NASA Technical Memorandum 100731

A Case Study Demonstration of the Soil Temperature Extrema Recovery Rates After Precipitation Cooling at 10-cm Soil Depth

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PREFACE

From the invention of maximum and minimum thermometers in the 18th century, diurnal temperature extrema in their two forms--diurnal temperature maxima and diurnal temperature minima-- have been taken for air in many parts of the world. At some stations, these extrema temperatures have been taken at various soil depths also, and the behavior of these temperatures at a 10-cm depth at the Tifton Experimental Station in Georgia, USA, is the subject of this report.

After a precipitation cooling event, the diurnal temperature maxima drop to some minimum value and then start a recovery to higher values. This recovery is similar in concept to the behavior of thermal inertia and it represents a measure of response to heating as a function of soil moisture and soil property.

A recovery is defined as three or more monotonically consecutive increasing values of diurnal temperature maxima following some cooling event and its subsequent initial drop in the diurnal temperature magnitude. Eight different curves were fitted to a wide variety of data sets for different stations and years, and both power and exponential curve fits, in particular, were consistently found to be statistically accurate least-square fit representations of the raw-data recovery values.

For the case study demonstration shown in this report, these "best fit" power and exponential curves with their appropriately determined coefficients for the Tifton Experimental Station case were assumed equivalent to, and were substituted for, the raw data values themselves. These curves were shown to be predictable throughout the entire recovery period from information available 1 day after its onset. At that point, the capability for predicting the curves was interpreted, subsequently, as a capability for predicting the raw data values themselves.

The predictive procedures used were multivariate regression analyses, and these procedures were applicable to soils at a variety of depths besides the 10-cm depth demonstration presented here. The eventual goal of the research is to predict the future soil temperature behavior from the data available on the same day as the precipitation cooling event.

INTRODUCTION

Temperature variations at the Earth's surface manifest themselves in two well-known cyclic patterns of diurnal and annual periods, due principally to the effects of diurnal and seasonal changes in solar heating as well as to the gains and losses of available moisture. In this report, a related but very different third cycle has been identified, with a variable mesoscale period of 3 or more days. This is the period of recovery or return to the approximate level of original values of a series of 3 or more consecutive monotonically increasing diurnal soil temperature extrema, DTE, at 10 cm below the soil after precipitation cooling.

The diurnal temperature cycle mentioned above is related to the variable of temperature readings taken at fixed intervals throughout a 24-hour period. Although the daily temperature high occurs many times after midnight, the DTE variables in their two forms, diurnal temperature maxima, DTMAX (also referred to as T in this paper), and diurnal temperature minima, DTMIN, are not constrained absolutely by a specific time of day, and only are affected by the diurnal cycle in an integrated way. These variables do undergo an annual period by rising in value in the summer and declining in value in the winter. Modern texts do not treat the behavior of the DTE variables specifically as a separate topic; e.g., Rosenberg et al. (1983); Budyko (1982 and 1974); Brutsaert (1962); Oke (1978); Baver, Garner, and Garner (1972); and Geiger (1966).

Measurements of diurnal temperature extrema are not new. Air temperature measurements, for example, have been taken in many parts of the world from the time of the invention of maximum and minimum thermometers in the 18th century (Middleton, 1966; Landsberg, 1962; Six, 1782). At some stations, these extrema temperatures have been taken at various soil depths also, and the behavior of these temperatures at a 10-cm depth at Tifton Experimental Station in Georgia is the subject of this report.

After a precipitation cooling event, the diurnal temperature maxima drop to some minimum value and then start a recovery to higher values. An idealized schematic of such an individual T drop and recovery is shown in Appendix A. In Figure A-1, the recovery leg of 3 or more days is represented by "2," which begins at the minimum values of DTMAX (0). This recovery is similar in concept to the behavior of thermal inertia and it represents a measure of response to heating as a function of soil moisture and soil property. Remote-sensing measurements of thermal inertia were the impetus for the Heat Capacity Mapping Mission satellite, HCMM, which was launched in 1978 (Short and Stuart, 1982). A recovery is defined as three or more monotonically consecutive increasing characteristic values of diurnal temperature maxima, T, following some cooling event and its subsequent drop in the diurnal temperature magnitude.

The T drops and recoveries in the March-through-August period for Tifton Experimental Station data for the years 1979 and 1980 at a bare soil depth of 10 cm (the study considered here) are shown in Figures 1 and 2. The asterisks along the bottom of the two plots identify the cooling events and the initiation of their recoveries. More than 30 occurred in each year.

OBJECTIVES

In the procedure which was adopted, eight different curves were fitted to those recoveries which occurred in the March-through-August period for a wide variety of data sets for different stations and years and as a result, both power and exponential curve fits were consistently found to be statistically accurate least-square fit representations of the raw data recovery values.

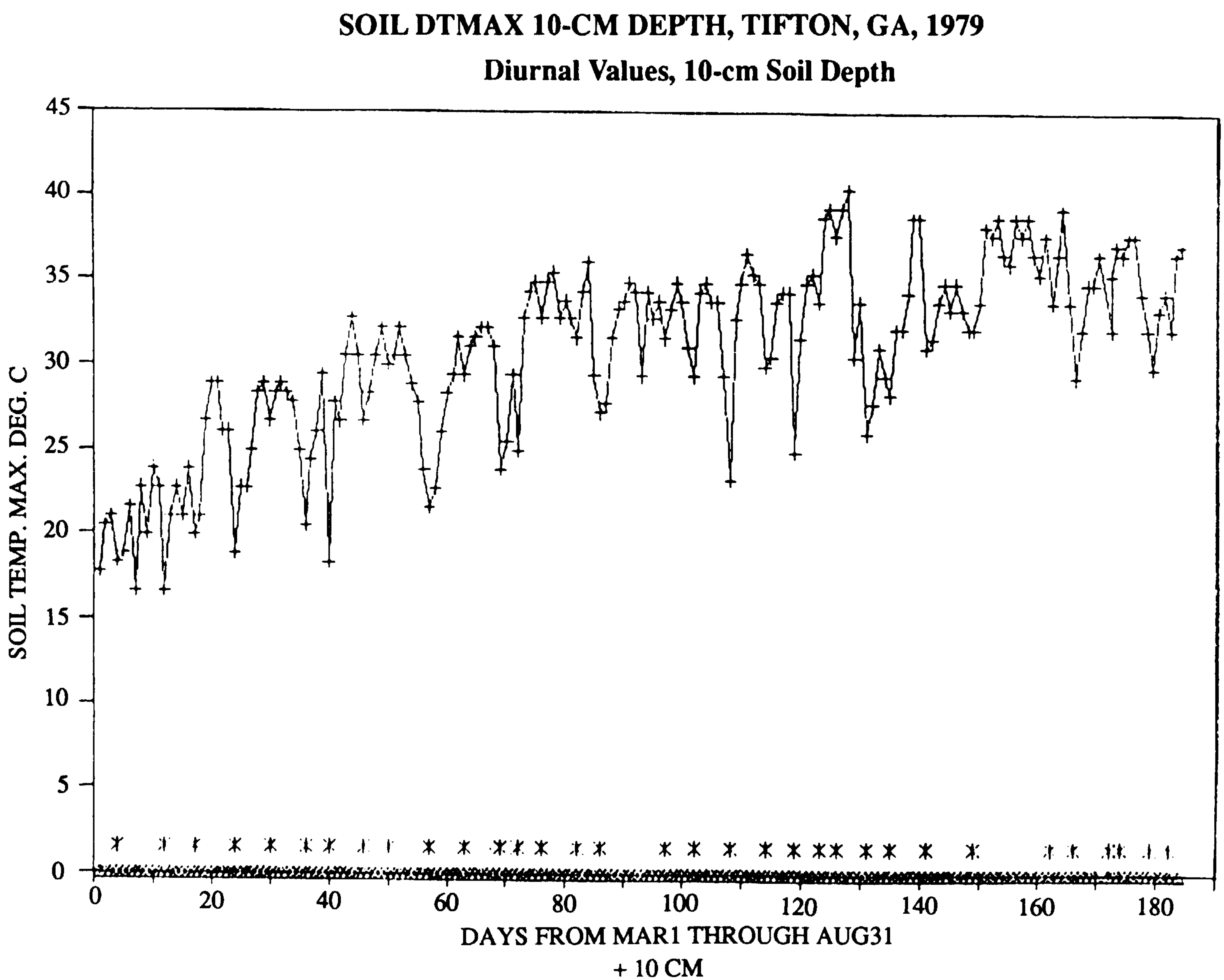

Figure 1. T Variable at 10-cm Soil Depth, Tifton, GA, 1979.

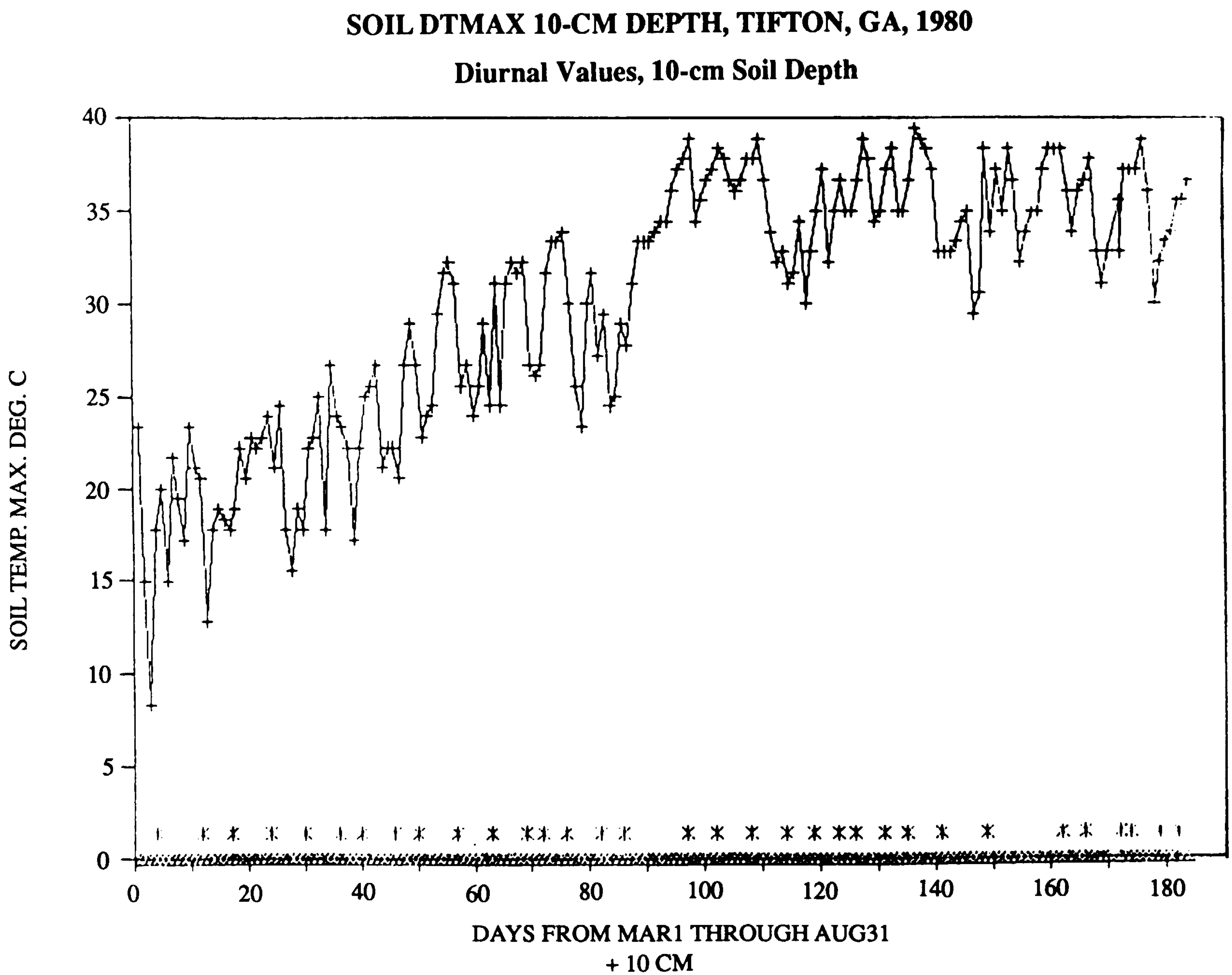

Figure 2. T Variable at 10-cm Soil Depth, Tifton, GA, 1980.

