Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea surface temperature

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SOUTHERN Africa is subject to recurrent droughts which cause severe food shortages. There is considerable evidence[1] that El Niño[2] warm events in the Pacific Ocean are linked to below-average rainfall in southern Africa, and the 1991–92 El Niño event was accompanied by the worst drought in southern Africa this century, affecting nearly 100 million people. But although models can predict El Niño events a year in advance[3–6], the drought was not anticipated, increasing relief costs. Here we present data showing a strong correlation between an El Niño index and both rainfall and maize yield in Zimbabwe. Surprisingly, the correlation with maize yield is stronger than that with rainfall, with more than 60% of the variance in yield accounted for by sea surface temperatures in the eastern equatorial Pacific Ocean—half-way around the world. We also show that model predictions of the El Niño index provide accurate forecasts of maize yield in Zimbabwe, with lead times of up to a year. As maize is the most important food crop for the ten-nation Southern African Development Community region[7], we suggest that this approach could provide an effective early-warning system for southern African drought-induced famines.

Maize is by far Zimbabwe's most significant food source[7]. Figure 1 (solid lines) shows annual variations in Zimbabwe rainfall and national average maize yield for the period 1970–93. Earlier data on the maize crop are unreliable. The annual average rainfall is derived by summing monthly weighted averages of rain gauge reports. Throughout the period under review there were ~1,150 stations spread fairly evenly throughout the country.

Before independence in 1980, the bulk of the marketed maize came from large-scale commercial farms. Since 1980, however, the Grain Marketing Board has stimulated a marked increase in the volume grown and marketed by small-scale, communal farmers and in the overall area sown to maize. The overwhelming bulk of maize produced is now rain-fed. Adoption of hybrid varieties has also been widespread. This has resulted in a slight trend towards an increase in overall yields, but has also contributed to wider differences in yields between good and poor years. Temperature and the distribution of rainfall during the growing season influence plant growth. Maize needs moisture during inflorescence for the pollen to stick to the tassels and, later, to fill the grain. January to March is the critical period. Despite additional climate and economic influences on the maize crop, it is evident in Fig. 1 that fluctuations in average yields clearly follow those in annual rainfall. The strength of this connection is clearly demonstrated by the variations in recent years. Average yields reached a high of 2.4 tonnes per hectare (t ha^{-1}) in 1986, and a low of 0.4 t ha^{-1} in 1992. What is of more interest, however, is that yields also track changes in an index of El Niño Southern Oscillation (ENSO).

Figure 1 (dashed lines) shows an index of ENSO, scaled to be in the same units as the corresponding Zimbabwe variables. Specifically, the index is the sea surface temperature (SST) anomaly in the NINO3 region (90°–150° W, 5° S–5° N) of the eastern equatorial Pacific. This primary manifestation of ENSO is widely monitored, and is reported monthly in the *Climate Diagnostics Bulletin* produced by the Climate Analysis Center of the US National Weather Service. We prefer it as an ENSO index to the still more widely used Southern Oscillation Index (SOI) because it is far less noisy; that is, it has less month-to-month variability due to atmospheric fluctuations distinct from ENSO.

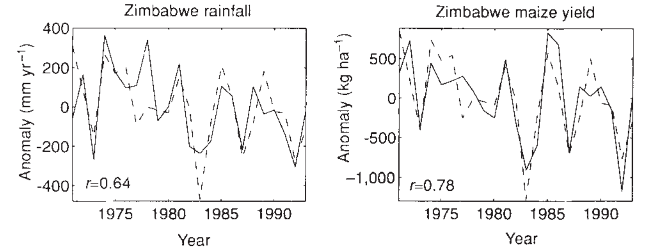

FIG. 1 Solid lines, annual variations in Zimbabwe rainfall (left) and maize yield (right) for the period 1970–93 ('1970' denotes the 1969–70 growing season, November 1969 to May 1970). Yield data were collected by the extension service of the Zimbabwe Ministry of Lands, Agriculture and Water Development. Dashed lines, SST anomalies in the NINO3 region of the eastern equatorial Pacific (see text). r is the correlation coefficient of the two curves.

The dashed lines of Fig. 1 are for the NINO3 index averaged for February and March, the heart of the growing season. The strength of the correspondence between rainfall in Africa and the surface temperature of the ocean almost half-way around the world is astonishing: the correspondence between NINO3 and the maize yield is even better. (There is only one chance in five that the difference between yield and rainfall is accidental: the correlation coefficient r of NINO3 is 0.64 with rainfall and 0.78 with maize yield; according to the standard F-test for correlation coefficients, the difference is significant at the 82% level for a sample of size 23.) It may be that fluctuations in maize yield are amplified by rainfall variations in the drier parts of the country. The spread of hybrids is an additional, nation-wide amplifier. On the other hand, the stronger connection of NINO3 SST to maize yield may be due to the other climate factors influencing plant growth.

Because the NINO3 SST values of Fig. 1 are simultaneous with the growing season, their predictive value is limited. The solid curves in Fig. 2 show the correlations of rainfall and maize yield with observed NINO3 SST at all lead times beginning with the January of the previous growing season (that is, more than 1 year in advance). Correlations are still fairly high in the autumn preceding the growing season, but decrease rapidly as the lead time lengthens.

