The Effect of Bias in Divisional and State Mean Temperatures on Weather-Crop Yield Model Predictions: A Case Study in Indiana[1]

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ABSTRACT

Historical series of mean temperatures for climatological divisions and the state of Indiana contain systematic biases, the greatest being about −1.0°C in the Central Division in the 1940s. When these data are used in weather-management, crop-yield models they translate into biases in yield simulation and prediction. The magnitude and distribution of the yield prediction bias depends on the mean temperature bias and the type of model. The effect of the mean temperature bias on corn (*Zea mays* L.) yield production was examined for two models: in the first, the historical climatological series was used to fit the regression coefficients, and in the second, *a priori* regression coefficients were used. For each of the two models, yield simulations and predictions were made with both the original published mean temperatures and with those adjusted to the climatological network base for 1976. In the first model, the regression-fitting process averaged the effect of the temperature bias over the entire record. The estimates of corn yield trends attributed to management were slightly greater when the adjusted temperatures were used in the regression model than when the published temperatures were used. The use of the adjusted temperatures resulted in slightly higher yield predictions but the differences were generally less than 5% of the mean absolute difference between the model predictions and the yields reported by the U.S. Department of Agriculture Statistical Reporting Service. In the second model, the temperature bias was translated directly into the yield simulation, which with adjusted temperatures averaged 113 kg ha^{-1} higher than that simulated with the original temperature data in the 1950s and 1960s. Although the yield production and simulation errors caused by the mean temperature bias is nontrivial, the temperature bias contributed a relatively small part of the total variance in the yield modeling.

1. Introduction

The development of meaningful relationships between weather and crop yields from historical records is complicated when each of the weather and crop yield data series is not from the same population. The effect of technology or management in contributing to the upward trend in crop yields is well recognized. To account for this known heterogeneity in the yield series, almost all workers have included management indices or trend variables in multiple regression studies of weather and crop yields. Thompson (1975, 1969), Decker *et al.* (1976, p. 23), and Newman (1978, p. 45) used years or time-trend variables to define management. Perrin and Heady (1975) and Nelson and Dale (1978a,b) used the amount of nitrogen fertilizer applied to corn land in a particular year to label technology. The heterogeneity in the time series of state and climatological division monthly means of temperature and precipitation, however, has not been considered in weather-crop yield studies.

Several climatologists studying weather variability and climate change, e.g., Mitchell (1961) and Schaal (1982), have been concerned about the heterogeneity introduced into divisional and state mean temperature data by the changing climatological station base. Workers searching for relationships between crop yields and weather have assumed that mean temperatures for crop reporting districts (CRD) and states, based on data from many stations, provide an adequate climatological series. Nelson *et al.* (1979), however, showed that systematic changes in network configuration and management have created systematic biases in mean temperatures for climatic divisions and the state. Using 1976 as the base year, they found that the greatest temperature biases for the summer months in Indiana occurred in the 1940s (Fig. 1). For example, in 1943, corrections of −1.5°F were needed to adjust the monthly mean temperatures for the Central Climatological Division to those obtained with the 1976 network-management base. The greatest bias in the state mean temperature (Fig. 1) occurred in 1949 when the monthly mean June, July, and August temperatures had to be reduced 0.8°F for comparison with state

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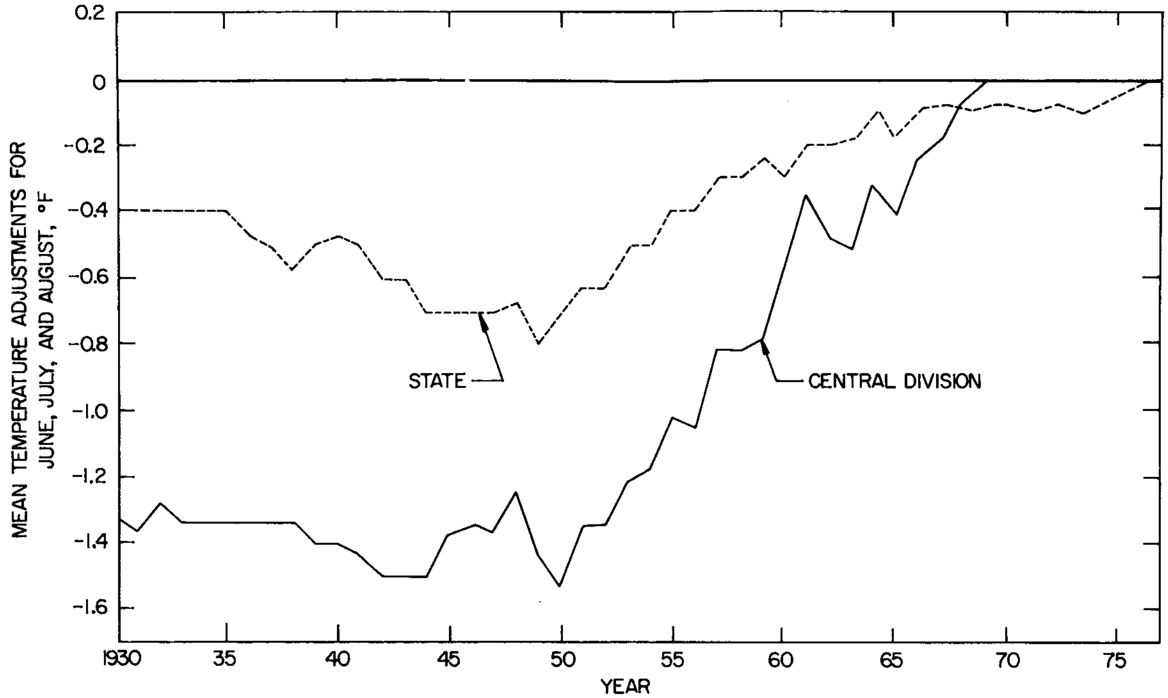

FIG. 1. Corrections to adjust Indiana State and Central CRD mean temperatures to 1976 network configuration base, from Nelson *et al.* (1979, Figs. 3 and 4).

mean temperatures calculated from the 1976 network configuration. For weather-crop yield models sensitive to temperature changes, such biases should affect the models and predicted crop yields.

