On planetary torque signals and sub-decadal frequencies in the discharges of large rivers

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Abstract

We revisited dynamical aspects of the possible influence of solar inertial motion in the modulation of sub-decadal cycles in Po River in Europe and Paraná River in South America. That influence has been studied empirically, taking into account spectral concordances around $\sim 8$-yr periodicities on both the river flows and the so-called solar $T$ torque ($T = dL/dt, L=$ orbital angular momentum modulus). These studies showed an outstanding coherence between the absolute value of $T$ and the river discharges series, suggesting an intriguing relationship linked to solar system dynamics. In order to study this empirical relationship on physical grounds, we specified the relevant planetary dynamics related to these cycles, considering not only the $T$ torque, but also the vectorial nature of the planetary torque. We propose to analyse this relationship in a broader sub-decadal spectral band. Doing so, we found that the planetary dynamics involved in $|T|$, is governed by 6.56 yr, 7.86 yr and 9.92 yr periodicities, mainly related to Jupiter, Saturn and Neptune. We demonstrate that these cycles are caused by the variation of the

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vectorial torque strength. Analysing the discharge of Paraná River around this sub-decadal band from 1904 to 2012, we found the following significant spectral lines: 6.49 yr, 7.61 yr, 8.67 yr, and 10.45 yr. Then, taking into account the importance of the vectorial torque and searching for a possible physical mechanism linking planetary dynamics and Sun’s internal activity, we follow the evolution of the orbital angular momentum vector respect to the Sun’s spin axis of rotation, finding virtually the same Paraná River discharge peaks: 6.33 yr, 7.68 yr, 8.62 yr and 9.92 yr. This result is also relevant to the main spectral line of Po River discharges (8.2-8.7 yr), which is more related to that spectrum than $|T|$ spectral lines. Our more accurate solar system dynamics model shows, that if these rivers are physically related to solar barycentric motion, the vectorial nature of planetary torque is essential to capture their full concordances at sub-decadal scale. Moreover, taking into account that this new evidence is based on a possible solar spin-orbit interaction, this findings not only could improve the predictability of these river’s flows, but in turn, could be used as a proxy of a working solar spin-orbit interaction. We discuss key issues that need to be addressed in the future.

Keywords: Sun-planets interactions, solar barycentric motion and planetary dynamics, planetary forcing on climate, sun-rivers relationships (Paraná and Po Rivers)
1. INTRODUCTION

1.1. Background

The Sun’s influence on terrestrial climate as a forcing mechanism (i.e., an agency whose own dynamics has the ability to alter the energy balance of the climate system and therefore to produce climate variability) is not a new subject, and it has been studied for a long time (e.g., Humphreys, 1910, and references therein). The thermonuclear energy produced in the solar nucleus travels outward interacting with the outermost Sun’s layers, as a result, sunlight is emitted which subsequently reaches the Earth. The solar internal equilibrium, governed mainly by the near-steady nuclear fusion process under high temperature and density of the internal core, implies a solar luminosity or total solar irradiance (TSI) that would be nearly constant (often called “the solar constant” in the past) or varying extremely slowly. However, the near-surface and outermost layer of the Sun’s convective zone and photosphere often exhibits a host of time-dependent phenomena, including time-changing light output. First of all, the Sun poses a powerful dynamo which produces a complex and varying magnetic field, with surface manifestations such as sunspots, faculae, and magnetic network. This solar activity modifies the TSI reaching the Earth on different timescales through different mechanisms, the most obvious one observed is the 11-yr Schwabe cycle (cyclic variations in phase with the sunspot cycle and with amplitude of about 0.1%). Moreover, solar magnetic activity also produces a strong variation in the spectral solar irradiance (SSI), basically in the UV spectral zone, this is several magnitude orders larger than Schwabe variations on TSI (Fontenla et al., 2011). Secondly, there is evidence of solar tempera-
ture variations that would affect the TSI on long timescale (Fröhlich, 2009). Following Ehrlich (2007), small variations in solar temperature may produce fluctuations in solar luminosity and then, would cause climatic variability in longer timescales.

The most important energy source of Earth’s climate system is the TSI. Systematic variations on TSI are commonly the only solar forcing mechanism considered in tropospheric temperature and climatic evolution (e.g., Gray et al., 2010; IPCC, 2007; Jones et al., 2012), i.e., taking into account systematic changes in solar constant. Nevertheless, the solar energy interaction with terrestrial atmosphere seems to be more complex than previously assumed. It seems that the solar activity forcing’s contribution to global and regional climate is certainly underestimated (Agnihotri et al., 2011; Soon et al., 2011; Stott et al., 2003) while the solar contributions to the key aspect of climate dynamics may be incorrectly presented (Soon and Legates, 2013). Even the small variations in TSI from Schwabe cycles, produce detectable changes in tropospheric temperature variations (Hood et al., 2013; Scafetta and West, 2007), but UV variations can play an even more significant role on tropospheric temperature by means of some putative mechanisms involving mainly stratospheric ozone field and planetary waves (e.g., Barlyaeva, 2013; de Jager and Usoskin, 2006, and references therein). It is interesting to note that, in general, the mentioned works only took into account the toroidal component of the magnetic solar field (i.e., by using the sunspots as the most common solar proxy); nevertheless, the polar solar activity, related to poloidal component of solar dynamo, can also affect the tropospheric temperature (de Jager et al., 2010). Therefore, it is fair to say
that the Sun’s action on tropospheric climate activity is still under study and debate, with a lot of poorly resolved issues and many open questions.

Changes in the Earth’s energy budget due to incoming solar radiation, however, are not necessarily caused solely by Sun’s own or intrinsic variations (i.e., are not necessarily originated by the own solar internal dynamics). For example, they can depend on factors external to the Sun, which in turn can modify the way in which the solar energy reaches the planet. The clearest example of these external factors is the so-called astronomical or orbital forcing (e.g., Cubasch et al., 2006) that is connected to the ever-changing Earth orbital parameters and insolation quantities (Laskar et al., 2004). Changes in the Earth’s orbital eccentricity, due to planetary perturbations; in the precessional speed of the terrestrial rotation axis and changes in the Earth spin axis orientation (obliquity) in the inertial space (both phenomena originated in the luni-solar and planetary perturbations and also in terrestrial’s mass re-distribution), modify the TSI received on the planet (both on average and for a particular geographical location), with periodicities ranging from 14 ka to 100 ka (1 ka = 1000 yr); these are the well-known Milankovitch cycles. The interaction of this forcing mechanism with the solar radiation is a purely geometric effect (i.e., it doesn’t affect the intrinsic TSI or SSI emitted by the Sun).

There is also a growing body of evidence indicating that solar internal activity is influenced or modulated, at least at some extent, by planetary movements. The Sun’s spatial location is not fixed within the Solar System. Considered as a punctual mass, the Sun revolves around the solar system barycentre in the gravitational field of the other N-1 bodies of the system.
This is the so-called solar inertial motion. The Sun is not a perfect sphere and departures from sphericity generate torques in this gravitational field, consequently, the Sun’s orientation changes secularly with respect to a spatial inertial frame (e.g., Fränz and Harper, 2002). This is why a more general name like solar barycentric motion is preferred. This putative planetary influence in solar internal dynamics would now be physical, not geometrical in contrast to the earlier discussion of the ever-changing Sun-Earth configuration.

The planetary hypothesis of solar cycle is an old idea that sporadically developed more than 100 yr ago, focusing mainly on the more prominent solar periodicity, namely the mean Schwabe sunspot cycle of 11.1 yr that is similar to the Jupiter orbital period of about 11.8 yr (Brown, 1900; Wolf, 1859). Since then, several works have described (mostly phenomenologically rather than physically), the possible planetary influence on solar activity, mainly through the modulation of sunspots cycles, as a proxy of the possible modulations on solar dynamo (Charvátová, 2009; Fairbridge and Shirley, 1987; Javaraiah, 2005; Jose, 1965; Landscheidt, 1999; Wood and Wood, 1965). Much more recently, this hypothesis has been revived with more specific evidence of the possible Sun-planets interaction (Scafetta, 2012a, b; Scafetta and Willson, 2013a; Tan and Cheng, 2013), highlighting several important aspects about the possible underlying physical mechanisms involved (Cionco and Compagnucci, 2012; Scafetta, 2012a; Wolff and Patrono, 2010). Abreu et al. (2012), have suggested that the planets can be torquing the solar tachocline with periodicities similar to those observed in long-term solar activity proxy series, but Cameron and Schüssler (2013) recently criticized their methodology and
conclusions regarding the statistical significance of the suggested Sun-planets correlations.

Several authors have also shown plausible dynamical planetary signals in climatic patterns on Earth, mainly in zonal-global temperature records and auroral activity cycles (Charvátová and Střeštík, 2004; Landscheidt, 1987; Leal-Silva and Velasco Herrera, 2012; Scafetta, 2012b, 2010; Scafetta and Willson, 2013b). These scientific research contributions elevated the planetary hypothesis to another level: namely that the planetary dynamics not only would alter the operation of solar activity cycles, but the planetary effects/signals would also be detectable in terrestrial climatic patterns. If this effect is real, a new perspective or even revolution about the physical studies of solar action on climate should be considered. This is because it is supposed that the Sun is the mediating agency between planets and climate. Taking into account all these causes that produce variations on the external energetic inputs of the Earth’s climate system, in addition to radiative and orbital-geometrical forcing, it seems to be reasonable to put forward a research hypothesis concerning the existence of a planetary forcing, because this particular forcing would be an external agent to the Sun, that would modulate the way in which solar energy is produced, perturbing the solar magnetic activity, while its full interactive dynamics can be accurately described by theoretical formulations coming from solar system dynamics.

