ATMOSPHERIC-OCEANIC INFLUENCE ON INTERANNUAL LENGTH-OF-DAY VARIABILITY LINKED TO EL NIÑO/SOUTHERN OSCILLATION

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Variations in the rotation rate of the Earth, or equivalently in LOD (Length-Of-Day), consist in a number of free and forced oscillations superimposed on a "red noise" background (Eubanks, 1993). They are important quantities closely related to many geophysical phenomena. On a time scale longer than or about 10 years, it is usually accepted that the secular variation and the decade fluctuation are caused by core-mantle coupling and tidal energy dissipation (Lambeck, 1980).

On time scale of about one year and shorter, the seasonal and short-term variations (including annual and semiannual components) have been established beyond any doubt to be caused by meteorological and solar lunar tidal effects. Many authors (Barnes et al., 1983, Rosen and Salstein; 1983, Chao, 1988, 1989; Dickey, 1989,1993) have been confirmed the relationship between seasonal LOD variations and variations in the polar component of the atmospheric angular momentum.

A less studied spectral band takes into account LOD variations in the time scales shorter than 10 years and longer than 1 year. These kinds of variations are usually called interannual components. It is well accepted that they are linked to El Niño–Southern Oscillation (ENSO) atmospheric global-scale events (Stefanick, 1982; Chao, 1984).

El Niño (EN) effect historically refers to a massive warming of the coastal waters of Peru and Ecuador. Unusual warm temperatures in the equatorial Pacific Ocean characterize it.

In normal non-El Niño conditions cool water is typically observed in the eastern part of the tropical Pacific Ocean (phenomenon called "cold tongue").

Cold tongue temperatures vary seasonally being warmest in the northern hemisphere springtime and coolest in the northern hemisphere fall. El Niño can be thought as an exaggeration of the usual seasonal cycle (TAO project, 1998).

During typical El Niño conditions, warm water spread from the eastern Pacific Ocean towards the east (in direction to South America). The "cold tongue " became weak and the usually weak winds in the western Pacific blow strongly towards the east pushing the warm water (TAO Project, 1998).

El Niño phenomenon is fairly well known since long time ago, however the atmospheric component of ENSO phenomenon, the Southern Oscillation, is a recent discovery. Specifically, this effect consists in an oscillation in surface temperature between southeastern tropical Pacific and Australian-Indonesian regions (Cane, 1992).

The Southern Oscillation Index (SOI) is a measure of the strength of tropical Pacific atmospheric circulation, based on sea level pressure difference between Tahiti (French Polynesia) and Darwin (Australia). Low SOI is associated with weaker than normal trade winds and El Niño conditions (Chao, 1984; TAO Project, 1998).

The strong connection between SOI and Sea Surface Temperature (SST) is immediately apparent: when the waters of the eastern tropical Pacific are abnormally warm (El Niño event) sea level pressure drops in the eastern Pacific and rises in the west (low SOI) (Cane, 1992).

Through MEM spectral analysis, we will be able to evince an unexpected feature of the ENSO phenomenon due to the presence of at least two La Niña episodes during the last

10 years. For that, the oceanic influence might cause a light departure in LOD variability from the classical 36-month period associated with the life cycle of individual atmospheric ENSO event (Black et al., 1996).

DESCRIPTION OF THE DATA

We utilized a 3811 days long LOD time series in the period January 1988 - June 1998 from the EOP C04, daily combined series of Earth Orientation Parameters from the IERS (International Earth Rotation Service). Our goal is an interannual LOD time series to examine empirically the relationship between ENSO and interannual LOD variations. To perform it, we removed well-known long and short-period variations trying do not damage the interannual signal as follows:

First at all, we removed the tidal effects produced by the gravitational attraction of the Sun and Moon predicted in the model of Yoder (Yoder et al., 1981). Nevertheless, annual and semiannual components are particularly strong and therefore hard to remove. Thus, we modeled long period (decade) and remaining seasonal variations as in LOD as a sum of sine functions. The parameters were estimated using a least-squares adjustment.

