak et al. (2005) reported that the MT of a black multi-pot and conventional system exceeded 40°C. A MT higher than 40°C has often been reported to significantly reduce plant growth and cause

Table 1. Minimum, maximum, and daily average air temperature (AT) and media temperature (MT) during a 10-day period in May, June, July, and August, 2006.

	May 22–31		June 15–24		July 11–20		August 11–20	
Temperature	AT	MT	AT	MT	AT	MT	AT	MT
					(°C)			
Minimum	17.53	21.92	18.16	22.2	19.89	24.33	21.71	25.89
Maximum	34.54	35.7	35.82	34.6	35.79	36.37	35.07	35.86
Average	25.84	28.12	26.97	28.6	27.65	29.2	27.47	30.1
St. Error*	±0.005	±0.003	±0.005	±0.003	±0.005	±0.002	±0.005	±0.002

*Standard error, calculated based on 15-min data.

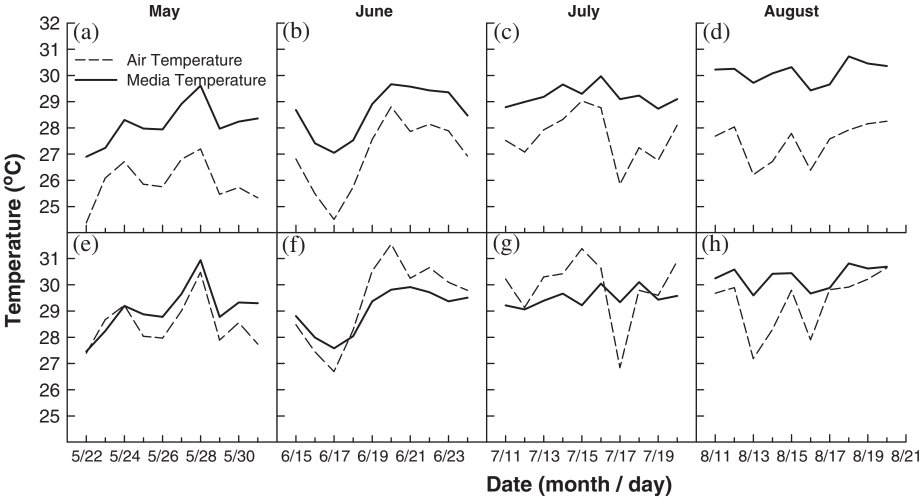

Fig. 2. Daily average air and media temperature during 10 days in May (a); June (b); July (c), and August (d), and daytime (0600 h–0800 h) average of air and media temperature for 10 days in May (e); June (f); July (g), and August (h).

root death and injury of container-grown plants (Irmak et al. 2004). However, in our study the MT, based on 15-min recorded data, was below that value, suggesting that the short irrigation intervals successfully moderated the increase of the MT. For instance, we found in our study that when the irrigation was triggered, the MT decreased rapidly (Fig. 1b). This effect of irrigation on MT was more evident during the periods of the day when there was a high AT (1200 h to 1800 h) (Fig. 1c).

Association between media and air temperature

Time period: 0600 h to 0800 h. The correlation between ΔMT and ΔAT was positive and significantly different from zero ($P < 0.01$) at a time lag of 45, 60, 75, and 90 min from May 22 to May 31 (Table 2). The correlation between ΔMT and ΔAT for all five individual replicates was significantly different from zero ($P < 0.01$) for 28 different combinations of AT-MA, MT-MA and time lag (Table 2). The lowest correlation was found for MT_3-AT_5-L_{75} ($r = 0.38$, df = 66) and the highest correlation was found for MT_6-AT_6-L_{75} ($r = 0.59$, df = 66).

From June 15 to June 24, the correlation between ΔMT and ΔAT was positive and significantly different from zero ($P < 0.01$) for the 0, 15, 30, and 45 min time lags. The correlation between ΔMT and ΔAT for all five individual replicates was significantly different from zero ($P < 0.01$) at 15 different combinations of AT-MA, MT-MA, and time lag (Table 2). The lowest correlation was found for MT_4-AT_2-L_{45} ($r = 0.38$, df = 66) and the highest correlation was found for MT_5-AT_3-L_{30} ($r = 0.45$, df = 66).

The correlation between ΔMT and ΔAT was positive and significantly different from zero ($P < 0.01$) for the 0, 15 and 30 min time lags from July 11 to July 20. The correlation between ΔMT and ΔAT was significantly different from zero ($P < 0.05$) for all five individual replicates at seven different combinations of AT-MA, MT-MA and time lag. The lowest correlation was found for MT_3-AT_3-L_0 ($r = 0.31$, df = 67) and the highest correlation was found for MT_6-AT_4-L_0 ($r = 0.40$, df = 67).

From August 11 to August 20, the correlation between ΔMT and ΔAT was negative, but not significantly different from zero ($P < 0.05$). The correlation between ΔMT and ΔAT was significantly different from zero ($P < 0.1$) for three individual replicates at 12 different combinations of AT-MA, MT-MA and time lag, which are shown with a plus sign in Table 2. The lowest correlation was found for MT_2-AT_3-L_{45} ($r = -0.27$, df = 65) and the highest correlation was found for MT_3-AT_3-L_{45} ($r = -0.33$, df = 65).

Overall, there was a positive and significant ($P < 0.05$) correlation between ΔMT and ΔAT during May, June, and July from 0600 h to 0800 h. However, this relationship was negative and not significant during August. The correlation between ΔMT and ΔAT decreased as follows: May > June > July > August. The correlation between ΔMT and ΔAT increased due to an increase of the number of consecutive data that were used for calculating AT-MA and MT-MA during May and June. In other words, the correlation was higher for a longer-term moving average.

Time period: 0800 h to 1000 h. The correlation between ΔMT and ΔAT was positive and significantly different from zero ($P < 0.01$) for: the 30, 45, 60, and 75 min time lags during May, the 60, 75, 90, 105, and 120 min time lags during June, the 90, 105, and 120 min time lags during July, and the 60, 75, 90, 105, and 120 min lags during August (Table 3).