The 1979 and 1980 data sets for the case study demonstration for this paper were included in the curve fitting procedure. The resultant power and exponential curves with their appropriately determined coefficients for the Tifton Experimental Station case were then assumed to be accurate representations of the raw data values for the T recoveries in the 1979 and 1980 data sets. As such, the assumption was made that these curves could be substituted for the raw data values themselves, with very little error. At this point, procedures were adopted to predict these power and exponential curves for each recovery throughout the entire recovery period, with information available 1 day after the onset of the recovery.

These procedures involved multivariate regression analyses. For example, the slopes of the exponential and power curves and the final value of T at the completion of a recovery can be predicted from the drop in T caused by the precipitation cooling, the 1-day rise in the value of T which occurs on the day following the cooling event, and the indications of when in the March-through-August period the cooling event took place. The accuracy of these predictions has been indicated by a direct comparison of the curve-fitted values of the slopes for the exponential and power curves with the predicted values. In addition, the predicted value for T at the completion of each recovery was compared to the raw data values for the exponential curve fit. The same procedures are applicable to soils at a variety of depths besides the 10-cm depth demonstration explained here.

The eventual goal of the research is to predict the future soil temperature behavior at various depths up to and including the soil surface interface from first principles, starting with the data available at the time of the precipitation cooling event, rather than information available 1 day after the onset of the recovery.

DATA

All the temperature data, T, processed over the March-through-August period and used or referred to in this work were obtained from the National Oceanic and Atmospheric Administration's (NOAA) publication entitled, "Climatological Data," (U.S. Department of Commerce, Georgia, 1979, 1980). The data are collected from each state. The data sets that were initially acquired were from the states of Georgia and Iowa for years in the late 1970s and early 1980s. All data were obtained from bare soil plots.

The Georgian data were initially selected because of the good year/bad year crop yields, and the no drought/drought contrast from the 1979/1980 crop years. Note that some other years in the late 1970s were also considered. Data for nine stations in Georgia and two stations in Iowa were processed for 2 to 5 years each, and from these data sets, the Tifton Experimental Station data sets for the years of 1979 and 1980 were chosen for the case study demonstration (U.S. Department of Commerce, Georgia, 1979, 1980; Iowa, 1977, 1978).

Tifton data sets had proven to be very complete over the years considered, compared to some of the other data sets, and this is the principal reason they were chosen as the case study. No other outstanding features characterized these data sets from any other station--especially for those stations in the State of Georgia.

The years of 1979 and 1980 differed in their precipitation distribution, shown in Appendix A, Figures A-3 and A-5. The 1980 precipitation was characterized by a 25-day period from May 25 through June 18 with only a trace of rainfall on 1 day, June 9. The 1979 precipitation was well distributed, with no extensive drought periods. Local statistics indicated that corn and soybean yields in 1980 were roughly half of the yields of 1979. The corn and soybean crops were still in the ground during the 25-day period of no precipitation in 1980. The soil type at Tifton Experimental Station has been characterized as Tifton loamy sand.

In the 6-month period of March through August, there were 33 drops and recoveries in the 1979 Tifton data set, or 5.5 per month, which was high compared to some of the other data sets processed. In the 184-day, 6-month period of the 1979 Tifton series, the minimum number of days in the recovery period for the 33 events (each event requiring at least 3 consecutive days of monotonically increasing values of T) was 99 days. Because some recoveries were longer than 3 days, the actual total time in the mesoscale recovery period was 127 days--or 69 percent of the entire 184-day period. For the data sets tested, this mesoscale cycle of 3 or more days appears to occur approximately three to five times per month in northern midlatitudes, with no elongated periods of drought.

As stated in the objectives, this recovery is not unique to the 10-cm depth alone. Data are taken at soil depths of 5, 10 and 20 cm at the Tifton Station, and these values from March through August for 1979 are shown in Appendix A, Figure A-2. In this figure, the T values almost always appear to drop to a minimum temperature for all three soil depths on the same day, for the 33 precipitation cooling events. In some cases, the minimum T values are the same for all three soil depths after the precipitation cooling. The same procedures that are shown here for the 10-cm soil depth can be just as easily applied to the 5-cm and 20-cm soil depth data. Soil depths greater than 230 cm have not been tested. For contrast, the 1980 data sets are shown in Appendix A, Figure A-3 from the Tifton Experimental Station for the same three soil depths. The effects of the severe 25-day drought period mentioned above have resulted in high values of T for the 5-cm soil depth values located roughly between the 90- to 120-day abscissa scale of Figure A-3. The individual drops and recoveries for both of these plots are indicated by the asterisks along the Y axis, just above the abscissa scale.

The Tifton Experimental Station's soil, listed as Tifton loamy sand, can have its available water, without refurbishment, drop an order of magnitude in 30 to 40 days. The data came from experiments in which soil, to a 60-cm depth, was wetted to field capacity, when three varieties of peanut plants reached the wetting stage and did not recover overnight. These peanut irrigation experiments were conducted out-of-doors with rainfall-controlled shelter covers (Stansell et al., 1976).

The Weather Bureau under the U.S. Department of Commerce, Environmental Science Services Administration, is responsible for the station data described above (Hughes, 1970). A standard set of instruments and procedures have been recommended for the stations participating in this network, and these specifications are detailed in the Weather Observing Handbook No. 2, Substation Observations (U.S. Department of Commerce, 1970). A detailed report on each substation is kept also and any deviations from the standard format for any station are listed. The standard-plus-additional recording instrumentation for the Tifton Experimental Station are listed as maximum and minimum thermometers in cotton region shelters, 8-inch standard rain gauge, evaporation pan, anemometer (odometer), Hooke gauge, Stilling well, Six's water thermometer, and Palmer soil thermometers at 2- , 4- , and 8-inch depths, (personal communication, National Weather Service).

PROCEDURE

The 1979 and 1980 10-cm soil depth data sets for the Tifton Experimental Station shown in Figures 1 and 2, were curve-fitted for the 33 and 32 recoveries for the T variable, respectively. The eight different curves fitted are listed below in Table 1.

Table 1.

1. T = A + B*T	5. T = 1/(A + B*t)
2. T = A* EXP (B*t)	6. T = t/(A*t + B)
3. T = A* (t**B)	7. T = A + B*LOG (t)
4. T = A + B/t	8. T = EXP(A + B/t)

where: T - Diurnal Temperature Maximum
A - Constant/Intercept
B - Constant/Slope
t - Days for Recovery

A basic assumption made in the report is that the "best fit" power and exponential curves with their appropriately determined coefficients for the Tifton Experimental Station case study demonstration are equivalent to, and substitutable for, the raw data values for the T variable recoveries. A basis for this assumption is the "goodness of fit" of these curves to the raw data values; these are indicated by the adjusted R**2 values for each of the recoveries in 1979 and 1980. These values are shown in Appendix B, Figures B-1 and B-2, for the years 1979 and 1980. In Figure B-1 for 1979, only three values of the exponential and two values of the power curves have adjusted R**2 values below 0.7; in Figure B-2 for 1980, three values for the exponential and five values for the power curve have adjusted R**2 values below 0.69. A second check on the validity of this assumption can be inferred from the accuracy of the predicted total T recovery compared to the real raw data, shown in Figure 6, which will be discussed below.

The computer programs used are from the Biomedical Computer Programs, BMD (Dixon, 1973), which were modified for personal computers; the programs called Curve, Regress, and Resid were used (Galbraith, 1986). From these curve fits, values of the slope, B, were obtained and plotted against the number of days from February 25 that the event took place.

With the curve-fitted values for the slopes, B, in hand for the 1980 data, a second and different procedure outlined above in the Objectives, was undertaken to estimate the values of these same 1980 slopes. A multivariate linear regression and residual analysis was run on a data set composed of four raw-data independent variables: (1) the 1-day drop, and (2) the 1-day rise in T on the day before and the day after the precipitation event, (3) the minimum values of T on the day of the event, and (4) the number of days from February 25 that the event took place for the combined 65 total events in 1979 and 1980. These four independent variables are different from the consecutively monotonically increasing raw data values of T which constitute a recovery from a precipitation cooling event. The 1979 curve-fitted values of B obtained above were used as the fifth and dependent variable for 1979, while no values of B were used for the dependent variables for the 1980 data set. The regression and residual analysis run on this data set yielded a predicted set of values for the slopes, B, for the 1980 data set, which were then labeled the "regression estimate." These regression estimate values could then be compared to the values for the slopes obtained above from the curve-fitting procedure, for each of the eight curves listed in Table 1. In Figures 3 and 4, this comparison of curve-fitted values for slope versus the regression estimate values of slope for the 1980 data set was made for the exponential and power curves--curves 2 and 3--listed in Table 1. The comparison of the two methods for the other six curves (Table 1) are shown in Appendix C, Figures C-1 through C-6.

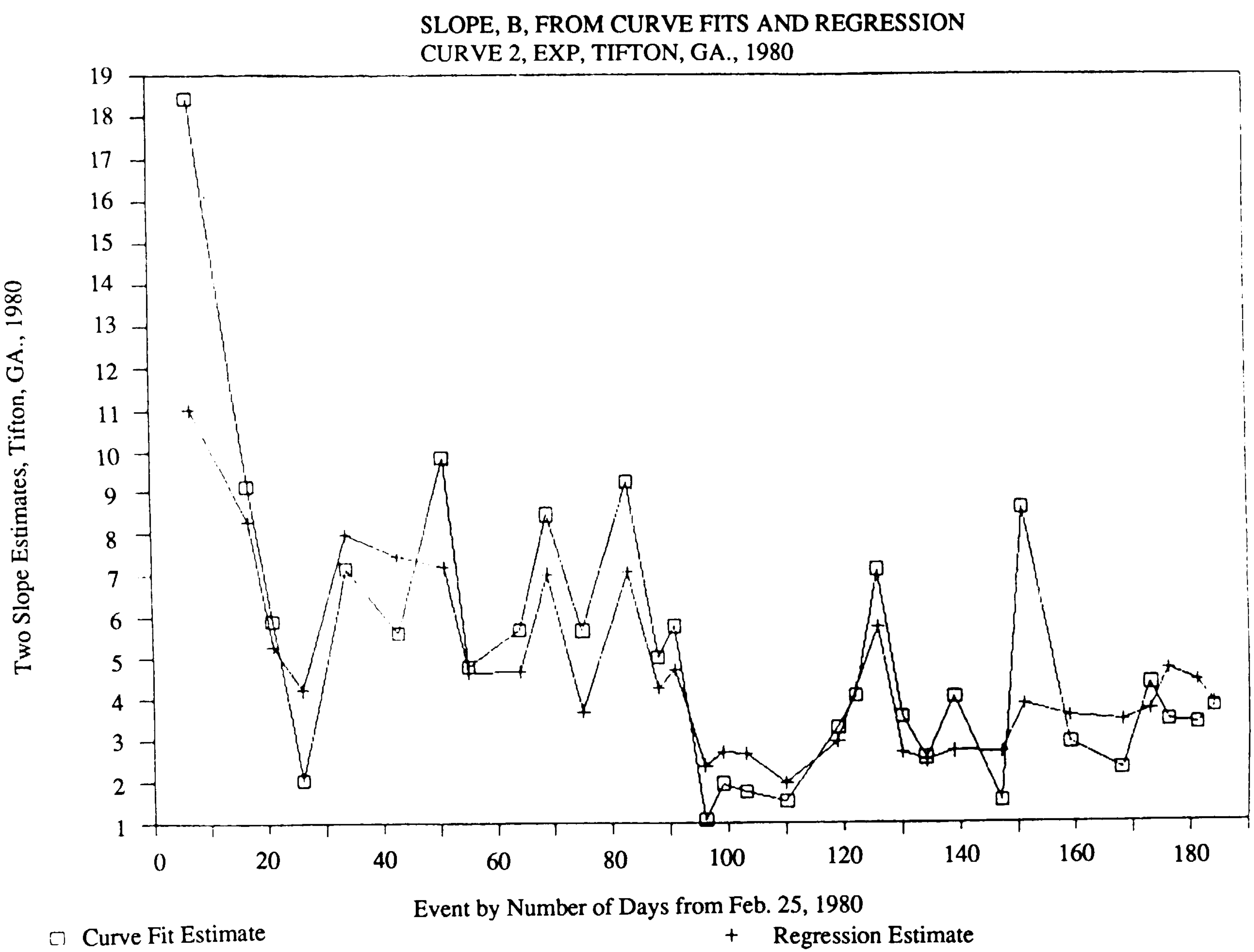

Figure 3. Comparison of Curve Fit to "Regression" for Curve 2 (Table 1)--Projection of Slope, B, in 1980 from 1979 Data.

