MODELING THE EFFECT OF TEMPERATURE ON FLOWERING OF 
HIBISCUS MOSCHEUTOS

Shi-Ying Wang, Royal D. Heins, William H. Carlson, and Arthur C. Cameron
Department of Horticulture
Michigan State University
East Lansing, MI 48824-1325
U.S.A.

Keywords: Bud development, decision support, hibiscus

Abstract

Effects of forcing temperature on phenological and morphological development of 
Hibiscus moscheutos 'Disco Belle Mixed' were determined by growing plants under long 
days in glass houses set at 15, 18, 21, 24, or 27°C. Actual rather than setting temperatures 
were used in the analysis. Time from the onset of long-day forcing to visible bud (VB) 
decreased from 101 to 24 days as average daily temperature (ADT) increased from 15.7 
to 25.0°C, and time from VB to flower decreased from 54 to 29 days as ADT increased 
from 19.4 to 27.6°C. Although higher ADT accelerated flowering, the diameter of the 
first flower, total number of flower buds per plant, and plant height at flowering 
decreased as ADT increased. A curvilinear model was used to describe the effect of ADT 
on days to VB or flower. An exponential model was developed to quantify the 
relationship between flower bud diameter, ADT, and days to flower. The models can be 
implemented in a decision-support system to predict the ADT required to achieve a target 
flowering date or the flowering date at a given ADT, bud diameter, or both.

1. Introduction

Crop scheduling and timing are important in the floricultural industry. The flowering 
date for most plant species can be controlled by manipulating cold treatment, 
photoperiod, and temperature. Having enough information to quantify these responses is 
critical.

Hibiscus is a taxon in Malvaceae, the mallow family. It includes about 200 species of 
tropical and subtropical trees, shrubs, subshrubs and herbs (Storey and Nwoke, 1985). 
The horticultural hybrids of Hibiscus moscheutos are crosses between H. moscheutos, H. 
coccineus and H. militaris (Clausen and Ekstrom, 1989). Previous research has shown 
that H. moscheutos 'Disco Belle Mixed' is an obligate long-day plant without a cold 
requirement for flowering (Heins, et al., 1997; Cameron, et al., 1996). Under long-day 
conditions, average daily temperature (ADT) is the primary factor influencing flower 
initiation and development; increasing ADT decreases time to flower. Low or excessive 
high temperatures may slow plant development and affect crop scheduling and timing. 
Flower diameter, plant height, and flower bud number also may be influenced by 
temperature.

The objectives of this study were to 1) quantify the influence of forcing temperature 
on time to visible bud (VB) and flower, 2) develop a bud development model to simulate 
bud development dynamically in response to ADT and other variables, and 3) determine 
the effect of forcing temperature on flower bud number, flower size, and plant height at 
flowering of H. moscheutos 'Disco Belle Mixed'.
2. Materials and methods

2.1. General experimental procedures

_Hibiscus moscheutos_ 'Disco Belle Mixed' seedlings obtained in 128-cell flats from Raker's Acres Greenhouse (Litchfield, Michigan) were transplanted into 13-cm plastic pots (one plant per pot). Ten plants per temperature treatment were grown under long days in glass houses set at 15, 18, 21, 24, or 27°C (for both day and night) in the spring of 1996. Long days consisted of natural days plus a 4-hour night interruption (2200 to 0200 hr) provided by high-pressure sodium lamps at 200 μmol m⁻² s⁻¹. Temperature in each glass house was recorded continually with a CR-10 datalogger (Campbell Scientific, Logan, Utah), so actual rather than setting temperature was used in the analysis. The diameter of a selected flower bud on each plant was measured every two to three days. Because a young bud was surrounded by bracelets, measurement of bud diameter at 6 mm and below included them. Dates of VB and flowering were recorded. At anthesis, plant height, total number of flower buds, and diameter of the first flower were recorded.