1.2. Empirical correlations between planetary T torque and river discharges.

Aim of this work

Some very interesting evidence regarding planetary forcing on climate have been presented with relation to discharges from several large river
basins. The river flow hydrology can be considered a very good climate proxy that is, in turn, closely dependent on or coupled to the tropospheric dynamics. Basically, we are referring to the works by Antico and Kröhling (2011); Landscheidt (2000); Tomasino et al. (2000); and Zanchettin et al. (2008). The basic results of these works is that both Po and Paraná Rivers have sub-decadal periodicities that are related to similar periodicities in the variation of the inertial solar orbital angular momentum modulus ($L$), i.e. periodicities in the so-called solar $T$ torque ($T = dL/dt$). Taking into account these spectral concordances, these studies have been limited to periodicities around ($\sim 8$ yr).

Here we clarify that $T$ is not the “solar” torque per se but only the derivative of $L$. But $T$ is purely of planetary origin, because considering the constancy of the mass of the Sun, the variations of $L$ only depend on the masses, velocities and accelerations of the Solar System planets. Therefore, we prefer to call it planetary $T$ torque instead of the often more commonly used term “solar torque”.

The empirical results showed very good correlations between maxima and minima in annual series of $T$ and river discharge series ($D$ series) for Po and Paraná Rivers over the 20th century. For Po River, Landscheidt (2000) remarked that: “After 1933, all maxima of $|dL/dt|$ coincide relatively closely with outstanding discharge maxima, whereas all the $|dL/dt|$ minima mark discharge minima”, and “Before 1933, the relationship was reversed by a $\pi$ radians phase shift. It occurred when $dL/dt$ was exposed to a perturbation that deformed the sinusoidal course of the change in the Sun’s orbital angular momentum” (the Italics are ours). We note that this result refers to the
absolute value, $|T|$, not $T$. In this approach, if a correlation exists between $D$ and $T$ series, only its extreme values seem to be important, not the sign of $T$. Another observed fact by Tomassino et al. (2000) is that the periodicity of the strongest spectral peak (8.7 yr) of the Po River discharge is very close to the recorded mean length of the $|T|$ cycle reported by Landscheidt (2000). Both papers also reflected on the coincidence of river flows with the $|T|$ parameter and not $T$ itself. On the other hand, the newer paper by Zanchettin et al. (2008) confirm a remarkable statistical correlation between $D$ series and extrema in $T$ series, in support of the earlier proposed planetary-climate forcing relation. The North Atlantic Oscillation (NAO) was proposed as potential link between the Sun and Po River discharge, since NAO was known to be significantly correlated with both solar activity and decadal variability in the climate of northern Italy. These authors also found a correlation relationship between the 22-yr Hale sunspots cycles, Po’s $D$ series spectra (with the main periodicity detected at 8.2 yr) and precipitation series ($P$ series). Interestingly, Zanchettin et al. (2008) also mentioned the existence of “perturbations” in $T$ series (a brief time when the sinusoidal amplitude of $T$ series drops significantly); these perturbations were also related by these authors to extrema in $P$ and $D$ series (Zanchettin et al., 2008, Fig. 4 on pg. 6).

For the Southern hemisphere, Antico and Kröhling (2011), analysed solar signals and hydrological variability in Paraná River (the fifth most important river according to drainage area and the second largest drainage basin in South America) roughly covering the last century. They, based on results from previous works, assume sub-decadal periodicities of Paraná River’s $D$
series in the range 7-9 yr. Then using a multi-taper technique (Ghil et al., 2002), they showed that Paraná’s $D$ series and planetary $|T|$ series shared significant spectral power inside this particular band. This work is very interesting because of the huge drains area addressed (about $3 \times 10^6$ km$^2$) which supposed to imply a strong climatic connection, and also because the phenomenological concordance between $D$ and $|T|$ series. Indeed, from this spectral coincidence, Antico and Kröhling (2011) showed that Paraná’s $D$ series and planetary $|T|$ series are in general out-of phase, showing a great coherence at high level of significance (Antico and Kröhling, 2011, Fig. 4). Such a co-relationship is very impressive, because it suggests an immediate response of Paraná River to planetary forcing (see Antico and Kröhling, 2011, for a discussion of these topics). Notably, the “perturbation” in $|T|$ series around 1935 seems also to be seen in Paraná’s $D$ series. Antico and Kröhling (2011) further shown that this sub-decadal band is not present in sunspot time series, implying that solar irradiance would not be directly related (at these timescales) with Paraná River’s discharge, suggesting that other physical mechanism linking solar activity and Earth atmosphere should be sought after.

All these works related to Po and Paraná Rivers show empirical evidence in favour of a direct planetary forcing on climate, and they are also very important because of the potential improvement in predictive capabilities of discharge from these rivers. In these works, an outstanding correlation between an exclusive planetary origin parameter ($T$), and rivers’ $D$ series suggest a planets-Sun-river relationship. This raises the natural question about the possible physical mechanisms among planetary motions, the Sun’s
internal functioning and Earth rivers dynamics. Of course, the full treatment of this issue is minimally a huge interdisciplinary challenge.

A first step in this direction is to go deeper into the previously published river’s discharge and planetary torque relationships. At this point, several questions appear. The most satisfactory or convincing phenomenological relationship appears with $|T|$, but not directly with $T$. It is worth noting that Zanchettin et al. (2008) did use $T$ time series, but only refers to its maximum and “perturbed” values when comparing with Po’s $D$ series. Antico and Kröhling (2011) analysed $|T|$ series and, as mentioned earlier, focusing only on the common 7-9 yr band between $|T|$ and $D$ series; they do not present detailed spectral peaks analysis in this band. First of all, examining Fig. 1 of Antico and Kröhling (2011), we note that the 7-9 yr band in $D$ series is significant at the 50-95% confidence level, whereas for $|T|$ series the signal is detected above the 95% level. We reproduced these spectra (see Sec. for details on calculations) in Fig. 1 here. Note that at the significance levels of 50-95%, both spectra share a rather broad spectral band, containing information from periods smaller than 7 yr and larger than 9 yr. Therefore, we propose to study these relationships at sub-decadal timescale but without being limited to this 7-9 yr band, i.e., taking into consideration a broader spectral band (certainly we will take into consideration periods between ~ 6-10 yr).

The planetary torque acting on the Sun is, by definition, a vectorial quantity. The solar barycentric movement is basically quasi-planar in short timescales; nevertheless, several important dynamical details arise taking into account full 3D geometry (see Cionco and Compagnucci, 2012). Therefore,
it is very important in this matter to assess the complete role of $T$ and $Γ$, the bona-fide vectorial torque. In principle, there is no physical justification to take into account only the $T$ torque in the study of these planetary-climate relationships. In addition it is absolutely unclear why the most important concordances occur with $|T|$ and not with $T$, furthermore, the absolute value $|T|$, has no immediate dynamic interpretation; it is merely the absolute value of $dL/dt$, which is a scalar quantity.

Also, it is interesting to inquire about planetary spectral frequencies involved at sub-decadal timescale: in addition to 8.6 yr and 7.73 yr periods reported in $|T|$ and $T$ series by Tomasino et al. (2000) and Zanchettin et al. (2008), respectively, Antico and Kröhling (2011) took only into consideration the 7-9 yr band; but we see that significant planetary signal exist in a broader band. Therefore, an exploration related to planetary dynamics is imperative in order to known what is the physical origin of the planetary signal against which we are comparing the rivers’ flow variations.

Classical tidal effects related to terrestrial planets (i.e. effects of deformations or departures in solar figure due to differential tide-generating forces), has been involved as possible underlying physical Sun-planets mechanisms, but in general, they were discredited (e.g., Okal and Anderson, 1975). Nevertheless, some planetary alignements involving terrestrial planets and also Jupiter, could be important respect to solar cycle (Hung, 2007; Scafetta, 2012a). Therefore, the involvement of terrestrial planets in this issue is interesting to discriminate. But, a set of other specific questions appeared at this point. For instance: Which planets or planetary configurations are responsible of the spectral power observed in the sub-decadal band? With
respect to the abovementioned “torque perturbations”, why does it occur? What is its origin and interpretation in terms of planetary dynamics? Is it a merely descriptive definition or a clear dynamical effect?

In this exploratory study, we present both useful notes and original results that contribute to clarification of this interdisciplinary research. The aim is to investigate the relevant planetary dynamics involved in the production of sub-decadal periodicities and to search for any evidence regarding to a plausible physical Sun-planets mechanism related to these cycles. We pay particular attention on the Paraná’s sub-decadal band because of the significant power spectrum shared with $|T|$ torque in addition to the alleged outstanding coherence between $|T|$ and $D$ series, which suggest a working planets-Sun-river relationship. We add that our results are also relevant for the 8.2-8.7 yr peak reported for Po River.

