CHARACTERISATION OF THE DYNAMIC RESPONSE OF THE VEGETATION COVER IN SOUTH AMERICA BY WAVELET MULTIRESOLUTION ANALYSIS OF NDVI TIME SERIES

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ABSTRACT

The use of temporal records of vegetation properties oriented to understand the influence of weather and climate ecosystems has been a traditional research technique. Vegetation is an extremely sensitive indicator of changes in many factors of the environmental behaviour such as climate, soil and land management. Since the availability of long records of satellite observations has become easier to researchers the challenge to monitor the vegetation behaviour and to correlate it with the climate process has influenced recent remote sensing studies. A well-known parameter accepted by researchers of the remote sensing community for the study of vegetation is the normalised difference vegetation index (NDVI).

The methodologies aiming at the study of vegetation temporal dynamics attempt to measure the amplitude, periodicity, or any other temporal variation of the vegetation index. One of the most appropriate tools for the study of the dynamics of any system is Fourier transform. It became a more attractive tool particularly after the development of the fast Fourier transform (FFT) algorithm. In the last decade a new tool, known as wavelet transform (WT) has made its appearance for the study of stationary and non-stationary signals.

The purpose of the present study is to point out some particular features of the wavelet transform that can be used to characterise the dynamical behaviour of the NDVI time series. The final goal of this work is to study the dynamical behaviour of the vegetation cover in some regions of South America by using monthly NDVI data and wavelet transform (WT) techniques as a mathematical tool.

1. INTRODUCTION

The use of temporal records of vegetation properties oriented to understand the influence of weather and climate ecosystems has been a traditional research technique. Vegetation is an extremely sensitive indicator of changes in many factors of the environmental behaviour such as climate, soil and land management. Since the availability of long records of satellite observations has become easier to researchers the challenge to monitor the vegetation behaviour and to correlate it with the climate process has influenced recent remote sensing studies. A well-known parameter accepted by researchers of the remote sensing community for the study of vegetation is the normalised difference vegetation index (NDVI).

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The main source of information used in this work is a set of 114 NDVI/GAC images collected by the AVHRR sensor on board of NOAA satellites during 9.5 years (January 1982 to June 1991). The methodological approach employed in this study attempts to make use of the wavelet transform (WT) techniques for the analysis of NDVI time series. The set of NDVI data provides us with temporal information. The present study is an extension of a previous work on NDVI time series analysis using Fourier transform and facing the problem of locating and mapping areas of similar dynamical behaviour of the vegetation in South America (Menenti et al.., 1991).

The outcome of the CWT process is a two-dimensional graph, called the scalogram, which represents the magnitude the wavelet coefficients occurring at different times and scales and in which is relatively easy to observe the moment when any disturbance or separation of the "normal" behaviour occurs. The magnitude of the wavelet coefficients represents its importance. The visualisation of changes in the magnitude of the wavelet coefficients is an easy matter when they are enhanced by colour or grey levels. But, on the other hand, it is a hard task to choose a parameter that clearly describes the appearing changes on the graph. In this work the variance of the coefficients magnitude was considered a practical indicator of their importance. This parameter can be used for the characterisation of the temporal behaviour of the time series and the localisation of disturbances appearing in some cases.

2. MATERIALS AND TOOLS

2.1. Data and Area of Study

The input data for this study are 114 NDVI (AVHRR/GAC) images corresponding to 9.5 years (1982, 1993, ..., 1991 Jan. to June) of South America. These images are 1024 columns x 1280 raws in size.

Table 1, Geographical location of 10 time series in South America

Time series on	Geographical Location
Sector 1	Brazil, North Manaos
Sector 2	Brazil, South of Teresinha
Sector 3	Brazil, North of Rio de Janeiro
Sector 4	Peru, North of Lima
Sector 5	Bolivia, South East of the country
Sector 6	Paraguay, North
Sector 7	Uruguay, North of Montevideo
Sector 8	Chile, centre of the country, near Talca
Sector 9	Argentina, province of Córdoba
Sector 10	Argentina, province of Buenos Aires

In order to reduce the high amount of data provided by the NDVI images and taking into account the above mentioned objective, the present study makes only partial use of the available data. To this end, only 10 arbitrary sectors of South America were chosen. Each sector, measuring 32 x 32 pixels, is represented by the average values of that area. Consequently, the data for this work are 10 time series of 114 points (months) in length.