We then subtract from LODR time series the estimated sum obtained above. The resultant is called interannual LOD series. Finally, in order to perform the cross-spectral analysis, we averaged the interannual signal in monthly values.

Analysis were performed using SOI data as well as four regional SST data sets: El Niño 1+2 (SST1-2 in the successive) includes observational data from the area 0° to 10° S and 90° W to 80° W, El Niño 3 (SST 3) extends from 5° N to 5° S and 150° W to 90° W, El Niño 4 (SST4) takes the same belt in latitude but extends from 160° E to 150° W and finally El Niño 3.4 (SST 3.4) spans the area from 5° N to 5° S and 170° W to 120° W.

The SST and SOI series are provided by the Climate Prediction Center (CPC) of the National Center for Environmental Prediction (NCEP). They were taken along the same period as LOD but they provide only one data per month.

SPECTRAL ANALYSIS

The maximum entropy method for spectral analysis was first suggested by Burg in 1967. Its application to problems of geophysical and astronomical interest has met with considerable success due to the advantage of being able to find sharp spectral peaks where other classical methods fail (Andersen, 1974; Marple, 1987).

Since its outset, MEM has been a tool in the development of parametric or modeling approaches to high-resolution spectral estimation. The maximum entropy spectrum is very closely related to autoregressive (AR) spectral analysis. In fact, MEM and AR power spectral density are identical for Gaussian processes and a known autocorrelation sequence of uniform spacing (Marple, 1987).

The MEM estimates the power spectral density (PSD) function after determining a set of model coefficients based on a procedure to obtain AR spectral estimates.

When the appropriate AR model is not known, many different orders must be tried and compared for to select a suitable order. To carry it out, we compute the first error criterion developed by Akaike (1969) that indicates which model to choose. It is called final prediction error (FPE). According to the principle of parsimony, the order selected is the one for which FPE is minimum (Jones, 1976; Marple, 1987).

FPE criterion was used to search the wright order before applying MEM for power spectra estimation. The FPE plot as a function of the length of the autorregresive process involved is shown in Figure 1.

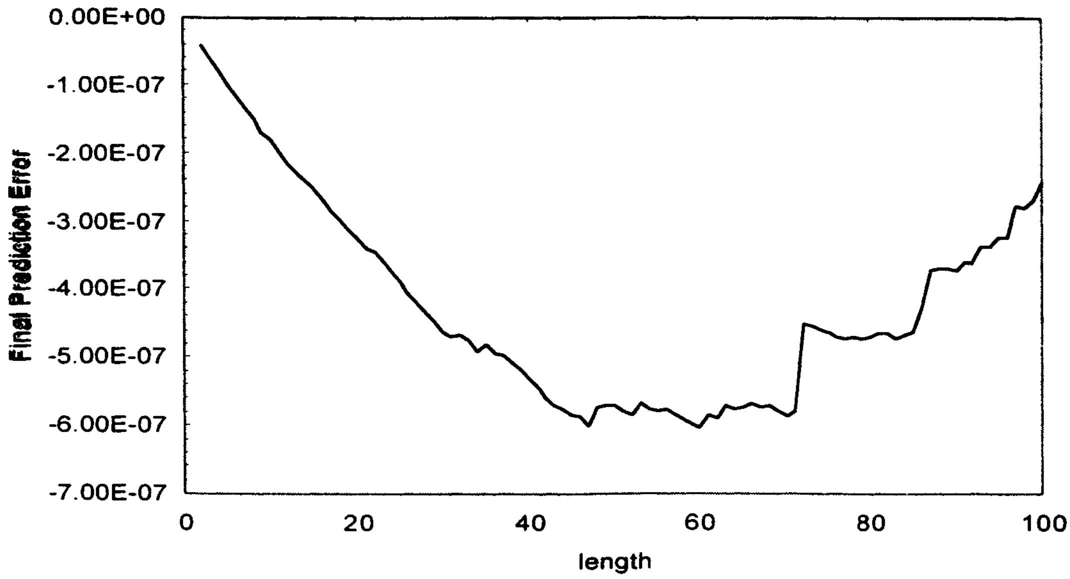


Figure 1. Final Prediction Error of the autoregressive process computed for LODR series

