INT. J. REMOTE SENSING, 1999, VOL. 20, NO. 10, 2117–2124

Exploring the correlation between Southern Africa NDVI and Pacific sea surface temperatures: results for the 1998 maize growing season

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(*Received 10 September 1998; in final form 8 December 1998*)

Abstract. Several studies have identified statistically significant correlations between Pacific sea surface temperature anomalies and NDVI anomalies in Southern Africa. The potential predictive value of the relationship was explored for the 1998 maize growing season. Cross-validation techniques suggested a more useful relationship for regions of wet anomaly than for regions of dry anomaly. Observed 1998 NDVI anomaly patterns were consistent with this result. Wet anomalies were observed as expected, but wide areas of expected dry anomalies exhibited average or above-average greeness.

1. Introduction

In the drylands of Africa, water limitation is the primary factor responsible for interannual variations in performance of rainfed crops. Hundreds of millions of people depend upon the success of these crops for their livelihood. As a consequence, national and international early warning systems devote considerable effort to monitoring growing conditions. In conjunction with political and socio-economic data, food security analysts use this information to identify potential famine areas. Decision makers can then authorize appropriate responses to unfolding emergencies (USAID 1998, FAO 1998).

Vegetation index images are used routinely by food security analysts to monitor crop conditions. Climate forecasts at the outset of the growing season also support disaster preparedness. Numerical modelling of the El Niño–Southern Oscillation (ENSO) phenomenon in the equatorial Pacific contributes to these climate forecasts.

Correlations have been noted between a key ENSO indicator and anomalous patterns in vegetation index images. These correlations suggest an ability to depict ENSO teleconnections and forecasts as patterns of vegetation index anomalies. In this letter we explore this possibility for the case of the 1998 growing season in Southern Africa and Madagascar (figure 1).

2. Background

The Famine Early Warning System (FEWS), a project of the US Agency for International Development (USAID), has long used Normalized Difference

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 1999 Taylor & Francis Ltd
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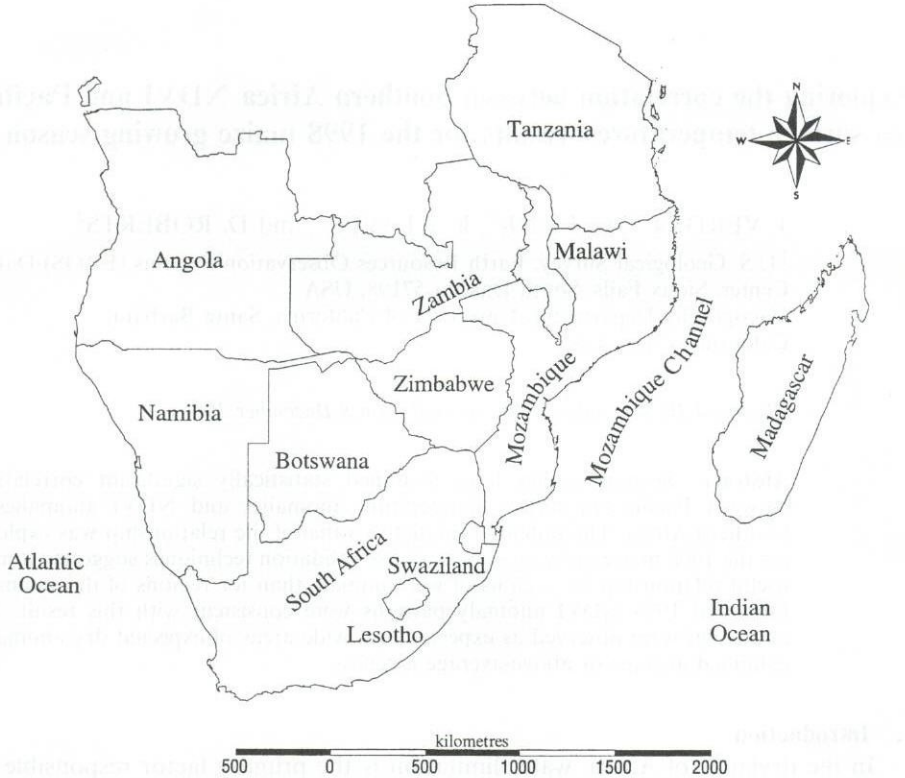

Figure 1. The countries of Southern Africa and Madagascar for which NDVI and SST anomalies were analysed.

Vegetation Index (NDVI) images to monitor crop growing conditions over broad regions of semi-arid sub-Saharan Africa (Hutchinson 1991). NDVI has been shown to be correlated with a number of measures of the relative abundance of green biomass, including leaf area index, intercepted fraction of photosynthetically active radiation and density of chlorophyll in plants (Sellers 1985, Tucker and Sellers 1986). It has also been used to predict crop yields (Rasmussen 1992, Groten 1993, Unganai and Kogan 1998) and demonstrates a significant correlation with annual and monthly rainfall totals (Malo and Nicholson 1990, Nicholson and Farrar 1994). The useful properties of the NDVI led to its adoption by FEWS as an operational indicator for food security monitoring.

