An empirical model for predicting diurnal air-temperature gradients from edge into old-growth Douglas-fir forest

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(Received 3 January 1992; accepted 9 July 1992)

ABSTRACT


Edge — the boundary line between clearcut and adjacent old-growth forest — is one of the critical landscape elements in the highly fragmented forest landscapes of North America’s Pacific Northwest. Ecological phenomena at edges may be better understood by examining the physical environments near the edge. To further this objective diurnal air temperature gradients were measured along 16 gradients from the edge into the interior old-growth Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco] forest over the 1989 and 1990 growing seasons and analyzed effects of edge orientation (relation of edge-facing to the azimuth) and macroclimate (local weather conditions of the clearcut) on these gradients were also explored through regression analysis. The air temperature gradient was expressed with a simple exponential equation involving three intermediate variables of interest: air temperature in the interior forest (TEMPIF), difference in air temperature between the edge and inside the forest (Delta AT), and changing ratio of temperature along the gradient (SLOPE). Linear or nonlinear regression equations were developed to predict TEMPIF, Delta AT, and SLOPE. Correlation analysis always preceded regression analysis, in which the relationships between the regression parameters and independent variables representing edge orientation and macroclimate were further explored. A computer model developed from the final empirical relationships successfully predicted air temperature gradients, circumventing the need for time-consuming field measurements with expensive meteorological instruments, and generated new information about the influences of edge orientation and macroclimate on air temperatures. TEMPIF, Delta AT, and SLOPE were shown to be highly sensitive to the dependent variables. Although model application should be limited to

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edges created by recent (10- to 15-year-old) clearcuts adjoining old-growth Douglas-fir forest, the modeling approach could be applied to edges with different characteristics by modifying the relationships.

INTRODUCTION

Extensive use of dispersed clearcutting in the last several decades has created a highly fragmented ("checkerboard") forest landscape in North America's Pacific Northwest (Franklin and Forman, 1987). As a result, edge — the boundary line between clearcut and adjacent old-growth forest — has become one of the most important features of this landscape. Indeed, forest values such as wildlife habitat and biological diversity have been fundamentally changed because of the significant amount of edge and result edge effects created by the "checkerboard" (Yahner, 1988; Franklin, 1989; Lehmkuhl and Ruggiero, 1991).

Environment of the edge is unique, clearly distinguishable from that of the clearcut and interior forest (Chen, 1991). Both biological (Chen et al., 1992) and physical variables respond to edge environments, producing edge effects (i.e., ecological phenomena associated with edge). For instance, as one moves along a gradient from the edge into the old-growth Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco] forest, the microclimate changes considerably depending on edge orientation (i.e., relationship of edge-facing to the azimuth) and macroclimate (i.e., local weather conditions). Air temperature — one of the key variables characterizing energy flow in the biosphere (Lee, 1978; Campbell, 1986) and critical to predicting other meteorological variables (Bocock et al., 1977; Taconet et al., 1986; Dwyer et al., 1990), ecosystem processes in the Douglas-fir forest (Zobel et al., 1976; Waring and Franklin, 1979; Chapin et al., 1987), and natural disturbances (Beck and Trevitt, 1989) — is of particular interest.

The ability to predict microclimatic patterns near forest edges under specific macroclimatic conditions across a range of edge orientations is important to those managing forest resources. To this end, we (1) examine the empirical relationships between air temperature, edge orientation, and macroclimate along gradients from the edge into the old-growth Douglas-fir forest, (2) use regression analysis to develop a computer model based on those empirical relationships to predict diurnal air temperatures over such gradients during the growing season, and then (3) evaluate the model's ability to predict gradients for varying edge orientations and macroclimates. Our results can be used as inputs to ecological simulation models (e.g., Dale and Hemstrom, 1984; Running et al., 1989) and as an independent variable for analyzing biological processes (e.g. Edmonds, 1987; Peters, 1990; Dreistadt et al., 1991).
old-growth Douglas-fir forest (ge). For instance, as an independent variable, edge orientation, and forest age, number of tree species, and variation in microclimates, producing edge temperatures over such a wide range of conditions. Air temperature was measured every 15 s with thermocouples and Campbell's 21X microloggers 2 m above the ground; measurements were averaged over 30-min intervals. Equipment remained at each transect until a clear day was recorded (usually 3–10 days), then was moved to another.