The correlation between ΔMT and ΔAT was significantly different from zero ($P < 0.01$) at 8, 23, 56, and 65 different combinations of AT-MA, MT-MA, and time lags for May, June, July and August, respectively (Table 3). The highest correlation was found for MT_6-AT_5-L_{45} ($r = 0.58$, df = 65) in May, for MT_6-AT_6-L_{75} ($r = 0.53$, df = 65) in June, for MT_5-AT_6-L_{105} ($r = 0.62$, df = 66) in July, and for MT_6-AT_6-L_{120} ($r = 0.70$, df = 65) in August. Overall, the correlation between ΔMT and ΔAT was positive and significantly different from zero ($P < 0.01$) for many combinations of AT-MA, MT-MA, and time lag from 0800 h to 1000 h for all 4 months. The results also

Table 2. **Correlation between ΔMT and ΔAT based on different moving averages and time lags. Results are for 0600 h to 0800 h during May, June, July, and August.**

Time lag (min)	Media temperature moving average*																									
	15 minutes ($n=2$)					30 minutes ($n=3$)					45 minutes ($n=4$)					60 minutes ($n=5$)					75 minutes ($n=6$)					
120																										May 22–31
105																							$\underline{\mathbf{5}}$			
90						2	2	3					**5**	4				**5**	5	5	1	4	5	5		
75		2			4	**1**	**3**	**5**	4	4		**3**	5	$\underline{\mathbf{5}}$	5	1	**4**	5	$\underline{\mathbf{5}}$	5	2	**5**	5	$\underline{\mathbf{5}}$	5	
60		**2**	**3**	3	**3**	1	3	4	**5**	**5**	1	2	3	5	$\underline{\mathbf{5}}$	**2**	3	4	5	$\underline{\mathbf{5}}$	**2**	3		5	$\underline{\mathbf{5}}$	
45		1	2	**3**	3				3	4	**1**	1			5	2	2								5	
30	1		1	1							1															
15	**1**																									
0	1																									
120																										June 15–24
105																										
90																										
75																										
60																					3					
45	1	1	1			3	2				5	4				$\underline{\mathbf{5}}$	**4**	5	4	5	**5**	3				
30	**2**	**2**	2	1	1	**3**	**4**	2	2	2	$\underline{\mathbf{5}}$	5	4	4	4	4	$\underline{5}$	$\underline{\mathbf{5}}$	**4**	**4**	3	**4**	**4**	**4**	4	
15	1	1	**2**	2	1	2	2	**3**	2	**2**	4	$\underline{\mathbf{5}}$	$\underline{\mathbf{5}}$	**5**	**5**	4	4	5	$\underline{\mathbf{5}}$	4		3	4	4	**4**	
0				**2**	**2**			2	**3**	2			4	4	4								3	4	4	
120																										July 11–20
105																										
90																										
75			2																							
60		2	2																							
45	2	**2**	**2**	2	2																					
30	**2**	1		**2**	**2**	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	
15	2			2	2	2	2	2	2	2	3	3	3	3	3	**3**	**3**	3	3	3	3	3	3	3	3	
0						**3***	**2**	**2**	**2**	**2**	**3**	**3**	**3**	**3**	**3**	3*	3*	**3**	**3**	**3**	**3***	**3***	$\underline{\mathbf{3}^{*}}$	$\underline{\mathbf{4}^{*}}$	**4**	
120																										August 11–20
105																										
90																										
75																										
60						1^{+}					$\mathbf{1}^{+}$	1				1	1				1	1	1	1		
45	$\mathbf{1}^{+}$	$\mathbf{1}^{+}$	**1**	1	1	$\mathbf{1}^{+}$	$\underline{\mathbf{1}}^{+}$	$\underline{\mathbf{1}}^{+}$	$\mathbf{1}^{+}$	$\mathbf{1}^{+}$	1	$\mathbf{1}^{+}$	**1**	$\mathbf{1}^{+}$	**1**	**1**	**1**	**1**	$\mathbf{1}^{+}$	**1**	**1**	**1**	**1**	**1**	**1**	
30	1	1	1	**1**	**1**		1	1	1	1		1	1	1	1		1	1	1	1		1	1	1	1	
15														1	1											
0																										
	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	
	Air temperature moving average (min)																									

1, 2, 3, 4, and 5: Number of replicates that are significantly different from zero ($P<0.01$); Bold: Highest r for each combination of air and media temperature moving average; #: Combinations with high correlation coefficient for each period; *: All replicates are significantly different from zero ($P<0.05$); +: Three replicates are significantly different from zero ($P<0.1$); n: Number of consecutive data that average made over them; ΔMT: Media temperature gradient; ΔAT: Air temperature gradient; MA: Moving average.

Table 3. **Correlation between ΔMT and ΔAT based on different moving average and time lags. Results are for 0800 h to 1000 h during May, June, July, and August.**

