Predicting Winter Wheat Phenology Using Temperature and Photoperiod

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ABSTRACT

Various phenological models and temperature synthesis models were tested for use with winter wheat. For winter crops the need for hourly temperature arises for accurate calculation of chill units and heat units. Since only maximum and minimum temperatures were available, methods of synthesizing the diurnal temperature curve were tested for their ability to replicate both actual hourly temperatures and growing degree-hours. A logarithmic function with constant shape coefficients was selected for future use in phenological models because of its ability to replicate the above quantities, and the lack of data needed for statistically fitting the shape coefficients in each case. For synthesizing hourly values all root mean square errors were less than 6°F whereas other functions tested had errors as large as 20°F. This logarithmic function was analytically integrated to yield degree-hours and chill units. Daily root mean square errors for growing degree-hours for the constant coefficient logarithmic model were less than 34 degree-hours for all months tested. Other models had values as large as 100 degree-hours when the mean daily degree-hour total was 644.

Four models for predicting phenological development of winter wheat were examined. These four were the Adjusted Biometeorological Time Scale model (A-BMTS), the chill-heat relationship model, the critical chill model and the critical photoperiod model. The chill-heat relationship model failed to adequately predict development. The root mean square errors for heading date for the fourteen crop years of data available were ±4.8 days for the A-BMTS model, ±2.9 days for the critical chill model and ±2.8 days for the critical photoperiod model. These compared to ±2.8 days for using the mean date of occurrence. Other stages were better predicted by the critical photoperiod model than any other model or the calendar date. For the soft dough stage the critical photoperiod model had a root mean square error of ±2.4 days compared to ±3.5 days for the critical chill model, ±4.9 days for the A-BMTS model and ±4.6 days for the calendar date.

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I. INTRODUCTION

The final goal of any crop modeling is to determine the total yield of the crop. In order to find this total production for a county, state or nation two quantities must be known. The first quantity is the yield per acre, and the second is the number of acres in production. Techniques using information provided by crop calendars can be employed to obtain both quantities.

The study presented in this paper examines several different crop calendars for use with winter wheat. In this chapter the need for such models for global scale crop forecasts will be demonstrated along with a brief description of the growth habit of wheat.

1.1 The Definition and Purpose of a Crop Calendar

The objective of this study is to compare techniques for predicting various phenological events in wheat. Various methodologies will be tested in order to find the best approach for handling future phenological data. As will be shown in the next chapter, a number of different techniques may be applicable.

In the past several years, there has been renewed interest in the derivation of crop calendars for many crops. The phrase "crop calendar" is used to describe the various events in the life cycle of the crop. The independent variables used to predict the crop calendar generally include meteorological parameters such as temperature and precipitation, physical parameters like photoperiod, and crop physiological characteristics such as variety. The first two types of parameters in the above list can easily be described quantitatively, but placing numerical values on physiological characteristics may be difficult.

Certain terminology must be introduced to accurately describe a crop calendar. Two similar terms that are used to describe changes in crops are crop growth and crop development. Crop growth concerns the gain in size of a plant without any changes in the growing parts. Crop development describes the progress of internal changes in the plan that occur with or without external changes. In most cases, only the external changes in the plant can be observed, and the periods defined by these changes are called stages. When only internal changes in the plant are occurring, these are referred to as phases. Crop calendars are used to model crop development by predicting the occurrence of particular stages.

Phenology is a science dealing with observation of characteristic phenomena of an organism throughout its life cycle. Therefore it can also be said that a crop calendar predicts the phenology of the crop.

1.2 Uses of a Crop Calendar

As was stated previously, a crop calendar has uses in finding both yield per acre and the number of acres in production. In yield modeling, dates of various growth stages in the plant are necessary, because many yield models use the environmental parameters before and after certain stages. In many crops, final yield may be closely related to weather conditions during specific stages, more so than other stages (Fischer, 1973).

It is in the identification of an individual crop that a crop calendar has its primary application. Recent satellite technology has produced resolution capability of 70 m in the LANDSAT program (Harper, estimated values on a global scale and provide necessary information to avoid or lessen the impact of large-scale food shortages and famine.

1.3 Growth Habit of Winter Wheat

The growth habit of most major crops can be described as being of either the spring or winter type. In temperate latitudes most crops with the spring growth habit are sown sometime in the early spring and are harvested during the same growing season sometime in summer or early autumn. Corn is a good example of a spring type crop.

A crop with winter growth habit requires a period of exposure to cool temperatures to initiate the reproductive portion of its life cycle. In general a winter type crop is sown in autumn and begins to grow. As temperatures decrease toward winter, the plant enters a stage called dormancy in which much of the visible portion of the plant may appear to die off. However if the plant is not winter killed, it survives in this state throughout the winter season and with the exposure to cool temperatures undergoes the chilling process that is required for the plant to initiate the reproductive portion of its life cycle. It is in the reproductive cycle that the grain itself is produced by the plant. The plant renews the active growth cycle in the spring and is generally ready for harvest in early to mid-summer.

For wheat, both spring and winter types exist. In temperate latitudes the winter type is generally preferred since it tends to outyield spring types. Thus for much of the U. S. Great Plains and temperate zones in other countries such as the U.S.S.R., winter wheat is widely grown.

1976). Thus, individual fields of crops can be observed. As changes take place during the development of crops, the spectral signatures as viewed from the satellite may change. In order to identify a given crop it will be necessary to know the crop stage. This will provide human interpreters or automated systems with a guide for identifying what crop is planted in a given field.

The LACIE (Large Area Crop Inventory Experiment) program is designed to use the satellite data from the LANDSAT system, combined with global weather analysis from the WMO, to provide realistic estimates of crop production on a global scale. It is this world wide requirement of LACIE that necessitates the use of crop calendars. Although the dates of various stages at a given location may not vary greatly from year to year, the site to site variation of dates on a global scale is great. Also a number of countries will not provide information on typical dates of stages for crops grown in their nations. Therefore, methods of determining when these stages will occur, based on other information that these countries will provide, need to be developed. Daily values of temperature are reported for much of the world. Since temperature, as will be shown later, is one of the major factors controlling plant development, crop calendars based on temperature may be able to provide the required phenological information.

Near real time reporting of the crop shortages and surpluses will help the world food situation. Even in the U.S., where an efficient crop reporting program has been devised, it takes several months after harvesting for final yield values to be reported. Application of a complete LACIE type program will provide a faster method of reporting

II. PREVIOUS RESEARCH

It was decided to separate the review of the previous research into three sections. This was done to illustrate the three distinct subject areas from which information for modeling can be obtained. The first section relates previous work done in the crop modeling field, with an emphasis on that which applies to winter wheat. A review of pertinent agronomic research is presented in the second section. The final section discusses some work done with fruit trees and how this may relate to winter crops.

2.1 A Brief History of Crop Phenology Modeling Applicable to Winter Wheat

The general developmental response of plants to environmental factors has been known as long ago as the 1700's. The primary factors were found to be temperature and photoperiod. Robertson (1968) provides a detailed description of much of this early scientific work. The response to temperature has been found to be a linear function of the mean daily temperature above an effective threshold temperature. This concept has been given the name "growing degree-days", and may be expressed as:

$$K = \sum_{i=s_1}^{s_2} (T_{m_i} - T_B) , \tag{2.1}$$

where the subscript i denotes the days between stages s_1 and s_2, T_{m_i} is the mean temperature on day i, T_B is a known threshold temperature, and K is the model total. In equation (2.1), the term $(T_{m_i} - T_B)$ should be set equal to zero if it is numerically less than zero. The value of K will depend on the stage being modeled and the location of the site. When the right side of equation (2.1) equals K, the plant is assumed to have reached stage s_2.

The limits of application of this equation were demonstrated by Nuttonson (1955). In this volume, he effectively summarized all the wheat data then available on a global basis and found mean values of K for the major stages of emergence to heading and heading to ripe for each site. For winter wheat, this study was done solely with the variety Kharkof in the U.S. and the local variety being grown at that time in other countries. His results for K showed that K varied from site to site and was site specific. The coefficient of variation of K ranged as high as 25% at some sites.

Nuttonson's work demonstrated the applicability of the degree-day concept at some sites but did not provide the universal model needed for a global program. In addition, the high coefficient of variation at other sites showed that there must be some problems with the degree-day concept.

Wang (1960) is one of many who has criticized the degree-day or "heat unit" system. He finds several problems originating from the threshold value employed in the degree-day system. The lower threshold temperature often varies throughout the life cycle of the plant. An upper threshold temperature also exists, and when ambient temperatures exceed this upper threshold value, plant development will not proceed. This implies the existence of an optimum temperature for plant development between the upper and lower threshold temperatures. He also notes the works of other authors showing the effects of other factors on plant development. These factors include solar radiation, duration of light exposure, wind, and moisture.

Some of these factors are somewhat accounted for in the model devised by Robertson (1968), which will be discussed in depth later. Recent theoretical work by Sharpe and DeMichele (1977) and Sharpe et al. (1977) shows much promise in relating actual development rate functions to temperature, but further research remains to be done before such a model can be successfully applied to field crops. Until such work is completed, a Robertson type model or a heat sum total will probably be the most reliable method of relating temperature to development.

It was recognized early in the 1800's that increased hours of sunlight accelerated plant development. Nuttonson (1955) recognized this as a possible reason for the variation in the total degree-days from site to site, and introduced a concept termed "photothermal units". These are obtained by multiplying the daily degree-day value by the daylength (L_i), and may be expressed as:

$$K' = \sum_{i=s_1}^{s_2} L_i(T_{m_i} - T_B) \,, \qquad (2.2)$$

with K' the model total.

In general, this method provided a better coefficient of variation of K' than simple degree-days alone but did not provide the universal model for winter varieties that was desired. It did however show that the length of day (called "photoperiod") was a necessary quantity for any universal model.

Garner and Allard (1920) were the first to understand the concept they termed "photoperiodism". Many plants require exposure to a certain number of uninterrupted hours of daylight or uninterrupted hours of darkness before the reproductive cycle will occur. Plants of the former type are called "long-day plants" and those of the latter "short-day plants". If the required photoperiod conditions are not met, the plant will not enter the reproductive portion of its life cycle in spite of any favorable thermal environment.

It was this concept along with ideas similar to those suggested by Wang that led to the development of the model devised by Robertson (1968). The model was initially developed using a variety of spring wheat. This model is now referred to as the Robertson Biometerological Time Scale (BMTS) and can be expressed as:

$$1 = \sum_{i=s_1}^{s_2} \left[a_1(L_i-a_o) + a_2(L_i-a_o)^2\right]\left[b_1(T_{X_i}-b_o) + b_2(T_{X_i}-b_o)^2 + b_3(T_{N_i}-b_o) + b_4(T_{N_i}-b_o)^2\right] . \qquad (2.3)$$

In this case T_{X_i} is the maximum temperature, T_{N_i} is the minimum temperature, a_o and b_o are the photoperiod and temperature thresholds respectively and a_1, a_2, b_1, b_2, b_3, b_4 are model coefficients. As before, if a parentheses () term is less than zero it is set to zero (there are some exceptions to this rule, but these would not normally apply to wheat, so this discussion will use this zeroing convention). Examination of the model shows that it consists of three quadratic expressions:

$$V_{1_i} = a_1(L_i-a_o) + a_2(L_i-a_o)^2 ,$$

$$V_{2_i} = b_1(T_{X_i}-b_o) + b_2(T_{X_i}-b_o)^2 ,$$

$$V_{3_i} = b_3(T_{N_i}-b_o) + b_4(T_{N_i}-b_o)^2 .$$

Rewriting yields:

$$1 = \sum_{i=s_1}^{s_2} V_{1_i}(V_{2_i} + V_{3_i}) \quad . \qquad (2.4)$$

Should either V_{1_i} or the sum $(V_{2_i} + V_{3_i})$ be equal to zero, the daily contribution will also be zero. Thus, if the critical number of hours of daylight has not been met in a long-day plant, favorable temperature conditions will have no effect on plant development.

The use of quadratic expressions for independent factors does provide, in addition to a threshold value, an optimum value with proper coefficients. The coefficient and threshold values (a_0, a_1, a_2, b_0, b_1, etc.) are found via an iterative regression technique. As with earlier models, the right hand side is summed until it equals the left hand side. When this occurs the plant is considered to have attained stage s_2.

Robertson's original work was done on a variety of spring wheat called Marquis. Using data from several Canadian sites, the model derived reasonable expressions for each of the terms. When the model was applied to independent data from Brazil it provided good results in predicting the various stages.

It was a desire for a variety-independent model that prompted an attempt to derive BMTS coefficients for winter wheat. All eighteen site-years to be listed in the next chapter were used in the program. No provision for varietal differences were made.

As was noted in Robertson's original paper, "no solution" is one of the possible results for the model. This is what occurred for all but one stage of this data set. The primary cause for the failure of this model is the varietal differences. As will be shown later, the heat required by each variety varies greatly. This in turn, leads to poor fitting by the regression procedure and inaccurate BMTS model coefficients.

In recent years, there has been more work done with this model. Williams (1974a) used the BMTS on a single variety of barley grown in Canada. He obtained data for between 42 and 56 site-years with which to do the procedure. Williams (1974b) then did a critical evaluation of the performance of the BMTS. Based on a comparison of model-derived parameters to known agronomic values, he concluded that the model-derived values were probably applicable within the area in which the model had been developed. He had much less confidence in the applicability of the model in areas climatically different. He felt that a better model needed to be devised.

With the failure of the initial analysis of the BMTS and study of the commentary by Williams, further attempts using the BMTS in this paper were rejected. Instead, a more physically based, variety specific model was to be tried. It is this type of model which will be discussed in future sections.

Despite the problems outlined above, the BMTS model can be applied to some situations. The Earth Satellite Corporation (1976) has adapted this model along with a yield model, and integrated this with satellite data in a first step for a universal spring wheat program. The results are still preliminary, and it appears that some tuning of the models needs to be done, but results for the program appear encouraging.

Other models for winter wheat have been much less common. Very little research was done after Nuttonson's photothermal units were tried and did not provide the desired result. But in recent years a few attempts on winter wheat have been made.

Neghassi (1974), using a data base of seven crop years at North Platte, Nebraska, applied a variety of methods to try to explain the variation of dates of certain developmental stages. He used a slightly more sophisticated version of degree-days that employed an upper threshold temperature in addition to a lower threshold, a solar thermal unit that used daily net radiation, and a potential evapotranspiration sum. He found that none of these measures provided a better estimate for the developmental stages than did the mean number of days between stages. The data used by Neghassi is also part of the data set to be employed in this paper and will provide results for comparison.

Feyerherm et al. (1977) developed a universal model for winter wheat by modifying the model and values found by Robertson (1968) for Marquis (spring) wheat. He recognized from agronomy research that such factors as soil moisture, soil temperature, amount of chilling, and variety were very important in determining the rate of development of winter wheat. These factors will be discussed further in the following section. In an effort to account for these factors, he found a statistically based modifier to the basic Robertson model. This modifier was found by using the climatological values of January mean temperature and yearly mean rainfall. By assuming that these two parameters were important for determining soil moisture and temperature, amount of chill, and for the variety most popular in an area, this would provide a meaningful value with which to modify the base model.

However, Feyerherm's statistical technique, along with the extrapolation of the spring wheat model to winter wheat, led to the belief that many errors were possible. All fitting was done with the heading date only. Tests of this model employing the data to be used in this paper shall be presented later.

2.2 Pertinent Research in Agronomy

A tremendous amount of research has been done by agronomists on winter wheat and many other crops. However the crop modeler should not expect much of this research to be applicable to his problem. Most of this research is oriented toward other goals, particularly those associated with breeding more productive crops. Also, much of this work is done in controlled environments, with conditions rarely approaching field conditions. Thus considerable care must be taken when attempting to adapt this information for modeling purposes.

Review of some of this work reveals that for the case of winter crops other factors beside air temperature and photoperiod are important for crop development. These secondary factors include variety, chill requirement, soil temperature and soil moisture.

Varietal differences were noticed many years prior to intentional research programs. Two different varieties planted side by side would develop at different rates, even though they were exposed to exactly the same environmental conditions. For some crops it is common to hear a variety being referred to as a 100 day variety in a given location. This would indicate that in this location under normal weather conditions this variety would take one hundred days between planting and harvesting. Another variety might be classified as a 110 day variety, and so on. This provides the grower with some idea of how long this variety will take to mature and whether it will be suited for his operation.

Other factors, related to the variety will need to be considered in order to select the best variety for a given location. One of these factors is the degree of winter habit that the variety exhibits. All true winter crops require a period of exposure to temperatures between approximately zero to twelve degrees centigrade for a period of time of approximately ten to sixty days in order to proceed into the reproductive portion of the life cycle. The greater amount of chilling required, the greater the degree of winter habit. This process of chilling is sometimes referred to as vernalization. During this process the dormant apical meristem of the plant is converted to one which will proceed into the reproductive stages (Trion and Metzger, 1970). Plants failing to receive sufficient chilling will either fail to flower or do so much later than normal.

