Impact of COVID-19 on the Spatio-temporal Distribution of CO₂ Emission

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ABSTRACT: CO₂ is the determining factor of global warming, affecting the intensity and rate of global warming. Although the outbreak of COVID-19 deeply affected the emission of global carbon, the impact on the temporal variation and spatial distribution of CO₂ emission rate (ECO₂) is not yet conclusive. This study systematically analyzed the spatial-temporal distribution of ECO₂ from 2019 to 2021 based on one latest near real-time CO₂ dataset named GRACED. Studies show that COVID-19 has no significant impact on the spatial distribution of CO₂ in the world, but significantly reduce the values. From the perspective of the seasonal cycle, the outbreak of COVID-19 caused a shift in the minimum ECO₂ in 2020 from the Northern Hemisphere summer (JJA) to the Northern Hemisphere winter (MAM), reflecting the impact of the COVID-19 outbreak on global ECO₂. As for the temporal variation, the impact of the COVID-19 outbreak on the monthly cycle mainly occurred in 2020, especially from March to June of that year. By 2021, the global mean values of ECO₂ had largely recovered to 2019 levels as the impact of COVID-19 faded.

1. INTRODUCTION

Global warming refers to the climate change in which the earth-atmosphere system is generally heating up in a specific period (e.g. the Industrial Revolution) that is considered one of the most challenges faced by human beings currently [1]. Global warming has a significant impact on the environment, such as rising temperatures, lifting sea levels, melting ice and snow, and prolonging the growing season of animals and plants [2]. In addition, global warming also can influence the frequency of extreme weather events [3], such as the extreme rainstorm in Henan, China in 2021 [4]. Since global warming is related to the survival and development of human beings, it attracts widespread attention. For instance, countries across the world had signed United Nations Framework Convention on Climate Change, Kyoto Protocol, The Paris Agreement, and other documents successively to achieve carbon emission reduction by strengthening cooperation between countries. In 2021, China also specified targets for "peak carbon dioxide emissions" and "carbon neutrality" to slow global warming.

Global warming is affected by various factors, in which greenhouse gases are considered to be the major factor in recent global warming. The greenhouse gases in the atmosphere mainly include water vapor, carbon dioxide (CO₂), methane, nitrous oxide, tropospheric ozone, freon, etc. [1]. The factors that can affect the equilibrium radiation of the earth-atmosphere system are called radiative forcing factors and their effects are called radiative forcing. IPCC Sixth Assessment Report (AR6) pointed out that CO₂ has the strongest radiative forcing since the Industrial Revolution, which is the leading factor contributing to global warming [5].

COVID-19 is an infectious disease caused by a new coronavirus called Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) [6]. COVID-19 broke out in late 2019 and has become a global pandemic. To prevent the spreading of the virus, governments around the world have implemented many kinds of strict control policies. Among them, the large-scale reduction of related activities such as industry and transportation has led to a sharp decline in the burning of fossil fuels [7]. Since 2021, with the full implementation of vaccination, governments of different countries have gradually relaxed the lockdown policies on COVID-19. Consequently, the economic activities of each country have recovered, and the impact of COVID-19 on the emission rate of global CO₂ (ECO₂) is gradually weakening [7]. Researchers focused on the impact of COVID-19 on ECO₂ as well. For example, Liu et al. [8] and Le Quere et al. [9] used the global daily scale data of CO₂ to verify the significant influence COVID-19 has on the temporal variation of ECO₂. Dou et al. [7] analyzed the influence of COVID-19 on spatial distribution by using global daily scale data from different CO₂ emission sources. However, previous studies mainly focused on the spatial distribution [7] or temporal variation of global ECO₂ [8-9] rather than analyzing the overall influence of COVID-19 on the temporal variation and spatial distribution of ECO₂ simultaneously. As for the period, former researchers mostly focused on 2019
and 2020 (around the outbreak of COVID-19) and did not study the influence of the relaxation of COVID-19 policies (in 2021, post-COVID-19 period) due to the limitation of the time coverage of the dataset. In allusion to the above issues, this paper will analyze the overall impact of COVID-19 on the spatio-temporal distribution of global $E_{CO2}$. At the same time, the period of this research will be extended, covering the pre-COVID-19 period (2019), the outbreak period (2020), and the post-COVID-19 period (2021).

The acquisition methods of $CO2$ spatial distribution and temporal variation data include ground-based measurement, satellite observation, and model simulation [10]. In general, the accuracy of ground-based observation data is high but the space coverage is low. The spatial coverage and accuracy of satellite data are high, but the observation period is limited. The time series of simulation data is long enough and the spatial coverage is high, but the reliability of the results is low. To overcome the shortcomings of the above methods, some researchers fused the emission inventory and proxies (e.g. nitrogen dioxide concentration, nighttime light index, power plant emission, etc.) of $CO2$ to produce a $E_{CO2}$ dataset with high spatial and temporal resolution [11-13], which is called the mixed dataset. Compared with traditional ones, the mixed dataset has the characteristics of higher accuracy and spatio-temporal resolution, so it is more suitable for studying the long-term change of $CO2$ on a global scale.

