

RAPID ESTIMATION OF HEAT ACCUMULATION FROM MAXIMUM AND MINIMUM TEMPERATURES

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Abstract. A method is presented for estimating heat accumulation by using daily maximum and minimum temperatures and assuming the sine curve as an approximation of the diurnal temperature curve. A table is given for estimating heat accumulation for a given day, and a computer program is described for accumulating heat units over a 1-year period. The technique permits the use of an upper as well as a lower threshold and has a precision in the order of $\pm 5\%$.

INTRODUCTION

Ecologists often use heat accumulation above a given threshold to measure or predict the effect of temperature on biological processes. This heat accumulation is most commonly expressed in degree-days and is estimated by measuring the area contained above a threshold temperature and under the trace on a thermograph chart. The procedure is time consuming, but most of the simpler graphical methods are not sufficiently precise. Arnold (1960) devised a method of estimating accumulated heat units by means of daily maximum and minimum temperatures only. Although his system greatly extends the data available for computing accumulated heat, it is limited to a narrow range of maximum and minimum temperatures and does not allow for the introduction of an upper temperature threshold. Arnold's method has been extended so that these limitations no longer apply, and a computer program has been produced that greatly facilitates calculations. The method is outlined in the following section.

METHOD

The principal assumption of the method is that the diurnal temperature curve, which is typically skewed to the right and contains minor variations, is similar to the trigonometric sine curve, which is symmetrical and smooth. Under this assumption the daily mean temperature, which is necessary to the computation, is taken to be the average of the maximum and minimum, whereas with the actual curve this is not always true. However, Arnold has shown that for any given day the area under a sine curve, the amplitude of which has been adjusted to the daily maximum and minimum temperatures, closely approximates the area under the temperature curve.

In extending Arnold's method four situations were considered: two involving a lower temperature threshold only (as in Arnold's paper) and two involving both an upper and a lower threshold.

Case 1: Daily minimum above lower threshold (K1); no upper threshold

This is the simplest case (Fig. 1, A), and the heat units are calculated directly from the difference between the mean daily temperature and the threshold.

Case 2: Daily minimum below lower threshold (K1); no upper threshold

This situation and the equation giving the area are shown in Fig. 1, B. Table 1 provides an array of solu-

tions for this case for any combination of minimum temperatures from 0°F to 50°F and maximums from 52°F to 120°F over a lower threshold of 51°F. The heat units accumulated on a given day over a base of 51°F are estimated by entering the table at the appropriate maximum and minimum temperatures for that day and reading the degree-days from the body of the table—e.g., maximum = 80°F, minimum = 47°F, heat units = 13.

Heat units above a threshold other than 51°F can be obtained in one of two ways: by shifting the maximum and minimum scales by the difference between the required threshold and 51°F or by adding the algebraic difference (51°F—required threshold) to the daily maximum and minimum temperatures. This procedure is similar to that given by Arnold, but Table 1 allows for a wider range of maximums and minimums and hence for a greater range of threshold temperatures.

Case 3: No restriction on daily minimum; daily maximum exceeds upper threshold (K3); horizontal cutoff at upper threshold

This situation and the equation for computation are shown in Fig. 1, C. The application of the upper threshold in this manner is somewhat artificial in that heat is accumulated at a constant rate for the period when the temperature exceeds the upper limit (K3). The technique has proven useful, however, where temperatures above the upper threshold diminish rather than arrest a process. Calculation of heat units may be made from Table 1 as follows: first, the total heat units for the day are read from the table without regard to the upper limit (K3); the scales are then shifted (or a constant is added to the temperatures) so that the new base temperature becomes the upper limit K3. The heat units between the two limits K1 and K3 are given by the difference between the two values.

Case 4: No restriction on daily minimum; daily maximum exceeds upper threshold (K2); vertical cutoff at upper threshold

This situation and the expression for computation are shown in Fig. 1, D. Here no heat units are accumulated for the period when the temperature exceeds the upper threshold (K2). This approach is useful where temperatures in excess of the upper threshold arrest a process. This case does not lend itself to tabular presentation, and the computation is best accomplished by using a computer.