SLOPE, B, FROM CURVE FITS AND REGRESSION
CURVE 3, POWER, TIFTON, GA., 1980

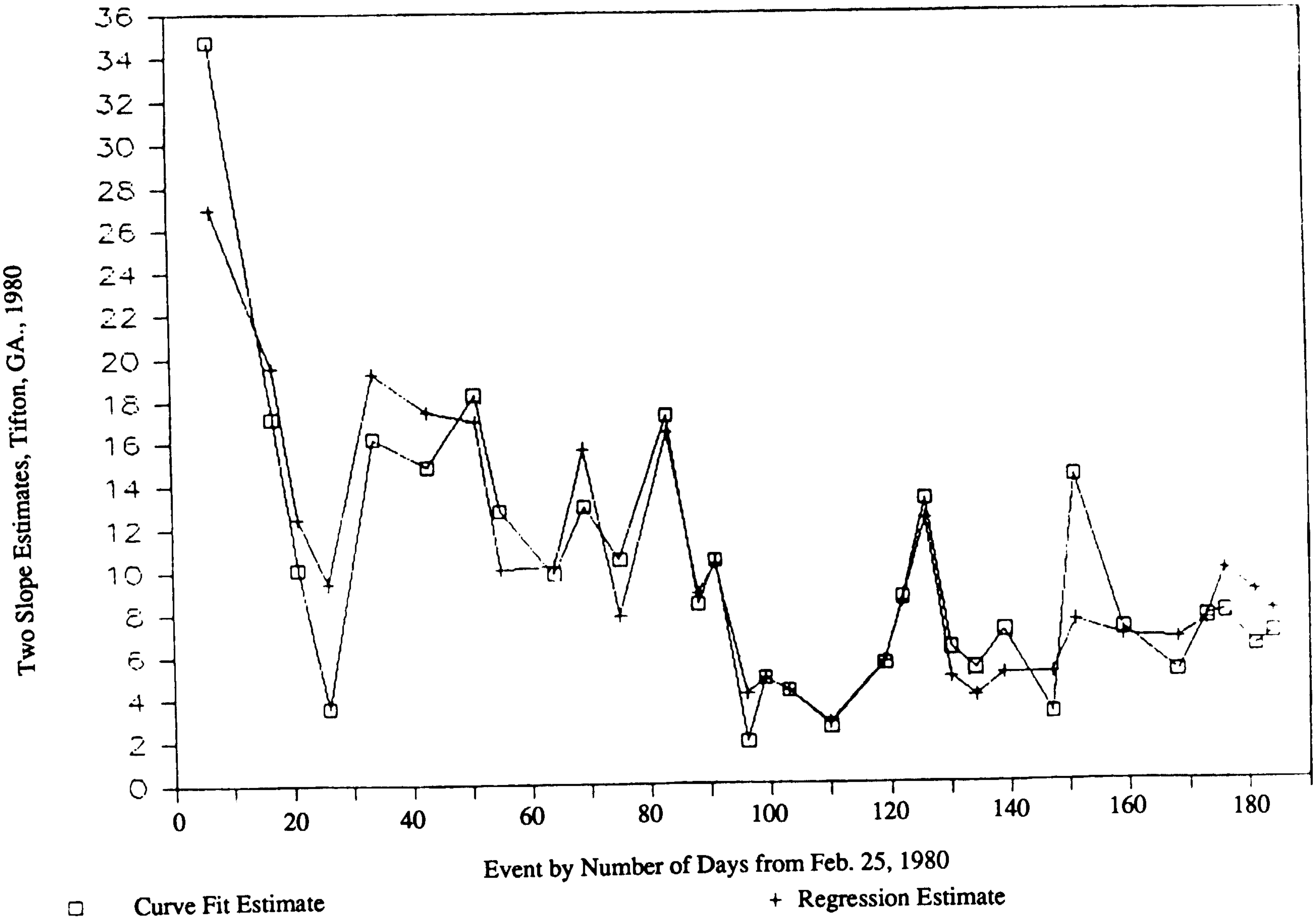

Figure 4. Comparison of Curve Fit to "Regression" for Curve 3 (Table 1)--Projection of Slope, B, in 1980 from 1979 Data.

The dependent variables used above in the regression analysis had been obtained from statistical sampling of a number of variables perceived to be related to the slope of the recovery curve. The 1-day drop and next-day rise around the precipitation cooling event are highly deterministic of the slope of the recovery curve for the variable T, and also reflect the total temperature which this variable will undergo in its recovery to equilibrium. This is shown in Figure 5, where the 1-day drop and 1-day rise in T have been taken arbitrarily as percentages of the minimum temperature, T(0), and have been plotted for the 1979 data set, with the total temperature of recovery from the precipitation event, again as a percentage of the minimum temperature, T(0). Not only are the general shapes of these curves similar to one another, but they also resemble the general shapes of the plots for the curve-fitted values of B for the 32 recoveries in 1980, shown in Figures 3 and 4.

Finally, a second estimated variable, the total temperature recovery for the 32 precipitation cooling events in 1980, has been predicted using exponential curve values for the 1979 and 1980 values of slope, in a regression and residual statistical analysis similar to that described above for predicting the slopes, B. The estimated values of total temperature recovery from the "regression estimate" have been plotted directly against the raw data values they are supposed to approximate, and are shown in Figure 6. That is, the total or final temperature at the end of the recovery period of 3 or more days was predicted in the "regression estimate" from data available after 1 day from the start of the recovery and then compared directly to the actual raw-data final temperatures. The processed data set included the same set of 65 values for the four independent variables from the 1979 and 1980 data sets used in the "regression estimate" for the 1980 slopes described above. In addition, a fifth independent variable was the curve-estimated values for slopes for 1979, and the 32 "regression estimate" values for the slopes obtained above. The sixth and dependent variable consisted of the raw data values for total temperature recovery for 1979, and no values for slope, B, for 1980; these 1980 values were estimated form the residual analysis.

DISCUSSION

The estimate of the two variables, slope B, and total temperature recovery, which were discussed above, have been made deliberately more difficult. In a real situation, estimates would not be made for the entire season all at once, but rather one at a time, on the day after a minimum value of T has been observed. The station data for a number of seasons--not just the single-season 1979 data set--would be used. These larger data sets should improve the accuracy of the estimate. The three monotonically increasing values of T necessary as a minimum requirement for a recovery would be assumed 1 day after a precipitation event causes a drop in temperature, T. Synoptic weather data can be used to predict the next precipitation event which would be followed by another subsequent drop and recovery in T. If no precipitation event is imminent, the assumption can be made that the recovery to equilibrium can be predicted as shown above, from 1 day after the precipitation event.

Because the calculation was deliberately made more difficult and does not represent the normal usage of the method, no quantitative estimate of the accuracy of the fits was made for the curve fits versus the "regression estimate" shown in Figures 3, 4 and 6. Figures 3 and 4 demonstrate the comparison of the "curve fit" values of B to the "regression estimate" values of B. Similar comparisons were made for the other six curves in Table 1, and were plotted in Appendix C, curves C-1 through C-6. However, for the power curve in Figure 4, which was in the best agreement for the comparison of the curve fit and "regression estimate," more than one-third of the points from both methods are exactly superimposed on one another. The exponential curve in Figure 3 and the modified power curve and modified exponential curve, Appendix C's Figures C-4 and C-6, respectively, also show good agreement for the comparison.

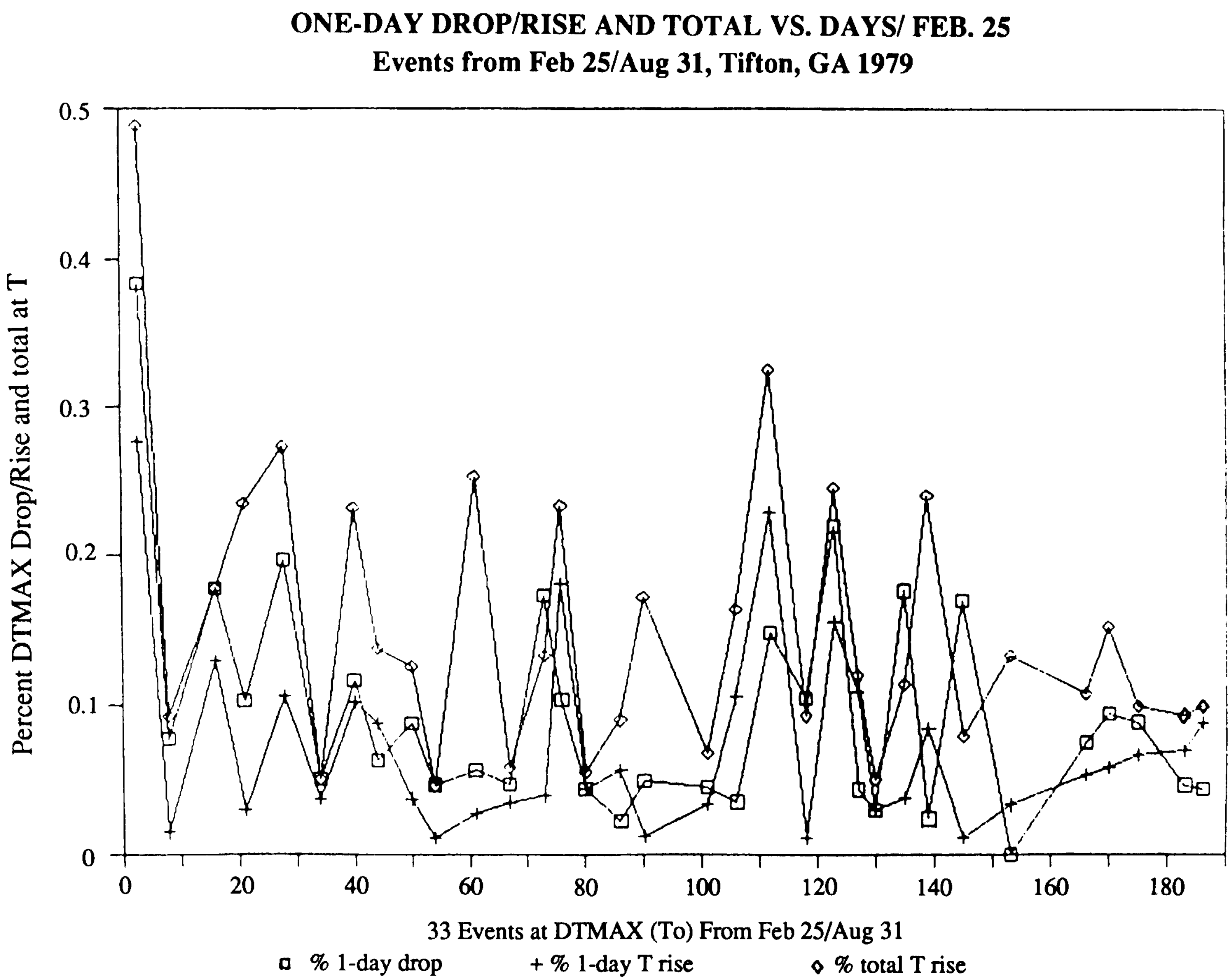

Figure 5. One-Day T Variable Drop, Rise; Total T Recovery--Plot of Raw Data Values, Tifton, GA, 1979.

