Planetary, Solar and Climatic Oscillations: An Overview
Nicola Scafetta
Dipartimento di Scienze della Terra, dell’ambiente e delle risorse
Università degli Studi di Napoli Federico II, Napoli

Abstract
Solar activity and climate change are characterized by specific oscillations. The most relevant ones are known in the literature as the cycles of Bray–Hallstatt (2100–2500 year), Eddy (800–1200 year), Suess–de Vries (200–250 year), Jose (155–185 year), Gleissberg (80–100 year), the 55–65 year cluster, the 40–50 year cluster plus bidecadal and decadal oscillations, and others.

Herein I review some of my publications on this topic and show that these oscillations emerge from a specific set of planetary harmonics - the orbital invariant inequalities - produced by the Jovian planets (Jupiter, Saturn, Uranus, and Neptune) and other basic astronomical frequencies related to the soli-lunar tides and orbital period of the planets. The result suggests that both solar activity and climatic changes are modulated by harmonic planetary forcings. Since these same harmonics are also found in the climate system, they can be used, in first approximation, to model and forecast climate change.

As an example, I briefly comment and update a semi-empirical model for climate change proposed 8 years ago by the author (Scafetta, Earth-Science Reviews 126, 321, 2013), which uses some of the above astronomically determined oscillations in addition to volcanic and anthropogenic components. The proposed model’s result continues to surpass the performance of the CMIP5 models used by the IPCC, in particular after 2000, in reconstructing the global surface temperature record.

Introduction
When the 11-year solar cycle was discovered, Wolf (1859) well understood the physical problem that this discovery posed and hypothesized that it could emerge from a planetary influence by Venus, Earth, Jupiter, and Saturn. The idea was that some type of periodic forcing linked to the orbital motion of the planets (for example, gravitational tides) could synchronize the internal dynamics of the Sun by causing it to vary harmoniously at specific frequencies. The 11-year solar cycle is today known in the scientific literature as the Schwabe sunspot cycle.

The theory has always been taken with a certain skepticism because the distance of the planets from our star is so great that the gravitational tides induced by them on the surface of the Sun are tiny. They are, in fact, so small - that is, of the order of a millimeter or smaller - to be considered entirely negligible: see, for example, the discussion in Scafetta (2012a). However, so far nobody has been able to explain in an alternative way why solar activity oscillates with a cycle of around 11 years.

In fact, the most modern theories on the solar dynamo assure us that the solar activity should oscillate, but they do not tell us that it must oscillate with the observed period and phase (Tobias, 2002). These models are appropriately calibrated to obtain something that vaguely resembles reality (Jiang et al., 2007). Their inability to predict the main cycle observed in solar activity is also recognized by the same critics of an astronomical influence on the Sun (cf.: de Jager and Versteegh, 2005). Therefore, what is causing the Sun to oscillate with a period, although variable, around 11 years remains a great mystery.
In the last 50 years, many improvements have been made, and our knowledge about solar activity has significantly increased. It has been discovered, for example, that the 11-year solar cycle is only one of the most evident and macroscopic solar cycles.

In fact, it is a variable cycle, as mentioned. Longer and shorter solar activity oscillations have also been observed. For example, the 11-year solar cycle almost disappeared during the great solar minimum of Maunder from 1645 to 1715; period during which the climate on Earth cooled significantly by experiencing a Little Ice Age (Eddy, 1976). Other grand solar minima were observed during the Dalton minimum (1790-1830), around 1900-1920, and another one is expected between 2020-2040 (Scafetta, 2012b). This pattern makes an oscillation of about 115 years (cf: Scafetta, 2012b; Scafetta, 2014).

In fact, several studies have determined that, in addition to the Schwabe's 11-year sunspot cycle and its associated 22-year Hale magnetic cycle, solar activity is characterized by several longer oscillations. These are now known in the scientific literature as the cycles of Bray – Hallstatt (2100–2500 years), Eddy (800–1200 years), Suess – de Vries (200–250 years), Jose (155–185 years), from Gleissberg (80–100 years), the 55–65-year cycles and others: see the numerous citations in Scafetta (2020). Identical fluctuations are also observed in climate records, suggesting a close link between solar variability and climate.

