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No evidence for global decrease in CO_2 concentration during the first wave of COVID-19 pandemic

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Abstract Numerous studies have reported that CO_2 emissions have decreased because of global lockdown during the first wave of the COVID-19 pandemic. However, previous estimates of the global CO_2 concentration before and after the outbreak of the COVID-19 pandemic are limited because they are based on energy consumption statistics or local specific in-situ observations. The aim of the study was to explore objective evidence for various previous studies that have claimed the global CO_2 concentration decreased during the first wave of the COVID-19 pandemic. There are two ways to measure the global CO_2 concentration: from the top-down using satellites and the bottom-up using ground stations. We implemented the time-series analysis by comparing the before and after the inflection point (first wave of COVID-19) with the long-term CO_2 concentration data obtained from World Meteorological Organization Global Atmosphere Watch (WMO GAW) and Greenhouse Gases Observing Satellite (GOSAT). Measurements from the GOSAT and GAW global monitoring stations show that the CO_2 concentrations in Europe, China, and the USA have continuously risen in March and April 2020 compared with the same months in 2019. These data confirm that the global lockdown during the first wave of the COVID-19 pandemic did not change the vertical CO_2 profile at the global level from the ground surface to

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the upper layer of the atmosphere. The results of this study provide an important foundation for the international community to explore policy directions to mitigate climate change in the upcoming post-COVID-19 period.

Keywords COVID-19; Carbon budget; CO_2 profile · Corona · Global Atmosphere Watch (GAW) · GOSAT (Greenhouse Gases Observing Satellite) · World Meteorological Organization (WMO)

Introduction

Global lockdown procedures (e.g. social distancing, city blockades and quarantine) were strongly enforced in many countries such as China, the USA and European countries to minimise the transmission of COVID-19. Various previous studies have reported that CO_2 emissions decreased because of the global lockdown (Le Quéré et al., 2020a; Moersen, 2020; Rugani & Caro, 2020; Simpkins, 2020). The World Meteorological Organization (WMO) announced that the COVID-19 global lockdown may lead to a 4–7% reduction in fossil fuel emissions over 2020 (WMO, 2020). According to the International Energy Agency (IEA), global CO_2 emissions are expected to decline by 8%, nearly to levels from 10 years ago, which would be the largest decline since the end of World War II (Tollefson, 2020).

In China, which is the world's highest greenhouse gas emitter, the lockdowns resulted in a 10% reduction in greenhouse gases up to the end of March compared with the previous year (Tollefson, 2020). A 72% drop in CO_2 emissions was reported in Paris (McGrath, 2020) and 75% (Dario Papale1 et al., 2020) in the city centre of Heraklion, Greece compared with normal concentrations. The lockdown caused significant CO_2 reduction in 12 sites in Kolkata, India, ranging from 24.56 to 45.37% (Mitra et al., 2020). There is a prior study to estimate industrial CO_2 reductions due to the COVID-19 global lockdown. The aviation sector is expected to have the largest CO_2 reduction (75%) owing to the lockdown (Le Quéré et al., 2020b), and a ~ 43% decrease is expected for other industries such as transportation and power plants. These studies forecast that this would be the largest decline since World War II (Le Quéré et al., 2020b; Otley, 2020). An 8.8% drop in global CO_2 emissions (1.551 Gt CO_2) was also reported from January 1, 2019 to June 30, 2020: China 3.7% (187.2 Mt CO_2), EU & UK 12.7% (205.7 Mt CO_2), USA 13.3% (338.3 Mt CO_2), India 15.4% (205.2 Mt CO_2), Russia 5.3% (40.5 Mt CO_2), Japan 7.5% (43.1 Mt CO_2), Brazil 12.0% (25.9 Mt CO_2) (Liu et al., 2020).