Recently, Dou et al. [7] proposed a mixed dataset named “near-real-time Global Gridded Daily $CO2$ Emissions Dataset” (i.e. GRACED). Compared to the previous dataset, this dataset not only divides the sources of $E_{CO2}$ but also improves the temporal resolution (daily scale) and span (2019 to current). Correspondingly, this research will use the GRACED dataset to study the impact of COVID-19 on the spatial distribution and temporal variation of global $E_{CO2}$.

## 2. DATA AND METHODOLOGY

### 2.1 Data

High spatial and temporal resolution $CO2$ data plays an important role in studying global carbon distribution and making reduction policies. Recently, Dou et al. [7] combined fossil fuel combustion data, industrial emission data, and satellite data to obtain a near real-time (2019 to present) emissions dataset with high temporal (daily scale) and spatial (global $0.1^\circ \times 0.1^\circ$ grid) resolution (Near-real-time Global Gridded Daily $CO2$ Emissions Dataset, i.e. GRACED). This paper used the total $CO2$ emission data from 2019 to 2021 to carry out the follow-up study (https://carbonmonitor-graced.com/datasets.html, last access: 2022.10.16).

### 2.2 Methodology

In this study, we use the global mean of $E_{CO2}$ to represent the overall distribution, as shown below:

$$E_{CO2} = \frac{1}{N} \sum_{i=1}^{N} f_{ECO2} (n)$$

where $N$ is the total number of grids of GRACED dataset and $f_n$ is the Gaussian weight factor, which is related to latitude. $E_{CO2}(n)$ is $E_{CO2}$ at the $n^{th}$ grid.

The difference of $E_{CO2}$ between different years is represented by relative difference (RD). For example, the RD of $A$ relative to $B$ is:

$$RD = \frac{VA - VB}{VB} \times 100\%$$

where $VA$ and $VB$ are the values of $A$ and $B$.

### 3. RESULTS

#### 3.1 Spatial Distribution

##### 3.1.1 Global Distribution of $CO2$

Overall, the outbreak of COVID-19 does not disturb the regions occurring maximum and minimum of $E_{CO2}$ and has no significant impact on the global distribution of $E_{CO2}$ (Figure 1). Specifically, the high-value regions of $E_{CO2}$ are found in regions that are highly influenced by human activities, including East Asia, Southeast Asia, the Indian Peninsula, the Middle East, Europe (mainly Western Europe), West Africa, South Africa, and coastal areas of North and South America. There are many factories, traffic, and human activities in these regions, leading to a lot of $CO2$ emissions. The low-value regions of $E_{CO2}$ are mainly located in the high latitudes and the low-middle latitudes where there is less human influence, such as dust source areas (e.g. Taklimakan Desert, Gobi Desert, Sahara Region, Victoria Desert, etc.), grassland areas (e.g. Savannah in central Africa, Great Artesian Basin in Australia, etc.), tropical rainforest areas (e.g. Amazon Rainforest), plateau areas (e.g. Tibetan Plateau Region), and vast ocean areas. In addition, $E_{CO2}$ from long-distance transport between regions and regions, such as ships and aircraft, does not change significantly from year to year.

Figure 1. Spatial distribution of $E_{CO2}$ in (a) 2019, (b) 2020, and (c) 2021. The annual average is shown in panel (d).
However, from the perspective of the global mean, there is a significant change in the impact of \( \dot{E}_{\text{CO}_2} \) on COVID-19 in different years (Figure 1). The mean value of \( \dot{E}_{\text{CO}_2} \) in different years is 212.4 kgC/h, with the highest value in 2021 (217.7 kgC/h) and the lowest value in 2020 (203.6 kgC/h), with a difference of 7%. This indicates that although COVID-19 does not completely affect the overall distribution of \( \dot{E}_{\text{CO}_2} \), it still has an impact on special regions, resulting in changes in the annual mean of global \( \text{CO}_2 \). In this paper, the relative difference (RD) \( \dot{E}_{\text{CO}_2} \) in different years will be used to analyze the impact of COVID-19 on global \( \dot{E}_{\text{CO}_2} \).

