Forecasting the interannual trends in terrestrial vegetation dynamics using time series modelling techniques

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ABSTRACT

The sensitivity and response of vegetation to climatic perturbations operates over a range of temporal scales. Provision of information on the state of vegetation prior and post climatic perturbations is a critical starting point for forecasting the dynamics of terrestrial systems. A simplistic methodology for generating forecasts that integrate remotely sensed data using time series modelling techniques is discussed in this paper. We focus on forecasting the behaviour of terrestrial South American vegetation in the presence of interannual perturbations by the ENSO using simplistic time series modelling techniques. Coarse resolution (1 degree x 1degree) NDVI data products, derived from the NOAA AVHRR which are available for the period of 1981 to 1992 were used as the primary input for the simulations. Forecasts were generated using ARIMA modelling methodology. The model outputs were validated against the finer resolution 8 km x 8 km AVHRR NDVI data set, which extends from 1981 to 1999. Considering the spatial scales involved and the relative simplicity of the techniques, this methodology provides a rapid and effective means of analysing vegetation dynamics over the spatio-temporal domain.

Keywords and phrases: forecasts, interannual perturbations, time series modelling, NDVI, ENSO, ARIMA

INTRODUCTION

Climate change is a problem with unique characteristics. It is global, long-term, and involves complex interactions between environmental, economic, political, institutional, social and technological processes. Whilst it is generally believed that climatic change will have substantial effects on the functioning of the biosphere, the exact nature of these effects is unclear, there is, however, a general expectation that changes in terrestrial vegetation patterns will result and these changes will not be biologically uniform. Provision of information on the state of vegetation prior and post climatic perturbations is a critical starting point for analysing the dynamics of terrestrial systems (Shimabukuro *et al.*, 1997). Existing methods, fail to incorporate in-situ terrestrial vegetation data and are unable to validate or test the accuracy of the forecasts generated. This is mainly attributed to the logistical problems associated with the collection of data at terrestrial levels.

Arguably the only feasible approach is the intensive and extensive use of remote sensing instruments, which provide information, at the required spatio- temporal scales. A sensor of particular interest is the National Oceanographic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) that provides data suitable for monitoring terrestrial vegetation dynamics. Data recorded by this sensor are used to calculate the Normalized Difference Vegetation Index (NDVI), a mathematical combination of radiation flux recorded in the red and near infrared portion of the electromagnetic spectrum (Perry and Lautenschlager, 1984). NDVI is a sensitive indicator of the condition of green vegetation and can be used as a surrogate measure of the response of vegetation to climatic disturbances (Yang *et al.*, 1998).

CASE STUDY AND OBJECTIVES

We focus on analysing the effects of El Niño Southern Oscillation (ENSO) perturbations on terrestrial South American vegetation. ENSO is the largest known global climate variability signal on interannual time scales. It is a quasi-periodical fluctuation between warm El Niño and cold La Niña states of the Pacific sea surface temperatures and has a recurrence oscillation period of approximately 2 -7 years (Philander, 1990). Previous studies have identified interannual NDVI variability signals associated with the ENSO (Asner *et al.*, 2000, Li and Kafatos, 2000). Further work of this nature, which quantifies the response of vegetation to climatic perturbations, is essential for the understanding of vegetation dynamics in terrestrial systems. This investigation aims at evaluating the temporal sensitivities of vegetation to ENSO forcing, with specific focus on the El Niño events that occurred in 1982/83, 1986/87, 1991/92 and 1997/98 years. Usage of remotely sensed terrestrial vegetation data, as input for time series model simulations that incorporate the inherent nature of the AVHRR instrumental record is arguably the unique aspect of this investigation.

DATA AND ANALYSIS

The study was based on a transect across South America which passes through the largest extent of the Amazon Basin. Two sets of terrestrial vegetation data were used for the analysis.

a) Coarse monthly NDVI products with a spatial resolution of 1 degree x 1 degree (or 110 km x 110 km), covering the period from October 1981 to December 1992

b) Finer 8km by 8km NDVI image products for the period of November 1981 to December 1999.

