Questioning the seasonality of SARS-CoV-2: a Fourier spectral analysis

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INTRODUCTION

After almost 2 years from the start of the COVID-19 pandemic, the scientific community is still arguing about many of the characteristics of this virus and its spread, as well as what the best course of action in the fight against it is.1,2 While the public may find this lack of consensus disheartening, every scientist knows this was to be expected when dealing with such unprecedented phenomena, especially given the enormous uncertainty around the data that concern it. Every analysis that has tried to leverage information on a global scale, in fact, had to deal with the limitation of having a largely inhomogeneous data set, where differences in the data collection process and, even more importantly, in the actions taken by each country contributed to confounding the factors being studied.3

In this complex context, at the end of 2021, as the virus has been around for almost 2 years, a discussion started about the possibility of COVID-19 following a seasonal pattern, similar to many other viral infections, like measles and influenza, for example. This idea gained momentum probably because of how the contagion receded during the summer months in many Western countries, to start climbing back up with the start of autumn and finally reaching a new peak during the winter holidays.

From a scientific perspective, the debate on an infection pattern that repeats over a 1-year period has been driven by several analyses investigating the correlation between SARS-CoV-2 and various climatic (and environmental) factors, such as temperature, humidity and UV radiations. The rationale behind this research is that if a negative correlation between SARS-CoV-2 and higher temperatures and exposure levels to UV radiation can be demonstrated, then lower COVID-19 infection rates should happen in...
some given seasons of the year. Humidity, instead, appears to have a U-shaped relation with SARS-CoV-2 infection rates, as only values that hover 50% seem to shorten the virus life.

Along this line of research, remarkable are the studies of D’Amico et al who used a multivariate regression to assess the influence of temperatures and vaccinations on mortality rates in temperate climate countries. They found a negative correlation with temperatures and discovered that the vaccination’s effect grew larger as the temperature decreased.4 Similarly, Ma et al studied the problem in the USA using a generalised additive mixed model. Their findings are that temperatures are negatively correlated with COVID-19, in an almost linear way, in the range of 20°C–40°C.5

However, some other research begins to point out the weaknesses of many of the aforementioned studies. For example, Fontal et al while studying the negative correlation between the virus and both higher temperature and humidity, found that there are moments in which this correlation can be inverted, typically corresponding to summer outbreaks in certain regions.6 The authors suggest that this can be due when various human activities take over, like intensive use of air conditioning, lack of preventive measures and uncontrolled mass gatherings. Also, Sera et al have expressed their concerns, concluding that the effect of weather, while present, is negligible when compared with the decisive impact of control interventions.7 More interestingly, Baker et al have argued that climate factors can play an important factor in the infection when the virus is in the endemic stage. In contrast, during the pandemic stage, it only drives modest changes.8 Finally, very inspiring theoretical results were achieved also in a study by Telles et al where it has been demonstrated that a combination of factors, including climate, control policies and the use of urban spaces could influence the seasonality of COVID-19.9

Beyond these scientific studies, the positive effect of good weather seems to contrast with several COVID-19 contagions that have broken out, with broad impact, even if with unfavourable climates to the spread of the virus. For example, while this is completely anecdotal, one could wonder what mechanisms were behind the resurgence of the contagion in May 2020 in Israel.10 Similarly, the 2021 Olympic Games in Japan took place during the summer when the weather was optimal, but the virus spread, even in the presence of high security standards.11 In the same period, the European Football Championship took place, and this tournament was connected with an increase of new cases in many involved countries.12 Not to say about the 4 July 2021, US presidential Speech, when the US President declared the final success in beating the pandemic, but a new peak hit strong just a few weeks later.13 Finally, the third wave across Europe started at the end of 2021 summer in many eastern countries, when the temperatures were still relatively high.

