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Relationship between ENSO and winter-wheat yields in Sonora, Mexico

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RESUMEN

El trigo invernal es uno de los principales cultivos en los valles irrigados por ríos en el estado de Sonora, en el noroeste de México. Se explora la hipótesis de que, aunque principalmente determinado por las mejoras tecnológicas, los rendimientos del trigo reflejan todavía las variaciones de los factores climáticos de año a año, particularmente durante las fases extremas de El Niño-Oscilación del Sur (ENOS). Se analizan las series de tiempo de los rendimientos de trigo anuales para cinco distritos de riego; para eliminar las tendencias de largo plazo debida al desarrollo tecnológico, se obtuvieron los rendimientos residuales mediante el ajuste de un modelo logístico. Las series residuales se exploraron primero por medio del Análisis de Correlación; todas las series fueron correlacionadas significativamente al menos con otra serie. Esta variabilidad común se extrajo por medio del Análisis de los Componentes Principales; el primero fue suficiente para este propósito y respondió a una fracción relativamente grande de la variación total (63%). La serie de tiempo de amplitud de este componente se comparó con índices del ENSO; El Niño (La Niña), parecen producir un aumento (una disminución) en rendimientos del trigo; esto es consistente con los informes anteriores de un aumento (disminución) de la precipitación en la región del noroeste de México noroeste durante estos eventos.

PALABRAS CLAVE: Cultivo trigo invernal, efectos ENSO, Noroeste México, Sonora.

ABSTRACT

Winter-grown wheat is one of the main cultivates in river-irrigated valleys of the state of Sonora, northwest Mexico. Although largely determined by technological improvements and management, wheat yields may still reflect year-to-year variations partially determined by climatic factors, including the extreme phases of El Niño-Southern Oscillation. We analyzed time series of yearly wheat yields for five locations; yield residuals were obtained from a logistic model in order to eliminate long-term trends due to technological development. The series of residuals were found to be significantly correlated to at least one other series. This common variability was extracted by means of Principal Component Analysis. The first component accounted for a 63% of total variance. The amplitude time series of this component was compared to indices of ENSO. El Niño (La Niña) episodes seem to result in an increase (decrease) in wheat yields, which is consistent with previous reports of an increased (decreased) precipitation over northwest Mexico during these events.

KEYWORDS: Winter-wheat culture, ENSO effects, northwest Mexico, Sonora.

INTRODUCTION

Wheat is one of the most cultivated cereals worldwide and a major source of food for humankind both through direct consumption and as forage. It is grown mostly in the subhumid and semiarid plains of the mid-latitudes, known as the Earth's grain belt (Thompson, 1975). These regions are subject to climate fluctuations, known to play an important role at determining year-to-year variations in wheat productivity (Michaels, 1981; Mjelde and Keplinger, 1998).

Summer high temperatures limit the extent of the grain belt towards the tropics (Thompson, 1975). In Mexico wheat is grown from fall to spring, from seeding in early November to harvest in May of the following year. Production in northwest Mexico is in irrigated areas; irrigation results in high yields accounting for some 40% of world production (Bell *et al.*, 1995). Wheat areas in Mexico are mostly restricted to a few river-irrigated valleys in the states of Sonora and Sinaloa, although some locations in the Baja California Peninsula (e.g. Santo Domingo and San Quintín valleys) are also cultivated using large quantities of underground water.

Wheat culture extended into northwest Mexico after the Mexican Revolution: it resulted from the development of hydraulic infrastructure, from financing support, and particularly from the "green revolution" technology. These factors enabled a large increase in average production per unit area (Aguilar-Camín, 1977; Appendini 1988). Today the region contributes about 40% of the national production (Salinas-Zavala *et al.,* 1998). It has remained at high but steady levels for the last 15 years, while the population growth rate remained relatively high. These two trends caused Mexico to become a net grain importer since 1976, following several years of production large enough to satisfy domestic demand and to export some surplus (Hewitt, 1976).

Year-to-year variations of yield have increased (Valdez-Cepeda, 1993), and climate appears as the most likely cause of such fluctuations. Michaels (1981) noted that the high-yield varieties (HYV) of seeds used in Mexico since the early 1960s are sensitive to climate variability. Several authors have found that climate variations affect agricultural yields in North America, particularly regarding extreme conditions associated to El Niño-Southern Oscillation (ENSO). Hansen *et al.* (1998) found a relation between ENSO and the yields of maize, soy bean, peanut and tobacco in Southwest U.S. Adams *et al.* (1999) estimated that ENSO effects on agriculture may result in losses in the order of 2-4 billions dollars for the U.S. For Mexico, ENSO may result in significant variations in the yields of some major agricultural products, including wheat (Tiscareño-López *et al.*, 1998).