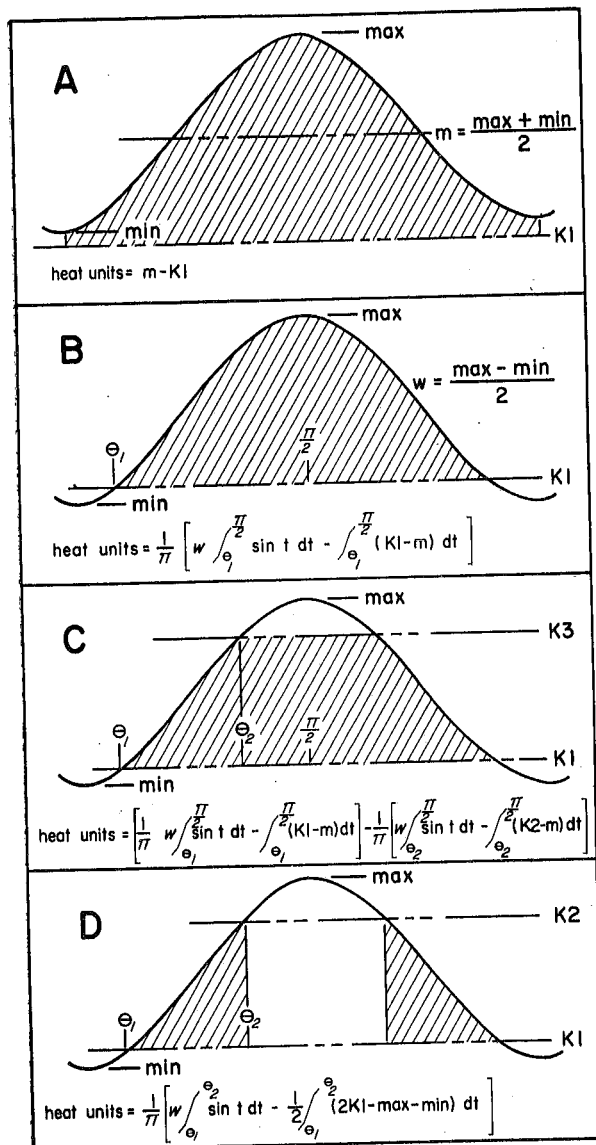


FIG. 1. Four cases in the calculation of accumulated heat units by means of a sine curve. In each case the horizontal axis is time (1 day), the vertical axis is temperature, and the hatched area represents the accumulated heat units.

PROGRAM

A FORTRAN program has been written which calculates heat accumulation using: (1) the lower threshold only (cases 1 and 2); (2) an upper threshold with a horizontal cutoff (case 3); and (3) an upper threshold with a vertical cutoff (case 4). The input consists of a serial listing of daily maximum and minimum temperatures. The output is a 12 (month) \times 31 (day) table giving the total accumulated heat units (to nearest whole degree-day) at the end of each day. The lower threshold $K1$ and the upper thresholds, $K3$ for a horizontal cutoff and $K2$ for a vertical cutoff, are set by the user for each run. The program tests the magnitude of each pair of maximum and minimum temperatures against the assigned values of $K1$, $K2$, and $K3$ and uses the appropriate

method for calculating degree-days. An IBM 1620II can compute and print the three heat-accumulation patterns for a 6-month period in about 3 min. Prints of the program with control specifications are available from the Forest Research Laboratory of the Department of Fisheries and Forestry, Fredericton, N. B.

PRECISION

The computer program (and Table 1) gives the area under the sine curve with amplitude specified by any given pair of maximum and minimum temperatures. Error in the method stems from the assumption that the area under the sine curve is identical to that under the diurnal temperature curve. Arnold (1960) compared the sine curve area with areas from thermograph traces and found the difference to be extremely small (2-4% of the total of accumulated heat units). Although he suggested procedures for refining the estimates in critical cases, he concluded that the technique was generally satisfactory. The introduction of the upper temperature thresholds with either a horizontal or a vertical cutoff does not seem to affect precision. The areas under thermograph traces for a 6-month period were measured and compared the accumulated heat units with those computed from daily maximum and minimum temperatures for the same station. Even with horizontal or vertical cutoffs, the difference between the four methods never exceeded 5% of the total of accumulated heat units.

INTERPRETATION

The foregoing sections have dealt with the mechanics of an efficient technique for the estimation of heat accumulation. A caveat with respect to interpretation of such data is in order. There are two limitations to interpretation regardless of the level of refinement in the estimation of heat accumulation. First, the method provides, at best, a measure of only one of the many environmental parameters. Clearly one cannot expect heat accumulation alone to explain all variation in a biological response. Second, there are two assumptions implicit in the use of heat-accumulation units:

- 1) It is assumed that the response of the plant or animal to temperature is linear and that this response is constant over a growth period.
- 2) It is assumed that biologically meaningful temperature thresholds for various age classes of the subject organism are available. These limitations are critical to any biological interpretation of heat accumulation and users of the technique, including the refinement presented here, should have a clear awareness of this fact. A more complete consideration of the problems inherent in the interpretation of the response of organisms to temperature is provided by Wang (1960) for plants and by Andrewartha and Birch (1954, p. 129-205) for animals.

CONCLUSION

The estimation of heat units by measuring the area under a sine curve as proposed by Arnold is an efficient tool of considerable value to ecologists. The precision of the estimate is not affected by the introduction of upper temperature thresholds and is well within the tolerances imposed by the ability of the ecologist to make biological interpretations of the data. The technique is simple and greatly increases the number of stations that

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can be used, as only maximum and minimum temperatures are required. This method in conjunction with a computer program greatly speeds the estimation of accumulated heat units without appreciable loss in precision.

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