The objective of this paper is to determine if the biases found in the temperature series have any marked effect upon 1) the parameter estimates in weather-crop yield regression models and their predicted yields, and 2) the predicted yields in models with *a priori* coefficients. A positive finding suggests that studies similar to that for Indiana by Nelson *et al.* (1979) should be considered for all states for which weather-crop yield regression predictions are desired.

2. Data and procedures

Since October 1956, the delineation of the climatological divisions used in Indiana by the U.S. Department of Commerce (USDC), Environmental Data and Information Service (EDIS), has been identical to that used for the nine crop reporting districts (CRD) by the U.S. Department of Agriculture (USDA) Statistical Reporting Service (SRS). For this recent period, the divisional mean monthly temperatures and precipitation published for June, July and August in *Climatological Data* (CD), Indiana (USDC, EDIS, 1957–77) were used in this study as the "original" CRD temperature and precipitation series. State monthly mean temperature and precipitation values were not published in CD after December 1955, and the "original" state means were computed from the weighted[3] CRD means. For the period 1931–56, the "original" CRD monthly mean temperatures and precipitation were computed from published CD data for all stations within the respective CRD, and the state means from the weighted CRD means. The "adjusted" CRD and state monthly mean temperatures used in this paper were those computed by Nelson *et al.* (1979). No systematic biases in the CRD or state average precipitation series were found, and the "original" precipitation means were used.

The average corn (*Zea mays* L.) yields for the nine CRD and the state were obtained from the *Indiana Annual Crop and Livestock Summary* (USDA, SRS, 1931–76). Final SRS yield estimates were used throughout the study, i.e., usually those published in the following year's crop summary, which contains yield data for the last two or three years. The average corn yields reported by SRS have an error associated with them. Steyaert (1977) reported that SRS crop

[3] CRD weights used for computing state average monthly mean temperatures and total precipitation from the CRD means are the ratios of the areas of the respective CRD to the total area of the state. For Indiana, the weights are: NW (1), 0.115; NC (2), 0.107; NE (3), 0.099; WC (4), 0.114; C (5), 0.169; EC (6), 0.072; SW (7), 0.138; SC (8), 0.109; SE (9), 0.077.

yield estimates are within 4–8% at the State level, and have greater error at the CRD level.

a. Yield models (Model 1) with fitted regression coefficients

The management trend and weather variables considered in this study were those used in the multiple linear regression model by Thompson as reported by Benci *et al.* (1975, p. 4–8), with the exception that the quadratic time trend variable was not used. The model, Model 1, may be expressed as

$$\text{Yield} = b_0 + \Sigma b_i X_i, \quad (1)$$

where Yield is the dependent variable, average CRD or state corn yields in bushels per acre (bu a^{-1}), b_0, b_i are fitted regression coefficients, and X_i are the independent weather or management variables. The 12 weather variables considered in (1) were the departures from the respective "normals" (means for period of record) for the following weather elements:

1) Total pre-season precipitation (PSP), September through June
2) PSP^2
3) July precipitation
4) (July precipitation)^2
5) August precipitation
6) (August precipitation)^2
7) June mean temperature
8) (June mean temperature)^2
9) July mean temperature
10) (July mean temperature)^2
11) August mean temperature
12) (August mean temperature)^2

Note that temperatures are expressed in degrees Fahrenheit, precipitation in inches, and yield in bushels per acre throughout this paper for consistency in later comparisons with results from an *a priori* regression model in which the coefficients relate to English units.

Two time-trend management variables were used. Time 1 was a linear time-trend variable which increased by one each year from 1 in 1931 through 30 in 1960, and then continued in subsequent years as a constant, 30. Time 2 was a linear term which was 0 before 1961 and began with a value of 1 in 1961, increasing each year by one. The third time-trend variable used by Thompson, the square of Time 2, was not used in this study because Nelson and Dale (1978a) found it provided unstable results when used to predict yields for subsequent years.

Since the greatest mean temperature biases found in Indiana occurred in the Central CRD, the effect of the mean temperature bias on weather-crop yield regressions should be most evident in that CRD, assuming temperature is a significant factor in corn production. Therefore, data for the Central CRD and State were used for this study. Stepwise regression[4] procedures (Draper and Smith, 1966) were used to fit Model 1 with both original and adjusted monthly mean temperature data. A critical F value of 2.0 was chosen for the addition and deletion of a variable. The weather and yield data for 1970 were not used in the regressions because of possible spurious inputs caused by the severe Southern Corn Leaf Blight (*Helminthosporium maydis* Nisik, Miy.) epipthytotic (Tatum, 1971). A reduced model was selected which contained the weather variables included most frequently in the regressions for the Central CRD and State. This reduced model (Model 1) was used to fit each of six record periods, 1931–71, 1931–72, . . . , 1931–76. Each regression was tested by predicting the average corn yield for the year immediately following the period for which the parameters were estimated, after the method of Nelson and Dale (1978b). For example, Model 1 fitted to the 1931–71 data was used to predict the 1972 corn yield, using the trend variables and the respective departures from normal for the monthly mean temperatures and precipitation for the predicted year. A table of differences, yield predicted ($\hat{Y}_{10}$) with Model 1 and original mean temperatures minus yield predicted ($\hat{Y}_{1A}$) with Model 1 and adjusted mean temperatures was generated for the Central CRD and State for each of the six test years. The differences between the official yields (Y_{SRS}) reported by the SRS and $\hat{Y}_{1A}$ were also calculated.