Following this scientific debate, in this work, we chose another technical perspective in order to investigate the 1-year seasonality hypothesis, employing techniques from signal processing in order to study the presence of evidence towards periodicity in the COVID-19 recurrent outbreaks, or lack thereof. Relying on a Fourier spectral analysis of the daily SARS-CoV-2 infections data, at a worldwide level, we looked for peaks in the frequency spectrum that could inform us about the length of the recurrent cycles of COVID-19 outbreaks. This has allowed us to question on the sinusoidal seasonality assumed to recur over 1-year period, solely.

METHODS

We focused our study on a wide selection of worldwide countries, chosen following the Köppen climate classification.14 This classification divides climates into five main groups, where each group is considered based on seasonal precipitation and temperatures. The five main groups are: tropical (A), dry (B), temperate (C), continental (D) and polar (E). We analysed 30 different countries that cover all the five groups, with several of the selected countries belonging to two or more groups, given their vast geography (eg, India, Russia and the USA, to cite a few). The complete list of the 30 countries follow below, each with its prevalent type of climates: Argentina (B, C), Australia (A, B, C), Austria (D, E), Belgium (C), Brazil (A, C), Canada (C, D, E), Chile (B, C, D), Colombia (A, C), Croatia (C), Denmark (D), France (C), Germany (C, D), Hungary (D), India (A, B, C, D), Indonesia (A), Italy (B, C), Japan (A, C, D), Mexico (A, B, C), Morocco (B, C), Norway (D, E), Portugal (C), Russia (D, E), Saudi Arabia (B), South Africa (B, C), South Korea (C, D), Spain (B, C), Sweden (D, E), Turkey (B, C, D), UK (C) and USA (B, C, D, E).

Notice that our selection includes 18 out of the 20 countries of the group of 20. China was excluded just because its SARS-COV-2 data are not made available on a regular basis. Also, the European Union (EU) was not considered as a whole. Yet, in place of EU, we included the following EU members: Austria, Belgium, Croatia, Denmark, France, Germany, Hungary, Italy, Portugal, Spain and Sweden. The period of observation for our study started on 1 February 2020 until 4 December 2021, with the decision not to take into consideration the strong SARS-CoV-2 outbreak that hit Europe in December 2021, as the progression of this wave was still ongoing in many of the investigated countries during our analysis.

The method we adopted for our investigation was a Fourier spectral analysis. In particular, we used a Discrete Fourier Transform (DFT) to examine the periods length in the spectrum of the COVID-19 data, by converting the time series of the number of the new daily SARS-CoV-2 cases to the frequency domain.15 This Fourier frequency spectrum analysis was performed with the precise intent to obtain a converted peak spectrum, indicating the strength and the recurrence of the pandemic waves. In particular, we looked for peaks in the frequency spectrum that could reasonably indicate a periodicity with a certain
length. Employing a spectral analysis on the time series of the COVID-19 cases has allowed us to understand, with less ambiguity, the period length of the recurrent outbreaks, instead of counting and observing the number of infections, directly.

The 1-dimensional DFT $y[k]$ of length N, of the length-N sequence $x[n]$, is defined as follows:

$$y[k] = \sum_{n=0}^{N-1} e^{-2\pi i \frac{k}{N} n} x[n],$$

where $y[k]$ corresponds to the magnitude of the kth frequency and $n$ represents the nth day of the time series, with x being the daily number of SARS-COV-2 cases registered on that nth day of the series. The number of the analysed days (ie, the sampling period) was equal to 730 (2 years). Since our study’s real period of observation started on 1 February 2020 (until 24 December 2021), the string x was left padded with zeros to reach 730 samples. This zero padding did not alter the validity of the operation since in all the considered countries no SARS-COV-2 infection was registered before 1 February 2020. To conclude, using a Python library called SciPy (https://scipy.org/), we performed a DFT of the time series of the SARS-COV-2 data of each country, that returned all the peaks in the frequency spectrum at their corresponding frequency which can be inverted to obtain the repetition period.

