Possible Origin of Some Periodicities Detected in Solar-Terrestrial Studies: Earth’s Orbital Movements

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Abstract Periodicities matching planetary cycles have been argued to be detected in key geophysical time series. In general, these periodicities were indirectly attributed to a planetary influence on solar activity. This supposes that planetary gravity affects the internal functioning of the Sun’s dynamo, that is, the planetary hypothesis (PH) of the solar cycles. The Earth’s heliocentric dynamics already includes the planetary gravitational effects on the Sun. Taking into account this fact, these periodicities, ultimately attributed to possible planetary modulations of the solar activity, could have a more direct origin in cyclical changes in the relative Sun-Earth geometry, but then, wrongly or partially explained invoking internal solar changes. We present an original decomposition analysis of the high-precision ephemeris DE431 from NASA/JPL in order to obtain and classify the most important planetary/lunar purely periodic changes of the Earth’s orbital movement at sub-Milankovitch scales. A comprehensive list of cyclical changes of the Earth’s orbital parameters involved in the relative Sun-Earth position and the Earth’s speed around the Sun is given. We show that these particular geophysical quasi-periods are identifiable in the cyclic oscillations of these orbital parameters. Since the Earth’s movement in space physically affects the manner in which the solar radiant flux reaches the planet, these oscillations provide, unlike the PH, a clear, causal, and testable link for their possible attribution.

1. Introduction

One of the most important methodological challenges in Earth sciences is the establishment of the syllogism of detection-attribution-mechanism via a sequential chain of causal reasoning. This process begins with the observation of periodicities (quasi-periods) present in geophysical time series, going from the inquiry about the physical causal link for their attribution to the theoretical explanation of their mechanisms of actions/impacts within the terrestrial system. The Milankovitch-oriﬁcial forcing on the climate system is one of the most interesting cases of study in this regard. The Milankovitch theory of paleoclimates (Berger et al., 1993; Milankovic, 1941) clearly offers a causal link (i.e., insolation variations by orbital changes in ten to hundred thousand years) that permits the attribution of well observed periodicities imprinted in the geologic and oceanic sedimentary records (e.g., Hays et al., 1976; Imbrie, 1982), to long-term oscillations in two specific elements of the relative Earth’s orbit around the Sun, and in the axial tilt of the Earth. Nevertheless, the attribution of some periodicities, for example, the “100 kyr problem,” and the proposal of a terrestrial mechanism driving these insolation cycles and producing such evident climate changes as polar and mountain-top glaciations (see e.g., Litaudet al., 2020; Paillard, 2010) are still under debate. Indeed, Milankovitch theory was strongly attacked or even ignored, at least until the beginning of the seventies, to be a “weak forcing,” with undetectable effects from the climate models of that epoch of 1970s. The “100 kyr problem” referred to above is about the strong signal of eccentricity detected in sedimentary (including paleomagnetic) records, instead of the eccentricity producing almost negligible seasonal insolation changes of small amplitudes, at most 2 W m⁻² peak-to-trough in several kyr (see e.g., Berger & Andjelic, 1988; Berger et al., 2005; Kaufmann & Juselius, 2016; Lisiecki, 2010).

A similar methodological issue arises with the solar activity impacts on the Earth. Although there is no doubt about the existence of some clear signatures of solar-radiative forcings in the climate system related to the most evident ~11 years Schwabe cycle and its modulating ~22 years Hale magnetic polarity cycle, and also possibly the imprint on paleoclimates of longer quasi-cycles at centennial scales (see e.g., Gray
et al., 2010), there are other more elusive solar quasi-periods, from annual to multi-decadal time scales, very similar to those argued to be detected in, for example, geomagnetic indices or climatic proxies (see e.g., Le Mouël et al., 2019a; Le Mouël et al., 2019b), which impose the need to propose conceivable mechanisms capable of generating obvious responses in the Earth system at those short time scales.

Specifically, a wide set of data series of primary geophysical interest and connected to a Sun-Earth relationship is linked to planetary cycles. Although several ideas have been proposed for linking planetary movement and internal climate dynamics (e.g., direct gravitational effects, electromagnetic planetary forces affecting the heliosphere, etc.), the main body of hypotheses relies on direct planetary influence on solar activity (i.e., the planetary hypothesis [PH]). These kinds of associations can be found profusely in solar/geophysics literature and we present a selection of them in what follows. Charvátová (2007) identified common periodicities in proxies of solar activity, geomagnetic indices, and cosmic rays series, with planetary periodicities present in the solar movement around the Solar System barycentre, that is, the solar barycentric motion (SBM), especially the 1.6 years period, and others similar to harmonics of the synodic periods of the terrestrial planets. Hydrologic cycles of large rivers have been linked to specific SBM’s periodicities (Antico & Kröhling, 2011; Tomasinio et al., 2004; Zanchettin et al., 2008); these associations were made by means of common periodicities (~8 year) present in both the discharges of these rivers (the Po River in Europe and the Paraná River in South America) and the orbital angular momentum of the Sun. Spectral analyses of the global surface temperature records (i.e., Hadley Centre-Climatic Research Units temperature [HadCRUT], series) by Scafetta (2010) show conspicuous periodicities around ~9, ~20, and ~60 years. In addition, Scafetta (2012a) has studied the historical records of mid-latitude auroras from 1700 to 1966 showing, basically, the same set of spectral peaks. Scafetta (2010) and Scafetta (2012a) mainly attributes these periodicities to specific SBM frequencies, and also the ~9 years quasi-period to lunar origin. Le Mouël et al. (2020) confirm these periodicities in new HadCRUT data series and detect new ones in the decadal and interannual time scales, mainly ~11 years, ~6.5, ~5.3, ~4.7, and also ~9.1 years, which the authors attributed to solar cycles. Le Mouël et al. (2019a) and Le Mouël et al. (2019b) detect short periodicities in climatic and geomagnetic indices, identifying periodicities at ~47, ~32, ~22, ~11 years, ~9, ~5.5, and ~3.6 years. Recently, these authors (Courtillot et al., 2021) propose that all of these aforementioned quasi-periods have a planetary origin through the PH. In addition, there are other authors that, on the contrary, have criticized the determinations and/or the attribution of some of the above-mentioned superficial temperature periodicities (especially the 60 years period), to planetary cycles (see e.g., Cuypers et al., 2021; Holm, 2014), but their comments have been since replied to (Le Mouël et al., 2021; Scafetta, 2016).

The working hypotheses and conclusions of these works are based on empirical/phenomenological correlations or more analytical arguments, but in general, those detected cycles are directly related to the SBM and this movement connected through solar activity with these geophysical phenomena. Although at present, there are proposed mechanisms linking planetary frequencies to the manifestations of the solar dynamo (see Cionco & Compagnucci, 2012; Scafetta, 2012b; Stefani et al., 2019, for overviews and reviews on these topics), the main drawback with the PH is the lack of a clear physical link between planetary gravity and an internal dynamical forcing in the Sun able to explain all the alleged periodicities in the different time scales involved, say, from annual to centennial. In addition to this fact, these solar periodicities, apart from the ~11 and ~22 years, have been questioned not only on their spectral significance but also on their own dynamical origins, being under specific circumstances consistent with random noise produced in the solar dynamo, that is, they are obtained without the hypothesis of a regular forcing (see Cameron & Schuessler, 2019, especially Figure 1, and references therein).

In this work, we propose a different view on the subject of the geophysical quasi-periods linked to planetary cycles. The seed idea is that the heliocentric dynamics of the Earth already considers the gravitational planetary effect on the Sun. Some of these periodicities often attributed to possible planetary modulations to the solar cycles, and also detected in the SBM, could be fully or partially originated in periodic changes in the Earth’s orbital movement itself, then, wrongly explained by or partially attributed to changes in the internal functioning of the Sun. In what follows, we understand by “main periodic oscillations” the purely periodic (nonsecular) component, that is, at sub-Milanković scale, of the Earth’s orbital elements variations. Therefore, it is fundamental to specify the main periodic oscillations of the Earth within the heliosphere, especially in those parameters which directly affect the incoming solar radiant fluxes. In what follows, we
consider the solar radiant fluxes to be both the density fluxes of photon energy but also solar wind charged particles emitted by the Sun. Moreover, those periodicities reported in geophysical time series that were linked to the PH have not been studied with respect to physically significant orbital forcings. They have only been analyzed within the frame of the proposed hypothetical changes in the Sun. The possibility of an orbital forcing of the incoming solar fluxes has been, in general, ignored in this context. One reason could be that the Milanković theory was constructed to explain major glaciations, then, dismissing the high-frequency changes in orbital parameters (Cionco & Soon, 2017). Indeed, Milanković forcing just takes into account the secular (i.e., variations whose amplitudes are proportional to time) and very long-term periodic variations of the Earth’s orbit. Although short-term orbital variations were also studied (shorter than Milanković scales, i.e., lesser than few $10^3$ years, Cionco & Soon, 2017; Loutre et al., 1992; Scafetta et al., 2019), the Milanković forcing relies on the specific effects of just two orbital parameters, namely, the eccentricity $e$ and the longitude of the perihelion $\omega$ (in addition to the Earth’s obliquity, which is the axial tilt of the Earth), manifested as modulation of the insolation reaching the top of the atmosphere. In this work, we propose to consider a wider set of orbital parameters including not only these three elements related to Milanković forcing, but also other meaningful dynamical parameters in the context of the Sun-Earth geometry.