2.2. Model for time to VB or flower

A nonlinear model (Wang, 1986):

\[ D = \frac{CTT}{ADT - T_{base}} \]  \[1\]

was fitted to the observed data when temperature-response curves were developed for days (D) from forcing, to VB (D_{VB}) or flower (D_{FLW}). The CTT and T_{base} are defined as cumulative thermal time and base temperature, respectively (Table 1).

2.3. Model for bud development

Model theory is based on the work of Fisher, et al. (1996). The abbreviations and parameters used in the models are listed in Table 1. Bud diameter (B in mm) at time t (days) under constant temperature conditions depends on the initial bud diameter (B₀ in mm) at time t₀ and time from t₀ to t:

\[ B = B_0 e^{k(t-t_0)} \]  \[2\]

To incorporate plant response to temperature, the rate parameter k in Eq. 2 can be replaced by a temperature function, f(T), so that Eq. [2] becomes

\[ B = B_0 e^{f(T)(t-t_0)} \]  \[3\]

Assuming flowers open at some constant maximum bud diameter, B_f in mm, that can be calculated from the number of days from any value of B to flowering (D_{BF}):

\[ B_f = B e^{f(T)D_{BF}} \]  \[4\]

Therefore, D_{BF} can be estimated by
2.4. Estimating parameters and statistical analysis

Parameter estimates and asymptotic 95% confidence limits for nonlinear functions were estimated with SAS's nonlinear procedure, NLIN (SAS Institute, Inc., Cary, N.C.). Means together with 95% confidence intervals were calculated by SAS's analysis of variance procedure, ANOVA (SAS Institute, Inc., Cary, N.C.) for days from forcing to VB or flower, the diameter of the first flower, total number of flower buds, and plant height at flowering. The orthogonal polynomial coefficients for trend analysis were calculated from Statistical Methods (Khanizadeh, Agriculture Canada, Quebec).

2.5. Experiment for bud model validation

The bud model validation experiment was conducted in the spring of 1997. Plugs of *Hibiscus moscheutos* 'Disco Belle Mixed' were transplanted into 13-cm plastic pots. Seedlings were grown in a glass house at 20°C for four weeks after the transplant, then moved to another glass house at 26°C. The photoperiod in the glasshouses was natural daylength with a 4-hour night interruption (2200 to 0200 HR). Chlormequat (Cycocel) at 1500 ppm was sprayed the second week after transplant. When most plants had visible buds, five plants were put in each of five glass houses set at 17, 20, 23, 26, or 29°C. The protocols for photoperiod control and data collection were the same as those for the model-development experiment.

3. Results

Time from forcing to VB decreased from 101 to 24 days as ADT increased from 15.7 to 25.0°C, and time from forcing to flower decreased from 146 to 52 days as ADT increased from 17.2 to 26.4°C (Fig. 1). Fitting Eq. [1] to the data set from forcing to VB and flower resulted in a highly significant model fit (Table 2) with an $R^2$ of 0.998 and 0.994, respectively. The estimated $T_{base}$ and CTT were 12.9°C and 284°C days for VB and 12.2°C and 715°C days for flowering, respectively.

Although a higher ADT accelerated flowering, total number of flower buds, plant height at flowering, and the diameter of the first flower decreased as ADT increased (Table 3).

Bud expansion rate increased as temperature increased from 19.4 to 27.5°C, and the estimated $k$ values from Eq. [3] increased with temperature (Fig. 2). However, the $k$ value for 27.5°C was only 0.8% higher than that for 24.4°C. A quadratic function for $f(T)$ was fit to the estimated $k$ values as

$$k = c_1 + c_2 T + c_3 T^2$$  \[6\]

and resulted in an $R^2$ of 0.98 (Table 4). Therefore, Eq. [3] became

$$B = B_0 e^{f(c_1 + c_2 T + c_3 T^2)(t-t_0)}$$  \[7\]

The parameters $c_1$, $c_2$, and $c_3$ were estimated from Eq. [7] when the entire data set was used.