CO_2 is the largest contributor to climate change, accounting for 82% of the total radiative forcing by all long-lived greenhouse gases over the past decade (WMO, 2019). CO_2 is used as the benchmark that warms the atmosphere. The method of measuring CO_2 is largely dependent on direct measurements on the Earth's surface or indirect estimations based on energy consumption statistics (Eggleston et al., 2006). There are significant limitations in exploring global CO_2 concentrations from the in situ survey of a specific point where the lockdown due to COVID-19 is enforced. Estimation according to fuel use among industrial sectors does not reflect the global CO_2 concentration in the atmosphere.

There is a concern that inaccurate estimates of the CO_2 reduction caused by COVID-19 may cause confusion in policy priorities for mitigating climate change. In particular, such estimates are likely to be used as evidence that countries are passively responding to climate change compared with the past. Despite abundant interest in this problem, the changing CO_2 trend before and after the COVID-19 outbreak has seldom been empirically examined using global CO_2 concentration data from the Greenhouse Gases Observing Satellite (GOSAT) and global monitoring stations. This research is designed to objectively present CO_2 reductions due to the first wave of COVID-19 outbreak through inter-country and continental comparisons of CO_2 concentrations using GOSAT and global-level observation data.

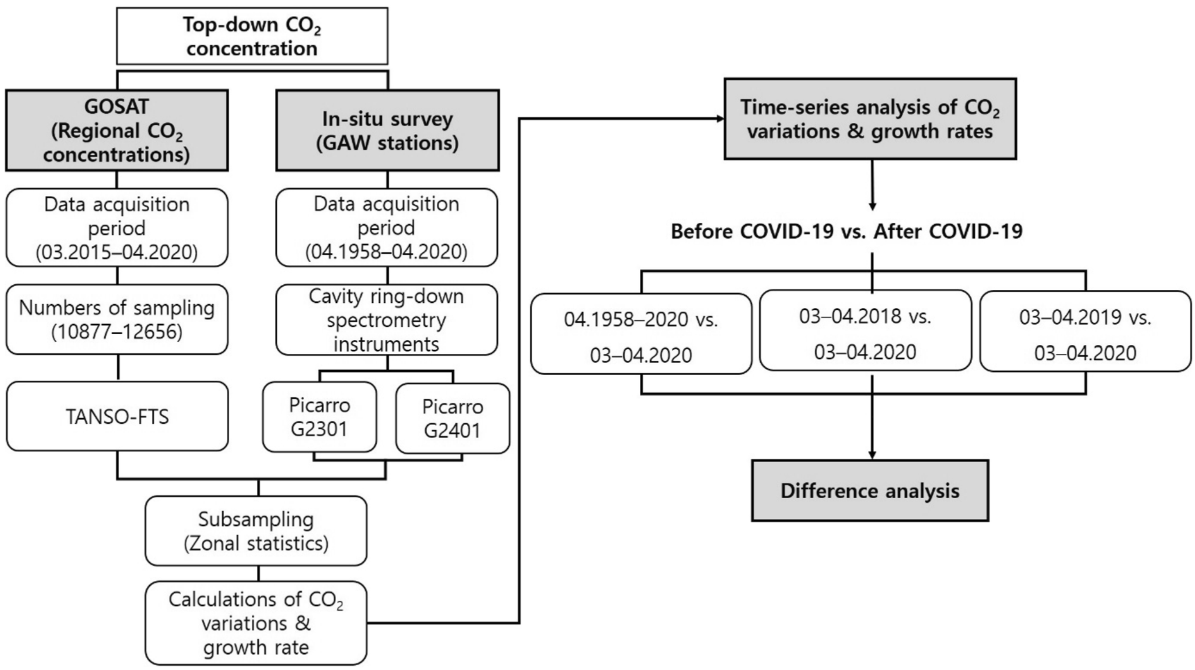


Fig. 1 Flowchart for the data analysis procedures

Materials and methods

There are two ways to measure the global CO_2 concentration: from the top-down using satellites and the bottom-up using ground stations (Fig. 1) (Hwang et al., 2021). Launched in 2009, the GOSAT is the first satellite dedicated to greenhouse gas measurements. GOSAT is considered the most advanced satellite for CO_2 observation among existing satellites, and its usefulness has been validated in several previous studies (Houweling et al., 2015; Janardanan et al., 2016; Lindqvist et al., 2015; Park et al., 2018; Um, 2015). GOSAT orbits the Earth approximately 14 times per day, and over a period of 3 days, the same area is measured with an average error range of 4 ppmv (1% precision). GOSAT raw data are collected as Level 1 and processed to Level 2, which calculates the vertical atmospheric mixing of CO_2 per unit area (10.5 km) on the Earth's surface. In this study, we used version 02.81 of the GOSAT Level 2 data verified by the ground-based XCO_2 reference of the Total Carbon Column Observing Network (TCCON) (Hwang & Um, 2017a; NIES GOSAT Project, 2019; Park et al., 2017).