Power spectral density values for different autorregresive orders are given in Table 1. Note that when the order for the AR process is increasing, the power spectrum estimates becomes rough and both, wide and heights of the spectral peaks change dramatically. Nevertheless, in this case amplitudes for the principal components remains being almost the same values.

Table 1. Power spectral density values estimated from the maximum entropy method apply to LODR. Only 32-month and 2.1-month period is considered. These values correspond to different AR orders between 31 and 100. Optimal values in the sense of FPE criterion are highlighted.

	AR order	31	*60*	83	100
32-month	PSD (dB)	-7.56	***-2.8***	-5.25	-4.48
	A (mas.)	63.5	***65.7***	63	61.6
2-month	PSD (dB)	-1.1	***2***	-8.74	-6.1
	A (mas.)	250.4	***250.5***	213	234

Interannual LOD series was utilized as input data in the calculus of the power spectral density function using MEM method. The corresponding power spectrum shown in Figure 2 a. The interpretation of this plot needs some care and has rather a qualitative character for the following reasons: 1) even large values of MEM PSD do not necessarily mean an important excess of power in the true PSD function and 2) it is difficult to estimate the detected spectral peak "by eye" because the relative height of two peaks says nothing about the relative amplitude (Brzezinski, 1995).

This draw exhibits important peaks expressing: a 32-month period component and three other peaks in 63, 69 and 116 days. Despite 63 and 69 days are very close, we neglect the possibility it might be the same peak because the same feature appears in different AR orders.

Once the maximum entropy coefficients of $\hat{P}_{MEM}(f)$ have been estimated, we can derive the corresponding integrated power spectrum estimation in order to calculate the mean amplitude of oscillation. Amplitude definition depends on the choice of the arbitrary edge frequencies and is exactly valid in the case of a harmonic term.

Numerical values of these parameters at the highlight peaks of the power spectral density estimated by MEM are shown in Table 2.

Table 2. Significant peaks of the maximum entropy power spectra applied to LODR. These values correspond to 60 in AR order and they are optimal in the sense of final prediction error (FPE).

Frequency (cpy)	0.38	3.14	5.32	5.8
Period (months)	32.02	3.88	2.29	2.1
PSD (dB.)	-2.8	-6.9	-7.3	2.
A (mas.)	65.7	110.6	145.4	250.5

We also applied MEM algorithm to estimate maximum entropy cross power spectrum following Brzezinski's (1995) procedure to compare interannual LOD time series, Southern Oscillation Index (SOI) and Sea Surface Temperature (SST) time series respectively.

In order to implement the procedure some assumptions have been made. The two series we want to compare must be a representation of two stationaries in the wide sense, zero-mean stochastic processes. Obviously, both are taken in the same temporal limits and have to be sampled at the same time interval.

Although all our time series are real-valued, CSD is a complex quantity by definition. It can be proved (Ulrych and Jensen, 1974; Brzezinski, 1995) that the cross power spectrum of a given two series z_1 and z_2 can be obtained as a combination of the power spectra of z_1, z_2 and two auxiliary series $\bar{z} = z_1 + z_2$ and $\tilde{z} = z_1 + i z_2$ as

$$P_{z_1 z_2}(f) = \frac{1}{2}\left\{\left[P_{\bar{z}}(f) - P_{z_1}(f) - P_{z_2}(f)\right] + i\left[P_{\tilde{z}}(f) - P_{z_1}(f) - P_{z_2}(f)\right]\right\}$$

where f refers to the frequency $f \in (0, f_N)$ for two real-valued time series and f_N is the Nyquist frequency. Hence combining these four MEM PSD functions, we obtained the MEM Cross Power Spectrum Estimation $\left(\hat{P}_{Z_1 Z_2}\right)$.