Using the maximum entropy method we confirm that relevant involved dynamics (basically due to Jupiter, Saturn and Neptune) produces peaks at: 9.2 yr, 7.86 yr, 6.56 yr in $|T|$, they are caused by the variation of the vectorial torque strength. Analysing the discharge of Paraná River around this sub-decadal band from 1904 to 2012, we found the following significant spectral lines: 6.49 yr, 7.61 yr, 8.67 yr, and 10.45 yr. Then, searching for a possible physical mechanism linking planetary dynamics and Sun’s internal activity, we found a very significant sub-decadal spectral band in the oscillations of the orbital angular momentum vector as seen from the Sun’s spin axis of rotation. Moreover, while analysing this band, we found a set of frequencies, much closer to spectral features in Paraná and Po River flow analyses: 6.33 yr, 7.68 yr, 8.62 yr, and 9.92 yr. These findings are very interesting because
a solar spin-orbit coupling has been argued as a possible underlying physical mechanism linking Sun activity and planetary motions. Our more accurate solar system dynamics model shows that, if these rivers are physically related to solar barycentric motion, the vectorial nature of planetary torque is essential to capture the full concordances at sub-decadal timescale. Moreover, taking into account that this new Sun-river linkage evidence is based on a possible solar spin-orbit interaction, this findings not only could improve the predictability of these river’s flows, but in turn, could be used as a proxy of a working solar spin-orbit interaction. We also provide an important discussion about the possible physical links in these putative Sun-planets and Sun-rivers interactions.

2. THE SUN’S ORBITAL ANGULAR MOMENTUM VARIATION

To clarify the nature of the planetary torque on the Sun, lets us study the relationship between $\mathbf{L}$ and $T$:

$$\mathbf{L} = M_\odot \mathbf{r} \times \mathbf{v},$$

where $M_\odot$ is the Sun mass ($\simeq 2 \times 10^{33}$ g), $\mathbf{r}$ and $\mathbf{v}$ are the position and velocity of the Sun in a barycentric reference system. Of course, $\mathbf{r}$ and $\mathbf{v}$ are due to the reflex barycentric motion produced by the other eight planetary bodies of the system:

$$\mathbf{r} = -\frac{1}{M_t} \sum_{j=1}^{8} m_j \mathbf{p}_j,$$
\[ v = - \frac{1}{M_t} \sum_{j=1}^{8} m_j \dot{p}_j, \]  

(3)

where \( M_t \) is the Sun mass plus the planetary mass of the system; \( m_j \) is the corresponding planetary mass; \( \dot{p}_j \) and \( \ddot{p}_j \) are the heliocentric planetary position and velocity. We have chosen a heliocentric system for positioning the planets because in general, planetary ephemerids are based on this reference system. Now, using this simple relationship:

\[ L^2 = \mathbf{L} \cdot \mathbf{L}, \]  

(4)

we formally have:

\[ \frac{d\mathbf{L}}{dt} = \frac{\mathbf{L}}{L} \cdot \frac{d\mathbf{L}}{dt}. \]  

(5)

The second factor in this multiplication is the planetary vectorial torque, \( \mathbf{\Gamma} \), which now by virtue of Eqs. 2 and 3 has a clear dependence on planetary dynamics. Then, from Eq. 5 we have:

\[ T = \frac{1}{E} (\tau_x L_x + \tau_y L_y + \tau_z L_z) \]  

(6)

where \( \tau_x \), \( \tau_y \) and \( \tau_z \) are the planetary vectorial torque components. In Fig. 2, the \( T \) values are plotted from 1900-2013 at a monthly resolution. The solar barycentric dynamical parameters used in these calculations are obtained by using a code pack developed by the author. It is designed to calculate the basic (Sun’s barycentric position, velocity and acceleration) and more specific features of solar barycentric motion. This version is based on the planetary outputs of Mercury6.2 program (Chambers, 1999) in high precision.
Bullirsch-Stoer mode. Mercury6.2 is a state of the art Fortran code widely used in celestial mechanics and planetary system formation simulations. In Fig. 2, the contribution of giant and terrestrial planets to $T$ is clearly seen. The terrestrial planets have a non-negligible contribution because $T$ depends not only on solar position, but also on its velocity and acceleration. For example, if a pure keplerian potential is acting between the Sun and only one planet $i$ of the Solar System, the Sun’s barycentric acceleration is:

$$\ddot{r} = G \frac{m_i}{p_i^2} \dot{p}_i,$$  \hspace{1cm} (7)

$G$ is the gravitational constant; $m_i$ is the planetary mass; $p_i$ is the heliocentric planetary distance; then, terrestrial planets influence is evident because of their shorter distances to the Sun (see Wood and Wood, 1965, for a general comparison of solar dynamic quantities).

2.1. The $T$ torque component of giant planets

Fig. 3 shows $T$ torque component of giant planets, $T_G$. This figure reveals that $T_G$ long-term signal is basically ruled by the cyclical combination of Jupiter and Saturn ($T_{JS}$) motions, i.e. by their synodic period (J-S), which for the last century we obtain a mean value of $J-S = 19.84$ yr. Of course, main extrema in $T$ (i.e., the peaks of $|T|$) appears at semi-synodic period, i.e., the second harmonic of J-S frequency (i.e., each planetary quasi-alignments, conjunction-opposition), also called “spring tidal period”, which is 9.92 yr in our simulations. Nevertheless, the effect of the other giant planets, Neptune and Uranus, is not negligible. For example, around 1990, $T_G$ shows a rapid variation, and this is due to an unusual, i.e., non-periodic extreme conjunction (very straight planetary alignment that involves the fourt Giants, see.
that produces a rapid but gradual angular momentum inver-
tion of the solar barycentric orbit and consequently, an extreme increase
of its orbital inclination \cite{Cionco and Compagnucci, 2012}. As far we know,
this is the first report on this “anomaly” in $T$ evolution. But, we can also
see the so-called “perturbation” in $T$ series. Beginning in $\sim 1934$, Neptune
counteracts notably the other three Giants’ torques. The planetary config-
uration responsible of this scenario is seen in Fig. 4. Other configura-
tions generate a similar drop in 1970 ($\sim 36$ yr later, i.e., about one synodic period
between Saturn and Neptune). Also the $T$ torque component combined from
Jupiter, Saturn and Neptune ($T_{JSN}$) is depicted in Fig. 3 (see Sec. 3 for
additional explanation on this parameter).

At this juncture, our first conclusion is that the term “perturbation”
widely used with relation to planetary forcing on river discharge is purely
descriptive: those drops in $T$ torque, obey the normal giant planet dynamics
(it involves strongly Jupiter, Saturn and Neptune), they have about 36 yr
period and they are not produced by any anomalous situation or external
force to the Sun-giant planets system. Indeed, as was mentioned earlier, a
really unusual situation occurs in shorter timescales (i.e., exceptional orbital
inversion) not related to terrestrial planets, that can only be clearly seen in
a detailed $T$ torque representation using monthly data.

3. SUB-DECADAL BAND AND GIANT PLANETS PERIODS

Figs. 2 and 3 tell us that giant planets should produce the sub-decadal
spectrum periodicities reported in $|T|$. Not all authors have used the same
type of planets in their calculations, but on the other hand, it is important to
assess if the short period terrestrial planets can contribute to some extent to any shift or feature in the spectrum of $|T|$, taking into account the tidal hypothesis of solar cycle. Therefore, we are going to address this question, which can be easily assessed by means of spectral analysis. We performed the same multi-taper analysis as Antico and Kröhling (2011), using the same SSA-MTM-toolkit software (Ghil et al., 2002) available at http://www.atmos.ucla.edu/tcd/ssa/, taking into account all the planets ($|T_{all}|$) and only giant planets ($|T_G|$). For the analysis, we take one data point per year, as is obtained from our simulations (no averaging was performed over the data). The planetary equations of motions were integrated using Bullirsch-Stoer scheme. The initial conditions time was the fiducial J2000.0 epoch (January 1st 2000 at noon of the Terrestrial Time, i.e., 11:58:55.816 UCT). The orbital integration time span covers from 1904 (to correspond with our Paraná River’s data) to 2012. Fig. 5 shows that the effect of terrestrial planets in $|T|$ spectrum is negligible at this band, then $|T_{all}|$ and $|T_G|$ virtually coincide. The result at sub-decadal timescale, is coincident with that reported by Antico and Kröhling (2011).

MTM method is a powerful tool for estimating low-amplitude harmonic oscillations in a relatively short time series with a high degree of statistical significance. Because the statistic of the $F$ test is used, the results do not depends on the amplitude of the signal detected (independently of the considered frequency) (Ghil et al., 2002), but MTM is certainly a low resolution method in terms of spectral lines determination. Therefore, we performed another spectral analysis over $|T_G|$ but using maximum entropy method (MEM), in order to assess more specific giant planets frequencies
involved in the generation of this band. As the readers may know, MEM is an autoregressive (AR) parametric method dependent on data used, its fundamental parameter is the order \( M \) of the adjusted AR model (i.e., the number of used poles), and must be lesser than certain maximum in order to avoid spurious results, mainly at the extreme of Nyquist interval (e.g., Penland et al., 1991; Press et al., 1992). MEM has been very useful in order to isolate decadal frequencies in climatic series and also planetary frequencies (Scafetta 2012b-c, 2010). For MEM calculations, we used the cited SSA-MTM-toolkit and a Fortran code based on MEMCOF routine of Press et al. (1992) fast and robust for large data sets and high pole order \( M \) used. We used the same data set from 1904 to 2011 then \( N = 109 \) values were taken. For a rational estimate of pole numbers we begin with \( M = 20, M = 36 \) (\( N/3 \)) and \( M = 54 \) (\( \sim N/2 \)). We assume, as customary in the literature, \( N/2 \) to be the maximum allowed value. The result is shown in Fig. 6, where the spectra of each pole number adopted are seen. There is no practical difference between \( M = 36 \) and \( M = 54 \), and we decide to use \( M = 54 \) because the peaks are sharp and stable. Also, the effect of the interval sampling in the frequency space \( df \) was checked. The peaks’ frequencies stabilizes from \( df = 2^{11} = 2048 \), a little smaller interval than the \( 1/N \) usually considered in Fourier transform applications, hence we have used this interval hereafter in calculation planetary spectra. We found a significant period of 7.86 yr, but also two sharp peaks at 9.92 yr, and 6.56 yr. In addition, for a more stringent analysis, we repeat on \( |T_G| \) the spectral calculation taking into account giant planets dynamics starting from 800 A.D. (i.e., this long integration covers the frequently studied period in connection to the suspected solar Grand Min-
ima and Little Ice Age events), assuming ergodicity and stationary planetary frequencies. The spectral peaks obtained are virtually the same confirming the results shown in Fig. 6.