In recent years, the irregularly recurring interannual oscillations of Pacific sea surface temperature (SST) and atmospheric pressure known as ENSO events have gained much attention for their associations with anomalous weather patterns in various parts of the globe (Glantz 1996). Important teleconnections during warm ENSO events for Southern Africa include increased rainfall in the north and north-east (especially parts of Tanzania and Zambia) and decreased rainfall in the south-east (especially southern Zimbabwe, southwestern Mozambique, and north-eastern South Africa). These anomalies have been described by Ropelewski and Halpert (1987), Cane *et al.* (1994), Barnston *et al.* (1996) and Nicholson and Kim (1997).

Remote sensing research has also been directed toward the question of ENSO impacts in Southern Africa. Time series NDVI data have been analysed for expressions of the ENSO signal. Patterns illustrating the spatial propagation of drought through the region have been shown through the application of principal components analysis (Anyamba and Eastman 1996). Furthermore, negative NDVI anomalies in Southern Africa, indicative of drought, have been shown to be associated with positive (warm) Pacific SST anomalies (Myneni *et al.* 1996).

The present study was undertaken in late 1997, when the largest ENSO warming event of the century was firmly established and the Southern Africa maize growing season was about to begin. It was recognized that the situation presented the opportunity to explore the predictive value of the SST-NDVI correlation reported by Myneni *et al.* (1996) in conjunction with NCEP forecasts of Pacific SST anomalies. Experimental forecast NDVI anomaly images were produced for January, February, and March of 1998. The intent was to respond to the call of the early warning community for climate forecasts with greater spatial and temporal resolution, in a readily useable format (Farmer 1997). We report the level of agreement between forecast and actual NDVI anomaly images for the period, and present results of a statistical cross-validation to assess the expected skill of the method in any given year.

3. Data

A time series of 16 years (1982–1997) of monthly maximum-value NDVI composite images was prepared for January, February, and March. Each image array was made up of 550 lines of 630 samples each, with dimensions of 0.0625 degree of latitude and longitude, about 6 km. The images for the years 1982–1993 were provided by the NASA/Global Inventory Monitoring and Modeling Studies group (Los *et al.* 1994). Mean monthly NDVI 'normal' images were based on these years, to be consistent with FEWS operational methods. Each month's time series through 1997 was completed using NDVI images in the FEWS archive at USGS. NDVI anomaly images were then prepared by differencing the individual monthly images and their respective monthly normal images.

The eastern equatorial Pacific from 5° S to 5° N latitude and 90° W to 150° W longitude, known as the NINO3 region, is an area whose SST anomalies are widely tracked as an ENSO indicator. A time series of monthly SST anomaly values, dating back to 1950, has been developed by NOAA's Climate Prediction Center (NOAA/CPC) and is continually updated (Woodruff *et al.* 1993). Monthly NINO3 SST anomaly data for the 16-year period were downloaded from the NOAA/CPC World Wide Web site. Forecast NINO3 SST anomalies for 1998 were also provided by NOAA/CPC (J. Kousky, personal communication).

4. Methods

The time series of 16 images each for January, February, and March were partitioned into groups of 5 and 11 images. The group of five images represented years of ENSO warm events (1983, 1987, 1992, 1993 and 1995) and the group of eleven represented the other years. On a pixel-by-pixel basis, a two-tailed *t*-test was applied to identify locations having significantly different NDVI anomalies during ENSO warm events than during other years, at the 0.01 confidence level. For each month, regions of wet (greener than average) and dry (less green than average) pixels were identified.

Within each of the monthly wet and dry regions, mean NDVI anomaly was calculated for each of the 16 years of record. These values were used to develop regression estimators of mean regional NDVI anomaly using NINO3 SST anomalies as the independent variable. Six estimators were developed, one for each wet and dry region for each month (January, February, and March). NCEP's coupled model forecast SST anomalies (Ji *et al.* 1996) were then substituted into the regressions to obtain estimates of mean NDVI anomalies in the wet and dry regions for the upcoming 1998 season.

During the course of the 1998 season, actual NDVI images from FEWS operations were collected and processed into monthly NDVI anomaly images. These were compared with the forecast NDVI anomaly patterns to evaluate them.