It is to notice that all the data used for our DFT investigation are available at the following site https://github.com/owid/covid-19-data, with the instructions on how to use made available at: https://github.com/owid/covid-19-data/blob/master/public/data/README.md. The results of all the DFT computations are fully reproducible by using the method described above. The DFT code can be downloaded from: https://github.com/mistermagpie/covid_periodicity. It is finally worth mentioning that all that aforementioned data on COVID-19 infections (OWID) are maintained by the Johns Hopkins University Centre for Systems Science and Engineering.16

Patient and public involvement

Patients and/or the public were not involved in the design, or conduct, or reporting or dissemination plans of this research.

RESULTS

Figures 1–5 reveal that, in the observed period, all the 30 DFT plots of figures 1–5 have three different sectors coloured in orange, green and pink (from right to left). Those sectors display temporal intervals, respectively, equal to 3–6 months (orange), 6–9 months (green) and 9–12 months (pink). They should be interpreted as follows: if one observes for a certain country the presence of a peak in a given coloured sector of the plot (say the green one, for example), this means that country has been hit by a COVID-19 outbreak, which has occurred with a period of 6–9 months. More precisely, if that peak lies on the x-axis in correspondence of a value of k=2, this implies that we have had two outbreaks of similar magnitude per year in that country. Coming now to our results, our 30 DFT plots of figures 1–5 reveal that, in the observed period, all the 30 investigated countries have seen the recurrence of at least one COVID-19 wave, repeating over a variable period in the range 3–9 months, with a peak of magnitude (roughly equivalent to the number of new infections) at least half as high as that of the highest peak ever experienced since the beginning of the pandemic until December 2021. These findings suggest that strong COVID-19 outbreaks may repeat with cycles of different lengths, without a precisely predictable seasonality of 1 year.

Given the well-known Fourier uncertainty principle,17 we developed a further analysis. We returned to the leftmost plots of figures 1–5, looking for the COVID-19 peaks, recurring in each country, but adopting a more traditional technique. Specifically, using a 7-day rolling average as the raw data of leftmost plots of figures 1–5 present a weekly periodicity, due to the way COVID-19 tests are carried out and registered, we considered a peak has happened in a given day n, if the number of SARS-COV-2 infections registered in that day was larger than the number of daily SARS-COV-2 cases reported in the 28 days both before and after n. Not only, but to be considered a peak, the number of infections registered on that day n had to be larger than a given threshold computed as the 85% of the average of the daily cases reported in
Figure 1  Plots for Argentina, Australia, Austria, Belgium, Brazil and Canada. Leftmost plots: on the y-axis number of new daily SARS-CoV-2 cases in the period 1 February 2020–24 December 2021 (x-axis). Rightmost plots: Fourier frequency spectrum on the y-axis, with dots lying on the red line corresponding to wave peaks. Coloured sectors indicate precise recurring cycles: pink (9–12 months), green (6–9 months) and orange (3–6 months). The k index on the x-axis of the rightmost plots indicated the repetition frequency on a semilogarithmic scale (on a 1-year period).
Figure 2  The same plots of figure 1 but for Chile, Colombia, Croatia, Denmark, France and Germany.
Figure 3  The same plots of figure 1 but for Hungary, India, Indonesia, Italy, Japan and Mexico.
Figure 4 The same plots of figure 1 but for Morocco, Norway, Portugal, Russia, Saudi Arabia and South Africa.
Figure 5  The same plots of figure 1 but for South Korea, Spain, Sweden, Turkey, UK and USA.
Seasonality typically refers to a single, recurring pattern with a fixed frequency. The results we achieved highlight how, with COVID-19, strong evidence of a seasonal pattern that repeats over a 1-year fixed period cannot be found. Instead, several repeating outbreaks, not necessarily occurring with a fixed frequency, can be observed. In particular, the Fourier spectral analysis of the time series of the SARS-CoV-2 cases of all the 30 countries we have studied has revealed the recurrence of at least one COVID-19 wave (often two or more), repeating over a variable period, in the range 3–9 months, with peaks of magnitude comparable to that of the highest peak ever experienced since the beginning of the pandemic until December 2021. Indeed, the situation is more complicated than previous studies have revealed. In fact, while some of them consider COVID-19 as a seasonal low-temperature infection, the precise role of temperature, humidity and exposition to UV radiation remains poorly understood. From this perspective, our study has tried to follow an alternative path with spectral analysis of the series of the daily SARS-CoV-2 cases, while looking for peaks in the frequency spectrum to understand the presence of repeating cycles and quantify their lengths.

