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A COMPARISON STUDY ON THE MONTHLY AVERAGE CONCENTRATION OF CARBON DIOXIDE (CO_2) IN ANMYEON ISLAND IN THE REPUBLIC OF KOREA AFTER THE COVID-19 PANDEMIC VIA STATISTICAL REASONING

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Although lockdowns following the COVID-19 pandemic temporarily curbed global carbon dioxide (CO_2) emissions in 2020, many studies suggest that the average concentration of CO_2 in the atmosphere continues to increase. CO_2 is a representative greenhouse gas, and most of it is emitted by burning fossil fuels, such as coal, oil, and natural gas. Anmyeon Island has a representative climate change monitoring center and has been monitoring greenhouse gases, including CO_2, for the longest time in the Republic of Korea. In this paper, we compare the monthly average concentration of CO_2 in Anmyeon Island before and after the COVID-19 pandemic. Our analysis produced the following results: (i) the monthly average concentration of CO_2 in Anmyeon Island increased significantly from January 2020 to December 2020 compared to that from January 2019 to August 2019; (ii) the monthly average concentration of CO_2 in Anmyeon Island increased significantly from January 2021 to December 2021 compared to that from January 2020 to August 2020. Our study shows statistically comprehensive results compared to the studies that limit their discussions to the average rate of increase (or decrease) that is compared with that of the previous year, as presented in the 2020 Global Atmospheric Monitoring Report, Climate Research Division, National Institute of Meteorological Sciences in the Republic of Korea. The implications of our findings are briefly discussed.

Keywords: Carbon dioxide (CO_2), COVID-19 pandemic, climate change, statistical significance

INTRODUCTION

Climate change and the COVID-19 pandemic have driven investment and interest in a decarbonized economy (Organisation for Economic Cooperation and Development (OECD), 2021–2022). For example, on December 13, 2022, the European Union (EU) announced that a provisional agreement was reached to introduce the 'Carbon Boundary Adjustment System' (CBAM). According to CBAM, the EU is expected to impose additional tariffs on carbon-emitting imports by 2026 at the earliest (Council of the EU, Press release, December 2022). U.S. President Joe Biden signed an executive order directing the federal government to achieve net-zero emissions by 2050 (Bloomberg news, 12 December 2021). On March 22, 2022, the U.S. Securities and Exchange Commission announced draft regulations requiring companies listed on the New York Stock Exchange to disclose information on carbon emissions. On October 19, 2021, the U.K. government announced a detailed net-zero strategic plan for all sectors of

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industry, including electricity, hydrogen production, industry, heating and transport, etc (GOV.UK report, October 2022). On August 2022, India submitted an upgraded Nationally Determined Contribution (NDC) to United Nations Framework Convention on Climate Change (UNFCCC). According to the revised NDC, India has committed to reducing carbon emissions per unit of gross domestic product (GDP) by 45% by 2030, compared to the previous year (United Nation Report, 2022). See the OECD report (2021–2022) and Chang and Lee (2022, Section 5) for details.

Carbon dioxide (CO_2) is a representative greenhouse gas that contributes to climate change (see Material and Method for details). It is mostly emitted by the burning of fossil fuels such as coal, oil, and natural gas. As global warming progresses, changes in precipitation, atmospheric pressure, and soil moisture occur across the globe, which increases the possibility of meteorological disasters such as floods, droughts, melting glaciers, rising sea levels, etc. It must be remarked that once emitted, CO_2 remains in the atmosphere for 300 to 1000 years (National Aeronautics and Space Administration (NASA), October 2019), which makes it difficult to reduce the average concentration of CO_2 by reducing emissions of CO_2 within a short period of time. Because the amount of CO_2 contained in the atmosphere is relatively small compared to other gases, the average concentration of CO_2 is expressed using parts per million (ppm) (Environmental Protection Agency (EPA), 2022). It exists as a gas at room temperature and is non-toxic to living things, but a high concentration of CO_2 lowers the specific gravity of oxygen (O_2), causing poisoning symptoms (such as difficulty in breathing, dizziness, fatigue, etc.) and may result in unconsciousness, convulsions, coma, and death (EPA, US, 2015). See Review of CO_2 in Material and Method for details.

The OECD, NASA, and European Space Agency (ESA) have homepages for monitoring global CO_2 concentrations. Moreover, Environmental Protection Agency (EPA) presents detailed guidelines (such as sources, emissions and trends, and strategies to reduce greenhouse gases) on greenhouse gas including CO_2. World Health Organization (WHO) mentions that climate change is projected to cause about 2500,000 additional deaths per year (WHO, October 2021).

The rest of this article is organized as follows. In Material and Methods, we present a review of related work, and in Results, we compare the monthly average concentration of CO_2 in Anmyeon Island before and after the COVID-19 pandemic. In Conclusion, we present a summary of our findings and their implications.