Because the greatest mean temperature biases occurred in the 1941–45 period, the Model 1 regressions for the 1931–76 record also were used to simulate what the corn yields would have been from 1941 through 1945 under 1976 management levels. If temperature were significant in the yield prediction, one might expect any differences in $\hat{Y}_{10} - \hat{Y}_{1A}$ to be greatest during that period.

b. Yield model (Model 2) with a priori coefficients

Since the development of the corn crop varies with respect to the calendar month from year-to-year, it was anticipated that the poor registration of the monthly mean temperatures used in Model 1 may decrease the sensitivity of the weather-corn yield model to the temperature bias. A weather-corn yield model in which a variable crop calendar is considered and which also provides *a priori* coefficients, is one by Leeper *et al.* (1974). This model also contains a beginning available soil water variable and weekly weather interaction terms. Since Leeper *et al.* developed the regression coefficients with data from high fertility experiments, there was no explicit technology variable included in the model, and the yield prediction is for the high level of management used in their experiment. Their model, hereafter called Model 2 and used only for the Central CRD, was as follows:

[4] All multiple regressions were computed on the Purdue University Computing Center CDC-6500 with the Northwestern University Statistical Package for the Social Sciences Regression program.

$$Y = 1566.37 - 83.06W - 1.069W^2 + 42.9392 \sum_{i=1}^{10} (R_i t_i) - 8.1130 \sum_{i=1}^{10} (R_i t_i^2) + 0.3654 \sum_{i=1}^{10} (Th_i t_i) - 0.1013 \sum_{i=1}^{10} (Th_i t_i^2) - 0.5014 \sum_{i=1}^{10} (R_i Th_i t_i) + 0.0974 \sum_{i=1}^{10} (R_i Th_i t_i^2) - 3.9802W \sum_{i=1}^{10} (R_i t_i) + 0.7907W \sum_{i=1}^{10} (R_i t_i^2) - 0.061W \sum_{i=1}^{10} (Th_i t_i) + 0.0121W \sum_{i=1}^{10} (Th_i t_i^2) + 0.0482W \sum_{i=1}^{10} (R_i Th_i t_i) - 0.0097W \sum_{i=1}^{10} (R_i Th_i t_i^2), \quad (2)$$

where

Y Yield (bushels per acre),
W amount of available soil water (inches) in the crop root zone at planting,
R_i total weekly precipitation (inches) for the ith week,
Th_i mean daily maximum temperature (°F) for the ith week,
t_i ith week, where $t_1 = 1, t_2 = 2, \ldots, t_{10} = 10$.

For the Central CRD, W was assumed to be 11 inches. The ten-week summary period used in (2) begins six weeks before and ends four weeks after the corn tasseling date. Since the "original" and "adjusted" mean daily maximum temperatures and precipitation for each of the ten weeks were not available from Nelson *et al.* (1979), the "original" Th_i and R_i weekly CRD means were estimated from the daily averages of the respective weather variables from four of the most representative and long-term stations in the Central CRD: Frankfort, Greensburg, Greenfield, and Whitestown. At Greenfield and Whitestown the temperature observations were taken in the morning during some periods of the record, and for these periods the observational day maximum temperature and precipitation were set back one day before calculating the daily averages for the Central CRD. The "adjusted" Central CRD mean daily maximum temperatures were obtained by applying the Central CRD mean temperature correction (Fig. 1) to the original mean daily maximum temperature series, assuming the same bias in the maximum and mean temperatures.

These weather data were used in (2) to predict corn yields for the Central CRD for each year from 1951 to 1980. Since the predictions were for high levels of technology, a technology factor was required to reduce them to the average management level in the Central CRD. This technology factor was developed by computing a management ratio (R) of the Central CRD yield reported by SRS to that predicted using the adjusted mean daily maximum temperatures in Model 2 for each year (j), $Y_{SRS_j}/\hat{Y}_{2j} = R_j$, and regressing these management ratios on years. The trend $\hat{R}_j$ for the jth year was then used to correct the yield predicted for high management with Model 2 to the predicted yield for the Central CRD for the respective year. The Model 2 predictions were made with both the original and adjusted temperature series and compared. The predicted yields were also compared with Y_{SRS}.

3. Results and discussion

a. *Effect of temperature bias in yield models (Model 1) with fitted regression coefficients*

Regression coefficients for the stepwise regressions (1) for the Central CRD for two periods, 1931–71 and 1931–76 are shown in Table 1 for both original and adjusted temperatures. The standard errors for each of the regression coefficients (s_{b_i}) and their level of significance (α) have also been included. The management trend variables, pre-season precipitation, July precipitation, July precipitation squared, June temperature squared, July temperature, and August temperature appeared in all four regression runs. All of these variables except June temperature squared were used in the reduced Model 1.