The 1997-99 period provided an excellent opportunity for the identification of ENSO effects in the main wheat production areas in Mexico. The 1997-98 El Niño was one of the strongest ever recorded (e.g., Wolter and Timlin, 1998). Major changes in the equatorial wind field resulted in anomalously high temperatures over the eastern Pacific from June 1997, to May 1998. Then, within 30 days temperatures dropped some 8°C, as conditions shifted to the opposite extreme of ENSO during La Niña 1998-99. Such a sudden large shift had never been recorded. It had not been anticipated by present models (MacPhaden, 1999).

For estimating the influence of climate on wheat yields, long-term increasing trends due to technological improvement must first be removed. No general method seems to exist for this purpose. Nicholls (1997) considered a simple linear trend to account for the effect of technology. Based on the use of fertilizers, Thompson (1975) used two linear tendencies for an overall analysis of U.S. agriculture. Stommen (1977) used three linear functions to represent the tendency of the technological increase in agriculture in Oklahoma during 1930-1975. Finally, Odumodu and Griffiths (1980) proposed an arc-tangent function to account for the effect of technology on wheat yields in Texas and Oklahoma.

In the present work we analyze wheat yields from the main production areas in Sonora, Mexico, as related to ENSO activity. First, we apply a logistic model to account for the effect of technological development, and we test the residuals for correlations and autocorrelations. Next, principal component analysis (PCA) was used to separate spatially coherent variability from spatially incoherent, local variability. The rationale of this approach is that strong ENSO episodes are a common and major source of climate variability, so that principal components should extract the changes best related to this type of variability.

DATA AND METHODS

Primary data for this analysis are time series of annual wheat yields from five main productive locations in Sonora, as provided by the offices of the Ministry of Agriculture (SAGAR) in Caborca, Guaymas, Yaqui Valley, Yaqui Colonies, and Navojoa (Figure 1). For comparison, we also considered the series of national average yields as provided by INEGI (1997) and FAOSTAT (1998).

To discriminate the effects of climate from those of technology, we first considered wheat yield as a function of technological development and environmental effects. Following Odumodu and Griffiths (1980), a simple general model of wheat yield can be expressed as:

$$Y_i = Yt_i + Yc_i + e_i , \qquad (1)$$

where Y_i is the average yield in a year i, Yt_i is the average yield expected from the application of a given technology under average climatic conditions, Yc_i is the variation in yield resulting from a given climate scenario, and e_i is an error term which includes other effects on yield.

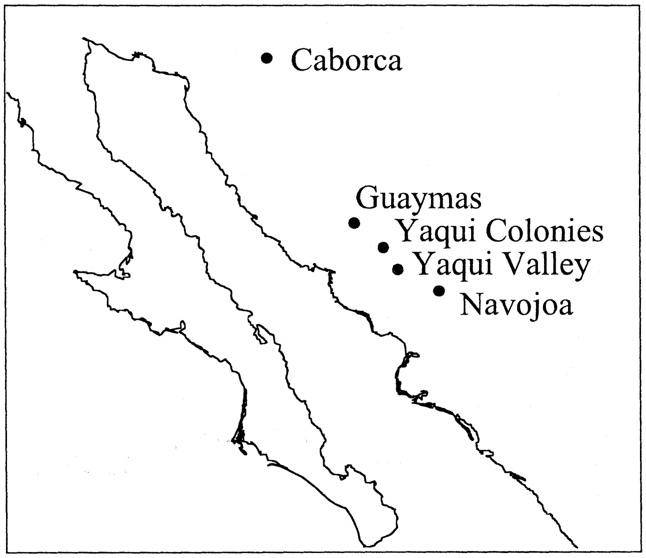

Fig. 1. Locations of the five irrigation districts considered in the analysis.

The problem is how to determine Yt_i in order to substract this value from the observed Y_i. The result, $Yc_i + e_i$ may be considered an estimate of Yc_i, the quantity of interest. We assume that the increasing trend in wheat yields may be approximated by the simple logistic curve

$$Yt_i = a \bullet (1 + \exp(b - c (X_i)))^{-1} , \qquad (2)$$

where a is the maximum average yield that can be obtain from technological development (i.e., from the logistic asymptote), b is the integration constant that defines the position of the curve relative to the origin, c is the average growth rate of yield, and X_i is the time span time in years (year i minus the initial year).

The model was adjusted to all yield series in order to compute a series of Yt_i; the values were then subtracted from the corresponding observed yield. The resulting series of residuals were examined for normality by means of a Shapiro-Wilks' *W* test, and for autocorrelations using the Box and Ljung *Q*-statistic to test whether the logistic model was able to remove the autoregressive structure related to long-term trends associated with technological development.

Over their common period (1981-1999), the series of residuals were examined for paired correlations. Then Principal Component Analysis (PCA; e.g., Storch and Zwiers, 1999) was applied. The number of principal components (PCs) to be extracted was defined as the minimum that resulted in residual correlations (i.e. correlations after the components are subtracted from the original series) being non-significant ($p < 0.05$). This implies that the extracted PCs will contain the fraction of variability that accounts for significant correlations between the series; that is, variability that is common between locations.