Cross-validation (Michaelsen 1987) was also used to determine a skill statistic (defined as follows) for each NDVI anomaly estimator. Including data for 1998 to obtain a 17-year time series, one year at a time was withheld and its NDVI anomaly estimated by regression using the remaining 16 data points. Skill was calculated as $R=[1-(\mathrm{MSE}/\mathrm{MSA})]^{1/2}$, where R is the skill statistic, MSE is the mean square error in estimating withheld points, and MSA is mean square anomaly, or variance, of the dataset. The MSA can be interpreted as the error incurred by forecasting using only the long-term mean. Positive skills range up to 1.0 for perfect forecasts. Negative skills occur when the forecasts are outperformed by the long-term mean.

5. Results

The *t*-test images (figure 2) show the spatial pattern of pixels which were significantly wetter (green) or drier (red) during warm ENSO event years. These patterns change substantially from month to month. In January, the ratio of the number of wet to dry pixels was 1.32, indicating an aggregate *increase* in precipitation in Southern Africa. There is a distinct north-south pattern to the distribution of wet/dry pixels, with South Africa, Mozambique and Zimbabwe being mostly dry, and Angola, Zambia and Tanzania being generally dry. The wet/dry dichotomy appears to shift north over the next two months; by March only Tanzania and Angola exhibit significantly greener than average conditions, and the ratio of the number of wet to dry pixels is 0.34.

Table 1 summarizes the correlation coefficients (r), coefficients of determination (r^2), and cross-validated skill statistics (R) for the six regression estimators, along with forecast and observed mean NDVI anomaly values for the *t*-test regions. These numbers suggest that increased greenness is more readily predicted than drought. The cross-validated skills for wet regions varied between $+0.36$ and $+0.39$, a range recognized to be of practical value for preparation of seasonal climate forecasts (Barnston *et al.* 1996). Our estimates for the dry region exhibited negative skills for all months. The performance of the regression estimators for 1998 reiterates this finding. The wet region estimates are of the same sign and order of magnitude as the observed values, while the dry region estimates were off by up to 0.08 NDVI, predicting considerable drought for areas which actually showed average greenness.

6. Discussion

Forecast NDVI anomaly patterns strongly resemble the consensus forecast of the Southern Africa Regional Climate Outlook Forum (FEWS 1998). The north (wet)–south (dry) dichotomy is also consistent with previous work that divided the subcontinent into Southern African and Eastern Equatorial regions (ibid, Ropelewski and Halpert 1987). However, both forecasts predicted drought for regions that in fact experienced average to above-average rainfall in 1998. Cross validation skill better foretold observed forecast performance than did simple correlation statistics.