The World Data Centre for Greenhouse Gases (WDCGG) classifies bottom-up measurements from the ground into three groups according to the role of the station: Group 1 is a global station that is not affected by anthropogenic disturbances and biospheric CO_2 uptake; Group 2 is a regional station that cannot completely exclude the effects of local geographic features or anthropogenic sources and Group 3 is a contributing station that does not formally register with Global Atmosphere Watch (GAW) but shares data. Global and regional stations are operated according to GAW guidelines for quality assurance (Hwang & Um, 2016c; Müller, 2007). Contributing stations are those that conform to GAW measurement guidelines.

Lockdowns were extensively implemented from March to April 2020 in Europe because of high concentrations of confirmed COVID-19 cases. Europe has contributed more to global climate change than any other continent. Vegetation zones are distributed according to climate zones (Hwang & Um, 2016a). Europe has all the global climatic zones except the tropics. GOSAT XCO_2 data acquired in Europe have been produced with more validation procedures than

Table 1 Descriptions of the seven WMO/GAW stations used in this study

Station GAW ID/country	Station category	Latitude, Longitude	Elevation (metres above sea level)/station land use
MLO/USA	Global	19.54°N 155.58°W	3397/Forest, rural
ZEP/Norway	Global in the Arctic	78.90°N, 11.88°E	475/Gravel and stone
CMN/Italy	Global	44.16°N, 10.68°E	2165/Forest, rural
SSL/Germany	Regional	47.90°N, 7.91°E	1205/Forest, rural
BIR/ Norway	Regional	58.38°N, 8.25°E	190/Forest, rural
TOH/Germany	Contributing	51.80°N, 10.53°E	801/Forest, rural
IPR/Italy	Contributing	45.80°N, 8.62°E	210/Small town on the eastern coast of Lake Maggiore

those from other continents because TCCON is much denser than other continents (8 out of 23 worldwide TCCON sites) (Hwang et al., 2020). Europe is the second smallest continent in the world after Australia but because 44 countries are concentrated in one region; it is therefore an ideal area to intensively study biospheric carbon uptake and CO_2 emissions across countries over short durations (Hwang & Um, 2016b; Hwang et al., 2020a, 2020b). The data obtained at the European GAW stations were used to compare the CO_2 concentrations before and after the COVID-19 outbreak. For GOSAT XCO_2, CO_2 concentrations before and after the COVID-19 outbreak were evaluated for Europe, the USA and China using data acquired in March 2018, March–April 2019 and March–April 2020. An unpaired *t* test was performed to verify the mean difference between CO_2 measurements before and after the COVID-19 outbreak.