3.1. Planetary origin of these peaks

The above MEM analysis comes from a dynamical oscillatory system. These cycles seem to be a robust result in planetary dynamics and come from giant planet periodicities; then, we will attempt an assessment of the physical origin of these peaks in $|T_G|$. $T_G$ is the physical signal that responds to planetary dynamics; therefore, the half-periods of significant oscillations in $T_G$ should be approximately the origin of the main periods in $|T_G|$. The 9.92 yr period is obviously the second harmonic of the synodic period of Jupiter and Saturn (J-S). On the other hand, Neptune, as we discussed before, due to its long distance from the Sun, has a significant effect on $T$ signal. The measured synodic period with Jupiter (J-N) is 12.80 yr, therefore, its half value (6.40 yr) is strongly related to this 6.56 yr observed period (which is perturbed by other planetary harmonics as S-N/3 ~ 12 yr and J-U= 13.81 yr.)

With regard to the 7.86 yr peak, it is not obviously related to any planetary mean motion or synodic periods. Hence, we suggest an association with the mean period between pronounced extrema in $|T_G|$ series. For that, we calculate the average period between $|T_G|$ extrema (we used our high resolution 15-day output series) as follows. First, we select the most prominent extrema between 1904 and 2012 (13 values) and determine the time between consecutive values, then an average of these values is obtained: 7.272 yr. In addition, we obtain an average of the time at which $|T_G|=0$, and that is 7.992
yr. The mean value between the two extremas is: 7.86 yr (two decimals).

The role of Neptune seems to be determinant in the generation of the involved frequencies. As a check, we generate a synthetic solar system, composed by Jupiter, Saturn and Neptune, with the same initial conditions (J2000.0). The $T$ torque coming from this subsystem ($T_{JSN}$) was already shown in Fig. 3. This figure shows that the $T_G$ is basically explained by these three planets, regardless of planet Uranus. Again, we search for the presence of periodicities and re-draw the spectral analysis over $|T_{JSN}|$. We obtained the following peaks through MEM calculations: 9.80 yr, 7.82 yr, 6.33 yr. This result suggests these three planets are indeed the main physical cause of the above reported periodicities. Therefore, the physical and dynamic origins of this broader sub-decadal band in $|T|$ spectrum is now confirmed with our detailed analyses.

It is worth noting that MTM spectra of $|T_{JSN}|$ is similar to the Fig. 6 shown for $|T_G|$. Nevertheless, the MTM analysis of $|T|$ obtained only taking into account Jupiter, Saturn and Uranus, degrades the spectra significantly (results not shown here).

Our results show that in the sub-decadal band, the giant planet dynamics (basically coming from Jupiter, Saturn and Neptune) provides three important spectral peaks with clear physical meaning. Next, we are going to perform a comparison between $|T_G|$ frequencies and the rivers discharge frequencies at sub-decadal band. Regarding Po River, we remember that [Tomasino et al. (2000) and Zanchettin et al. (2008)], have reported a spectral line between 8.2-8.7 yr. Now, we want to assess the spectral peaks present in the Paraná River inside this broad sub-decadal band.
4. PARANÁ RIVER’S PEAKS

A significant peak of 8.85 yr was reported by Robertson and Mechoso (1998) for Paraná River (Posadas gauging station, 27°S 56°W) using MTM technique, Krepper et al. (2008) have established oscillatory components between 8.4-9.2 yr (using Posadas and four south Brazilian gauging stations).

We analysed Paraná River discharge series from Secretaría de Recursos Hídricos of Argentina (http://www.hidricosargentina.gov.ar/acceso--bd.php), we follow Antico and Kröhling (2011) by using the same Corrientes (27°28.5'S, 58°50'W) gauging station data (see Fig. 7). To date, there are daily data and monthly averaged data from January 1st, 1904 to August 31th, 2012. For the analysis we starts with monthly data and performed the analysis both using monthly and annual-mean data, the annual data were obtained averaging monthly data for the corresponding year. Therefore, we have taken into account $N = 1304$ (for monthly basis analysis) and $N = 108$ (annually averaged data). For the annual analysis, we have only taken into account data till 2011 because 2012 datasets are incomplete.

Results from the annual data sets are showed in Fig. 8. The figure depicts the same MTM spectral band marginally significant to 95%, but the MEM spectra (order $M = 54$, i.e., $N/2$) show prominent peaks at: 6.49 yr, 7.61 yr, 8.67 yr and 10.45 yr. The MEM error bands of these peaks are evaluated using the 95% confidence interval provided by SSA-MTM-toolkit. It seems that Paraná River has more peaks in this spectral zone than $|T|$ torque of giant planets. Strictly inside the 7-9 yr band only one peak around 7.61 yr is commonly shared between planetary $|T|$ and the river record. Then, we redraw the analysis on monthly-basis. The series has 1304 data, hence we
expect more power in the signal. Accordingly, Fig. 9 shows a more significant and broader MTM spectral band. The raw MEM spectrum shows the same peaks as those in Fig. 8.

Now, we address the problem of the significance of these peaks, we want to be sure that these peaks are statistically meaningful signals, i.e., that we are not fitting a substantial amount of noise in the AR model. The MEM spectra can be constrained with red-noise spectra using a Monte Carlo permutation test, as was made in the excellent paper of Pardo-Igúzquiza and Rodríguez-Tovar (2005). The MAXEMPER software coming from this publication evaluates the statistical significance of the spectral estimates using the mean power spectra of the $N'$-th random permutation. This mean spectra is using for testing the null hypothesis from which the spectra of the random permutations are sampled. The outputs include the achieved significance levels of the power spectrum estimated for each frequency. Fig. 10 shows the confidence level of the signal that reaches 95% and higher. Panel a) shows significant power in $\sim 7$-10.5 yr band for $M = N/4$, panel b) depicts the same for $M = N/3$ and the last one shows the significant spectra for $M = N/2$.

We see how the central 7-9 yr band is refined in more detailed spectral lines: in addition, the 6.45 yr line is increasing in importance reaching the 99% confidence level, the 10.45 yr peak is only visible with a (reasonable) value of $M = N/2$, but significant at 95% level against red-noise spectrum.

In order to carry out a even more stringent analysis and eliminates red noise of monthly series, we performed a singular spectrum analysis (SSA) by using the same SSA-MTM-toolkit. Following Robertson and Mechoso (1998) the application of SSA to Paraná River has its own difficulties, mainly
because of the low significance of the eigenvectors used (i.e., low variance explained). It is important to note according to Allen and Smith (1996), that regardless of whether or not the T-EOFs pairs are significant, they are extremely effective as narrow-band filter. We used a conservative $M = 130$ spectral window (enough to resolve 6 yr periodicities) with 11 temporal empirical orthogonal functions (T-EOFs); then, we selected those T-EOFs which are oscillatory according to the corresponding test (specifically, strong FFT). Hence we retain three oscillatory pairs (T-EOFs 1-2, 4-5, 6-7), and performed the reconstruction using the corresponding principal components (Fig. 11). Then we used this reconstructed-filtered signal to perform MEM. The result in Fig. 12 yields basically the same spectral peaks as shown in Fig. 8.

Therefore we accept that these detected peaks with $M = N/2$, are statistically significant, at least for comparing with theoretical results. Then, taking into account the coincidences of spectral peaks in both analysis, and by concordance with earlier studies, we identified the Paraná River peaks using annual data results (6.49 yr, 7.61 yr, 8.67 yr, 10.45 yr).

5. THE SCALAR TORQUE MODULUS, $|T|$, AND VECTORIAL TORQUE, $\Gamma$, VARIATION

The importance of the bona fide vectorial torque $\Gamma$ should be addressed and highlighted. So far, torque parameter, $T$, is the only physical quantity cited in this issue, but $T$ is a scalar that only take into account $L$ variations. Of course, $\Gamma = \frac{dL}{dt}$ is the quantity that measures the total angular momentum variation of the inertial movement of the Sun. Then, let us to
analyse the torque strength or vectorial torque modulus $|\Gamma| = \tau$. Following Eq. 5 we have:

$$|T| = \tau |\cos(\Gamma, L)|$$

the argument of the cosine function is the angle between $\Gamma$ and $L$ associated directions. Of course, in what follows, we discard the contribution of the terrestrial planets and only consider the influence of the giant planets.

As the planetary movement is quasi-planar, and the solar $L$ vector is basically directed to $z$-axis of the inertial system for long time intervals (e.g., Charvátová, 2009; Jose, 1965), we can expect that $\cos(\Gamma, L)$ to be almost constant, i.e., that cycles in $|\Gamma|$ due to giant planets, to be the real origin of these sub-decadal frequencies in $|T_G|$. For testing this idea, we calculate the MTM and MEM spectrum of $\tau$, which are shown in Fig. 13. Both MTM spectra and the MEM peaks in Fig. 13 are coincidental and agrees with $|T_G|$ spectra previously shown in Fig. 5. An analysis of cosine function of Eq. 8 do not show any significant power in the sub-decadal band. The reason that previously analyses only take $T$ into account but do not analyse the vectorial torque in this problem is unknown to us, at least on physical grounds. Analysing the torque modulus the same relationships should have been found and this seems to be more clear and natural.