The maximum bud diameter for flowering ($B_f$) was estimated as 36.4 mm, based on Eqs. [4] and [6]. The average diameter for the last bud measurement of all plants was

$$D_{av} = \frac{\ln(B_f / B)}{f(T)}$$  \[5\]
29.7 mm. The mean x-intercept of the linear regression lines between ln(B) and D_{BF} for each temperature treatment was 38.6 mm.

Based on the parameter estimates (Table 4) from the exponential bud development model, days from any bud measurement to flower could be calculated. The predicted days to flower closely fit the observed date of the validation experiment (Fig. 3). For all 305 bud measurements on 25 plants in five different temperature treatments, the linear regression between observation and prediction resulted in an $r^2$ of 0.92 and a standard error of ± 2.4 days. However, most of the predicted times to flower were longer than the observed times at 17 and 29°C.

In the model-validation experiment, total number of flower buds and plant height at flowering tended to increase as temperature (from VB to flower) increased. However, this difference was not statistically significant. The first flower size was also similar among temperature treatments. The average flower bud number, plant height, or flower diameter was 14.5, 37.5 cm, or 18.1, respectively.

4. Discussion

The influence of temperature on time to VB and flower can be quantified through Eq. [1]. Most researchers (Roberts and Summerfield, 1987) now use a linear model to quantify the relationship between temperature and rate of development (reciprocal of the time taken to reach flowering) as

$$\frac{1}{f} = a + bT$$

[8]

It is true that the thermal time and base temperature can be calculated mathematically from the constants $a$ and $b$. However, no biological meaning can be determined directly from Eq. [8]. The biological meaning represented by the parameters CTT and $T_{base}$ in Eq. [1] is much clearer. In addition, data transformation is unnecessary when Eq. [1] is applied. Compared with Eq. [8], Eq. [1] is simpler.

_Hibiscus_ should be grown at warm temperatures. _H. rosa-sinensis_ grown under 5°C were severely damaged and did not survive, while those under 11°C grew slowly (Karlsson. et al., 1991). Criley (1980) reported that minimum air temperature for best growing conditions for several European varieties should be 16 to 18°C (day) and 13 to 16°C (night). In the current study, development of _H. moscheutos_ ‘Disco Belle Mixed’ required a higher temperature. The estimated base temperature was about 13°C. The base temperatures estimated from Eq. [1] are close to the estimated 14.1°C from Eq. [7] when the rate parameter $k$ of bud development is set to zero. The maximum $k$ value, which means the most favorable condition for bud development, is estimated at 25.6°C. However, a warmer forcing temperature resulted in a shorter plant with fewer buds and smaller flowers (Table 3).

Conditions prior to VB had little effect on bud development. Plants in the validation experiment were treated with growth regulators and grown in similar conditions until the VB bud stage. Compared with the plants in model-development experiment, those plants were shorter and had fewer buds, but flower size remained similar. The relationship between temperature and bud development was not changed by chlormequat treatment, and the bud model’s prediction of time to flower was generally within ± 3 days.

Both 17°C and 29°C used in the validation experiment were out of the actual temperature range in the model-development experiment. Time to flower at those two temperature treatments might have been overpredicted because the bud development rate at 17°C and 29°C was not as low as extrapolated from Fig. 2.

The models presented in the current study provide a guide for controlling greenhouse temperature to match a target marketing date in commercial hibiscus production. From Eq. [1], one can estimate the days from the onset of long days to VB or flower under different forcing temperatures, and _vice versa_. Visible bud was first recorded when bud
diameter was about 2 mm. After VB, the bud development model allowed prediction of
days to flower, given a certain bud size and ADT, or ADT required, given a certain bud
size and desired days to flower (Fig. 4).

Acknowledgments

The authors acknowledge the Bedding Plants Foundation, Inc., for providing partial
funding of this project, Raker’s Acres Greenhouse for providing the seedlings, Dr. P. R.
Fisher for his assistance in developing the SAS code, and Cara Wallace for her careful
editing.