The GAW stations were selected considering the latitudinal bands (Table 1; Fig. 1) of CMN located in the Europe's southernmost Mediterranean coast (44.16°N) to ZEP located at the northernmost pole (78.90°N) to measure the Earth's background atmosphere. Schauinslan (SSL) in Germany was selected to study long-term CO_2 in Western Europe because the station has the longest continental CO_2 record available since 1972. Three GAW stations located in the European continent (BIR: Birkenes Atmospheric Observatory (Norway), TOH: Torfhaus (Germany) and IPR: Ispra (Italy)), were selected to measure changes in the local CO_2 concentration before and after the COVID-19 outbreak. These sites are equipped with cavity ring-down spectrometry

Table 2 Specifications of GOSAT and GAW stations (PICARRO, 2017, 2019; Tadić et al., 2012)

Category	GOSAT	GAW station	
Sensor	TANSO-FTS	Picarro G2301	Picarro G2401
Measurement technique	Fourier Transform Spectrometer Mechanism	Cavity Ring-Down Spectroscopy (CRDS)	Cavity Ring-Down Spectroscopy (CRDS)
Precision	1% for CO_2 (4 ppmv)	< 25 ppb	< 20 ppb
Time resolution	4 s/interferogram (5-point observation cross track)	< 3 s	< 3 s
Spectral range	Band 1: 0.758–0.775 μm (O_2) Band 2: 1.56–1.72 μm (CO_2, CH_4) Band 3: 1.92–2.08 μm (CO_2, H_2O) Band 4: 5.56–14.3 μm (CO_2, CH_4)	–	–
Lower detection limit (sensitivity)	1 ppm	75 ppb at 5 min	60 ppb at 5 min