RESULTS

An estimation of the power spectral density function using MEM was performed according with the procedure described above, on SOI data. Correspondingly, we used the same value for the autoregressive process involved using the FPE criteria. This condition is also necessary to perform the cross-spectral estimation by MEM in order to compare the behavior of both as a function of the frequency into the same spectral window.

Three important peaks can be identified both in the individual power spectra density function (figure 2b) and in the cross–power spectrum (figure 2c) with different amplitudes. Some numerical results are given in Table 3.

Table 3. Power spectral density values (in dB) estimated from the maximum entropy method applies to interannual LOD and Southern Oscillation Index (SOI). All these values correspond to 60 in AR order and they are optimal in the sense of final prediction error (FPE).

Peaks in common (months)	LOD free	SOI
32	-2.80	61.70
3.88	-6.93	---
2.29	-7.30	74.20
2.1	-9.22	64.00

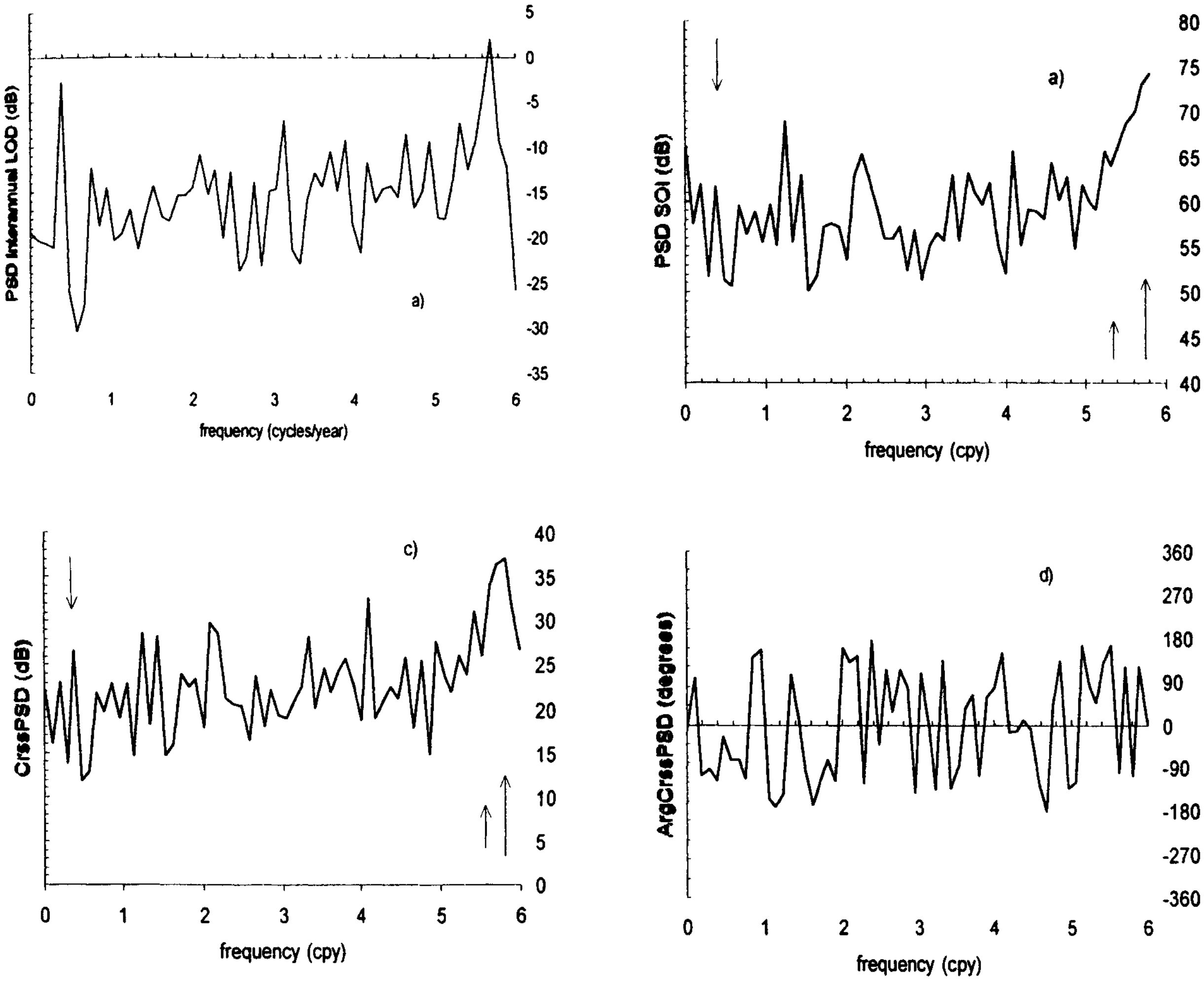


Figure 2. MEM Power and Cross-Power Spectrum of interannual LODR series and SOI series. Units of PSD are decibels.: a) Power Spectrum of the LODR, b) Power Spectrum of SOI, c) Cross Power Amplitude Spectrum, d) Cross Power Phase Difference Spectrum. Arrows indicated remarkable peaks in both.

Comparing SOI with interannual LOD, the phase difference is on average about 108 degrees. Many authors have related interannual LOD variation with ENSO as its excitation mechanism. Consequently, we expected to find such agreement from the comparison between LOD and SOI only for periods upper than 1 year. This event is shown in the 32-month period peak in both PSD functions. This result is relatively close to the primary oscillation period of 36 months for the Angular Atmospheric Momentum (AAM), with phase strongly linked to ENSO phenomena (Black et al., 1996).

