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Impact of climatic change on the values of effective temperature sum

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INTRODUCTION

Boreal coniferous forests cover more than two thirds of the land area of Finland, our example country. In this part of the world the biome spans from 60°N to 69°N. Temperature is known to be a very important ecological factor in the humid climate prevailing in this area (Mikola, 1980). A common variable used in ecological studies to describe the response of ecological systems to temperature is the effective temperature sum (called 'heat sum' by Sarvas (1972)). The idea underlying the practical definition of this variable is, first, to define a function for relating the ecological response, $r$, in place $x,y$, to temperature, $T$ which is function of time, $t$:

$$r = r(x,y,T(t)).$$ (1)
Then, given the temperature distribution:

\[ \varphi = \varphi(x, y, T(t)) \]

one obtains a "general effective temperature sum", GETS, from the integral:

\[ \text{GETS}(x, y) = \int \tau(x, y, T) \varphi(x, y, T) dT \]

We make some simplifying assumptions. Although the response function \( \tau(\cdot) \) at least for some ecological processes essentially varies in time (Sarvas, 1972) and most likely also space, we assume, in the first place, that the response function is universal. Moreover, following the early example of Reaumur (1735, quoted by Sarvas (1972)) we define the response function as a broken linear curve:

\[ \tau_0 = \begin{cases} 
0 & , T < T_0 \\
T - T_0 & , T > T_0 
\end{cases} \]

where \( T_0 \) is the baseline temperature (Figure 1.). Based on this function the Effective Temperature Sum, \( ETS \), is defined as:

\[ ETS(T_0) = \int \tau_0(T) \varphi(T) dT \]

\( ETS \) is used as the ecological indicator variable for quantifying the responses of the taiga ecosystems to potential climatic changes.

The aim of this study is to develop an equation which describes the response of the \( ETS \) variable to a change in i) the mean temperature, in ii) the standard deviation of temperature, and in iii) the baseline temperature. The results are illustrated in the form of nomograms.
VARIATIONS IN THE TREE GROWTH AND IN THE EFFECTIVE TEMPERATURE SUM

Tree growth declines by a factor of 2-3 from the southern taiga (≈61°) to the regions near to the northern timberline (≈69°) (Yearbook..., 1983). Year-to-year variation in terms of standard deviation can be calculated based on the tree ring indices. The data by Mikola (1960) from the years 1880-1944 suggests that the year-to-year variation increases towards north (Table 1.).

Effective temperature sum, ETS, is calculated for the official statistics using a baseline temperature of +5°C. This data indicates that, from ≈61°N to ≈70°N, the ETS decreases by a factor of about 2 (Heino and Hellsten, 1983). The data is from the years 1961-1980. Year-to-year variation in this data increases towards north (Table 2). The similarities of the growth data and the ETS data indicate that ETS could be used as an indicator of ecosystem response to the temperature climate. Of course, ETS is only a rough aggregated variable without much relevance to processes at a specific location at a given time. The reason why ETS, nonetheless, appears to predict productivity rather well may be related to the special features of the climate. In such a humid climate a very crucial thing is the length of the photosynthetically active period which is largely determined by temperature (Pelkonen, 1981).
A METHOD FOR CALCULATING ETS FROM CLIMATOLOGICAL DATA

In this section we develop an equation which predicts the ETS as a function of the mean temperature, the standard deviation in temperature, and the baseline temperature.

It is important to note that, at least in Finland, the temperature frequency distributions on an annual basis are very close to Gaussian distributions (Heino and Hellsten, 1983). It is thus possible to describe the temperature distribution by using only two parameters: the annual average temperature, \( \bar{T} \), and the standard deviation of temperature, \( \sigma \):

\[
\varphi(T) = \frac{N}{\sqrt{2\pi}\sigma} \exp\left[ -\frac{(T-\bar{T})^2}{2\sigma^2} \right]
\]

\[
\int_{-\infty}^{\infty} \varphi(T) dT = N \quad \cdots \text{number of days}
\]