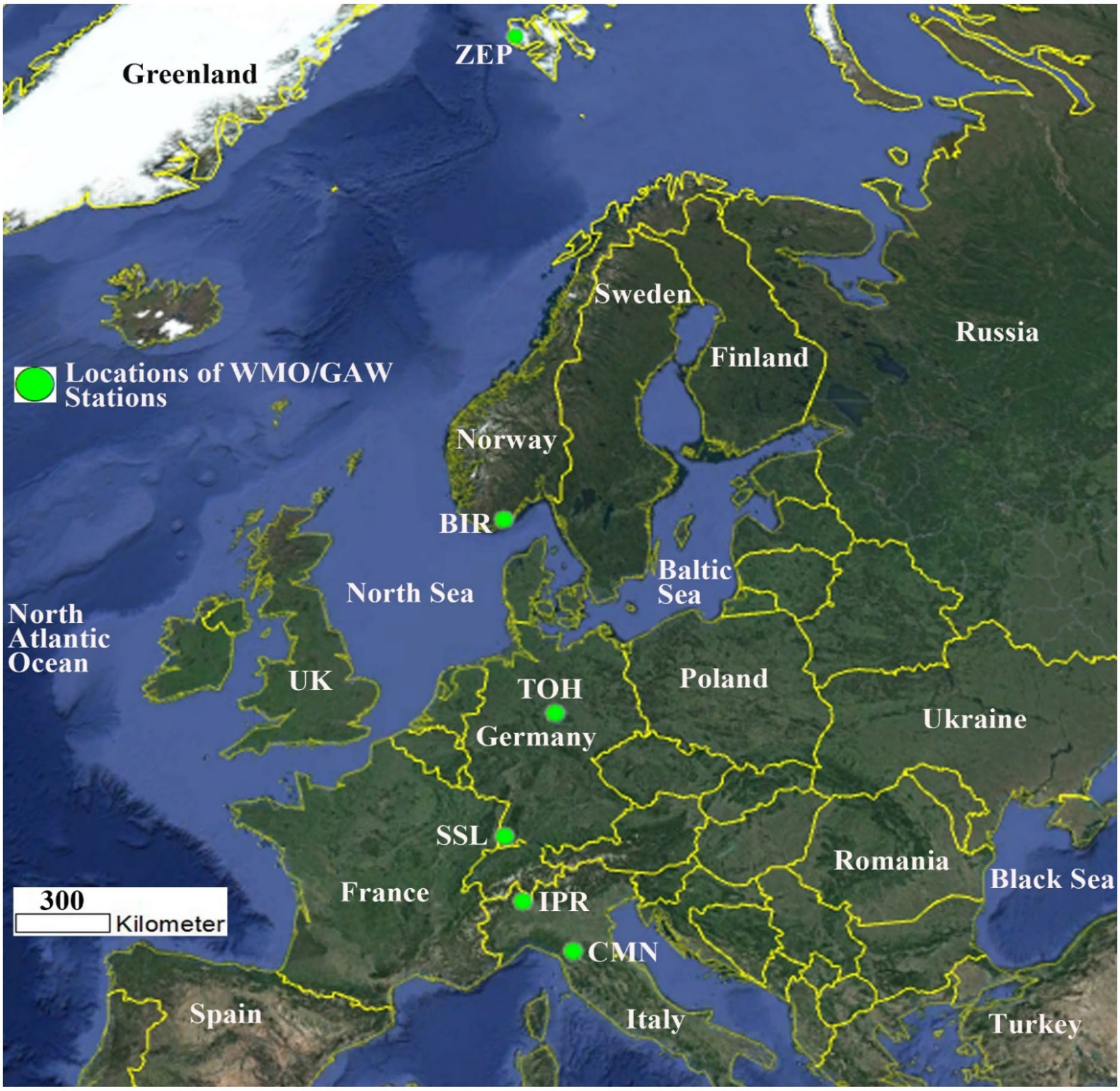


Fig. 2 Six WMO/GAW stations deployed across latitudinal bands from the Arctic to the Mediterranean Sea. ZEP Zeppelin mountain (Norway), BIR Birkenes Atmospheric Observatory (Norway), TOH Torfhaus (Germany), SSL Schauinslan (Germany), IPR Ispra (Italy), CMN Monte Cimone (Italy)

instruments, such as Picarro G2301 and G2401, and satisfy performance requirements of the WMO-GAW program of WMO (WDCGG, 2020) and Integrated Carbon Observing System (ICOS) Atmospheric Station Specification in Europe for the measurement of CO_2 (Table 2) (ICOS, 2017; Marshall, 2018). Most GAW sites have more than one CO_2 intake height. Data collected from the highest intake were used to minimise potential errors due to local influences. The MLO was used as a reference for background CO_2 in the Northern Hemisphere for the six GAW stations in Europe. The measurement precision range is respectively 1% (4 ppmv) for GOSAT and 20–25 ppb for GAW station (PICARRO, 2017, 2019; Tadić et al., 2012) (Fig. 2).

Analysing the changes in CO_2 concentrations across countries or continents before and after the COVID-19 outbreak is a fundamental task to be performed prior