The regression coefficients for this reduced Model 1 for the Central CRD are shown in Table 2. The standard deviations for the regression coefficients (s_{b_i}) and their level of significance (α) were included only for the 1931–76 models, since they were representative of those for the other periods. The difference between the corresponding regression coefficients in the two models, one using original and one using adjusted temperatures, did not exceed the standard error of a single regression coefficient in all cases. The greatest differences in regression coefficients were found between model runs for the periods ending in 1973 and 1974. This was caused primarily by the unusual July drought conditions and poor yields in 1974 which affected the regression coefficients, primarily those of July precipitation and Time 2, as explained by Nelson and Dale (1978a). All weather variables had negative regression coefficients, except for July precipitation. The absolute values for July and August temperature coefficients were slightly greater for the adjusted temperature series than those for the original temperatures, partially compensating for the lower adjusted temperatures, but the coefficients were well within their respective standard errors. The management trend estimates for both the 1931–60 and 1961–76 periods

TABLE 1. Regression coefficients (b_i) for Eq. (1) stepwise regressions of Indiana Central CRD corn yield (bu a^{-1}) on indicated time trend and weather variables, 1931–71 and 1931–76, 1970 removed, for both original and adjusted mean temperatures. Standard error (s_{b_i}) and level of significance (α) shown for each regression coefficient, as well as adjusted coefficient of determination (R^2), standard error from regression (s_e), and significance level (α) for regression estimate.

Trend and weather variables (departure from normal)	b_i for Model 1 using original mean temperatures		b_i for Model 1 using adjusted mean temperatures	
	1971 s_{b_i} α	1976 s_{b_i} α	1971 s_{b_i} α	1976 s_{b_i} α
Time 1 1931–60	0.736 ± 0.11 0.000	0.702 ± 0.12 0.000	0.759 ± 0.10 0.000	0.731 ± 0.11 0.000
Time 2 1961–	2.929 ± 0.35 0.000	2.908 ± 0.23 0.000	3.099 ± 0.32 0.000	3.035 ± 0.22 0.000
Preseason Precip (PSP)	−0.350 ± 0.15 0.023	−0.471 ± 0.14 0.003	−0.357 ± 0.14 0.016	−0.481 ± 0.14 0.002
PSP^2				
Jul precip	3.144 ± 0.62 0.000	3.519 ± 0.62 0.000	3.287 ± 0.58 0.000	3.667 ± 0.60 0.000
$(\text{Jul precip})^2$	−0.507 ± 0.19 0.013	−0.569 ± 0.20 0.008	−0.501 ± 0.18 0.010	−0.561 ± 0.19 0.006
Aug precip	1.351 ± 0.94 0.162		1.297 ± 0.89 0.155	
$(\text{Aug precip})^2$		−1.865 ± 0.83 0.031		−1.893 ± 0.80 0.023
Jun temp				
$(\text{Jun temp})^2$	−0.181 ± 0.09 0.055	−0.157 ± 0.08 0.070	−0.252 ± 0.09 0.011	−0.226 ± 0.09 0.021
Jul temp	−0.663 ± 0.45 0.151	−0.979 ± 0.47 0.045	−0.700 ± 0.41 0.098	−0.997 ± 0.44 0.031
$(\text{Jul temp})^2$				
Aug temp	−1.136 ± 0.39 0.007	−0.901 ± 0.39 0.028	−1.145 ± 0.37 0.004	−0.929 ± 0.38 0.019
$(\text{Aug temp})^2$				
Constant	46.26 ± 2.36 0.000	48.07 ± 2.49 0.000	45.74 ± 2.14 0.000	47.48 ± 2.33 0.000
Adjusted R^2	0.94 0.000	0.95 0.000	0.95 0.000	0.95 0.000
s_e	4.79	5.22	4.52	5.02

were slightly greater for the regressions in which the adjusted rather than the original temperature means were used. The regression-fitting process compensated for the effect of the greater temperature bias before 1960, as can be shown by simulating the yields for each year with the 1931–76 Model 1 and plotting the management and weather components of the differences, $Y_{10} - Y_{1A}$, in the bottom part of Fig. 2. The management component is the yield simulated with normal weather, i.e., with temperature and precipitation departures from normal = 0. The weather component is the sum of only the weather terms in Model 1. Since higher July and August temperatures decrease corn yields, and the temperatures were biased upward through the 1950s, the original temperature series imposed a negative corn yield increment before about 1956 and a positive increment in the 1960s and 1970s. This was offset by the biased management trend. As a result, the overall $\hat{Y}_{10} - \hat{Y}_{1A}$ in Fig. 2 fluctuates about the zero line ($\hat{Y}_{1A} = 0$). The total corn yield increase over the 46-year period attributed to management with the adjusted mean temperatures was 3.9 bu/a more than that estimated with the original mean temperatures.

The difference between the average Central CRD corn yield simulated with the adjusted mean temperatures and those reported by SRS, $\hat{Y}_{1A} - Y_{SRS}$, are also plotted in Fig. 2. The base, or 0 line, is Y_{SRS}. The

TABLE 2. Regression coefficients (b_i) for Model 1 regressions of Indiana Central CRD average corn yield (bu a^{-1}) on indicated time trend and weather variables for 1931–71, . . . , 1931–76, 1970 removed, for both original and adjusted mean temperatures. Standard error (s_{bi}) and level of significance (α) shown only for 1931–76 regression coefficients, but adjusted coefficient of determination (R^2), standard error from regression (s_e) and level of significance (α) shown for all regression models.