Each of the analyzed series is actually a sample function, and is subject to sampling errors. A problem called degeneracy (Anderson, 1963) may be present when the sampling errors of the eigenvalues of two or more successive components overlap, i.e., if they are large enough to prevent neighboring eigenvalues from being statistically different. To address this issue, the sampling errors of the eigenvalues were estimated after North *et al.* (1982) as:

$$\Delta\lambda = \lambda \, (2/N)^{0.5} , \qquad (3)$$

where λ is the eigenvalue and N is the number of degrees of freedom.

Finally, the amplitude time series (or scores) of the extracted components were examined for possible relations to ENSO. We used the Southern Oscillation Index (SOI), as provided by the Climate Diagnostic Center (NOAA, U.S.A.) on their web site (www.cdc.noaa.gov). For comparison with yearly yields, the monthly SOI values were averaged on a yearly basis. We also used "Tropical Pacific Cold and Warm Episodes by Season", a proxy of the intensity of ENSO events in the equatorial central Pacific provided by the Climate Prediction Center, National Centers for Environmental prediction (NOAA, U.S.A.) on their web site (www.cpc.ncep.noaa.gov). This includes cold (C), average (0) and warm (W) quarters into five categories, which were graded as follows: C+, graded as –3; C, as –2; C-, as –1; 0, as 0; W-, as +1; W as +2 and W+, as +3. The four quarters were averaged for each year to result in a yearly, quantitative series (CPC).

RESULTS

Figure 2 shows the series of wheat yields for the analyzed locations, including the national yields for comparison. Included are the yields as estimated by the logistic model; the correlations between the observed and estimated values are shown in Table 1. This table also includes the model parameters and the results of the Shapiro-Wilks' *W* test of normality of the residuals (i.e., observed minus estimated yields).

The series of residuals, considering only the common period of 1981-1998, are plotted in Figure 3. Their autocorrelation functions are shown in Figure 4. Table 2 presents a summary of the autocorrelations, including standard errors and the Box and Ljung *Q* test for the significance of the autocorrelation coefficients.

Table 3 presents Pearsons' paired correlations between series of residuals at the five locations. The results of the principal components analysis (PCA) of these series are found in Table 4, including eigenvalues, sampling errors, proportion of variance, and maximum (paired) residual correlation after successive extraction of the five principal components (PCs). To further explore the potential occurrence of degeneracy among the extracted components, Figure 5 shows the eigenvalues with the corresponding sampling error intervals.

Table 5 presents the factor loadings and the proportion of variance accounted by the first principal component (PC_1) for each of the series of residuals. The amplitude time series of this PC_1 is shown in Figure 6, plotted with the residuals of the national yields and the two indices of the ENSO (SOI and CPC) used for comparison.

DISCUSSION AND CONCLUSIONS

One problem at examining the effects of climate variability on agricultural yields is to discriminate the effects

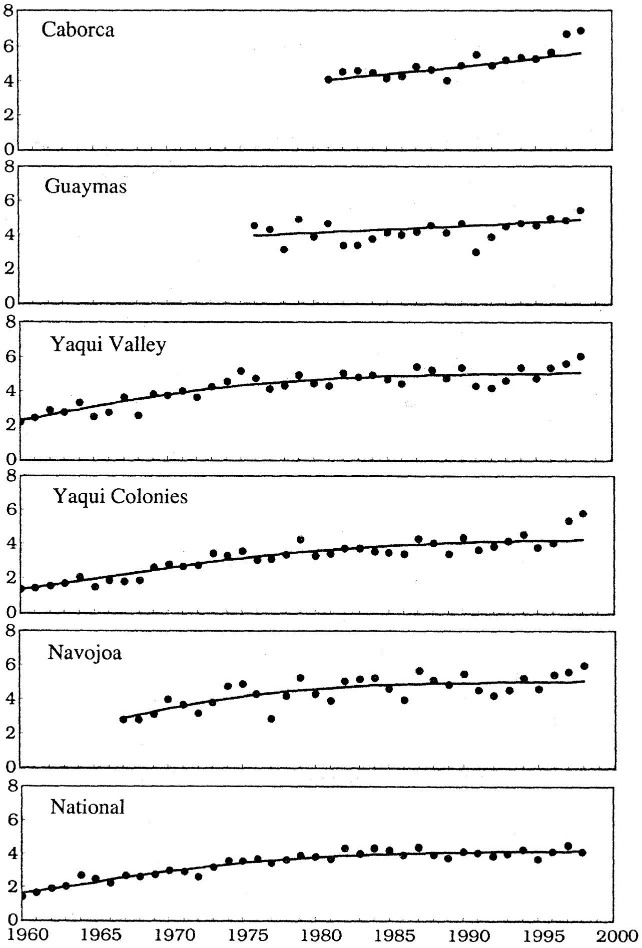

Fig. 2. Series of annual average wheat yields (ton/h) for Mexico (national average) and for the five locations shown in Figure 1; observed values (dots) and estimates from the logistic model (curve).