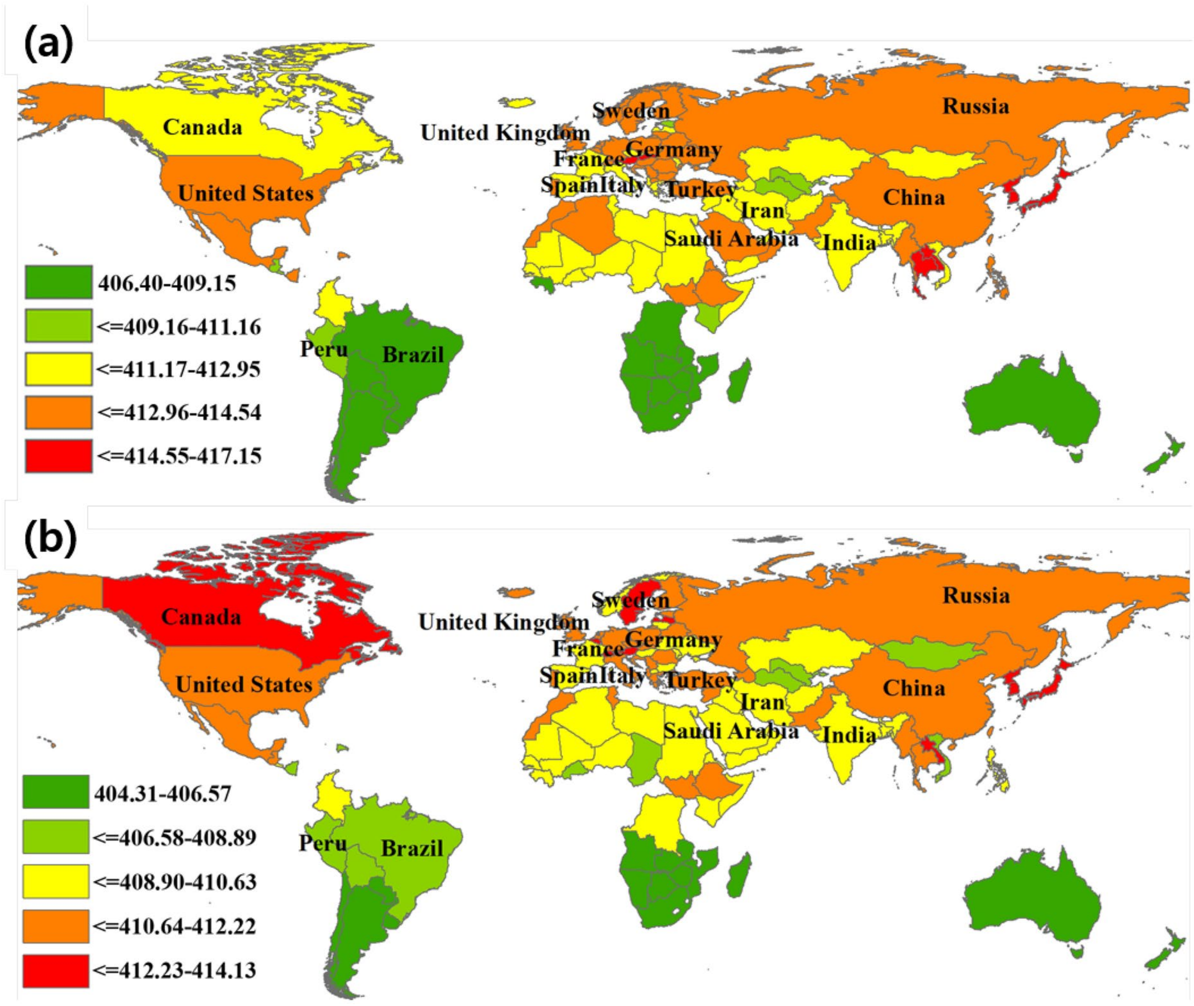


Fig. 3 GOSAT XCO_2 concentrations before and after the COVID-19 outbreak (unit: ppm): **a** March–April 2020; **b** March–April 2019

to exploring decreased global CO_2 concentrations. The mean CO_2 concentrations per country and Europe were calculated based on GOSAT measurements from March to April 2020 versus 2019 (Fig. 3; Table 3). The annual variations of the GOSAT XCO_2 concentrations before and after the COVID-19 outbreak were obtained by subtracting 2019 from 2020 in the yearly CO_2 data: GOSAT XCO_2 concentrations for March–April 2020 versus March–April 2019.

Results

Compared with 2019, there was a 2.2 ppm (part per million) increase in XCO_2 concentrations (column-averaged CO_2) in 103 countries (Fig. 4) in 2020 where GOSAT signals were present during the COVID-19 pandemic (April 2020 versus April 2019: 2.34 ppm, March 2020 versus March 2019: 2.12 ppm). The increasing CO_2 concentration trend is prominent in the Northern Hemisphere where developed countries are concentrated. However, before and after the COVID-19 outbreak, the year-on-year growth trend has shown no significant difference between the Southern and Northern Hemispheres. A CO_2 reduction has not been identified in Europe, China or the USA; therefore, the CO_2 concentration change in the east–west direction is confirmed to be insignificant. This result means that the lockdown due to the COVID-19 pandemic did not change the

Table 3 Summary statistics for XCO_2 concentration values (unit: ppm)