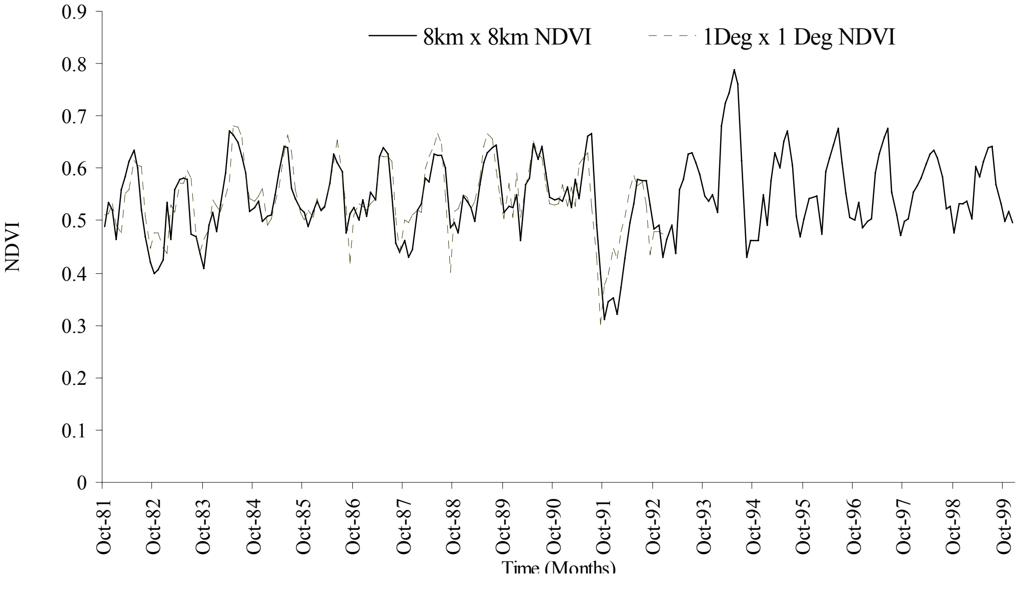

Figure 1: a comparison of the 1degree x 1 degree and 8 km x 8 km NDVI data sets

Figure 1 is comparison of the mean 1 degree x 1 degree (or 110 km x 110 km) and 8 km x 8 km time series NDVI data. Both the series show a correlation of $r = 0.81$, $s = 0.01$, $p < 0.001$. This can be attributed to the different spatial scales the data were obtained from. Both series show pronounced seasonal oscillations, which correspond to the vegetation phenological cycles where maximum NDVI values are observed between May and August. Annual variations in the NDVI values are seen to be 0.2 to 0.3 units. The temporal trends in the vegetation was then compared against monthly Southern Oscillation Index (SOI) time series data. SOI is the accepted indicator of the phase and amplitude of ENSO cycles and is calculated from the sea level pressure difference between Darwin and Tahiti. We use the SOI as an indicator of the ENSO activities and as a surrogate for sea surface temperatures or the climatic variablities of the period in concern. Interannual signals in the NDVI and SOI data were extracted using time series modelling techniques. First, an additive seasonal decomposition model was applied to the series to filter out the seasonal noise. Then, to facilitate clear depiction of interannual signals, irregularities in the seasonally decomposed time series were exponentially smoothed using the 'Winters' model. Both of these extraction procedures incorporate memory decay components for the series based on past history of the data this is very attractive considering the nature of the terrestrial vegetation data.