After confirming that cycles in the modulus of $\Gamma$ torque produces the observed periods in $|T|$, we now return our attention to the directional variations of $L$ in space. In addition to these angular momentum inversions, $L$ vector has a precessional-like and nutational-like movements around $z$-axis.
of the inertial system. We note that the inclination of the solar baricentric orbit (SBO) has variations of few degrees (\(\sim 1-6\) deg) (see Cionco and Compagnucci, 2012, for a detailed report on SBO inclination and also for a general figure of SBO elements). This kind of nutation in obliquity, for use in a standard astronomical term (note that the SBO inclination is the angle between \(z\)-axis of the inertial system and \(L\)), is certainly of very low amplitude, especially because the inclination of the SBO is almost constant in this studied period of about 100 years. But the precession-like movement of the SBO orbit is easily seen following the evolution of the ascending node (\(\Omega\)) of the SBO, this is the same precessional movement of \(L\) around \(z\)-axis of the inertial system, because \(L\) is normal to the orbital plane by definition, and the nodal line is perpendicular to \(z\)-axis of the inertial system. Fig. 14 shows \(\Omega\) variations in the studied period. We can clearly see as \(\Omega\) varies between 0 and 360 deg and also performs bounded oscillations (i.e., \(\Omega\) librates), alternatively, through the time. Therefore, this effect is not a classical precessional movement (a secular movement at constant speed; see e.g., Murray and Dermott, 1999), but a precession-regression movement at a variable speed. Nevertheless, for simplicity sake, we will refer to this movement as a precesional change of \(L\) around inertial \(z\)-axis.

At this moment, it is important to note that planetary tidal effects and spin-orbit coupling have been the main lines of inquiry about the underlying physical mechanism in the planetary hypothesis of solar cycle. The giant planets frequencies involved in the sub-decadal band ruled out classical tidal effects in this problem, i.e., tidal effects involving terrestrial planets. As we discussed, the time evolution of \(L\) is not trivial. The angular momentum
vector has basically its most important component along z-axis of the inertial system, it has continuous oscillations, precessional-like changes and brief and sporadic rotations of about one year, when solar orbit is gradually inverted (Cionco and Compagnucci, 2012). This means that planetary torque also produces appreciable changes in the direction of angular momentum in the inertial space and also more specifically, with respect to the Sun’s spin axis ($S$). Authors such as Javaraiah (2005) and Juckett (2003) have analysed Sun’s rotation and sunspots distribution showing similar periodicities found in $T$ series (i.e., $\sim 8$ yr). That, has been considered as the evidence of a spin-orbit coupling in the Sun. Perryman and Schulze-Hartung (2011) have taken this mechanisms into consideration and have argued that exoplanetary systems could be a useful environment for further testing and corroboration of a solar spin-orbit coupling hypothesis. These authors have only taken into account variations in spin rate of the Sun’s rotation axis respect to variations in $T$ torque.

We have already calculated the frequencies involved in the variation of the modulus of $\Gamma$ which, in turn, rules $L$ variations. Therefore, keeping in mind the idea about the physically probably solar spin-orbit interactions, the obvious next step in our phenomenological research is to evaluate the directional change of $L$, but with respect to the Sun’s spin axis, $S$.

6. SEARCHING FOR A SPIN-ORBIT RELATIONSHIP AND NEW EVIDENCE ON SUN-RIVERS RELATIONSHIP

The simplest way to determine a possible relationship between $S$ and $L$ is by studying the orientation of $L$ respect to $S$ through the time. As far as
Juckett (2000) studied the normalized projection of \( \mathbf{r} \) towards \( \mathbf{S} \), he proposed this projection (which is basically the \( \cos(\mathbf{r}, \mathbf{S}) \)) as an spin-orbit indicator and searched in this indicator for giant planets signal at over-decadal and longer timescales. Nevertheless, the use of \( \mathbf{r} \), instead of \( \mathbf{L} \), could be inadequate. Although \( \mathbf{r} \) is perpendicular to \( \mathbf{L} \), by definition (then variations in \( \mathbf{r} \) can express variations in \( \mathbf{L} \)), \( \mathbf{r} \) evolves with Sun’s orbital motion, independent of \( \mathbf{L} \) position in the inertial space, then, that proposed indicator, has other frequencies not related to the relative evolution between \( \mathbf{L} \) and \( \mathbf{S} \). Moreover, taking into account that \( \mathbf{S} \) is neither fix in the inertial system, the situation is even more complex in reality because it evolves secularly.

To accomplish this task, the ecliptical-inertial system will be the linkage between the angular momentum and the Sun associated coordinate system. We adopted the Inertial Heliographic System (IHS) attached (but not fixed) to the Sun (Burlaga, 1984; Fränz and Harper, 2002). In this system the \( z \)-axis is defined along the Sun’s spin axis and the \( x-y \) plane coincides with the solar equator. Then, the system is defined with respect to the inertial system by means of the Sun’s obliquity \( \epsilon_S \), and the longitude \( \Psi_S \) of the intersection between the ecliptic and the solar equator (Fig. 15). We adopted their values referenced to the epoch J2000.0 (Fränz and Harper, 2002):

\[
\epsilon_S = 7.25 \quad \text{(9)}
\]

\[
\Psi_S = 75.76 + 1.397 (t_0 - t) \quad \text{(10)}
\]

where \( t_0 - t \) is the fraction of Julian century from J2000.0. Then the \( x \)-axis of
the IHS system \((\mathbf{X}_S)\) is the intersection of the solar equator and the ecliptic of the corresponding epoch. Therefore, we linked the inertial and the IHS system by means of the following rotation matrix product:

\[
(x_s, y_s, z_s)^t = R(\epsilon_S)R(\Psi_S)(x, y, z)^t
\]

\((x_s, y_s, z_s)\) are the components in the IHS system of the \((x, y, z)\) vector in the inertial system.

The positioning of \(L\) with respect to \(S\) can be accomplished as usual in spherical astronomy, i.e., using two spherical angles associated with two orthogonal directions on the celestial sphere: \(\delta\) measured from the Sun’s spin axis toward \(L\) (a kind of colatitude angle), and \(\alpha\), measured from \(\mathbf{X}_S\) towards the arc of great circle that connect \(S\) and \(L\) (a longitudinal angle)(Fig. 15). Both angles are defined by the following expressions:

\[
\cos(\delta) = \frac{Lz_s}{L}
\]

\[
\cos(\alpha) = Lx_s [L^2 - Lz_s^2]^{-1/2}
\]

where \(Lz_s\) and \(Lx_s\) are the \(z\) and \(x\)-component of \(L\) in IHS. Then, we follow the evolution of \(L\) respect to \(S\) for the same period consistently with Paraná River data. We analysed from 1904-2012 A.D., and then performed spectral analysis to both positional angles. Fig. 16 show the evolution of \(\alpha\) and \(\delta\). The co-latitudinal angle \(\delta\) shows very small amplitude oscillations but a sudden increase around 1990 because of the above-mentioned orbital inversion (\(L\) inversion). The longitudinal angle \(\alpha\) shows more important oscillations of about 20 deg in amplitude, with marked peaks each \(\sim 38\) yr, (which are
also visible, but lesser pronounced, in $\delta$). These secondary peaks occur at
Jupiter, Saturn and Neptune alignments (remember that the recorded mean
S-N period is $\sim 36$ yr). The exceptional four giant planets alignment of 1990
is also seen.

Consequently, MEM and MTM analyses of $\delta$ do not show any significant
spectrum (results not shown here), but $\alpha$ evolution shows very significant
spectral power in the sub-decadal band. This spectrum is showed in Fig. 17,
where Paraná MTM spectrum is also depicted for comparison. In this figure,
we have plotted two vertical lines delimiting the spectral zone in which the
power of $D$ is larger than 50% red noise significance level. Surprisingly, we
note that the Paraná spectrum is much more similar to $\alpha$ spectrum than the
$|T|$ spectrum at sub-decadal band (approximately four peaks can be seen in
both spectra inside this spectral zone). Indeed, MEM spectrum of $\alpha$ shows
significant peaks, coincident with Paraná River peaks (Fig. 18). We can see
four significant peaks at 6.33 yr, 7.68 yr, 8.62 yr and 9.92 yr. These peaks
are certainly the same as Fig. 6, with the addition of a peak in 8.62 yr.