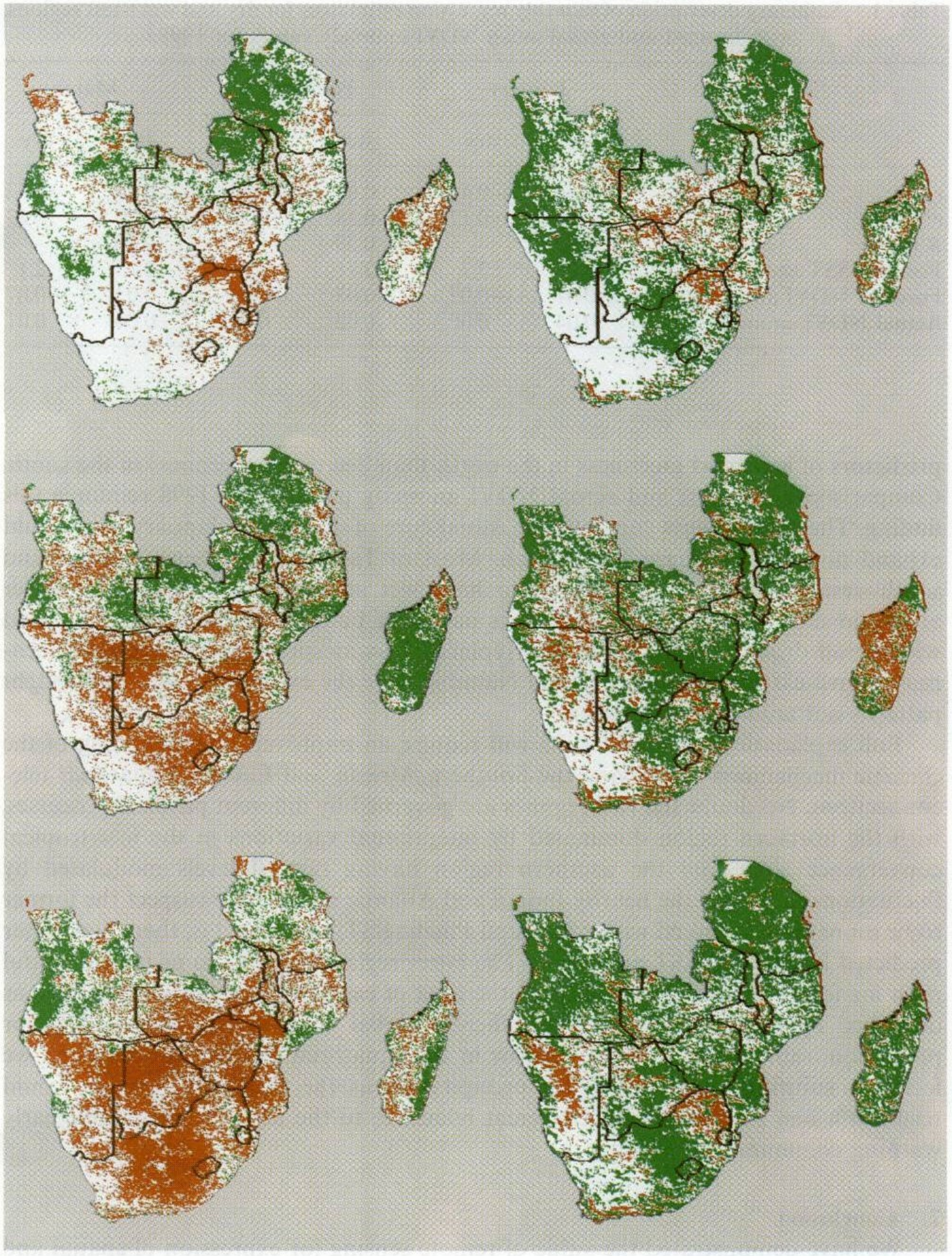

Figure 2. Forecast (left) and actual (right) NDVI anomaly patterns for (top to bottom) January, February, and March. Dry anomalies are in red, wet anomalies are in green. Mean area anomaly values are those reported for the forecast row of table 1.

Our correlation values (table 1) are comparable to values reported in similar studies carried out with conventional climatological data (Nicholson and Kim 1997). However, cross-validation statistics suggest that NINO3 SSTs are more accurate

Table 1. Summary description of monthly regression estimators for dry and wet *t*-test regions, with forecast and actual mean NDVI anomaly values for 1998.

	January		February		March	
	wet	dry	wet	dry	wet	dry
r	0.54	−0.41	0.62	−0.44	0.44	−0.52
r^2	0.30	0.17	0.38	0.20	0.20	0.27
R (skill)	0.39	—	0.39	—	0.36	—
Forecast SST anomaly (°C)	3.2	3.2	2.7	2.7	2.1	2.1
Forecast NDVI anomaly	0.07	−0.07	0.05	−0.04	0.03	−0.07
Actual NDVI anomaly	0.04	0.00	0.02	0.02	0.04	0.01

predictors of increased greenness in the north than decreased greenness in the south. Comparison of forecast and actual NDVI anomaly patterns for 1998 reinforce this finding. The *t*-test images suggested an initial core of drought in January that would expand north in February and March. Most of Tanzania, northern Zambia, and south-western Angola were forecast to have wet anomalies. In 1998, these latter areas did exhibit wet anomalies, but as part of a broader phenomenon. Expected widespread drought in the south was replaced by widespread above-average greenness. North-eastern South Africa and Namibia were the exception, showing drought patterns not unlike those forecast.

Full explanation of these results will require an improved understanding of the climatic mechanisms underlying the Southern African and Eastern Equatorial teleconnections. No doubt the two regimes are governed by different physical processes, with the northern region dominated by interannual variations in the intertropical convergence zone, and the southern region having rainfall levels modulated by fluctuations in SST of the nearby Indian and Atlantic oceans. We suspect the former to be more directly linked with equatorial Pacific SST, and that it is, therefore, better predicted by NINO3 SST anomalies. The latter regime suggests to us that a fruitful path for follow-on research will be in the area of canonical correlation analysis, as described by Barnston *et al.* (1996) wherein global fields of SST are used as for prediction, rather than a single window in the equatorial Pacific. Furthermore, we feel that substitution of NDVI for precipitation as the predicted variable would result in a new forecast product of great relevance to the needs of the famine early warning community.

7. Conclusion

We have demonstrated the value of remote sensing for expression of spatial and temporal patterns of ENSO response in a food security context. Cross-validation has been shown to be a powerful measure of the expected performance of equatorial Pacific SST for forecasting Southern Africa NDVI.

Acknowledgments

The authors wish to thank Drs C. J. Tucker and S. O. Los for their advice and assistance in assembling the monthly NDVI time series used in this study. J. Kousky supplied both the historical and forecast NINO3 SST anomalies. J. Verdin acknowledges the opportunity to work at the University of California, Santa Barbara, that was granted by the training program of the US Geological Survey's National Mapping Division. Work by R. Klaver was performed under US Geological Survey contract 1434-CR-97-CN-40274.

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