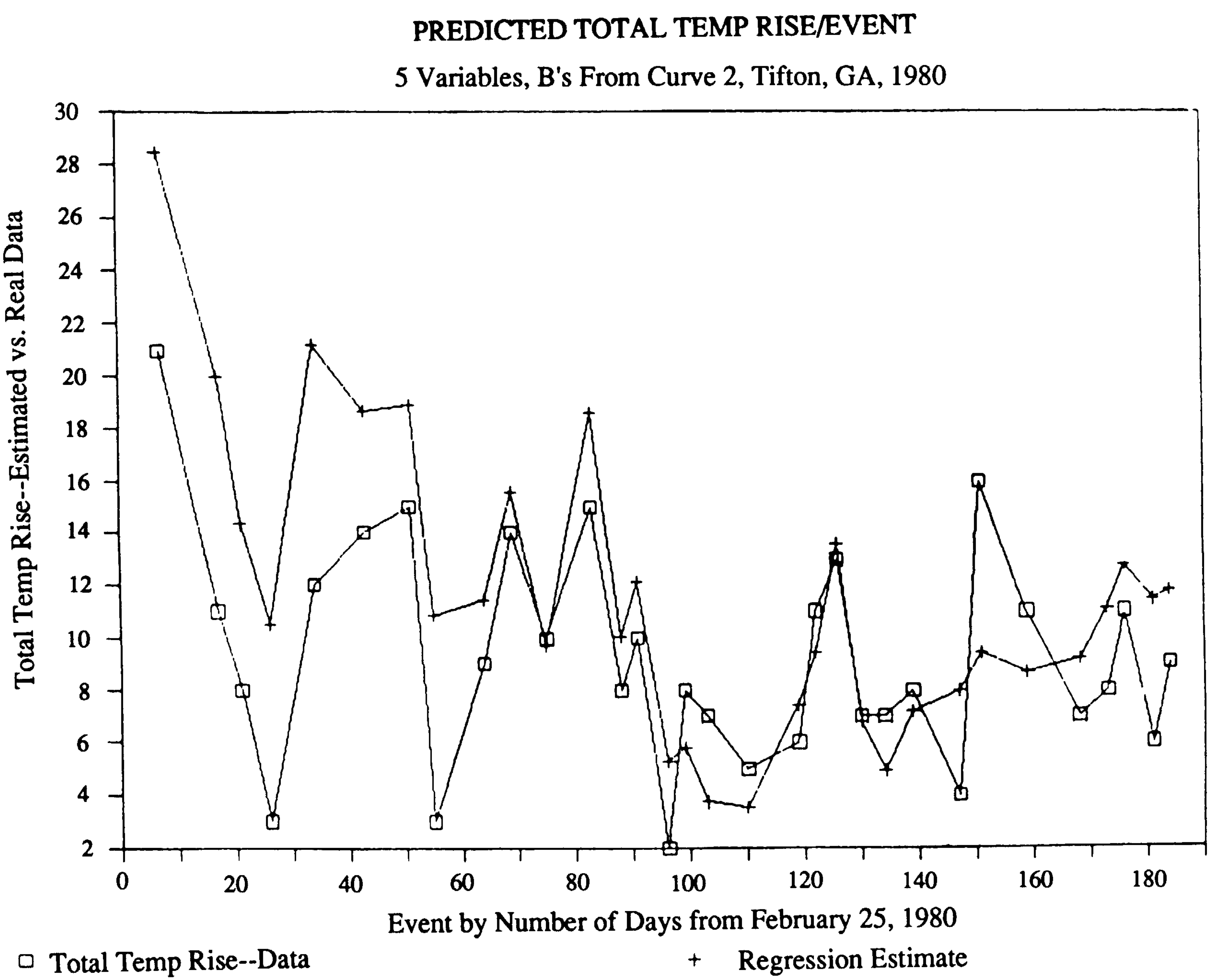

Figure 6. Comparison of Raw Data to "Regression Estimate" for Curve 2 (Table 1)--Projection of **Total T Recovery in 1980 from 1979 Data.**

For the results of the second predictive procedure described above, the "regression estimate" for the total temperature, T, recovery for the exponential curve example shown in Figure 6 follows the pattern for the raw data values in general, but is higher in value for the first half of the 1980 season.

From Figures A-2 and A-4 in Appendix A, the pattern of drops and recoveries in the variable T that have been discussed for soil at the depth of 10-cm, are reflected also in the raw data for the 5- and 20-cm soil depths--the same procedures used to predict the slopes and total temperature recovery for the 10-cm data can be used to predict simultaneously the same values at various levels of soil depth.

Some additional complications which have been considered include the cooling effect of the precipitation when its temperature is less than the ground temperature, an effect most likely to occur in the early season, March and April, as well as the relative cooling effect of precipitation when it occurs at different times and over different periods in the diurnal cycle. The ultimate objective of the research was to explain the recovery of the T variable from first principles, a subject which has not been addressed in this paper.

CONCLUSIONS

The previously neglected T variable, although admittedly an integrated function of the variables changing in a diurnal cycle, offers some unique insight into the conditions immediately below the Earth's surface. Each value of T can take approximately 24 hours to develop, and this period of time allows a quasi-equilibrium condition to be established in soils at different depths below the surface. Given these conditions initially, the slower mesoscale recovery period of T, 3 or more days for the data sets tested, indicates a quite regular trend in soils below the surface. This recovery characteristic is so regular as to be predictable at certain stages along the recovery, so long as another precipitation event and subsequent cooling does not occur to initiate the drop and recovery cycle all over again. The period of 3 or more days is ideal for agricultural planting, irrigating, and harvesting decisions which are made over these periods as well as mini-scale meteorological modeling which could be made with additional synoptic information. The T recoveries themselves constitute a significant portion of the total time considered for the March-through-August period, approximately two-thirds of the time for the data shown here. The T recoveries in the 1979 Tifton data are underway for 69 percent of the total days considered; for the 1980 data, the comparable figure is 66 percent.

With respect to an earlier collaboration with Professor Landsberg, this report expands the statistical analysis to eight curves, while substantiating the power curve recovery assumption for the predictive model which was used. The model discussed with Professor Landsberg was based on the same 1979 Tifton Experimental Station data as the basis for the predictions, as was done for this report, but projections were made for the T variable behavior not only for other years but for other station data sets as well. These predictions were made over the nine Georgian stations and two Iowan stations previously mentioned in the Data section of this report (Welker, 1984).

ACKNOWLEDGEMENT

Without the patience, insights, advice and encouragement of Professor Helmut Landsberg of the University of Maryland, this report would not have been written. I acknowledge his help with gratitude, and assume sole responsibility for any speculations, errors, or mistakes contained within the body of this paper.

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APPENDIX A

T DROP AND RECOVERY FOR THREE SOIL DEPTHS

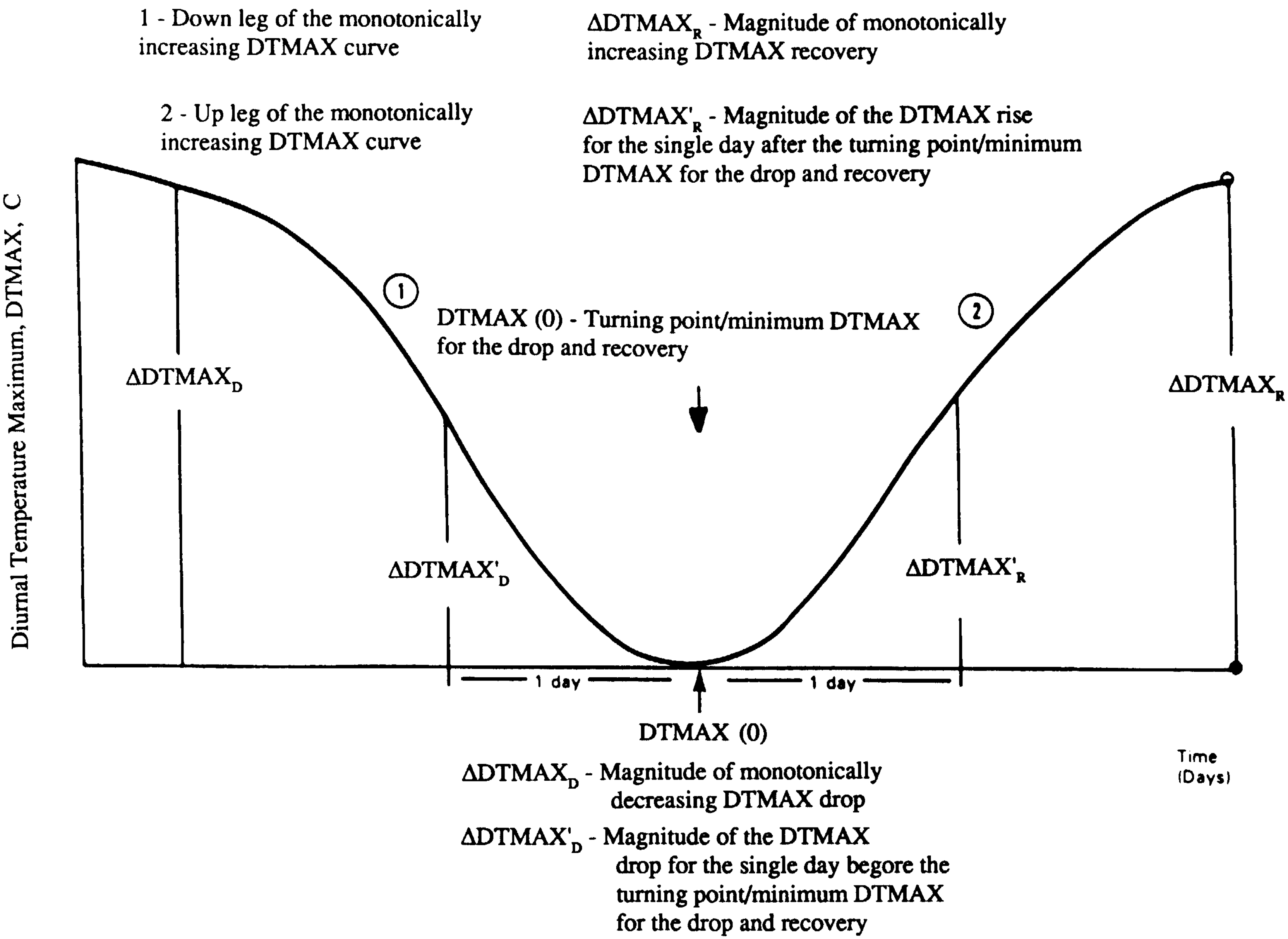

Figure A-1. Idealized Schematic of a Single T Drop and Recovery.