The biochemical reactions that take place during the chilling phase are not well understood. According to Gott (1957) the reaction may be schematically described as

$$A \rightleftharpoons A' \rightarrow B \, . \qquad (2.5)$$

The final chilling product B is produced from the first product A'. A' is either produced from substance A, or converted back to substance A depending on the ambient temperature. The rates of these reactions are not truly known and, therefore, very little more about proposed reaction scheme can be discussed. It is the simplest scheme that can explain the observed physiological reactions of the plant.

A lack of understanding or agreement also exists concerning how effective chill varies with temperature. Nix (1977) has proposed a chill unit function

$$CU = \sum_{i=P}^{FI} \sum_{j=1}^{24} (12 - T_{ij}) , \qquad (2.6)$$

for

$$0°C \le T_{ij} \le 12°C ,$$

where T_{ij} is the hourly temperature for hour j on day i, and i is a daily increment from planting (P) to a phase referred to as floral initiation (FI). Obviously, greatest effective chill occurs at 0°C, and no chill occurs at temperatures greater than 12°C or at temperatures less than 0°C. Note that this function does not allow for the reverse reaction ($A' \rightarrow A$) to occur. This reverse process which usually takes place at high temperatures (greater than 12°C) is sometimes referred to as de-vernalization (Blair and Patterson, 1962).

A review of other agronomy articles suggests still another possible solution. As was mentioned earlier, some risk exists in attempting to relate controlled environment results to field conditions, but sufficient evidence from various sources seems to indicate that in this case such an extrapolation is justified. Hänsel (1953) noted the effective hastening of flowering in winter rye by vernalization treatment in a temperature range of -5 to +15°C, with a broad maximum effect at -1 to +9°C. Bierhuizen (1973) further suggested that temperatures greater than 15 to 17°C can have a de-vernalizing effect in reversing the vernalizing process already completed.

Similar work has been done with winter wheat. Chujo (1966a) observed a relative maximum vernalizing effect about 4 to 8°C with a minimum near 1°C, and another minimum above 11°C. A similar maximum in vernalization response was found by Trione and Metzger (1970) near 7°C with minimums at 0°C and 12°C. Further work by Chujo (1966b) indicates that alternating temperatures on a daily basis between optimum chilling conditions and high reversal temperatures will cancel out vernalizing effects. Also, Chujo (1970) has shown that plants treated at less than optimum chill conditions, then exposed to warm temperatures, will be more adversely affected in reproductive development than plants treated for the same period of time under optimum chilling conditions, then exposed to similar warm temperatures.

This work suggests that a chilling response function can be developed, although specific details of such a function can not be precisely expressed. For winter wheat, this function should have a maximum chilling of about 6°C with zero chill at both 0°C and 12°C. A maximum value of negative chill should occur at and above 18°C. A function with these characteristics shall be tested on the data set to be examined in this paper.

Once a chill function has been determined, a method of usage must be formulated. Several possible techniques exist. One method is to sum chill units until a certain total is reached, and then begin summing heat units. This method has been applied to fruit tree research by Ashcroft et al. (1976) and will be discussed later. A second method has been developed by Nix (1977) and is conceptually illustrated in Figure 2.1. This graph shows the amount of heat units needed to reach floral initiation as a function of chill received for a given variety. As more chilling occurs, the amount of heat required for floral initiation decreases. Although Nix indicates that this situation is most true for

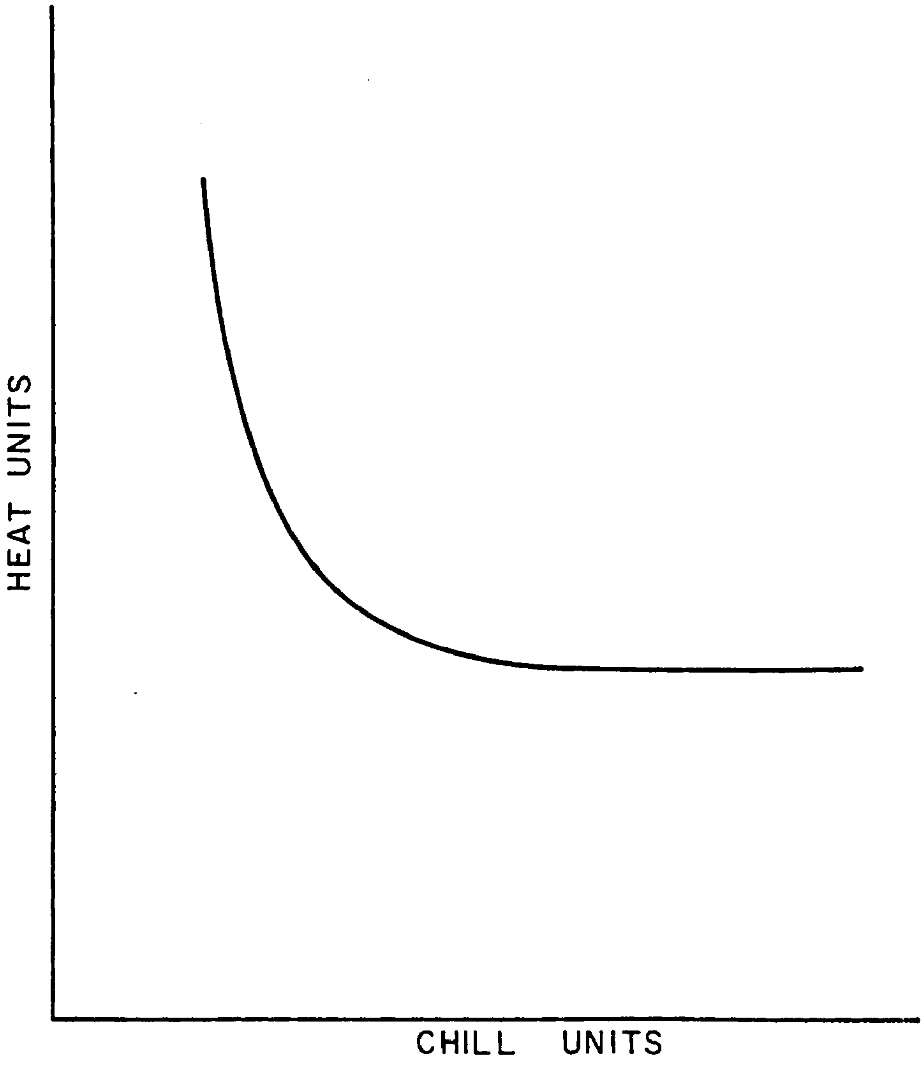

Figure 2.1. Amount of heat required for floral initiation as a function of chill received for one variety (after Nix, 1977).

floral initiation, he has stated that it is probably applicable to stages such as jointing and heading. It should be noted that although the function relating the required heat for floral initiation to the chilling received will vary with variety, the general shape of the function will remain similar. In general, a variety properly selected for a given area will receive sufficient chilling during the winter season in ambient environmental conditions (Bierhuizen, 1973).

The dependence of sufficient chill on variety has been examined rather extensively by Martinić (1967, 1969, 1973). Since all varieties received vernalization treatment at the same temperature, not much quantitative information can be concluded from these results. It was quite obvious that each variety possesses its own vernalization requirement. However no numerical method for determining when the vernalization requirement for varieties in the natural environment is met can be deduced.

Another of the secondary factors controlling crop development is soil moisture. Nix (1977) has suggested the general response of crop development to soil moisture, and this is conceptually illustrated in Figure 2.2. Very small values of soil moisture would greatly retard the crop development. As soil moisture increased, this trend reverses, and for moderate amounts of soil moisture crop development is actually accelerated. As soil moisture approaches field capacity, no modification of the development units occur.

In general, soil moisture is normally not observed. A number of methods have been developed for modeling soil moisture. These methods usually involve the determination of the potential evapotranspiration from the observed daily meteorological parameters. However, a large

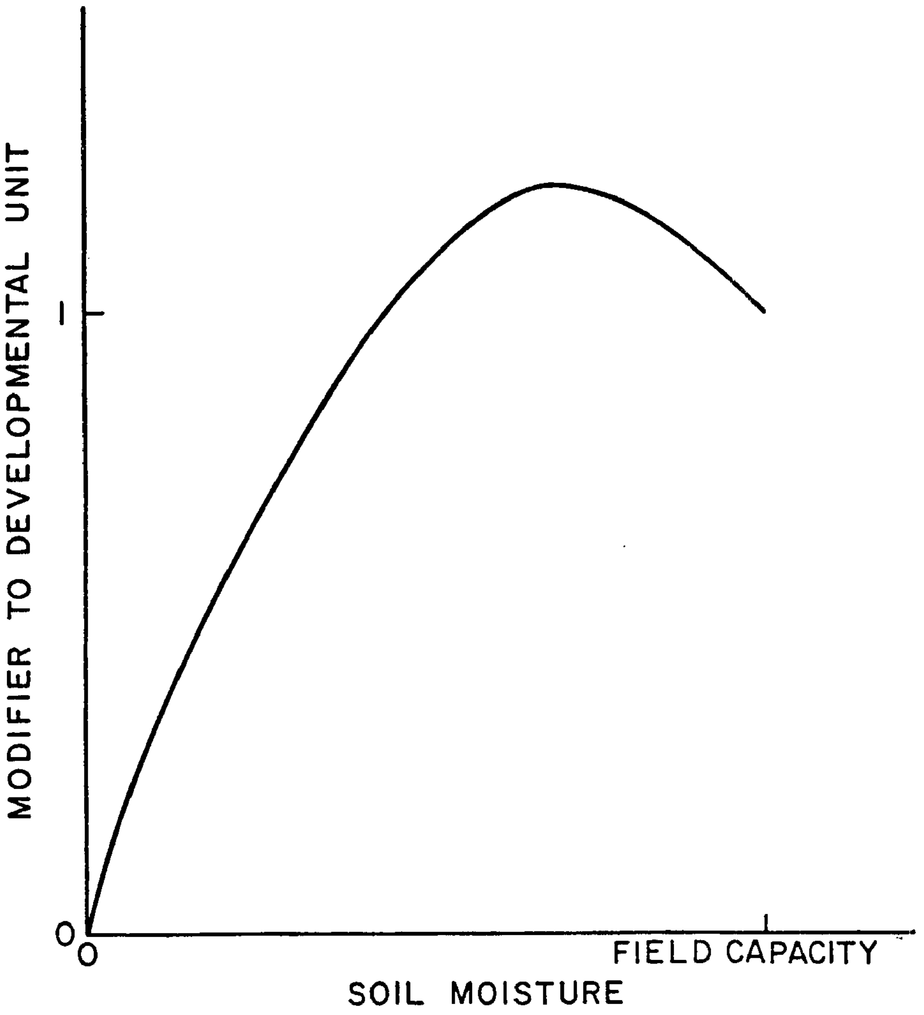

Figure 2.2. Conceptual model of multiplicative modifier to developmental units as a function of soil moisture (after Nix, 1977).

source of error can occur in the conversion from potential to actual values (Smith, 1975). As Smith also points out, the choice of potential evapotranspiration formula is often quite limited. Formulae such as Penman's, require observations of sunshine, temperature, humidity and wind. In many cases, such observations are not readily available, particularly for climatological stations. Even if these parameters are available, such formulae should not in general be used for daily values of moisture or for small land areas. Other sophisticated methodologies exist, such as that developed by Baier et al. (1972); however here again a large number of input parameters are required, making application of such methods difficult.

Therefore, soil moisture calculations are not included in most crop development models. Errors in calculation of values, and lack of quantitative understanding of plant interaction, make application of such data extremely difficult. However recognition of soil moisture differences as a possible source of error in crop development models is necessary.

The final secondary factor involved in crop development is soil temperature. This factor is probably more important than air temperature during the periods of planting to emergence, winter chilling, and prior to spring growth initiation. This is because it is during these times that most or all of the living portion of the plant is located below the soil surface. As the plant matures following germination and spring growth initiation, soil temperature becomes less important (Bierhuizen, 1973).

In wheat, the soil temperature of greatest importance occurs at crown depth, which is the region of the major root structure, located a few centimeters below the surface (Nix, 1977). In most cases soil temperature data is not usually reported at crown depth if at all, and it may be difficult to approximate soil temperature at this depth using air temperature.

Soil temperature is a complex function of such factors as soil type, color, ground cover, soil moisture, radiative effects and air temperature (Geiger, 1973). As such, soil temperature models require a great deal of input information, which again is not generally available from climate reports. A one significant figure guess at soil temperature may be obtained by using a running mean of air temperatures of about 10 days as suggested by Willis (1978). This method may be used where necessary, and little or no soil temperature data exists. Most phenological models simply employ daily air temperature for all growth stages, rather than attempting to model soil temperature.

Another triggering mechanism has been suggested by Welsh (1978). This method uses the fact that most varieties of wheat in temperate climates are long-day type plants. A critical photoperiod must be reached before reproductive development occurs. Welsh has suggested that for each variety a heat sum accumulation begin in the spring after this critical photoperiod has been exceeded. Thus in Welsh's opinion the chill requirement of the plant is not an important factor since it has been met well before the critical photoperiod occurs. This technique shall also be tested in this paper.

2.3 Fruit Tree Research

Fruit trees also must undergo a period of exposure to cool temperatures in order to produce fruit during the following growing season. This chill treatment appears to be similar to that required in winter crops. Thus methods used for determination of the completion of rest in fruit trees may be applicable to winter crops. This is not to imply that the physiological processes are the same in both wheat and fruit trees, but the mathematical methods used in fruit tree research may be applicable for use with wheat.

Chilling functions for fruit trees such as those suggested by Richardson et al. (1974), Ashcroft et al. (1976), and Aron (1975) are similar to the one suggested for wheat which was discussed earlier. All of these functions require hourly temperatures for use. Richardson et al. (1974) used a linear approximation to estimate hourly temperatures for use with chill units. This method has received criticism from authors such as Aron (1975), Sanders (1975) and McCarthy (1977). These researchers found that application of this linear model failed to provide accurate values of chilling in their location. An examination of this linear method will follow later in this paper.

III. METHODS AND MATERIALS

This chapter discusses the general approach to the problem of structuring phenological models. The first section outlines the concepts behind the models to be tested. The available data, both meteorological and phenological are discussed in the next section. The final two sections illustrate the mathematical approaches for synthesizing the temperature curve for both heat units and chill units.

3.1 Methodology and Conceptual Model

All of the phenological models examined in this paper will be variety specific. That is, each variety will possess its own model values. As was suggested in Chapter II, varietal differences as they relate to plant development can be significant. Previous models developed by other authors fail to directly account for varietal differences.

If all the necessary data were available, a set of model values for each variety would be determined. Varieties could then be grouped by certain characteristics. Relationships between characteristics of varietal groups and climate could be used to determine varietal types being grown in locations where the variety is not known.

Unfortunately the data presently available are not adequate for this type of analysis. Instead as a preliminary step, a detailed investigation of which modeling procedure is best suited for winter wheat phenology will be undertaken. This will involve the development and testing of four models. One of these models will be the adjusted Biometeorological Time Scale (A-BMTS) model discussed in the previous chapter. Also to be tested will be the chill-heat relationship model suggested by Nix (1977) and illustrated in Figure 2.1. The final two models to be tested will involve the summing of heat units after some requirement is met. One of these models to be developed is based on completion of chilling prior to the start of heat unit sums and is referred to as the critical chill model. The second model to be developed from the concept suggested by Welsh (1978) will require a certain photoperiod to be obtained before heat unit sums are started. This model will be entitled the critical photoperiod model.

3.2 Data Available

The data for this problem consist of two components. The first component is the dates of observation of the various stages to be modeled. The second component is the accompanying meteorological information.

3.2.1 Phenological Data

The phenological data available at the time of this study are listed in Table 3.1. Listed for each site and year is the variety used, and the dates of the following phenological stages: seeding, emergence, spring growth initiation, jointing, heading and soft dough. Each of these stages can be identified by some external change in the plant.

Seeding is the physical planting of the seed. The appearance of the radicle identifies emergence. Spring growth initiation is determined by cutting back the senescent area prior to the expected date. The cut area will green-up a few days prior to the actual time of spring growth initiation and therefore provides a guide for when to start to observe the noncut area. Jointing is identified by the appearance of two nodes and can be referred to as the beginning of

TABLE 2.1 List of Phenological Data.