		Media temperature moving average																								
		15 min ($n=2$)					30 min ($n=3$)					45 min ($n=4$)					60 min ($n=5$)					75 min ($n=6$)				
	Time lag (min) \ Air temperature moving average (min)	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75
May 22–31	120																									
	105																									
	90	1	1				**1**	**1**	**1**													4				
	75	**1**	**1**	1			1	1	1													**4**	4	4		
	60	1	1	**1**	1		1	1	1	1	1	1	1				**4**	4	3	3		5	$\underline{\mathbf{5}}$	$\underline{5}$	4	$\underline{4}$
	45			2	**2**	1				**2**	2	**3**	**4**	**3**	**3**	3	3	**4**	**4**	**4**	4		5	$\underline{\mathbf{5}}$	$\underline{\mathbf{5}}$	$\underline{\mathbf{4}}$
	30				2	**2**				2	**3**	2	2	3	3	**2**	2	3	4	4	**4**				5	$\underline{5}$
	15					2								2	3	2					4					
	0																									
June 15–24	120			**2**	**2**	**1**	1	**1**	**1**	**1**	**1**	**1**					**5**	**5**	5			**5**	5	$\underline{5}$		
	105					1			1	1	1	1					3	5	**5**	5		4	**5**	$\underline{\mathbf{5}}$		
	90									1	1								5	**5**		4	4	5	$\underline{5}$	$\underline{5}$
	75																3	4		5					$\underline{\mathbf{5}}$	$\underline{\mathbf{5}}$
	60																				**5**				4	$\underline{5}$
	45											1	**3**	4	4	4					4					
	30	**1**					**1**	1					1	**4**	**4**	**4**					4					
	15		**1**										1	2	4	4										
	0																									
July 11–20	120	4	4	4	4		**5**	**5**	**5**	5	5	**5**	**5**	**5**	5	5	**5**	**5**	5	$\underline{5}$	$\underline{5}$	**5**	**5**	**5**	$\underline{\mathbf{5}}$	$\underline{\mathbf{5}}$
	105	**4**	**4**	**4**	**4**		5	5	5	**5**	**5**	5	5	5	**5**	**5**	5	5	**5**	$\underline{\mathbf{5}}$	$\underline{\mathbf{5}}$	5	5	5	5	$\underline{5}$
	90	1	4	4	4	**4**	2	5	5	5	5	3	5	5	5	5	2	5	5	5	5	1	4	5	5	5
	75					4																				
	60					5																				
	45																									
	30																									
	15																									
	0																									
August 11–20	120						5					5	5				**5**	5	5	5	5	**5**	**5**	$\underline{5}$	$\underline{5}$	$\underline{5}$
	105	4	4				**5**	5	5	5		**5**	**5**	5	5	5	5	**5**	$\underline{\mathbf{5}}$	$\underline{\mathbf{5}}$	$\underline{\mathbf{5}}$	5	5	5	$\underline{\mathbf{5}}$	**5**
	90	**5**	5	4	4		5	**5**	**5**	**5**	5	5	5	**5**	**5**	**5**	5	5	5	5	5	5	5	5	5	5
	75	3	**5**	**5**	4	4		5	5	5	**5**			5	5	5										
	60			4	**5**	**4**					5															
	45					4																				
	30																									
	15																									
	0																									

1, 2, 3, 4, and 5: Number of replicates that are significantly different from zero ($P < 0.01$); Bold: Highest r for each combination of air and media temperature moving average; $\underline{\#}$: Combinations with high correlation coefficient for each period; n: Number of consecutive data that average made over them; ΔMT: Media temperature gradient; ΔAT: Air temperature gradient; MA: Moving average.

indicated that there was a strong correlation between ΔMT and ΔAT for all 4 months. The correlations between ΔMT and ΔAT are in increasing order as follows: August > July > June > May. The *r* value was higher for the long-term moving average as compared with the short-term moving average. Also, the number of individual replicates that had a correlation between ΔMT and ΔAT that was significantly different from zero was higher for the long-term moving average than for the short-term moving average (Table 3).

Time period: 1000 h to 1200 h. The correlation between ΔMT and ΔAT from 1000 h to 1200 h was positive, and significantly different from zero ($P < 0.05$) for many combinations of AT-MA, MT-MA, and time lags during May, July and August (Table 4). However, it was only significant ($P < 0.05$) for two out of five individual replicates in June. The maximum correlation was found for MT_6-AT_4-L_{105} ($r = 0.51$, df = 63) during May, for MT_6-AT_6-L_0 ($r = 0.48$, df = 65) during July, and for MT_6-AT_6-L_0 ($r = 0.40$, df = 64) during August. The values of *r* between ΔMT and ΔAT are in increasing order as follows: May > July > August > June. The number of individual replicates that had a correlation between ΔMT and ΔAT that was significantly different from zero was higher for the long-term moving average compared with the short-term moving average during May, July, and August (Table 4).

Time period: 1200 h to 1400 h. The correlation between ΔMT and ΔAT from 1200 h to 1400 h was negative during May, June, and July and positive during August. The correlation was significantly different from zero ($P < 0.05$) for four out of five individual replicates for all 4 months (Table 5). The maximum *r* was obtained for MT_3-AT_5-L_{60} ($r = -0.52$, df = 64) during May, for MT_4-AT_5-L_{30} ($r = -0.35$, df = 66) during June, for MT_4-AT_4-L_{60} ($r = -0.33$, df = 65) during July, and for MT_6-AT_6-L_{15} ($r = 0.36$, df = 65) during August. The highest value for *r* between ΔMT and ΔAT occurred in May ($r = -0.52$). For this period the correlation between ΔMT and ΔAT was not affected by the long-term moving average (Table 5).

Time period: 1400 h to 1600 h. The correlation between ΔMT and ΔAT was not significantly different from zero ($P < 0.1$) from 1400 h to 1600 h for all 4 months.

Time period: 1600 h to 1800 h. The correlation between ΔMT and ΔAT from 1600 h to 1800 h was negative during May and June, and positive during August. The correlation was significantly different from zero ($P < 0.05$) for May, June, and August. However, the correlation was not significantly different from zero ($P < 0.1$) for any combination of AT-MA, MT-MA and time lag for July (Table 6). The maximum correlations were obtained for MT_5-AT_6-L_{30} ($r = -0.38$, df = 64) during May, for MT_4-AT_6-L_{105} ($r = -0.41$, df = 64) during June, for MT_6-AT_4-L_{15} and MT_6-AT_5-L_{15} ($r = 0.57$, df = 67) during August. The value of the *r* between ΔMT and ΔAT was affected by the long-term moving average (Table 6).

Time period: 1800 h to 2000 h. The correlation between ΔMT and ΔAT from 1800 h to 2000 h was negative for all 4 months and was significantly different from zero ($P < 0.05$) for May, June, and July (Table 7). The maximum *r* was obtained for MT_5-AT_6-L_{120} and MT_6-AT_2-L_0 ($r = -0.44$, df = 85) during May, for MT_6-AT_5-L_{15} ($r = -0.52$, df = 84) during June, for MT_5-AT_5-L_{105} ($r = -0.28$, df = 84) during July, and for MT_5-AT_6-L_{60} ($r = -0.27$, df = 84) during August. The highest *r* value between ΔMT and ΔAT occurred in June. The correlation between ΔMT and ΔAT from 1800 h to 2000 h was effected by the long-term moving average during May, June, and July (Table 7).

Air temperature as predictor of media temperature

One of the objectives of this study was to predict media temperature as a function of air temperature. Based on the best combination of ΔMT, ΔAT, and time lag that was found for each time period and month, one model was obtained as a function of ΔAT to predict ΔMT for each month and time period (Table 8). The best model was found for the period from 0800 h to 1000 h in August based on the combination of MT_5-AT_4-L_{105} (Eq. 5):

$$\Delta MT = -0.104 + 0.512 \times \Delta AT \qquad (5)$$

To use this model, three steps are necessary: first, calculate the moving average of the previous four consecutive air temperature observations; second, calculate ΔAT based on Eq. 3; and third, to use a ΔAT that is based on seven time lags (105 min).