To extend the lead time for prediction, we use a simulation model able to predict variations in the tropical Pacific associated with ENSO. The model we use, that of Zebiak and Cane[8,9], has been used to predict ENSO since 1985, and its performance is

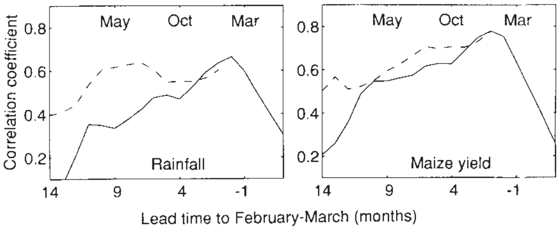

FIG. 2 Solid lines, correlation coefficients of rainfall (left) and and maize yield (right) with observed NINO3 SST at all lead times beginning with the January of the previous growing season (that is, more than 1 year in advance). Dashed lines, correlation coefficients with the observed rainfall (left) and maize yield (right) obtained for forecasts from each calendar month using the ENSO prediction model of Zebiak and Cane[8,9].

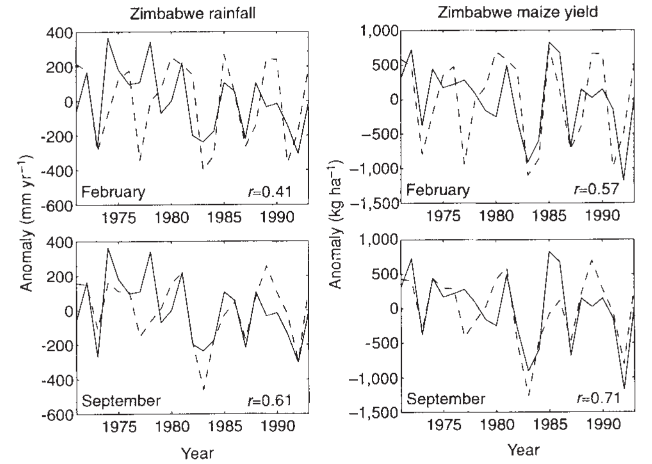

FIG. 3 As Fig. 1, but here it is the model-derived forecasts from the preceding February and September that are compared with the observed values.

well documented[3-6]. The forecast scheme we adopt is the following. Given the data needed to initialize the model for a particular month, we use it to forecast the NINO3 SST anomalies for the following February–March. The forecast NINO3 value is then used as a predictor for the rainfall or maize yield.

The dashed lines in Fig. 2 show the correlation with the growing season rainfall and maize yield obtained for forecasts from each calendar month. In contrast to the results for the observed NINO3, there is little fall-off in correlation as the lead time increases. Longer lead forecasts are now possible. Figure 3 is similar to Fig. 1, but now the forecasts from the preceding February and September are compared with the observed values. Of course, the correlations are not as high as for the values of NINO3 actually observed during the growing season, but they are high enough to give significant skill. (For the less skilful February forecast the correlation with rainfall is 0.41, significant at the 99.5% level, whereas that with maize yield is 0.57, significant at the 99.9% level. For the September forecasts the corresponding correlations are 0.61 and 0.71.) The February forecast anticipates maize yield in Zimbabwe a full year ahead—before the previous harvest is in. The September forecast could be available in October, before the time for planting.

Obviously, the possible prediction schemes are far from exhausted. For example, the year-to-year change of the SOI has been used as a predictor of the Australian wheat crop[10]. However, in view of the shortness of the maize time series, we prefer to stop at a point where our prediction procedures are so straightforward that there can be little question of artificial skill (that is, the danger that in a short record a random coincidence of variations will be mistaken for a true relation between the variables). The high correlations already obtained leave little room for improvement by technical elaboration. Figure 1 suggests that better ENSO predictions are a primary requirement for substantially improved maize forecasts. Additional improvement would require the use of more localized factors as predictors. It would be especially desirable to go beyond national crop yields to regional forecasts.

As noted above, the 1991–92 drought in southern Africa was the worst this century. The Southern African Development Community (SADC) region's cereal harvest was halved and nearly 100 million people living in the 10 SADC states and South Africa were affected. Fortunately, widespread famine was averted by responsive actions by local governments and aid from the international community.

This successful response is all the more notable because the drought was not anticipated (though the ENSO warm event was[11]). Regional grain stocks were known to be low before the growing season, but good rains in October and November 1991 prompted optimism instead of corrective action. Consequently, the subsequent relief effort was more costly and more precarious. Ultimately, some 11.6 million tons of drought-related commodities had to be imported within a 13-month period[12], a considerable logistic achievement.

We believe that the results reported here indicate that long-term forecasts, although hardly infallible, are sufficiently reliable to be useful inputs to the SADC Regional Early Warning System. ENSO forecasting models can provide indications of probable average crop yields even before the previous harvest is in. As the growing season approaches the forecasts become more skilful, and as it begins, estimates can be further sharpened by folding in information on the current ENSO state. It is both scientifically noteworthy and fortunate that the stronger connection is not to rainfall but to maize yield, one link closer to the food supply.

The ENSO cycle will surely continue, and there will surely be another drought threatening the welfare of the people of southern Africa. An effective early warning system is in place, and relevant climate knowledge continues to grow. Next time we will be better able to anticipate and react early to minimize the cost and the damage to the community. ☐

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Origin of the slab component in arc lavas from across-arc variation of B and Pb isotopes

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AT convergent margins, the subducting oceanic slab is thought to dehydrate, producing fluids which metasomatize the overlying mantle wedge where island-arc magma forms. However, the nature and origin of the metasomatizing fluid, its source composition and its relation to the genesis of the chemical characteristics of arc magmas are largely controversial. Across-arc variation in the chemistry of arc lavas provides a useful key to this problem, because it may reflect the changes in the physical conditions of the subducting slab that control mass transfer from slab to mantle wedge as a function of depth. Here we report clear across-arc variations in the concentrations and isotopic compositions of boron

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