The most important change of the Earth’s motion around the Sun is the annual cycle, that is, the Keplerian motion of the Earth in its orbit. This annual cycle, with an amplitude of $\sim 2.5 \times 10^5$ km in the heliocentric distance $r$ (i.e., the maximum departure from its mean value), produces the most evident changes in total solar irradiance (TSI) of $\sim \pm 3.2\%$, about 6.4% between perihelion and aphelion. In addition, the solar cycle of $\sim 11$ years produces a change of $\sim 0.1\%$ in the received TSI flux (i.e., between maximum and minimum); in spite of this variation, the imprint of the Schwabe cycle is argued to be detectable in the Earth system especially within the atmosphere (Gray et al., 2010; Le Mouël et al., 2019a). In this work, we are not, in general, interested in these Keplerian changes, but instead we focus on the additive and persistent periodical changes to that Keplerian motion, produced by the perturbative effects of the other bodies of the Solar System. In addition, we are not proposing an alternative explanation of the well-known terrestrial effects of the Schwabe and Hale cycles. Instead, we are showing the main periodicities present in the Earth orbit and consistent with an orbital forcing, some of them also contributing to the $\sim 11$ and $\sim 22$ years bands, but especially the similar ones to those weaker solar cycles at annual and multi-decadal time scales.

It may be surprising but important to stress that a general description of these periodic perturbations to the Earth orbital movement (especially of those with shorter time scales) is not widely available, even in astronomy textbooks. Nevertheless, semi-analytic planetary theories such as the VSOP87 (Variations Séculaires des Orbits Planétaires) series (Bretagnon & Francou, 1988) do account for these perturbations in their final products. It is worth noting that in VSOP87 series, the orbital elements of the Earth-Moon barycentre are analyzed rather than the single Earth in its orbit. Nonetheless, the VSOP87B and D solutions give the heliocentric spherical coordinates of the single Earth, but not its orbital elements. At present, the most accurate orbital solutions valid for very long time-span (i.e., longer than VSOP series), for example, for the whole Holocene, are the EPM2018H ephemeris of The Institute of Applied Astronomy of the Russian Academy of Sciences (Cionco & Pavlov, 2018; Pitjeva & Pitjev, 2019) and the DE431 NASA/JPL ephemeris (Folkner et al., 2014). Numerical ephemerides such as DE431 account for these orbital perturbations directly, integrating accurate planetary models at each convenient time step. But the outputs of these ephemerides do not directly show, for example, which disturbing planets produce specific oscillations to the Earth movement at certain frequency band. Fortunately, there exist approaches to handling such a problem which permit the expansion in trigonometric series of long-term numerical ephemerides. This permits the identification and evaluation of the main disturbing terms in each orbital parameter obtained from these ephemerides. In particular, Kudryavtsev (2007, 2016, 2017), unlike the procedure involving classical Fourier analysis, developed and used a method in which both amplitudes and arguments of the series terms (based on planetary ephemerides) are adjusted as high-degree polynomials of time. Then, the periodic perturbations in certain orbital parameter can be identified and expanded in a trigonometric series, with their planetary origins clearly determined.

We present in this study an original analysis of the Earth’s orbit (as a single body), using the high-precision ephemeris DE431 by means of the frequency analysis method devised by Kudryavtsev (2007), in order to identify and classify the most important planetary and lunar periodic perturbations in relevant orbital parameters for the solar-terrestrial-relation studies. A general result is that we have found, within the Earth’s
orbital parameters analyzed, virtually all these claimed planetary periodicities reported in geophysical time series and related to the PH. Owing to the fact that these oscillations of the Earth orbital movements in space physically affect the manner in which the solar radiant fluxes reach the planet, they should be fully considered in the physical analysis of weak but persistent impacts of extraterrestrial forcings on Earth.

2. Methods

2.1. On Obtaining the Main Periodic Oscillations of the Earth Orbital Motion

Let us first suppose that just two bodies (the Sun and the Earth) orbit around the Solar System barycentre (hereinafter the barycentre). According to Newton’s law of gravitation, both bodies describe idealized Keplerian ellipses around the barycentre. The Sun is not only the main source of energy of the Earth’s atmosphere, but by far, contains almost all of the Solar System mass. Then, it is useful to describe the Earth’s orbit around the Sun, that is, transfer the origin of the System from the barycentre to the heliocentre. Consequently, in the heliocentric system the equation of motion of the Earth, of mass $m$, is:

$$ \ddot{r} = -G(M + m) \frac{r}{r^3} $$

(1)

where $r$ and $\dot{r}$ are, respectively, the Earth heliocentric position and acceleration; $G$ is the gravitational constant; $M$ is the mass of the Sun. The solution of Equation 1 implies the determination of six constants (or elements), by means of which we can calculate $r$ and the velocity, $\dot{r}$, of the Earth around the Sun at a specific time $t$, by using the well-known formulas of the two-body problem. Some of these constants were already mentioned in Section 1 such as $e$, which, in addition to the semi-major axis $a$, define the ideal Keplerian orbital ellipse around the Sun. Other elements such as the longitude of the perihelion $\sigma$, the orbital inclination, and a temporal reference indicating the Earth position in its orbit at a particular moment are given (see e.g., Murray & Dermott, 1999, for a representation of the Keplerian elements). This orbital Keplerian movement produces the annual/semi-annual cycles around the Sun.

Let us suppose now that another body, Jupiter for instance, is also orbiting the barycentre. In this case, Equation 1 just undergoes a “little” modification (see Murray & Dermott, 1999):

$$ \ddot{r} = -G(M + m) \frac{r}{r^3} + Gm_j \nabla_r [R_d(d_j) + R_r(r, r_j)] $$

(2)

where $m_j$ is Jupiter’s mass ($\sim 10^{-3}M$); $d_j$ is the Earth-Jupiter relative distance; $r$, is the heliocentric distance of Jupiter. The additional term to Equation 1, that is, the gradient $\nabla_r$, is a small quantity which describes the perturbative effect of Jupiter on the Keplerian Sun-Earth motion through the function $R_d + R_r$; that is, the Earth’s disturbing function, which is composed of a leading term, $R_d$, the direct perturbation of Jupiter to the Earth, and $R_r$, which indirectly perturbs the Earth motion, because it not only depends on the Sun-Earth distance, but mainly, on the Sun-Jupiter distance (see e.g., Murray & Dermott, 1999). Then, the indirect part of the disturbing function exists because the origin of the reference system is transferred to the heliocentre, and its purpose is to describe the action of the planets on the Sun, that is, the SBM (see also Brouwer & Clemence, 1961; Knezevic, 1993).

The determination of these non-trivial periodic changes to the Earth’s movement produced by the planetary/lunar perturbations is the main goal of this work. To accomplish this task, the original method by Kudryavtsev (2007), SK method hereinafter, was applied to DE431 ephemeris of the Earth as a single body. It is indeed possible to physically relate periodic variations in terrestrial dynamics parameters to planetary/lunar perturbations which produce such periodicities. This can be done via a simple geometrical variable, for example, the mean orbital longitude $\lambda$, which describes the mean angular position of the planets in their orbits from an arbitrary origin. First, the SK method was applied to the selected orbital parameters to be analyzed, to approximate their long-term secular trends as polynomials of sixth degree. The remaining components are expanded in trigonometric series, where both amplitudes and arguments of the series terms are high-degree polynomials of time. When performing this analysis, we compute and analyze more than 150,000 terms of different frequencies. These frequencies are obtained as linear combinations of integer multipliers of a number of basic frequencies specific to the planetary/lunar mean longitudes and to other significant variables in the Moon motion. In our study the values of integer multipliers could vary from $-20$
to +20. Therefore, we assume that in our parametric search we have considered nearly all reasonable linear combinations of planetary/lunar frequencies and their corresponding periods. Among them the algorithm gradually selects and orthogonalizes all terms of the largest amplitudes which eventually compose the final series.