In order to identify possibly distinct sources or confirm ocean-atmospheric influence on interannual LOD variations, the NCEP SST data were analyzed separately with some detail for regions along the tropical Pacific Ocean corresponding to the data sets previously defined as SST 1-2, SST3, SST4 and SST3-4 (D. Salstein, personal communication, 1998). Numerical values of the PSD function by MEM are given in Table 4.

Table 4. Power spectral density values (in dB) estimated from the maximum entropy method applied to interannual LOD and Sea Surface Temperatures (SST) in different regions along the tropical Pacific Ocean. All these values correspond to 60 in AR order and they are optimal in the sense of final prediction error (FPE).

Peaks in common (months)	LOD free	1+2	3	4	3. 4
32	-2.80	46.64	42.42	36.67	42.36
3.88	-6.93	63.13	54.85	49.6	36.91
2.29	-7.30	67.2	59.89	49.42	59.05
2.1	-9.22	76.28	71.28	70.73	71.16

Again, despite 63 and 69 days are very close peaks, we neglect the possibility that they be the same peak due to the fact that the same feature appears in different AR orders. In addition, all remarkable peaks between 40 and 60 days can be attributed to the Madden-Julian oscillation (Madden, 1987). However, one unexpected peak rises in the 4-month period for LOD. Such a peak can not be explained as a residual in the interannual LOD time series building because SOI and SST series have not any processes at all besides MEM application.

Cross-power spectrum values on different regions where SST is available are plotted in figure 3, where also LOD power spectral estimates are given to contrast. The phase difference between interannual LOD and different regional SST data sets is about 122 degrees on average.

Although large values of MEM PSD function do not necessarily mean a real important excess of power in the true spectrum (Brzezinski, 1995), a fairly good agreement was reached in both comparisons.