MODEL DEVELOPMENT

Modeling basics

The air temperature gradient into the forest for any given time \( t \) (0–24 h) can be expressed by a simple exponential equation:

\[
\text{TEMP}(t) = \text{TEMP}_{\text{IF}}(t) + \Delta\text{AT}(t) \exp[-\text{SLOPE}(t) \cdot \delta] \quad \text{SLOPE}(t) \geq 0
\]  

(1)
where TEMP is air temperature (°C) at time t and δ is distance (m) from the edge into the forest. TEMPIF, ΔAT, and SLOPE are the primary intermediate variables of interest herein, representing, respectively, air temperature in the interior forest, difference in air temperature between the edge and forest, and change ratio of temperatures along the gradient. A positive ΔAT indicates that air temperatures decrease with distance from the edge, a negative ΔAT that they increase. Diurnal changes in air temperature from the edge into the forest can be predicted by simulating the dynamics of these three variables over a 24-h period.

TEMPIF, ΔAT, and SLOPE were independently estimated from field data (134 days of air temperatures) through regression analysis. First, appropriate regression equations were fit to the data for each of the three variables of interest. We further examined the relationships between these parameters involved and five independent variables representing edge orientation (θ) and macroclimate through correlation analysis and then developed further regression equations, generating final equations for the relationships between TEMPIF, ΔAT, and SLOPE and edge orientation and macroclimate:

\[
\text{TEMPIF} = \text{function}(T_{\text{min}}, T_{\text{max}}, T_{\text{min2}})
\]

\[
\Delta AT = \text{function}(\theta, T_{\text{max1}}, T_{\text{min}}, T_{\text{max}}, T_{\text{min2}})
\]

\[
\text{SLOPE} = \text{function}(\theta, T_{\text{min}}, T_{\text{max}}, T_{\text{min2}})
\]

Four independent variables used to describe the macroclimate are: \(T_{\text{max}}\) (daily maximum), \(T_{\text{min}}\) (daily minimum), \(T_{\text{max1}}\) (the previous day's maximum), \(T_{\text{min2}}\) (the next day's minimum air temperature). Based on these relationships, a computer model written in TURBO C++ was developed to predict diurnal air-temperature gradients with distance from the edge into interior forest given specific information on edge orientation and macroclimatic conditions. Edge effects were evaluated via combinations of ΔAT and SLOPE, which are highly correlated because of their intrinsic relationship in equation (1), the basis for model development. The model was verified by examining the sensitivities of TEMPIF, ΔAT, and SLOPE to edge orientation and macroclimate.

Following is a detailed explanation of how we estimated each of the three intermediate variables composing the empirical model for predicting diurnal air-temperature gradients.

**Estimation of TEMPIF**

The literature proposes many methods for simulating the diurnal pattern of air temperatures based on energy budget (Myrup, 1969; Lemon et al.,
Air temperatures at edges

and $\delta$ is distance (m) from
Slope are the primary
presenting, respectively, air
atmosphere temperatures along the
he decrease with distance
phi. Diurnal changes in air
one predicted by simulating

stantly estimated from field
regression analysis. First,
coefficients for each of the three
relationships between these
ables representing edge
ous equation analysis and then
ing final equations for the
PE and edge orientation

The macroclimate are: $T_{\text{max}}$
the previous day's maximum
ature. Based on these
C++ was developed to
ance from the edge into
rientation and macrocli-
a combinations of $\Delta AT$
iently of their intrinsic relationships
ement. The model was
Slope to

We estimated each of the
ical model for predicting

We used a simple combination of sinusoidal curve fitting in this study. A
similar method, previously applied (DeWit et al., 1978; Floyd and Brad-
Hoogenboom and Huck, 1986; Rothermel et al., 1986), was found to be the best under most circumstances (Reicosky et al., 1989). The
original approach requires the daily maximum and minimum temperatures
and the times of these extremes. We modified that approach in three ways:
(1) by adding to the simulation $T_{\text{max}}$ and $T_{\text{min}}$ which provide the information on trends in local weather condition, (2) by empirically estimating the
time of the temperature extremes $t_1$ (time of minimum temperature) and $t_2$
time of maximum temperature), and (3) by beginning the simulation
period at one
and ending it at the next $t_1$. Traditionally, $t_1$ and $t_2$ have been calculated from time of sunrise and
set depending upon the location (latitude and longitude) of study sites
and days of the year (DeWit et al., 1978; Parton and Logan, 1981; Beck and
Trevitt, 1989). However, in our study, these two variables did not signifi-
cantly correlate with location and Julian day (by a $F$-test) so that the means
were used. The means computed for $t_1$ ($n = 114$) and $t_2$ ($n = 119$) from the
field data for the two seasons studied were 5.43 and 14.40 h, respectively.
The model algorithms are:

$$
\begin{align*}
\text{TEMPIF} &= T_{\text{av1}} - \text{AMP1} \left[ \cos \left( \pi (t - t_1) \right) \right] & t \leq t_2 \\
\text{TEMPIF} &= T_{\text{av2}} - \text{AMP2} \left[ \cos \left( \pi (t + L')/(24 - T') \right) \right] & t > t_2
\end{align*}
$$

where

$$
\begin{align*}
T_{\text{av1}} &= (T_{\text{min}} + T_{\text{max}})/2 \\
\text{AMP1} &= (T_{\text{min}} - T_{\text{max}})/2 \\
T_{\text{av2}} &= (T_{\text{min2}} + T_{\text{max}})/2 \\
\text{AMP2} &= (T_{\text{max}} - T_{\text{min2}})/2 \\
T' &= t_2 - t_1 \\
L' &= (24 - T') - t_2
\end{align*}
$$
Fig. 1. Linear relationship of diurnal air temperature in the interior forest (TEMPIF) and local macroclimate (i.e. air temperature of adjacent clearcut); n = 34 (minimum temperatures) and 39 (maximum temperatures).

\[ T_{\text{max}} = 3.1012 + 0.7556 \, T_{\text{maxc}} \quad R^2 = 0.95 \text{ and MSE} = 0.736 \]

\[ T_{\text{min}} = 2.1859 + 0.8566 \, T_{\text{minc}} \quad R^2 = 0.84 \text{ and MSE} = 1.034 \]

Estimation of \( \Delta AT \)

As for TEMPIF, the diurnal pattern of \( \Delta AT \) values also produces a sinusoidal curve (Fig. 2). Two-stage regression analysis was used to estimate \( \Delta AT \). In first-stage regression, we divided the curve in two, before
and after time of maximum $\Delta AT (t')$, and fit this curve with the following equations:

$$
\Delta AT = \begin{cases} 
\beta_0 - (\beta_0 - \beta_1) \cos(\pi t/\Delta_1) & t \leq t' \\
\beta_2 - (\beta_0 - \beta_2) \cos[\pi (t + \Delta)/\Delta_2] & t > t'
\end{cases}
$$

where $\beta_0$ is the maximum $\Delta AT$, $\beta_1$ is the average $\Delta AT$ during time interval $\Delta_1$, $\beta_2$ is the $\Delta AT$ during time interval $\Delta_2$, and $\Delta$ is the difference between $\Delta_1$ and $\Delta_2$ ($\Delta_2 - \Delta_1$).

Fig. 3. Timing of the maximum $\Delta AT (t')$ as a function of edge orientation ($\theta$); $t'$ occurs earliest at an northeast-facing edge ($\theta = 74.8$) and latest at a southwest-facing edge ($\theta = 254.8$).
Correlation analysis showed that $t'$ was strongly related to $\theta$ (Fig. 3). Thus, in second-stage regression, we fit the following cosine equation (non-linear) to estimate $t'$:

$$t' = 12.925 + 3.3216 \cos\left[\pi(\theta + 74.78)/180\right]$$

MSE = 2.793

In this equation, the value 74.78 indicates that maximum $\Delta AT$ occurs earliest at a northeast-facing edge.

Correlation analysis showed that $\beta_0$ was strongly related to $\theta$ and diurnal temperature fluctuation, $\Delta t$ (i.e., $T_{\text{max}} - T_{\text{min}}$). In second-stage regression, we square-root transformed the independent variables ($\Delta t$) and fit the following non-linear equation to estimate $\beta_0$:

$$\beta_0 = \sqrt{\Delta t} \left[1.0869 + 0.1828 \cos\left[\pi(\theta - 197.18)/180\right]\right]$$

MSE = 1.372

In this equation, the value 197.18 indicates that $\beta_0$ is maximum at a southwest facing edge (Fig. 4a).