Location	Year	Variety	Seeding	Emergence	S.G.I.	Jointing	Heading	Soft Dough
North Platte	62-63	Scout	9/06	9/11	3/09	4/28	5/23	6/14
	63-64		9/25	10/02	3/21	5/01	5/27	6/16
	64-65		9/15	9/21	3/15	5/03	5/28	6/23
	65-66		8/30	9/04	3/14	5/02	5/31	6/21
	66-67		9/19	9/25	3/27	5/01	5/26	6/30
	68-69		9/23	9/30	3/17	5/03	5/27	6/24
	69-70		9/16	9/22	3/07	5/03	5/27	6/22
	70-71		9/22	9/29	3/16	5/08	6/02	6/23
	71-72		9/23	10/01	3/22	5/06	6/01	6/26
Sidney, MT	63-64	Winalta	9/11	9/18	4/03	5/18	6/22	7/11
	64-65		9/30	10/10	4/12	6/01	6/21	7/17
	65-66		9/27	10/06	3/28	5/31	6/27	7/22
	66-67		9/15	9/23	3/28	6/02	6/25	7/23
	67-68		9/15	9/23	3/15	6/05	6/26	7/25
Akron, CO	75-76	Centurk	10/08	10/19	2/10	5/11	6/10	6/29
Garden City	74-75	Sage	9/25	10/03	2/23	4/14	5/14	6/06
	75-76		10/01	10/07	2/05	4/14	5/27	6/07
Manhattan, KS	75-76	Eagle	9/25	10/04	2/24	4/13	5/04	6/11

shooting. The stage in which the ears first emerge from the tube formed by the leaf sheath is called heading. The soft dough stage occurs when the grain contents have a doughlike texture.

The dates listed in Table 3.1 do not represent the date at which every plant reaches that particular stage. Within a field, microclimatic differences and genetic factors cause each plant to reach that stage at a slightly different time. Thus a given plant may reach the stage in question a few days before or after the date given. The dates in the table represent an interpretation of when 50% of the field has reached that stage.

Interpretational differences may therefore place a limit on the accuracy of the model being developed. This is particularly true with those stages that require some subjective interpretation such as spring growth initiation. These interpretational differences will generally increase if different people do the interpretation. While little can be done to avoid these errors except to have a single person do all the observing, it should be recognized that some errors in any model will arise from this problem.

Another problem can be seen in the table relating to variety at each site. Since a different variety exists at each site, it will be difficult to separate site effects from varietal effects. It would be desirable to have a given variety at two or more sites in order to more clearly identify varietal traits. Such data are not presently available.

3.2.2 Meteorological Data

A limited amount of meteorological data was available at each site. In general, at most locations only daily maximum and minimum temperature and precipitation were available. All values given are shelter quantities and therefore not totally representative of the plant's environment.

As noted in Section 2.1, most models only require this type of data. However for the chill functions illustrated earlier hourly temperatures are required. Also for early spring days, use of the mean temperature for determining heat units may not be representative. This is illustrated in Figure 3.1. Heat units above a 40°F threshold temperature are calculated using both an hourly and mean temperature. Three different minimum temperatures are shown. Different maximum temperatures are listed on the abscissa.

For a minimum temperature at or above the threshold temperature, both the hourly calculation and the heat units given by the mean temperature are approximately the same. However for the case where the minimum temperature is below and the maximum above the threshold temperature, the heat units found by using the mean temperature seriously underestimate the actual heat units determined from hourly temperatures. For example, compare the heat units for two separate days. Day A has a minimum of 40°F and a maximum of 65°F. Day B has a minimum temperature of 20°F and a maximum of 65°F. When using hourly temperatures to calculate heat units it would take approximately two day B's to equal a single day A. Simple degree-days using mean temperature would require more than four day B's to equal the heat units of one day A.

Thus for techniques involving the calculation of chill units, and proper accounting of heat units for days in early spring, hourly temperatures are needed. With the data available in this paper, a

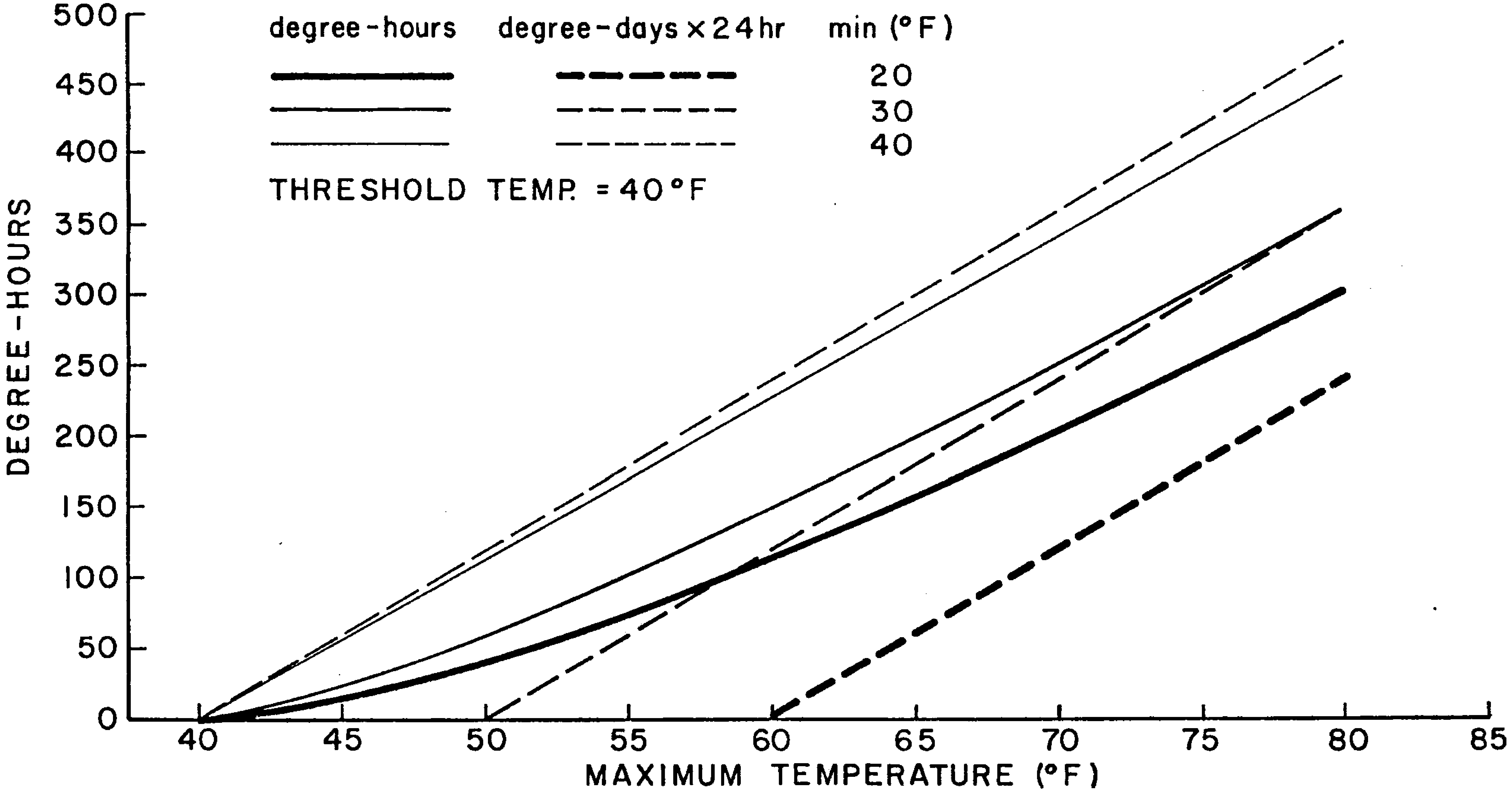

Figure 3.1. Comparison of calculated degree-hours and degree-days for different minimum temperatures as a function of maximum temperature.

technique of synthesizing hourly temperatures from maximum and minimum temperatures will be necessary for the determination of these quantities.

3.3 Methods of Synthesizing the Diurnal Temperature Trace

Now that the need for hourly values of temperature has been demonstrated, techniques for synthesizing the diurnal curve from maximum and minimum values need to be presented. Previous methods used in other research are discussed in the subsection entitled "Linear Models". The second subsection illustrates a curvilinear method, and how this model can be integrated for obtaining growing degree-hours.

3.2.1 Linear Models

Methodologies of estimation of hourly temperatures from maximum and minimum temperatures are relatively uncommon in the meteorological literature. This is despite the obvious need for such techniques. Hourly data are generally available only at first order stations, and these data are often quite costly. Maximum and minimum temperatures are often readily available, but lack the information content of hourly values.

The need for hourly temperatures in fruit tree research has brought about two similar methods of obtaining such values from maximum and minimum temperatures. These methods employ a linear approximation of the change of temperature with time.

One of these models has been proposed by Richardson et al. (1974). They required hourly temperatures for calculation of chilling units in orchards. Temperature data from the orchards were limited to maximum and minimum values. To obtain hourly values the following expression was used

$$T_n = T_N + (T_X - T_N)(n-1)/11 \qquad (3.1)$$

$$\text{for} \quad 1 \le n \le 12 \quad ,$$

where T_n is the temperature for hour n, T_N the minimum temperature, and T_X the maximum temperature. This expression provided hourly temperatures for the first twelve hours. The second twelve hours were found by doubling the chill found from the above expression.

This expression assumes that the second portion of the day is similar to the first half. Sanders (1975) felt that it would be more realistic to proceed from the maximum temperature to the following day's minimum. He used two expressions which are to be used sequentially,

$$T_n = T_{N_i} + (T_{X_i} - T_{N_i})(n-1)/9 \qquad (3.2a)$$

$$\text{for} \quad 1 \le n \le 10 \quad ,$$

$$T_n = T_{N_{i+1}} + (T_{X_i} - T_{N_{i+1}})(n-1)/13 \qquad (3.2b)$$

$$\text{for} \quad 1 \le n \le 14 \quad ,$$

where i indicates the day. Sanders' adjustment of a rise time of ten hours and a fall time of fourteen hours provides a more realistic period of diurnal temperature trend.

Regardless of which linear method is used, the characteristics of how well the technique performs is similar. In general, hourly temperatures are underestimated during the hours of temperature rise, and overestimated during the hours of falling temperature. According to Richardson, these self-cancelling errors tended to be totally cancelling over a period of several weeks. In coastal regions such as California where sea breeze phenomena often dominate hourly temperature variations, Aron (1975) has found that the errors of the Richardson Model tend to accumulate rather than cancel. Thus the use of linear models for hourly temperatures should be restricted to appropriate locations.

3.3.2 Curvilinear Models

In an effort to better describe the hourly progression of temperatures a search for a more realistic synthesis function was begun. Actual hourly temperatures were examined by first normalizing them such that the minimum on a given day was zero and the maximum was one. Graphs of this normalized temperature versus time showed that for a large majority of days at a given location the shape of this function was approximately a constant. Therefore, if a function with the proper shape could be found, a good estimation of the hourly temperatures would be possible by fitting this function to the observed maximum and minimum temperatures.

A number of functions was tried. The synthesis function finally decided upon was

$$T_t = A \ln (Ct + 1) + B \, , \tag{3.3}$$

where T_t is the temperature at time t, C is the shape coefficient related to the site and time of year, and A and B are constants for the given day. This function is evaluated twice each day, once for the period of rising temperatures and then for the period of falling temperatures. Allowing the subscript 1 to indicate the rising period of temperatures and 2 the falling period then

$$B_1 = T_{N_i} , \tag{3.4a}$$

$$A_1 = (T_{X_i} - T_{N_i})/\ln(\Delta t_1 C_1 + 1) , \tag{3.4b}$$

and

$$B_2 = T_{X_i} , \tag{3.5a}$$

$$A_2 = (T_{N_{i+1}} - T_{X_i})/\ln(\Delta t_2 C_2 + 1) . \tag{3.5b}$$

In these expressions Δt_1, Δt_2 indicate the hours of temperature rise and fall respectively and should sum to 24 hours. The value of t is reset to zero at each maximum and minimum.

The value of C controls the shape of the curve. This is illustrated in Figure 3.2. For small values of C the expression reduces to the linear case. For large values of C the function tends toward a step function. The actual diurnal curve is better approximated by some intermediate value of C. Some fitted values of C to actual hourly data will be given in the next chapter.

Another advantage of using this curvilinear expression is that it is analytically integrable. Thus a heat unit expression in degree-hours can be obtained directly by knowing only the maximum and minimum temperature and the shape function. A single day's heat unit total can be found by summing two expressions relating the heat units for the rising and falling portions of the diurnal curve. Referring to Figure 3.3 the total heat units for the given day correspond to the shaped region under the curve and above the threshold temperature T_B. Allowing t_{B_1} to represent the time when the temperature rises to T_B,

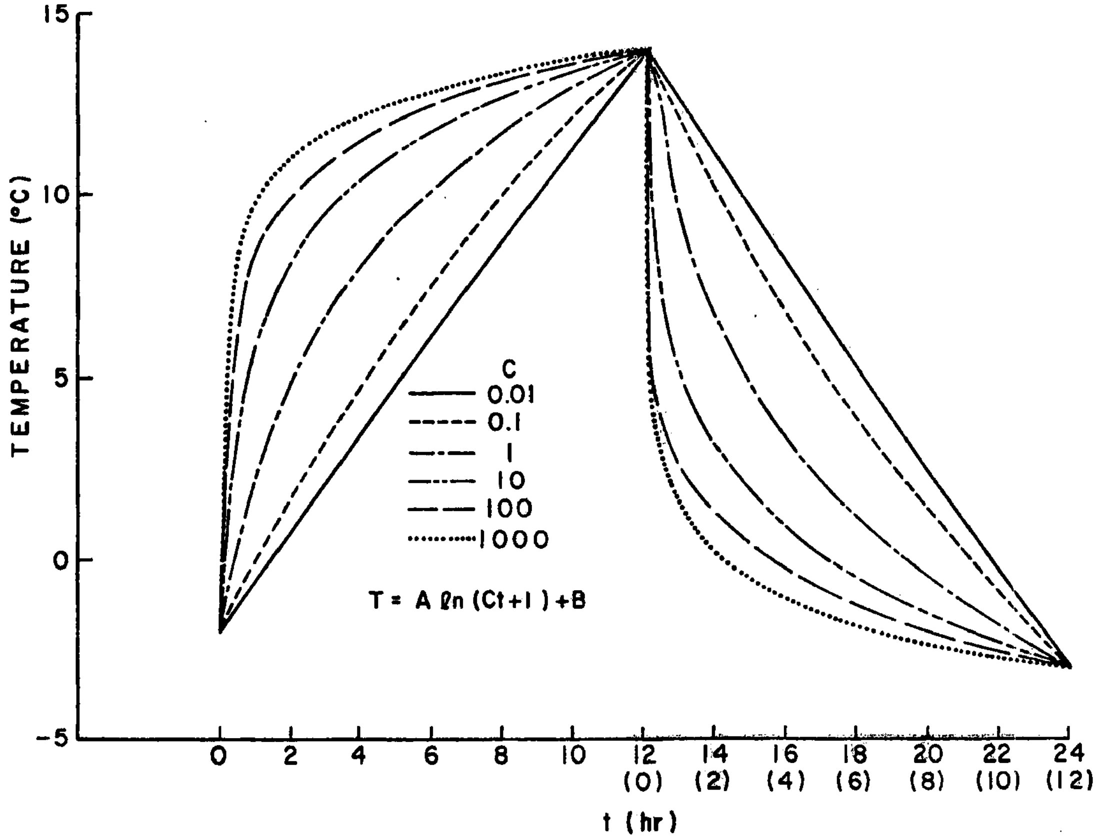

Figure 3.2. Effect of the value of the shape coefficient (C) on synthesized diurnal curve for T_{N_i}=-2°C, T_{X_i}=13°C, $T_{N_{i+1}}$=-3°C, Δt_1=Δt_2=12 hours.