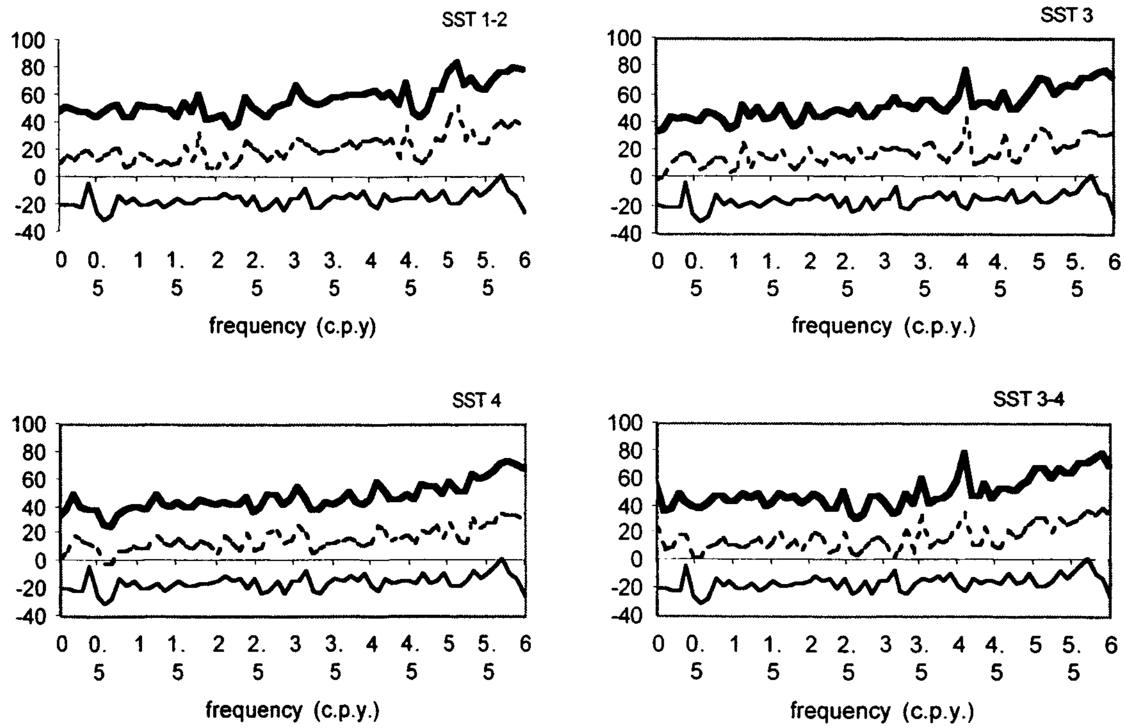


Figure 3. MEM Power spectral estimates of interannual LOD (solid line) and SST (bold solid line) in regions 1-2, 3, 4 and 3-4 respectively. The Cross-Power Spectra estimate (dotted line) is also shown. Units are dB.

Classical Power spectra was also used to compare time series of interannual LOD and its atmospheric-oceanic inferred excitations. We operate directly on the data sets yielding a PSD estimate. Such a periodogram uses a Hamming window to reduce the side lobes in the spectral estimate. In order to produce a statistically stable spectral estimate, the data must be segmented into possibly overlapping intervals and the sample spectrum of each segmented averaged (Marple, 1987).

Over a total number of 128 samples, we selected 16 samples per segment and 10 samples to shift to the beginning to the next segment. These quantities were taken to reach an agreement between stability and spectral resolution. The results were smoothed using a Gaussian-shaped low pass filter with a window with in the time domain of about 43 months (full width to half maximum, FWHM).