Correlation analysis showed that $\beta_1$ appeared to be highly related to $T_{\text{max}}$, $T_{\text{min}}$, $T_{\text{maxi}}$, $\theta$, and a new variable, $\sigma$ (i.e., $(T_{\text{max}} - T_{\text{min}})/(T_{\text{maxi}} - T_{\text{mini}})$, representing the ratio of diurnal temperature fluctuation. $\beta_1$ values were larger near southeast-facing edges with higher values of $\sigma$. Therefore, we fit the following non-linear equation in second-stage regression to estimate $\beta_1$:

$$\beta_1 = \sigma \left[1.9230 + 0.6459 \cos\left[\pi(\theta - 126.09)/180\right]\right]$$

MSE = 0.649

In this equation, the value 126.09 indicates that $\beta_1$ is maximum at a southeast-facing edge regardless of changes in $\sigma$. The predicted pattern is illustrated in Fig. 4b.

Correlation analysis showed that $\beta_2$ was significantly related to $\theta$ and diurnal temperature difference between $T_{\text{max}}$ and $T_{\text{min2}}$. In second-stage regression, we fit the following non-linear equation to estimate $\beta_2$:

$$\beta_2 = (T_{\text{max}} - T_{\text{min2}}) \left[0.0927 + 0.01612 \cos\left[\pi(\theta - 115.26)/180\right]\right]$$

MSE = 0.686

In this equation, the value 115.26 indicates that $\beta_2$ is maximum at a southeast-facing edge. The predicted pattern is illustrated in Fig. 4c.

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Fig. 4. Distributions, from second-stage regression, of predicted (a) $\beta_0$ values relative to edge orientation ($\theta$) and diurnal temperature fluctuation, $\Delta t$ (i.e., $T_{\text{max}} - T_{\text{min}}$), (b) $\beta_1$ values relative to $\theta$ and the ratio of diurnal temperature fluctuation, $\sigma$ (i.e., $(T_{\text{max}} - T_{\text{min}})/(T_{\text{maxi}} - T_{\text{mini}})$), and (c) $\beta_2$ values relative to $\theta$ and diurnal temperature fluctuation, $\sigma$ (i.e., $T_{\text{max}} - T_{\text{min2}}$). $T_{\text{max}}$ and $T_{\text{min}}$ = daily maximum and minimum air temperatures, respectively; $T_{\text{maxi}}$ = previous day's maximum; $T_{\text{min2}}$ = next day's minimum.
Estimation of SLOPE

SLOPE was estimated from field data for TEMPIF and ∆AT to void the autocorrelation between SLOPE and the other two variables. Two-stage regression analysis was used again to estimate SLOPE. Prior analysis (correlation analysis) suggests that changes in SLOPE over time are related to macroclimate. Because $T_{\text{max}} - T_{\text{min}}$ plays an important role in determining SLOPE before 14.40 h (the computed mean for $t_2$) and $T_{\text{max}} - T_{\text{min2}}$ after 14.40 h, in first-stage regression we divided the sinusoidal curve in two sections and fit the data with the following equation (nonlinear):

$$SLOPE = \gamma\left[\kappa_0 + \kappa_1 \cos\left(\pi(t - \kappa_2)/180\right)\right]$$

(4)

where $\kappa_0$, $\kappa_1$, and $\kappa_2$ were the parameters need further estimation in second-stage regression. $\gamma$ is the variable computed as follows:

$$\gamma = \begin{cases} T_{\text{max}} - T_{\text{min}} & t \leq 14.40 \\ T_{\text{max}} - T_{\text{min2}} & t > 14.40 \end{cases}$$

$SLOPE$ estimates had to be corrected after first-stage regression. A very large ($> 0.5$) or small ($< 0.004$) $SLOPE$ value suggests the absence of a clear edge effect (Fig. 5). Hence, before further statistical analysis, estimated $SLOPE$ values were reset to zero if they fell outside the range 0.004–0.5 (i.e., if there was no edge effect).