MATERIAL AND METHODS

In this section, we present a review of the related work—properties, derivations, sources, the hazards and uses of CO_2, emissions and sources of CO_2 in the Republic of Korea, and a summary of literature showing the increase in CO_2 concentration in the air despite of the COVID-19 lockdown. We also present the advantage of our method.

REVIEW OF CARBON DIOXIDE (CO_2)

We summarize the properties, derivations, sources, hazards and uses of Carbon Dioxide (CO_2) in Table 1.

Table 1. Properties, derivations, sources, hazards, and the uses of CO_2 (CDC, EPA, US, NASA, Ministry of Environment Report)

Properties	(i)	(1) gas: colorless, odorless, specific gravity = 1.53 (air = 1.00). (2) liquid: volatile, colorless, odorless, specific gravity (-37°C) = 1.101, specific volume 8.76 cu. ft/lb (70°F, 1atm). (3) solid (dry ice): white, snow-like flakes or cubes, specific gravity = 1.57 (-79°C), melting point = -78.5°C (sublimes, 1atm).
	(ii)	All forms are non-combustible. Soluble in water (carbonic acid, H_2CO_3), hydrocarbons, and most organic liquids. Nontoxic (solid); an asphyxiant gas.
	(iii)	Fire-extinguishing properties
	(iv)	Optical property of absorbing some of the infrared radiant energy emitted from the earth.
	(v)	Once emitted, CO_2 remains in the atmosphere for 300 to 1000 years. Remark 1. Carbon molecules in CO_2 that absorb infrared waves become excited and release some of the energy to maintain a stable state, which increases the temperature of the earth's surface.
Derivations and Sources	(i)	Gaseous – CO_2 is present in the air to the extent of 0.03% by volume and 0.0474% by weight. But is not economically recoverable. Its chief sources are: (1) the end-product of the complete combustion of fossil fuel (coal, diesel fuel, gasoline, oil, natural gas, etc.) and respiration, (2) the cracking of hydrocarbons, (3) the action of heat or acid on limestone, marble, and other carbonates, (4) the fermentation of carbohydrates, and (5) natural spring or wells.
	(ii)	Liquid – by compressing and cooling the gas to about -37°C.
	(iii)	Solid (dry ice) – by expanding the liquid to vapor and snow in presses that compact the product into blocks. The vapor is then recycled.
Hazards	(i)	Hazard (solid): damaging to solid and tissue; keep away from mouth and eyes. Tolerance (gas): 5000 ppm in the air.
	(ii)	Acts as both a stimulant and depressant on the central nervous system. See Table B-1 in EPA for details on the acute health effects of high concentrations of CO_2.
Uses	Dry ice, which is solid CO_2, is used as a coolant; Used in fire extinguishers; Particularly effective in extinguishing fires by electricity, where it is difficult to use water; Elucidation of mechanisms in organic chemistry, metallurgy, and biochemical reaction; Radiation source in thickness gauges and other instruments; Radiocarbon dating in geology and archaeology; Used for water and wastewater treatment, among others.	

As we can see from Table 1, CO_2 is a representative greenhouse gas that causes climate change. It is mostly emitted by the burning of fossil fuels such as coal, oil, and natural gas.

Known Statistics: Emissions and Sources of greenhouse gases in the Republic of Korea

We summarize the emissions of greenhouse gases in the Republic of Korea from 2019 to 2021 in Table 2 (E-country indicator in the Republic of Korea, Ministry of Environment in Republic of Korea, 2019-2021).

Table 2. The emissions of greenhouse gases in the Republic of Korea from 2019 to 2021 (unit: million tons of CO_{2eq}).

Sector	Year 2019	Year 2020 (Tentative estimate)	Year 2021(Tentative estimate)
Energy	611.5	570	590.6
Industrial Process	52.0	48.5	51.0
Agriculture	21.0	21.0	21.2
Waste	16.9	17.1	16.7
Sum	701.4	676.6	679.6

According to the Ministry of Environment in the Republic of Korea, emissions decreased continuously in 2019 and 2020 due to a decrease in coal-fired power generation and economic contraction. In 2021, emissions were expected to increase by 3.5% from the previous year to 679.6 million tons of CO_{2eq} due to economic recovery (E-country indicator in the Republic of Korea).

In the Republic of Korea, greenhouse gas emission sources are classified into energy, industrial processes, agriculture, and waste. The main emission source worldwide is the energy sector. Greenhouse gases emitted from the energy sector account for 87% of greenhouse gases in the Republic of Korea. In the Republic of Korea, greenhouse gas emissions from the energy sector increased by 154% between 1990 and 2019 (E-country indicator in the Republic of Korea).

Literature showing the increase in the average concentration of CO_2 in the atmosphere despite the COVID-19 lockdown

We present literature that shows that the average CO_2 concentration continues to rise despite the COVID-19 lockdown.