These results, of course, have made this research not only fascinating from an astrophysical point of view, but also very useful because it can be used to develop models able to predict climate changes: see, for example, the analyzes proposed in Neff et al. (2001), Kerr (2001), Ogurtsov et al. (2002), Steinhilber et al. (2012) and other studies including those proposed by Scafetta and colleagues.

Therefore, understanding solar dynamics has become increasingly important. Due to the inability of traditional solar models to explain the observed solar activity changes, in the last twenty years several works have appeared for re-proposing and modernizing Wolf's 1859 idea of a link between solar variability and planetary motions, which still today appears to be the only one capable of explaining solar oscillations.

Experimental evidence of a planetary influence on solar activity ranges from the discovery that various solar flares and other phenomena of a certain intensity occurred during specific planetary alignments (Hung, 2007; Bertolucci et al., 2017; Morner et al. 2015), to the observation that there is a certain spectral coherence between solar records and the functions deduced from the orbital motions of the planets of the solar systems. One of these commonly used functions is the motion of the sun relative to the center of mass of the solar system, which must, however, be understood as a proxy for conveniently determining the natural gravitational oscillations characterizing the solar system (Fairbridge and Shirley, 1987; Abreu et al., 2012; Scafetta and Willson, 2013; Scafetta et al., 2016; and others).

One of the author's latest work (Scafetta, 2020) identifies theoretically a set of planetary harmonics which appear to be responsible for the observations. These derive from the synodical cycles of the great jovian planets (Jupiter, Saturn, Uranus and Neptune) and their combinations or mutual beats. The main physical characteristic of these harmonics is that they are invariant with respect to any rotating reference system such as the sun and the heliosphere. This property is necessary to activate the synchronization processes between weak external harmonic forcings and an oscillating dynamic system, as initially discovered by Huygens in the 17th century who was impressed by the mutual synchronization of two pendulums attached to the same wall which after a while began to oscillate in the same way (Strogatz, 2009). For these properties, these planetary oscillations have been labeled "orbital invariant inequalities".

Section 1 summarizes the orbital invariant inequality model proposed Scafetta (2020). The result is purely theoretical and can be obtained only by using the well-known orbital periods of the four Jovian planets: Jupiter, $T_1 = 11.86$ year; Saturn, $T_2 = 29.46$ year; Uranus, $T_3 = 84.01$ year; and Neptune, $T_4 = 164.79$ yr. The model prediction is then compared versus the empirical results by
Neff et al. (2001), McCracken et al. (2013) and Scafetta et al. (2016). This model reconstructs the main long solar cycles.

Section 2 briefly discusses additional spectral coherence evidences linking planetary motions to climatic oscillations observed in the global surface temperature record at the decadal and multidecadal scales. Details regarding the material and methods yielding these results are found in Scafetta (2010, 2012a-d, 2013; 2014; 2016 2018; 2021a).

Section 3 updates the graphs published in Scafetta (2013) that compare the performance of the CMIP5 climate models adopted by the Intergovernmental Panel on Climate Change (IPCC) in 2013 versus a semi-empirical model that uses some of the identifies astronomical-coherent climate oscillations to reconstruct the natural variability of the climate system. The semi-empirical model also contains volcano and anthropogenic signatures evaluated as discussed in the above publication.

Finally, the conclusion section summarizes the results and briefly comments on them. Extended comments are found in the original papers.

1) The orbital invariant inequalities induced by the jovian planets
This section briefly recalls the definition of the orbital invariant inequalities. Details are found in Scafetta (2020).

In celestial mechanics, given two harmonics of period $T_1$ and $T_2$ and two integers $n_1$ and $n_2$, it is said that there is a resonance if $T_1/T_2 = n_1/n_2$. In general, this identity is not true and an inequality with frequency $f$ and period $T$ is defined as:

$$f = \frac{1}{T} = \left| \frac{n_1 - n_2}{T_1 - T_2} \right|.$$

(1)

The simplest cases deduced from equation (1) are the conjunction periods between two planets, also called synodal periods, see Table 1, which are defined as a beat, that is, as:

$$f_{12} = \frac{1}{T_{12}} = \left| \frac{1}{T_1} - \frac{1}{T_2} \right|.$$

(2)