Before applying the CWT, the time series were "cleaned up" removing some outliers. The sequences are also detrended in order to avoid the appearance of "end effects" in the transformed series. In order to get a dyadic length; the length each sequence has been extended from 114 to 128 points. The additional points are assumed to be the average values of the last 3 years. In Table 1 we have the location of the 10 arbitrarily selected sectors in South America. These sectors are numbered 1 to 10. In order to display only 10 years of the results, each time series length was reduce to 120 months after the CWT operation.

2.2 Wavelet Transform

The French scientists Grossmann and Morlet introduced wavelets in the late 1980's as functions whose translations and dilations can be used a basis for expansions of other functions. Morlet, a geophysicist, called these functions "*wavelets"* (little waves). Wavelets are functions generated from one single function ?(x), called *mother wavelet*, by its dilations and translations. Daubechies (1990, 1992) showed that these functions ? are orthonormal bases of $L^2(R)$, which is the vector space of the measurable, square integrable 1-d functions *f*(x). In the one dimensional case, this family of functions can be expressed as,

$$\psi_{a,b}(x) = \frac{1}{\sqrt{|a|}}\,\psi\left(\frac{x-b}{a}\right) \qquad a,\, b \in R \quad a > 0 \tag{1}$$

In equation (1) a is an scaling, or dilation, parameter while b is a shift or translation parameter.

The *mother* wavelet has to satisfy

$$\int_{-\infty}^{\infty} \psi(x)\,dx = \hat{\psi}(0) = 0 \tag{2}$$

where $\hat{\psi}(\omega)$ is the Fourier transform of ?(x). The condition on ?(x) given by (2) implies at least some oscillations. This condition, known as *condition of admissibility,* can also be expressed as in (3).

$$C_\psi = \int_{-\infty}^{\infty} \frac{|\hat{\psi}(\omega)|^2}{|\omega|}\,d\omega < \infty \tag{3}$$

The shift parameter b in $\psi_{a,b}(x)$ gives the position of the wavelet; while the dilation parameter a, governs its frequency. The definition of wavelets as dilates of one function means that high frequency wavelets correspond to $a < 1$ or narrow width, while low frequency wavelets have $a > 1$ or wider width.

Fig. 1 shows two examples of wavelets: in (a) we have the Mexican hat wavelet, which is used in continuous wavelet transform. In (b) we have the popular Daubechies wavelet which is very used in discrete wavelet transform. Both wavelets were respectively used in our CWT and DWT applications.

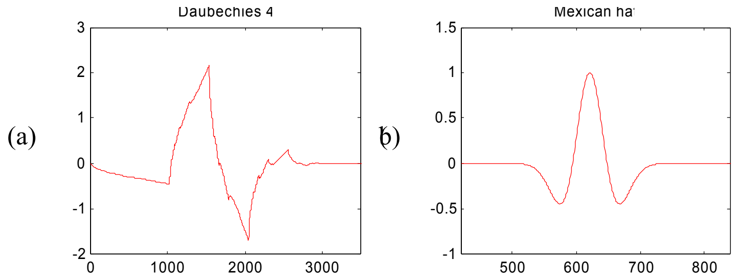

Fig. 1.- (a) Daubechies wavelet (D4), (b) Mexican hat wavelet

In practice, computation of f is carried out as a discrete operation, using sum rather than integral. The Discrete Wavelet Transform (DWT) is an extension of the wavelet series for finite-length discretized signals in a way analogous to the Discrete Fourier Transform. The DWT is applicable to sampled continuous time signals. It is derived by quantizing the scale and the shift parameters. As with the CWT, it decomposes a function into a series of wavelet basis functions which are dilated and translated.