Two peaks of 7.68 yr and 8.62 yr practically coincides with Paraná peaks
inside 7-9 band (7.61 yr and 8.67 yr). Particularly, we obtain a 8.62 yr
period very close to the Po and Paraná Rivers strongest peak. We can not
exactly establish the origin of this peak in $\alpha$ spectrum, but its value is close
to the mean duration of a cycle of $\tau$ (8.3 yr). The percentage difference
$(|\nu_c - \nu_p|/\nu_p) \times 100$, where $\nu_p$ is the Paraná River frequency peaks and $\nu_c$ is
the frequency peak of the $\alpha$ spectrum is lesser than 5%. As final note, we
see in Fig. 17 a prominent and broad bi-decadal band in $\alpha$ spectrum. The
median of the power spectrum in this band is $\sim 22$ yr, i.e., a Hale magnetic
7. SUMMARY, DISCUSSION AND CONCLUDING REMARKS

We have re-evaluated key dynamical aspects related to the evidence presented in the past linking solar inertial motion and discharges from Po and Paraná Rivers. It was not the intention of this work to fully confirm the existence of a Sun-river link, but to investigate and clarify the most important dynamical issues related to planetary and solar dynamics involved in this problem, coming from spectral coincidences. We have explained the cycles and the physical origin of the signals present in the oscillations of $|T|$, the most important parameter taken into account in these empirical evidences. The cycles in $|T|$ are produced by natural oscillations of the vectorial torque modulus due to giant planets, mostly Jupiter, Saturn and Neptune. These cycles ranged from $\sim 6.5-10$ yr. Our analysis of Paraná discharge series confirm this band as significant in river’s dynamics. Moreover, we proposed a new solar spin-orbit relationship (i.e., by positioning $\mathbf{L}$ with respect to $\mathbf{S}$) and we found basically the same Paraná discharge spectral peaks in the spectrum of the longitudinal variations ($\alpha$ angle variations) of $\mathbf{L}$ with respect to $\mathbf{S}$. This result stresses the importance of the vectorial torque in this problem. It is not only that the modulus variations are important, but also the directional variations that $\mathbf{\Gamma}$ produces on $\mathbf{L}$ in the inertial space. In addition, Po River shows a sub-decadal spectral peak (8.2-8.7 yr) more similar to $\alpha$ spectrum peaks than $|T|$ spectrum peaks. This results suggest that, if these rivers are physically linked to solar dynamics, it seems that solar influence do not affect them in the same manner; that is, if the Sun and these rivers are
resonant systems (in this spectral band), some frequencies are enhanced and other attenuated. This, could be related to the climatic mechanism involved in the Sun-rivers relationship.

As was already mentioned, NAO was proposed as a possible driver of this inferred Sun-rivers connection. Zanchettin et al. (2008) have showed that NAO is correlated with both solar activity and Po River discharge at sub-decadal time-scale. Scafetta (2010) suggests a NAO and solar inertial motion relationship at multi-decadal timescale. Oscillatory modes between 7-8 yr have been detected by Paluš and Novotná (2009) in NAO and geomagnetic index. Georgieva et al. (2012) have shown strong connection among heliospheric activity, geomagnetism and NAO oscillations. Therefore, changes in solar magnetic activity, NAO oscillations and variations of hydrological patterns related to Po River, are expected to be strongly connected.

By other hand, Robertson and Mechoso (1998) have related at sub-decadal time-scale, anomalous cool events in tropical North Atlantic (tNA) with high South-America rivers runoff. This seems to have motivated Antico and Kröhling (2011) to propose a possible relationship NAO-Paraná. Of course, a more difficult issue to address is the influence that NAO (as a whole atmospheric-oscillatory system) might have over South-America, at this sub-decadal timescales. Certainly, the tNA affects intertropical South-America via, e.g., decadal variability of the summer monsoon system (Robertson and Mechoso, 1998); then, it is possible that tNA acts as agency between South-American precipitation regime and NAO.

It is interesting to note that, at interannual time-scale, El Niño-Southern Oscillation (ENSO), very important in Paraná River discharge (with peaks
clearly visible in Fig. 12 between ~4-6 yr), is related to NAO. ENSO can affects NAO, but the inverse relationship has not been yet detected as was showed by Mokhov and Smirnov (2006). Therefore, the NAO influence in South America is an important issue than need to be clarified at different time-scales.

Precipitation regime plays a fundamental role in Paraná discharge. This large basin presents very inhomogeneous regions with different hydrological patterns. The average annual precipitation decreases from east to west (i.e., as we move away from the Atlantic Ocean), but also from north to south (de Petris and Paquini, 2007). Pinto Neto et al. (2013) have recently showed that thunderstorm days in Brazil are correlated to solar activity; but a very specially feature arise from their work: the most southern data set used, coming from Porto Alegre city station, shows a broad spectral peak around 8 yr. They related their findings to possible magnetic activity changes in Earth atmosphere. Porto Alegre city is almost at the same latitude than Corrientes gauging station (Fig. 7). Therefore, it is imperative to study the rainfall regime in other cities of the Paraná basin, looking for these sub-decadal periodicities, and particularly, a possible north-south gradient with these periodicities (taking into account Pinto Neto et al. (2013) results).

South-east of Brasil is the centre of the South Atlantic Magnetic Anomaly (SAMA). It produces the sinking of charged particles trapped in atmospheric belts (Pinto et al., 1992). This anomaly (unique phenomenon in the world) affects almost all Paraná basin, but is stronger at the south-east of the basin. Therefore, solar, geomagnetic and atmospheric activity should be carefully investigated, as a whole, in this region. We think that Sun-climate relation-
ship with magnetic activity variations, should be considered as the potential underlying origin of these Sun-river relationships. Sub-decadal variations of charged particles coming from the Sun (for instance, driven by a solar spin-orbit interaction), could interact with Earth atmosphere and geomagnetism, producing complex climatic patterns.

Earth climate variations with relation to a possible solar spin-orbit coupling have also been argued by Shirley (2009), taking into account solar meridional fluxes changing velocities. Geomagnetic activity is strongly dependent on solar dynamo, through changes or alternations in poloidal and toroidal fields (e.g., Georgieva et al., 2012), then a possible relationship between heliospheric parameters and the Earth atmosphere, and this as a trigger of hydrometeorological signals, is expected. A spin-orbit coupling hypothesis was called upon to explain some phenomenological concordances between $L$ variations and solar activity, through solar rotation and functioning of a magnetohydrodynamical dynamo. The original idea seems to be first proposed by Jane Blizard (1981), and has since been taken into consideration also by Javaraiah (2005), Juckett (2003, 2000), Perryman and Schulze-Hartung (2011), Shirley (2006), Zaqarashvili (1997). The idea is that planets can transfer orbital momentum to the Sun’s rotational angular momentum, and this variation could interact with the solar dynamo through a putative mechanism. Therefore, some part of the orbital angular momentum could be transferred to spin angular momentum. The inverse can also be true as was shown by Javaraiah (2005). As was mentioned Javaraiah (2005) and Juckett (2003) show evidence that certain periods in Sun’s rotation are very similar to periods in $T$ power spectrum, especially the 8-yr periodicity. Here, we
have presented a complementary side of this possible physical phenomena, i.e., the study of the directional variations between \( L \) and \( S \). It is also interesting to note that, oscillations of \( \sim 8.5 \) yr have also been measured in solar cycle (Rozelot, 1994). Periods from 6-8 yr has been found in drifts of latitudinal bands of near-equal rotational velocity in the Sun (Makarov et al., 1997).

At present, there is still no clear physical mechanism to explain how this transference of angular momentum might be achieved. Certainly, the planetary orbits do not exhibit any dissipative-anomalous behaviour that can be suspicious of this kind of coupling between Sun and planets. Neither any abnormal behaviour in orbital energy (that would affect planetary semi-major axis) nor orbital angular momentum that also must modify the eccentricity and the inclination of the planets.

In planetary dynamics, spin-orbit coupling refers to spin-orbit resonance (see e.g. Murray and Dermott, 1999, Chap. 5 for this subject), i.e., a commensurability that appear between the spin rate of a body and its orbital period. In general, the spin axis of the body is considered parallel to its orbital angular momentum vector (spin perpendicular to the orbit or zero obliquity approximation). The mechanism behind this coupling is the tidal friction originated by a planet over a satellite (Goldreich and Soter, 1966), or by the Sun to the planets (Goldreich and Peale, 1966; Peale and Gold, 1963). Goldreich and Soter (1966), argue that tides raised on the Sun by planets have virtually no effect on the rotation and orbit of the Sun. But this does not preclude the fact that certain internal solar dynamics can be susceptible to external gravitational modulation and perturbation (Scafetta,
2012a,b; Wolff and Patrone, 2010). Our problem at hand is more complex, because the solar orbital angular momentum has great variations (in modulus and direction), unlike of the orbital angular momentum variations of the planets. A model of solar spin-orbit coupling was out of the scope of this work; we only arrived at a spin-orbit relationship following the dynamics involved in this problem. But we can say that any model of solar spin-orbit interaction should consider (see e.g. Peale, 2005): a) an adequate expansion of the gravitational potential of the Sun that accounts for the Sun’s permanent figure, and the calculation of the corresponding planetary torque; b) the tidal torque of the planets and; c) (last but not of any lesser importance) the frictional torque coming from different solar internal zones (tachocline, convective envelope, etc). These zones have different shapes/forms (e.g., ellipticities) and then, they could precesses at different rates (Poincaré, 1910). Therefore, these ingredients are essential to a detailed description of the Sun’s spin axis evolution (tilt and rate) and its possible coupling with the orbital angular momentum at different time-scales. Our findings also suggest that, at least, we must consider planets Jupiter, Saturn and Neptune. For example, Chang et al. (2012), recently shown how a young star can modify its axial tilt by the magnetic torque that arises from the Ohmic dissipation in a Hot-Jupiter planet system, at the expense of the spin-orbit energy (see Eq. 17 of that paper for a spin-orbit coupling expression). The idea of Abreu et al. (2012) about the planetary tidal interaction in the tachocline, which has been modelled as an ellipsoidal figure, is a good candidate for spin-orbit coupling interaction, and should further be studied in this context.

Our aim was mainly to clarify the dynamics of the involved planets in
this problem and specify the spectral frequencies and their origins related to
the sub-decadal band, in order to find any hint about the possible underlying
Sun-planets physical mechanism. Considering the fact that terrestrial planets
are not related to our studied sub-decadal frequencies, classical tidal effects
can probably be ruled out as a possible mechanism.