Equation 2 can be generalized for a number $n$ of harmonics such as:

$$f = \frac{1}{T} = \left| \sum_{i=1}^{n} \frac{a_i}{T_i} \right|,$$

(3)

where $a_i$ are integers. Among all the possible orbital inequalities given by equation (3), there is a small subset which is defined by the condition:

$$\sum_{i=1}^{n} a_i = 0.$$

(4)

The synodal periods (Eq. 2) and all beats among them characterize the frequencies of this subset. The condition imposed by equation (4) is very important because it defines a set of invariant harmonics with respect to a rotating system such as the Sun and the heliosphere. In fact, given a rotating reference system centered in the Sun with period $P$, the orbital periods or frequencies seen relative to it are given by:

$$f' = \frac{1}{T'} = \frac{1}{T_i} - \frac{1}{P}.$$

(5)

Hence, with respect to this rotating frame of reference, the orbital inequalities are given by:

$$f' = \frac{1}{T'} = \left| \sum_{i=1}^{n} \frac{a_i}{T_i} \right| = \left| \sum_{i=1}^{n} \frac{a_i}{T_i} - \sum_{i=1}^{n} \frac{a_i}{P} \right|.$$

(6)
If the condition of Eq. 4 is imposed, we have that $f' = f$ and $T' = T$. Therefore, this specific set of orbital inequalities remains constant regardless of the rotating frame of reference from which they are observed. In other words, for example, the conjunction of two planets is an event that is observed in an equivalent way in all rotating systems centered in the Sun. For this physical property, the orbital inequalities fulfilling by the condition given by equation (4) can be defined as invariant.

Table 2 reports the orbital invariant inequalities generated by the large planets (Jupiter, Saturn, Uranus, and Neptune). They are listed using the formalism:

$$T = (a_1, a_2, a_3, a_4),$$

where $a_1$, $a_2$, $a_3$ and $a_4$ are integers such that their sum gives zero, according to Eq. (4). Each index refers to a jovian planet according to the usual order from Jupiter to Neptune.

The harmonics are divided into clusters or groups that recall the solar oscillations known in the scientific literature and which have been listed above in the Introduction. The same harmonics are also shown in Figure 1 and reveal a harmonic structure with a base period of 179.2 years. This periodicity corresponds to a frequency of 0.00558 1/year and the resulting harmonic is known as the Jose’s cycle (1965).

The harmonics were listed using two indices $M$ and $K$. The most important here is $K$ which is equal to half the sum of the absolute values of the coefficients $a_i$ that form a harmonic. Since Eq. 4 must hold, $K$ indicates the number of synodal frequencies between the Jovian planets that make up these orbital invariant inequalities.

![Figure 1: The orbital invariant inequalities of Jovian planets. Note the clusters structured according to a harmonic series based on the Jose cycle.](image)
<table>
<thead>
<tr>
<th>(Jup, Sat, Ura, Nep)</th>
<th>((M, K))</th>
<th>(T) (year)</th>
<th>cluster</th>
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<tr>
<td>(1, −3, 5, −3)</td>
<td>(5, 6)</td>
<td>42.1</td>
<td>~ 45 yr</td>
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<td>(0, 0, 4, −4)</td>
<td>(4, 4)</td>
<td>42.8</td>
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<td>(5, 5)</td>
<td>43.7</td>
<td></td>
</tr>
<tr>
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<td>(5, 6)</td>
<td>43.7</td>
<td></td>
</tr>
<tr>
<td>(1, −2, 0, 1)</td>
<td>(2, 2)</td>
<td>44.5</td>
<td></td>
</tr>
<tr>
<td>(0, 1, −1, 0)</td>
<td>(1, 1)</td>
<td>45.4</td>
<td></td>
</tr>
<tr>
<td>(1, −4, 2, 1)</td>
<td>(4, 4)</td>
<td>46.3</td>
<td></td>
</tr>
<tr>
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<td>(5, 6)</td>
<td>47.2</td>
<td></td>
</tr>
<tr>
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<td>55.8</td>
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<td>57.1</td>
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</tr>
<tr>
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<td>(5, 5)</td>
<td>58.6</td>
<td></td>
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<td></td>
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<tr>
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<td>(5, 6)</td>
<td>1159</td>
<td></td>
</tr>
<tr>
<td>(1, −3, 1, 1)</td>
<td>(3, 3)</td>
<td>2318</td>
<td>Bray–Hallstatt</td>
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*Table 2: The orbital invariant inequalities of the Jovian planets up to the orders \(M\) (= maximum value \(a_i\)) and \(K\) (= half the sum of \(|a_i|\)).*
Figure 2: Solar and climatic frequencies compared with orbital invariant inequalities.