Year/month	Category	Mean	Maximum/minimum	Standard deviation (number of observation points)
2020.4	Worldwide including oceans	411.4	429.31/397.38	3.18(12,400)
	Worldwide land	411.99	429.31/397.38	3.43(7164)
	Europe	413.43	420.74/402.07	2.11(728)
	USA	413.69	426.18/408.26	2.14(625)
	China	413.50	424.36/406.82	2.75(545)
2019.4	Worldwide including oceans	409.11	425.59/394.12	2.99(10,877)
	Worldwide land	409.65	425.59/394.11	3.23(5887)
	Europe	411.31	425.59/401.49	2.44(542)
	USA	411.80	418.11/404.39	1.99(502)
	China	411.71	421.16/404.43	2.78(386)
2020.3	Worldwide Including oceans	410.2	426.21/397.04	3.047(12,098)
	Worldwide land	411.52	426.21/397.04	3.206(5644)
	Europe	413.13	421.03/406.17	2.451(373)
	USA	412.93	422.90/407.36	2.26(360)
	China	413.27	422.94/406.60	3.16(570)
2019.3	Worldwide including oceans	408.01	430.04/394.98	3.051(12,513)
	Worldwide land	409.40	430.04/394.98	3.023(5819)
	Europe	410.54	418.35/398.19	2.247(490)
	USA	411.47	430.05/404.37	2.49(476)
	China	410.53	420.69/403.65	2.803(662)
2018.3	Worldwide including oceans	405.57	436.90/394.95	3.05(12,565)
	Worldwide land	407.08	436.90/394.95	2.98(6451)
	Europe	408.34	414.53/402.89	2.32(88)
	USA	408.44	417.27/403.88	2.03(582)
	China	408.70	417.25/396.46	3.2(549)

vertical CO_2 profile at the global level. It is well known that the MLO is a representative WMO Global Atmosphere Watch (GAW) station for measuring the Earth's background air because it is located in the Pacific Ocean (Buermann et al., 2007).

There was a 2.71 ppm increase in CO_2 concentrations measured at MLO (Fig. 4) in 2020 compared with 2019 (April 2020 versus April 2019: 2.88 ppm, March 2020 versus March 2019: 2.54 ppm). The WMO announced that the global annual average CO_2 concentration was 407.8 ppm in 2018, an increase of 2.3 ppm compared with the previous year (WMO, 2019). The annual increase in CO_2 concentration before and after the COVID-19 outbreak (2.71 ppm) is substantially higher than the annual average increase (2.3 ppm) in 2018, which shows that the pandemic has not reduced CO_2 emissions. In April 2020, the global mean of the GOSAT observations was 411.99 ppm, which is 4.22 ppm lower than that of the MLO (416.21 ppm). The GOSAT XCO_2 data present the vertical column from the Earth's surface to the top of the atmosphere and are generally somewhat lower than the CO_2 concentration measured near the Earth's surface (Um, 2015).

A GOSAT XCO_2 signature reduction compared with the previous year is not found in Europe, China or the USA (Fig. 5). The GOSAT XCO_2 signature in April 2020 (411.99 ppm) shows an increase of 2.33 ppm across the worldwide land compared with the April 2019 value (409.66 ppm). In Europe, an increase of 2.12 ppm was observed in April 2020 (413.43 ppm) compared with April 2019