Our more accurate solar system dynamics model shows, that if these
rivers are physically related to solar barycentric motion, the vectorial nature
of planetary torque is essential to capture their full concordances at sub-
decadal scale. Moreover, taking into account that this new evidence is based
on a possible solar spin-orbit interaction, this findings not only could improve
the predictability of these river’s flows, but in turn, could be used as a proxy
of a working solar spin-orbit interaction.

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To be provided

References

Abreu, J. A., Beer, J., Ferriz-Mas, A., McCracken, K. G., Steinhilber, F.
2012. Is there a planetary influence on solar activity? Astronomy and As-
trophysics 548, A88.

Agnihotri, R., Dutta, K., Soon, W. 2011. Temporal derivative of Total Solar
Irradiance and anomalous Indian summer monsoon: An empirical evidence
for a Sun-climate connection. Journal of Atmospheric and Solar-Terrestrial
Physics 73, 1980-1987.
Allen, M. R., Smith, L. A. 1996. Monte Carlo SSA: Detecting irregular oscillations in the Presence of Colored Noise. Journal of Climate 9, 3373-3404.

Antico, A., Kröhling, D. M. 2011. Solar motion and discharge of Paraná River, South America: Evidence for a link. Geophysical Research Letters 38, 19401.

Barlyaeva, T. V. 2013. External forcing on air-surface temperature: Geographical distribution of sensitive climate zones. Journal of Atmospheric and Solar-Terrestrial Physics 94, 81-92.

Blizard, J. B. 1981. Solar Motion and Solar Activity. Bulletin of the American Astronomical Society 13, 876.

Brown, E. W. 1900. A possible explanation of the sun-spot period. Monthly Notices of the Royal Astronomical Society 60, 599.

Burlaga, L. F. 1984. MHD processes in the outer heliosphere. Space Science Reviews 39, 255-316.

Cameron, R. H., Schüssler, M. 2013. No evidence for planetary influence on solar activity. Astronomy and Astrophysics 557, A83.

Cionco, R. G., Compagnucci, R. H. 2012. Dynamical characterization of the last prolonged solar minima. Advances in Space Research 50, 1434-1444.

Chambers, J. E. 1999. A hybrid symplectic integrator that permits close encounters between massive bodies. Monthly Notices of the Royal Astronomical Society 304, 793-799.
Chang, Y.-L., Bodenheimer, P. H., Gu, P.-G. 2012. Coupled Evolutions of the Stellar Obliquity, Orbital Distance, and Planet’s Radius due to the Ohmic Dissipation Induced in a Diamagnetic Hot Jupiter around a Magnetic T Tauri Star. The Astrophysical Journal 757, 118.

Charvátová, I. 2009. Long-term predictive assessments of solar and geomagnetic activities made on the basis of the close similarity between the solar inertial motions in the intervals 1840 1905 and 1980 2045. New Astronomy 14, 25-30.

Charvátová, I., Střeštík, J. 2004. Periodicities between 6 and 16 years in surface air temperature in possible relation to solar inertial motion. Journal of Atmospheric and Solar-Terrestrial Physics 66, 219-227.

Cubasch, U., Zorita, E., Kaspar, F., Gonzalez-Rouco, J. F., von Storch, H., Prömmel, K. 2006. Simulation of the role of solar and orbital forcing on climate. Advances in Space Research 37, 1629-1634.

de Jager, C., Usoskin, I. 2006. On possible drivers of Sun-induced climate changes. Journal of Atmospheric and Solar-Terrestrial Physics 68, 2053-2060.

Depetris P.J. y Pasquini A.I. (2007) The Geochemistry of the Paran River: An Overview. In M.H. Iriondo, J.C. Paggi, y M.J. Parma (Eds.). The Middle Paran River: Limnology of a Subtropical Wetland. Springer-Verlag Berlin Heidelberg.

Ehrlich, R. 2007. Solar resonant diffusion waves as a driver of terrestrial
climate change. Journal of Atmospheric and Solar-Terrestrial Physics 69, 759-766.

Fairbridge, R. W., Shirley, J. H. 1987. Prolonged minima and the 179-yr cycle of the solar inertial motion. Solar Physics 110, 191-210.

Fontenla, J. M., Harder, J., Livingston, W., Snow, M., Woods, T. 2011. High-resolution solar spectral irradiance from extreme ultraviolet to far infrared. Journal of Geophysical Research (Atmospheres) 116, 20108.

Fränz, M., Harper, D. 2002. Heliospheric coordinate systems. Planetary and Space Science 50, 217-233.

Fröhlich, C. 2009. Evidence of a long-term trend in total solar irradiance. Astronomy and Astrophysics 501, L27-L30.

Georgieva, K., Kirov, B., Koucká Knížová, P., Mošna, Z., Kouba, D., Asenovska, Y. 2012. Solar influences on atmospheric circulation. Journal of Atmospheric and Solar-Terrestrial Physics 90, 15-25.

Ghil, M., and 10 colleagues 2002. Advanced Spectral Methods for Climatic Time Series. Reviews of Geophysics 40, 1003.

Goldreich, P., Peale, S. 1966. Spin-orbit coupling in the solar system. The Astronomical Journal 71, 425.

Goldreich, P., Soter, S. 1966. Q in the Solar System. Icarus 5, 375-389.

Gray, L. J., and 14 colleagues 2010. Solar Influences on Climate. Reviews of Geophysics 48, 1-53.
Hood, L., Schimanke, S., Spangehl, T., Bal, S., Cubasch, U. 2013. The Surface Climate Response to 11-Yr Solar Forcing during Northern Winter: Observational Analyses and Comparisons with GCM Simulations. Journal of Climate 26, 7489-7506.

Humphreys, W. J. 1910. Solar Disturbances and Terrestrial Temperatures. The Astrophysical Journal 32, 97-111.

Hung C.-C., 2007. Apparent Relations Between Solar Activity and Solar Tides Caused by the Planets. NASA Technical Memorandum TM 2007-214817.

IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Javaraiah, J. 2005. Sun’s retrograde motion and violation of even-odd cycle rule in sunspot activity. Monthly Notices of the Royal Astronomical Society 362, 1311-1318.

Jones, G. S., Lockwood, M., Stott, P. A. 2012. What influence will future solar activity changes over the 21st century have on projected global near-surface temperature changes? Journal of Geophysical Research (Atmospheres) 117, D05103, 1-13.

Jose, P. D. 1965. Sun’s motion and sunspots. The Astronomical Journal 70, 193.
Juckett, D. 2003. Temporal variations of low-order spherical harmonic representations of sunspot group patterns: Evidence for solar spin-orbit coupling. Astronomy and Astrophysics 399, 731-741.

Juckett, D. A. 2000. Solar activity cycles, north/south asymmetries, and differential rotation associated with solar spin-orbit variations. Solar Physics 191, 201-226.

Krepper, C. M., N. O. Garcia, and P. D. Jones, 2008 Lowfrequency response of the upper Paraná basin, Int. J. Climatol., 28, 351360.

Landscheidt, T. 2000. River Po discharges and cycles of solar activity. Hydrol. Sci. J. 45(3), 491493

Landscheidt, T. 1999. Extrema in sunspot cycle linked to Sun’s motion. Solar Physics 189, 415-426.

Landscheidt, T. 1987. Cyclic distribution of energetic X-ray flares. Solar Physics 107, 195-199.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., Levrard, B. 2004. A long-term numerical solution for the insolation quantities of the Earth. Astronomy and Astrophysics 428, 261-285.

Leal-Silva, M. C., Velasco Herrera, V. M. 2012. Solar forcing on the ice winter severity index in the western Baltic region. Journal of Atmospheric and Solar-Terrestrial Physics 89, 98-109.

Makarov, V. I., Tlatov, A. G., Callebaut, D. K. 1997. Long-Term Variations of the Torsional Oscillations of the Sun. Solar Physics 170, 373-388.
Mokhov, I. I., Smirnov, D. A. 2006. El Niño-Southern Oscillation drives North Atlantic Oscillation as revealed with nonlinear techniques from climatic indices. Geophysical Research Letters 33, 3708.

Murray, C. D., Dermott, S. F. 1999. Solar system dynamics. Solar system dynamics by Murray, C. D., 1999.

Okal, E., Anderson, D. L. 1975. On the planetary theory of sunspots. Nature 253, 511-513.

Paluš, M., Novotná, D. 2009. Phase-coherent oscillatory modes in solar and geomagnetic activity and climate variability. Journal of Atmospheric and Solar-Terrestrial Physics 71, 923-930.

Pardo-Igúzquiza, E., Rodríguez-Tovar, F. J. 2005. MAXENPER: a program for maximum entropy spectral estimation with assessment of statistical significance by the permutation test. Computers and Geosciences 31, 555-567.

Peale, S. J., Gold, T. 1965. Rotation of the Planet Mercury. Nature 206, 1240-1241.

Peale, S. J. 2005. The free precession and libration of Mercury. Icarus 178, 4-18.

Penland, C., Ghil, M., Weickmann, K. M. 1991. Adaptive filtering and maximum entropy spectra with application to changes in atmospheric angular momentum. Journal of Geophysical Research 96, 22659-22671.
Perryman, M. A. C., Schulze-Hartung, T. 2011. The barycentric motion of exoplanet host stars. Tests of solar spin-orbit coupling. Astronomy and Astrophysics 525, A65.