Then, the pure periodic variations in the orbital parameter $X$ over time, $\Delta X_{pe}(t)$, can be obtained at zeroth-order in $t$ for the amplitudes and by using the first-order of the argument frequencies only, that is:

$$\Delta X_{pe}(t) = \sum_{j=1}^{N} S_j \sin[A \cdot p_j] + C_j \cos[A \cdot p_j],$$  

where $N$ is the number of terms of the series; $S_j$ and $C_j$ are constant amplitudes; $A = (\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_i)$ is the vector of the mean orbital longitudes of the involving bodies; and $p_j = (p_{i1}, p_{i2}, p_{i3}, \ldots, p_{ij})$ is a particular combination of integers. The mean orbital longitude for planet $i$ is written here as:

$$\lambda_i = n_i(t - t_0) + \lambda_{0i},$$  

where $n_i$ is a frequency named the orbital mean motion in the case of the planetary bodies, and in the case of the Moon they correspond to the first-order frequencies associated with the Delaunay arguments of the Moon, $D, F, l$, and the mean longitude of the Moon in its orbit, $L$, given with respect to the equinox of date (see e.g., Bretagnon & Francou, 1988). The $\lambda_{0i}$ angle is an initial phase related to the reference time $t_0$, the so-called epoch, which in our case was J2000.0, that is, 01/1/2000 about 12 h UTC. The analysis is performed over the full length of the DE431 ephemeris, that is, approximately from 15,151 BP to 15,241 AP.

As the series expansions (Equation 3) need to be truncated at certain level of precision (the series can involve several thousand of terms, see e.g., Kudryavtsev, 2016, 2017), and we were interested in the most important periodic oscillations of the selected orbital parameters, so we restricted ourselves, in principle, to the first 250 terms of each expansion. Prior results show that this threshold corresponds to oscillations of the order of 0.4 km in distance or $\sim 3 \times 10^{-9}$ au (au: astronomical unit); in addition, this corresponds to precision of the order of $\sim 1 \times 10^{-8}$ or better in non-dimensional quantities. Nonetheless, in Section 4, we discuss an extension to the expansion in $r$, searching for specific oscillations. For these purposes, it is enough to consider the planets and the Moon as main disturbers of the Earth motion. Thus, we use 12 combinations of mean frequencies (i.e., maximum $i = 12$). Accordingly, the mean orbital longitudes of the planets from Mercury to Neptune were assigned with the index $i = 1, \ldots, 8$ (e.g., the Earth is $i = 3$); and the Delaunay arguments have the indexes $i = 9, \ldots, 11$, with $\lambda_9 = D, \lambda_{10} = F, \lambda_{11} = l$, and $\lambda_{12} = L$. In this way, the argument of the harmonic oscillation for the term $j$ of the series can be represented as:

$$A \cdot p_j = (p_{i1}n_i + \cdots + p_{i2}n_{i2})t + \phi_{0j},$$  

where $\phi_{0j}$ is the initial phase of the $j$–term. From here, it is straightforward to obtain the periodicity, $T$, of such particular $j$–oscillation:

$$T = \frac{2\pi}{n \cdot p_j},$$  

where $n$ is the vector of frequencies of the considered variables. For example, one of the most important perturbations is produced by the trigonometric argument $\lambda_3 - 2\lambda_4$ (i.e., $p_j = 0, 0, 0, 1, -2, 0, 0, 0, 0, 0, 0, 0$), where $\lambda_3$ and $\lambda_4$ represent the corresponding mean orbital longitudes of the Earth and Mars, respectively. In the case of this term, its period is 15.78 years. In addition to the period of the $j$–oscillation in the element $X$, the strength or amplitude of the $j$–rank oscillation, $P_j$, can be obtained by the combination of both harmonic amplitudes:

$$P_j = \sqrt{S_j^2 + C_j^2},$$  

which permits the establishment of a relative ordering, following the amplitudes of each considered perturbation. In the next subsection, we identify meaningful parameters to be expanded in order to obtain their periodic oscillations.
2.2. On Selecting Relevant Orbital Parameters for the Analysis

The observed solar radiant fluxes at \( r \), \( f(r) \) (radiant power per unit of area), for example, the 10.7-cm solar radio flux, are affected by the changing Sun-Earth distance (even for spaceborne measurements). They depend on the inverse-squared-law of the distance:

\[
f(r) = f_0 \left( \frac{1 \text{ au}}{r} \right)^2, \quad (8)
\]

where \( f_0 \) is a specific solar radiant flux at a fiducial distance, in this case, on a spherical surface at 1 au from the Sun (i.e., at a fix distance of 149,579,870.7 km). The same \( 1/ r^2 \) law holds, for example, for modeling the density of the solar wind within the heliosphere. Following the model described by Equation 8, the measurement of solar fluxes at the Earth orbit is solely affected by changes in the Sun-Earth distance. As a well-known result of the two-body problem, the heliocentric distance depends on three Keplerian elements, namely, \( a \), \( e \) and \( \sigma \), and also on the exact angular position of the Earth in its orbit, that is, the true-orbital longitude \( \lambda \) (see Murray & Dermott, 1999):

\[
r = \frac{a(1 - e^2)}{1 + e \cos(\lambda - \sigma)}. \quad (9)
\]

Now, it is straightforward that an oscillation of amplitude \( dr \) in the heliocentric distance produces a variation \( df(r) \) in the instantaneous solar fluxes:

\[
\frac{df(r)}{f(r)} = \frac{-2}{r} \frac{dr}{r}. \quad (10)
\]

It is important to stress that we are particularly interested in the non-Keplerian oscillations of \( r \), originated in the periodic perturbative variations in \( a \), \( e \), \( \sigma \) and also \( \lambda \).

For the whole Earth, the amount of solar energy \( J \), received between two orbital positions \( \lambda_a \) and \( \lambda_b \), associated with the solar flux \( f_0 \) is (Loutre et al., 2004; Milanković, 1941):

\[
J = f_0 T \frac{R^2}{2} \left( \frac{1}{1 - e^2} \right)^{3/2} (\lambda_b - \lambda_a) = f_0 T \frac{R^2}{2} \left( 1 + \frac{e^2}{2} + \frac{3}{8} e^4 + O(e^6) \right)(\lambda_b - \lambda_a). \quad (11)
\]

where \( R \) is the Earth’s radius, \( T \) is the duration of the year. Considering the small value of \( e \), we have used a binomial expansion for \( (1 - e^2)^{3/2} \). The same dependence on the element \( e \) is valid for the energy received by each hemisphere or by the whole Earth annually.

On the Earth, the effect of the incoming solar radiation at the top of the atmosphere also depends on the inclination of the Sun’s rays. For example, the instantaneous solar irradiance (the insolation) above a geographic parallel of latitude \( \phi \), \( I_\phi \), depends not only on \( r \) but also on the zenith angle \( z \):

\[
I_\phi(r,z) = TSI_0 \left( \frac{1 \text{ au}}{r} \right)^2 \cos z, \quad (12)
\]

where TSI0 is the "solar constant" (generally reckoned in W m\(^{-2}\)), that is, TSI at 1 au. Variations over time in TSI0 are supposed to be produced by the solar magnetic activity cycles, resulting in the solar-radiative forcing on the climate system.

From a climatic point of view, there is a solid theoretical background to reckon insolation quantities using different metrics for a specific orbital position or an orbital interval, for example, daily irradiation, seasonal irradiation, latitudinal insolation gradients, etc (see Cionco, Soon, & Quaranta, 2020). The variations of these quantities over time permit the determination of several forcing indices, evaluating them at different latitudes to be used in the analysis and interpretation of climate proxies or paleoclimates models. These are the bases of Milanković-orbital forcings on climate system. Therefore, in our exploration of possible interactions of these orbital periodic terms with intrinsic solar fluxes, we also consider these orbital forcings at shorter time scales (i.e., shorter than the Milanković’s scales); they are valid expressions no matter the temporal basis used.
It is important to stress that, for practical applications of these formulas in a climatological sense, all the parameters reckoned from the equinox must be specified from the *true equinox of the date*, that is, from the equinox affected not only by precession but also by nutation (see e.g., Cionco & Soon, 2017). The long-term evolution (longer than several thousand years) of the equinox is included in the precession formulas, whereas the shorter periodic changes are incorporated in the nutation model. Consequently, precession is just considered as a progressive effect affecting λ and σ, and it is excluded from the present periodic short-term analysis. Then, the involved orbital longitudes reckoned from the equinox of the date and having the nutational periodicities are named λ and σ. In this way, independent of the orbital perturbations, the precise instant of the year at which, for example, equinoxes occur is fixed at λ = 0°,180°; the solstices are at λ = 90°,270°; etc.