Trend and weather variables	b_i for Model 1 using original mean temperatures, 1931 through indicated year					
	1971	1972	1973	1974	1975	1976 s_{b_i} α
Time 1 1931–60	0.743	0.740	0.739	0.709	0.709	0.716 ± 0.13 0.000
Time 2 1961–	2.926	3.056	3.094	2.701	2.707	2.679 ± 0.22 0.000
PSP	−0.401	−0.385	−0.375	−0.512	−0.512	−0.506 ± 0.15 0.002
Jul precip	2.978	2.940	2.958	3.823	3.823	3.806 ± 0.66 0.000
(Jul precip)^2	−0.497	−0.498	−0.498	−0.703	−0.703	−0.697 ± 0.21 0.002
Jul temp	−1.030	−1.025	−1.005	−1.146	−1.147	−1.141 ± 0.47 0.021
Aug temp	−0.961	−0.910	−0.892	−1.017	−1.015	−0.999 ± 0.42 0.022
Constant	44.65	44.60	44.58	45.99	45.98	45.87 ± 2.59 0.000
Adjusted R^2	0.93	0.94	0.95	0.92	0.93	0.94 0.000
s_e	5.10	5.06	4.99	5.82	5.74	5.67

Trend and weather variables	b_i for Model 1 using adjusted mean temperatures, 1931 through indicated year					
	1971	1972	1973	1974	1975	1976 s_{b_i} α
Time 1	0.784	0.780	0.779	0.757	0.757	0.767 ± 0.12 0.000
Time 2	3.110	3.224	3.251	2.881	2.874	2.830 ± 0.22 0.000
PSP	−0.421	−0.407	−0.399	−0.538	−0.538	−0.530 ± 0.16 0.002
Jul precip	3.041	3.003	3.017	3.900	3.901	3.877 ± 0.65 0.000
(Jul precip)^2	−0.493	−0.494	−0.494	−0.701	−0.700	−0.691 ± 0.21 0.003
Jul temp	−1.055	−1.054	−1.040	−1.173	−1.169	−1.155 ± 0.47 0.019
Aug temp	−0.976	−0.932	−0.919	−1.034	−1.043	−1.017 ± 0.42 0.019
Constant	43.35	43.35	43.36	44.56	44.56	44.40 ± 2.41 0.000
Adjusted R^2	0.93	0.94	0.95	0.91	0.93	0.94 0.000
s_e	5.05	5.00	4.93	5.79	5.71	5.65

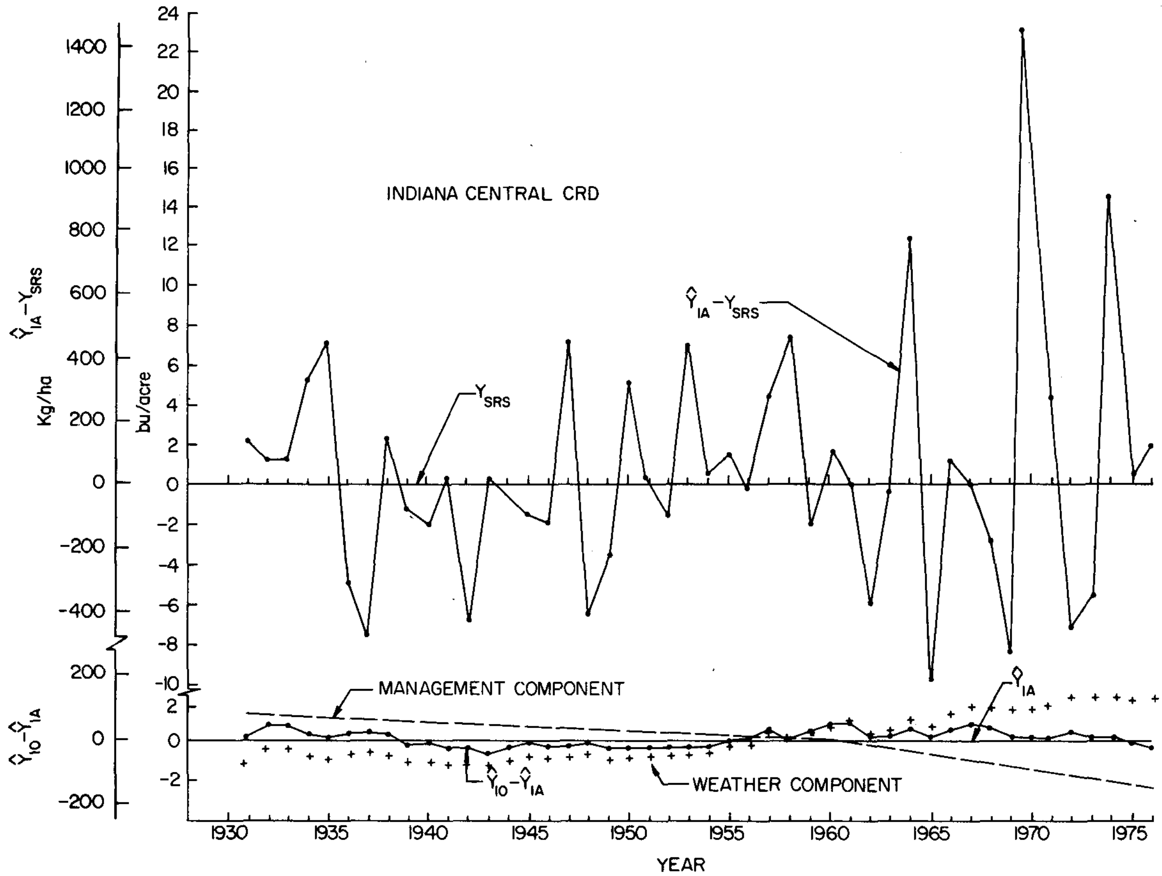

FIG. 2. Difference between average corn yield (Y_{SRS}) reported by SRS for Indiana Central CRD and yield ($\hat{Y}_{1A}$) simulated with regression Model 1, 1931–76, and adjusted mean temperatures for indicated year (top), and difference between yields simulated with original and adjusted mean temperatures ($\hat{Y}_{10} - \hat{Y}_{1A}$) (bottom). Management and weather components of $\hat{Y}_{10} - \hat{Y}_{1A}$ are also plotted for indicated year at bottom.

variability of the model predictions around Y_{SRS} is much larger than that for $\hat{Y}_{10} - \hat{Y}_{1A}$.