Fig. 5. Effect of changing ratio of diurnal air temperatures from edge into interior forest ($SLOPE$) on temperature in the interior forest (TEMPIF) with distance from the edge. $SLOPE$ values $> 0.05$ (fast change over short distance) or $< 0.004$ (little or no change over long distance) are not considered in the model because they do not produce meaningful edge effects.
IPF and $\Delta AT$ to void two variables. Two-stage SLOPE. Prior analysis $E$ over time are related
ant role in determining
inusoidal curve in two (nonlinear):

(4)

Further estimation in as follows:

Because $K_2$ values estimated from equation (4) appear to be stationary
over time, the mean (115.2) was used to produce the final SLOPE esti-
mates. Re-estimated values of $\sigma_0$ and $K_1$ had harmonic changing patterns
so that we used a three-term Fourier series in the second-stage non-linear
regression of the form:

$$K_0, K_1 = A_0 + A_1 \sin\left[\pi(t + \omega_1)/12\right] + A_2 \cos\left[\pi(t + \omega_2)\right]$$

MSE $= 7.413 \times 10^{-8}$ for $K_0$
MSE $= 2.182 \times 10^{-8}$ for $K_1$

where $A_0$ is the mean value $A_1$ and $A_2$ are the amplitudes of the first and
second harmonics of the series, and $\omega_1$ and $\omega_2$ are the phase changes. The
predicted patterns of $K_0$ and $K_1$ are illustrated in Fig. 6 and estimated
coefficients listed in Table 1.

Because the variable $y$ has a discontinuity at 14:40 h (Fig. 7), a linear
smoothing technique (Harvey, 1981) was used over the 3-h window 12.90–
15.90 to make a smooth prediction and still minimize the residuals.
Fig. 7. Linear smoothing of discontinuity feature resulting from estimating the changing ratio of diurnal air temperatures from edge into interior (SLOPE) in second-stage regression with different independent variables for the periods before and after 14.40 h, the computed mean time of maximum temperature.

MODEL EVALUATION

The diurnal air-temperature gradients from the edge into interior forest simulated by the model are similar to those described by Chen (1991). Air temperature varied sinusoidally over the simulation period (Fig. 8), increasing exponentially during the day and decreasing at night with distance from the edge. In the mid-morning and late afternoon, there was little to no difference in air temperature (horizontal line) at the edge and inside the forest. Figure 8 further illustrates the influence of local macroclimate on air temperature gradients; on warm, sunny days (Fig. 8a) the gradients are sharper and on cool, cloudy days weaker (Fig. 8b).

The influence of edge orientation is evident by comparing both simulated maximum air temperatures at four contrasting edges (0 m; Fig. 9) and

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\kappa_0$</th>
<th>$\kappa_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>$8.6905 \times 10^{-5}$</td>
<td>$1.6946 \times 10^{-6}$</td>
</tr>
<tr>
<td>$A_1$</td>
<td>$3.756 \times 10^{-5}$</td>
<td>$1.5024 \times 10^{-4}$</td>
</tr>
<tr>
<td>$A_2$</td>
<td>$2.8765 \times 10^{-5}$</td>
<td>$2.0443 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\omega_1$</td>
<td>$1.633 \times 10$</td>
<td>$1.084 \times 10$</td>
</tr>
<tr>
<td>$\omega_2$</td>
<td>$8.91$</td>
<td>$-1.594 \times 10$</td>
</tr>
</tbody>
</table>

$A_0$ = mean; $A_1$, $A_2$ = amplitudes of first and second harmonics; $\omega_1$, $\omega_2$ = phase changes.
estimating the changing
in second-stage regression
and after 14.40 h, the

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the gradients are
paring both simu-
es (0 m; Fig. 9) and
iguration 4) for determining

: $10^{-6}$
: $10^{-4}$
: $10^{-4}$
: 10
: 10

, $\omega_2$ = phase changes.