The basic and one of the most used metrics for evaluating the incoming solar radiations is the mean daily insolation at the parallel of latitude \( \phi \), \( W_\phi \), that is, the averaged irradiance received during a full rotational day. It is characterized by a fixed and constant value of the true longitude at certain day, \( \lambda_{dl} \) (Berger et al., 2010; Cionco, Soon, & Quaranta, 2020):

\[
W_\phi(\lambda_{dl}) = \frac{\text{TSIo}}{\pi} \left( \frac{1 \text{ au}}{r(\lambda_{dl})} \right)^2 F_\phi(\lambda_{dl},e). \tag{13}
\]

\( F_\phi(\lambda_{dl},e) \) is, for a given orbital position, solely a function of the terrestrial obliquity, \( e \). \( F_\phi \) is independent of any orbital element. Accordingly, Equation 13 serves as a natural forcing function allowing for variations of the orbital elements \( a \), \( e \) and \( \sigma \). Other forcings such as the seasonal irradiation or, more generally, intra-an-nual lapses of irradiation for parallels of latitude are independent of \( r \), as shown under Equation 11, being an exclusive function of \( e \) (Berger et al., 2010; Cionco, Soon, & Quaranta, 2020).

Regarding the obliquity variations in Equation 13, the torque produced by the main bodies of the Solar System changes the Earth’s spin axis position over time. Nutation changes are mainly driven by the retrograding motion of the lunar orbit, which is characterized by the changing position of the lunar nodes (i.e., the intersection of the lunar orbital plane with the ecliptic), that is, the Lunar Nodal Cycle (LNC) with a period of 18.6 years and amplitude of \(~ 4.5 \times 10^{-3} \text{ rad in obliquity} \) (see Cionco, Soon, Elias, & Quaranta, 2020); the effects of the nutation in longitude will be discussed in Appendix A. Thus, this oscillation in obliquity is a very well-known issue and is not connected with our orbital analysis.

To gain insights into how \( e \) and \( \sigma \) interact to produce variations under Equation 13, we follow the Milanković approach (see also Berger et al., 1993), which consists in showing how these two elements are mixed in these formulas. For example, Equation 13 can be expanded in powers of \( e \) (see Appendix A), which at third order in the eccentricity reads:

\[
W_\phi(\lambda_{dl}) = \frac{\text{TSIo}}{\pi} \left( \frac{1 \text{ au}}{a} \right)^2 \left[ 1 + 2e \cos(\lambda_{dl} - \sigma) + e^2 \left( \cos^2(\lambda_{dl} - \sigma) + 2 \right) + 4e^3 \cos(\lambda_{dl} - \sigma) \right] F_\phi(\lambda_{dl},e) + O(e^4). \tag{14}
\]

Sedimentary records show that, very probably, the most important orbital forcing indices that can be obtained independently of the metric used are based on summer time (see e.g., Loutre et al., 2004). Then, evaluating Equation 14, at the solstices we found, for each hemisphere, the June mid-month insolation (Northern Hemisphere summer, \( \lambda_{dl} = 270^\circ \)), and the December mid-month insolation (Southern Hemisphere, \( \lambda_{dl} = 90^\circ \)). Making use of the so-called *non-singular elliptic elements* \( h = e \sin \sigma \) and \( k = e \cos \sigma \) and differentiating Equation 14, we have at third order in the eccentricity (see Appendix A):

\[
\frac{dW_\phi^{(e)}}{W_\phi} = -2 \frac{da}{a} + \left( \frac{r}{a} \right)^2 \left[ \pm 2 + 6 h \pm 12 h^2 \pm 4k^2 \right] dh + 4k(l \pm 2h) dk. \tag{15}
\]

The \( \pm \) sign holds for the Southern and the Northern Hemisphere, respectively; \( r \) is \( r \) evaluated at the solstitial points. The \( h \) parameter reckoned from the moving equinox of the date is called the *climatic precession* index (although at short-term scale, it is fundamentally affected by nutation). Then, \( e \) and \( \sigma \) can be replaced...
by \( h \) and \( k \) variables; indeed, they are preferred in the semi-analytical development of planetary equations (Kudryavtsev, 2016, 2017; Simon et al., 2013).

We have shown that the received solar fluxes strongly depend on \( r \); nevertheless, there are important differences taking into account the temporal bases used to reckon them: the instantaneous fluxes depend on the full variations of \( r \), through perturbations in \( a \), and in \( e \) and \( \sigma \) variables (i.e., \( h \) and \( k \) variables), and also on the Keplerian (i.e., annual cycle) and non-Keplerian (i.e., perturbative) oscillations of \( \lambda \) (Equations 9 and 10). For the whole Earth, annual and intra-annual lapses of insolation depend exclusively on the disturbing oscillations of \( e \) (Equation 11). The eccentricity is fully related to \( h \) and \( k \) elements: \( e^2 = h^2 + k^2 \), then intra-annual/annual irradiation is fully dependent on \( h \) and \( k \) oscillations. At daily scale, solar irradiation at parallel of latitude depends exclusively on \( a \), \( h \) and \( k \) elements. Therefore, in order to trace the non-trivial origins of the cyclic variations of these incoming solar quantities, we need to study the perturbative periodic oscillations in \( r \), \( a \), \( h \), \( k \) and also \( \lambda \) parameters. Unfortunately, a determination of the planetary/lunar perturbations on \( \lambda \) using expansion methods, such as the SK method, is non-effective because of the existence of numerous terms with similar frequencies and amplitudes. A way of resolving this problem is to expand the mean orbital longitude \( \lambda_o \) (Kudryavtsev, 2016, 2017; Simon et al., 2013). In Appendix B, we show how \( r \) can be casted as a function of \( \lambda_o \).

In addition to these orbital parameters, the analysis of other quantities whose oscillations can express changes in a "normal" direction to the orbital plane can also be meaningful. The orbital inclination regarding the ecliptic of reference or, for example, the oscillations of the Earth's orbital movement normal to the Sun's equator can be useful for this task. This last movement can be quantified through changes in the heliographic colatitude of the Earth, \( \theta \), that is, the angle between the Sun's spin axis and the Sun-Earth's radius vector, \( r \):

\[
\cos \theta = \frac{\mathbf{r} \cdot \mathbf{r}_s}{rr_s},
\]

where \( \mathbf{r}_s \) is the projection of \( \mathbf{r} \) onto the solar spin axis. For that, we applied several rotation matrices to relate the inertial equinox and ecliptic J2000.0 system to the solar heliographic system (Burlaga, 1984). Vieira et al. (2012) have studied long-term variations of orbital inclination regarding anisotropies in the solar density fluxes of radiation. Nevertheless, the \( \cos \theta \) parameter is better to describe terrestrial oscillation in a reference frame fixed to the Sun, because this parameter has accounted not only for inclination oscillations but also for all the frequencies of the latitudinal oscillations of the Earth observed from the Sun (annual cycle, semi-annual cycle, etc.). This is why it could be relevant in the interpretation of notable present annual-scale periodicitities in the study of TSI measurement, possibly related to hemispheric differences in the Sun's irradiance (Mordvinov & Willson, 2003, see also Section 4). As the solar spin axis (i.e., the \( z \)-axis of the heliographic frame) precesses around the ecliptic's pole at a rate of \( \sim 1.4^\circ \) per century with a tilt of \( \sim 7.25^\circ \) (Urban & Seidelmann, 2013), an additional term \((i = 13)\) is added to the SK method expansion, in particular to Equation 3, that is, \( \lambda_{13} = 1.42(t - 2000.0) / 100.0 \), with \( t \) reckoned in years.

Therefore, following previous analysis, we have decided to expand \( r \), \( a \), \( h \), \( k \) and \( \lambda_o \) (replacing \( \lambda \)), and to get a wider perspective of the orbital oscillations in the heliosphere, we also expand \( \cos \theta \) and the Earth's orbital speed, \( v = | \dot{\mathbf{r}} | \).

3. Results

A selection of the main periodicities of \( r \), \( a \), \( h \), \( \lambda_o \), \( \cos \theta \), and \( v \) is shown in Tables 1–6, respectively. The full outputs (including oscillations in \( k \)) can be obtained as supporting information (http://sai.msu.ru/neb/ksm/periodicities.zip) and they are necessary for the complete analysis of our results. Every periodicity is represented in the form of a single cosine-function. The full outputs include the amplitude, as defined by Equation 7, frequency and phase, at the epoch J2000.0, of every argument. Additionally, we give the combination of integers used to calculate the frequency of each term and the corresponding period.