In this case, the coefficients $c_{m,n}$ can be written,

$$c_{m,n} = \langle \psi_{m,n}(x), f \rangle = \int \psi_{m,n}(x) f(x)\,dx \tag{4}$$

where

$$\psi_{m,n} = 2^{-m/2}\,\psi(2^{-m}x - n\,b_0) \tag{5}$$

The wavelet coefficients in (4) represent bandpass-filtered versions of the original signal (Vetterli and Herley, 1992).

3. EXPERIENCES AND RESULTS

3.1. Continuous wavelet transform

The methodological approach used in this presentation intends to demonstrate the usefulness of the wavelet transform by applying it to a set of 10 NDVI time series and discussing the results observed in their respective scalogram. When a CWT is applied to a 1-dimensional time series a 2-dimensional diagram is obtained. This diagram, which is called "phase plane" or *scalogram*, represents the magnitude of the wavelet coefficients having the time-scale in ordinates and the time in abscissa. Each point in the scalogram represents the magnitude of the wavelet coefficient corresponding to the respective time and time-scale. Wavelet coefficients are a measure of the intensity of the local variations of the signal for the scale under consideration. The value of a coefficient will be large when the dilated wavelet is close to the scale of the heterogeneity in the signal. The value of a coefficient is small when the local signal is smooth for that particular scale. Hence, the value of a coefficient for a particular location and at any scale can be understood as a characterisation of the dynamical behaviour of the signal at that specific time and for a given time-scale (or time resolution). For example, the "earlyness" or lag of a crop, as well as periodicity of a signal, can be directly visualised in the *scalogram* or phase-plane of the time-series.