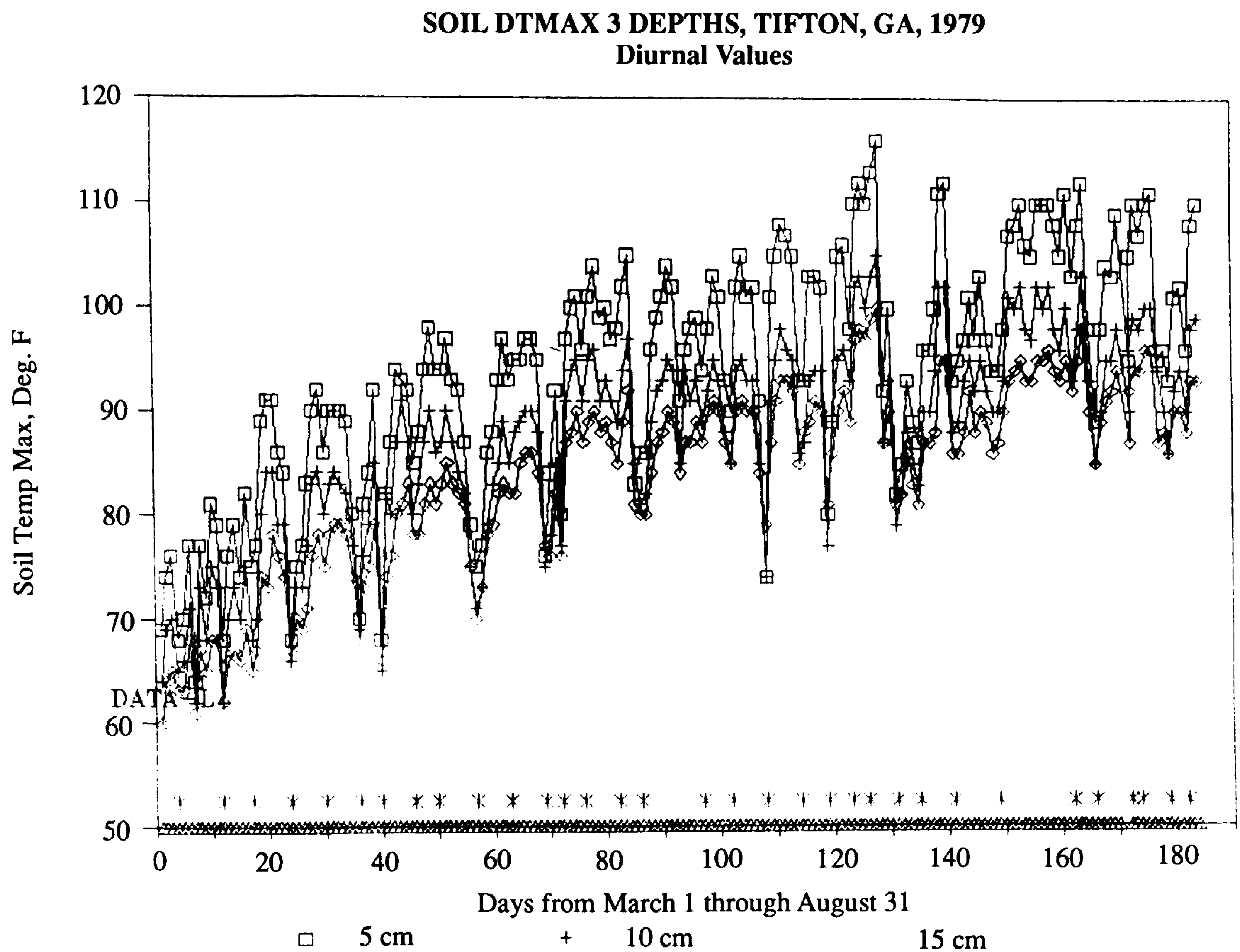

Figure A-2. T Values for Soil at three depths: 5 cm, 10 cm, and 15 cm for Tifton, Georgia, 1979.

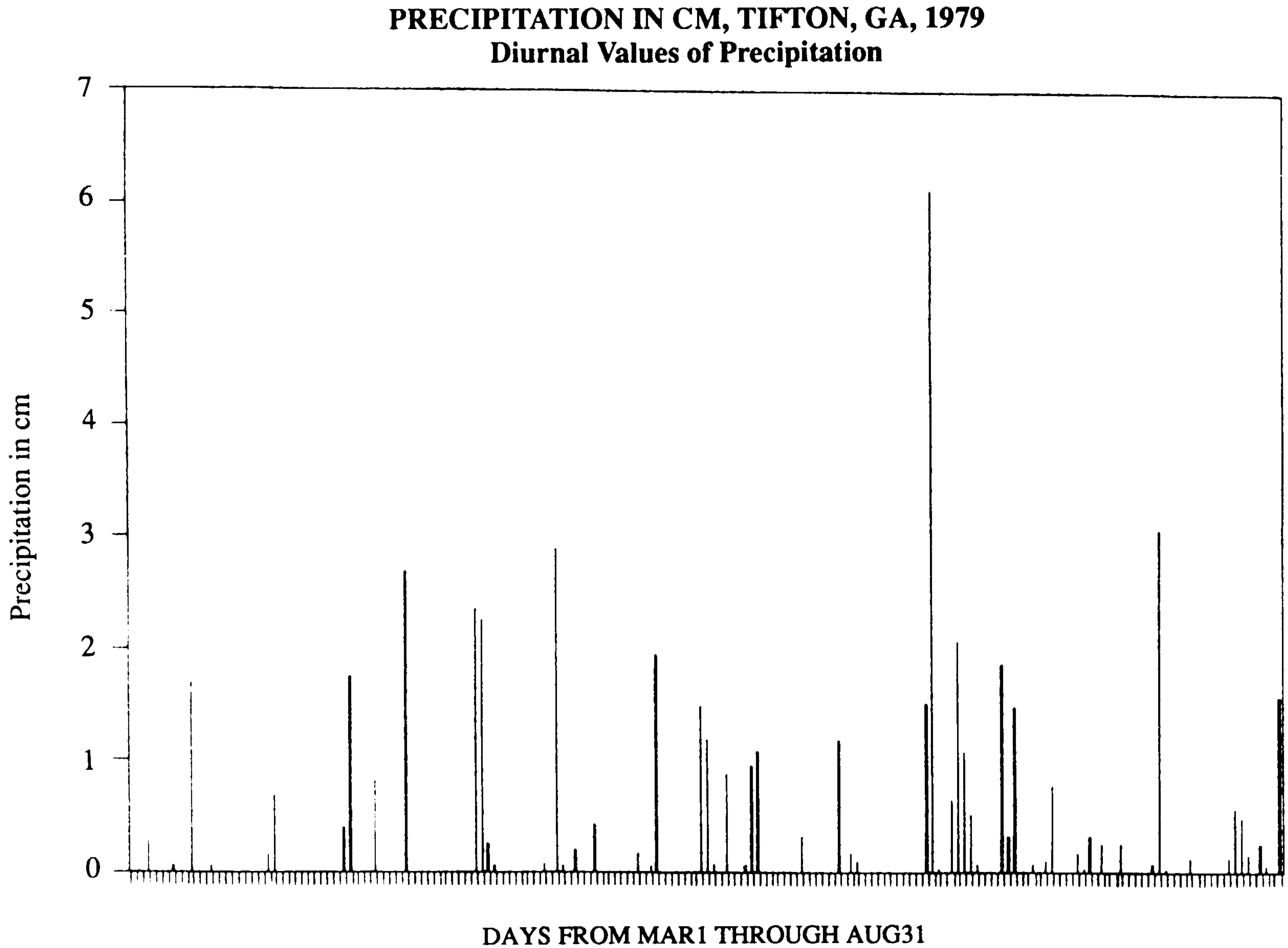

Figure A-3. Diurnal values of precipitation in cm, Tifton, Georgia, 1979.

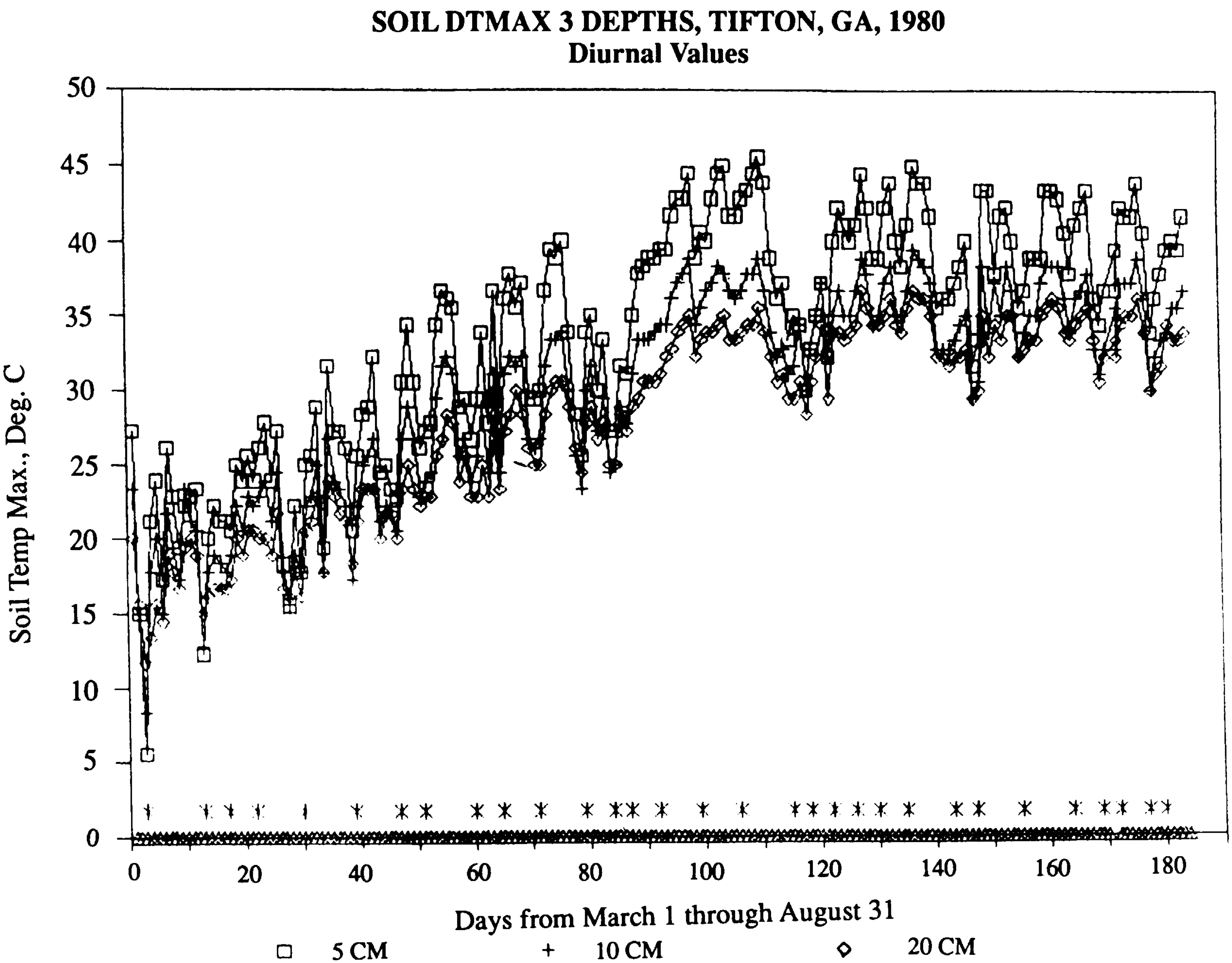

Figure A-4. T values for soil at three depths: 5 cm, 10 cm, and 15 cm for Tifton, Georgia, 1979.