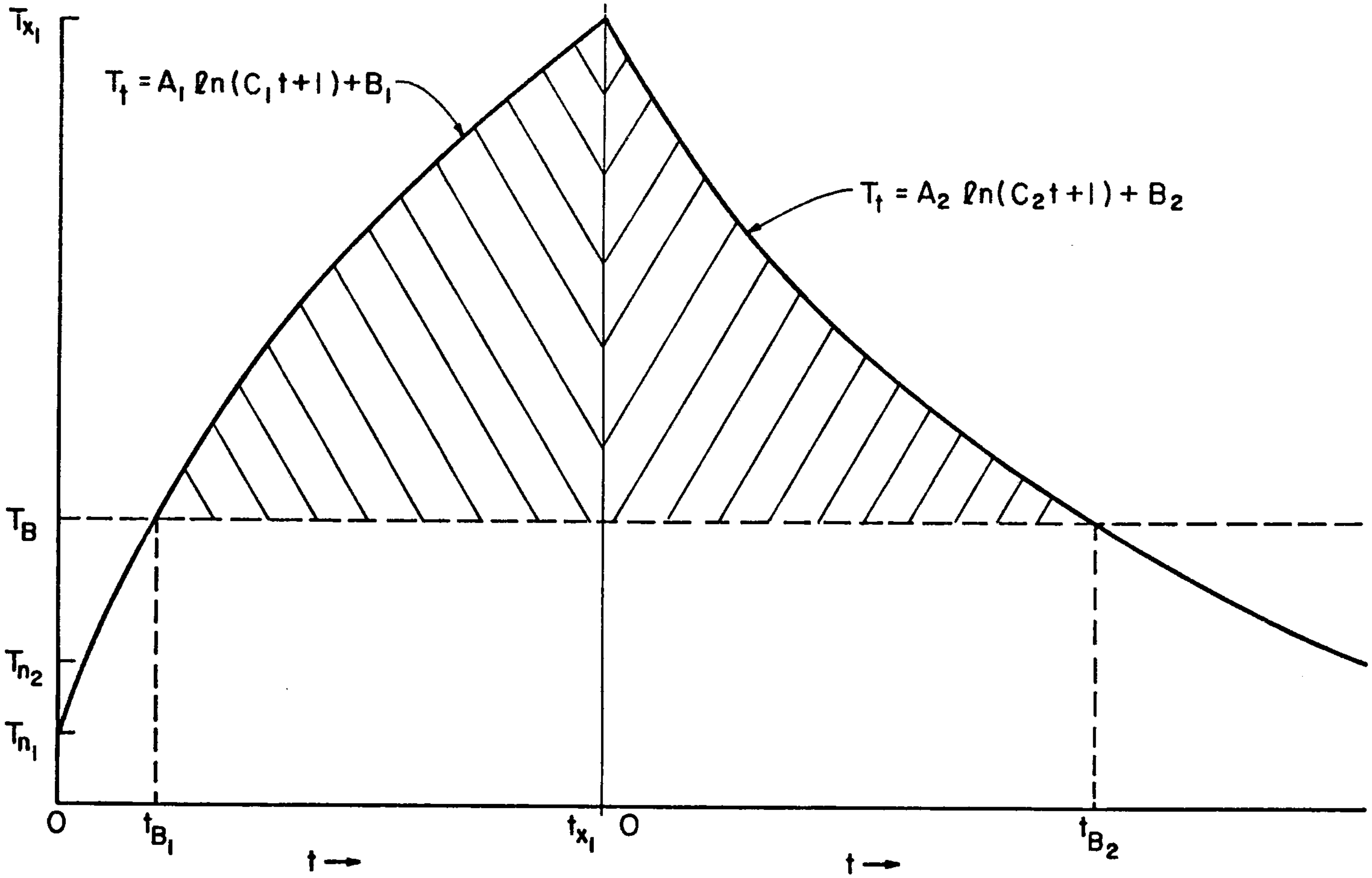

Figure 3.3. Graphical relationship between degree-hours (shaded region) and diurnal temperature curve.

and t_{X_1} the time of the maximum temperature then the shaded region S_1 for the rising curve is

$$S_1 = \int_{t_{B_1}}^{t_{X_1}} T(t)dt - T_B(t_{X_1} - t_{B_1}) \ , \tag{3.6}$$

or

$$S_1 = \int_{t_{B_1}}^{t_{X_1}} \left[A_1 \ell n(C_1 t + 1) + B_1\right]dt - T_B(t_{X_1} - t_{B_1}) \ . \tag{3.7}$$

Solving this expression yields

$$S_1 = \frac{A_1}{C_1} \left\{\left[C_1 t_{X_1} + 1\right]\left[\ell n(C_1 t_{X_1} + 1) - 1\right] - \left[C_1 t_{B_1} + 1\right]\left[\ell n(C_1 t_{B_1} + 1) - 1\right]\right\}$$

$$+ (B_1 - T_B)(t_{X_1} - t_{B_1}) \ . \tag{3.8}$$

Through similar arguments an expression relating the heat units for the falling curve (S_2) can be found. The order of integration is reversed since temperatures are falling with time. Also since t is set to zero for this curve at the time of maximum temperature, $t_{X_2} = 0$. Therefore mathematically

$$S_2 = \int_{0}^{t_{B_2}} \left[A_2 \ell n(C_2 t + 1) + B_2\right]dt - t_{B_2} T_B \ , \tag{3.9}$$

where t_{B_2} is the time during the falling curve that the threshold temperature T_B is reached. Solving yields

$$S_2 = \frac{A_2}{C_2}\left\{\left[C_2t_{B_2} + 1\right]\left[\ln(C_2t_{B_2} + 1) - 1\right] + 1\right\} + t_{B_2}(B_2 - T_B) \ . \qquad (3.10)$$

Thus the total heat units for the entire day (S) are given by

$$S = S_1 + S_2 \ . \qquad (3.11)$$

The value for t_B can be found easily by solving equation (3.3) for t and substituting T_B for T. This expression will provide valid values for t_{B_1} only when T_B is greater than T_{N_i} and less than T_{X_i}, and valid values for t_{B_2} when T_B is greater than $T_{N_{i+1}}$ and less than T_{X_i}. Three other possibilities exist. If T_B is greater than T_{X_i} then the degree-hour total for the day is zero and equations (3.8, 3.10, 3.11) should not be used. If T_{N_i} is greater than T_B then t_{B_1} should be set to zero, and similarly if $T_{N_{i+1}}$ is greater than T_B, then t_{B_2} should be set to Δt_2.

3.4 Chill Unit Expressions

As was noted in Chapter I there is some disagreement on the relationship between effective chill in the plant and temperature. Two different methodologies were suggested. One is the linear relationship suggested by Nix. The other method as suggested by a number of authors is a more complicated function with both a maximum and minimum effective chill. Both of these models should be tested, and need hourly temperatures for proper usage. It would be convenient then if these expressions could be integrated into the synthesized diurnal temperature curve.

Nix's expression as related in equation (2.6) may be written as

$$CU = 12 - T \tag{3.12}$$

for

$$0°C \leq T \leq 12°C .$$

Substituting this expression to find chill for the rising portion of the curve (CU_1) yields

$$CU_1 = \int_{t_o}^{t_{12}} \left[12 - A_1 \ell n(C_1 t + 1) - B_1\right] dt , \tag{3.13}$$

where t_o and t_{12} are the times in hours of when the temperature reaches 0°C and 12°C respectively. Integrating yields

$$CU_1 = (12 - B_1)(t_{12} - t_o) - \frac{A_1}{C_1}\left\{\left[C_1 t_{12} + 1\right]\left[\ell n(C_1 t_{12} + 1) - 1\right] - \left[C_1 t_o + 1\right]\left[\ell n(C_1 t_o + 1) - 1\right]\right\} . \tag{3.14}$$

This expression will provide the total effective chill for the rising portion of the diurnal curve. The falling portion can be obtained in a similar manner by using the falling portion's subscripted values (A_2, B_2, C_2) and reversing the order of integration. The daily chill total can then be obtained by summing the chill totals from the two portions of the diurnal curve.

The other function as suggested by the work of Chujo, Trione and Metzger, and Hänsel is much less regular, and specifics about its exact relationship with temperature are not well known. The general characteristics are described in Section 2.2. A simple function with these characteristics in the interval from 0°C to 18°C is

$$CU = \sin\left(\frac{\pi}{12} T\right) . \tag{3.15}$$

As was done with the Nix chill function, we can integrate this function with the synthesis function. Thus for the rising curve

$$CU_1 = \int_{t_0}^{t_{18}} \sin\left\{\frac{\pi}{12}\left[A_1 \ln(C_1 t + 1) + B_1\right]\right\} dt , \tag{3.16}$$

where t_{18} is the time that the temperature reaches 18°C. For temperatures greater than 18°C the CU value is set to -1. Equation (3.16) can be integrated by substitution of variables to yield

$$CU_1 = \frac{\cos E_1}{C_1}\left\{\frac{e^{S_1}(\sin D_1 S_1 - D_1 \cos D_1 S_1)}{1 + D_1^2}\right\} + \frac{\sin E_1}{C_1}\left\{\frac{e^{S_1}(\cos D_1 S_1 + D_1 \sin D_1 S_1)}{1 + D_1^2}\right\}\Bigg|_{t_0}^{t_{18}} , \tag{3.17}$$

where

$$S_1 = \ln(C_1 t + 1) ,$$

$$D_1 = \frac{\pi}{12} A_1 ,$$

$$E_1 = \frac{\pi}{12} B_1 .$$

This function, hereafter called sin type chill, provides the chill total for the rising portion of the diurnal temperature curve. As was done earlier, the falling portion can be found by using the coefficients subscripted 2 and reversing the order of integration. The daily chill total is given by the sum of CU_1 and CU_2.

IV. RESULTS

Three sections are presented. The first compares the various methodologies of synthesizing the dirunal temperature curve. The second section examines some of the methods previously mentioned for predicting winter wheat phenology. Finally a brief discussion of possible future research is presented in the last section.

4.1 Comparison of Linear and Curvilinear Models With Hourly Temperature Data

This section deals with the problem of synthesizing the diurnal temperature curve from maximum and minimum temperatures. The modeling procedure for each of the various methods is discussed in the first subsection. The remaining subsections present the results for the various methods in comparison to actual hourly values. Results for both actual hourly temperatures and degree-hours are given.

4.1.1 Modeling Procedure

For a number of the methods outlined earlier, hourly temperatures were required. With several possible models available for synthesizing the diurnal temperature curve, procedures needed to be devised with which to test the ability of each function to replicate the actual daily curve. Two types of tests were formulated to examine the goodness of fit of the various functions. One test was to simply compare actual hourly temperatures. The other test was to compare total daily modeled degree-hours to actual degree-hours.

It should not be assumed that the model which best describes hourly temperatures will best describe heat units also. Since the diurnal temperature curve consists of both a rising and falling portion, there is the possibility that the errors in the calculation of degree-hours for one portion may be canceled by errors in the other portion. It should also be remembered that hourly temperature values were necessary for two purposes, both the calculation of heat units and chill units. Thus both of the above tests should be viewed in the selection of the best model.

Four different temperature synthesis functions were selected to be examined. These four functions are not an exhaustive list of types of functions presently being used nor even the variety of methodologies used for any one single type of function. Rather, they represent several systems that differ in overall design in an attempt to describe the same parameter.

The models to be used are:

1) Sin curve - This model uses a sin curve with a period of 24 hours to represent the hourly progression of temperature. A single day's maximum and minimum temperatures are used to generate an entire day of hourly values. More sophisticated techniques of using sin curve models exist, however since these methods are applicable for daylight hours only, these are not used.

2) Linear - A model essentially the same as that proposed by Sanders (see eqns. 3.2a,b). This model was considered more accurate than Richardson's (eqn. 3.1).

3a) Fitted Logarithmic - This is the curvilinear model illustrated in section 3.3.2. The proper values for C_1 and C_2 were found via an iterative technique. For each month of available monthly data, degree-hours were calculated using both actual hourly data and equations (3.8, 3.10). The iterative procedure adjusted the values of C_1 and C_2 until the smallest least squares difference between the calculated and observed degree-hour values were obtained.

3b) Constant Coefficient - Based on experience obtained from the fitting procedure in 3a), the values for C_1 and C_2 were set to 0.4 and 0.3 respectively for all months. The logarithmic model was then run with these values for the C's. The intention of this model was to see if the use of a constant coefficient model would produce appreciably more error than the fitted model. It would be desirable to use this standard constant coefficient model at all sites and simply adjust the hours of temperature rise and fall based on each month of the year, rather than fitting each month to actual hourly data. In many locations no nearby hourly observations are available.

In addition to the above tests, clear and cloudy days were separately grouped for some months of hourly data. This was done in order to examine whether preparing a fitted logarithmic model for each type of day would appreciably decrease the error due to the estimation of hourly values.

Due to limited computer resources, a large analysis of actual hourly data was not possible. Hourly data had to be hand entered from either Local Climatic Data publications or read off hygrothermograph charts. A total of eight months of hourly temperature observations and sky conditions (where possible) were placed on computer disk files. A list of these data appears in Table 4.1.

Table 4.1 List of Hourly Temperature Data, Rise and Fall Time, and Fitted Logarithmic Model Shape Coefficients.

SITE	MONTH	YEAR	Δt_1	Δt_2	FITTED C_1	FITTED C_2
North Platte, Nebraska	January	1964	7	17	0.135	0.281
North Platte, Nebraska	June	1962	11	13	0.260	0.222
North Platte, Nebraska	March	1962 1963 1964	10	14	0.537	0.362
			Clear Days Only		0.690	0.343
			Cloudy Days Only		0.281	0.415
Sidney, Montana	January	1975	6	18	0.416	0.369
Sidney, Montana	March	1975	8	16	0.520	0.420
Sidney, Montana	June	1975	11	13	0.150	0.304

4.1.2 Results for Hourly Temperatures

In an effort to determine how well each of the models outlined above performs in estimating hourly temperatures, each was run with the available hourly data. The statistic deemed most desirable to illustrate how well a given model performs was the root mean square error. This can be expressed as

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} (O_i - E_i)^2}{n}} \quad , \qquad (4.1)$$

where the root mean square error (RMS) for any given hour after sunrise is given by the observed temperature (O_i), the model estimated temperature (E_i) and the number of days (n). The closer the estimated temperatures are to the observed, the smaller the RMS error. If the errors about the actual values are normally distributed, then the RMS error would represent the difference between the actual and estimated temperature for 67% of the cases.

Figures 4.1 - 4.6 contain the hourly RMS errors for temperature calculated using the data listed in Table 4.1. Note the change of scale of the ordinate on some figures.

Examination of these graphs show that in general, the fitted logarithmic model performs best with RMS errors ranging between 1°F to about 5°F. For most cases the constant coefficient model closely parallels the fitted model with errors rarely exceeding 1°F above that of the fitted model.

The linear and sin curve models performed much worse than either of the logarithmic models. RMS errors of as much as 20°F occurred with the sin curve model. These errors were greatly reduced during summer

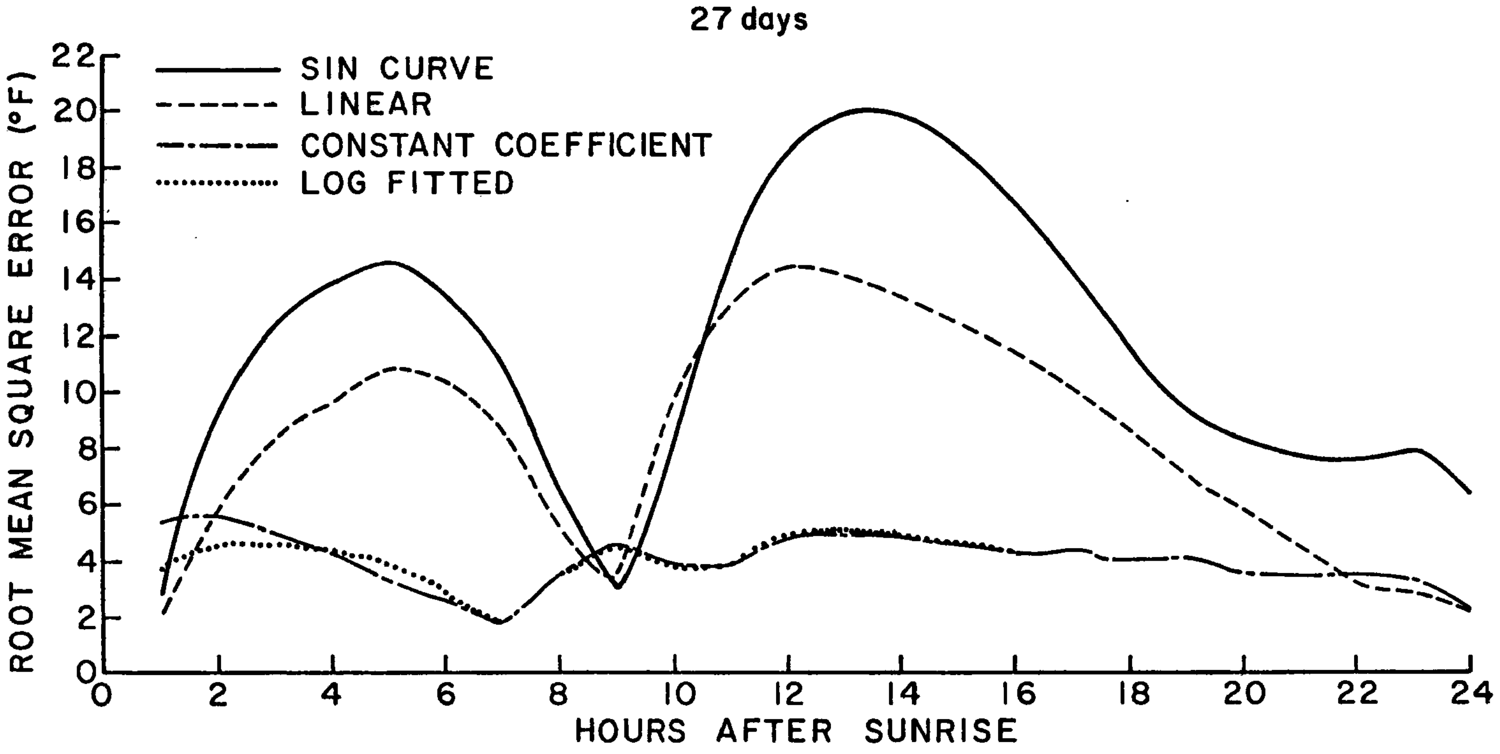

Figure 4.1. Hourly temperature root mean square error, North Platte, January.