Fig. 8. Simulated diurnal air-temperature gradients with distance from the edge into interior forest as influenced by macroclimate: (a) for a warm, sunny day (7 September 1990), model inputs were $T_{\text{max}} = 24.63$, $T_{\text{min}} = 17.78$, $T_{\text{max}1} = 25.87$, $T_{\text{min}1} = 5.11$ (all °C), and $\theta = 225^\circ$; (b) for a cool, cloudy day 23 August 1989, model inputs were $T_{\text{max}} = 17.56$, $T_{\text{min}} = 10.25$, $T_{\text{max}1} = 17.19$, $T_{\text{min}2} = 8.17$ (all °C), and $\theta = 45^\circ$. 
Fig. 9. Simulated maximum diurnal air-temperatures at four edges (0 m) as influenced by edge orientation (θ) and diurnal air-temperature gradients at four θs at the computed mean time of maximum (14.40 h) and minimum (5.43 h) temperatures for the following macroclimatic model inputs: $T_{\text{max}} = 26.0$, $T_{\text{min}} = 10.0$, $T_{\text{max1}} = 27.0$, $T_{\text{min2}} = 15.2$ (all °C).

air temperature gradients with distance from the edge for different edge orientations (Fig. 10). In the early morning, temperature is highest (11.8°C at 5.43 h) at an east-facing edge, which receives direct sunlight then, and lowest (9.4°C) at a west-facing edge, which is completely shaded (Fig. 9). However, temperature at an east-facing edge peaks earliest (13.93 h) of all
for different edge orientations is highest (11.8°C) with the computed mean maximum temperature of 38.89 °C. Air temperatures decline with distance from the edge into interior forest, although south- and west-facing edges have steeper temperature gradients (temperature differences of 4.04 and 3.63°C, respectively) than do the other edge orientations (Fig. 10a). The depth of edge influence is greater at the east- and south-facing edges than at the other two orientations because east and south edges receive radiation earlier in the day than do the other two and have longer periods for edge effects to accumulate. However, at 5.43 h, the computed mean time of minimum temperature in the simulation period, temperatures decrease with distance from the edge at east-facing orientations, increase at west-facing orientations, and remain relatively unchanged at north- and south-facing orientations (Fig. 10b). These differences all relate to the distribution of solar radiation over time.

Generally, the combination of a larger $\Delta AT$ and a smaller SLOPE indicates a stronger and deeper edge effect, the combination of a smaller $\Delta AT$ and a larger SLOPE a weaker (or no) edge effect. Evaluation of edge effect (0 m) as influenced by the computed mean the following macroclimatic model inputs (15 July 1990) $T_{\text{max}} = 38.89$, $T_{\text{min}} = 9.13$, $T_{\text{max1}} = 26.9$, $T_{\text{min2}} = 9.41$ (all °C), and (b) at a south-facing edge ($\theta = 180°$) for the macroclimatic model inputs for the same day given in Table 2.

![Fig. 10. Sensitivity of $\Delta AT$ and SLOPE (a) to edge orientation ($\theta$) for the macroclimatic model inputs (15 July 1990) $T_{\text{max}} = 38.89$, $T_{\text{min}} = 9.13$, $T_{\text{max1}} = 26.9$, $T_{\text{min2}} = 9.41$ (all °C), and (b) at a south-facing edge ($\theta = 180°$) for the macroclimatic model inputs for the same day given in Table 2.](image-url)
effects becomes more complicated, however, with all other combinations of these two variables. For example, it is difficult to evaluate the significance of edge effects for air temperature gradients at east- and west-facing edges in the mid-afternoon (Fig. 10a), where both $\Delta AT$ and SLOPE are smaller; an index, such as degree days, has been frequently used in analyzing biological responses. Application of this index, however, is also questionable in analyzing many biological processes. Further study is urgently needed to understand how $\Delta AT$ and SLOPE, separately and in combination, characterize edge effects.

Sensitivity analysis showed that TEMPIF, computed independent of edge orientation, is indeed very sensitive to the input values for macroclimate. Recall from model development (see Fig. 1 and related text) that TEMPIF is linearly related to the maximum and minimum air temperatures in the clearcut; the equation coefficients (0.7556 and 0.8566, respectively) reflect the air-temperature differences in these two environments.