The comparison of Tables 1–4 gives an idea about which of the parameters that define the heliocentric distance are more affected by the non-Keplerian disturbing oscillations at specific spectral bands. Some periodicities show a clear non-linear reinforcement in Equation 9. For example, the main planetary term
Table 1
Selected Perturbations to the Heliocentric Distance $r$, Following DE431 Expansion by the SK Method

| $j$  | Argument | Period (year) | $P_j$ (km)   |
|------|----------|---------------|--------------|
| 1    | $1D$     | 0.0809        | 0.4613E+04   |
| 2    | $1\lambda_3 - 1\lambda_4$ | 1.0921        | 0.2436E+04   |
| 5    | $1\lambda_2 - 1\lambda_4$ | 1.5987        | 0.8116E+03   |
| 6    | $2\lambda_3 - 2\lambda_4$ | 1.0677        | 0.7065E+03   |
| 18   | $1\lambda_5$ | 11.8620       | 0.9411E+02   |
| 21   | $2\lambda_3 - 3\lambda_4$ | 2.4695        | 0.7391E+02   |
| 22   | $3\lambda_2 - 5\lambda_4$ | 8.1019        | 0.7026E+02   |
| 30   | $1\lambda_3 - 1\lambda_4$ | 2.1353        | 0.5168E+02   |
| 33   | $1\lambda_3 - 2\lambda_4$ | 15.7810       | 0.4764E+02   |
| 39   | $2\lambda_3 - 4\lambda_4$ | 7.8905        | 0.3529E+02   |
| 42   | $3\lambda_2 - 5\lambda_4$ | 2.9276        | 0.3049E+02   |
| 57   | $4\lambda_3 - 7\lambda_4$ | 3.5945        | 0.1312E+02   |
| 67   | $5\lambda_2 - 8\lambda_4$ | 7.8361        | 0.9845E+01   |
| 68   | $1\lambda_4 - 1\lambda_3$ | 0.3173        | 0.9690E+01   |
| 70   | $3\lambda_3 - 6\lambda_4$ | 5.2603        | 0.9155E+01   |
| 82   | $2\lambda_5$ | 5.9310        | 0.5992E+01   |
| 97   | $8\lambda_3 - 13\lambda_3$ | 238.9196      | 0.4222E+01   |
| 103  | $1\lambda_3 + 1D - 1l$  | 8.8504        | 0.3613E+01   |
| 104  | $1\lambda_3 + 1D - 4F + 3L$ | 4.6524        | 0.3565E+01   |
| 110  | $1\lambda_3 - 2\lambda_4 + 4F - 4L$  | 6.5991        | 0.2990E+01   |
| 124  | $1\lambda_5 - 5\lambda_4$ | 40.3329       | 0.2328E+00   |
| 131  | $4\lambda_3 - 8\lambda_4 + 3\lambda_4$ | 1.783.4122   | 0.1853E+01   |
| 137  | $1\lambda_4 - 4\lambda_4$ | 6.5751        | 0.1687E+01   |
| 144  | $1\lambda_6$ | 29.4572       | 0.1543E+01   |
| 155  | $3\lambda_3 - 5\lambda_4 - 4\lambda_4$ | 229.3002      | 0.1280E+01   |
| 163  | $2\lambda_5 - 5\lambda_6$ | 883.2639      | 0.1125E+01   |
| 170  | $2\lambda_6$ | 14.7286       | 0.1024E+01   |
There are no other non-lunar-planetary detectable periodic effects, but they are easily observable in the other parameters, which supposes a stronger interaction of these planetary terms through \( h, k \) and \( \lambda_3 \) parameters.

With the exception of \( \cos \theta \), which has a prominent long-term period of 25,769.5 years originated in the solar spin axis' precession rate \( (\lambda_4, j = 4) \), there are no other non-lunar-planetary detectable periodic effects modeled in DE431. The parameter \( \cos \theta \) shows a marked dominance of annual and near-annual periodicities. Indeed, the number of periodicities around 1 year is sensibly larger than the other parameters. As already mentioned in Section 2.2, we have retained for \( \cos \theta \) those periodicities originated in the annual/semi-annual cycles \((j = 1, 2, 3, 5, 6, \text{and } 7)\) in order to show how this basic movement produces heliocentric oscillations at annual scale.

The Moon produces the most important short-term oscillations in \( r \) through \( D \) angle, that is, the difference between the mean longitudes of the Moon and of the Sun (period 0.08 years or \( \sim 29.54 \) d), which is also the most important term in \( a \), \( \lambda_3 \) and \( v \); nevertheless, the \( \lambda_3 + D \) term (period 0.07 years or \( \sim 27.32 \) d) is \( j = 1 \) in \( h \) and \( k \). Even in \( \cos \theta \), after the terms related to annual and semi-annual cycles, \( F \) angle (linked to the lunar perigee) is the most important term, rank \( j = 8 \), period 27.21 days. A direct comparison with the VSOP2013 (Simon et al., 2013) outputs for the Earth-Moon barycentre shows huge differences, mainly in the amplitudes of \( a \), of the order of \( 10^3 \) au due to the lunar \( D \) argument, which is not present in the Earth-Moon barycentric dynamics. As expected, the amplitudes of the main planetary terms are quite similar in both VSOP2013/SK expansions. The Moon also participates in longer periodicities such as the term \( j = 238 \) in \( h \), of 25.9 years period, and the longer 423 years period, \( j = 178 \) in \( \lambda_3 \).

Although all the specific bands are in general populated by several periodicities, the intra-annual; besides the annual one, is especially dense. Notably, planetary perturbations due to Mercury \((\lambda_1 - \lambda_3, 115.89 \) days), Venus \((4\lambda_2 - 5\lambda_3, 243.15 \) days), by Mars \((3\lambda_3 - 3\lambda_4 \sim 260 \) d), and even by Jupiter \((3\lambda_3 - 5\lambda_3 \sim 141.64 \) d) are observed within the intra-annual band.

Around decadal band, the main contribution comes from Jupiter \((11.86 \) years); but for \( a \), the term \( 7\lambda_3 - 13\lambda_4 \) \((j = 175)\), period 11.35 years, is the most important. This last period also appears in \( r \) with the same rank. The second harmonics of Jupiter-Saturn synodic period, 9.93 years, is \( j = 185 \) in \( r \). There are several planetary terms around 11–12 years band in \( r \) and other parameters. There are interesting subdecadal periodicities such as the Moon's perigee precession \( \lambda_3 + D - l \), of 8.85 years, and especially the term \( 3\lambda_2 - 5\lambda_3 \) due

| \( j \) | Argument | Period (year) | \( P_j \) (km) |
|---|---|---|---|
| 175 | \( 7\lambda_3 - 13\lambda_4 \) | 11.3503 | 0.9898E+00 |
| 184 | \( 3\lambda_2 - 5\lambda_3 + 2\lambda_4 \) | 22.1349 | 0.9107E+00 |
| 185 | \( 2\lambda_3 - 2\lambda_4 \) | 9.9294 | 0.9092E+00 |
| 190 | \( 3\lambda_2 - 6\lambda_4 + 3\lambda_5 \) | 11.3302 | 0.8706E+00 |
| 212 | \( \lambda_3 - 2\lambda_4 + 2\lambda_6 \) | 220.8563 | 0.7188E+00 |
| 243 | \( 3\lambda_3 - 5\lambda_5 \) | 12.0235 | 0.4614E+00 |
| 245 | \( 3\lambda_2 - 7\lambda_3 + 4\lambda_4 \) | 302.4340 | 0.4514E+00 |

The original \( J \)-rank and the \( P_j \) amplitude of the corresponding term are indicated.
Table 2

| j  | Argument | Period (year) | $P_j$ (km) |
|----|----------|---------------|------------|
| 1  | 1D       | 0.0809        | 0.1345E+06 |
| 6  | 1D − 1l  | 1.1274        | 0.1291E+04 |
| 7  | $1\lambda_2 − 1\lambda_3$ | 1.5987 | 0.1138E+04 |
| 16 | $2\lambda_2 − 3\lambda_3$ | 3.9834 | 0.2209E+03 |
| 19 | $1\lambda_3 − 1\lambda_5$ | 1.0921 | 0.1642E+03 |
| 23 | $1\lambda_4 − 1\lambda_3$ | 0.3173 | 0.9619E+02 |
| 24 | $1\lambda_3 − 2\lambda_5$ | 1.2028 | 0.9606E+02 |
| 30 | $3\lambda_5 − 5\lambda_3$ | 8.1019 | 0.6831E+02 |
| 32 | $1\lambda_3 − 2\lambda_4$ | 15.7810 | 0.6450E+02 |
| 37 | $2\lambda_3 − 3\lambda_4$ | 2.4695 | 0.4801E+02 |
| 43 | $2\lambda_3 − 4\lambda_4$ | 7.8905 | 0.4083E+02 |
| 53 | $3\lambda_5 − 5\lambda_4$ | 2.9276 | 0.2206E+02 |
| 65 | $1\lambda_4 + 1D − 1l$ | 8.8504 | 0.1645E+02 |
| 77 | $3\lambda_3 − 6\lambda_4$ | 5.2603 | 0.1091E+02 |
| 79 | $3\lambda_3 − 5\lambda_4$ | 0.3878 | 0.1073E+02 |
| 81 | $4\lambda_3 − 7\lambda_4$ | 3.5945 | 0.1038E+02 |
| 92 | $5\lambda_5 − 8\lambda_3$ | 7.8361 | 0.8161E+01 |
| 106 | $5\lambda_3 − 9\lambda_4$ | 4.6547 | 0.5088E+01 |
| 114 | $5\lambda_3 − 8\lambda_4$ | 1.3396 | 0.4648E+01 |
| 120 | $1\lambda_3 − 1\lambda_6$ | 1.0352 | 0.4062E+01 |
| 123 | $8\lambda_2 − 12\lambda_3$ | 238.9196 | 0.3746E+01 |
| 131 | $1\lambda_3 − 2\lambda_6$ | 1.0729 | 0.3261E+01 |
| 133 | $4\lambda_3 − 8\lambda_4$ | 3.9452 | 0.3163E+01 |
| 138 | $1\lambda_3 − 2\lambda_4 + 4F − 4L$ | 6.5991 | 0.2733E+01 |
| 147 | $1\lambda_3 − 5\lambda_7$ | 40.3329 | 0.2367E+01 |
| 163 | $4\lambda_3 − 8\lambda_4 + 3\lambda_5$ | 1.783.4122 | 0.1807E+01 |
| 175 | $7\lambda_3 − 13\lambda_4$ | 11.3503 | 0.1611E+01 |