We recognise that, with our analysis, we have avoided quantifying precisely the role attributed to various climatic factors or control measures, like temperatures or vaccination. This can be seen as a limitation of our study as the magnitude of the effects of those factors should be investigated thoroughly. Yet, there are precise motivations behind our choice. On one side, we have decided to avoid taking part in the scientific discussion about the dominant role of climate versus control measures, including vaccination, as the best solutions that can drive substantial changes to the pandemic trajectory. On the other side, we have tried to observe a natural phenomenon, just resorting to a mathematical technique able to detect the presence of evidence towards periodicity/non-periodicity in the spread of COVID-19, with neutrality and regardless of the underlying factors. Another factor that could have an influence on the seasonality is how urban spaces are lived and the corresponding impact on the spreading patterns of the virus. While we recognise that this factor is important and comparable with those of climate and policies, we admit that we have not addressed this issue in this study.

Another technical limitation of our approach was the decision not to put a special focus on those countries where...
| Country  | Climate types | Number of peaks | Distance between the two highest peaks (days) | Dates of the two highest peaks (more frequent clades) | Dates of the remaining peaks (more frequent clades) |
|----------|---------------|----------------|-----------------------------------------------|------------------------------------------------------|---------------------------------------------------|
| Argentina | B/C           | 3              | 214                                           | 21 October 2020 (20B/C/D) 23 May 2021 (20J Gam., 21G Lambda) | 11 January 2021 (20B, 20I Alpha, 20J Gam.)       |
| Australia | A/B/C         | 3              | 432                                           | 4 August 2020 (20B/C/F) 10 October 2021 (21J Delta) | 30 March 2020 (19A/B, 20A/B/C)                   |
| Austria   | D/E           | 5              | 376                                           | 13 November 2020 (20A) 24 November 2021 (21J Delta) | 28 March 2020 (20A/B/C) 1 April 2021 (20I Alpha) 15 September 2021 (21J Delta) |
| Belgium   | C             | 4              | 148                                           | 30 October 2020 (20A/B) 27 March 2021 (20I Alpha) | 15 April 2020 (20A/C) 12 August 2020 (20A/C)   |
| Brazil    | A/C           | 4              | 87                                            | 27 March 2021 (20J Gamma) 22 June 2021 (20J Gamma) | 28 July 2020 (20B) 12 January 2021 (20B, 20J Gamma) |
| Canada    | C/D/E         | 4              | 93                                            | 9 January 2021 (20B/C/G) 12 April 2021 (20I Alpha, 20J Gamma) | 22 April 2020 (19A, 20B/C) 13 September 2021 (21I/J Delta) |
| Chile     | B/C/D         | 6              | 55                                            | 14 April 2021 (20J Gam., 21G Lambda) 8 June 2020 (20J Gam., 21G Lambda) | 12 June 2020 (19A, 20B/D) 1 October 2020 (20D/B) 25 January 2021 (20B/D/G, 20I Alpha) 15 November 2021 (21J Delta) |
| Colombia  | A/C           | 4              | 159                                           | 20 January 2021 (19A, 20B/C) 28 June 2021 (21H Mu) | 16 August 2020 (20A/B) 2 November 2020 (19A, 20B) |
| Croatia   | C             | 6              | 333                                           | 13 December 2020 (20B) 11 November 2021 (21J Delta) | 1 April 2020 (20A) 15 July 2020 (20B) 29 August 2020 (20B) 21 April 2021(20I Alpha) |