$\Delta AT$ and SLOPE, computed on the basis of edge orientation and macroclimate, were found to be sensitive to both, as determined by a test on an extremely hot day (15 July 1990). $\Delta AT$ was highest (0.62°C) at 5.43 h and peaked earliest (9.93 h) at an east-facing edge, which received direct solar radiation earliest; it peaked highest (5.98°C) at a south-facing edge, latest (15.93 h) at a west-facing edge, and at about the same time (13.93 h) at a north-facing edge as did maximum air temperature in the clearcut (Fig. 10a). SLOPE values at east- and south-facing edges were smaller than those at north- and west-facing edges (Fig. 10a), a smaller value indicating a greater depth of edge influence (recall Fig. 5). At night, values for both variables differed little among the four edge orientations. $\Delta AT$ and SLOPE values varied considerably according to macroclimate conditions (Fig. 10b, Table 2). When the weather was stable and cool (conditions c and d. Table 2).

### TABLE 2
Simulation inputs (°C) for four different weather conditions (a, b, c and d) and their daily temperature differences

<table>
<thead>
<tr>
<th>Input *</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$</td>
<td>38.89</td>
<td>24.84</td>
<td>19.88</td>
<td>17.19</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>9.13</td>
<td>6.15</td>
<td>11.13</td>
<td>13.15</td>
</tr>
<tr>
<td>$T_{\text{max}}1$</td>
<td>35.52</td>
<td>18.03</td>
<td>23.84</td>
<td>20.22</td>
</tr>
<tr>
<td>$T_{\text{min}}2$</td>
<td>9.41</td>
<td>7.27</td>
<td>7.99</td>
<td>10.25</td>
</tr>
<tr>
<td>Daily difference</td>
<td>(29.76)</td>
<td>(18.69)</td>
<td>(11.89)</td>
<td>(4.04)</td>
</tr>
</tbody>
</table>

* $T_{\text{max}}$ = daily maximum air temperature; $T_{\text{min}}$ = daily minimum air temperature; $T_{\text{max}1}$ = previous days' maximum air temperature; $T_{\text{min}2}$ = next day's minimum air temperature.
other combinations of variables and west-facing edges and SLOPE are smaller; values for both variables are smaller than those in the clearcut (Fig. 10b, conditions c and d).

\[2), \Delta AT \text{ and SLOPE values are small, indicating a weak edge effect. With warmer and more variable weather (conditions a and b), values for } \Delta AT \text{ and SLOPE increased, and edge effects became stronger and more distinctive.}

The model has two weaknesses. First, using sinusoidal curves may be problematical. These curves were divided in two, with the two sections joined to maintain least squares error (nonlinear regression) or averaged locally (i.e., for SLOPE). Sinusoidal functions were used throughout model development because both the first and second derivatives at the conjugations of the two sections of the curve were zero, indicating a smooth, continuous regression line there and a minimum error. However, with sinusoidal functions, the modeler has less control of the changing ratios of the independent variables over time. A solution would be to use more Fourier terms, but this might create problems of overparameterization or further analysis of regression residuals. Nevertheless, other types of functions (e.g., exponential) should be explored for estimating the parameters involved in the regression analysis.

Second, the technique for estimating regression coefficients (parameters) is problematical. With this method, only the mean was computed, and the variances associated with the mean were not carried through model construction. Because of the large number of regressions (about 700,000), we did not check the error distributions but instead assumed a normal distribution with zero mean for residuals. However, further analysis of the variances may help increase model capability and improve precision so that the model might be applied more widely and help provide some other unusual cases.

Despite the preceding weaknesses, this empirical model successfully produced diurnal air-temperature gradients from the edge into interior forest, circumventing the need for time-consuming field measurements with expensive meteorological instruments and generating new information about the effects of edge orientation and macroclimate on air temperatures. Although applications of the model should be limited to recently created edges (i.e. 10- to 15-year-old clearcuts) adjacent to old-growth Douglas-fir forests on relatively flat (< 10°) terrain, our modeling approach could be applied to other types of edges by modifying the relationships developed herein for TEMPIF, ΔAT, and SLOPE with information about other variables (e.g., edge age, forest structure near the edge, seasonal dynamics of regional weather conditions, topographic features). We think that this model can be to be a powerful tool for evaluating edge effects in the forested landscape.
ACKNOWLEDGEMENT

The study was supported by a Prentice and Virginia Bloedel Professorship awarded to the College of Forest Resources, University of Washington; the Pacific Northwest Research Station, USDA Forest Service; and grants awarded to the Olympic Natural Resources Center by USDA Forest Service New Perspective's Program. We thank Carol Perry, Steve Lowe, and Douglas Maguire for review and helpful suggestions.

REFERENCES