Through the south-north gradient the distributions vary by both \( \bar{T} \) and \( \sigma \) (Figure 2.). Selecting the broken linear function (Eq. 4), and the normal distribution for \( \varphi \) ETS can be calculated as the function of the baseline temperature, \( T_0 \), the mean temperature, \( \bar{T} \), and the standard deviation, \( \sigma \), in the following way:

\[
ETS(T_0, \bar{T}, \sigma) = \int_{T_0}^{\infty} (T - T_0) \frac{N}{\sqrt{2\pi}\sigma} \exp\left[ -\frac{(T-\bar{T})^2}{2\sigma^2} \right] dT =
\]

\[
= \frac{N\sigma}{\sqrt{2\pi}} \exp\left[ -\frac{(\bar{T}-T_0)^2}{2\sigma^2} \right] + \frac{N}{2} (\bar{T} - T_0) \left[ 1 + \text{erf}\left( \frac{\bar{T} - T_0}{\sqrt{2\sigma}} \right) \right]
\]

where

\[
\text{erf}(x) := \frac{2}{\sqrt\pi} \int_0^x e^{-t^2} dt
\]
Eq. 7 can now be used to calculate the $ETS$ from different observed values of $T_0$, $\bar{T}$ and $\sigma$ (Figures 3-6). Moreover, it can also be used in connection with model calculations, such as those by Manabe and Stouffer (1980), to quantify the responses of ecosystems, in terms of $ETS$, to possible predicted values of climatic change.

Eq. 7 can be developed further. If one defines a "reduced" (dimensionless) temperature $\Theta$ by

$$\Theta := \frac{\bar{T} - T_0}{\sigma}$$

(8)

the $ETS$ can be expressed in the following way

$$ETS = N \sigma \rho(\Theta)$$

(9)

where

$$\rho(\Theta) = \frac{1}{\sqrt{2\pi}} e^{-\Theta^2/2} + \frac{\Theta}{2} \left[1 + \text{erf}\left(\frac{\Theta}{\sqrt{2}}\right)\right]$$

(10)

is a universal function for all values of $(T_0, \bar{T}, \sigma)$. After having calculated $\Theta$ via Eq. (8) the same nomogram (Figure 7) can be used for all $T_0$-values.

We hope that the Eq. 7 through Eq. 10 and the nomograms would be useful in assessing the ecological response of the northern boreal forests to possible changes in the temperature climate.
REFERENCES:


Table 1 Standard deviation in tree growth. Data from years 1880-1944 (Mikola 1950).

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude (°N)</th>
<th>σ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tammela</td>
<td>61.5</td>
<td>14.4</td>
</tr>
<tr>
<td>Padasjoki</td>
<td>61.0</td>
<td>12.1</td>
</tr>
<tr>
<td>Kuru</td>
<td>61.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Pohjankangas</td>
<td>61.5</td>
<td>13.1</td>
</tr>
<tr>
<td>Saarjärvi</td>
<td>63.0</td>
<td>14.1</td>
</tr>
<tr>
<td>Kainuu</td>
<td>64.5</td>
<td>12.9</td>
</tr>
<tr>
<td>Savukoski</td>
<td>67.5</td>
<td>16.5</td>
</tr>
<tr>
<td>Lappi</td>
<td>69.0</td>
<td>17.3</td>
</tr>
</tbody>
</table>

Table 2 The mean, the maximum value, and the minimum value of effective temperature sum. Data from years 1961-80 (Heino & Hellsten, 1983).

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude (°N)</th>
<th>mean</th>
<th>maximum</th>
<th>minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helsinki</td>
<td>60.5</td>
<td>1350</td>
<td>1551</td>
<td>1102</td>
</tr>
<tr>
<td>Jokioinen</td>
<td>61.0</td>
<td>1229</td>
<td>1417</td>
<td>1002</td>
</tr>
<tr>
<td>Jyväskylä</td>
<td>63.0</td>
<td>1147</td>
<td>1344</td>
<td>915</td>
</tr>
<tr>
<td>Kajaani</td>
<td>64.5</td>
<td>1049</td>
<td>1284</td>
<td>802</td>
</tr>
<tr>
<td>Sodankylä</td>
<td>66.0</td>
<td>786</td>
<td>984</td>
<td>577</td>
</tr>
<tr>
<td>Utajoki</td>
<td>70.0</td>
<td>622</td>
<td>908</td>
<td>412</td>
</tr>
</tbody>
</table>
Figure 1. The broken linear function used to relate the ecological response to temperature.
Figure 2. Temperature frequency distributions on five locations in Finland (Heino & Hellsten, 1983). The fractions left from the vertical axis are omitted when calculating ETS with the +5°C base line temperature.
Figure 3. Nomogram based on Eq.7 for deriving ETS from the mean temperature and the standard deviation of temperature. Baseline temperature for τ(·) is fixed at +5° C. (N=365 days).
Figure 4. Same as Figure 3. but with baseline temperature fixed at +3°C.
Figure 5. Increase in ETS corresponding to an increase of 2 Kelvin in the mean temperature. Horizontal axis refers to the initial mean temperature.
Figure 6. Relative increase in *ETS* corresponding to the increase of 2 Kelvin in the mean temperature.
Figure 7. Nomogram based on Eqs.8-10 for obtaining ETS from the ‘reduced’ temperature θ. (N=365 days).