The models were obtained at different combinations of MT-MA, AT-MA, and time lags for different time periods and months (Table 8). To facilitate their use, the empirical models were simplified. Common combinations of MT-MA and AT-MA were selected for all time periods and months in order to be able to develop more common models. The best combination of MT and AT corresponds to the most significant MT × AT replicates. The results indicated that the 60-min moving average for media temperature and the 60-min moving average for air temperature were the best combinations for all time periods and months. The best common time lag varied between time periods, but was similar for all months. The best time lag was 15 mins for the 0600 h to 0800 h period, 90 min for the 0800 h to 1000 h period, 15 min for the 1000 h to 1200 h period, 75 min for the 1200 h to 1400 h period, 30 min for the 1600 h to 1800 h period, and 105 min for the 18:00 h to 2000 h period (data not shown). Thus, for each time period one model to predict ΔMT as a function of ΔAT was obtained (Table 9).

Although we did not consider other environmental variables as predictors of the media temperature, we used different models for different time periods during the day. This approach could be considered as reasonable for integrating the complexity of the relationship between variables that affects the media temperature of containerized plants.

Table 4. Correlation between ΔMT and ΔAT based on different moving average and time lags. Results are for 1000 h to 1200 h during May, June, July, and August.

		Media temperature moving average																								
		15 min ($n = 2$)					30 min ($n = 3$)					45 min ($n = 4$)					60 min ($n = 5$)					75 min ($n = 6$)				
May 22–31	120						3					**4**					4					5	5			
	105						2	**3**				2	**4**				**5**	**5**	5			**5**	**5**	**5**	**5**	
	90							2	3			3	3	**4**	4		4	5	**5**	**5**		2	5	5	5	5
	75			1				2	**3**	3	2		3	3	**5**	4		4	5	5	**5**			5	5	**5**
	60	**1**	2	1	**2**		**2**		2	**3**	**3**			3	3	**5**				5	5					5
	45		**1**			**2**				2	3					4					5					
	30			**1**	1	1																				
	15				1	1																				
	0		1																							
June 15–24	120		1																							
	105			**1**																		1				
	90				**1**												1					1	**1**	1	1	
	75			1	1	**1**						1					1	1	1			**1**	1	**1**	1	1
	60						**1**	1				**1**	**1**	2	1		**2**	**2**	**2**	**2**	2		1	1	**1**	**1**
	45						1	1	1	1		2	2	**2**	2	2		1	1	2	**2**					1
	30		**1**	1			2	**2**	**2**	**2**	1		3	2	**2**	**2**				2	2					
	15								1	2	**2**					2										
	0										1															
July 11–20	120						1	1														2				
	105																									
	90																									
	75																									
	60																					1				
	45																					**3**	3			
	30											1	2	2	2	2	1	3	3	2	2		**3***	3*	3	3
	15										1	**1**	**3**	3	3	3	1*	**4**	**3***	3*	3		4	**5***	**5***	4
	0	**4***	**2**			**1**	**1**	**4***	**3**	**2**	**3**	1	2*	**4**	**4**	**3**	**1**	2	4	**4***	**4***			4	4*	**4***
August 11–20	120		1	1	1	1				2	2		3	**3**	**3**	**3**			**3**	**3***	**4***		1	3	4*	4*
	105					1					3					3*					3*					
	90																									
	75																									
	60	1					**2**		1			3						2				3				
	45							1									1	2					2			
	30							**1**	**2**															3		
	15			**2**	2			1	2	**3**		1	3	2	3		1		4	4		1		**3***	**4***	4*
	0	**1**	**1**	1	**2**	**2**				2	**3**	**1**	**1**	2	3	4	**2**	**1**	1*	4*	4*	**2**	**2**		3*	**4***
		15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75
		Air temperature moving average (min)																								

1, 2, 3, 4, and 5: Number of replicates that are significantly different from zero ($P < 0.01$); Bold: Highest r for each combination of air and media temperature moving average; #: Combinations with high correlation coefficient for each period; *: All replicates are significantly different from zero ($P < 0.05$); n: Number of consecutive data that average made over them; ΔMT: Media temperature gradient; ΔAT: Air temperature gradient; MA: Moving average.

Table 5. Correlation between ΔMT and ΔAT based on different moving average and time lags. Results are for 12:00 pm to 2:00 pm during May, June, July, and August.

Time lag (min)	Media temperature moving average																									
	v15 min ($n=2$)					30 min ($n=3$)					45 min ($n=4$)					60 min ($n=5$)					75 min ($n=6$)					
120																					1	1	2	2	2	May 22–31
105		2				**3***						3				2	3	3	3	3	**2***	**2**	**2**	**3**	2	
90	2		3			1	**3**	3	3		**3**	3	**3***	3	3	**3**	**3**	**3**	**3**	**3**	1	2	2	2	**3**	
75		2		1	2		3	**4***	3	3	2	**3**	3	**3**	**3**	1	2	3	3	3						
60			**3**	**3**	**3**	2	3	3	**4***	**3***	1		3	3	3											
45	**2**	**2**	2	3	3					3																
30																										
15																										
0																										
120																										June 15–24
105																										
90																**1**										
75											**1**	1					2									
60						**3**	**3**	2	1	2		**3***	3	3			**3**	**3**	2				**3**	**2**		
45							1	**1***	**1**	1			**3***	3*	3			3	**3**	**3**				1	**1**	
30														**3***	**3**				1	3				1		
15									1	**3**					3										1	
0																				1						
120																										July 11–20
105																										
90												1					2	1				**2**	2	2		
75							**1**	1	1	1		**2**	2	2	1		**3***	**3**	**3**	2		1	**2**	**2**	2	
60								1	1	1		1*	**3***	**3**	**2**			1*	2	2					2	
45								**1***	**2**	**1**				3*	2				1*	**2***				2	**1**	
30																										
15																										
0																										
120																**1**	1	1			**2**	**2**	2*	2*		August 11–20
105																							2	2		
90																							**2**			
75																1	1				1	1				
60													1				**1**		1			1*				
45													**1**	**1**	1			**1**	1							
30													1	1	**1**			1	**1**	1				**2**	2*	
15														1	1					**2***					**3***	
0																				1*					2*	
	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	
	Air temperature moving average (min)																									

1, 2, 3, 4, and 5: Number of replicates that are significantly different from zero ($P < 0.01$); Bold: Highest r for each combination of air and media temperature moving average; #: Combinations with high correlation coefficient for each period; *: Four out of five replicates are significantly different from zero ($P < 0.05$) in May and June, and three out of five replicates are significantly different from zero ($P < 0.05$) in August; n: Number of consecutive data that average made over them; ΔMT: Media temperature gradient; ΔAT: Air temperature gradient; MA: Moving average.