| Denmark   | D             | 6              | 145                                           | 18 December 2020 (20B/E) 12 May 2021 (20I Alpha) | 8 April 2020 (20A/C) 23 September 2020 (20A/B/E) 16 March 2021 (20I Alpha) 16 August 2021 (21J Delta) |
| France    | C             | 5              | 161                                           | 7 November 2020 (20A) 17 April 2021 (20I Alpha) | 18 April 2020 (19B, 20A) 2 November 2021 (20I Alpha) 16 August 2021 (21J Delta) |
| Germany   | C/D           | 4              | 123                                           | 23 December 2020 (20A/E) 25 April 2021 (20I Alpha) | 2 April 2020 (19B, 20A/C) 10 September 2021 (21J Delta) |
| Hungary   | D             | 3              | 113                                           | 3 December 2020 (20A) 26 March 2021 (20A, 20I Alpha) | 13 April 2020 (20A) |
| India     | A/B/C/D       | 2              | 234                                           | 16 September 2020 (20A/B) 8 May 2021 (1A/J Delta) | – |
| Indonesia | A             | 3              | 167                                           | 1 February 2021 (20A/B) 18 July 2021 (21I/J Delta) | 26 September 2020 (20A/B) |
| Italy     | B/C           | 5              | 126                                           | 16 November 2020 (19A, 20A) 18 March 2021 (20E) | 26 March 2020 (20E, 20I Alpha) 11 January 2021 (20I Alpha) 27 August 2021 (20J Alpha) |
| Japan     | A/C/D         | 5              | 226                                           | 11 January 2021 (20B) 25 August 2021 (21J Delta) | 15 April 2020 (19B, 20A/B) 9 August 2020 (20B) 14 May 2021 (20I Alpha) |
| Mexico    | A/B/C         | 4              | 213                                           | 21 January 2021 (20A/B/C) 22 August 2021 (21I/J Delta) | 1 August 2020 (20A/B) 9 October 2020 (20A/B/C) |
| Morocco   | B/C           | 4              | 266                                           | 17 November 2020 (20A/B) 10 August 2021 (21J Delta) | 22 April 2020 (20A) 25 June 2020 (20A) |
| Norway    | D/E           | 6              | 167                                           | 22 March 2021 (20I Alpha) 5 September 2021 (21I/J Delta) | 29 March 2020 (19A, 20A/B) 23 November 2020 (20A/B/C/E) 10 January 2021 (20A/B/E, 20I Alpha) 26 May 2021 (20I Alpha) |

Continued
the number of cases has had high variability, the reason being most likely that the number of tests done each day can have varied as much. We could have normalised those cases with the number of tests, before subjecting them to the DFT, but this datum is often unreliable and may lead, in turn to unrealistic normalised values, so we decided to avoid this. An additional technical limitation of this study is that the Fourier transform may return results, especially at the lowest frequencies, with a variable degree of uncertainty. Hence, to confirm our results, we have developed a parallel analysis directly performed on the number of the new daily SARS-CoV-2 cases of interest.

Alternatively, we could have performed a spectral analysis of our epidemiological time-series with wavelets. These techniques appear somewhat attractive because they are more appropriate to treat non-stationary signals, but still have to deal with the natural limitation represented by the fact that the pandemic has been in progress so far, and we only have a 2-year data set. Not to mention the exclusion from our research of the intense SARS-CoV-2 outbreak started in December 2021 in many of the 30 considered countries. The motivation for this exclusion is that the progression of this wave was still ongoing at the moment of our study.