For the State, parameters for the indicated variables and periods are shown in Table 3 for Model 1 with both the original and adjusted state mean temperature series. As with the Central CRD, the greatest differences between regression coefficients occurred not between the models using original and adjusted temperature means but within each model between 1973 and 1974. The coefficients for Time 2 decreased and for July precipitation increased about 1.5 standard deviations from 1973 to 1974 for both adjusted and original mean temperature input. As in the Central CRD, the coefficients for the management trend variables were slightly greater for the model using adjusted state mean temperatures than those using the original temperature series. The average Indiana state corn yield was simulated with normal weather, 1931 management, and the 1931–76 Model 1 in Table 3 to be 40.8 bu a^{-1} with adjusted temperatures and 41.2 with the original temperature series. The 1976 yield with normal weather and 1976 management was simulated to be 108.4 bu a^{-1} with adjusted temperatures and 107.4 with the original temperatures. The total yield increase attributed to management over the 46-year period was 1.4 bu a^{-1} more with the adjusted temperatures, but this was only 2% of the estimated yield increase.

For each year, 1972 to 1977, the differences between the SRS yields and those independently predicted with the model developed with adjusted temperatures and the period of record ending the previous year, $\hat{Y}_{1A} - Y_{SRS}$, and the differences between the yields predicted with the original and adjusted temperature series, $\hat{Y}_{10} - \hat{Y}_{1A}$, are shown for the Central CRD and the State of Indiana in Table 4. For the Central CRD, the absolute error, $|\hat{Y}_{1A} - Y_{SRS}|$ averaged 8 bu a^{-1}, and $|\hat{Y}_{10} - \hat{Y}_{1A}|$ averaged 0.4 bu a^{-1}, about 5% of the $|\hat{Y}_{1A} - Y_{SRS}|$ error. For the State models, the mean $|\hat{Y}_{10} - \hat{Y}_{1A}|$ was 0.3, about 4% of the mean $|\hat{Y}_{1A} - Y_{SRS}|$ error. There was a small negative bias in ($\hat{Y}_{10} - \hat{Y}_{1A}$) for both the Central CRD and the State.

The simulated average corn yields for the Central CRD and State for each of the years, 1941 through 1945, using 1976 management levels (Time 1 = 30,

TABLE 3. Regression coefficients (b_i) for Model 1 regressions of Indiana state average corn yield (bu a^{-1}) on indicated time trend and weather variables for 1931–71, . . . , 1931–76, 1970 removed, for both original and adjusted mean temperatures. Standard error (s_{b_i}) and level of significance (α) shown only for 1931–76 regression coefficients, but adjusted coefficient of determination (R^2), standard error from regression (s_{e_i}), and level of significance (α) shown for all regression models.

Trend and weather variables	b_i for Model 1 using original mean temperatures, 1931 through indicated year						Trend and weather variables	b_i for Model 1 using adjusted mean temperatures, 1931 through indicated year					
	1971	1972	1973	1974	1975	1976 s_{b_i} α		1971	1972	1973	1974	1975	1976 s_{b_i} α
Time 1 1931–60	0.809	0.807	0.807	0.760	0.759	0.769 ± 0.12 0.000	Time 1	0.819	0.816	0.817	0.771	0.770	0.781 ± 0.12 0.000
Time 2 1961–	3.018	3.091	3.048	2.730	2.790	2.746 ± 0.20 0.000	Time 2	3.099	3.165	3.116	2.802	2.859	2.810 ± 0.20 0.000
PSP	−0.357	−0.350	−0.365	−0.499	−0.490	−0.482 ± 0.15 0.003	PSP	−0.374	−0.367	−0.385	−0.522	−0.512	−0.503 ± 0.15 0.002
Jul precip	3.419	3.403	3.332	4.686	4.681	4.650 ± 0.71 0.000	Jul precip	3.476	3.461	3.390	4.758	4.753	4.719 ± 0.71 0.000
(Jul precip)^2	−0.721	−0.719	−0.724	−1.074	−1.066	−1.052 ± 0.25 0.000	(Jul precip)^2	−0.719	−0.717	−0.723	−1.076	−1.068	−1.053 ± 0.25 0.000
Jul temp	−1.062	−1.062	−1.087	−1.210	−1.234	−1.227 ± 0.43 0.007	Jul temp	−1.041	−1.042	−1.070	−1.185	−1.209	−1.198 ± 0.43 0.008
Aug temp	−0.798	−0.772	−0.793	−0.845	−0.781	−0.758 ± 0.37 0.046	Aug temp	−0.782	−0.759	−0.783	−0.838	−0.776	−0.750 ± 0.37 0.050
Constant	39.04	39.06	39.17	40.68	40.44	40.39 ± 2.28 0.000	Constant	38.76	38.76	38.84	40.31	40.06	39.97 ± 2.25 0.000
Adjusted R^2	0.95	0.95	0.96	0.94	0.95	0.95 0.000	Adjusted R^2	0.95	0.95	0.96	0.94	0.95	0.95 0.000
s_e	4.48	4.43	4.37	5.06	5.02	4.97	s_e	4.51	4.45	4.40	5.09	5.05	5.00

TABLE 4. Average corn yields (Y_{SRS}) in bu a^{-1} for Central CRD and State of Indiana as reported by SRS for indicated year, 1972–77, and the differences from the yields ($\hat{Y}_{1A}$) predicted with Model 1 ending the previous year, 1971–76, using adjusted mean temperatures and those ($\hat{Y}_{10}$) using the original mean temperatures, for indicated year, mean and absolute mean errors.