of technological improvements. Most approaches (e.g., Hansen *et al.*, 1998) have assumed this effect as some long-term, increasing trend in yields; others have included shifts in yield trends resulting from some specific development (e.g., fertilization techniques; Thompson, 1975). If the available information is limited to time series of yields, the effect of technology must be assumed rather than estimated. Thus, this type of approach only provides a first insight into the potential effects of other sources of variability. The basic rationale is to apply some model to "remove" the assumed technological effect, then compare the deviations from the model to some climate indicator. If enough information is available for several locations, common variability can be extracted from the individual series in order to separate local variations from larger-scale signals. This component of variability can then be examined and, if a relationship is found consistent with current knowledge on culture and climate effects, the hypothesis of a causal relationship is reinforced.

In this study, all correlations between observed and predicted yields were significant at $p < 0.05$ (Table 1). Except for one case (Guaymas), they reached relatively high values (> 0.75), suggesting that the logistic model accounted for a large fraction of yield variability (60-90%). The four longest series (Yaqui Valley, Yaqui Colonies, Navojoa and National) resulted in realistic maximum yields (*a*, 4-5 ton/h) and growth rates (*c*, 0.12 - 0.15 ton/h/year). However, this was not the case of the two shorter series (Caborca and Guaymas). The short series do not contain information about the early years of low yields, and thus resulted in excessively small average growth rates and also in unrealistic high estimates of the maxima yields. This data quality problem should not be regarded as indicative of the inadequacy of the logistic model.

Table 1

Results of the logistic model adjusted for the national average yields and for the locations shown in Figure 1. The initial year is that determined by data availability, the model's parameters (a-c) are described in the text. Adjustment is provided by the correlation coefficient (*r*), its significance was tested for the observed number of data (*N*). Residuals were tested for normality by means of the Shapiro-Wilks' *W* statistic.

Location	**Initial year and parameters**				**Adjustment**			**Residuals**	
	X_o	*a*	*b*	*c*	*r*	*N*	*p*	*W*	*p*
Caborca	1981	91.64	3.07	0.02	0.857	18	< 0.001	0.944	0.334
Guaymas	1976	193.3	3.87	0.01	0.412	23	0.044	0.962	0.618
Yaqui Valley	1960	5.12	0.24	0.13	0.896	39	< 0.001	0.969	0.756
Yaqui Colonies	1960	4.35	0.81	0.12	0.914	39	< 0.001	0.877	0.023
Navojoa	1967	5.10	-0.28	0.15	0.769	32	< 0.001	0.935	0.240
National	1960	4.28	0.50	0.13	0.962	39	< 0.001	0.954	0.486