Table 6. Correlation between ΔMT and ΔAT based on different moving average and time lags. Results are for 1600 h to 1800 h during May, June, July, and August.

		Media temperature moving average: 15 min ($n = 2$)					30 min ($n = 3$)					45 min ($n = 4$)					60 min ($n = 5$)					75 min ($n = 6$)				
	Time lag (min) \ Air temperature moving average (min)	≥15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75
May 22–31	120																									
	105																									
	90																									
	75																									
	60																									
	45																					**3**	2	3	3	
	30												2	2	3	3	**4***	**4**	3	**4**	$\underline{\mathbf{4}}$	2	**3**	**3**	**3**	**3**
	15											**3**	**3**	**4**	**4**	$\underline{\mathbf{4}}$	1	4	4	3	$\underline{4}$			2		2
	0												3	3	3	3		1	3	3	3				2	2
June 15–24	120																**4***	$\underline{\mathbf{4}^*}$	**4***		**5***		**2**	2	2	
	105									2	2	**1***	**5***	**5***	$\underline{\mathbf{5}^*}$	$\underline{\mathbf{5}^*}$		2*	4*	2*				**2**	3	3
	90							**3**	**3**	**2**	**3***			2					2	**5***					**3***	**2***
	75														3					3	4					2
	60									2					4	4					4					
	45										3					4		1								
	30																									
	15																									
	0																									
July 11–20	120																									
	105																									
	90																									
	75																									
	60																									
	45																									
	30																									
	15																									
	0																									
August 11–20	120																									
	105																									
	90																									
	75																									
	60																4*	4*				4*	4*			
	45						2					4*	4*	4*			**4***	$\underline{\mathbf{4}^*}$	4*	4*		**4**	$\underline{\mathbf{4}^*}$	$\underline{4^*}$	4*	
	30	2	2	2	2	1	**4***	4	3	2	2	**4***	**4***	**4***	4*	4	4	4	$\underline{\mathbf{4}^*}$	**4***	**4***	4	4	$\underline{\mathbf{4}^*}$	$\underline{\mathbf{4}^*}$	4*
	15	**4**	**4**	3	2	2	4*	**4**	**4**	4	3	3	4	4	**4***	**4**			4	4	4			4	4	$\underline{\mathbf{4}}$
	0	1	4	**4**	**3**	**2**		4	4	**4**	**4**				4	4					4					4

1, 2, 3, 4, and 5: Number of replicates that are significantly different from zero ($P < 0.01$); Bold: Highest r for each combination of air and media temperature moving average; $\underline{\#}$: Combinations with high correlation coefficient for each period; *: All replicates are significantly different from zero ($P < 0.05$); n: Number of consecutive data that average made over them; ΔMT: Media temperature gradient; ΔAT: Air temperature gradient; MA: Moving average.

Table 7. Correlation between ΔMT and ΔAT based on different moving average and time lags. Results are for 1800 h to 2000 h during May, June, July, and August.

Time lag (min)	Media temperature moving average																									
	15 min ($n=2$)					30 min ($n=3$)					45 min ($n=4$)					60 min ($n=5$)					75 min ($n=6$)					
120						**2**	2	2	2		**3**	**4**	**4**	**4**	**5**	2	4	**5**	**5**	**5**	3	5	**5**	**5**	**5**	May 22–31
105							**2**	**3**	**3**	**3**	1	3	4	4	4		3	5	$\underline{5}$	$\underline{5}$			3	5	5	
90								1	1	3			2	5	5				3	5						
75										3																
60																										
45																										
30																										
15																3					5	4				
0											3	3				$\underline{\mathbf{5}}$	**4**	3			$\underline{\mathbf{5}}$	$\underline{\mathbf{5}}$	4	3	3	
120																										June 15–24
105																										
90																										
75																										
60																										
45																5					5	5				
30											5	4	3	1		**5**	5	5	5	5	**5**	$\underline{\mathbf{5}}$	$\underline{5}$	5	5	
15						5	4	2	3	1	**5**	**5**	5	5	5	5	**5**	**5**	**5**	5	5	5	$\underline{\mathbf{5}}$	$\underline{\mathbf{5}}$	$\underline{\mathbf{5}}$	
0						**5**	**5**	**5**	**5**	**5**	2	5	**5**	**5**	**5**		5	5	5	**5**			5	$\underline{5}$	$\underline{5}$	
120																**2**	3	3			**2**	**3**	2	$\underline{\mathbf{3}}$	1	July 11–20
105													**2**	1	1	1	$\underline{\mathbf{3}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{3}}$	2		1*	$\underline{\mathbf{2}}$	2	**2**	
90												**1**	1	$\underline{\mathbf{2}}$	**1**		1	2	2	**2**			2	2	2	
75														1	1				2	2						
60																										
45																										
30																										
15																										
0																										
120											1					1	1									August 11–20
105						1					**1**	1	1			**1**	**1**	1	1							
90						**1**	**1**	**1**	1		1	**1**	**1**	1	1	1	1	**1**	**1**	1						
75							1	1	**1**	1		1	1	**1**	1			1	1	1						
60									1	**1**				1	**1***					**1***						
45										1																
30																										
15																										
0																										
	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	15	30	45	60	75	
	Air temperature moving average (min)																									

1, 2, 3, 4, and 5: Number of replicates that are significantly different from zero ($P<0.01$); Bold: Highest r for each combination of air and media temperature moving average; $\underline{\#}$: Combinations with high correlation coefficient for each period; *: All replicates are significantly different from zero ($P<0.05$) in July and three out of five replicates are significantly different from zero ($P<0.05$) in August; n: Number of consecutive data that average made over them; ΔMT: Media temperature gradient; ΔAT: Air temperature gradient; MA: Moving average.