Yield prediction year	Central CRD			State		
	Y_{SRS}	$\hat{Y}_{1A} - Y_{SRS}$	$\hat{Y}_{10} - \hat{Y}_{1A}$	Y_{SRS}	$\hat{Y}_{1A} - Y_{SRS}$	$\hat{Y}_{10} - \hat{Y}_{1A}$
1972	107.2	−4.2	−0.1	104	−2.2	−0.3
1973	109.1	−1.3	−0.2	102	+2.1	−0.4
1974	74.8	+23.3	−0.1	71	+21.5	−0.1
1975	103.0	+0.4	−0.5	98	−3.7	−0.1
1976	115.5	+2.9	−0.8	110	+3.1	−0.3
1977	102.2	+15.8	−0.9	102	+9.4	−0.4
Mean	102.0	+6.1	−0.4	97.8	5.0	−0.3
|Mean|	102.0	8.0	0.4	97.8	7.0	0.3

Time 2 = 16) and the adjusted temperature series, are shown in Table 5. The differences between the yields simulated for the Central CRD with the original temperatures and those predicted with the adjusted temperatures are also shown in Table 5. $\hat{Y}_{10} - \hat{Y}_{1A}$ averaged −3.7 bu a^{-1}, about 32% of the range (11.6) in simulated corn yields. For the State, $\hat{Y}_{10} - \hat{Y}_{1A}$ averaged −1.5 bu/a, about 11% of the range (13.0) in yields simulated from 1941 to 1945.

b. *Effect of temperature bias in yield model (Model 2) with a priori coefficients*

For the Central CRD, the management ratios, $R_j = Y_{SRS_j}/\hat{Y}_{2A_j}$, were plotted for each year (j) from 1951 through 1980 in Fig. 3. Y_{2A_j} was predicted by using the same *a priori* regression equation (2) for every year and the adjusted temperature series. The R_j ranged from 0.34 in 1958 to 0.94 in 1980, and exhibited a linear trend. The R_j values from 1968 to 1972 are very similar to those reported for Indiana by Benci *et al.* (1975, p. 4–32). The regression estimate of R_j,

$$\hat{R}_j = -0.37 + 0.0142j, \qquad (3)$$

$r^2 = 0.76$, $s_{R\cdot j} = 0.07$, $s_{b_0} = 0.10$, $s_{b_1} = 0.0015$, increased from 0.36 in 1951 to 0.77 in 1980. In (3) the year j = 1951 was coded as 51, 1980 as 80.

The yields predicted with (2) for both original and adjusted temperature series were multiplied by the appropriate $\hat{R}_j$ to obtain two predicted yield series, $\hat{Y}_{20}$ and $\hat{Y}_{2A}$. The differences, $\hat{Y}_{2A} - Y_{SRS}$, are plotted against year in the top part of Fig. 4. The differences, $\hat{Y}_{20} - \hat{Y}_{2A}$, are plotted against year in the bottom part of Fig. 4. The mean temperature bias was translated inversely into a yield bias. The yield predictions, made with the original temperature series were 2–4 bu a^{-1} less than those computed with the adjusted temperatures in the early 50s, the yield bias decreasing with the temperature bias (Fig. 1) to 0 after 1969.

The estimates of the magnitude of the yield simulation bias attributed to the mean temperature bias in the early 1950s are non-trivial. Yet, the error is still relatively small compared to the variability between the predicted and reported SRS yields, as can be seen in Fig. 4. The average yield simulation error from 1951 to 1969 attributed to the temperature bias was −1.8 bu a^{-1}. This was about one-fourth of the mean absolute error, $|\hat{Y}_{2A} - Y_{SRS}|$, of 7.7 bu a^{-1} for the 30-year period.

TABLE 5. Average corn yields ($\hat{Y}_{1A}$) in bu a^{-1} simulated with the 1931–76 Model 1 for central CRD and state of Indiana, 1941 to 1945, assuming 1976 management levels and adjusted mean temperatures, and differences ($\hat{Y}_{10} - \hat{Y}_{1A}$) from yields simulated with the original mean temperatures, for indicated year, mean and mean absolute errors.

Year	Central CRD		State	
	$\hat{Y}_{1A}$	$\hat{Y}_{10} - \hat{Y}_{1A}$	$\hat{Y}_{1A}$	$\hat{Y}_{10} - \hat{Y}_{1A}$
1941	108.2	−3.8	103.4	−1.4
1942	111.1	−3.8	108.9	−1.5
1943	112.7	−3.8	107.5	−1.5
1944	102.7	−3.7	95.0	−1.6
1945	114.3	−3.5	108.0	−1.4
Mean	109.8	−3.7	104.6	−1.5
|Mean|	109.8	3.7	104.6	1.5

