ANALYSIS OF THERMAL SUMMATION MODELS

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SUMMARY

Four models for estimating day-degrees (D°) from diurnal temperature profiles were compared using Auckland and Christchurch (Harewood) temperature data for 1981. All models showed a close approximation to actual D° accumulations for Auckland. However, model performance for Christchurch data showed considerable deviation from expected performance. Possible reasons for this and implications for predictive population models are discussed.

INTRODUCTION

Temperature is often the key factor regulating development of poikilothermic organisms. Relating development to temperature through use of physiological time may give a more satisfactory comparison of growth between seasons and locations than use of chronological time. Physiological time as reflected by thermal summation of 'heat units' has been used for many years by agronomists in considering crop maturity (Leopold 1964). However, widespread use of thermal summation in forecasting insect development is relatively recent (Riedl *et al* 1976; AliNiazee 1979; Whalon and Smilowitz 1979).

Modelling of insect populations for predictive and descriptive purposes is receiving increasing attention. Many models use temperature as the driving variable and the cumulative summation of 'heat units' above a developmental threshold temperature is the mathematical basis. Heat units as expressed in day-degrees (D°) are therefore directly related to insect development. Relating life cycle events to accumulated D° can often provide more accurate predictions than relationships with chronological time. Whether the model is a simple wall chart or complex simulation the measurement of D° is central to model operation.

The D° model which postulates a linear relationship between development rate and temperature has been used for most of this century for organisms growing under variable temperature regimes (Sanderson 1910). Following determination of the lower threshold of development (T_0) through linear extrapolation, the most widely used method for temperature summation above T_0 is the Blunck-Bodenheimer formula (B_BODEN) (Blunck 1914; Bodenheimer 1925 (cited in Baker 1980)).

$$C = \sum (T - T_0)$$

where C = accumulated D° above the developmental threshold (T_0) and T = measure of daily effective temperature (minimum + maximum/2) (Arnold 1960).

While simple, limitations to this formula have been recognised (Arnold 1960), especially when the daily minimum temperature falls below T_0 . An alternative method suggested by Arnold uses the assumption that the diurnal temperature curve approximates a sine-wave. The daily maximum and minimum temperature will define the amplitude of the sine curve. Integration gives the area under the curve and an estimate of D° above T_0 . Baskerville and Emin (1969) extended Arnold's method and formalised the equations (SINE__1).

Baskerville and Emin's method has since found wide use in temperature-driven models. However, alternative methods have been proposed: SINE__2 (Allen 1976) and SINEXP (Parton and Logan 1981), the latter promising wide application in that it is designed to predict soil as well as air temperatures.

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Local climatic variation may lead to considerable differences between actual and estimated D° (Arnold 1960) with the consequent need to make adjustments for local error. Allen (1976) compared D° summations from several disparate sites in continental USA and developed an adjustment factor for D° calculations. However, little further work has been done with local variation, particularly in non-continental climates. Accordingly we present results of an investigation of the performance of the four diurnal temperature models in calculating D° from two distinct climatic zones in New Zealand; Auckland and Canterbury.

The climate in Auckland is characterised by warm humid summers, mild winters and a high annual rainfall maximised during winter. In contrast, lowland Canterbury has warm summers with occasional hot föhn northwest winds giving temperatures above 32°C . Winters are cool with frequent frosts and occasional light snowfalls. Rainfall is comparatively low (Tomlinson 1976).

METHODS

Hourly temperature records for Auckland Airport and Christchurch Airport (Canterbury), were provided by the New Zealand Meteorological Service, Wellington.

Diurnal temperature models used in this study assume, either wholly or in part, a sine-wave approximation to the diurnal temperature curve. All require daily maxima and minima temperatures. SINEXP (Parton and Logan 1981) also requires Julian dates and the latitude of the locality. This model uses a truncated sine-wave to predict variation of day temperatures and an exponential function to predict night temperatures.

SINE_2 (Allen 1976) requires the minimum temperature on the following day. This allows that the second daily minimum is not necessarily the same as the first. Both of these models provide for adjustment of the model to local conditions. Establishment of the correction factors may involve considerable time and resources. The temptation remains, therefore, to use the models directly as published so we investigated model performance at the two sites without incorporating local correction factors.

Full mathematical descriptions of the models are in the relevant papers. Each model was coded in FORTRAN 77 for use on a VAX 11/780 computer at Lincoln College.

Actual D° s were calculated from hourly temperatures above a threshold by integration using Simpson's Rule. Model outputs for the two sites were compared using a 100 day random sample of 1981 temperature data. Days from summer and winter were used approximately equally. D° accumulations from the models were also compared with actual D° accumulations over growing season months. Data for this exercise were from January to March and October to December, 1981.

T_0 must be determined for each organism and can vary considerably. In order to determine the possible impact of variable thresholds on model accuracy, three T_0 were used: 10° , 5° and 0°C .

RESULTS AND DISCUSSION

Table 1 presents the absolute mean error and root mean square error in model predictions of daily D° for the 100 day sample in both localities and for the three T_0 used. Both error terms indicate how well the model predictions fit the integration of actual hourly temperature recordings above T_0 . The absolute mean error has an intuitive appeal, whereas the root mean square error penalises large individual errors heavily, and as such is a better criterion of performance.