Our results show that these periodicities are especially observed in the exospheric zone of the Earth and Mars. The Moon also participates in multi-year periodicities through terms such as $1\lambda_3 − 2\lambda_4 + 4F − 4L$ (present in $r$, $a$, $h$, $k$, and $v$), 6.6 years period, and $F − l$, 6 years period in $\cos \theta$. Bi-decadal periodicities are observable in $r$, as $3\lambda_4 − 5\lambda_5 + 2\lambda_9$, period 22.13 years ($j = 184$). The 19.86 years period (Jupiter-Saturn synodic period) is just detected in $\lambda_3$ (ranks 116) at this level of precision.

Multi-decadal periodicities such as the mean orbital period of Saturn (29.46 years), the $\lambda_3 − 5\lambda_7$ term (40.33 years), the 60 years periodicity ($\lambda_5 − 2\lambda_9$), and the mean orbital period of Uranus (84.02 years) are all observed in $\lambda_3$, $h$, $k$, and in $\cos \theta$. In our expansion of $a$, just the 40.33 years period was observed. Nevertheless, the expansion of $r$ produces the periodicities 29.46 and 40.33 years at the $j = 250$ level of precision. This result is similar for the expansion of $v$.

Longer periodicities, such as the bi-centennial periodicity of 238 years produced by the high-order term $8\lambda_2 − 13\lambda_9$, are common to all the parameters; in $\cos \theta$ it appears as $8\lambda_2 − 13\lambda_9 + 1\lambda_{13}$ with a 236.7-year period. In the expansion of $r$, the 229.3-year ($j = 155$), the 220.86-year ($j = 212$), and the 302.43-year ($j = 245$) periodicities also appear. Centennial or millennial periodicities are more important in the angular variable $\lambda_3$, for which, after the $D$ argument, the combination $4\lambda_3 − 8\lambda_4 + 3\lambda_5$ produces the most important term, with a period of 1,783 years. This perturbation appears quite prominent in almost all the analyzed parameters, including $r$ ($j = 131$).

4. Discussion

First, we can assert that virtually all of the quasi-periods described in Section 1 are covered by the findings presented in Section 3. They are astronomically connected to planetary/lunar perturbations to the Earth’s Keplerian heliocentric motion.

Periodicities between 1.5 and 1.7 years, especially 1.6 years (Charvátová, 2007), are profusely found in all of the parameters analyzed. The most important term producing supra-annual oscillations in $r$ (also in $a$) is $\lambda_3 − \lambda_3$ of 1.6 years period ($j = 5$ in $r$). On annual time scale, the most conspicuous periodicity is 1.09 years, it is the most important planetary term in $r$ ($j = 2$) and it is present in all the analyzed variables. Near this period, the term $2\lambda_2 − 2\lambda_5$, 1.07 years period, appears as being significant in $r$ ($j = 6$) and $v$ ($j = 8$), adding power to this annual band. Mordvinov and Willson (2003) mentioned hemispheric differences in the Sun’s irradiance as the possible source of quasi-annual periodicities in TSI measurements. For example, the solar-radiative hemispheric anisotropies depend on contrasts of faculae and sunspots and also on the distribution of these specific magnetic features/zones on the Sun (Unruh et al., 1999; Vieira et al., 2012). These radiative models accounting for anisotropies do depend on the solar latitude of these zones, then periodic variations in the $\cos \theta$ will have an impact on the solar flux reaching the Earth.

Multi-year periodicities, such as $\sim 3.6$, $\sim 4.7$, $\sim 5.5$, and 6.5 years periodicity, are argued to be present in terrestrial data series, but were also attributed to the PH (e.g., Courtillot et al., 2021; Le Mouël et al., 2020). Our results show that these periodicities are especially observed in the ex-
The argument variables (ranks 30, 127, 129, and 213) and we found the 19.6 years period parameters (see Equation (8)) in addition to other near = 184. We found the 29.5 (term in this extra expansion. We also found at 2008 to 2021, the 40.33-year and 0.4302E−06 1.0921 883.2639 0.4491E−05 0.9665E−06 1.0729 1.1408 0.1982E−06 0.9704E−06 29.4572 0.1511E−04 0.6250E−03 7.8905 0.2944E−05 (adim)

| j  | Argument | Period (year) | Pj (km) |
|----|----------|---------------|---------|
| 144| $\lambda_3 + 2\lambda_4$ | 2.6704 | 0.8196E−05 |
| 145| $\lambda_3 - 5\lambda_2$ | 8.1019 | 0.2944E−05 |
| 146| $\lambda_3 - 2\lambda_2$ | 5.9310 | 0.2790E−05 |
| 147| $\lambda_3 + 2\lambda_4 + 1D$ | 8.8504 | 0.1420E−05 |
| 148| $\lambda_3 - 4\lambda_2$ | 15.7910 | 0.4491E−05 |
| 149| $\lambda_3 - 3\lambda_4$ | 1.3386 | 0.3546E−05 |
| 150| $\lambda_3 - 5\lambda_3$ | 1.1408 | 0.4835E−05 |
| 151| $\lambda_3 - 3\lambda_4$ | 1.2028 | 0.1864E−04 |
| 152| $\lambda_3 - 2\lambda_5$ | 11.8620 | 0.1511E−04 |
| 153| $\lambda_3 - 2\lambda_3$ | 2.6704 | 0.8196E−05 |
| 154| $\lambda_3 + 4\lambda_3$ | 3.9834 | 0.1987E−04 |
| 155| $\lambda_3 - 3\lambda_3$ | 1.1408 | 0.4835E−05 |
| 156| $\lambda_3 + 1D - 1I$ | 2.6704 | 0.8196E−05 |
| 157| $\lambda_3 - 2\lambda_5$ | 11.8620 | 0.1511E−04 |
| 158| $\lambda_3 - 2\lambda_3$ | 2.6704 | 0.8196E−05 |
| 159| $\lambda_3 - 2\lambda_3$ | 2.6704 | 0.8196E−05 |
| 160| $\lambda_3 - 2\lambda_5$ | 11.8620 | 0.1511E−04 |
| 161| $\lambda_3 - 2\lambda_3$ | 2.6704 | 0.8196E−05 |
| 162| $\lambda_3 - 2\lambda_5$ | 11.8620 | 0.1511E−04 |
| 163| $\lambda_3 - 2\lambda_3$ | 2.6704 | 0.8196E−05 |
| 164| $\lambda_3 - 2\lambda_5$ | 11.8620 | 0.1511E−04 |
| 165| $\lambda_3 - 2\lambda_3$ | 2.6704 | 0.8196E−05 |
| 166| $\lambda_3 - 2\lambda_5$ | 11.8620 | 0.1511E−04 |
| 167| $\lambda_3 - 2\lambda_3$ | 2.6704 | 0.8196E−05 |
| 168| $\lambda_3 - 2\lambda_5$ | 11.8620 | 0.1511E−04 |
| 169| $\lambda_3 - 2\lambda_3$ | 2.6704 | 0.8196E−05 |
| 170| $\lambda_3 - 2\lambda_5$ | 11.8620 | 0.1511E−04 |
| 171| $\lambda_3 - 2\lambda_3$ | 2.6704 | 0.8196E−05 |
| 172| $\lambda_3 - 2\lambda_5$ | 11.8620 | 0.1511E−04 |
| 173| $\lambda_3 - 2\lambda_3$ | 2.6704 | 0.8196E−05 |
| 174| $\lambda_3 - 2\lambda_5$ | 11.8620 | 0.1511E−04 |
| 175| $\lambda_3 - 2\lambda_3$ | 2.6704 | 0.8196E−05 |

At subdecadal band, periodicities ~8 years (Antico & Kröhling, 2011; Tomasino et al., 2004; Zanchettin et al., 2008) are found in all the parameters related to Venus and the Moon (i.e., 8.1 and 8.5 years). Even at decadal supra-decadal band, there are several periodicities such as 9.93 years, and specifically between 11 and 12 years, which bring extra power at the Schwabe cycle band and provide a regular and persistent forcing, independent of the ever-changing multi-decadal oscillations have a component linked to an orbital forcing, then they could be mainly associated with annual or seasonal irradiation periods because these periods are strongly dependent on h and k parameters (see Equation 11). Interestingly, the 61-year periodicity had been reported for daily irradiation at equinoxes at high latitudes and for the solstices (but at a lower significance level) for lower latitudes (Loutre et al., 1992), that is, when daily insolation is more dependent on climatic precession (e sin σ, e cos σ), that is, on the planetary h and k variables.