Table 8. Fitted equation for air temperature gradient (ΔAT) and media temperature gradient (ΔMT) for the best combination of air temperature versus moving average, media temperature versus moving average, and time lag for different times of the day during May, June, July, and August.

			$\Delta MT = \beta + (\alpha \times \Delta AT)$			
Time	Period	Best Combination	β	α	r^2	df
0600 h to 0800 h	May 22–31	MT_6-AT_6-L_{75}	−0.041	0.443	0.29	330
	June 15–24	MT_5-AT_3-L_{30}	−0.091	0.135	0.18	330
	July 11–20	MT_6-AT_4-L_0	−0.088	0.098	0.15	330
	August 11–20	MT_3-AT_3-L_{45}	−0.084	−0.512	0.12	203
0800 h to 1000 h	May 22–31	MT_6-AT_4-L_{45}	0.08	0.311	0.11	350
	June 15–24	MT_6-AT_6-L_{75}	−0.026	0.406	0.19	350
	July 11–20	MT_5-AT_6-L_{105}	−0.005	0.384	0.31	350
	August 11–20	MT_5-AT_4-L_{105}	−0.104	0.512	0.44	350
1000 h to 1200 h	May 22–31	MT_6-AT_3-L_{105}	0.173	0.431	0.18	320
	June 15–24	MT_5-AT_6-L_{60}	0.131	0.438	0.25	132
	July 11–20	MT_6-AT_6-L_0	0.125	0.444	0.25	266
	August 11–20	MT_6-AT_6-L_0	0.136	0.246	0.11	340
1200 h to 1400 h	May 22–31	MT_3-AT_5-L_{60}	0.799	−1.66	0.26	265
	June 15–24	MT_4-AT_5-L_{30}	0.587	−1.435	0.12	270
	July 11–20	MT_4-AT_4-L_{60}	0.437	−0.752	0.10	337
	August 11–20	MT_6-AT_6-L_{15}	0.225	0.385	0.12	201
1600 h to 1800 h	May 22–31	MT_5-AT_6-L_{30}	0.058	−1.816	0.17	264
	June 15–24	MT_4-AT_6-L_{105}	0.404	−2.804	0.16	331
	July 11–20	–	–	–	–	–
	August 11–20	MT_6-AT_4-L_{30}	−0.009	0.327	0.39	277
1800 h to 2000 h	May 22–31	MT_5-AT_6-L_{120}	−0.25	−0.706	0.15	427
	June 15–24	MT_6-AT_5-L_{15}	−0.434	−0.677	0.26	427
	July 11–20	MT_5-AT_5-L_{105}	−0.212	−0.414	0.07	436
	August 11–20	MT_4-AT_6-L_{60}	−0.131	−0.175	0.05	417

MT_4: Moving average for four consecutive media temperature; AT_5: Moving average for five consecutive air temperature; L_{105}: 105 min time lag between air and media temperature; α and β: Constant coefficient of equation; r^2: Coefficient of determination; df: degree of freedom.

Model evaluation

The data collected during June 2005 were selected for evaluating the set of models that was obtained. The mean square difference (MSD) of the predicted ΔMT versus the observed ΔMT was lower for the morning periods compared with the afternoon periods (Table 10). The lowest MSD was 0.006°C for the 0600 h to 0800 h period, 0.012°C for the 1000 to 1200 h period, and 0.021°C for the 0800 h to 1000 h period (Fig. 3). The low values for MSD indicated that the predicted values were close to the observed values (Kobayashi and Salam 2000). Thus, the empirical models were more successful in predicting ΔMT during the morning periods compared with the afternoon periods. The coefficient of determination of the simulated values versus the observed values was significant ($P < 0.05$) for all five time periods of 0600 h to 0800 h, 0800 h to 1000 h, 1000 h to 1200 h, 1600 h to 1800 h and 1800 h to 2000 h for June (Table 10). The highest r^2 was obtained for the 0800 h to 1000 h period with a value of 0.68, while the MSD was 0.021°C. This evaluation showed that these models can successfully predict media temperature as a function of air temperature for time periods less than an hour (15 min).

The maximum media temperature that was observed in June (36.9°C) was less than the 40°C that is considered as a critical value (Martin and Ingram 1993; Irmak et al. 2005). Thus, the strategy that was applied at this nursery to use short irrigation intervals protected the plants during our experiments from the harmful effects of high temperature of media. Our results are in agreement with those of Irmak et al. (2005), who reported lower media temperature for a multi-pot box system as compared with a conventional system due to differences in irrigation methods. Martin and Ingram (1992) suggested that irrigation during the afternoon could help to moderate the high temperatures of media that is composed of pine bark substrate. Our findings also agree with those Smith et al. (1964), who found that irrigation has a drastic impact on the variation of soil temperature.

The data for all seven time periods during the 4 months of this study indicate that there was a time lag between air temperature and media temperature (Tables 2, 3, 4, 5, 6, 7,

Table 9. Fitted equation for predicting media temperature gradient (ΔMT) as a function of air temperature gradient (ΔAT) in order to provide a common equation for different time periods during May, June, July, and August.