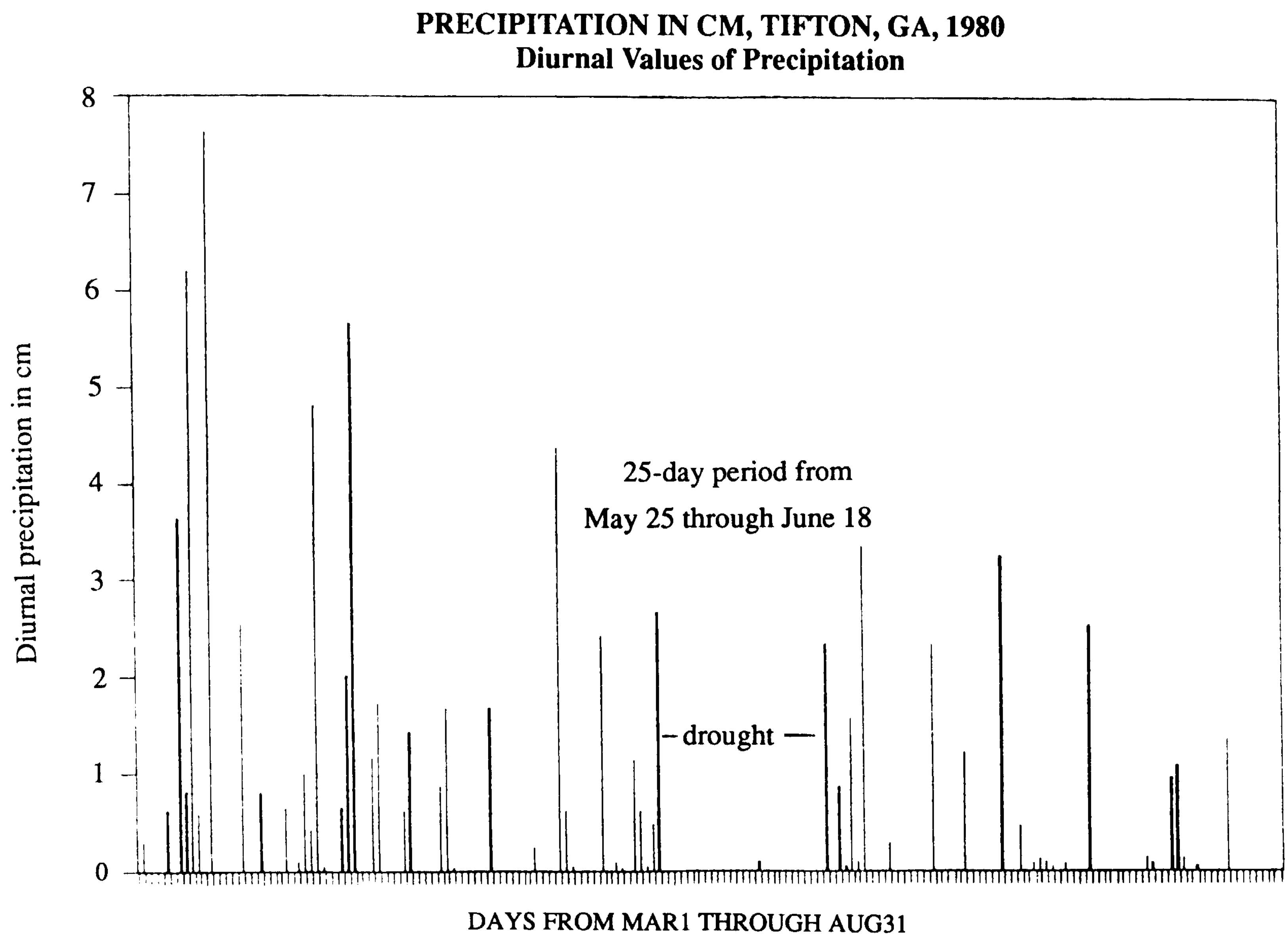

Figure A-5. Diurnal values of precipitation in cm, Tifton, Georgia, 1980.

APPENDIX B

ADJUSTED R**2 VALUES FOR EXPERIMENTAL AND POWER CURVE FITS TO T RECOVERY RAW DATA VALUES, GA., 1979 AND 1980

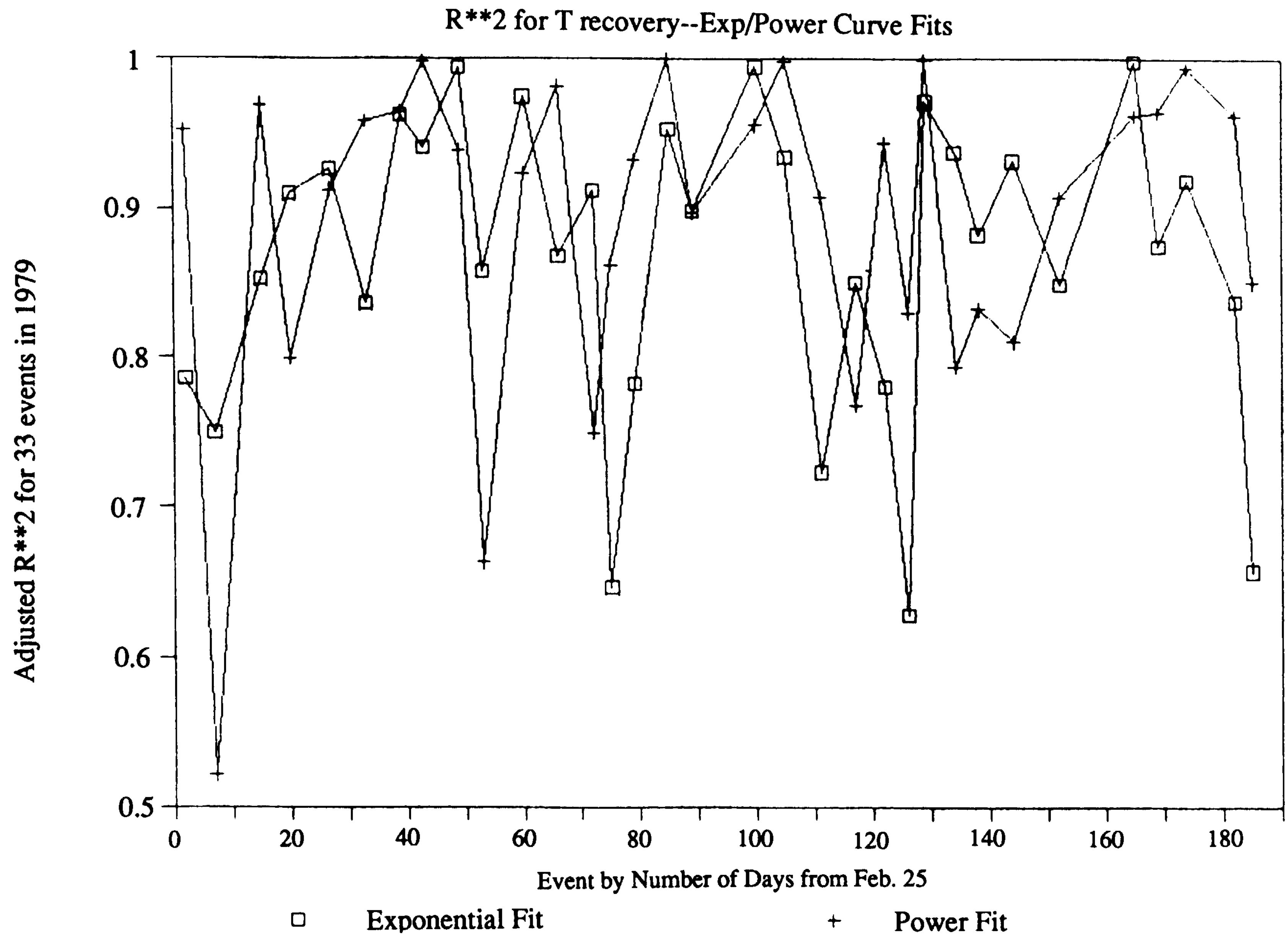

Figure B-1. Adjusted R**2 values for Experimental and Power Curve Fits to T, recovery raw data values, Tifton, Georgia, 1980

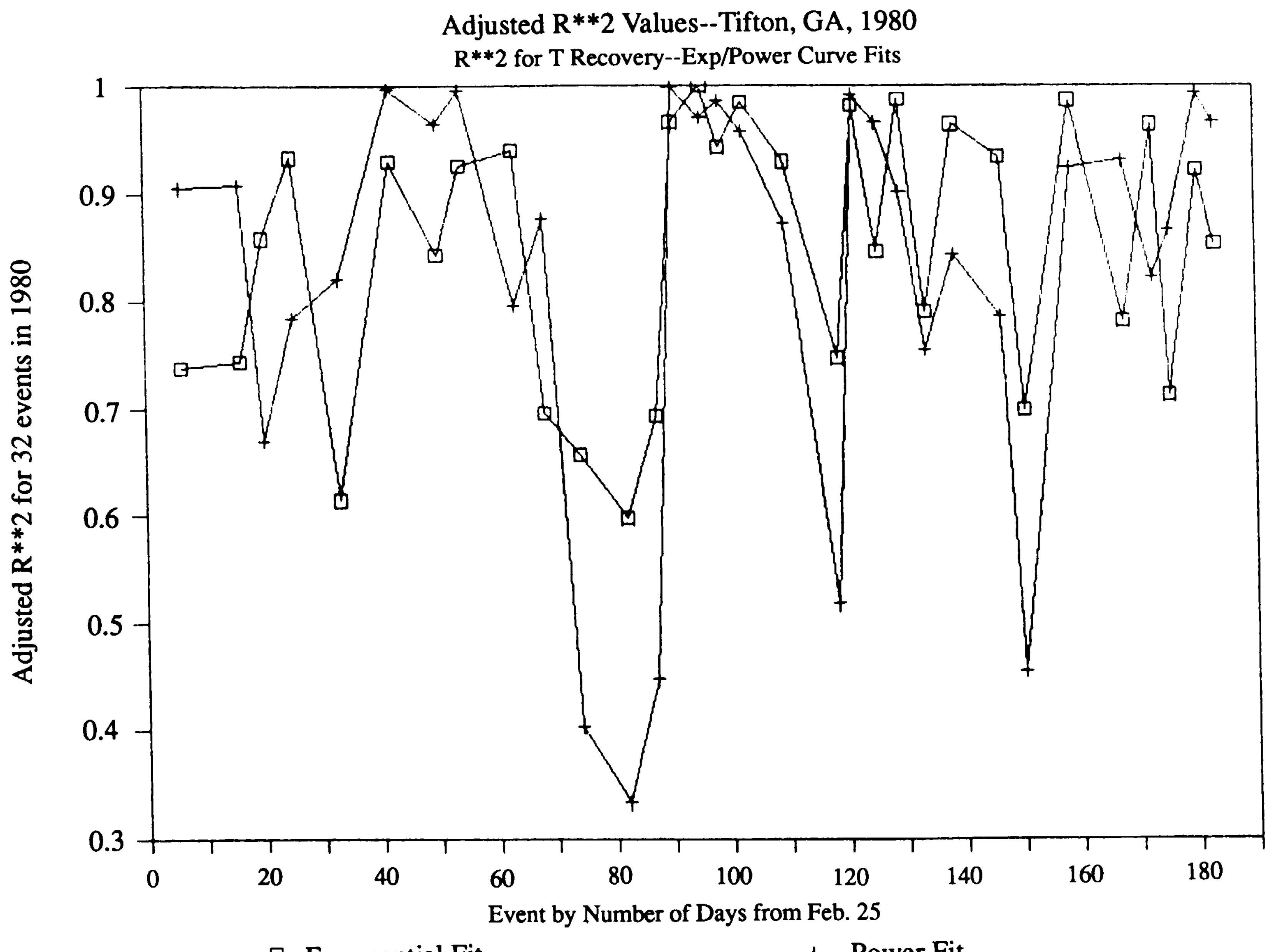

Figure B-2. Adjusted R**2 values for Experimental and Power Curve Fits to T, recovery raw data values, Tifton, Georgia, 1980

APPENDIX C

COMPARISON OF CURVE FIT TO "REGRESSION ESTIMATE" FOR CURVE 1
AND CURVES 4 THROUGH 8 (Table 1)