Taking into account these facts and the debate and potential importance of the ~60 yr in the surface temperature series (Le Mouël et al., 2021; Scafetta, 2016, and references therein), we extend the expansion of r to search for this (and other) periods. We find 60.9 years period at j = 356 due to $\lambda_3 - 2\lambda_5$ term in this extra expansion. We also found at j = 260, the 46.5-year periodicity. It is important to note that the ~60-year periodicity has been also related to Jupiter disturbing effect on the Solar System, and the consequent influx of interplanetary dust as a forcing of the Earth’s climate (Scafetta et al., 2020).

Similarly to the Schwabe band, around the Hale band (~22 years) we found several periods coincidental with periodicities argued to be detected in climatic data series which have also been connected to PH (Courtillot et al., 2021; Heredia et al., 2019; Scafetta, 2010). In particular, Le Mouël et al. (2019a, 2020) have detected specific periodicities at ~22.1 and ~21.8 years in temperature and in aa geomagnetic series, respectively. Heredia et al. (2019) have detected a quasi-bidecadal signal in climatic series from Southern Hemisphere which shows coherence with SMB parameters only sporadically. In our results, only the $\lambda_3$ parameter contains by far the most significant near bi-decadal periodicities, with 22.13 (j = 75) and 19.86 years period (j = 116), in addition to other near bi-decadal periodicities such as 23.88 (j = 118) and 23.57 years (j = 175). In the initial expansion of r, the 22.13 years period appears at j = 184. Nonetheless, in the extra expansion of r we found the 19.6 years peri-
It is important to note that the ordering established by the power $P_j$ does not invalidate the relevance of certain less disturbing terms in the spectral distribution of these periodicities. In other words, the analysis of the presented periodic oscillations must be carried out in specific frequency/period bands, and within that band one should evaluate the most relevant periodicities. For example, analyzing the Earth's speed in the spectral region between 6 and 13 years, we can identify nearly all the relevant peaks as described in Scafetta (2010) in his analysis of the DE431 ephemeris, in the context of the PH, using the maximum entropy method (MEM): $\lambda_3$ (11.86 years, $j = 27$), in combination with $7\lambda_3 - 13\lambda_4$ (11.35 years, $j = 230$); 8.1 years ($j = 54$); 7.89 (j = 70) and 7.84 years ($j = 114$); 8.85 ($j = 153$) and 6.6 years (a combination of $\lambda_4 = 2\lambda_3 + 4F - 4L$, $j = 180$, and $\lambda_4 = 4\lambda_3$, $j = 222$). We have not found the complementary peaks around 12 years, but in r, we found 12.02 years at $j = 243$, so we expect that this term may appear as a high order term in $v$. In addition, we have not detected the 9.1 ± 0.1-year periodicity, where the latter is attributed by Scafetta (2010) to fit the 8.85-year period and the LNC’s second harmonics (9.3 years); although we found the 9.93-year period, $2(\lambda_3 - \lambda_5 - \lambda_6)$, at $j = 228$, which in turn, seems to be not detected in that MEM analysis. The LNC is clearly present in the nutation formulations, but, in the DE431 modeling of the Earth orbital dynamics, it just affects some elements such as a higher order perturbation through interactions with the equatorial bulge of certain bodies. Therefore, the inclusion of the LNC mainly affects elements sensible to normal impulses to the orbit, such as the Earth's orbital inclination. Thus, we conclude that this peak, in the Earth's speed, is very probably of lunar origin, as argued by Scafetta, but likely attributable to $\lambda_3 + D - l$, 8.85 years period. Le Mouël et al. (2020) have also detected 9.1 ± 0.35 years periodicity in global temperature time series. That periodicity is consistent with the 8.85-year cycle.

Regarding the lunar effects on the climate system, it is important to note that the luni-solar tides are the most evident phenomena involving the Moon; nevertheless, the correct attribution of decadal/bi-decadal periodicities to lunar forcing could be a complex combination of very different physical effects on the Earth system such as tidal effects (i.e., a differential gravitational force), for example, with regard to the transition between El Niño-La Niña states of equatorial oceans (Liu & Qian, 2019); orbital forcing effects involving obliquity oscillations (i.e., periodic gravitational torques on the non-spherical Earth; Cionco, Soon, & Quaranta, 2020; Davis & Brewer, 2011); and periodic modulations of other orbital parameters (i.e., direct gravitational effects), as we have shown in this study.

At this point, it is unavoidable to discuss the issue of the direct impact of the amplitudes of these planetary/lunar factors on the solar radiant fluxes received on the Earth. The changes driven by these orbital variations produce a weak (i.e., small amplitude but time persistent) forcing on the top of the atmosphere. Although the equations presented in Section 2.2 are intended to show that the incoming solar fluxes are truly dependent on
Table 4

| $j$ | Argument | Period (year) | $P_j$ (arcsec) |
|-----|----------|---------------|----------------|
| 26  | 2$\lambda_3 - 3\lambda_4$ | 2.4695 | 0.3430E+00 |
| 28  | 1$\lambda_6$ | 29.4572 | 0.3206E+00 |
| 30  | 3$\lambda_2 - 7\lambda_3 + 4\lambda_4$ | 302.4340 | 0.2687E+00 |
| 35  | $1\lambda_5 - 5\lambda_7$ | 40.3329 | 0.2011E+00 |
| 36  | $2\lambda_3 - 5\lambda_6$ | 883.2639 | 0.1909E+00 |
| 42  | $4\lambda_2 - 5\lambda_3$ | 0.6657 | 0.1318E+00 |
| 52  | $4\lambda_3 - 7\lambda_4$ | 3.5945 | 0.9639E-01 |
| 65  | $4F - 4L$ | 4.6532 | 0.5861E-01 |
| 68  | $3\lambda_1 - 5\lambda_4 - 4\lambda_5$ | 229.3002 | 0.4934E-01 |
| 72  | $4\lambda_6 - 4\lambda_7$ | 11.3401 | 0.4474E-01 |
| 75  | $3\lambda_2 - 5\lambda_3 + 2\lambda_5$ | 22.1349 | 0.4186E-01 |
| 78  | $3\lambda_1 - 6\lambda_4 + 2\lambda_5$ | 46.5197 | 0.3643E-01 |
| 87  | $1\lambda_3 - 2\lambda_4 + 2\lambda_6$ | 220.8563 | 0.2848E-01 |
| 88  | $1\lambda_6$ | 164.7701 | 0.2829E-01 |
| 93  | $2\lambda_3 - 2\lambda_6$ | 9.9294 | 0.2438E-01 |
| 100 | $1\lambda_5 - 2\lambda_6$ | 60.9469 | 0.2228E-01 |
| 104 | $5\lambda_3 - 6\lambda_7 - 2\lambda_8$ | 1,326.8822 | 0.2119E-01 |
| 106 | $1\lambda_3 - 2\lambda_4 + 3\lambda_6$ | 25.9006 | 0.2037E-01 |
| 108 | $1\lambda_5 - 7\lambda_7$ | 1,010.1953 | 0.1978E-01 |
| 116 | $1\lambda_5 - 1\lambda_6$ | 19.8589 | 0.1482E-01 |
| 117 | $1\lambda_7$ | 84.0205 | 0.1481E-01 |
| 156 | $3\lambda_3 - 6\lambda_6 - 4\lambda_7$ | 618.9194 | 0.7067E-02 |
| 178 | $4\lambda_2 - 7\lambda_3 + 3F - 3l$ | 423.0174 | 0.5052E-02 |
| 189 | $1\lambda_3 - 3\lambda_6 + 1\lambda_7$ | 177.3671 | 0.4111E-02 |
| 197 | $1\lambda_5 - 4\lambda_6 + 4\lambda_7$ | 257.7287 | 0.3765E-02 |
| 231 | $1\lambda_3 - 2\lambda_4 + 1\lambda_5$ | 47.7656 | 0.2488E-02 |