References


House, New York.


lily (Lilium longiflorum Thunb.) in response to temperature. HortScience 31(3): 349-
352.

Netherlands.


Butterworths, London.

handbook of flowering, Boca Raton, Florida.

Wang S.Y., 1986. A modeling study of the effects of temperature and daylength on the
Table 1: List of abbreviations and parameters.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f(T))</td>
<td>Function quantifying (k) as a function of temperature</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>ADT</td>
<td>Average daily temperature</td>
<td>°C</td>
</tr>
<tr>
<td>B</td>
<td>Flower bud diameter</td>
<td>mm</td>
</tr>
<tr>
<td>(B_0)</td>
<td>Initial bud length</td>
<td>mm</td>
</tr>
<tr>
<td>(B_f)</td>
<td>Final bud diameter</td>
<td>mm</td>
</tr>
<tr>
<td>(c_1)</td>
<td>Parameter in (f(T))</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>(c_2)</td>
<td>Parameter in (f(T))</td>
<td>°C (-1) day(^{-1})</td>
</tr>
<tr>
<td>(c_3)</td>
<td>Parameter in (f(T))</td>
<td>°C (-1) day(^{-1})</td>
</tr>
<tr>
<td>CTT</td>
<td>Cumulated thermal time</td>
<td>°C d</td>
</tr>
<tr>
<td>D</td>
<td>Days</td>
<td>days</td>
</tr>
<tr>
<td>(D_{of})</td>
<td>Days to flower from the bud measurement</td>
<td>days</td>
</tr>
<tr>
<td>(D_{FLW})</td>
<td>Days from the onset of long-day forcing to flower</td>
<td>days</td>
</tr>
<tr>
<td>(D_{VB})</td>
<td>Days from the onset of long-day forcing to visible bud</td>
<td>days</td>
</tr>
<tr>
<td>(k)</td>
<td>Rate parameter in bud development model</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>(t)</td>
<td>Time</td>
<td>days</td>
</tr>
<tr>
<td>(t_0)</td>
<td>Time zero</td>
<td>days</td>
</tr>
<tr>
<td>(T_{base})</td>
<td>Base temperature</td>
<td>°C</td>
</tr>
</tbody>
</table>

Table 2: Nonlinear regression results from fitting Eq. [1] to the days from forcing to visible bud (VB) and flower (FLW) models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Estimate</th>
<th>Lower</th>
<th>Upper</th>
<th>(N^z)</th>
<th>(R^{2'})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_{VB})</td>
<td>CTT</td>
<td>284.2</td>
<td>250.7</td>
<td>317.8</td>
<td>5</td>
<td>0.998</td>
</tr>
<tr>
<td></td>
<td>(T_{base})</td>
<td>12.9</td>
<td>12.5</td>
<td>13.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(D_{FLW})</td>
<td>CTT</td>
<td>714.5</td>
<td>580.2</td>
<td>848.8</td>
<td>5</td>
<td>0.994</td>
</tr>
<tr>
<td></td>
<td>(T_{base})</td>
<td>12.2</td>
<td>11.1</td>
<td>13.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^z\) Number of data set used in the regression.

\(^{2'}\) \(R^2\) was calculated as 1-(SS\(_{residual}\)/SS\(_{corrected\, total}\)).
Table 3: Effect of average daily temperature (ADT) from forcing to flower on bud number, plant height, and flower size of *H. moscheutos* 'Disco Belle Mixed'.