PROJECTION OF RESULTS FROM TIFTON EXPERIMENTAL STATION, GA.,
IN 1980 FROM 1979 DATA

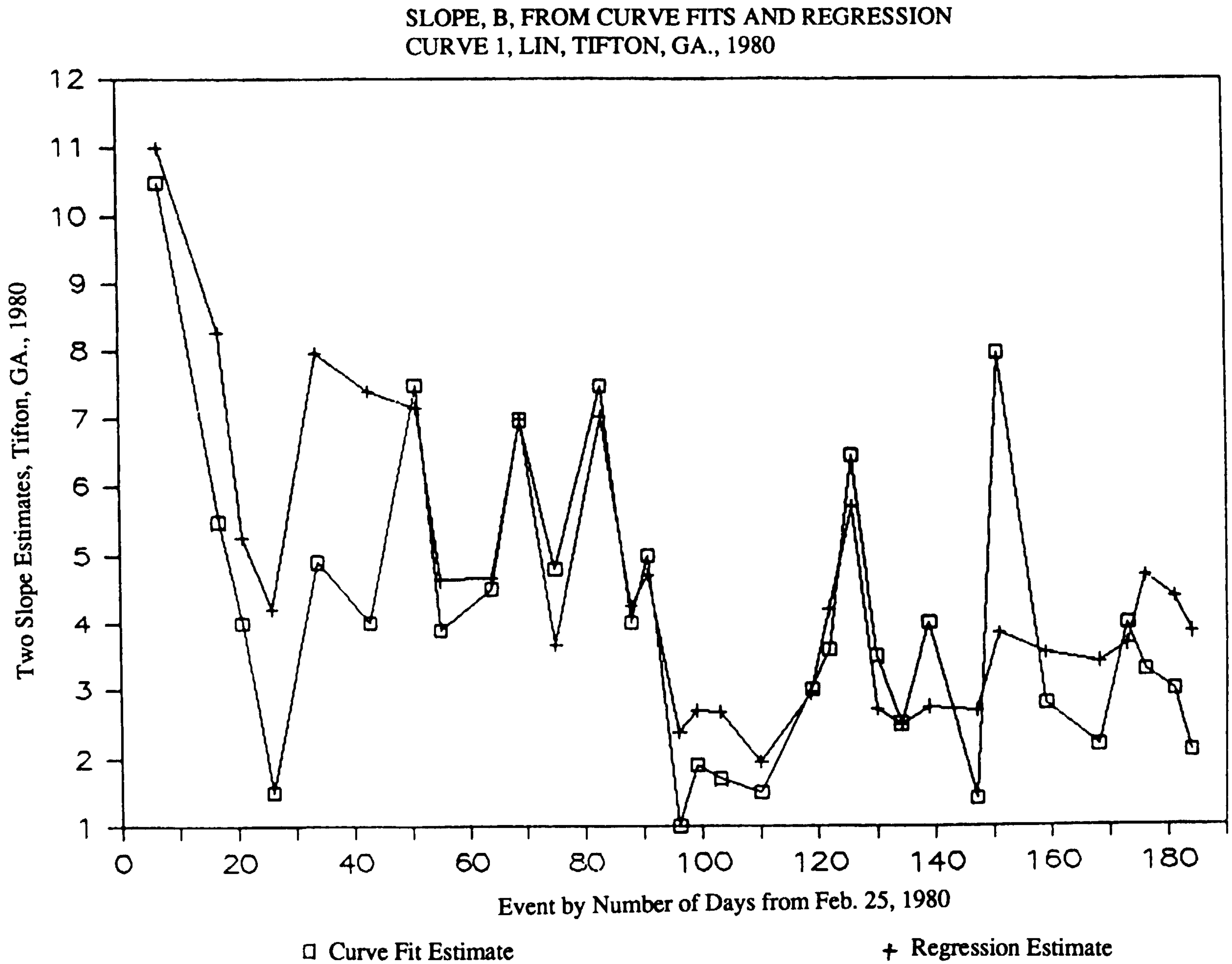

Figure C-1. Comparison of Curve Fit to "Regression Estimate" for Curve 1 (Table 1); Projection of Slope, B, in 1980 from 1979 Data.

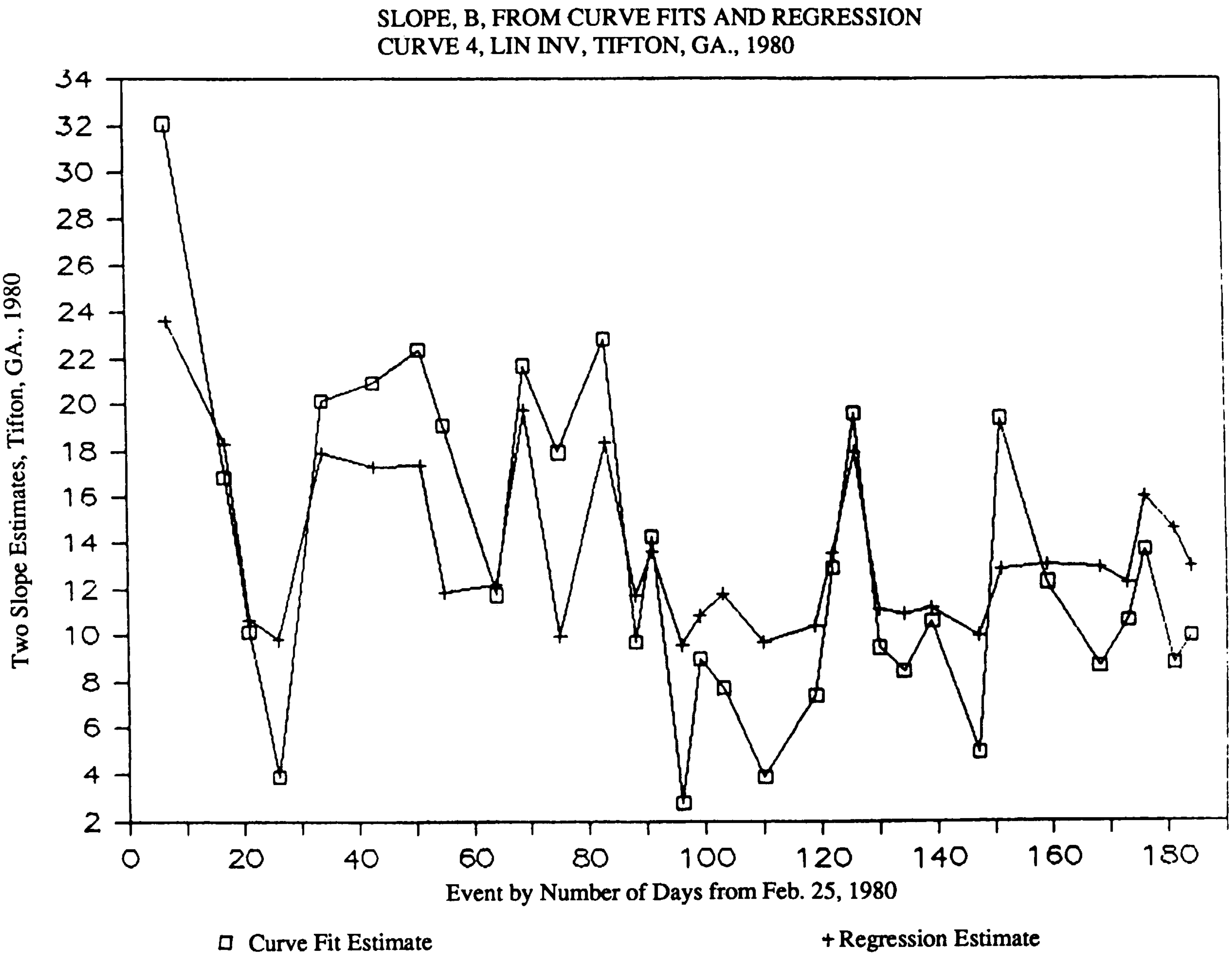

Figure C-2. Comparison of Curve Fit to "Regression Estimate" for Curve 4 (Table 1); Projection of Slope, B, in 1980 from 1979 Data.

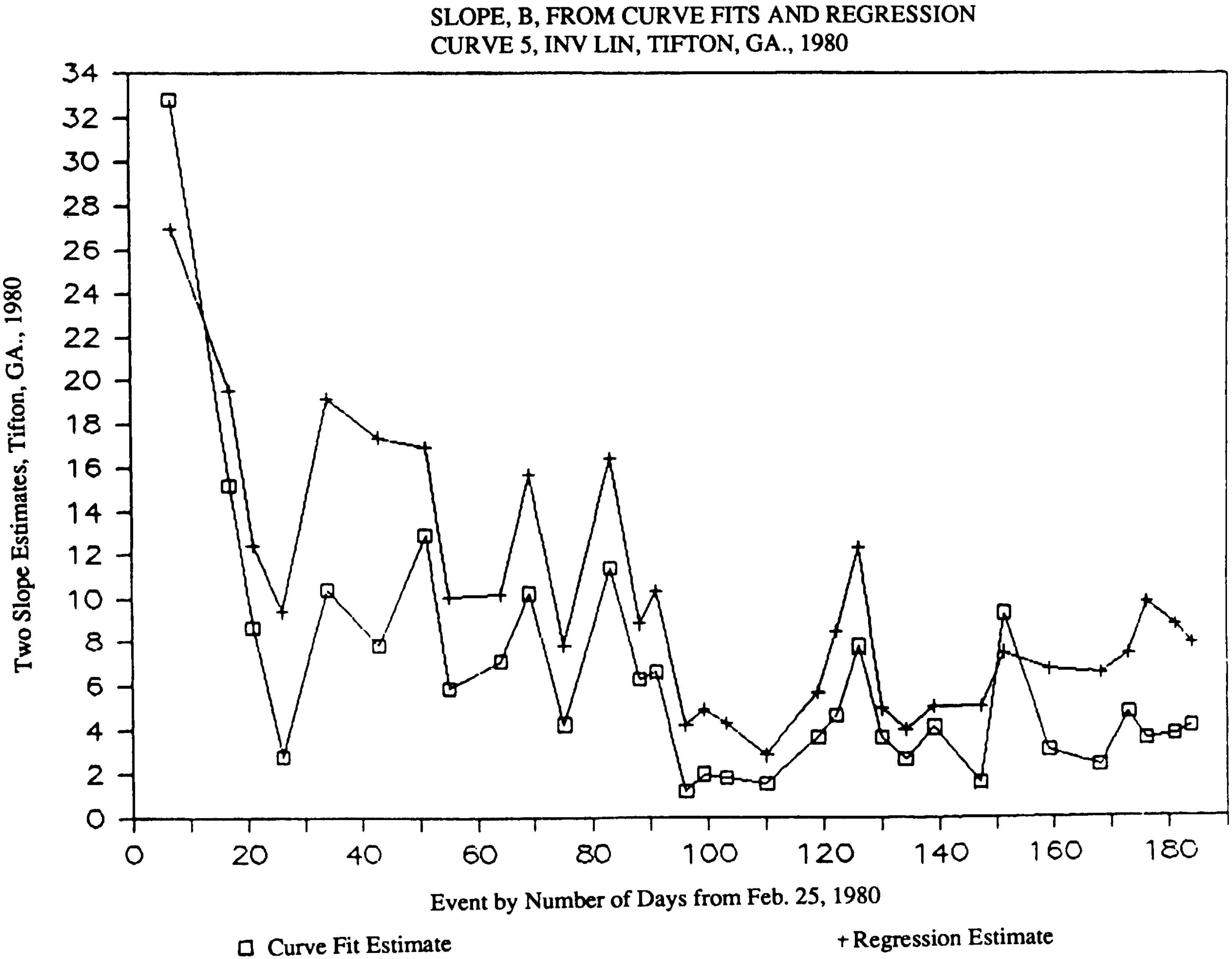

Figure C-3. Comparison of Curve Fit to "Regression Estimate" for Curve 5 (Table 1); Projection of Slope, B, in 1980 from 1979 Data.