For example, the cycle (1, -3,1,1) has K = 3 and can be decomposed into three synodal cycles as it is equivalent to (1, -1, 0, 0) - (0,1, -1, 0) - (0,1,0, -1). Therefore, (1, -3,1,1) is a beat obtained from the combination of the synodal cycles of Jupiter-Saturn, Saturn-Uranus, and Saturn-Neptune. In the same way it is possible to decompose any orbital invariant inequality. Hence, these harmonics are the beats of the synodal cycles and can all be obtained using the periods and time phases listed in Table 1.

The physical importance of the harmonics listed in Table 2 is shown in Figure 2 which compares a reconstruction of the inferred solar variability from a $^{14}$C record, and a climatic reconstruction deduced from a record of $^{18}$O from 9500 to 6000 years ago (adapted from Neff et al., 2001). As the figure shows, the two records are strongly correlated and have numerous common frequencies corresponding to the cycles of Eddy (800±1200 years), Suess - de Vries (200–250 years), Jose (155–185 years), Gleissberg (80–100 years), the cluster 55–65, the cluster 40-50 and others.

In Figure 2B the common spectral peaks in the two records are compared against the clusters of the invariant orbital inequalities (red bars) shown in Figure 1 and listed in Table 2. Figure 2 shows that the orbital model well agrees with all the principal frequencies observed in the solar and climatic data for millennia.
This can be shown more explicitly by directly reconstructing the great Bray–Hallstatt cycle (2100-2500 years). According to the proposed orbital model, this long oscillation is driven by the orbital invariant inequality (1,-3,1,1), which has a period of 2318 years. This cycle was studied in detail in McCracken et al. (2013) (Figure 3) and in Scafetta et al. (2016). Following the equations shown in Scafetta (2020), the complete reconstruction of the Bray–Hallstatt cycle (red curve in B) using the orbital invariant inequality (1,-3,1,1) (blue curve in A and B) is shown in Figure 4. To appreciate better the result, note that also the phase of the cycle is predicted by the same model.

2) Additional evidence linking planetary motions to climatic oscillations at the decadal and multidecadal scales

Additional analyses showed that climate oscillations and various gravitational oscillations of the solar system are spectrally coherent. In addition, also the soli-lunar tidal induced oscillations are expected to affects the Earth's climate by directly modulating the atmospheric and oceanic circulation. In general, we should expect the climate system to be mainly modulated by a series of complex cycles that mirror the astronomical ones. This hypothesis is currently supported by several empirical evidences using the available solar, astronomical, and climatic data proposed by a number of authors (e.g.: Scafetta, 2010, 2013; 2014; 2016; 2018; 2021a, and their references).

Figure 5 shows a time-frequency analysis comparison between the speed of the sun relative to the barycenter of the solar system (which can be considered a good proxy for empirically determining the main gravitational oscillations of the solar system) and that of the HadCRUT3 global surface temperature published in Scafetta (2014). The figure comparison clearly indicate that the global surface temperature is characterized by multiple astronomical oscillations at the decadal and multidecadal scales, as first noted in Scafetta (2010) and confirmed in Scafetta (2016, 2018) with the most advances spectral coherence techniques.
Figure 4: Reconstruction of the Bray – Hallstatt cycle (2100–2500 years) (red curve in B) using the orbital invariant inequality (1, -3,1,1) (blue curve in A and B). Details in Scafetta (2020).

The climate-astronomical common cycles include the following climatic and solar system oscillations at about: 5.93 years, 6.62 years, 7.42 years, 13.8 years, 20 years, 60 years. These oscillations are mostly related to Jupiter and Saturn, and the harmonics and subharmonics of their synodical cycle of 19.86 years. In particular, the quasi 60-year cycle is linked to three Jupiter and Saturn conjunction cycles that complete a great conjunction trigon.