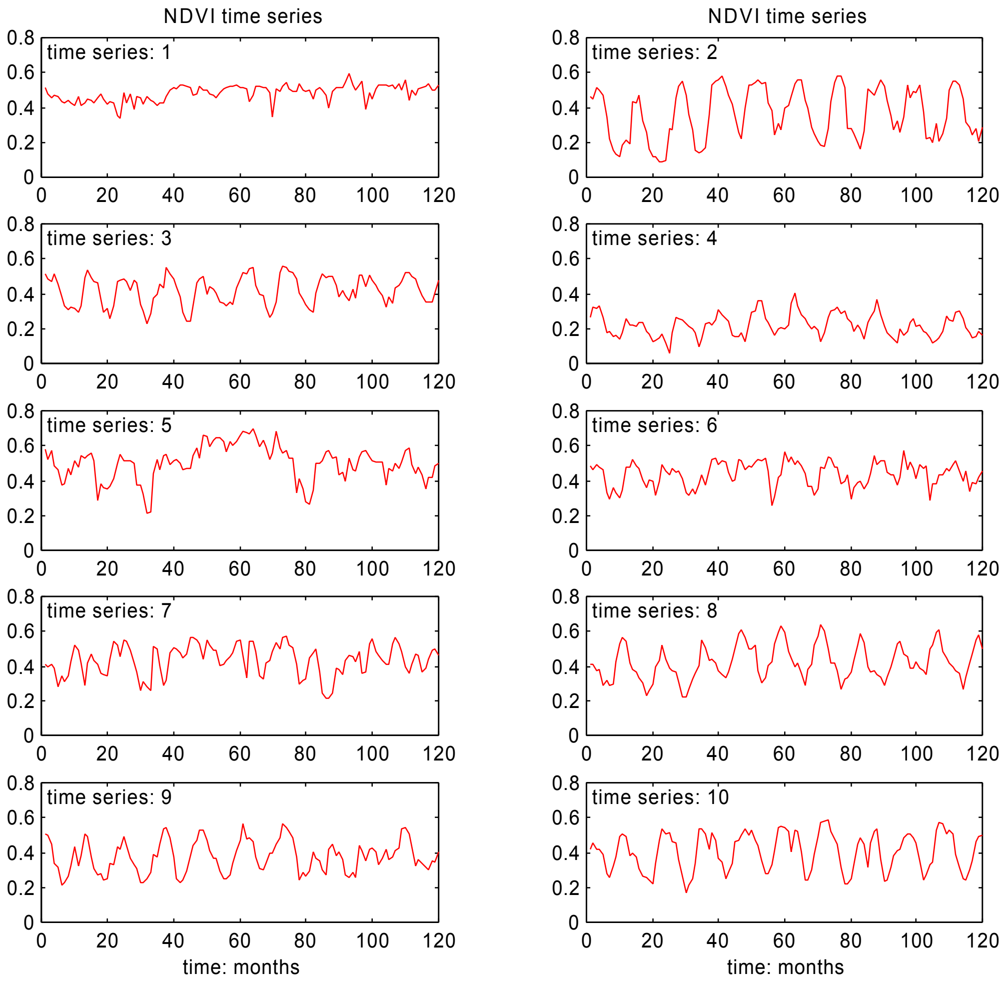

Fig. 2.- Ten NDVI time series corresponding to the 10 sectors of Table1

Fig. 2 shows the 10 NDVI time series selected from the respective points in the South American continent. In order to show the information provided by Fourier transform a FFT has been applied to each of the time series under study. In Fig. 3. We can see the absolute value of the first 30 alternate component of the Fourier transform carried out on the 10 time series. Two scalograms obtained as a result of applying the CWT to the time series 1 and 2 appears in Fig.4.

The time-scale units of the scalograms (ordinates) in Fig. 4 are given in months and the time coordinate units are in years. This means that the yearly component of the vegetation dynamics can be observed in the time-scale coordinate of 12 months. Each graphic represents 10 years of NDVI behaviour in the corresponding sector.

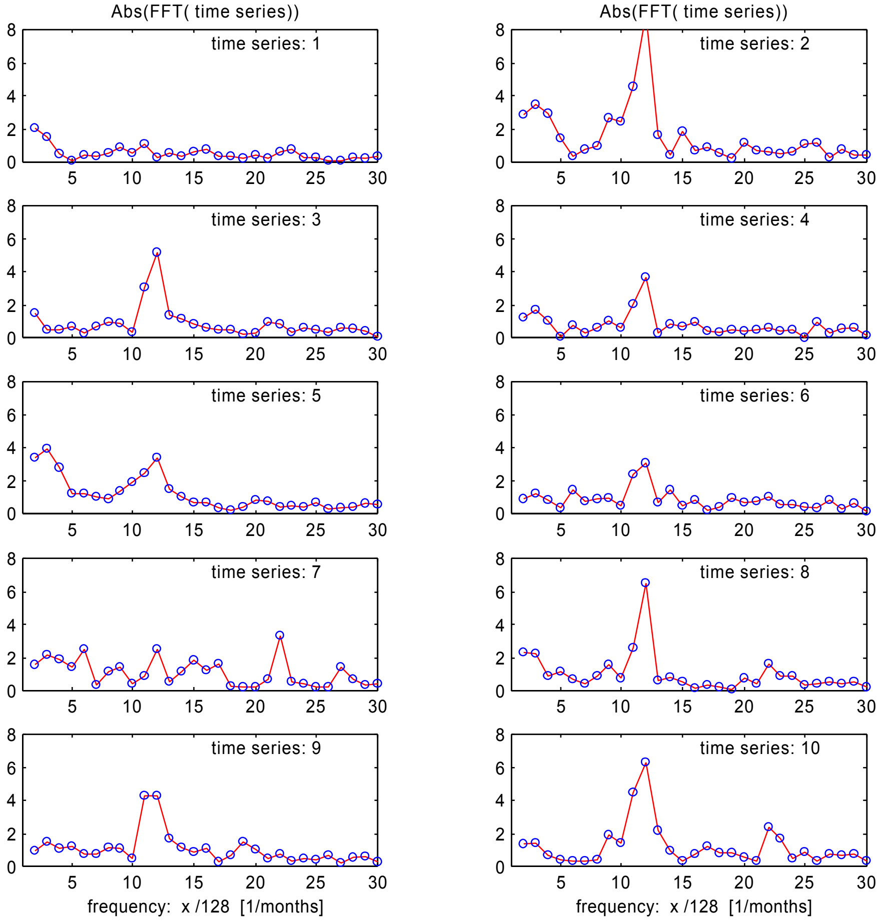

Fig. 3.- Absolute value of the Fourier transform carried on the 10 time series of Fig. 2