Table 3. Literature showing the increase in CO_2 concentration in the air despite the COVID-19 lockdown.

Literature	Main finding
UNEP (United Nations Environment Programme), May, 2020	Global carbon dioxide (CO_2) levels are rising sharply. Due to anthropogenic CO_2 emissions (such as emissions from human activities), CO_2 levels are not only increasing but also accelerating.
World Meteorological Organization, 23 November 2020.	CO_2 levels continue at record levels, despite the COVID-19 lockdown.
World Meteorological Administration, National Institute of Meteorological Sciences in Republic of Korea, July 2021.	CO_2 emissions on the Korean Peninsula increased in 2020, and the rate of increase was maintained. Despite a decrease in global and domestic CO_2 emissions, the average concentration of CO_2 in Anmyeon Island was found to be at an all-time high.
NASA, November 9, 2021.	CO_2 emissions fell by 5.4% in 2020 but the amount of CO_2 in the atmosphere continued to grow at about the same rate as the preceding years.

As we can see from Table 3, NASA's satellite detected that CO_2 emissions fell by 5.4% in 2020, but the amount of CO_2 in the atmosphere continued to grow at about the same rate as in the preceding years. See NASA (2020-2021) for details.

The advantage of our method

The report by the World Meteorological Administration, National Institute of Meteorological Sciences in the Republic of Korea is based on the average rate of increase (or decrease) compared with that of the previous year, which is simple and easy to understand. However, it does not give the decisionmaker detailed information about whether the difference is statistically significant or not. In this connection, see Chang (2022) and the references therein. The analytical method presented in this paper is not just the average rate of increase (or decrease) compared with that of the previous year but has the advantage of providing statistically valid and reliable results. See Results for details.

RESULTS

Known Statistics: Monthly average CO_2 concentration in Anmyeon Island in the Republic of Korea from 2019 to 2021

We summarize the monthly average CO_2 concentration in Anmyeon Island in the Republic of Korea from 2019 to 2021 in Table 4 (Korea Meteorological Administration 2019-2021).

Table 4. The monthly average CO_2 concentration in Anmyeon Island in the Republic of Korea from 2019 to 2021 (unit: ppm).

Month	Year 2019	Year 2020	Year 2021
January	419.0	424.3	425.6
February	420.0	423.6	426.5
March	421.1	423.5	426.8
April	422.0	424.2	427.1
May	420.5	423.4	424.8
June	416.8	418.5	421.8
July	413.6	414.4	419.0
August	411.8	413.6	415.6
September	412.8	414.8	416.3
October	416.2	418.7	421.9
November	419.3	421.9	425.7
December	421.2	423.6	426.7

Statistical comparison results

In this section, we present statistical comparison results on the monthly average CO_2 concentration in Anmyeon Island in the Republic of Korea from 2019 to 2021 with two different hypothesis statements.

Statistical reasoning and analysis (2019 vs. 2020)

We present the statistical comparisons of the two data sets: (i) monthly average CO_2 concentration in Anmyeon Island in the Republic of Korea from January 2019 to December 2019 and (ii) monthly average CO_2 concentration in Anmyeon Island in the Republic of Korea from January 2020 to December 2020. The following hypotheses are set for the monthly average CO_2 concentration in Anmyeon Island:

H_0 (Null hypothesis): Monthly average CO_2 concentration in Anmyeon Island from January 2020 to December 2020 $\leq$ Monthly average CO_2 concentration in Anmyeon Island from January 2019 to December 2019.

H_1 (Alternative hypothesis): Monthly average CO_2 concentration in Anmyeon Island from January 2020 to December 2020 > Monthly average CO_2 concentration in Anmyeon Isalnd from January 2019 to December 2019.

The basic principle of the analysis presented in this paper is the same as that of statistical control chart. We define the difference between the monthly average CO_2 concentration in Anmyeon Island in a specific year and the monthly average CO_2 concentration in Anmyeon Island of the previous year as the error (or natural variability or the chance causes of variation). Under the assumption that H_0 is true, the error (natural variability) is assumed to follow a normal distribution with a mean 0 and a finite variance that is greater than 0, which is an implicit assumption in our study.

Since the two-time series in Table 4 are correlated, and each month's data is paired with each other, a pairwise test was used to compare the average differences between the two populations (Chang and the references therein, 2022). Under the assumption that the null hypothesis is true, the monthly average CO_2 concentration in Anmyeon Island from January 2019 to December 2019 was compared with that of January 2020 to December 2020.

Table 5 shows the results obtained from the pairwise comparison test (significant level of test = 0.01) using Excel.