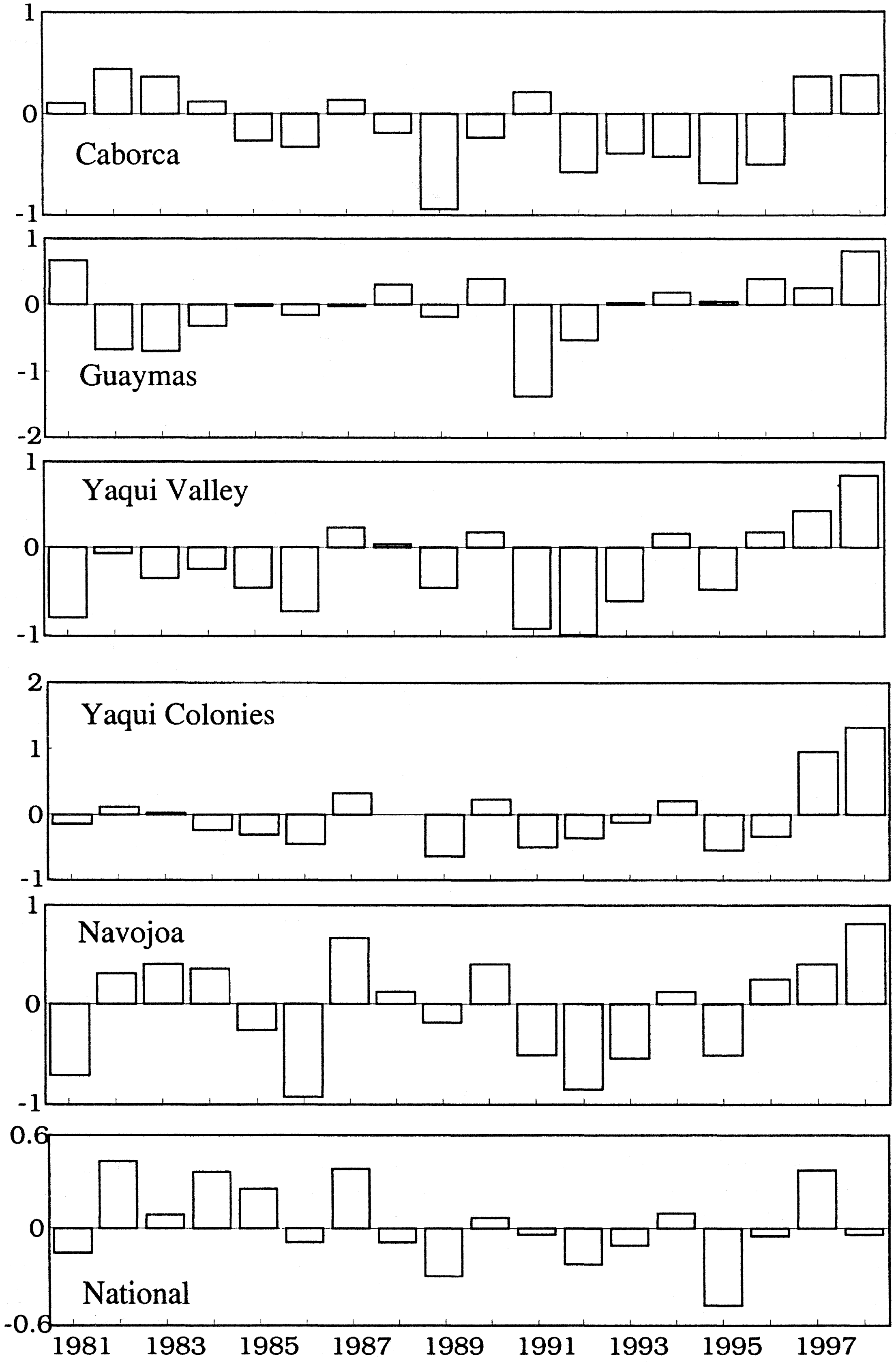

Fig. 3. Residuals of the logistic model (estimated minus observed value) for the series of wheat yields shown in Figure 2, period 1981-1998.