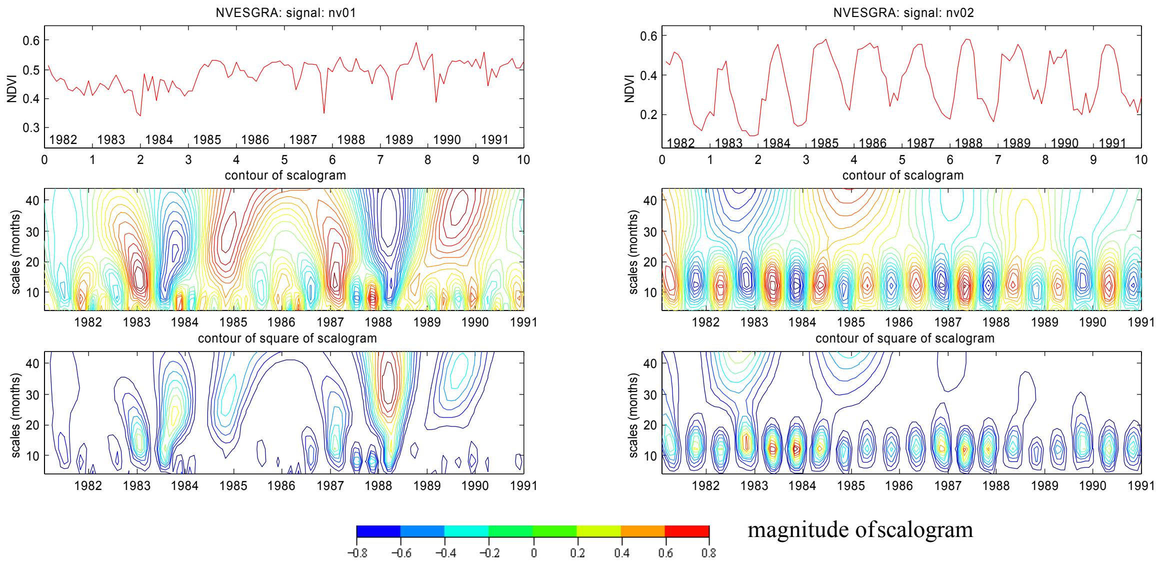

Fig. 4. Scalogram of time series 01 (left) and time series 02 (right). From top to down we have the signal, the scalogram and the square of scalogram

The relative magnitude of the wavelet coefficients is represented in colours: red represents positive values, blue negative values and green can be considered mean values. In this figure is clear to see the nearly perfect periodical behaviour some time series occurring at scale 12 months. Sectors 2, 3, 8, 9 and 10 present a regular periodical behaviour with a time period of 12 months. This regularity is not present in other sectors whose periodicity is "broken" during some years. One important point to remark here is that although periodicity can be well detected by Fourier Transform (Fig. 4), . But they do not show to see some discontinuity of that periodicity as can be clearly shown by the scalogram.

The CWT was applied to each of the 10 time series shown in Fig. 2 using a C-language programme which performs a convolution between the dilated and shifted Mexican hat wavelet and the time series to be analysed. One of the main features of the scalogram, and furthermore one of the most simple to obtain, is the variance measured in each scale. With our programme the information on the variance, or standard deviation of the scalogram was simultaneously obtained with it.