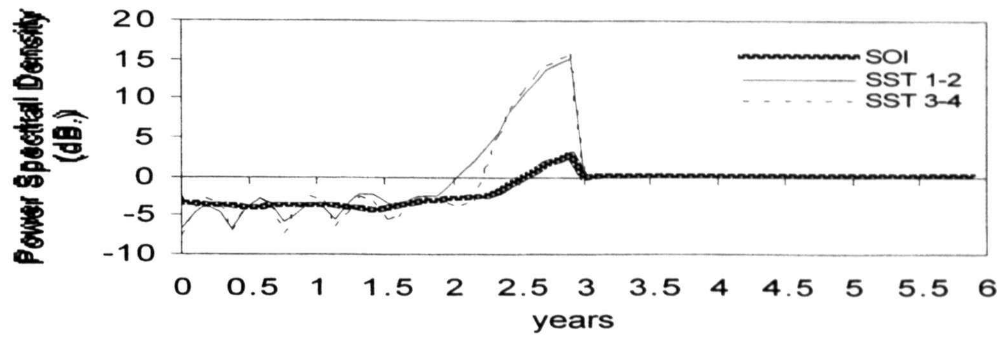


Figure 4. Power spectral density plot of SOI and SST in two different regions of the tropical Pacific Ocean for the period 1988 through 1998 after a low pass filtering.

A significant peak either in SOI and the regional SST spectra are found close to coincide with the 32-month peak showed above in the cross-power spectra by MEM. This is presented in Figure 4 when we plotted SOI and only two regional SST spectra. The peak is clearly seen if we plot the same data using a logarithmic scale (Figure 5).

CONCLUDING REMARKS

The maximum entropy method (MEM) has been widely applied for polar motion studies taking advantage of its performance on the management of complex time series. Despite mostly of the applications were developed to this field, MEM showed to be a powerful tool when it is used in real time series.

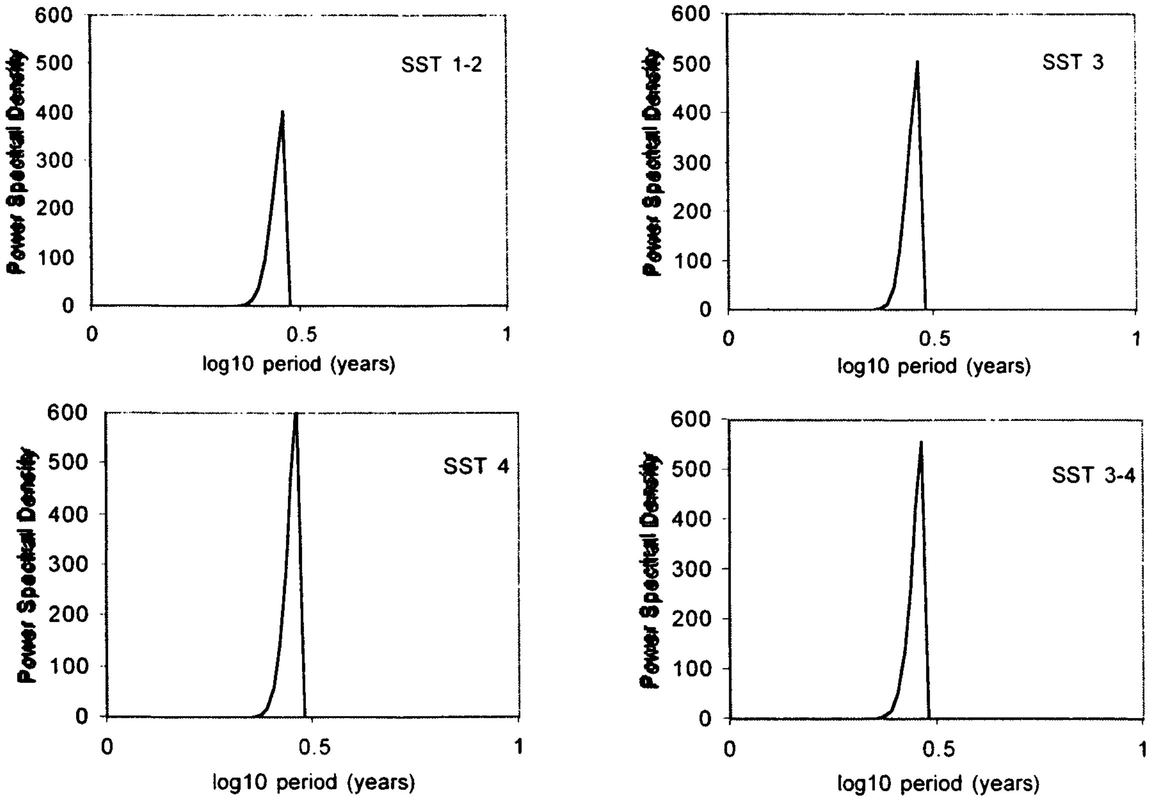
Estimations of the Cross-Power Spectrum density applying MEM were performed in order to compare LOD with SOI and SST time series, which are close related to El Niño-Southern Oscillation (ENSO) events.