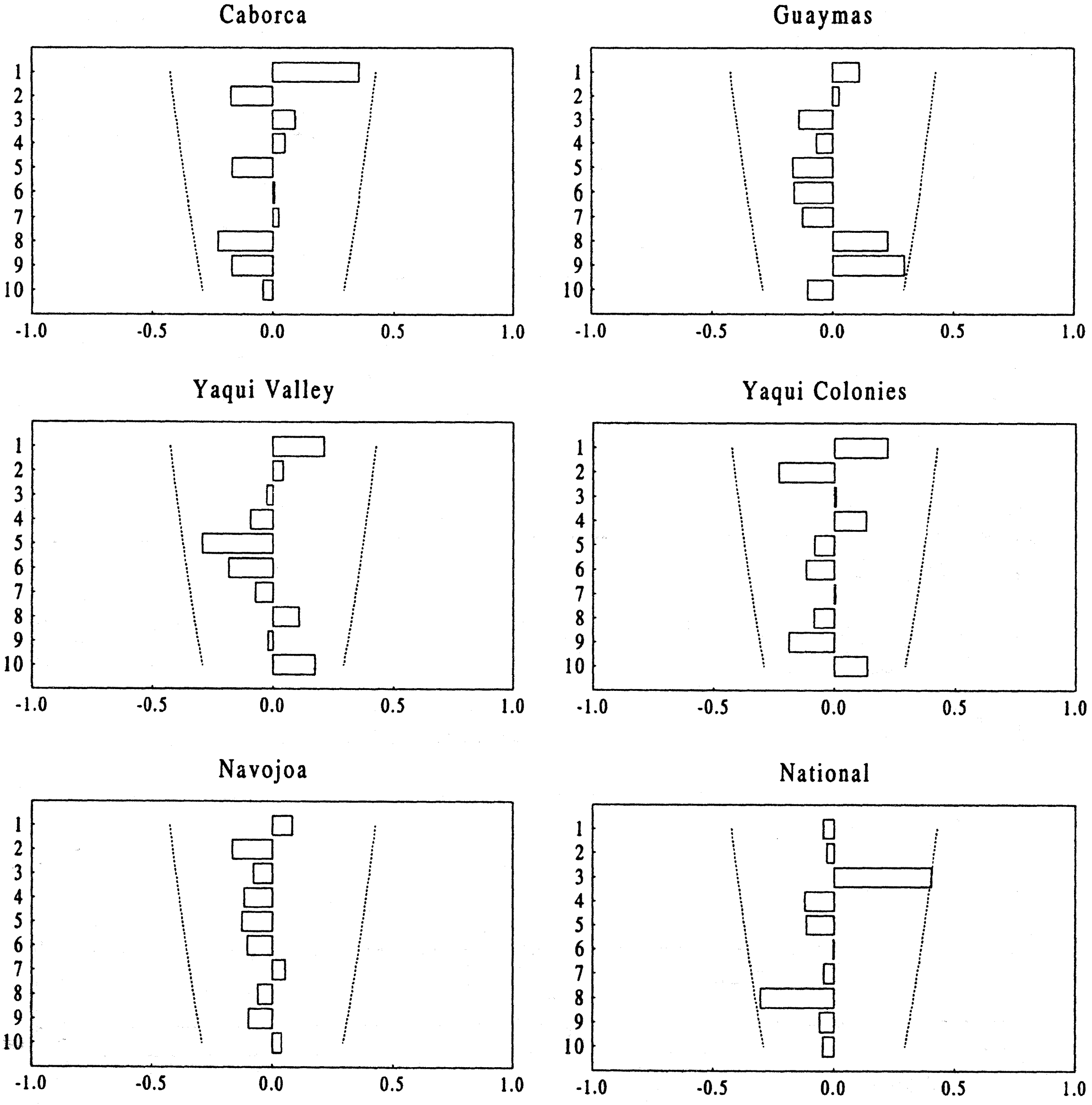

Fig. 4. Autocorrelation functions (bars) of the residuals shown in Figure 3, estimated for lags up to 10 years (y-axis), including their standard errors (dotted lines). No coefficient resulted significant ($p < 0.01$).

Table 2

Summary of the autocorrelations and their standard errors of the series of residuals, period 1981-98. Each column shows the minimum and maximum value for any lag up to 10 years. Significance was tested using the Box and Ljung Q statistics.

Location	Autocorr.		Stand. Err.		Q		p	
Caborca	-0.229	0.356	0.149	0.217	0.252	7.577	0.101	0.729
Guaymas	-0.164	0.294	0.149	0.217	0.252	8.651	0.518	0.932
Yaqui Valley	-0.292	0.211	0.149	0.217	0.941	6.573	0.332	0.875
Yaqui Colonies	-0.232	0.218	0.149	0.217	1.011	5.769	0.315	0.898
Navojoa	-0.166	0.081	0.149	0.217	0.139	2.714	0.683	0.987
National	-0.305	0.402	0.149	0.217	0.040	8.306	0.269	0.971

Table 3

Pearson-correlations half matrix between the residuals yields series, period 1981-98. Significant coefficients are marked (* for $p<0.05$, ** for $p<0.01$) for $N = 18$.

Location	Caborca	Guaymas	Yaqui Valley	Yaqui Colonies
Caborca	- - -			
Guaymas	-0.12	- - -		
Yaqui Valley	0.34	0.56*	- - -	
Yaqui Colonies	0.62**	0.48*	0.82**	- - -
Navojoa	0.51*	0.25	0.89**	0.70**

Table 4

Results of PCA analysis of the series of residuals, period 1981-1998. The eigenvalues are presented with their sampling error intervals, no degeneracy was observed. The proportion of variance accounted by each component, both individually and accumulated, are shown as percentage. The residual correlation is the maximum paired correlation (i.e., considering off-diagonal values only) after each extraction; that of the PC_1 resulted in this value being non-significant as compared to the critical $r = 0.45$ for $N = 18$ ($p < 0.05$).

PCs	Eigenvalues (λ)	Error intervals		Variance (%)		Residual Correlations
		$\lambda + \Delta\lambda$	$\lambda - \Delta\lambda$	Raw	Cumm.	
1	3.16	4.22	2.11	63.2	63.2	0.43
2	1.18	1.57	0.79	23.6	86.8	0.13
3	0.48	0.65	0.32	9.7	96.5	0.05
4	0.14	0.19	0.10	2.9	99.4	0.01
5	0.03	0.04	0.02	0.6	100	0.00

Analysis of the residuals showed that, in all cases, the logistic model successfully accounted for systematic, long term trends that may be attributed to a gradual improvement in technology. From the Shapiro-Wilks' *W* test, the null hypothesis that the residuals do not follow a normal distribution can be safely rejected ($p < 0.01$). In addition, no residual series showed any evidence of an autocorrelative structure that would be expected from a systematic trend (Figure 4); all autocorrelations were found not to be significant by the Box and Ljung *Q* test (Table 2).

After removing systematic trends, we examined the series of residuals (Figure 3) in search of coherent variability between locations that could be ultimately related to large-scale climatic changes. All series resulted significantly correlated to at least one other series, thus evidencing some degree of common variability (Table 3). Again, the logistic model removed any high, significant autocorrelation from the series of residuals, as highly autocorrelated series often result in an artificial amplification of significance when testing for paired correlations (see Pyper and Peterman, 1998). Here, paired correlations are unaffected by this statistical effect and may be considered reliable as estimates of covariability.