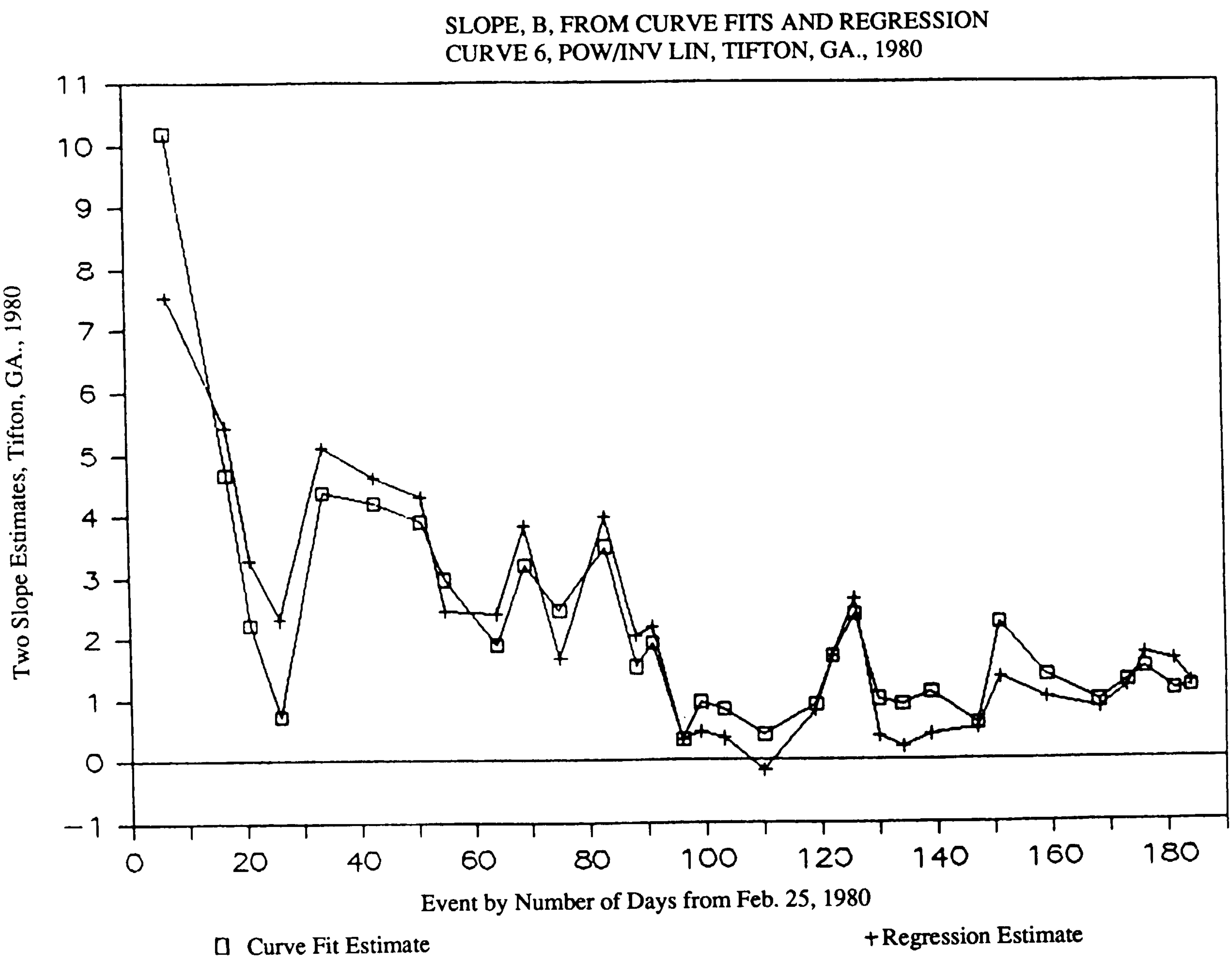

Figure C-4. Comparison of Curve Fit to "Regression Estimate" for Curve 6 (Table 1); Projection of Slope, B, in 1980 from 1979 Data.

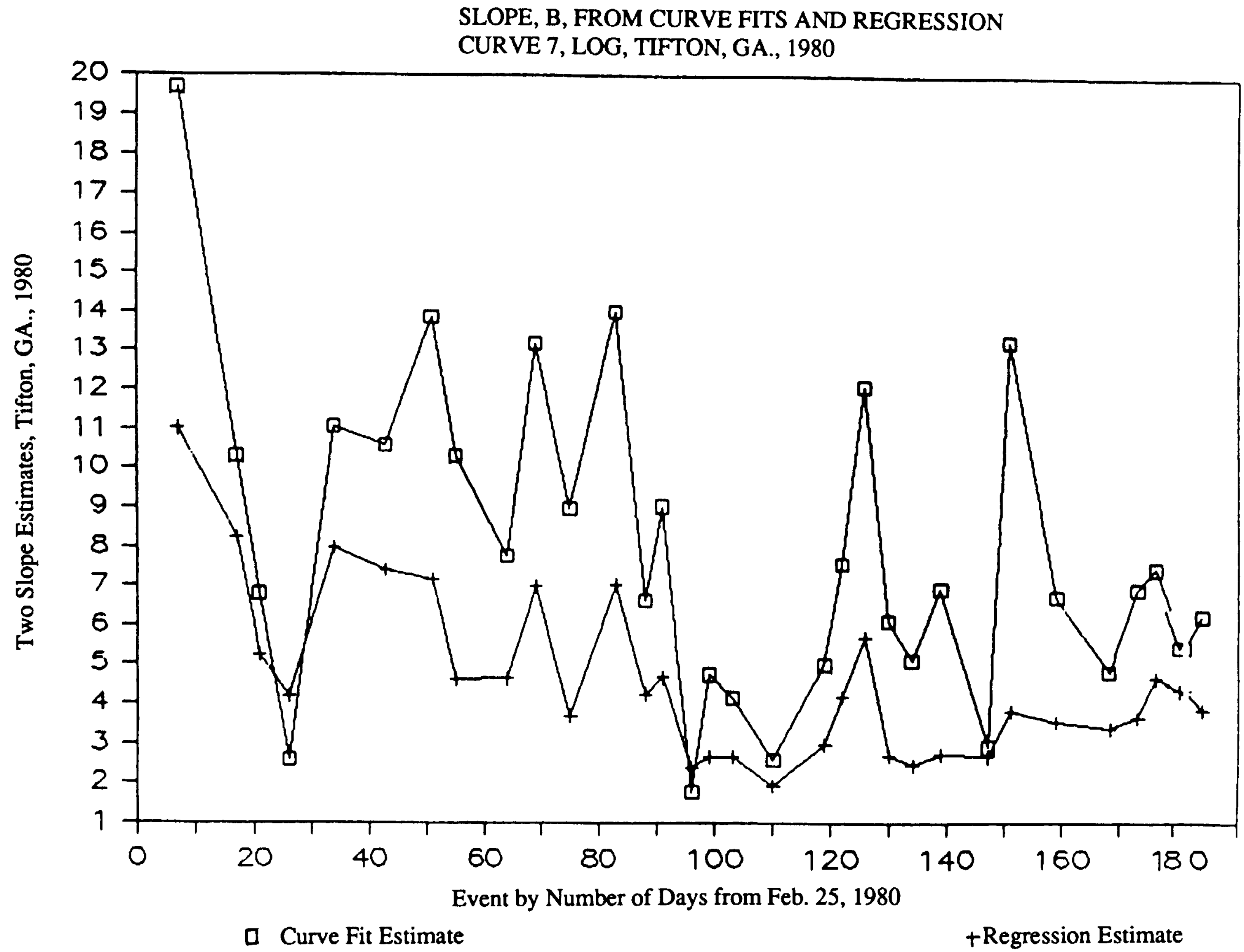

Figure C-5. Comparison of Curve Fit to "Regression Estimate" for Curve 7(Table 1); Projection of Slope, B, in 1980 from 1979 Data.

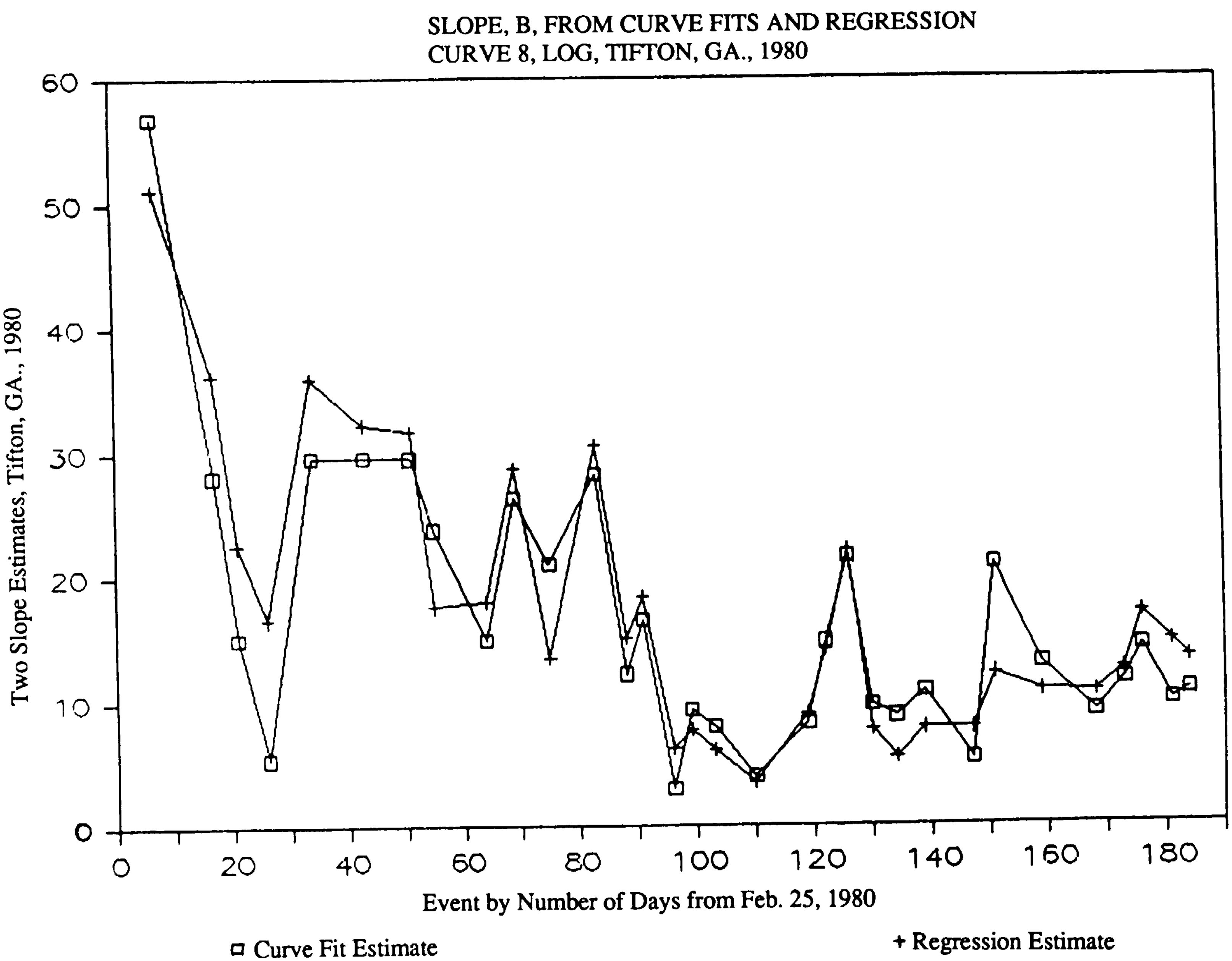

Figure C-6. Comparison of Curve Fit to "Regression Estimate" for Curve 8 (Table 1); Projection of Slope, B, in 1980 from 1979 Data.

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Report Documentation Page

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15. Supplementary Notes

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16. Abstract

Since the invention of maximum and minimum thermometers in the 18th century, diurnal temperature extrema--both minima and maxima--have been taken for air worldwide. At some stations, these extrema temperatures have been collected at various soil depths also, and the behavior of these temperatures at a 10-cm depth at the Tifton Experimental Station in Georgia is presented here.

After a precipitation cooling event, the diurnal temperature maxima drop to a minimum value and then start a recovery to higher values (similar to thermal inertia). This recovery represents a measure of response to heating as a function of soil moisture and soil property. Eight different curves were fitted to a wide variety of data sets for different stations and years, and both power and exponential curve fits were consistently found to be statistically accurate least-square fit representations of the raw data recovery values.

The predictive procedures used here were multivariate regression analyses, which are applicable to soils at a variety of depths besides the 10-cm depth presented.

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