4. Conclusions and recommendations

For weather management–crop yield regression models utilizing historical series of published state and divisional mean monthly temperatures and precipitation, systematic mean temperature biases may translate into nontrivial biases in yield simulation and prediction, but the patterns are obscured by the regression-fitting process. For the Central CRD and the State of Indiana, the yield prediction bias attributed to use of the original mean temperature series in fitted regression models was generally less than 5% of the mean absolute difference between the model predictions and the reported SRS yields in the 1970s. When the model was used for simulation of Central CRD corn yields in the 1940s assuming 1976 management levels, the average error between yield estimates using the adjusted and original temperature series was −3.7 bu a^{-1}, 32% of

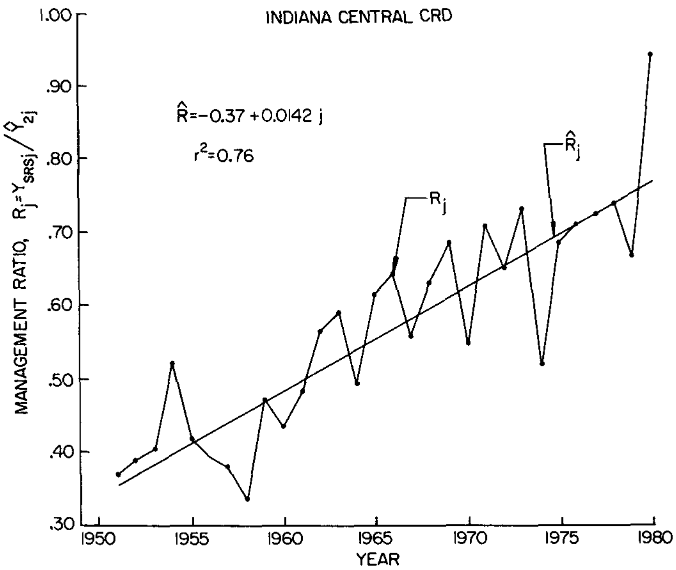

FIG. 3. Management ratio, R_j, of average corn yield (Y_{SRSj}) reported by SRS for Indiana Central CRD to yield estimate ($\hat{Y}_{2Aj}$) with Leeper *et al.* (1974) Model 2 and adjusted mean temperatures for indicated year (j), and regression trend.

the range in simulated average corn yields from 1941 to 1945. For the State, the error was -1.5 bu a^{-1}, about 11% of the range in simulated corn yields.

For a crop-yield model with *a priori* coefficients, the temperature bias was directly reflected in the prediction error. For the period of bias in the Central Indiana

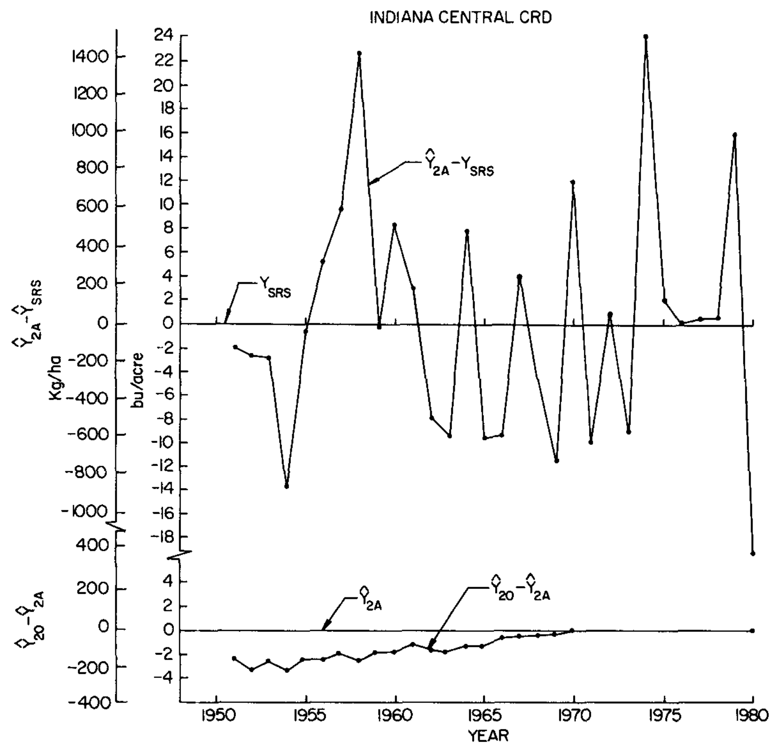

FIG. 4. Difference between average corn yield (Y_{SRS}) reported by SRS for Indiana Central CRC and $\hat{R}_j$ times yield estimate with Leeper *et al.* (1974) Model 2 using adjusted mean temperatures ($\hat{Y}_{2A}$) for indicated year; and difference between yield estimates made with original and adjusted mean temperature ($\hat{Y}_{20} - \hat{Y}_{2A}$).

CRD, it accounted for about a fourth of the mean absolute yield simulation error. However, since the Central CRD was selected because it had the greatest temperature bias of the nine CRDs in Indiana, it is likely that this is an extreme example.

Systematic biases in divisional and state mean temperatures are reflected in simulated and predicted crop yields. Only with analyses such as those by Nelson *et al.* (1979) or Mitchell (1961), can the CRD mean temperature bias and its effect on crop yield models be evaluated for other areas. Since the mean temperature bias-produced yield estimates are relatively small compared to the total yield prediction error, however, correcting other sources of error, such as weighting weather variables by crop acreages, rather than by CRD area, and selection of more direct measures of the crop environment, may be more productive avenues for improving large area crop yield modeling. Systematic changes in any series of areal mean temperatures have to be considered if they are used to evaluate climatic change, but until yield models and reported SRS yields become more accurate, we do not believe that removing the bias in CRD mean temperatures will cause any great improvement in modeling district and state average crop yields.

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