Principal component analysis was used to extract common variability among the series. Again, results were consistent with the existence of large-scale climate effects, as the extraction of the first principal component (PC_1) was enough to leave (paired) residual correlations smaller than the corresponding critical value (Table 4). This PC_1 accounted for a relatively large fraction of total variance (63%), and could be extracted without any evidence of degeneracy (Figure 5). All the factor loadings were significant ($p < 0.05$), thus evidencing that the PC_1 series does account for a significant fraction of variance that is common to the analyzed series (Table 5).

Nevertheless, the PC_1 turned out to be much closer to the series of the southern locations (Yaqui Valley, Yaqui Colo-

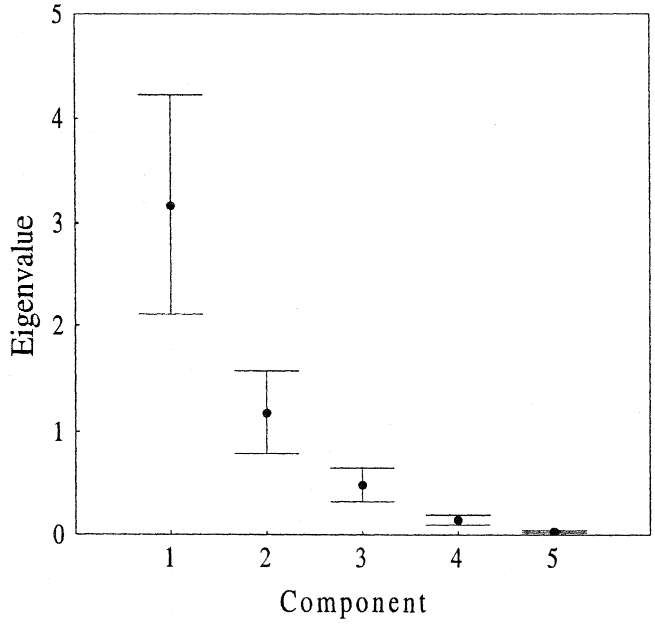

Fig. 5. Eigenvalues (dots) of the five principal components from the Principal Components Analysis of the series of residuals, including their sampling error intervals (whiskers).

nies and Navojoa) than to those to the north (Caborca and Guaymas, see Table 5). This difference is suggestive of two geographical modes of variability, but no significant residual correlation could be detected after the extraction of the first principal component (see Table 4). The information enabled the gross identification of the main common variations among the series as extracted within the PC_1, but may not be enough to further explore their differences. Thus, the existence of smaller-scales modes of variability remains to be explored, but will require more and longer series.

Meanwhile, we may examine the amplitude series of the PC_1 (Figure 6) as a series containing a significant fraction of variance which is common to the analyzed series. At this point, some considerations should be kept in mind. This component of yield variability should contain the signature of wide-scale climate changes, such as those related to ENSO. Nonetheless, other common sources of variability (e.g., market, financing, etc.) may obscure climate-related signals. Also, yields are determined in part by short-term management decisions (e.g., irrigation adjustments to dry/wet present conditions), and may not be highly sensitive to climate variability. This would be particularly true if such variations were relatively minor and could be compensated by management. Finally, regarding ENSO, it should be remembered that most of its variability is not followed by strong climate anomalies in Northwest Mexico; thus, yields may reflect only extreme events.

In conclusion, we find variability of the PC_1 to be strongly suggestive of ENSO effects on wheat yields in Sonora. Five moderate to strong ENSO episodes, indicated by arrows in Figure 6, occurred during the analyzed period: four El Niño events and one La Niña. Three of the El Niño events (1982-83, 1986-87 and 1997-98) were accompanied by increased yields within the PC_1, while low yields were observed during La Niña episode in 1988-89. Description of the mechanisms linking ENSO variations to wheat yields is beyond the scope of this preliminary analysis; but such responses are to be expected from the previously-documented trend towards increased (decreased) precipitation over northwest Mexico during El Niño (La Niña) events (Salinas-Zavala *et al.*, 1998).

Similar signals may be observed in the national yield serie, as might be expected from the relatively large contribution of Sonora to the national production. Yields of other wheat-producting regions of Mexico may also be affected by extreme ENSO phases: in fact, the signals of ENSO episodes seem to emerge better from the national serie that from PC_1. Wheat production is highly technified in Sonora as compared to some other regions (e.g., Sinaloa), thus local yields may be less sensitive to climate variability. If so, the analysis of yields series from other regions may further support the preliminary evidence of ENSO effects.

1991-95 was a period of a sustained positive ENSO phase which corresponded to overall low wheat yields in Sonora and at the national level. This seems to contradict

Table 5

Factor loadings and proportion of variance (as percentage) accounted by the first principal component for each of the series of residuals. Significant loadings are marked (* for $p<0.05$, ** for $p<0.01$) for $N = 18$.