changes in specific orbital parameters, they can also be used to estimate the effects of specific periodic terms on those solar energetic fluctuations. We note that the greatest of the well-established solar cycles, the ~11-year Schwabe cycle, clearly detected in the Earth system, is ~64 times smaller than the Keplerian annual variation on TSI (Section 1). The change (peak-to-peak) produced by, for example, the 1.09-year term in TSI is 0.0065%, which is in turn about 15.4 times smaller than the Schwabe cycle in TSI, that is, ∼0.09 W m⁻², well above the instrumental uncertainty in Active Cavity Radiometer Irradiance Monitor Satellite measurements of TSI considered by Scafetta and Willson (2013). Albeit the orbital forcing we are dealing with is very dense spectrally and its effects on certain frequency bands must be properly integrated, the small magnitude of these forcing cycles against the predominant annual variation represents a “small amplification problem.” This situation is common to all changes supposedly driven by the solar cycles, especially those different from the evident Schwabe or Hale cycles, where, in general, the authors usually search for coincidental periodicities between solar cycles and geophysical quasi-periods. All radiative forcings originating in solar cycles variations, which are apparently detected in the terrestrial system (e.g., Le Mouël et al., 2019a) need a clear amplification/synchronization mechanism within the Earth system. Short periodic forcings need rapid and significant amplifying feedbacks capable of generating obvious responses in the short term in order to be observed. A comprehensive list of possible atmospheric amplifying mechanisms has been reviewed in Gray et al. (2010). Specifically, short-term orbital forcings also need to be analyzed in the frame of the modeled feedbacks of the Earth system, such as fast-slow responses of dynamical systems (see e.g., Seshadri, 2017). In addition, other unexpected mechanisms involving orbital changes and internal climate dynamics could be operating on the Earth, as in the case of planet Mars, where the orbital dynamics of this planet has been linked to large-scale atmospheric circulation patterns; indeed, a weak spin-orbit coupling between the orbital and rotational angular momenta of Mars has been argued to possibly explain its remarkable dust storms (Newman et al., 2019; Shirley et al., 2020). In our opinion, regardless of the amplitudes of the forcing involved, one of the most promising mechanisms called upon to explain the bases of these complex mechanisms behind the interactions among these orbital oscillations and the Earth system will be through the Kuramoto models of synchronization, assuming that their components are under non-linear couplings. The synchronization of the oscillatory systems proceeds when the coupling between them reaches a critical value. Recently, Blanter et al. (2014), resolving an inverse problem, were able to find the couplings between solar cycles and geomagnetic data series using the correlations between both time series. In accordance with this result, Savostianov et al. (2020) shows that van der Pol models give the same result as Kuramoto models regarding the couplings between these phenomena. Thus, the synchronization of coupled oscillators seems to be a robust method to tackle the general problem of the solar-terrestrial coupling mechanism.

5. Conclusion

We presented, in a geophysical context, a systematic representation and discussion of the most important planetary and lunar periodic (i.e., non-secular) perturbations in the Earth heliocentric orbit. This catalog of planetary/lunar cycles, encompassing frequency, amplitude and phase of
The orbital forcing presented in this work needs to be analyzed in the spectral domain regarding the geophysical quasi-periodicities under scrutiny, that is, it is necessary to compare their phases and to evaluate spectral coherence and correlations (this will be part of a forthcoming work). Although there are mechanisms able to explain the synchronization of weak solar-terrestrial interactions under the framework of the Kuramoto models, the short-term orbital forcing also needs to be understood in the framework of the modeled feedbacks of the Earth system. Moreover, under the persistently quiet Sun situations, when changes in solar activity are weak (e.g., during Grand Minima events), it could be expected that oscillatory changes driven by orbital perturbations can play a more evident role in the climatic system.

We hope that our results will also inspire researchers to explore these topics and possible terrestrial feedback mechanisms by means of which geometrically induced changes in the incoming solar output originated in planetary/lunar cycles could be interacting with internal periodicities of the climatic system and the whole Earth system in general. For example, our results could be relevant for specific problems where the Sun-Earth dynamics is taken into account.

The hypothesis that some periodicities detected in conspicuous geophysical time series could be fully or partially originated in the Earth's orbital variations has the advantage of providing a clear, causal, and testable link: These orbital oscillations are persistent over time, at least during the whole Holocene, and do simultaneously produce changes to solar energy, independently of its wavelength, and to charged particles density fluxes reaching the Earth (e.g., Equations 10, 11 and 15). On the other hand, the presence of these orbital periodicities does not invalidate arguments showing connections between solar cycles and some geophysical quasi-periods, especially the periodicities at the well-known ~11 and ~22-year cycles. Our analysis shows the orbitally forced components of the solar radiant fluxes at the top of the atmosphere, some of which are coincidental with these Schwabe and Hale cycles.

The partial differentiation of Equations 9 and 13 with respect to $e$ and $\sigma$ gives the variations of $W_j$ in closed formulas due to the oscillations of these elements. Nevertheless, series expansions show how the eccentric-
The corrected longitudes $\lambda$ and $\sigma$ are:

$$\lambda = \lambda + N_L$$
$$\sigma = \sigma + N_L;$$

where $\lambda$ and $\sigma$ are obtained from DE431 ephemeris. The main nutational term in longitude is:

$$N_L = d\psi \sin \left( \frac{\Omega_0 - 2 \pi (t - t_0)}{18.6} \right).$$

where $d\psi = 8.34 \times 10^{-5}$ rad is the amplitude, and the time $t - t_0$ is reckoned in years. As a consequence of the small amplitude of LNC, we have:

$$\sin \sigma = \sin(\sigma + N_L) = \frac{h}{e} + N_L \frac{k}{e} \cos \sigma = \frac{k}{e} - N_L \frac{h}{e}$$
where we have used $\cos(N_p) \approx 1$ and $\sin(N_p) \approx N_p$. Note that $N_p$ is only significant at third-order in the eccentricity ($e^3 \sim 4.9 \times 10^{-6}$). Then, the multiplication of $N_p$ by at least $e^3$ produces terms of the order $e^4$ and higher, so that:

$$W^p_\phi = \frac{\text{TSI}_{ao} 1}{\pi} \left(\frac{1 \text{ au}}{a}\right)^2 \left[1 \pm 2h + 3h^2 + 2k^2 \pm 4h^3 \pm 4hk^2\right] P^p_j(\epsilon) + O(e^4). \quad (A7)$$

Now, differentiating this expression regarding $a$, $h$, and $k$, we have Equation 15 in the main text.

**Appendix B: Developments Using the Mean Longitude**

The best way to compute insolation-related quantities is to use true-orbital longitudes, that is, the exact Earth position in its orbit. Nonetheless, one can determine insolation quantities using the mean longitude $\dot{\lambda}_e$. For that, we make use of several well-known formulas of the two-body problem. First, the Kepler’s equation, which gives the position of a planet in its Keplerian (ideal) orbit:

$$E - e \sin E = n(t - t_0) = M; \quad (B1)$$

where $E$ is the eccentric anomaly; $M$ is the mean anomaly; $n$ is the Earth mean motion; $t_0$ is the time of the perihelion passage. The mean anomaly satisfies $M = \dot{\lambda}_e - \sigma$. In addition, the heliocentric distance of a planet can be expressed through the eccentric anomaly:

$$r = a(1 - e \cos E). \quad (B2)$$

There are several expansions of these angles that can lead to an analytical solution of the Kepler’s equation (see e.g., Murray & Dermott, 1999):

$$E = M + 2 \sum_{s=1}^{\infty} J_s(x) \sin(sM), \quad (B3)$$

where $J_s$ are Bessel functions of the first kind. Next, by differentiating Equation (B1), we note that:

$$\frac{dE}{dM} = \frac{a}{r}; \quad (B4)$$

hence,

$$\frac{a}{r} = 1 + 2 \sum_{s=1}^{\infty} J_s(x) \cos(s(\dot{\lambda}_e - \sigma)) \quad (B5)$$

which at third order in eccentricity is given by:

$$\frac{a}{r} = 1 + e \cos(\dot{\lambda}_e - \sigma) + e^2 \cos(2(\dot{\lambda}_e - \sigma)) + \frac{e^3}{8} \left[9\cos(3(\dot{\lambda}_e - \sigma)) - \cos(\dot{\lambda}_e - \sigma)\right] + O(e^4). \quad (B6)$$

Finally, by squaring Equation (B6) and using $\cos2x = \cos^2x - \sin^2x$, we have:

$$\left(\frac{a}{r}\right)^2 = 1 + 2e\cos(\dot{\lambda}_e - \sigma) + e^2(5\cos^2(\dot{\lambda}_e - \sigma) - 2) + e^3(13\cos^3(\dot{\lambda}_e - \sigma) - 9\cos(\dot{\lambda}_e - \sigma)) + O(e^4). \quad (B7)$$
Data Availability Statement
The NASA/JPL DE431 ephemeris used in this work is accessible via the JPL website (ftp://ssd.jpl.nasa.gov/pub/eph/planets/Linux/de431). The full outputs of this work are available at http://sai.msu.ru/neb/ksm/pertodicities.zip.

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