### 3.1.2 Effects of COVID-19 on Spatial Distribution of \( \text{CO}_2 \)

The overall decrease of \( \dot{E}_{\text{CO}_2} \) during the outbreak period (2020) compared to the pre-COVID-19 period (2019) is 8.4%, as shown in Figure 2 (a). In detail, except for central Japan, western and southern China, parts of Western Europe, and the eastern part of the United States, other regions of the world showed a downward trend of \( \dot{E}_{\text{CO}_2} \) in 2020, indicating that COVID-19 could significantly affect carbon emissions, leading to a global decline in \( \dot{E}_{\text{CO}_2} \). However, it is worth noting that the impact of COVID-19 on \( \dot{E}_{\text{CO}_2} \) is mainly concentrated in the mainland region, while the impact on the ocean region is not significant, which may be related to the characteristics of \( \text{CO}_2 \) itself: as one greenhouse gas, the global transmission of \( \text{CO}_2 \) takes a certain time, so the short-term impact of COVID-19 will be more significant in the emission source area.

As shown in Figure 2 (b), there is an overall 6.6% decrease in \( \dot{E}_{\text{CO}_2} \) in the post-COVID-19 period (2021) compared to the pre-COVID-19 period (2019). The decline quantity is less than that during the outbreak period (2020), indicating that human productive activities are gradually recovering. Specifically, \( \dot{E}_{\text{CO}_2} \) continued to decline in all regions except central Japan, northeastern Russia, southern China, eastern India, Western Europe, and the southeastern United States in 2021. Compared with Figure 2 (a), the data in Figure 2 (b) are intended to illustrate the impact of COVID-19 on global \( \dot{E}_{\text{CO}_2} \) is decreasing, indicating that the major economies have been revitalized and gradually recovered. However, the airline is still affected by COVID-19 and has not fully recovered in 2021.

As shown in Figure 2 (c), \( \dot{E}_{\text{CO}_2} \) in the post-COVID-19 period (2021) increases by 3.0% overall compared to the outbreak period (2020). Specifically, \( \dot{E}_{\text{CO}_2} \) increases in almost all regions except central Japan, southeast and western China, southern India, part of Western Europe, and the eastern United States. Except for sea routes, which have not been fully restored, other routes have also been gradually restored.

### 3.1.3 Seasonal Variations in Global Distribution of \( \text{CO}_2 \)

From the perspective of spatial distribution, seasonal changes have little impact on the spatial distribution of \( \dot{E}_{\text{CO}_2} \), and the high-and low-value areas of \( \dot{E}_{\text{CO}_2} \) in different seasons are consistent with their annual average distribution (Figure 3).
Figure 3. Global distribution of $\text{ECO}_2$ in different seasons (Column 1: MAM, Column 2: JJA, Column 3: SON, Column 4: DJF) for different years (Row 1: 2019, Row 2: 2020, Row 3: 2021, Row 4). MAM stands for March, April, and May; JJA for June, July, and August; SON for September, October, and November; DJF for December, January, and February. The global mean is shown at the lower right corner of each small panel as well.

From the numerical point of view, seasonal variation has a significant impact on $\text{ECO}_2$. In the pre-COVID-19 period (2019), the highest and lowest $\text{ECO}_2$ values are found in DJF (222.6 kgC/h) and JJA (209.1 kgC/h), respectively. And the concentrations of MAM (210.1 kgC/h) and SON (212.9 kgC/h) are similar. This may be because DJF is winter in the Northern Hemisphere, which requires burning a lot of fossil fuels for heating, leading to higher CO$_2$ concentrations in the environment. During the outbreak period (2020), the highest $\text{ECO}_2$ still occurs in DJF (231.4 kgC/h), but the lowest is found in MAM (182.0 kgC/h), which largely reflects the impact of COVID-19 on $\text{ECO}_2$. Since COVID-19 began in February 2020, various regions of the world implemented strict control measures, resulting in a sharp drop in $\text{ECO}_2$. $\text{ECO}_2$ in the MAM decreased by 13.3% in 2020 compared to 2019. Similarly, due to COVID-19, $\text{ECO}_2$ of JJA and SON also decreased to varying degrees in 2020. However, by 2020 DJF, $\text{ECO}_2$ had recovered to the 2019 level overall. In the post-COVID-19 period (2021), the highest $\text{ECO}_2$ occurs in DJF (236.7 kgC/h) and the lowest one in JJA (211.8 kgC/h), while the MAM (212.2 kgC/h) and SON (215.3 kgC/h) concentrations are similar. This is consistent with the seasonal variation of $\text{ECO}_2$ before COVID-19, indicating that the impact of COVID-19 on $\text{ECO}_2$ concentration has gradually weakened. Notably, there was a slight increase in $\text{ECO}_2$ for each season in 2021 compared to 2019, indicating that economic activities around the world have gradually recovered from the impact of COVID-19 and are moving forward steadily. From the perspective of a three-year average, the highest $\text{ECO}_2$ occurs in DJF (230.2 kgC/h), followed by SON (212.6 kgC/h) and JJA (206.9 kgC/h), and MAM (201.4 kgC/h). This is mainly due to $\text{ECO}_2$ from the MAM in 2020, reflecting the impact of the outbreak of COVID-19 on global $\text{ECO}_2$.