<table>
<thead>
<tr>
<th>ADT</th>
<th>Bud number</th>
<th>Plant height (cm)</th>
<th>Flower diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.2</td>
<td>47.5</td>
<td>68.9</td>
<td>20.6</td>
</tr>
<tr>
<td>18.9</td>
<td>34.3</td>
<td>66.5</td>
<td>17.3</td>
</tr>
<tr>
<td>21.4</td>
<td>23.6</td>
<td>55.3</td>
<td>20.0</td>
</tr>
<tr>
<td>25.5</td>
<td>17.8</td>
<td>53.5</td>
<td>19.2</td>
</tr>
<tr>
<td>26.4</td>
<td>12.3</td>
<td>46.2</td>
<td>16.9</td>
</tr>
</tbody>
</table>

P > F

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Parameter</th>
<th>Estimate</th>
<th>Lower</th>
<th>Upper</th>
<th>$n^*$</th>
<th>$R^2^y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>$c_1$</td>
<td>-2.89E-01</td>
<td>-5.72E-01</td>
<td>-5.14E-03</td>
<td>5</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>$c_2$</td>
<td>2.86E-02</td>
<td>4.25E-03</td>
<td>5.29E-02</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$c_3$</td>
<td>-5.56E-04</td>
<td>-1.07E-03</td>
<td>-3.96E-05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cubic</td>
<td>$c_1$</td>
<td>-3.16E-01</td>
<td>-3.67E-01</td>
<td>-2.65E-01</td>
<td>450</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>$c_2$</td>
<td>3.09E-02</td>
<td>2.64E-02</td>
<td>3.53E-02</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$c_3$</td>
<td>-6.03E-04</td>
<td>-6.99E-04</td>
<td>-5.06E-04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV, %</td>
<td></td>
<td>33.7</td>
<td>10.2</td>
<td>13.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Parameter estimates for the exponential model describing bud development (Eqs. [4], [6], and [7]).

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Estimate</th>
<th>Lower</th>
<th>Upper</th>
<th>$n^*$</th>
<th>$R^2^y$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k$</td>
<td>$c_1$</td>
<td>-2.89E-01</td>
<td>-5.72E-01</td>
<td>-5.14E-03</td>
<td>5</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>$c_2$</td>
<td>2.86E-02</td>
<td>4.25E-03</td>
<td>5.29E-02</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$c_3$</td>
<td>-5.56E-04</td>
<td>-1.07E-03</td>
<td>-3.96E-05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f(T)$</td>
<td>$c_1$</td>
<td>-3.16E-01</td>
<td>-3.67E-01</td>
<td>-2.65E-01</td>
<td>450</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>$c_2$</td>
<td>3.09E-02</td>
<td>2.64E-02</td>
<td>3.53E-02</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$c_3$</td>
<td>-6.03E-04</td>
<td>-6.99E-04</td>
<td>-5.06E-04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_f$</td>
<td>$B_f$</td>
<td>36.4</td>
<td>35.7</td>
<td>37.1</td>
<td>450</td>
<td>0.91</td>
</tr>
</tbody>
</table>

$^z$ Number in data set used in the regression.

$^y$ $R^2$ was calculated as $1 - (SS_{residual}/SS_{corrected\ total})$. 

167
Figure 1: Relationship between average daily temperature (ADT) and the number of days from forcing to visible bud (DVb) (▲) or from forcing to flower (DFlw) (●) in H. moscheutos 'Disco Belle Mixed'. Data points represent the treatment means. Error bars display the 95% confidence intervals. The curvilinear regressions are DVb = 284.2/(ADT-12.9) with an R² of 0.998 (solid line) and DFLw = 714.5/(ADT-12.2) with an R² of 0.994 (dashed line).

Figure 2: Estimates of k, the rate parameter in Eq. [2], obtained from fitting Eq. [2] separately to data from five temperature treatments (▲ symbol, ± asymptotic standard error), and the quadratic function f(T) (solid line) obtained from fitting Eq. [7] to data from all temperature treatments. The R² for the quadratic line is 0.89.
Figure 3: Predicted days from any measured bud diameter to flower through the exponential model against the observed days to flower for all 306 bud measurements on 25 plants in five different temperature treatments in the validation experiment. The regression has an $r^2$ of 0.92 and a standard error of 2.4 days.

Figure 4: Days to flower as a function of average daily temperature (°C) and bud diameter (mm) in H. moscheutos 'Disco Belle Mixed'.