Time	Period	Best Combination	$\Delta MT = \beta + (\alpha \times \Delta AT)$			
			β	α	r^2	df
0600 h to 0800 h	May 22–31	MT_5-AT_5-L_{15}	0.025	0.129	0.22**	51
	June 15–24	MT_5-AT_5-L_{15}	0.016	0.064	0.14*	40
	July 11–20	MT_5-AT_5-L_{15}	0.03	0.047	0.14*	33
	August 11–20	MT_5-AT_5-L_{15}	0.276	−0.079	0.16*	23
0800 h to 1000 h	May 22–31	MT_5-AT_5-L_{90}	0.192	0.263	0.08**	196
	June 15–24	MT_5-AT_5-L_{90}	0.206	0.276	0.1**	62
	July 11–20	MT_5-AT_5-L_{90}	0.091	0.203	0.19**	178
	August 11–20	MT_5-AT_5-L_{90}	0.042	0.196	0.3**	80
1000 h to 1200 h	May 22–31	MT_5-AT_5-L_{15}	0.294	0.418	0.08**	132
	June 15–24	MT_5-AT_5-L_{15}	0.226	0.327	0.1**	130
	July 11–20	MT_5-AT_5-L_{15}	0.162	0.333	0.2**	199
	August 11–20	MT_5-AT_5-L_{15}	0.189	0.23	0.1**	198
1200 h to 1400 h	May 22–31	MT_5-AT_5-L_{75}	0.566	−0.729	0.13**	161
	June 15–24	MT_5-AT_5-L_{75}	0.491	−0.543	0.05^{ns}	59
	July 11–20	MT_5-AT_5-L_{75}	0.399	−0.462	0.12**	102
	August 11–20	MT_5-AT_5-L_{75}	0.272	−0.29	0.1*	55
1600 h to 1800 h	May 22–31	MT_5-AT_5-L_{30}	0.426	0.205	0.07^{ns}	22
	June 15–24	MT_5-AT_5-L_{30}	0.529	0.208	0.09*	45
	July 11–20	–	–	–	–	–
	August 11–20	MT_5-AT_5-L_{30}	0.359	0.212	0.1**	75
1800 h to 2000 h	May 22–31	MT_5-AT_5-L_{105}	0.29	0.172	0.08**	131
	June 15–24	MT_5-AT_5-L_{105}	0.249	0.192	0.1*	41
	July 11–20	MT_5-AT_5-L_{105}	0.332	0.189	0.15**	116
	August 11–20	MT_5-AT_5-L_{105}	0.113	−0.105	0.2**	46

MT_4: Moving average for four consecutive media temperature; AT_5: Moving average for five consecutive air temperature; L_{105}: 105 min time lag between air and media temperature; α and β: Constant coefficient of equation; r^2: Coefficient of determination; df: degree of freedom; *: 0.05 significantly; **: 0.01 significantly; ^{ns}: not significant

and 8). However, there was not a clear trend for this time lag as a function of month and time period. The highest correlation between ΔMT and ΔAT was obtained for different time lags. When we used all combinations that had a significance of $P < 0.05$ for r, there was a similar time lag for all 4 months for each time period. The best common time lag for all four months was 15 min for the 0600 h to 0800 h period, 90 min for the 0800 h to 1000 h period, 15 min for the 1000 h to 1200 h period, 75 min for the 1200 h to 1400 h period, 30 min for the 1600 h to 1800 h period, and 105 min for the 1800 h to 2000 h period. The time lag between air temperature and soil temperature has

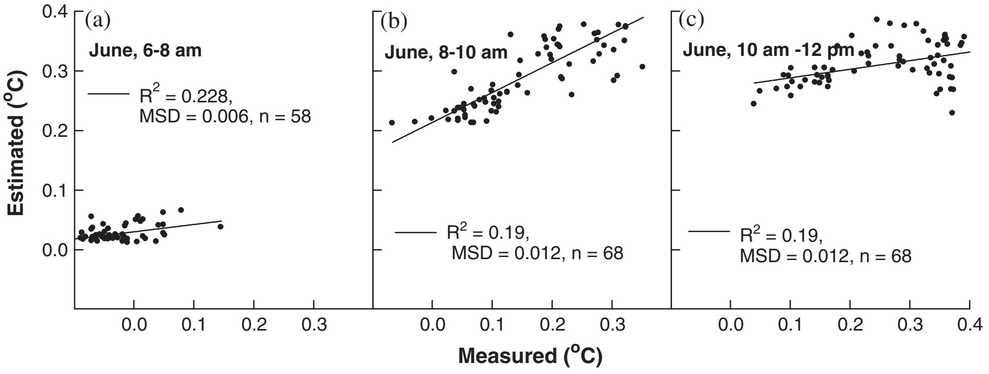

Fig. 3. Measured versus estimated media temperature gradient (ΔMT) during 10 days in June, 0600–0800 h (a), 0800–1000 h (b), and 1000–1200 h (c).

Table 10. Mean square difference (MSD) and coefficient of determination (r^2) of predicted versus observed values for different times of the day for June 2005 based on the equations as shown in Table 9.

Time	MSD (°C)	r^2	df
0600 h–0800 h	0.006	0.23	58
0800 h–1000 h	0.021	0.68	77
1000 h–1200 h	0.012	0.19	68
1600 h–1800 h	0.192	0.27	70
1800 h–2000 h	0.141	0.45	75

also been reported for field conditions by Brown et al. (2000), who provided a simple method for estimating daily mean soil temperature using the daily mean air temperature from the previous day.

In general, using a long-term moving average had a positive effect on increasing the correlation coefficient between ΔMT and ΔAT for all 4 months and all time periods. However, the time period from 1400 h to 1600 h did not show any response, apparently due to the combination effect of high air temperature and irrigation water temperature. The highest correlation coefficient between ΔMT and ΔAT was obtained for a moving average of 4, 5, and 6 consecutive air and media temperatures, but there was no clear trend within a month or time period that could have been caused by the interaction of irrigation water temperature with MT. The correlation between ΔMT and ΔAT of the individual replicates that were significantly different from zero were higher for the long-term moving average compared with the short-term moving average. Regardless of the highest r, when we considered all combinations that had a significant value for r, the 60-min moving average for media temperature and the 60-min moving average for air temperature were the best moving averages for all time periods and months.

One model was obtained to predict ΔMT as function of ΔAT for each time period and each month (Tables 8 and 9). The correlation between ΔMT and ΔAT was significant ($P < 0.05$, df > 132) for all equations, except for the 1200 h to 1400 h period during June and for the 1600 h to 1800 h period during May (Table 9). However, for some of the combinations the r^2 was very low. For instance, for the 1800 h to 2000 h period during July and August, r^2 was low (Table 8). The accuracy of these air-temperature-based models was evaluated and successfully predicted the media temperature. Although the relationships between ΔMT and ΔAT for all models were significant ($P < 0.05$), the coefficients of determination were low for some time periods and months. Overall, our results indicate that it is possible to predict media temperature as a function of air temperature during most of the time periods of the day.