Table 5. Pairwise comparison (2019 vs 2020) test result (significant level of test = 0.01) *t*-test results:

	Monthly Average CO_2 Concentration of in 2019	Monthly Average CO_2 Concentration in 2020
Sample average	417.8583	420.375
Sample variance	12.55174	17.37114
No. of observation	12	12
Pearson's correlation coefficient	0.971374	
Average difference in hypothesis test	0	
d.f.	11	
t statistics	-7.84145	
P(T<=t), one-sided test	3.95E-06	
P(T<=t), critical value, one-sided test	2.718079	
P(T<=t), two-sided test	7.9E-06	
P(T<=t), critical value, two-sided test	3.105807	

As can be seen from Table 5, the null hypothesis that the two population groups have the same mean is rejected because the *p*-value is 0.00000395, which is less than the 0.01 significance level. There is significant evidence that the monthly average CO_2 concentration in Anmyeon Island from January 2020 to December 2020 was greater than the monthly average CO_2 concentration in Anmyeon Island from January 2019 to December 2019, and the reliability of this conclusion is 0.99.

Statistical reasoning and analysis (2020 vs. 2021)

A similar analysis was carried out, and we present our statistical results in Table 6. The following hypotheses are set for the monthly average CO_2 concentration in Anmyeon Island:

H_0 (Null hypothesis): Monthly average CO_2 concentration in Anmyeon Island from January 2021 to December 2021 $\leq$ monthly average CO_2 concentration in Anmyeon Island from January 2020 to August 2020.

H_1 (Alternative hypothesis): Monthly average CO_2 concentration in Anmyeon Island from January 2021 to December 2021 > Monthly average CO_2 concentration in Anmyeon Island from January 2020 to December 2020.

Table 6. Pairwise comparison (2020 vs. 2021) of test result (significant level of test = 0.01) *t*-test results:

	Monthly Average CO_2 Concentration in 2020	Monthly Average CO_2 Concentration in 2021
Sample average	420.375	423.15
Sample variance	17.37114	17.50091
No. of observation	12	12
Pearson's correlation coefficient	0.969916	
Average difference in hypothesis test	0	
d.f.	11	
t statistics	-9.38426	
P(T<=t), one-sided test	6.95E-07	
P(T<=t), critical value, one-sided test	2.718079	
P(T<=t), two-sided test	1.39E-06	
P(T<=t), critical value, two-sided test	3.105807	0

As can be seen from Table 6, the null hypothesis that the two population groups have the same mean is rejected because the p-value is 0.000000695, which is less than the 0.01 significance level. There is significant evidence that the monthly average of CO_2 levels in Anmyeon Island from January 2021 to December 2021 was greater than the monthly average of CO_2 concentrations in Anmyeon Island from January 2020 to December 2020, and the reliability of this conclusion is 0.99.

CONCLUSION

The monthly average concentration of CO_2 in Anmyeon Island was compared before and after the COVID-19 pandemic. Our analysis produced the following results: (i) the monthly average concentration of CO_2 in Anmyeon Island significantly increased from January 2020 to December 2020 compared to that of January 2019 to December 2019; (ii) the monthly average concentration of CO_2 in Anmyeon Island increased significantly from January 2021 to December 2021 compared to that of January 2020 to December 2020.

Our study shows statistically comprehensive results compared to the studies that limit their discussions to the average rate of increase (or decrease) compared with that of the previous year, as presented in the 2020 Global Atmospheric Monitoring Report, Climate Research Division, National Institute of Meteorological Sciences in the Republic of Korea. Note that our analysis is based on the CO_2 concentration statistics in Anmyeon Island from 2019 to 2021, and our conclusion is valid only for this period.

Our findings have the following implications. As mentioned in Introduction, once emitted, CO_2 remains in the atmosphere for 300 to 1000 years (NASA, October 2019), which makes it difficult to reduce the average concentration of CO_2 by just reducing the emissions of CO_2 in a short period of time. Effective strategies to reduce CO_2 concentration for the transition to a decarbonized society are thus required. Specific measures may include the following:

- The establishment and implementation of government and corporate policies/ regulations for the re-organization of the domestic industrial structure for fossil energy reduction.

- The development of a digital platform for reducing fossil energy that can be realized gradually in the domestic environment.
- Digital transformation of the domestic industrial structure and supply chain based on 4th industrial revolution technologies (such as Artificial Intelligence, Big Data, Robots, Drones, Augmented Reality, Internet of Things, Blockchain Technology, etc.), improvement of the efficiency of energy, and the transition to renewable energy (such as solar energy, solar heat, wind power, hydropower, hydrogen energy, marine renewable energy, geothermal power, bioenergy, etc.) generation.
- Enhanced reforestation business.
- Investment in R&D on renewable energy technologies, development of an industrial ecosystem for the transition to a decarbonized society, investment on building decarbonization infrastructure, encouraging innovation in renewable energy technologies, etc.
- Enhanced international environmental cooperation.

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