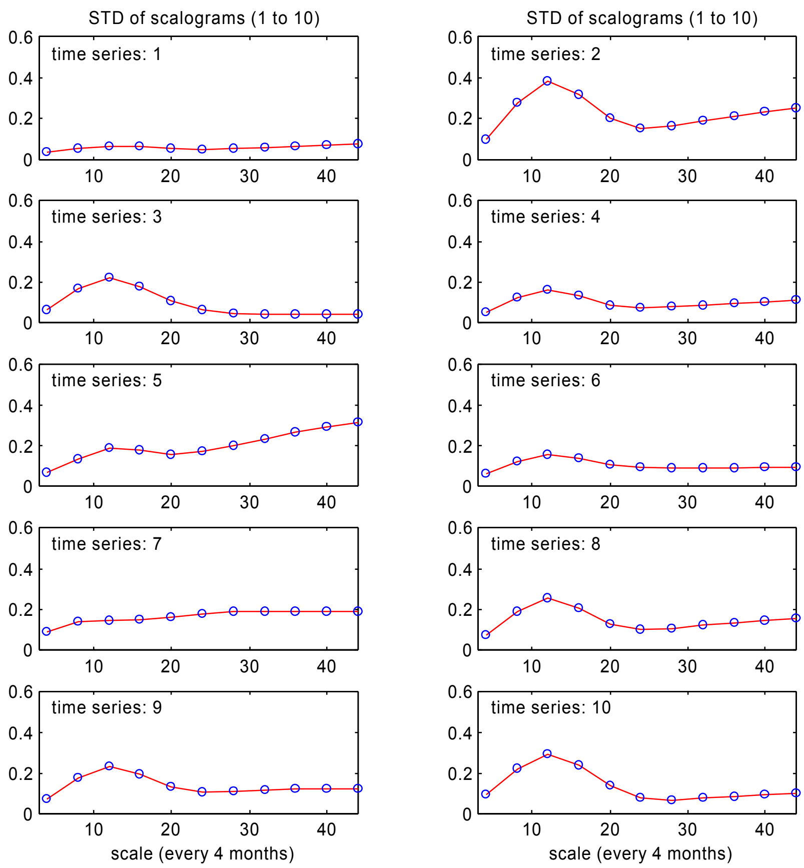

Fig. 5.- Standard deviations corresponding to the 10scalograms in Fig. 5

Fig. 5 shows the standard deviation of each scalogram. It shows different magnitudes at different scales. It is easy to see that almost all the curves exhibit a maximum about the 3rd scale step (i.e. months 12) which represents the yearly cyclic behaviour of some vegetated areas, only times series corresponding to sectors 1 and 7 have an almost flat appearance. These sectors correspond respectively to rain forest in Brasil, near the Equator, (no seasonal variations) and in Uruguay where the variation of NDVI signal is important but with a higher frequency (twice a year), therefore, the standard deviation curve is more distributed along different scales. This behaviour of the NDVI can obey a special soil management or a particular crop in that area. The presence of high frequencies in time series 7 can be clearly observed in the signal itself and in the Fourier transforms (Fig. 3).

Being the annual periodicity of the NDVI one important feature for charaterising some type of natural vegetation or crops, it is of great importance to take into account the strong correlation between the annual component of the Fourier spectrum and the amplitude of the standard deviation obtained from the scalogram. This property is clearly seen in Fig. 6.

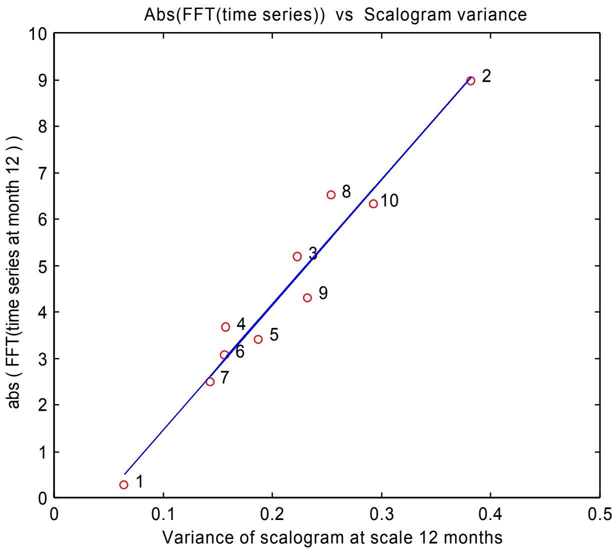

Fig. 6.- Correlation between the FFT (12 months) and the STD scalogram

3.2. Discrete Wavelet Transform

ion of the discrete wavelet transform was also considered in our study in order to see its potentiality for characterisation of the vegetation dynamics. Many wavelets can be used for performing this operation. In our case we used the Daubechies 4 wavelet which is shown in Fig. 1b.