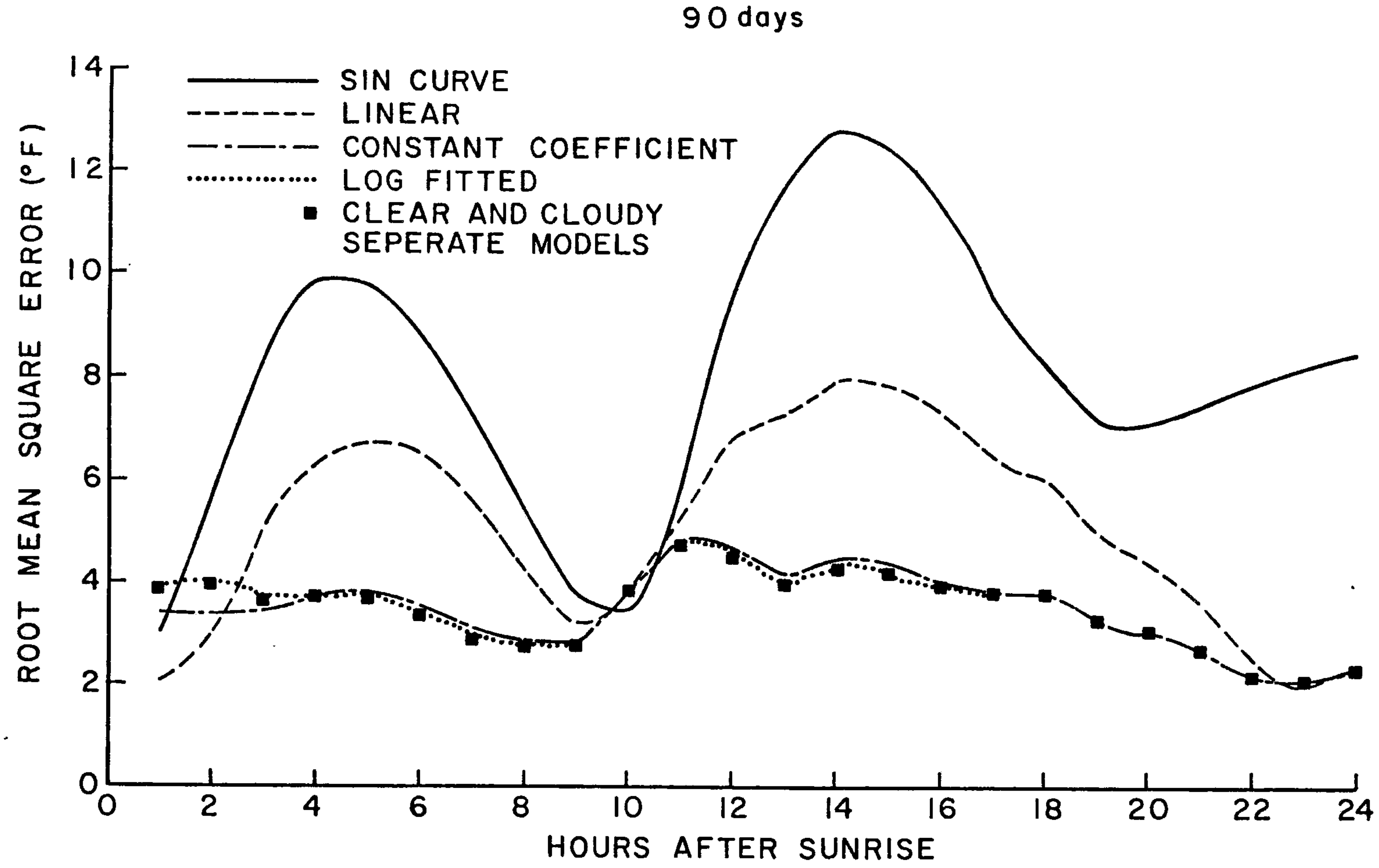

Figure 4.2. Hourly temperature root mean square error, North Platte, March.

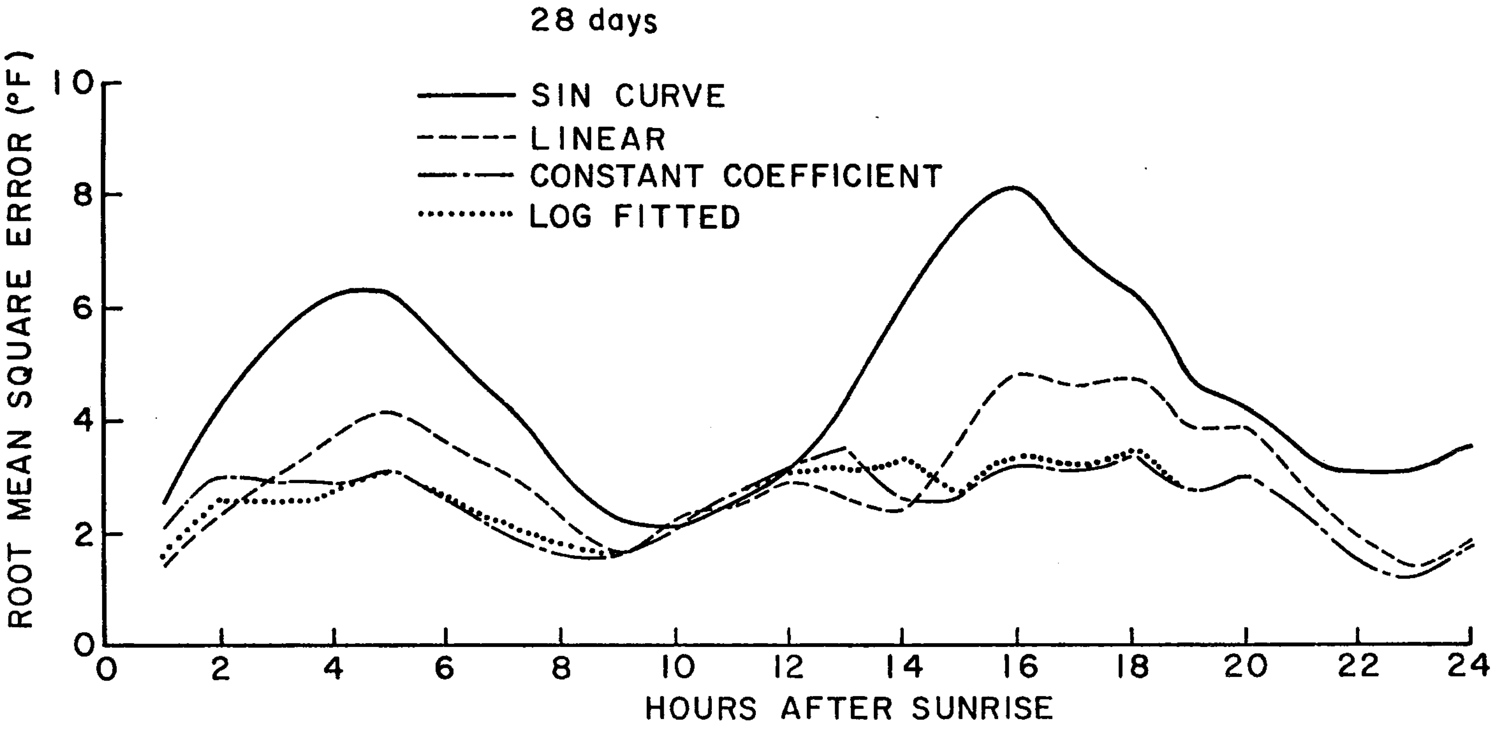

Figure 4.3. Hourly temperature root mean square error, North Platte, June.

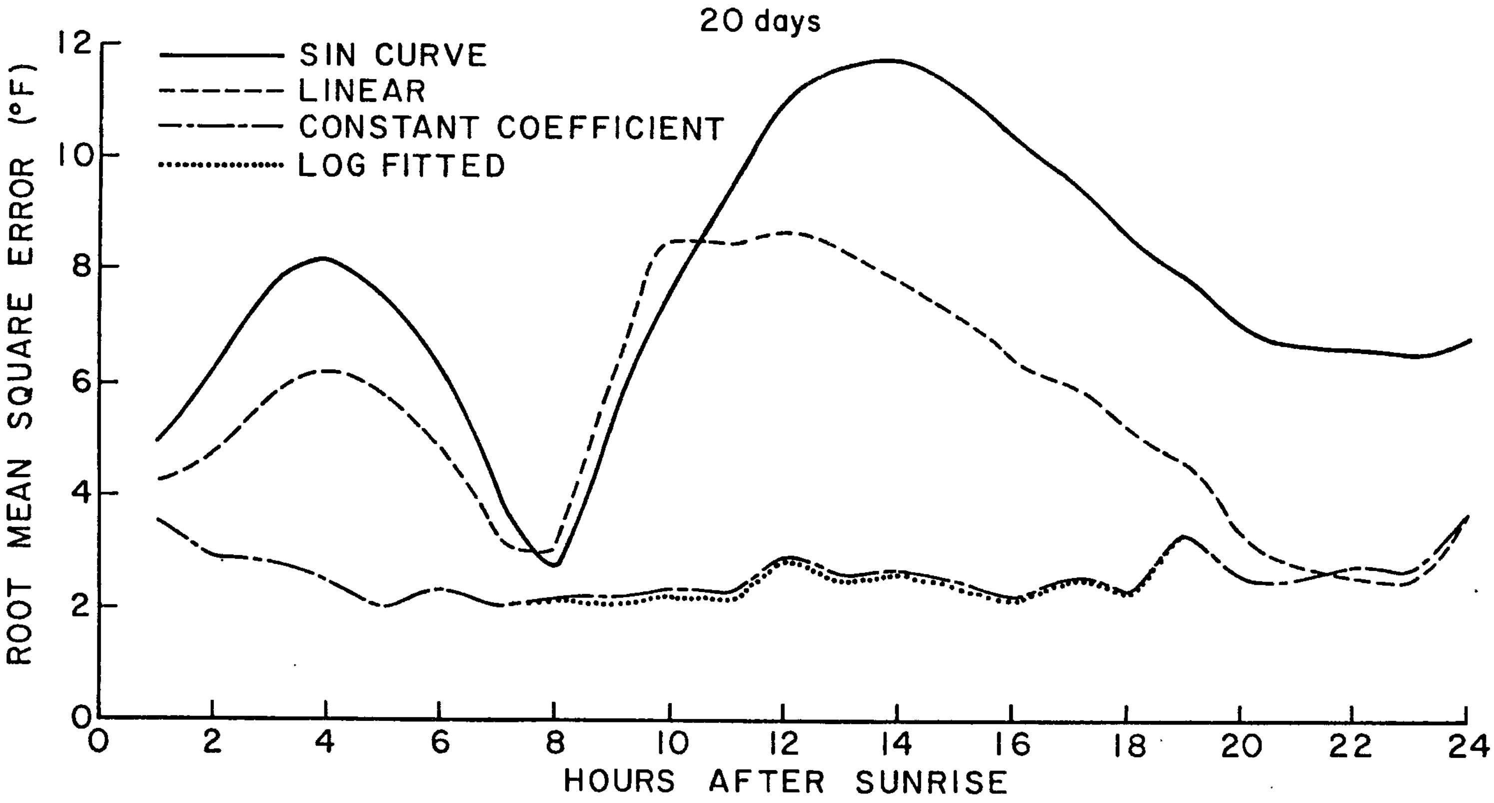

Figure 4.4. Hourly temperature root mean square error, Sidney, January.

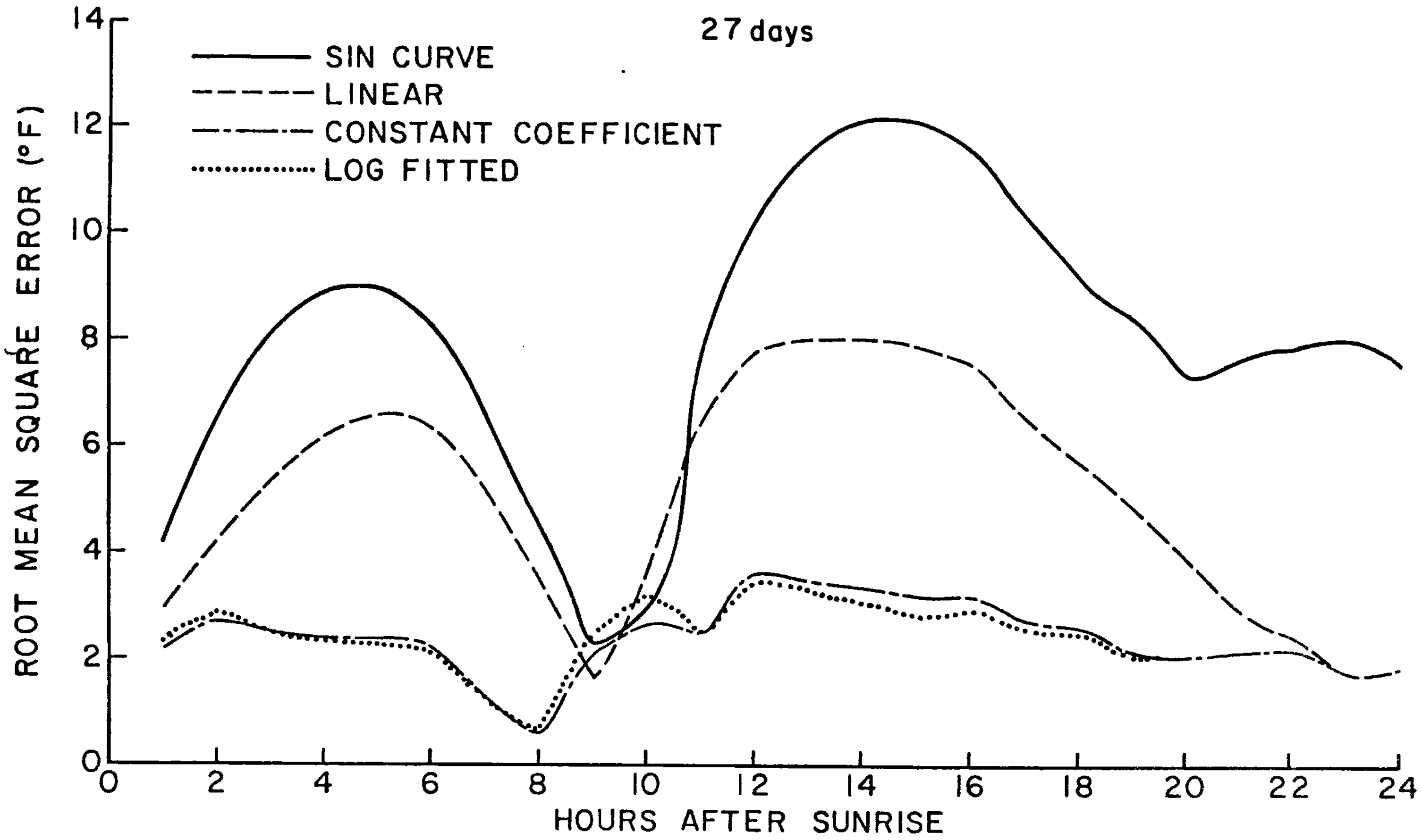

Figure 4.5. Hourly temperature root mean square error, Sidney, March.