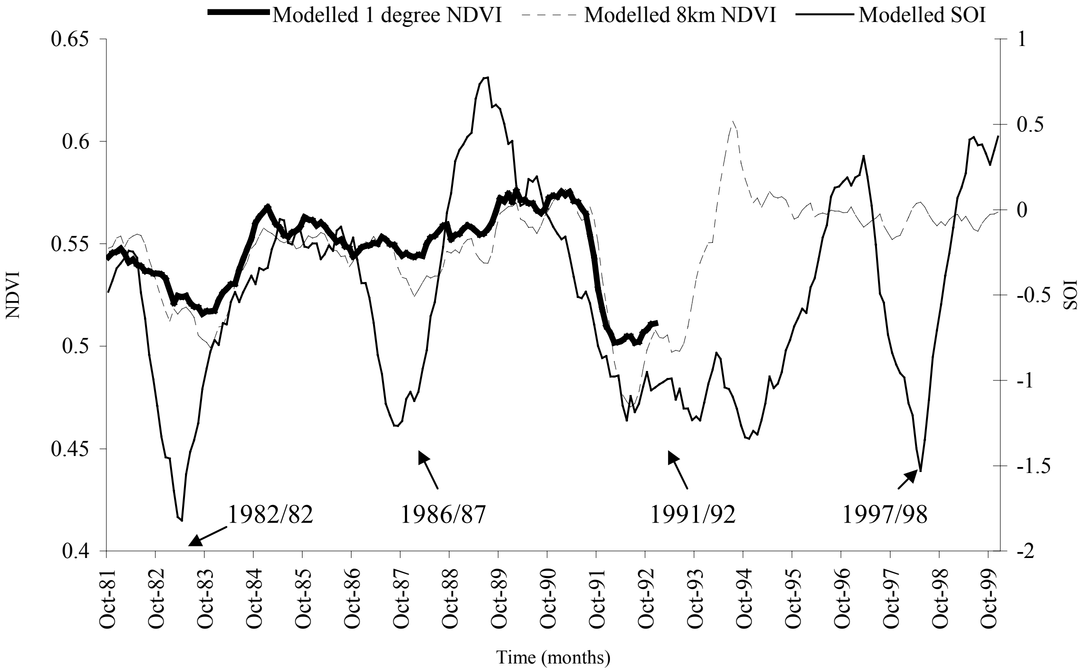

Figure 2: Comparison of the modelled NDVI and SOI series. El Niño events are denoted by negative values in the SOI series and vice versa.The positions of El Niño events are marked on the figure for reference.

Figure 2 shows the interannual derivatives of the NDVI and SOI time series data. Interannual variances of the NDVI are observed to be in the order of 0.04 to 0.05 units. The ENSO event of the early 1990s appears to be different compared to the well-defined events of the 1980s. A clearly marked phase difference (or lag) with SOI is observed for both of the NDVI series. NDVI values are seen to be dropping after an El Niño period. However, this trend can only be observed upto the period of 1992/93. For, despite the perturbation by the severe El Niño of 1997/98 vegetation response seems to be static and is seen to be almost stable (with NDVI values that are relatively higher than the previous years. The 'lag' between ENSO perturbations and vegetation response was estimated to be generally in the range of 4 – 6 months using a cross correlation model. It should be noted that the 'lags' differ for different El Niño events depending on their phase and amplitude. However, the NDVI series shows irregular or no lag spacing for the post 1992 period. This leads to the hypothesis that " Terrestrial vegetation is becoming less sensitive to ENSO perturbations".

TESTING THE HYPOTHESIS

A null hypothesis scenario based on assumption that the vegetation continues to be regulated by the ENSO at interannual scales was investigated to validate the proposed hypothesis. Simulations were generated using an Auto Regressive Integrated Moving Average (ARIMA) model. ARIMA models are an established (forecasting) technique in econometrics and are used as a complement to the 'trend regression approach' (Box *et al*., 1994). The model assumes that a one-dimensional data series evolves through time as the outcome of a statistical process (Clifford and McClatchey, 1996), capturing more elements of the behaviour of potentially inhomogeneous series (Janacek and Swift, 1993). In the environmental sciences, ARIMA modelling is used to represent a complex and possibly poorly specified system that operates in the presence of one or many noise sources, which is attractive when considering the nature of both terrestrial systems and the AVHRR instrumental record. The moving average (MA) component of the model incorporates past random fluctuations or 'shocks' to represent the time series (Z_t)

$$Z_t = a_t - f_1 a_{t-1} - f_2 a_{t-2} - \ldots f_q a_{t-q} \tag{1}$$

Where f_1 and f_2 are the MA coefficients and a is the random shock term. The auto regressive (AR) component estimates values of the dependent variable as regression functions of previous values and is expressed as:

$$Z_t = f_1 Z_{t-1} + f_2 Z_{t-2} + \ldots f_q Z_{t-q} + a_t \tag{2}$$

Mixing these models produces the ARIMA model, which generically takes the form

$$(p, d, q)(P, D, Q)S \tag{3}$$

Where the lower- and upper- case symbols represent the non-seasonal and seasonal components respectively. p is the order of differencing of the AR model, d is the order of series differencing, q is the order of differencing of the MA model and S is the seasonality (=12 for an annual trend in monthly data). This model provides two key advantages in relation to other forecasting techniques. First, they can be used to examine complex series, as they provide more *parasimonous* model fits (i.e., fewer model parameters have to be estimated) than pure AR or MA models alone. Second, the mixed structure can provide additional flexibility when an output series may result from more than one interacting process.

The 1 degree x 1 degree NDVI data for the period of 1981 October to 1990 December was used as the primary input. Input data was limited upto 1990 December due to the reported anomalies in the AVHRR record. The raw (unprocessed) SOI data upto December 1999 was used as the regressor (independent variable) to drive the model on the interannual scales. In other words, the model simulates the seasonal trends of the vegetation based on the cyclicities it infers from the NDVI time series and the interannual patterns based on the fluctuations of the regressor series. The outputs of the simulations were then validated against the trends exhibited by the 8 km x 8 km NDVI series.Results of the ARIMA simulation against the raw 8 km NDVI data are compared in figure 3. The model output shows a reasonably high correlation with the raw data ($r = 0.6204$, $s = 0.01$, $p < 0.001$) which is a good indication of the accuracy of the model considering the spatial scales involved. Seasonalities of the vegetation are clearly mimicked in the simulation.

Interannual derivatives of the ARIMA model simulation output and 8 km x 8 km NDVI data are compared in figure 4. NDVI values are seen to be decreasing post El Niño events and vice versa in the simulation. Whilst showing identical trends with the processed 8 km series till mid 1991 the simulation exhibits behaviours of different magnitudes in the latter periods. The simulation does not mimic the anomalous pattern of low and high NDVI values during the ENSO event of the early 1990s. Where the NDVI values show relative static behaviour in the post 1995 period the simulation shows NDVI values decreasing during the El Nino of 1997/98. A very low correlation of $r = 0.07746$, $s = 0.01$, $p < 0.001$ is obtained between the interannual derivatives of the 8 km raw data and the simulation. This can be explained by the fact that the simulation was generated on the basis of the null hypothesis, which assumes that the ENSO effect was responsible for interanual varations in the NDVI throughout the period.