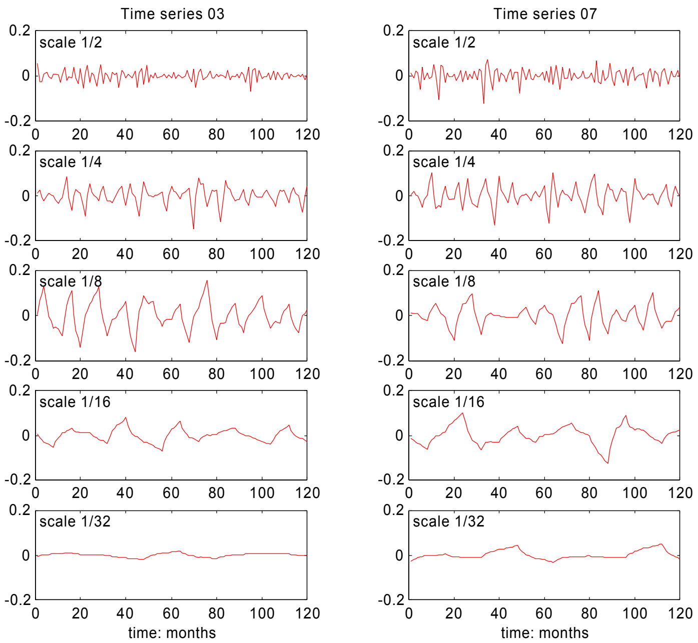

Fig. 7.- Details at 5 time-scales of time series 3 and 7 after applying the discrete wavelet transform (DWT)

As a result of applying one step of DWT to a 1-D signal, two resulting signals are obtained: one is called the "smooth" (low frequency or low resolution signal) and the other is called the "detail" (the high frequency component of the original signal). If, for example we are interested in studying fast temporal changes, we have to analyse the high frequency component or detail. In Fig. 7 we can observe the details of two of our time series, 3 and 7, as seen at 5 time scales. The details here observed are obtained as a result of application of 5 steps of DWT to the time series and reconstructing the detail corresponding to the respective scale.

It is useful to observe that being the two series different between each other, two different results are obtained. Different magnitudes of details at different scale levels and at different times are observed. Applying the absolute value or squaring the detail values we can have an idea of the "energy" corresponding to those two time series concentrated at different times and in different amounts. All this information can be associated to different factors affecting the NDVI dynamics at the geographical location under study. This is by now an open problem for us, and efforts will be conducted to take advantage of this property of the DWT.

4. CONCLUSIONS

The location and mapping of vegetation areas with similar dynamical behaviour has been of great importance in the study of NDVI time series. Very important results has been obtained by means of the application of Fourier transform to AVHRR-NDVI time series of South America. This report intends to demonstrate some advantages obtained by the application of the continuous wavelet transform (CWT) and discrete wavelet transform (DWT) for the characterisation of vegetation dynamics in comparison to the clasical Fourier transform.

In this work only 10 sectors at selected points of the area of interest were considered. The results obtained in our experiences show a good correlation between the data provided by Fourier transform and the wavelet transform with the addition of the localisation property. Further studies are foreseen in order to apply this approach to the complete South American region

The analysis of the results shows that the application of the wavelet transform to the analysis of time available data are a practical demonstration of the usefulness of this technique for the study of non-stationary time series which are typical in Earth sciences applications. The main advantage of wavelet transform as compared to Fourier analysis is its localisation property. In this sense, WT can be considered a complementary and useful tool to be used in the dynamical behaviour of the vegetation besides Fourier techniques or statistical approaches.

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