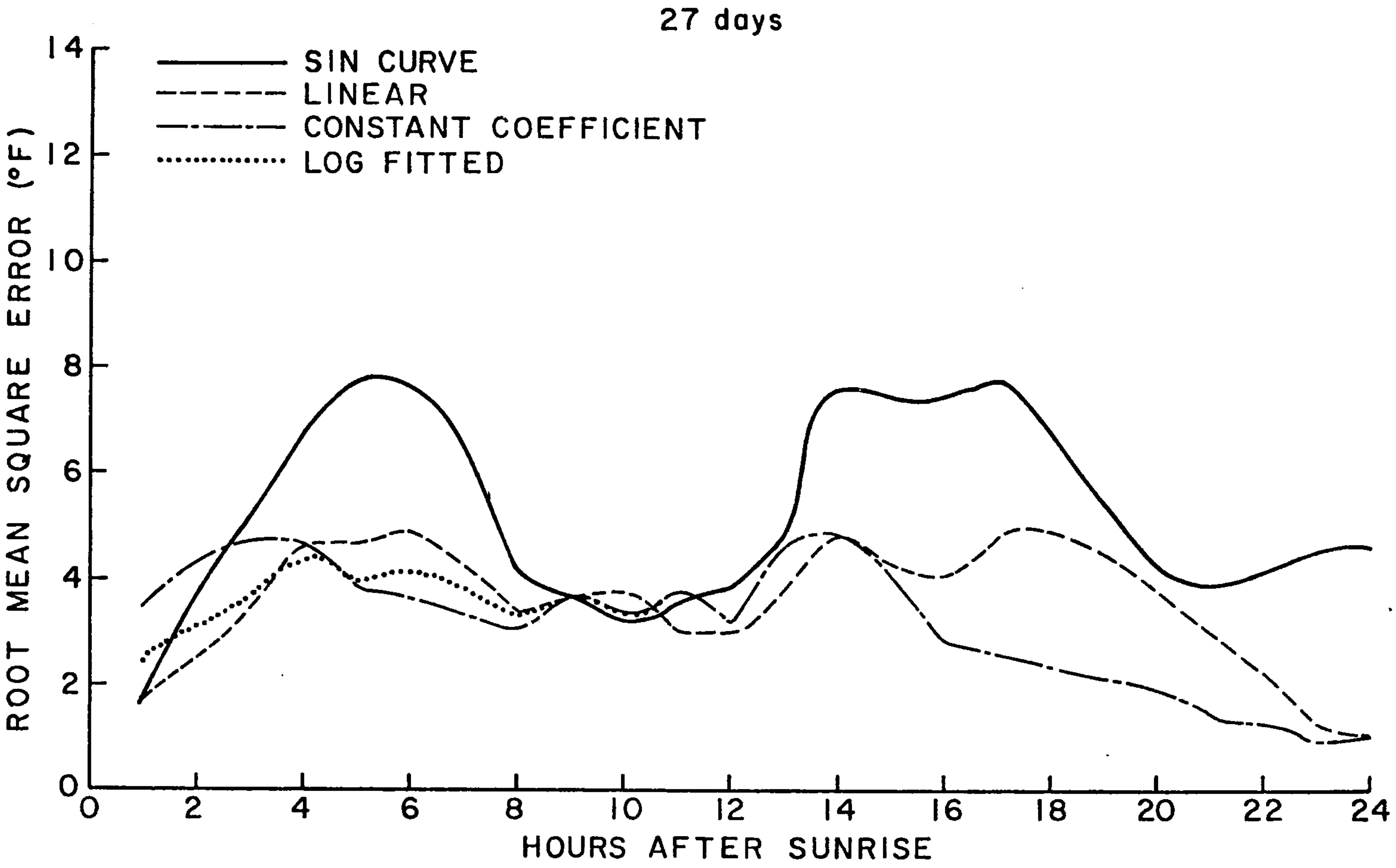

Figure 4.6. Hourly temperature root mean square error, Sidney, June.

months. This reduction is primarily due to the fact that the actual period of rising and falling temperatures are closer to the models' periods during summer than winter. In examining these errors it should be noted that neither of these functions were designed for replication of hourly values.

Trends in the RMS error with time of day for the logarithmic models are not obvious. However examination of residuals for the other two models shows why large errors are occurring, particularly during the winter season. During the morning hours the linear and sin curve models consistently underestimate the actual temperature by several degrees. The minimum RMS error occurring in these models between eight to ten hours after sunrise is due to this still rising modeled temperature curve crossing the then falling actual temperature curve. The large errors for the remaining afternoon and evening hours are due to overestimation of the actual temperature by these models. Thus, these errors in the linear and sin curve models are not random errors, but rather are systematic errors caused by the model design.

The RMS errors for hourly values for March at North Platte are shown in Figure 4.2. Since a total of ninety days of hourly observations were available, this month was chosen for separately modeling clear and cloudy days. Days with more than one hour of clouds below 10,000 feet were classified as cloudy days. Separate models were fitted for each type of day based on these data, then evaluated to see how much improvement over a single fitted model would be obtained. As illustrated in Figure 4.2, very little improvement overall was obtained by separating types of days. This suggests that much of the error is due to a very few days which bear almost no resemblance to the model. Thus refinement of the model by type of day does little to improve the prediction of hourly temperatures.

4.1.3 Results for Growing Degree-hours

As was shown in section 3.3.2, the logarithmic temperature curve synthesis model can be integrated to yield degree-hours. Similar expressions for degree-hours can be found for the linear and sin curve models. The daily degree-hour total obtained from using these models can be compared to degree-hour values calculated using actual hourly data.

Two types of statistics were chosen in order to examine the performance of each model. The root mean square error for daily degree-hour totals was calculated using equation (4.1) where in this case O_i is the observed daily degree-hours from actual hourly data and E_i is estimated daily degree-hours calculated from the proper model expression. The RMS error for degree-hours shows how well each day is predicted.

The second set of statistics chosen for examination is the monthly residuals. Both the sum of the residuals and the sum of the absolute value of the residuals are calculated. The sum of residuals (ΣRES) is given by

$$\Sigma \text{RES} = \sum_{i=1}^{n} (O_i - E_i) , \tag{4.2}$$

where the symbols are the same as described in the previous paragraph. The sum of the absolute residuals ($\Sigma|\text{RES}|$) can be expressed as

$$\Sigma|\text{RES}| = \sum_{i=1}^{n} |(O_i - E_i)| \quad . \tag{4.3}$$

By comparing the sum of the residuals to the sum of the absolute residuals, how well errors in the model will cancel over a period of time can be determined. A large positive sum of residuals that approaches the sum of the absolute residuals suggests that the model consistently underestimates the actual value. A large negative sum of residuals in comparison to the sum of absolute residuals indicates a tendency for the model to overpredict the actual value. A small value for the sum of residuals in comparison to the sum of absolute residuals suggests that the errors in the model tend to cancel over some period of time.

Thus the two types of statistics provide a guide to just how well the model does on a single day basis (RMS error), and tendencies for the model to either consistently overpredict or underpredict degree-hours over a period of time (residuals). This information is presented for the four basic models in Tables 4.2 and 4.3. Note that for a few months it was necessary to use a 0°F threshold temperature rather than 40°F since very few days in these months exceeded 40°F.

In general, the fitted logarithmic model performed best in both tests. The smallest RMS error occurred with the fitted model and no appreciable tendency to either overpredict or underpredict was evident. The next best model was the constant coefficient model. RMS errors were only slightly worse than the fitted logarithmic model. Residual analysis showed a slight trend to overpredict; however this error never exceeded 2.7% of the monthly total.

The remaining models show a greater tendency to overpredict actual degree-hour totals, particularly during winter months. Although the linear model performs about as well in summer as either of the two previously discussed models, both RMS and residual errors increase appreciably during winter months. Similar errors occur with the sin

Table 4.2 Results for Degree-Hour Models Using North Platte, Nebraska data.

MONTH	T_B	MODEL	ACTUAL DEGREE-HOURS	MODELED DEGREE-HOURS	SUM OF RESIDUALS	SUM OF ABSOLUTE RESIDUALS	DAILY ROOT MEAN SQUARE ERROR (DEGREE-HOURS)
January	0°F	Sin Curve	17390.5	19166.0	-1775.5	2215.6	100.27
		Linear	17390.5	18972.6	-1582.1	1616.0	71.45
		Fitted Log.	17390.5	17395.5	-5.0	668.0	32.06
		Const. Coef.	17390.5	17614.1	-223.6	710.2	33.81
March	40°F	Sin Curve	6953.0	7909.3	-956.3	1163.1	31.84
		Linear	6953.0	7032.8	-79.8	914.7	23.75
		Fitted Log.	6953.0	6888.7	64.3	878.3	22.64
		Const. Coef.	6953.0	6840.2	112.8	883.2	22.65
		Seperate Clear and Cloudy	6953.0	6844.1	108.9	854.9	21.93
June	40°F	Sin Curve	18423.5	18708.0	-284.5	836.5	36.29
		Linear	18423.5	18616.2	-192.7	485.1	21.40
		Fitted Log.	18423.5	18498.1	-74.6	453.2	20.30
		Const. Coef.	18423.5	18522.4	-98.9	447.4	20.30

Table 4.3 Results for Degree-Hour Models Using Sidney, Montana Data.

MONTH	T_B	MODEL	ACTUAL DEGREE-HOURS	MODELED DEGREE-HOURS	SUM OF RESIDUALS	SUM OF ABSOLUTE RESIDUALS	DAILY ROOT MEAN SQUARE ERROR (DEGREE-HOURS)
January	0°F	Sin Curve	9164.0	10050.0	-886.0	1157.0	86.42
		Linear	9164.0	9808.3	-644.3	686.3	47.81
		Fitted Log.	9164.0	9098.4	65.6	303.8	20.03
		Const. Coef.	9164.0	9156.3	7.7	306.3	20.04
March	0°F	Sin Curve	17003.5	18187.7	-1184.2	2406.8	94.82
		Linear	17003.5	17926.3	-923.4	1162.5	45.44
		Fitted Log.	17003.5	17036.4	-32.9	532.3	22.58
		Const. Coef.	17003.5	17148.7	-145.2	562.1	23.27
June	40°F	Sin Curve	14014.5	14376.0	-361.5	1229.5	54.84
		Linear	14014.5	14474.3	-459.8	680.6	34.97
		Fitted Log.	14014.5	14045.6	-31.1	651.9	28.91
		Const. Coef.	14014.5	14390.1	-375.6	613.9	31.51

curve model except to a greater degree. RMS errors three times greater than the fitted logarithmic model are common along with sizable residuals for winter months.

As was done earlier, fitted models for both clear and cloudy days were tested and are shown in Table 4.2. Almost no appreciable difference over a single fitted logarithmic model was obtained by using this technique. Again the probably reason for this is that the large errors are occurring on a very few days that bear little resemblance to the models.

4.2 Results for Phenological Models

Four phenological models were selected for testing in an effort to determine which best estimates the dates of the various stages. The first subsection examines the critical chill model when different chill functions and temperature synthesis functions are used. The next subsection examines the chill-heat relationship model. The critical photoperiod model is next presented. This is followed by a brief subsection describing the A-BMTS model. Finally a subsection comparing these models with the calendar date is presented.

4.2.1 Critical Chill Model

Based on the previous sections' results, two of the four temperature curve synthesis models were selected for subsequent tests on the phenological data. One of these models was the constant coefficient logarithmic model. Although this model was not quite as accurate as the fitted logarithmic model, it was not possible to prepare a fitted model for each month at each location. Therefore, the constant coefficient model was chosen since it was the next best available model. Also chosen for testing was the linear model similar to that suggested by Sanders (1975). A slight modification was introduced by varying the hours of rising and falling temperatures with the month in an attempt to provide more representative values during the winter months.

Tables 4.4 and 4.5 show the total degree-hours for each stage calculated using the constant coefficient logarithmic and linear models respectively. These tables were included in order to demonstrate the varietal and site differences in heat units. Large variations in year-to-year totals for a single stage at a given location are also common. This suggests that the end of the previous stage may not be a reasonable starting data for the heat unit summation of the following stage. In comparison to Neghassi's results for degree-days for the period from 1963 to 1970 at North Platte, no significant improvement was obtained for the stages of heading and soft dough. The models to follow will attempt to show techniques which are based more on the results of previous agronomic research.

In comparing the degree-hour totals of the linear model to the constant coefficient model only small differences are noted. This is not surprising since as was shown in section 4.1.3, only small differences exist between the two models for degree-hour calculations. It is noted however that the linear model's values are slightly greater than the constant coefficient. This tendency was also demonstrated in the previous section.

For the purposes of examining the performance of various variety specific models it will be necessary to eliminate any variety that

Table 4.4 Total Degree-Hours for Each Stage Calculated Using the Constant Coefficient Logarithmic Model.

SITE	CROP YEAR	PLANTING -EMERGENCE	EMERGENCE -SPRING GROWTH INITIATION	SPRING GROWTH INITIATION -JOINTING	JOINTING -HEADING	HEADING -SOFT DOUGH
North Platte	1962-63	2000	25800	12200	11200	14400
	1963-64	3800	18200	6900	13900	10100
	1964-65	2100	17400	10600	11800	16300
	1965-66	2600	22700	8500	14700	13000
	1966-67	3200	18900	9100	8600	18800
	1968-69	3300	11000	11400	10900	15800
	1969-70	3200	14800	7100	13900	15700
	1970-71	2100	11400	10600	9400	14400
	1971-72	3200	22100	8200	12500	14500
Sidney	1963-64	3100	17100	11600	16200	13700
	1964-65	2000	5300	13000	11400	16200
	1965-66	2200	7800	14400	13400	18909
	1966-67	3600	8300	13400	11200	18400
	1967-68	3000	9600	18100	9900	18600
Akron	1975-76	3600	8100	14400	15100	11300
Garden City	1974-75	3100	16500	6200	12800	14000
	1975-76	2800	15700	13600	16000	7700
Manhattan	1975-76	3600	27900	13300	8900	23300

Table 4.5 Total Degree-Hours for Each Stage Calculated Using the Linear Model.

SITE	CROP YEAR	PLANTING -EMERGENCE	EMERGENCE -SPRING GROWTH INITIATION	SPRING GROWTH INITIATION -JOINTING	JOINTING -HEADING	HEADING -SOFT DOUGH
North Platte	1962-63	2200	28100	12500	11300	14400
	1963-64	4000	20000	7000	14100	10200
	1964-65	2200	19400	10700	11900	16300
	1965-66	2700	24900	8700	14800	13100
	1966-67	3400	21000	9200	8600	18900
	1968-69	3500	12200	11600	11000	15900
	1969-70	3300	16500	7200	13900	15800
	1960-71	2300	12900	10700	9500	14500
	1971-72	3400	24300	8300	12600	14600
Sidney	1963-64	3200	19400	12300	16500	13800
	1964-65	2300	6200	13600	11500	16300
	1965-66	2500	9100	15200	13600	19000
	1966-67	3900	9500	14000	11400	18500
	1967-68	3200	10900	19200	9900	18800
Akron	1975-76	4000	9400	15000	15200	11400
Garden City	1974-75	3400	18500	6400	12900	14100
	1975-76	3000	17900	14600	16200	7700
Manhattan	1975-76	3800	30300	13800	9000	23400

doesn't possess several years of data. Thus in this paper, the remainder of the analyses will be limited to data from North Platte, Nebraska and Sidney, Montana. For all other varieties and sites, insufficient information exists for these types of tests.

One of the models believed to be applicable to winter wheat is the methodology developed by Richardson et al. (1974) for determining the completion of rest in fruit trees. This technique involved the accumulation of chill units until a certain requirement for the variety was met. Then a heat unit total was begun. When a certain total of heat units was reached, the plant was presumed to reach the stage in question. Thus the principle goals of this technique were to provide a starting date for the heat unit accumulation and a heat unit total for when the desired stage would be reached.