Through that, we could evince a good agreement in the period of almost 32-month and 2-months whereas an agreement in unexpected periods of 4 months. This would be a non-predicted feature of the ENSO phenomena though the reasons that might cause this effect are yet under study.

The remarkable accordance we found near a 2-month period in all the data sets analyzed agrees well with the almost 50-day period fluctuations in LOD related to meteorological events (Langley et al., 1981). More specifically, we refer to the eastward propagating global scale Madden-Julian oscillation in the tropical troposphere. Such a phenomenon also has a characteristic period of 40 – 50 days and this feature is associated with observed large scale variations in pressure, wind and convective activity near the equator (Madden and Julian, 1972; in Eubanks, 1993).

Complete studies relating tropical winds, precipitation, SST an convective variations processes over the ocean, indicate than Madden-Julian oscillations probably result from tight coupling between wind and SST over equatorial regions of the eastern Indian Ocean and the western Pacific Ocean (Eubanks, 1993). Space geodetic data and meteorological data agreed very well during the hardest El Niño periods of 1982-1983. Because of that the 1982-83 El Niño event was associated with an increase in the power of the 40-50 days oscillation (Eubanks, 1993) although such a relationship is disputable (Gambis, 1992).

Even though a 36-month period is consistent with the time scales associated with the life cycle of individual atmospheric ENSO event (Black et al., 1996), the variation of about 32-month we found in interannual LOD series might be linked as well through the ocean



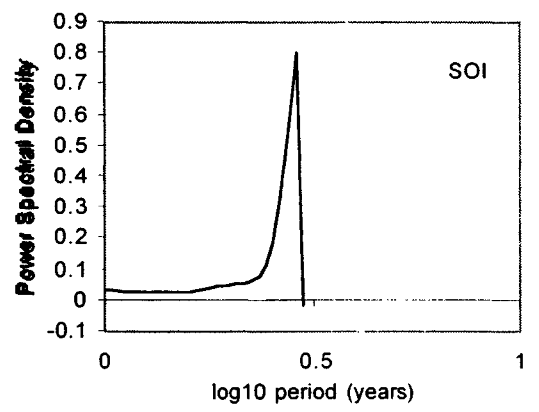


Figure 5. Log – linear spectral plot of SOI and SST along the tropical region of the Pacific Ocean for the period 1988 through 1998 after a low pass filtering; same as in Figure 5 .Note the agreement in frequency of the 33-month period.

mechanism that push this phenomenon. In fact, our data set includes not only three El Niño events (1991-92; 1993-94 and 1997-98) but also at least two La Niña events (1988 and 1995) (TAO Project, 1998).

El Niño and La Niña (or El Viejo) are opposite phases of ENSO cycle. La Niña events occur after some (but no all) El Niño phenomena and refer to the cold phase of ENSO. Unusual cold ocean temperatures in the equatorial Pacific characterize it (TAO Project, 1998).

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