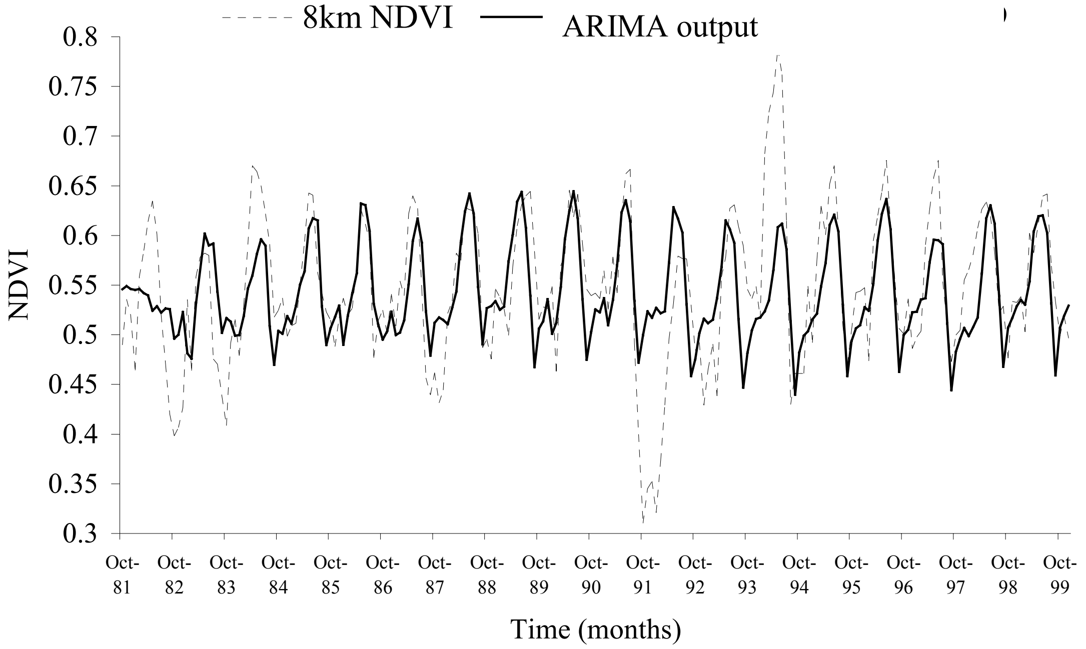

*Figure 4: Comparison of the ARIMA simulation output with the 8 km x 8 km raw NDVI data. Seasonalities of the vegetation are clearly mimicked in the simulation. Whilst the anomalous decrease in NDVI values (in both series) in the post 1991/92 El Niño period can be explained by the volcanic eruption of Mt. Pinatubo in 1991, which injected sulfate aerolsols into the stratosphere that decreased the NDVI values for months (*Asner *et al.*, 1997*); the anomalous increases in the NDVI values during the 1994/95 period remains unexplained.*

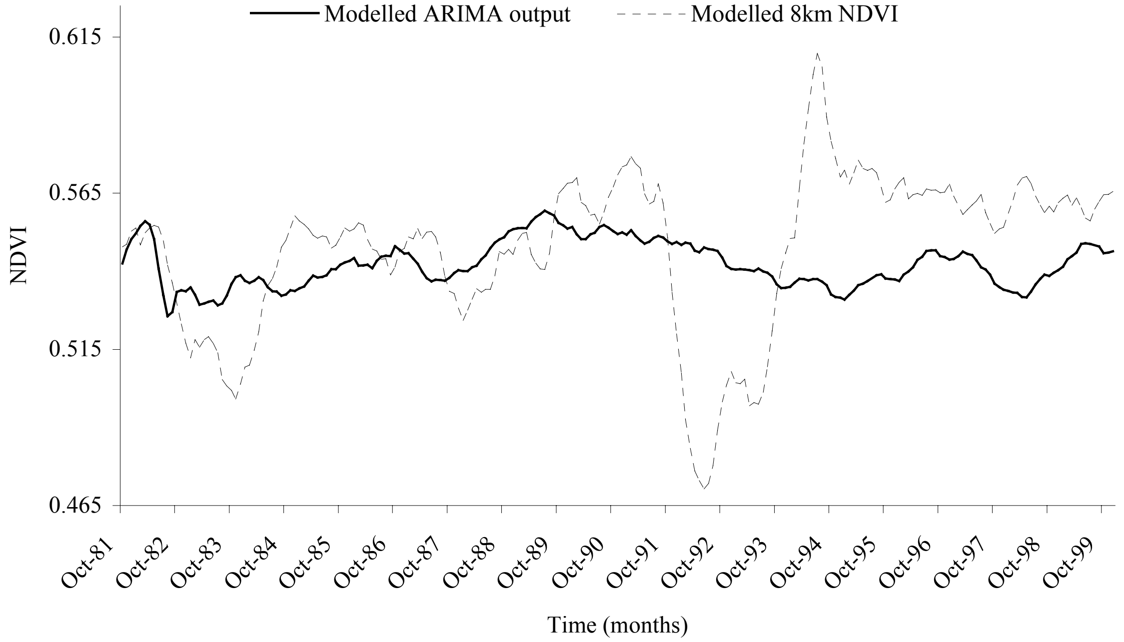

Figure 5: Comparison of the interannual derivatives of the ARIMA output and the 8 km x 8 km NDVI series. NDVI values are seen to be decreasing post El Niño events and vice versa in the simulation The simulation does not mimic the anomalous pattern of low and high NDVI values during the ENSO event of the early 1990s.