The method by which these concepts have been used for winter wheat is best illustrated in Figure 4.7. The chill function used in this case was the sin type chill determined by Equation (3.17). Daily values of chill were calculated and then summed until a certain total was reached. At that date, the chill unit summation was stopped and the degree-hour summation started. This summation was continued until the observed heading date was reached. This process was then repeated for the remaining crop years at North Platte. The mean and standard deviation of the degree-days were then calculated for a given chill total. The standard deviation of the degree-hours was then plotted against the chill requirement. The amount of chill which corresponded to the smallest degree-hour standard deviation was deemed to be the chill requirement of the variety. The mean value of the degree-hour total is then the necessary amount of heat required for heading after

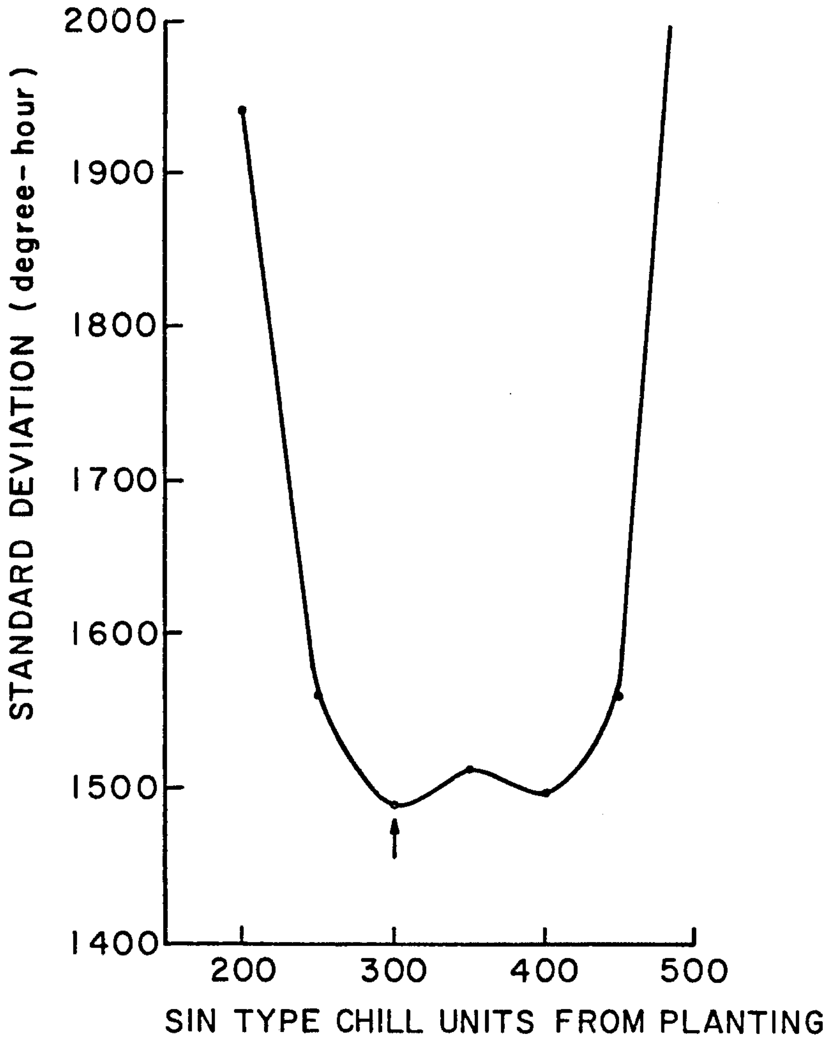

Figure 4.7. Standard deviation of degree-hours summed to heading after chill requirement is met versus chill requirement for North Platte data.

the chill requirement was met. For the variety Scout at North Platte the chill requirement given by this method was 300 and the heat necessary for heading was calculated to be 24800 degree-hours.

As was noted in Chapter II the chill requirement is applicable in wheat for reproductive stages only. In this paper these stages are jointing, heading and soft dough. Through experimentation it was found that fitting of this model using the heading date gave the most consistant results. This suggests that the other reproductive stages are more influenced in their timing by factors other than temperature. Factors such as soil moisture and soil temperature are known to have more of an effect on these stages than on heading. Therefore, the heading date was chosen for determination of chill requirement, and all the other stages used this chill total as a point for starting their heat unit accumulation.

A total of four different critical chill models were tested using this technique. These four arose from the matrix of the two chill functions and two temperature synthesis functions. Each model was independently fitted to the heading date by the method previously described.

Results for each of these models are shown in Tables 4.6 and 4.7 for North Platte and Sidney respectively. In stage-to-stage models the coefficient of variation can be examined, and the model possessing the lowest coefficient of variation is assumed to be the best method. However since each of the four models at a site has a different starting date, this statistic is not valid for this purpose. Instead either the standard deviation of the degree-hour total or a number labeled the predictive RMS error may be better suited. The predictive RMS error is determined by applying the model to the data and observing the date

Table 4.6 Degree-Hour Totals, Statistics and Predictive RMS Errors For Various Models at North Platte.

		MODELS USED: Temperature Synthesis Chill Function			
STAGE	CROP YEAR	Const. Coef. Sin	Linear Sin	Const. Coef. Nix	Linear Nix
Chill Total Used		300	300	8000	5000
Jointing	1962-63	14900	15800	13300	15500
	1963-64	9400	10000	7800	9300
	1964-65	12500	12500	11600	13300
	1965-66	12000	15600	10100	16500
	1966-67	15000	16000	13400	15900
	1968-69	12000	12200	11500	12300
	1969-70	11000	11700	9000	11300
	1970-71	15100	15300	14400	14900
	1971-72	14500	15200	13900	15500
	Summary				
	Mean	12900	13800	11700	13800
	Std. Dev.	2000	2200	2300	2400
	C.O.V.	0.157	0.159	0.197	0.177
	Predictive RMS Error	±6.1 days	±6.5 days	±7.2 days	±7.5 days
Heading	1962-63	26200	27100	24500	26800
	1963-64	23400	24200	21800	23400
	1964-65	27300	24500	23300	25200
	1965-66	26700	24400	24800	25200
	1966-67	23600	24700	21900	24600
	1968-69	22900	23200	22400	23300
	1969-70	24900	25700	22900	25200
	1970-71	24500	24800	23900	24000
	1971-72	27000	27800	26500	28100
	Summary				
	Mean	24800	25200	23600	25100
	Std. Dev.	1500	1500	1500	1500
	C.O.V.	0.059	0.059	0.064	0.061
	Predictive RMS Error	±3.3 days	±3.3 days	±4.0 days	±3.8 days
Soft Dough	1962-63	40600	41600	38800	41200
	1963-64	33500	34300	31900	33600
	1964-65	40500	40800	39600	41500
	1965-66	39700	39200	37800	40000
	1966-67	42400	43500	40700	43400
	1968-69	38700	39100	38200	39200
	1969-70	40500	41500	38600	41000
	1970-71	38900	39300	38300	38900
	1971-72	41500	42500	40900	42700
	Summary				
	Mean	39500	40200	38300	40200
	Std. Dev.	2600	2700	2600	2900
	C.O.V.	0.065	0.066	0.069	0.072
	Predictive RMS Error	±3.9 days	±4.0 days	±4.0 days	±4.0 days

Table 4.7 Degree-Hour Totals, Statistics and Predictive RMS Errors for Various Models at Sidney, Montana

		MODELS USED: Temperature Synthesis / Chill Function			
STAGE	CROP YEAR	Const. Coef. / Sin	Linear / Sin	Const. Coef. / Nix	Linear / Nix
Chill Total Used		200	500	8000	8000
Jointing	1963-64	13800	13900	12900	13800
	1964-65	14200	13700	13100	12400
	1965-66	16400	16000	14800	14100
	1966-67	15900	15000	14100	14500
	1967-68	20500	20200	18000	20100
	Summary				
	Mean	16200	15800	14800	15000
	Std. Dev.	2700	2600	2400	3000
	C.O.V.	0.166	0.167	0.164	0.200
	Predictive RMS Error	±4.2 days	±4.1 days	±3.9 days	±6.5 days
Heading	1963-64	30000	30300	29100	30400
	1964-65	25500	24700	24500	25200
	1965-66	29800	29400	28200	29600
	1966-67	27200	26400	25400	26400
	1967-68	30400	30100	28700	30100
	Summary				
	Mean	28600	28200	27200	28300
	Std. Dev.	2100	2500	2100	2400
	C.O.V.	0.074	0.089	0.078	0.084
	Predictive RMS Error	±3.5 days	±3.9 days	±3.5 days	±3.5 days
Soft Dough	1963-64	43700	44100	42800	44200
	1964-65	41700	41000	40700	41500
	1965-66	48700	48400	47100	48600
	1966-67	45500	44900	43700	44900
	1967-68	48900	48900	47300	48900
	Summary				
	Mean	45700	45500	44300	45600
	Std. Dev.	3100	3300	2900	3100
	C.O.V.	0.069	0.072	0.064	0.069
	Predictive RMS Error	±4.2 days	±4.4 days	±4.0 days	±4.1 days

predicted. Equation (4.1) is then applied with O_i being the actual date of the stage, E_i being the predicted date and n the number of years at the site.

Examination of Tables 4.6 and 4.7 shows that in most cases the constant coefficient method of temperature synthesis performs slightly better than the linear model regardless of which chill function was used. The choice between chill functions is not made as easily. The sin type chill function was better for a few more cases than the Nix type. Based on this and the fact that the sin type chill was best with the larger North Platte data set, this function was chosen for future use. The apparent ambiguity between chill functions possibly suggests that the actual chill function is some intermediate function of the two.

4.2.2 Chill-Heat Relationship Model

In section 2.2 the concept of photothermal units was discussed. A similar unit shall be used in this paper and termed hourly photothermal units. Essentially the daily total of hourly photothermal units are found by multiplying the degree-hours for the day found by Equations (3.8, 3.10, 3.11)by the photoperiod for that day. Such units will be necessary for trying to relate agronomic, controlled experimental results with long photoperiods to field results with environmental photoperiods.

Another seemingly different methodology for obtaining the time of occurrence of various reproductive stages was illustrated earlier in Figure 2.1. This figure provided a relationship between the total amount of chill received and the amount of heat units required for the event to occur. Grant (1964) presented sufficient information for the construction of similar figures for several varieties including the variety Winalta which is the variety grown at Sidney. A figure similar to that shown in Figure 2.1 was constructed for Winalta and is shown in Figure 4.8. In this figure the weeks of chill treatment (and corresponding sin type chill values) are shown on the abscissa and the hourly photothermal units required to reach the stage of anthesis are shown on the ordinate. Although the field data in this paper does not contain the stage anthesis, this date is usually within a very few days of the heading date. Therefore it would be expected that relationships for heading date would have a very similar functional relationship, although numeric values might differ slightly. As can be seen in this figure, great similarity between the theoretical function (Figure 2.1) and the growth chamber data exists. Similar figures can be constructed for other varieties with similar results.

When applying this concept to field data, however, no such functional relationship is observed. This is illustrated in Figure 4.9 for the Sidney (Winalta) data and in Figure 4.10 for the North Platte (Scout) data. In general, a seemingly random pattern is evident rather than the simple relationship shown in Figure 4.8.

The reason for this apparent problem in the modeling methodology is a good example of why care must be taken in attempting to adapt growth chamber research to field data. There exists a subtle difference between the growth chamber model and the field environment. In the growth chamber tests, the plants were exposed to chilling conditions immediately after emergence. In the field, plants are generally first exposed to warm temperatures for a considerable period of time during early fall, then chilling conditions during late fall and early winter.

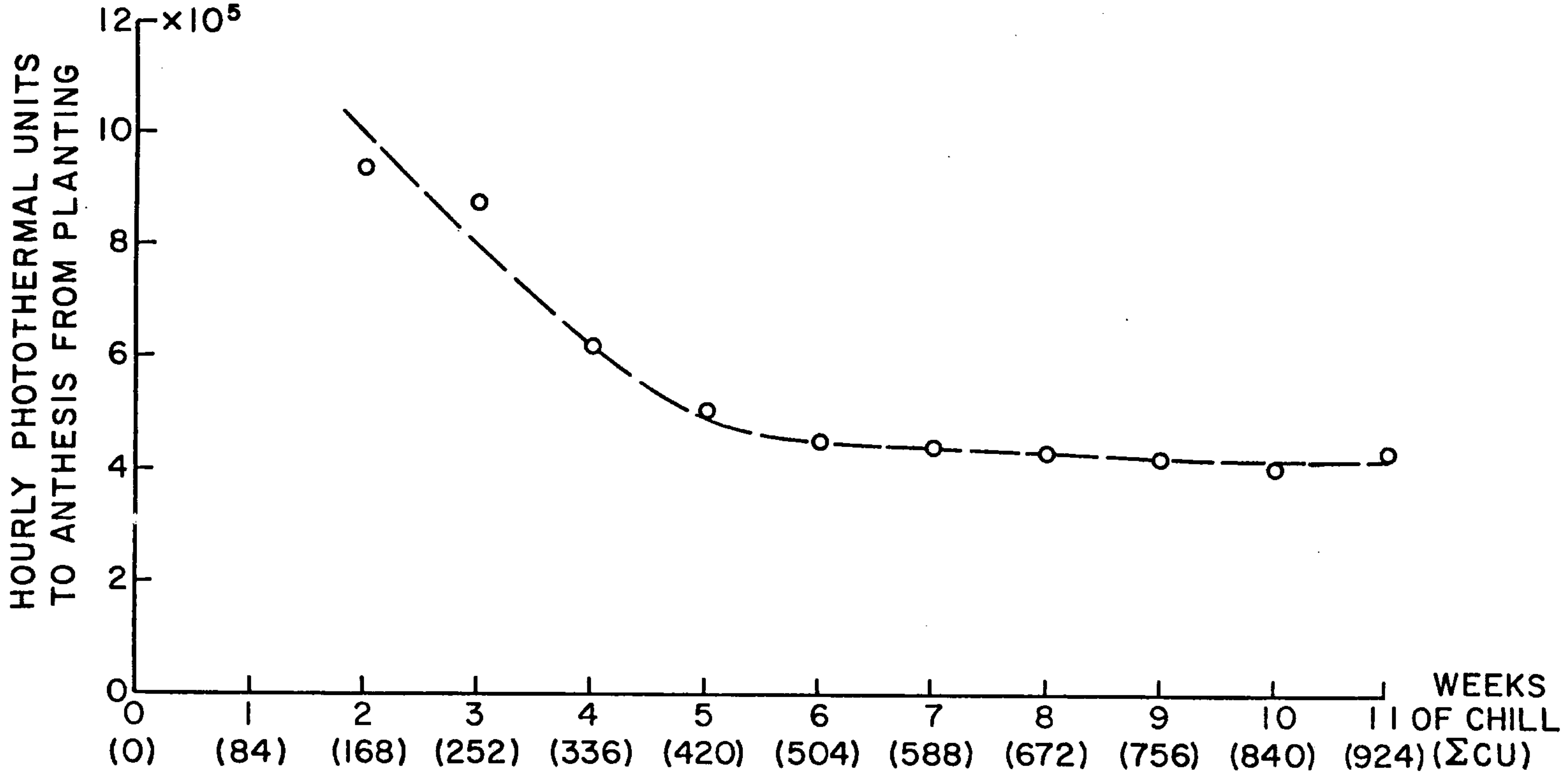

Figure 4.8. Relationship between total chill and hourly photothermal units to anthesis for variety Winalta (from Grant, 1964).

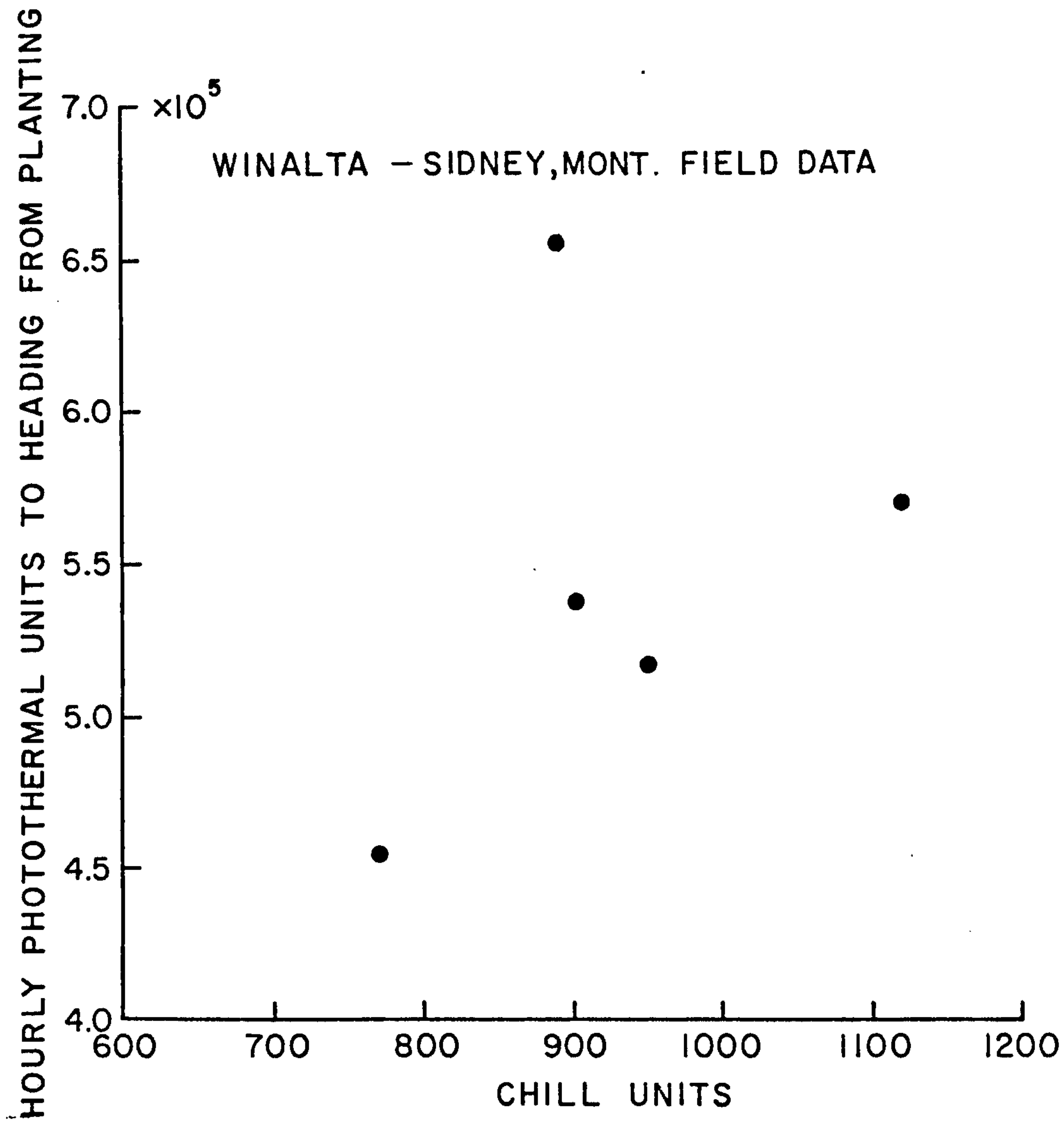

Figure 4.9. Values for field data for hourly photothermal units to heading as a function of total chill received for variety Winalta.