Pinto, O., Jr., Gonzalez, W. D., Pinto, I. R. C., Gonzalez, A. L. C., Mendes, O., Jr. 1992. The South Atlantic Magnetic Anomaly - Three decades of research. Journal of Atmospheric and Terrestrial Physics 54, 1129-1134.

Pinto Neto, O., Pinto, I. R. C. A., Pinto, O. 2013. The relationship between thunderstorm and solar activity for Brazil from 1951 to 2009. Journal of Atmospheric and Solar-Terrestrial Physics 98, 12-21.

Poincaré, H. 1910. Sur la précession des corps déformables. Bulletin Astronomique, Serie I 27, 321-356.

Press, W. H., Teukolsky, S. A., Vetterling, W. T., Flannery, B. P. 1992. Numerical recipes in FORTRAN. The art of scientific computing. Cambridge: University Press, —c1992, 2nd ed. .

Robertson, A. W., and C. R. Mechoso (1998), Interannual and decadal cycles in river flows of southeastern South America, J. Clim., 11, 25702581.

Rozelot, J. P. 1994. On the stability of the 11-year solar cycle period (and a few others). Solar Physics 149, 149-154.

Scafetta, N. 2012a. Does the Sun work as a nuclear fusion amplifier of planetary tidal forcing? A proposal for a physical mechanism based on the mass-luminosity relation. Journal of Atmospheric and Solar-Terrestrial Physics 81, 27-40.
Scafetta, N. 2012b. Multi-scale harmonic model for solar and climate cyclical variation throughout the Holocene based on Jupiter-Saturn tidal frequencies plus the 11-year solar dynamo cycle. Journal of Atmospheric and Solar-Terrestrial Physics 80, 296-311.

Scafetta, N. 2010. Empirical evidence for a celestial origin of the climate oscillations and its implications. Journal of Atmospheric and Solar-Terrestrial Physics 72, 951-970.

Scafetta, N., West, B. J. 2007. Phenomenological reconstructions of the solar signature in the Northern Hemisphere surface temperature records since 1600. Journal of Geophysical Research (Atmospheres) 112, 24.

Scafetta, N., Willson, R. C. 2013a. Empirical evidences for a planetary modulation of total solar irradiance and the TSI signature of the 1.09-year Earth-Jupiter conjunction cycle. Astrophysics and Space Science 287.

Scafetta, N., Willson, R. C. 2013b. Planetary harmonics in the historical Hungarian aurora record (1523-1960). Planetary and Space Science 78, 38-44.

Shirley, J. H. 2009. Have We Entered a 21st Century Prolonged Minimum of Solar Activity? Updated Implications of a 1987 Prediction. AAS/Solar Physics Division Meeting #40 40, #11.08.

Shirley, J. H. 2006. Axial rotation, orbital revolution and solar spin-orbit coupling. Monthly Notices of the Royal Astronomical Society 368, 280-282.
Soon, W., Dutta, K., Legates, D. R., Velasco, V., Zhang, W. 2011. Variation in surface air temperature of China during the 20th century. Journal of Atmospheric and Solar-Terrestrial Physics 73, 2331-2344.

Soon, W., Legates, D. R. 2013. Solar irradiance modulation of Equator-to-Pole (Arctic) temperature gradients: Empirical evidence for climate variation on multi-decadal timescales. Journal of Atmospheric and Solar-Terrestrial Physics 93, 45-56.

Stott, P. A., Jones, G. S., Mitchell, J. F. B. 2003. Do Models Underestimate the Solar Contribution to Recent Climate Change? Journal of Climate 16, 4079-4093.

Tan, B., Cheng, Z. 2013. The mid-term and long-term solar quasi-periodic cycles and the possible relationship with planetary motions. Astrophysics and Space Science 343, 511-521.

Tomasino, M., and F. Dalla Valle, 2000. Natural climatic changes and solar cycles: An analysis of hydrological time series, Hydrol. Sci. J., 45(3), 477-490.

Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., Frank, D. C. 2009. Persistent Positive North Atlantic Oscillation Mode Dominated the Medieval Climate Anomaly. Science 324, 78.

Wolf, R. 1859. Extract of a Letter to Mr. Carrington. Monthly Notices of the Royal Astronomical Society 19, 85-86.

Wolff, C. L., Patrone, P. N. 2010. A New Way that Planets Can Affect the Sun. Solar Physics 266, 227-246.
Wood, R. M., Wood, K., 1965. Solar Motion and Sunspot Comparison. Nature 208, 129-131.

Zanchettin, D., Rubino, A., Traverso, P., Tomasono, M. 2008. Impact of variations in solar activity on hydrological decadal patterns in northern Italy. Journal of Geophysical Research (Atmospheres) 113, 12102.

Zaqrashvili, T. V. 1997. On a Possible Generation Mechanism for the Solar Cycle. The Astrophysical Journal 487, 930.
FIGURE CAPTIONS (PLEASE, ALL FIGURES IN BLACK-WHITE or GRAY-SCALE -Figs. 7 and 15)

Fig. 1. MTM spectra comparison of Paraná $D$ series and planetary $|T|$ torque. The vertical dotted lines mark the common 7-9 band considered by Antico and Kröhling (2011). Inside this band, the spectral power of $D$ is significant at 50-95%. The simple inspection of this figure shows that $D$ signal is significant at this levels in a broader sub-decadal band.

Fig. 2. Planetary $T$ torque from 1900 to 2013 A.D. Dashed line: all the planets included; solid line: only giant planets. Physical units: solar mass (Ms), astronomical unity (AU) and days (d).

Fig. 3. Comparison between $T$ torque of only giant planets ($T_G$), $T$ from Jupiter and Saturn ($T_{JS}$), and from Jupiter, Saturn and Neptune ($T_{JSN}$) subsystem planets. The rapid variation in $T$ signal around 1990 is due to an unusual orbital inversion (i.e., angular momentum inversion) of solar barycentric orbit. The $T$ “perturbation” around 1935 is due to the normal dynamics that strongly involve Neptune planet.

Fig. 4. Planetary configuration at 1935 related to so-called $T$ perturbation.

Fig. 5. Raw multitaper (MTM) spectra of $T_G$ (only giant planets) and $T_{all}$ (all the planets). The terrestrial planets contribute with a negligible shift
of the spectral band at sub-decadal time-scale.

Fig. 6. Maximum entropy (MEM) spectra for $T_G$ with different number of poles ($M$) used.

Fig. 7. Paraná’s basin. The main rivers of Paraná system are showed. Corrientes city in Argentina is marked. Other South-American cities in Uruguay, Brazil, Bolivia and Paraguay are also indicated.

Fig. 8. MTM and MEM spectra of Paraná’s (annual basis analysis) $D$ series. The MEM error bands of these peaks are evaluated using the 95% confidence interval provided by SSA-MTM-toolkit.

Fig. 9. MTM and MEM Spectra of Paraná’s monthly $D$ series, showing a substantially more power in the sub-decadal band than Fig. 8.

Fig. 10. Results of the Monte Carlo permutation test (MAXEMPER software) performed to Paraná monthly $D$ series, showing the significance of these peaks against red noise null hypothesis. The pole order $M$ is showed (number of data $N=1304$).

Fig. 11. SSA-reconstructions (componentes 1-7) (bold line) and monthly data series (dotted line). Quasi-annual oscillations and the exceptional El Niño event in 1982 (order 960) are clearly seen. Both series are centred respect to their mean ($< D >$) values.
Fig. 12. MEM spectrum of the filtered $D$ monthly series showing the disappearance of noisy-peaks ($M = N/2$). The small window shows in detail that the same four peaks appear in the sub-decadal band. For comparison, the arrows indicate the peaks of the raw-annual data (Fig. 8).

Fig. 13. MTM and MEM power spectra of (vectorial) orbital solar torque modulus (only giant planets). The result is identical to $|T_G|$ spectrum.

Fig. 14. Ascending node evolution of the solar barycentric orbit (one point per year), the same oscillations are performed by $\mathbf{L}$ vector around the $z$-axis of the inertial system, in this case, the ecliptical J2000.0 system.

Fig. 15. Sketch of the IHS system showing the solar equator ($Q_{solar}$), the ecliptical plane (the $x$-$y$ plane of the inertial system) and its pole $\mathbf{Z}$ (the $z$-axis of the inertial system). The angles of orientation $\epsilon_s$ and $\Psi_s$ between the IHS and the inertial system are indicated (the orientation between $\mathbf{S}$ and $\mathbf{Z}$ was largely exaggerated by convenience). The $\mathbf{L}$ vector has a precessional-like movement around $z$-inertial axis (it was idealized by the shadowed ellipse). The position angles of $\mathbf{L}$ respect to $\mathbf{S}$ ($\alpha$ and $\delta$) are indicated with double arcs.

Fig. 16. $\alpha$ and $\delta$ evolution in the studied period. The most important peaks occur each $\sim 38$ yr, due to Jupiter, Saturn and Neptune alignments. The greatest peak around 1990 involve the four giant planets.
Fig. 17. MTM spectra of Paraná and α series. The vertical lines mark the band at which the spectral power of $D$ is significant at 50-95%. Surprisingly, in this sub-decadal band four peaks seem to be very similar in both series. Certainly, Paraná spectrum is more similar to α spectrum than $|T_G|$ spectrum. Also, a prominent bi-decadal band is also seen in α spectrum. Its median coincides $\sim$ with 22-yr Hale cycle.

Fig. 18. MEM spectra of Paraná $D$ series and α series (both on annual basis). It confirms the coincidence between four peaks. Therefore in the sub-decadal band Paraná’s $D$ series has virtually the same frequencies than α series (the porcentual error is lesser than 5%).
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