3.2. Time Variation of $\text{ECO}_2$

In general, $\text{ECO}_2$ has a significant diurnal/monthly variation characteristic, and the monthly cycle shows a tendency to decrease first and then increase, with the lowest value appearing near May and the highest value appearing near December (Figure 4).
Specifically, the diurnal variation of different years presents a regular cycle of around 1 week, which reflects the influence of human activities on \( E_{CO2} \). In each cycle, with high values on weekdays and low values on weekends, changes in \( E_{CO2} \) are related to the amount of \( CO2 \) emitted by people commuting to work in vehicles. From the perspective of monthly variation, the lowest values of different years all appear near May (summer in the Northern Hemisphere), and the highest values all appear in December (winter in the Northern Hemisphere), which is largely related to the heating of Northern Hemisphere in winter. From the analysis of different years, the diurnal and monthly changes of \( E_{CO2} \) were the same before (2019) and after COVID-19 (2021), but during the outbreak period (2020), \( E_{CO2} \) decreased to different degrees in all months of the year, especially in April 2020. Compared with that in 2019, it fell by 17%, highlighting the impact of COVID-19 on limiting \( E_{CO2} \). Since then, the concentration of \( E_{CO2} \) has gradually increased and approached the three-year average, indicating that the impact of COVID-19 is fading.

In conclusion, the impact of COVID-19 on \( CO2 \) mainly works during the outbreak period (2020), especially from March to June of this period. Since then, the impact of COVID-19 has gradually subsided, and by 2021, global \( E_{CO2} \) have returned to pre-COVID-19 levels overall.

4. CONCLUSION AND DISCUSSION

Global warming, as one of the most severe challenges faced by human beings at present, has attracted widespread attention from countries all over the world. Studies show that \( CO2 \) is the determining factor causing global warming, and its changes will affect the intensity and rate of global temperature rise. At the end of 2019, the outbreak of COVID-19 disrupted global industrial production, transportation and human activities, with potential implications for \( E_{CO2} \) as well. However, limited by the spatial and temporal resolution of datasets, there is no definitive conclusion on the impact of COVID-19 on the spatio-temporal distribution of \( E_{CO2} \).

This study systematically analyzed the \( E_{CO2} \) spatio-temporal distribution of COVID-19 from 2019 to 2021 based on one most recent near-real-time \( CO2 \) dataset, namely GRACED. The results show that COVID-19 has no significant impact on the global spatial distribution of \( CO2 \), that is, it does not affect the global maximum and minimum of \( E_{CO2} \) but has a significant impact on the values. In detail, the outbreak of COVID-19 has led to a significant drop in \( E_{CO2} \) (\( \bar{E}_{CO2} = 203.6 \, kgC/h \)) compared to 2019 (\( \bar{E}_{CO2} = 215.9 \, kgC/h \)). Whereas, \( E_{CO2} \) had returned to pre-COVID-19 levels (\( \bar{E}_{CO2} = 217.7 \, kgC/h \)) by 2021, indicating the impact of COVID-19 on \( E_{CO2} \) is mainly concentrated in 2020. From the perspective of different seasons, seasonal variation has no significant influence on the spatial distribution of \( E_{CO2} \), but has an obvious influence on its value. In 2019 and 2021, the highest and lowest values of \( E_{CO2} \) occurred in the winter (DJF) and summer (JJA) of the Northern Hemisphere, respectively. However, the MAM had its lowest \( E_{CO2} \) value in 2020, reflecting the devastating impact of the outbreak of COVID-19 on global \( E_{CO2} \). As for the time variation of \( E_{CO2} \), the diurnal variation of \( E_{CO2} \) has a weekly cycle, which may be related to the frequency of using transportation on and off days. The impact of the outbreak of COVID-19 on \( CO2 \) monthly variations mainly occurred in 2020, particularly during March and June. By 2021, global \( CO2 \) had largely recovered to 2019 levels as the impact...
of COVID-19 faded.

There are still some problems to be further considered. First, we notice that the $E_{\text{CO}_2}$ during the COVID-19 outbreak are still increasing in parts of Asia, Europe and the Americas. Subsequent studies need to combine data from different CO$_2$ sources in these regions to analyze the specific causes. In addition, the study regions are divided roughly in this paper, and subsequent studies will further subdivide the study area to conduct targeted analysis on the spatio-temporal distribution of $E_{\text{CO}_2}$ in specific countries and regions under COVID-19. Finally, most of this study only analyzed the spatio-temporal distribution of $E_{\text{CO}_2}$ under COVID-19, and the analysis of the causes is not specific enough. It is necessary to make more detailed analyzes in future studies.

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