CONCLUSION

The maximum media temperature that was observed in this study was 36.9°C, which was 3.1°C lower than the 40°C considered as critical for containerized crops. There was a time lag between air temperature (AT) and media temperature (MT) and correlation between ΔAT and ΔMT was affected by the time lag. Time lag varied between 15 and 105 min for different time periods. However, there was not a clear trend for this time lag as a function of month and time period. The 60-min moving average for media temperature and the 60-min moving average for air temperature were the best moving averages for all time periods and months. There was a significant correlation between ΔMT and ΔAT for the different time periods of the day during the four warmest months of the study period. The correlations between ΔMT and ΔAT were higher for the morning periods as compared with the afternoon periods. This could have been caused by the irrigation water temperature, which is not very different from MT during morning periods, but much lower than MT during afternoon periods. Our results indicate that it is possible to use air temperature as a predictor of the media temperature for containerized nursery crops during different time periods of the day.

ACKNOWLEDGEMENTS

This work was partially supported by a Special Grant from the US Department of Agriculture Cooperative State Research, Education and Extension Service (CSREES) and by State and Federal funds allocated to Georgia Agricultural Experiment Stations Hatch project GEO1654. The support provided by Monrovia Growers and especially by Mr. Stewart Chandler is greatly appreciated.

REFERENCES

Amberger, J.C. 2006. *Hot Trading Secrets: How to Get In and Out of the Market with Huge Gains in any Climate*. Hoboken, NJ: John Wiley and Sons.

Azam, F., A. Lodhi and S. Farooq. 2003. Response of flooded rice (*Oryza sativa* L.) to nitrogen application at two root-zone temperature regimes in a pot experiment. *Biology and Fertility of Soils* 38: 21–25.

Brown, S.E., K.S. Pregitzer, D.D. Reed and A.J. Burton. 2000. Predicting daily mean soil temperature from daily mean air temperature in four northern hardwood forest stands. *Forest Science* 46: 297–301.

Fretz, T.A. 1971. Influence of physical conditions on summer temperature in nursery containers. *HortScience* 6: 400–401.

Garcia y Garcia, A., G. Hoogenboom and L.C. Guerra. 2004. Container temperature and moisture for estimating evapotranspiration of nursery crops. ASAE Paper No. 042295. St. Joseph, MI: ASABE.

Goswami, D.Y., F. Kreith and J.F. Kreider. 2000. *Principles of Solar Engineering*, 2nd edition. Philadelphia, PA: Taylor & Francis.

Graves, W.R., M.N. Dana and R.J. Joley. 1989. Root zone temperature affects water status and growth of red maple. *Journal of the American Society for Horticultural Science* 114: 406–410.

Irmak, S., D.Z. Haman, A. Irmak, J.W. Jones, K.L. Campbell and T.L. Crisman. 2004. Measurement and analyses of growth and stress parameters of *Viburnum odoratissimum* (Ker-gawl) grown in multipot box system. *Journal of the American Society for Horticultural Science* 39: 1445–1455.

Irmak, S., D.Z. Haman, A. Irmak, J.W. Jones, B. Tonkinson, D. Burch, T.H. Yeager and C. Larsen. 2005. Root-zone temperatures of *Viburnum odoratissimum* grown in the multipot box system and conventional systems: measurement and analyses of temperature profiles and predicting root-zone temperatures. *Journal of the American Society for Horticultural Science* 40: 808–818.

Johnson, C.R. and D.L. Ingram. 1984. *Pittosporum tobira* response to container medium temperature. *HortScience* 19: 524–525.

Kobayashi, K. and M.U. Salam. 2000. Comparing simulated and measured values using mean squared deviation and its components. *Agronomy Journal* 92: 345–352.

Martin, C.A. and D.L. Ingram. 1988. Temperature dynamics in black poly containers. In *Proceedings of the Southern Nurserymen's Association Research Conference*, 33, 71–74. Marietta, GA: Southern Nurserymen's Association.

Martin, C.A., D.L. Ingram and T.A. Nell. 1991. Growth and photosynthesis of southern magnolia in response to increased and constant container volume. *Journal of the American Society for Horticultural Science* 116: 439–445.

Martin, C.A. and D.L. Ingram. 1992. Simulation modeling of temperatures in root container media. *Journal of the American Society for Horticultural Science* 117: 571–577.

Martin, C.A. and D.L. Ingram. 1993. Container dimension affects rooting medium temperature patterns. *HortScience* 28: 18–19.

Mathers, H.M. 2003. Summary of temperature stress issues in nursery containers and current methods of protection. *HortTechnology* 13: 617–624.

Niu, G., R.D. Heins, A.C. Cameron and W.H. Carlson. 2001. Day and night temperatures, daily light integral, and CO_2 enrichment affect growth and flower development of *Campanula carpatica* 'Blue Clips'. *Scientia Horticulturae* 87: 93–105.

Pring, M.J. 2002. *Technician's Guide to Day and Swing Trading*. New York, NY: McGraw-Hill.

Ruter, J.M. and D.L. Ingram. 1992. High root zone temperatures influence RuBisCo activity and pigment accumulation in leaves of 'Rotundifolia' holly. *Journal of the American Society for Horticultural Science* 117: 154–157.

Smith, G.D., F. Newhall, L.H. Robinson and D. Swanson. 1964. Soil temperature regimes, their characteristics and predictability. SCS-TP–144. Washington, DC: Soil Conservation Service, United States Department of Agriculture.

Stapleton, J.J., T.S. Prather, S.B. Mallek and T.S. Ruiz. 2002. High temperature solarization for production of weed-free container soils and potting mixes. *HortTechnology* 12: 697–700.

Tsakaldimi, M., T. Zagas, T. Tsitsoni and P. Ganatsas. 2005. Root morphology, stem growth and field performance of seedlings of two Mediterranean evergreen oak species raised in different container types. *Plant and Soil* 278: 85–93.

Watts, W.R. 1975. Air and soil temperature differences in controlled environments, as a consequence of high radiant flux densities and of day/night temperature changes. *Plant and Soil* 42: 299–303.

Wolukau, J.N., S. Zhang, G. Xu and D. Chen. 2004. The effect of temperature, polyamines and polyamine synthesis inhibitor on in vitro pollen germination and pollen tube growth of *Prunus mume*. *Scientia Horticulturae* 99: 289–299.