	Caborca	**Guaymas**	**Y. Valley**	**Y. Colonies**	**Navojoa**
PC_1 loading	0.593**	0.521*	0.943**	0.928**	0.888**
Proportion of variance	35.1	27.2	89.0	86.2	78.8

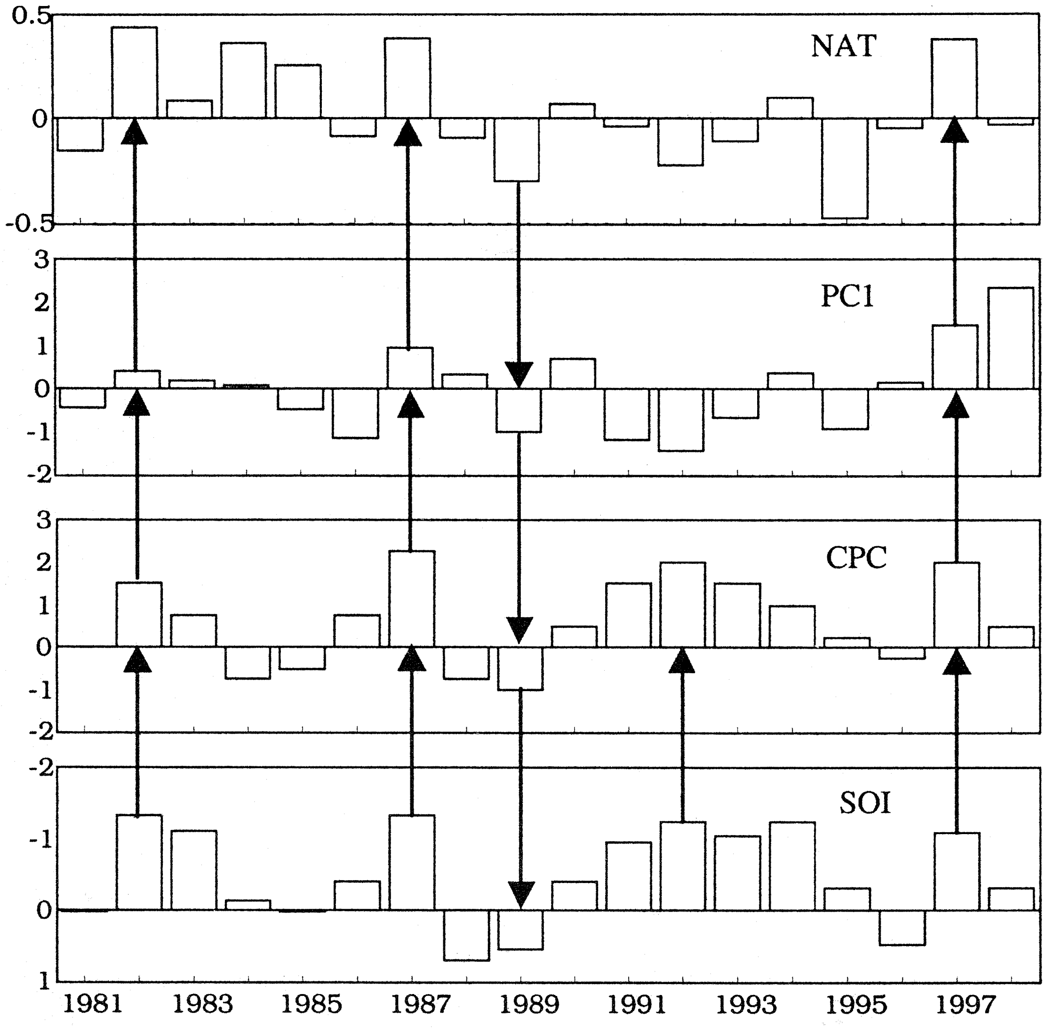

Fig. 6. Amplitude series of the first principal component of the series of residuals (PC1), plotted with the Southern Oscillation Index (SOI), the quantitative series of ENSO episodes enlisted by the Climate Prediction Center (CPC), and the series of residuals of the national average yields (NAT)

our proposed hypothesis on ENSO effects, especially if strong El Niño events have a positive effect on wheat yields. Tropical El Niño activity did not result in increased precipitation over northwest Mexico; instead, drought conditions prevailed for much of this period (Douglas and Englehart 1999). This exception thus further supports the idea of climate variations acting on wheat yields, but suggests that climate phenomena other than ENSO should also be explored.

Good ENSO forecast skills are useful in the prediction of wheat yields, particularly if strong ENSO events can be anticipated. The generalized increase in wheat yield during the 1997-98 El Niño was probably unrelated to management, as current culture practices did not undergo any significant modification during this season in most districts (Offices of Statistic of the Districts of Irrigation, SARH, pers. com.). Data for the 1998-99 season were not available at the time of this analysis. If our hypothesis is correct, low yields would be expected during this extreme, negative phase of the ENSO.

Early indicators of ENSO and near real-time forecasting are already available, and are used in other wheat producing regions worldwide (e.g., Mjelde and Keplinger, 1998). Our hypothesis may provide statistical link relating ENSO forecasts to regional wheat production.

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