To further validate the hypothesis, the correlations of the modelled NDVI values (for both data sets), and the ARIMA simulation output values against the modelled SOI values on a yearly basis were calculated and plotted against time as shown in figure 5. The correlations for the raw data show a decreasing trend over the period, as opposed to the increasing correlative trend in the ARIMA scenario. This clearly indicates that of vegetation activity is becoming less sensitive to the ENSO disturbances.

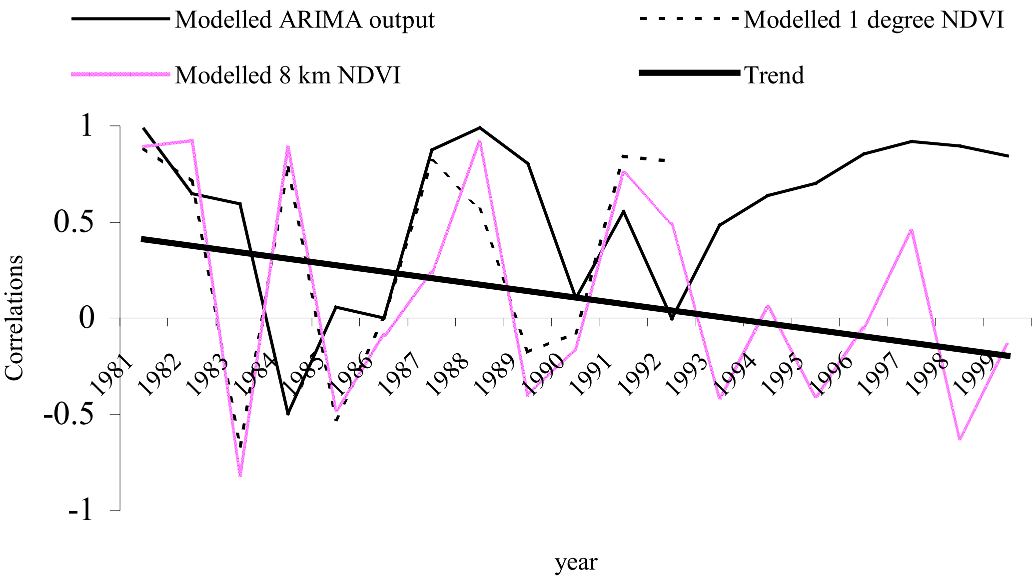

Figure 5: The time line of correlations for the interannual derivatives of the NDVI series and the ARIMA output series against the interannual derivative of the SOI series.

DISCUSSION

A methodology for analysing the sensitivities of vegetation to interannual climatic disturbances is outlined in this presentation. The processed NDVI and SOI time series show significant correlations in the pre 1993 period, suggesting a teleconnective relationship between the ENSO mechanism and terrestrial vegetation processes with a general response delay time of the order of 4 - 6 months. This relatively slow response can be explained by changes in the internal physiology of vegetation components as a result of ENSO forcing and the sensitivity of the NDVI to these changes. The behaviour of the terrestrial system in the post 1993 period contrasts strongly with previous periods. Vegetation processes (as expressed via NDVI values) seem to be relatively static to ENSO perturbations post 1993. A hypothesis that the terrestrial vegetation has become less sensitive to ENSO perturbations is suggested. This is supported by the results of the ARIMA simulation assuming a null hypothesis scenario. Correlative relationships between vegetation activity (NDVI values) and ENSO show a decreasing trend over the whole of the period of investigation. Suggesting that the vegetation is becoming less sensitive to the ENSO perturbations. It is seen that the seasonal cycles of the vegetation are not affected despite disturbances to the system in the interannual scale. From a terrestrial ecological perspective vegetation processes exhibit behaviours that are known as periodic (or seasonal) with repetition at regular time intervals (Chapman and Driver, 1996). Behaviour that is fluctuating yet periodic is accepted to be an indicator of dynamic equilibrium, an end state in which no further large scale change is anticipated (Coveny and Highfield, 1990). Therefore it can be argued that the seasonal cycles of the vegetation contribute to the processes of the system as a whole and have actively contributed to the system becoming less sensitive to the interannual climatic variablities. A full discussion of these arguments is beyond the scope of this paper.

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