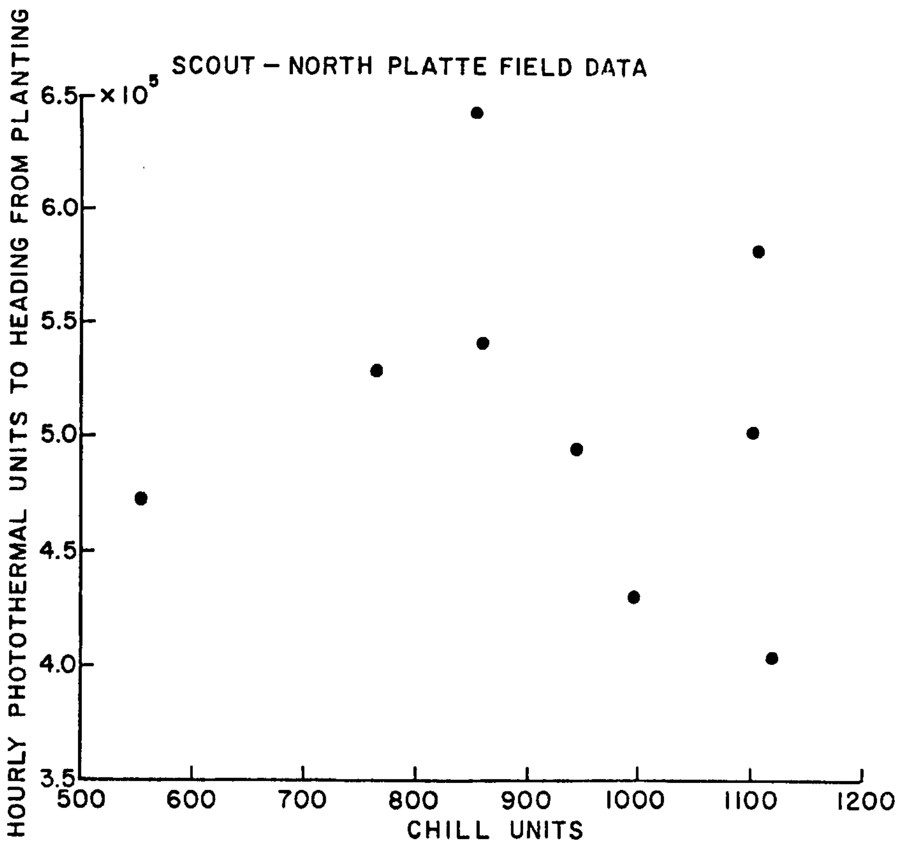

Figure 4.10. Values for field data for hourly photothermal units to heading as a function of chill received for variety Scout.

When comparing the chill-heat relationship model to the critical chill model, a much larger variation of heat units is found. For example for the Sidney (Winalta) data, the standard deviation of hourly photothermal units to heading date is 39000 for the critical chill model where heat units are summed after chilling. For the model illustrated in Figure 4.9 where the heat units are summed from planting, the standard deviation of hourly photothermal units is 75000. Similarly for the North Platte data, the critical chill model has a standard deviation of hourly photothermal units of 20000 and from Figure 4.10 the standard deviation is 73100. Therefore a model in which the heat units are summed after chilling is completed better predicts repreductive development than one which sums heat units from planting.

4.2.3 Critical Photoperiod Model

As was mentioned in Section 2.2, another mechanism for triggering plant development is a method to be described in this paper as the critical photoperiod model. This method uses the fact that many varieties of wheat are long-day plants. That is, some photoperiod must be exceeded before reproductive development will occur. Welsh (1978) has suggested that this critical photoperiod valud may be a better starting date than the date given by the chill model.

In order to test this model, a technique similar to that used to determine the chill requirement was employed. In this case, rather than use different chill totals for a starting point for heat unit accumulation, different photoperiods were used. Essentially this implies that the heat unit accumulation for a single critical photoperiod value at a given site is started on the same calendar day each year.

This model was fitted to the heading date and then the other stages used this common starting date for the hourly photothermal unit accumulation. The resulting critical photoperiods were found to be 12.25 hours and 13.25 hours for North Platte and Sidney respectively. Other relevant statistics for this model are shown in Table 4.8 along with comparative values for the critical chill model. The chilling requirements were 300 for North Platte and 525 for Sidney. The date when heat sums are started are coded as follows: the first number indicates the stage and the second number the day. For example, 2-80 is 80 days after emergence and 3-4 is 4 days after spring growth initiation.

As in previous tables of this type, the coefficient of variation cannot be used for model comparison due to the different starting dates. Either the standard deviation or the predictive RMS error should be used.

Based on these tests it appears as though the critical photoperiod model performs slightly better than the critical chill model. Improvements in predictive RMS errors of up to 1.1 days are noted. Therefore, it would seem that the best model for predictive purposes is the critical photoperiod model. However, care should be taken when attempting to implement this model in some cases. Since one of the basic assumptions of the model is that the variety being modeled is a long-day plant, this fact should be verified before attempts to model the variety are begun. It is known that some day-neutral varieties exist. For these cases a different modeling scheme will probably need to be developed.

Table 4.8 Dates Hourly Photothermal Summations Started, Hourly Photothermal Units and Statistics, and Predictive RMS Errors for Various Stages For the Chill Requirement Model and Critical Photoperiod Model.

SITE	CROP YEAR	DATE CHILL REQUIREMENT ACHIEVED	DATE CRITICAL PHOTOPERIOD REQUIREMENT ACHIEVED	JOINTING		HEADING		SOFT DOUGH	
				VALUES FOR CHILL MODEL	VALUES FOR PHOTOPERIOD MODEL	VALUES FOR CHILL MODEL	VALUES FOR PHOTOPERIOD MODEL	VALUES FOR CHILL MODEL	VALUES FOR PHOTOPERIOD MODEL
North Platte	1962-63	2-80	3-13	189000	144000	348000	306000	568000	531000
	1963-64	2-59	3-1	120000	89000	232000	297000	477000	450000
	1964-65	2-90	3-7	163000	143000	336000	315000	582000	561000
	1965-66	2-70	3-8	147000	91000	363000	313000	560000	507000
	1966-67	2-64	2-178	186000	109000	312000	268000	597000	539000
	1968-69	2-61	3-5	159000	147000	318000	306000	557000	545000
	1969-70	2-53	3-15	135000	92000	338000	295000	575000	532000
	1970-71	2-48	3-6	179000	140000	319000	279000	538000	499000
	1971-72	2-74	2-190	181000	110000	366000	295000	585000	514000
	<u>Summary</u>								
	Mean			162000	118000	337000	297000	560000	520000
	Standard Deviation			24000	25000	20000	17000	36000	33000
	Coefficient of Variation			0.148	0.210	0.059	0.055	0.064	0.063
	Predictive RMS Error			±4.1 days	±3.5 days	±2.9 days	±3.1 days	±3.2 days	2.3 days
Sidney	1963-64	2-148	3-4	185000	166000	442000	422000	660000	640000
	1964-65	2-182	2-179	195000	198000	378000	379000	635000	636000
	1965-66	2-163	3-10	221000	198000	440000	413000	737000	711000
	1966-67	2-160	3-10	211000	193000	391000	373000	681000	663000
	1967-68	2-116	3-23	279000	245000	436000	402000	730000	693000
	<u>Summary</u>								
	Mean			219000	200000	416000	399000	688000	668000
	Standard Deviation			37000	29000	39000	21000	44000	33000
	Coefficient of Variation			0.167	0.143	0.071	0.052	0.064	0.049
	Predictive RMS Error			±3.5 days	±2.8 days	±3.0 days	±2.4 days	±3.9 days	±2.8 days

Other features of Table 4.8 show a slight improvement in predictive accuracy when using hourly photothermal units instead of degree-hours (see Tables 4.6, 4.7). This is particularly true for the jointing stage. It should also be noted that in all but one case the chill requirement was satisfied well before the critical photoperiod requirement. However since these data are all from northern U.S. sites where varieties are likely to be true long-day type plants, this is to be expected. For varieties grown in milder latitudes the critical chill model might be expected to outperform the critical photoperiod model.

4.2.4 Adjusted Biometeorological Time Scale Model

The adjusted Biometeorological Time Scale (A-BMTS) model developed by Feyerherm et al. (1977) was discussed in detail in Section 2.1. Since this method is being used to model winter wheat phenology extensively at present, it was deemed desirable to include this model in this paper. Multiplier values of 1.05 and .82 were employed for varieties at North Platte and Sidney respectively. Results for this model are presented in the following subsection.

4.2.5 Comparison of Models with Calendar Dates

The final test performed was a comparison of modeling methods with calendar dates based on the mean date of occurrence of the stage at a particular site. Each model was then run using the data at North Platte and Sidney, and the predictive root mean square errors calculated. These results are presented in Table 4.9. For most stages the critical photoperiod model outperformed other models and the mean date of occurrence. Heading dates were comparably predicted by either the critical photoperiod model or the calendar date. For heading date for

SITE	METHOD	STAGE JOINTING	 HEADING	 SOFT DOUGH
North Platte	Calendar	±2.7 days	±3.0 days	±4.5 days
	A-BMTS model	±19.0 days	±5.2 days	±3.2 days
	Critical Chill model	±4.1 days	±2.9 days	±3.2 days
	Critical Photoperiod model	±3.5 days	±3.1 days	±2.3 days
Sidney	Calendar	±6.3 days	±2.3 days	±5.0 days
	A-BMTS model	±13.6 days	±4.2 days	±7.1 days
	Critical Chill model	±3.5 days	±3.0 days	±3.9 days
	Critical Photoperiod model	±2.8 days	±2.4 days	±2.8 days
Both Sites	Calendar	±4.3 days	±2.8 days	±4.6 days
	A-BMTS model	±17.3 days	±4.8 days	±4.9 days
	Critical Chill model	±3.8 days	±2.9 days	±3.5 days
	Critical Photoperiod model	±3.3 days	±2.8 days	±2.4 days

Table 4.9 Predictive Root Mean Square Errors for the Calendar Date, the Adjusted Biometeorological Time Scale Model (A-BMTS) Proposed by Feyerherm et al. (1977), the Critical Chill Model and the Critical Photoperiod Model for Each Stage at Each Site and Combined.

the combined sites, predictive root mean square errors for the calendar date of ± 2.8 days, the A-BMTS of ± 4.8 days, the critical chill model of ± 2.9 days and the critical photoperiod model of ± 2.8 days were obtained. For only one case, jointing date at North Platte, did the calendar date significantly better predict the stage.

In almost all cases the A-BMTS did not perform as well as either of the other models. It should be noted that the data used in this paper were not used to fit the A-BMTS model. Large predictive root mean square errors obtained for jointing date were due to the persistant early prediction of the stage by the A-BMTS. Although a slight difference in the definition of jointing exists between the model developed by Feyerherm et al. (1977) and that used in this paper, this difference could not account for more than five days difference (Willis, 1978). It therefore appears that errors in predicting jointing date by the A-BMTS model do exist. For the remaining stages, the A-BMTS did not previde the large predictive root mean square errors as it did for jointing; however in most cases both the calendar date and the critical photoperiod model better predicted the stage by a few days. For LACIE applications the critical photoperiod model appears promising and should be further investigated.

4.3 Suggestions for Future Research

The primary need in future years is more phenological data. It seems unfortunate that very little organized or coordinated effort is made to obtain such values. Phenological data suffer as do meteorological data in that when an event occurs it must be recorded at that time. Otherwise it is lost.

In addition to the obvious need for more data on different varieties, there exists a need for data for common varieties at a number of different sites. The ability of the hourly photothermal units to properly handle site-to-site variation has not yet been demonstrated and needs to be checked.

In regards to the modeling itself, a number of problems still exist. One is the prediction of spring growth initiation date. No method for determining this stage was presented in this paper because no suitable procedure could be formulated. For example, one parameter examined was consecutive days above freezing before spring growth initiation occurred. This varied between 2 and 39 days. Smika (1977) has suggested that soil temperature is the controlling parameter for spring growth initiation. Based on the North Platte data he has found that summing the mean soil temperature minus 25°F to a total of 45 degree-days would adequately predict spring growth initiation as long as the mean soil temperature was greater than 25°F for the period. Should the mean soil temperature fall below 25°F, the summation should be reset to zero and started over. This methodology is the best examined to date, and unless future research can provide better methods, it is recommended that this scheme be used.

Another question that needs to be resolved is when should heat sums for reproductive development be started. Two schemes were proposed in this paper. One was dependent on the vernalization of the plant and the other on the fact that many varieties of wheat are long-day plants. Each method yielded different dates for starting heat unit accumulations with nearly comparable results. If both processes needed to be completed independently, then it would be expected that good results would be obtained by the requirement that was last completed, but not the one first completed. In all but one case, the vernalization requirement was completed well before the photoperiod requirement. Therefore, modeling for the vernalization requirement might not be expected to yield satisfactory results since the photoperiod requirement occurred much later. Yet both models did work satisfactorily. This suggests that the two processes may not be independent requirements, but may in some way interact. Perhaps future agronomic research will shed some light on the subject.

Finally, the entire problem of crop modeling should be examined. In the models used in this paper it was found necessary to develop different model values for each variety. For practical use in the LACIE program, this requires a prior knowledge of the variety being grown in an area. This may not be practical in many instances. Yet models with no varietal considerations will possess much greater errors. This may also not be acceptable. Thus a fundamental decision should be made as to whether either of these methods and their associated problems are acceptable, or whether a new approach to the problem should be explored.

V. CONCLUSIONS

Phenological models for various crops are a necessary component of the LACIE program. Such models are needed for proper crop identification and crop yield modeling.

For winter crops the need for hourly temperature arises for accurate calculation of chill units and heat units. Since only maximum and minimum temperatures were available, methods of synthesizing the diurnal temperature curve were tested for their ability to replicate both actual hourly temperatures and growing degree-hours. A logarithmic function with constant shape coefficients was selected for future use in phenological models because of its ability to replicate the above quantities, and the lack of data needed for statistically fitting the shape coefficients in each case. For synthesizing hourly values all root mean square errors were less than 6°F whereas other functions tested had errors as large as 20°F. This logarithmic function was analytically integrated to yield degree-hours and chill units. Daily root mean square errors for growing degree-hours for the constant coefficient logarithmic model were less than 34 degree-hours for all months tested. Other models had values as large as 100 degree-hours when the mean daily degree-hour total was 644.

Four models for predicting phenological development of winter wheat were examined. These four were the Adjusted Biometeorological Time Scale model (A-BMTS), the chill-heat relationship model, the critical chill model and the critical photoperiod model. The chill-heat relationship model failed to adequately predict development. The root mean square errors for heading date for the fourteen crop years of data available were ±4.8 days for the A-BMTS model, ±2.9 days for the critical chill model and ±2.8 days for the critical photoperiod model. These compared to ±2.8 days for using the mean date of occurrence. Other stages were better predicted by the critical photoperiod model than any other model or the calendar date. For the soft dough stage the critical photoperiod model had a root mean square error of ±2.4 days compared to ±3.5 days for the critical chill model, ±4.9 days for the A-BMTS model and ±4.6 days for the calendar date. It was noted that the critical photoperiod model should be used with true long-day varieties only.

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16. Abstracts

Various phenological models and temperature synthesis models were tested for use with winter wheat. For winter crops the need for hourly temperature arises for accurate calculation of chill units and heat units. Since only maximum and minimum temperatures were available, methods of synthesizing the diurnal temperature curve were tested for their ability to replicate both actual hourly temperatures and growing degree-hours. A logarithmic function with constant shape coefficients was selected for future use in phenological models because of its ability to replicate the above quantities, and the lack of data needed for statistically fitting the shape coefficients in each case. For synthesizing hourly values all root mean square errors were less than 6°F whereas other functions tested had errors as large as 20°F. This logarithmic function was analytically integrated to yield degree-hour and chill units. Daily root mean square errors for growing degree-hours for the constant coefficient logarithmic model were less than 34 degree-hours for all months tested. Other models had values as large as 100 degree-hours when the mean daily degree-hour total was 644.

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ABSTRACT continued

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