Figure 5. Frequency comparison: [A] Time-frequency analysis (L = 110 years) of the speed of the Sun relative to the center of mass of the solar system. [B] Time frequency analysis (L = 110 years) of the HadCRUT3 temperature record after a quadratic fit was removed to eliminate the non-stationary upward bias (from Scafetta, 2014).
Figure 6. [Top] The average projection of the CMIP5 model ensemble against the GST HadCRUT4 record from January 1850 to January 2021 (black) (IPCCC, 2013). [Below] The solar-astronomical semi-empirical model with respect to the same climatic data proposed in Scafetta (2013). The colored area indicates 1-sigma dispersion from the average among the individual model simulations.

In fact, consecutive Jupiter-Saturn conjunctions occur at about 120° from each other, and after three events, the conjunction occurs nearly at the same position of the sky: see the discussion in Scafetta (2012d).

Moreover, we find among the astronomical cycles, the 9.93-year cycle due to the spring tide on the Sun of Jupiter and Saturn, and the 11.86-year orbital cycle of Jupiter. These two cycles bound and contribute to generate the 11-year solar cycle as explained in Scafetta (2012a, 2012b). In the diagram referring to the climate system we find the signature of the 11-year solar cycle, which was slightly longer at the beginning of the 20th century and became shorter at the end of the 20th century; the average period of this cycle during the considered period is 10.4 years, and the 5.2-year cycle, which is also evident in the temperature diagram, appears to be its first harmonic.

Finally, we find in the climate system a cycle with period equal to about 9.1-year. This oscillation is missing the main frequencies of the speed of the sun relative to the barycenter of the solar system. Scafetta (2010) and the supplement file in Scafetta (2012c) argued that this cycle is likely linked to a combination of the lunar apsidal line rotation period of 8.85 years, the first harmonic of Saros eclipse cycle of about 9 years and the first harmonic of the soli-lunar nodal cycle of 9.3 years. These three lunar cycles should induce equivalent tidal cycles with an average period of about 9.1 years that could affect the climate system.
Figure 7. [Top] Zoom of Figure 6 bottom. [Below] The same model against the UAH lower troposphere global temperature record calibrated on the HadCRUT4.6 in the period 1979-1990. The green area indicates the prediction of the average CMIP5 models. The yellow one is the prediction of the model proposed in Scafetta (2013).

3) Update of the semi-empirical climate model proposed in Scafetta (2013)

Scafetta (2013) proposed a semiempirical model based on several of the astronomically identifies cycles discussed above. A model with additional high frequency cycles was proposed in Scafetta (2021a). Herein we update the model proposed in 2013 to check its forecasting ability.

The Scafetta (2013) model includes a 9.1-year cycle due to solar-lunar tidal influence, and several astronomical-solar cycles such as a 10.5-year solar cycle, 20-year, 60-year, 115-year cycles and an asymmetric quasi-millennial cycle with minimum in 1700 and maxima in 1080 and 2060, as theoretically deduced from the astronomical-solar model discussed in Scafetta (2012b). The model was then completed with a volcano and anthropogenic component deduced from the prediction of the CMIP5 global circulation models assuming, however, a halved climate sensitivity to CO$_2$ forcing because the identified natural oscillations can reconstruct by alone at least 50% of the warming observed since the pre-industrial period of 1850-1900: see the discussion in Scafetta (2010, 2012c, 2012d, 2013).

Figure 6 compares the proposed astronomical-based model and the CMIP5 global circulation models’ average output versus the HadCRUT4.6 global surface temperature record from 1980 to
The proposed astronomical-based model not only fits climate data better than the IPCC models since 1850 (as demonstrated in Scafetta, 2013), but also predicts only a moderate warming from 2000 to 2100. The result would imply that climate adaptation policies should suffice to address future climatic changes, which is a relevant conclusion since the mitigation policies are far more expensive.

Moreover, it is necessary to consider that recent studies (Scafetta and Ouyang, 2019; Scafetta, 2021b) determined that about 20% of the global warming observed from 1950 to 2020 could be due to non-climatic factors such the warming associated the urbanization development of most of the inhabited world regions since 1950. By considering that about 0.15 °C of the warming recorded in the dataset could be spurious, the observed disagreement between the data and the CMIP5 prediction further increases, while the agreement between the data and the proposed astronomical-based model based on astronomical cycles further improves.