All models performed well on a daily basis where both the absolute mean error and root mean square error were $\leq 1 D^\circ$ for each site over the three T_0 . Each model over-estimated the daily D° for Christchurch with the exception of B_BODEN which under-estimated D° per day. All models tended to under-estimate the Auckland data. The slight increase in the error terms as T_0 drops from 10° to 0°C may be caused partly by rounding error in the calculations but mostly by the model not fitting the newly exposed portion of the curve.

TABLE 1: Absolute mean error and root mean square error for model predictions of daily day-degrees for a 100 day sample of temperature recordings through 1981 for Christchurch and Auckland.

Model	Absolute Mean Error (D°) ¹			Root mean square error (D°) ²		
	10°T _O	5°T _O	0°T _O	10°T _O	5°T _O	0°T _O
Christchurch						
B_BODEN	0.58	0.71	0.63	0.90	1.0	0.88
SINE__1	0.43	0.56	0.63	0.77	0.82	0.88
SINE__2	0.45	0.62	0.71	0.77	0.85	0.94
SINEXP	0.38	0.55	0.61	0.76	0.79	0.84
Auckland						
B_BODEN	0.48	0.43	0.43	0.61	0.55	0.54
SINE__1	0.37	0.42	0.43	0.47	0.52	0.54
SINE__2	0.43	0.53	0.54	0.56	0.67	0.69
SINEXP	0.39	0.44	0.45	0.49	0.57	0.58

$$^1 u = \sum_{i=1}^n \text{ABS} (X_i^O - X_i^S) / n \text{ (Parton and Logan 1981)}$$

$$^2 \text{rms error} = \text{SQRT} [\sum_{i=1}^n (X_i^O - X_i^S)^2 / n]$$

where u = absolute mean error, n = number of observations, X_i^O = observed D° for the i th observation, X_i^S = simulated D° for the i th observation, rms error = the root mean square error.

D° accumulated over the period October to March, illustrates the impact of error accumulated over time (Table 2). For Christchurch data using a 10°C T_O, the proportion of time the predicted accumulated D° occurred within the observed accumulated D° ± 2 days varied from 32 to 66%. Some models clearly provided a better fit to the Auckland data where SINE__1 and SINE__2 were within the 2 day accuracy criterion, 99% of the time. The most notable result was the improved accuracy in prediction for both sites as T_O dropped to zero. Detailed analysis showed that as T_O is lowered, the daily error in prediction remained marginally similar. However, the mean D° per day increased, so decreasing the error to mean ratio. Hence, the overall effect of the daily error in prediction is diluted by the increasing number of D° calculated as T_O falls.

TABLE 2: The proportion of time the predicted day-degree accumulations are within a 2 day maximum deviation from the actual day degree accumulations. Seasonal temperature data Oct-March, 1981. (n = 180 days, degrees = °C).

Model	Predicted within actual total ± 2 days					
	%					
	Christchurch			Auckland		
	10°T _O	5°T _O	0°T _O	10°T _O	5°T _O	0°T _O
B_BODEN	32	85	98	87	100	100
SINE__1	46	79	98	99	100	100
SINE__2	47	77	97	99	100	100
SINEXP	66	55	97	31	92	100

Fig. 1: Error in model prediction of day-degree accumulations for Christchurch during the period October — March 1981.

Because of lack of independence in the data there remains the possibility that the effect of a few large deviations between the observed and the simulated D° during October, might be reflected in the accumulations over the following months. Figures 1 and 2 present graphical representations of the deviation of the simulated accumulated D° totals over time for both localities. For Christchurch, all models except B_BODEN over-estimated accumulated D° . The magnitude of the error over time is very similar for SINE_1 and SINE_2. Few plateaus indicating stability in prediction were exhibited. Major perturbations in the lines occurred relatively slowly with the exception of rapid accumulation of negative error during January and February. Days of greatest deviation during these months were characterised by a rapid rise in temperature to over 30°C followed by a rapid fall in temperature: a pattern which indicates a hot northwest föhn wind with a cold front passing over later in the day. When considering the Auckland data, model prediction under-estimated accumulated D° in all cases. SINE_1 and SINE_2 showed much greater error stability over time which is reflected in the accuracy of prediction (Table 2).

The improved prediction by SINE_1 and SINE_2 of the Auckland data, although the difference in the magnitude of error was more marked, was due to two possible factors. Firstly, the diurnal temperature curve for Auckland is more readily approximated by the sine-curve model. Secondly, the average diurnal temperatures over October to March are somewhat higher for Auckland than those of Christchurch. This would have an effect on prediction equivalent to lowering the threshold by the same amount.

Fig. 2: Error in model prediction of day-degree accumulations for Auckland during October — March 1981.

CONCLUSION

In spite of the widespread use of thermal summation to drive temperature dependent population models, few critical studies of methods for D° calculation from diurnal temperature profiles exist. This is particularly so for non-continental regions bounded by maritime influences. If population models are to be used for predictive purposes, we must have confidence in their output. Perturbations proffered by error in the driving variable (temperature) will have an accumulated effect in addition to any error in biological factors.

This study clearly demonstrated regional differences in model output for calculation of D° where T_0 is high. The tested methods, without correction, are most suitable for climates characterised by high mean hourly temperatures and a temperature profile closely approximating the sine-wave model (e.g. Auckland). Where the temperature profiles are subject to rapid heating and cooling changes (e.g. Christchurch), model performance shows considerable deviation from actual D° accumulation for a T_0 of 10°C . Predictive population models based on D° accumulations at high thresholds for development would, therefore be more likely to have greater accuracy in Auckland than in Christchurch, particularly if no corrections are made for local variation.

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