### Table 1

| Country       | Climate types | Number of peaks | Distance between the two highest peaks (days) | Dates of the two highest peaks (more frequent clades) | Dates of the remaining peaks (more frequent clades) |
|---------------|---------------|-----------------|---------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------|
| Portugal      | C             | 5               | 70                                          | 19 November 2020 (20B/E) 28 January 2021 (20E, 20I Alpha) | 3 April 2020 (20B) 13 July 2020 (20B) 23 July 2021 (21J Delta) |
| Russia        | D/E           | 4               | 315                                         | 26 December 2020 (20B/C) 6 November 2021 (21J Delta) | 12 May 2020 (20I/B) 15 July 2021 (21J Delta) |
| Saudi Arabia  | B             | 3               | 412                                         | 20 June 2020 (20A) 6 August 2021 (21I Delta)          | 2 July 2021 (21I Delta) |
| South Africa  | B/C           | 4               | 178                                         | 11 January 2021 (20A, 20 hours Beta) 8 July 2021 (21I/J Delta) | 19 July 2020 (20B/D) 22 August 2021 (21I/J Delta) |
| South Korea   | C/D           | 7               | 46                                          | 15 August 2021 (21I Delta) 30 September 2021 (21I/J Delta) | 4 March 2020 (19B, 20C) 27 August 2020 (20A/C) 25 December 2020 (20C) 20 February 2021 (20C, 21I Alpha, 21D Eta) 23 April 2021 (20A, 20I Alpha) |
| Spain         | B/C           | 5               | 174                                         | 26 January 2021 (20E, 20I Alpha) 19 July 2021 (21I Delta) | 31 March 2020 (19B, 20A/B) 4 November 2020 (20B) 27 April 2021 (20I Alpha) |
| Sweden        | D/E           | 4               | 91                                          | 11 January 2021 (20A/E) 12 April 2021 (20I Alpha) | 29 April 2020 (19A, 20B/C) 18 June 2020 (20B) |
| Turkey        | B/C/D         | 5               | 139                                         | 2 December 2020 (20A/B, 20I Alpha) 20 April 2021 (20I Alpha, 20I hours Beta) | 16 April 2020 (20A) 15 August 2021 (21A/J Delta) 15 October 2021 (21J Delta) |
| UK            | C             | 6               | 193                                         | 9 January 2021 (20I Alpha) 21 July 2021 (21J Delta) | 22 April 2020 (19A, 20D) 16 November 2020 (20B/E) 8 September 2021 (21J Delta) 23 October 2021 (21J Delta) |
| USA           | A/B/C/D/E     | 5               | 245                                         | 11 January 2021 (20B/C/G, 21C Epsilon) 13 September 2021 (21J Delta) | 10 April 2020 (19A/B, 20B/C) 22 July 2020 (20B/C/G) 14 April 2021 (20I Alpha) |

The mean distance between the two highest peaks is 190 days (SD 100).

**CONCLUSION**

We have applied a mathematical technique from signal processing to investigate in 30 different countries the hypothesis whether COVID-19 outbreaks either repeat with a fixed periodicity or occur following unpredictable patterns. The Fourier spectral analysis of the time series of the SARS-CoV-2 cases we have examined has suggested that strong COVID-19 waves may repeat with cycles of different lengths, without a precisely predictable periodicity (1 year, or similar). With the scientific community that appears divided into two factions, which alternatively maintain the importance of the role of meteorological factors versus control measures (including vaccination), we argue we have provided an improved understanding of how the virus may spread, regardless of the presence of several factors that can further confound the scenario.
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Data availability statement Data are available in a public, open access repository. Data of this study are available in a public, open access repository (https://github.com/owid/covid-19-data/blob/master/public/data/README.md). The Python code for the peak searching algorithm is available at: https://github.com/riccardocappi/Seasonality-SARS-CoV-2). The DFT code is available at: https://github.com/mister-magpie/covid_periodicity. The DFT code is available at: https://github.com/mister-magpie/covid_periodicity. The DFT code is available at: https://github.com/mister-magpie/covid_periodicity. The DFT code is available at: https://github.com/mister-magpie/covid_periodicity.

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