In fact, Scafetta (2021b) showed that from 1980 to 2020, the real global warming trend should be more consistent with that observed in the UAH lower troposphere temperature record (Spencer et al., 2017). Figure 7 shows a zoom (from 1980 to 2032) of Figure 6 (bottom) using the HadCRUT4.6 record (top) and the equivalent diagram using the UAH6.0 record. The latter figure shows an even better agreement between the data and the prediction of Scafetta (2013)'s model, while the disagreement with the model predictions increases.

4) Discussion and Conclusion

Solar and climate data from the past 11,000 years show highly correlated variability characterized by several common harmonics such as the Bray – Hallstatt cycle (2100–2500 years), Eddy's (800–1200 years), Suess – de Vries (200–250 years), Jose (155–185 years), Gleissberg (80–100 years), 55–65 year cycles, bidecadal and decadal cycles, and others. Above we saw that all these harmonics are predicted by a set of orbital frequencies called the **orbital invariant inequalities** and other astronomical cycles usually related to the planetary orbital cycles, and their harmonics and subharmonics. Additional cycles are related to the Moon’s orbit.

In particular, the orbital invariant inequalities derive from the synodal cycles of the great jovian planets (Jupiter, Saturn, Uranus, and Neptune). These harmonics have an important physical characteristic: they are invariant with respect to any rotating reference system and, therefore, they have the potential to synchronize the solar dynamo at specific frequencies.

Scafetta's study (2020) complements other studies, including some of his own where the proposed planetary models predict the 11-year solar cycle, this time using the orbital harmonics produced by the first harmonic the (2, -5, 2) invariant inequality between Venus, Earth and Jupiter (which gives a period of 11.07 years), and the combination of Jupiter and Saturn tidal harmonics at 9.93 years and 11.86 years. That Venus, Earth, Jupiter and Saturn could be involved in generating the variable 11-year solar cycle was already guessed by Wolf back in 1856: see detailed discussions in Scafetta (2012a, 2012b, 2014).

Common criticisms to a planetary-solar-climate hypothesis have mostly focused on the physical mechanism by which the planets could influence solar activity. Even if, at the moment, the physical problem is not fully resolved yet, the criticism appears weak because it does not demonstrate the non-existence of such a mechanism, but only the fact that the exact mechanism or a multitude of them are still debated. Indeed, no solar model that assumes our star as a body physically isolated from the rest of the solar system has been able to explain the observed solar cycles at any time scale. The author would like to point out that critics should propose an alternative theory capable to explain better the multitude of the observations, not just complain that planetary-solar-climate hypothesis is not a fully established theory yet.

For example, it is entirely possible that the effect of the small gravitational tides of the planets on the Sun are amplified by a million times, by internal nuclear fusion mechanisms (see the model
proposed in Scafetta, 2012a) and/or that planetary periodic configurations modulate flows of matter inside or outside the solar system which, by falling on the Sun or on the Earth, could modulate its activity: see also Bertolucci et al. (2017) and Scafetta et al. (2020b). Furthermore, the harmonic synchronization processes can also be activated by weak oscillating forcings.

The important result is that all these astronomical oscillations are found in the climate system as well, which make possible, at least in principle, to partially forecast climate change on the decadal to secular or even millennial scales. Indeed, harmonic climate models have been proposed and also the updates shown above indicate that they perform much better than the CMIP5 global circulation models used for example by the IPCC.

The latter models not only fail to properly reconstruct all oscillations found in the climate system, but the data-model divergence has been significantly widening since 2020, which indicates that the CMIP5 and similar global climate models overestimate significantly the climate sensitivity to radiative forcing by at least a factor of two. This failure would be even larger if one considers that about 20% of the post 1950 warming could be spurious because due to urbanization and other non-climatic factors as also a comparison against the UAH global lower tropospheric temperature suggests (cf: Scafetta and Ouyang, 2019; Scafetta, 2021b).

In conclusion, the collected evidence shows, in a sufficiently convincing way (at least this is the opinion of the author), that solar activity is very likely modulated by planetary harmonics which are then impressed in the climate system of the Earth because these same harmonics are also observed in climate changes.

To understand the interconnection among these phenomena, it is necessary to discover not only how the Sun behaves but also the physics of the solar system and how the matter moves within it. For example, the 60-year cycle is observed also in the meteorite fall records (Scafetta et al., 2020) that, together with a cosmic ray flux, implies the possibility of climatic particle forcings of the cloud system which has an astronomical origin and complement the radiative ones.

**Bibliography**


Science of Climate Change