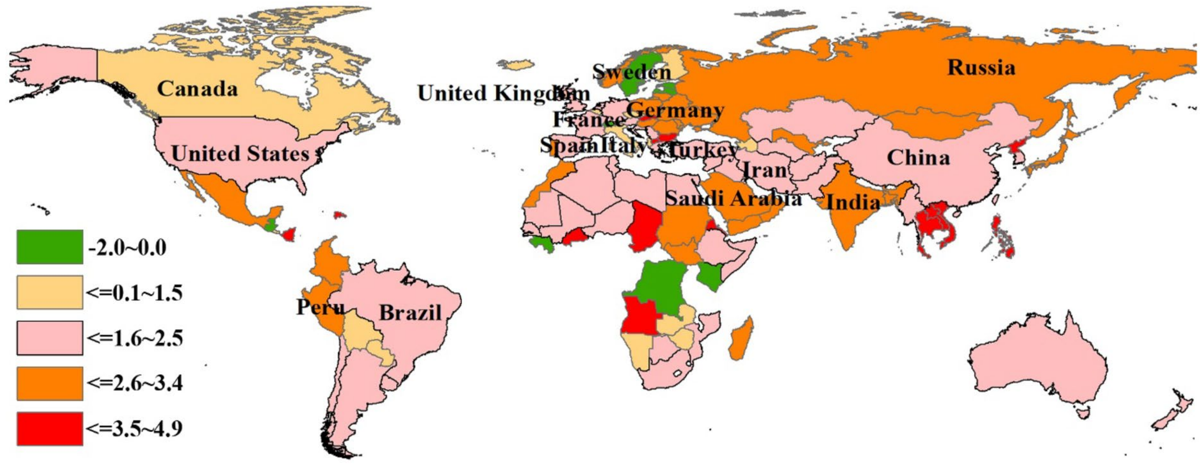


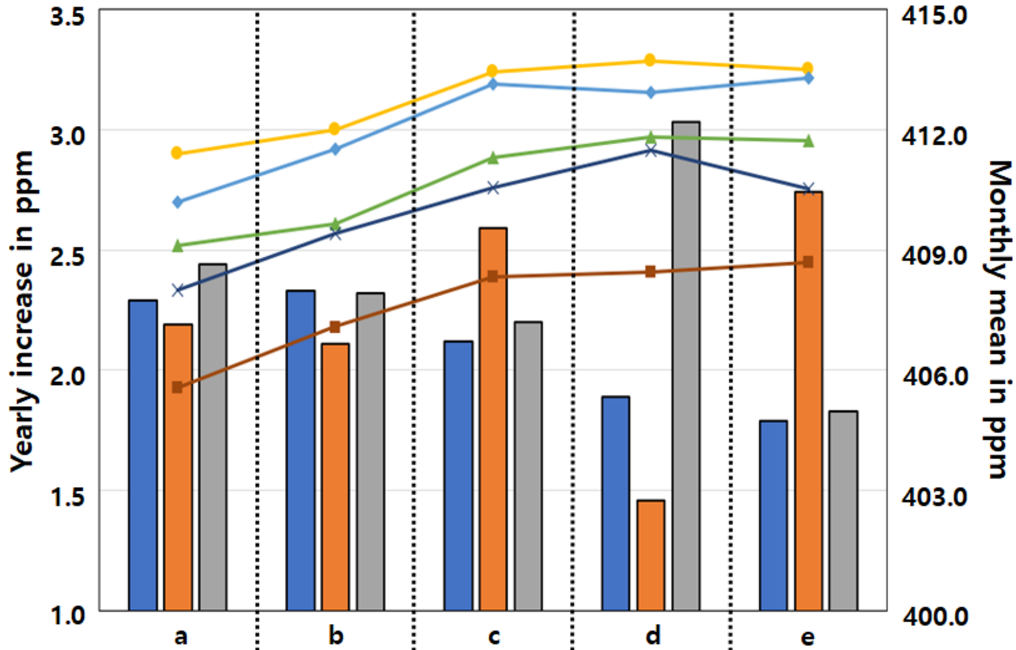
Fig. 4 Annual variations of GOSAT XCO_2 concentrations worldwide before and after COVID-19 outbreak (unit: ppm). *Number of observation points. †Obtained by subtracting the data from those of the same month in 2019 from the GOSAT/MLO measurements of March–April 2020 in the yearly CO_2 data. ** $p < 0.001$; unpaired t test. The names of the top 20 countries in terms of confirmed COVID-19 patients as of 30 April 2020 are marked on the map, excluding Belgium, the Netherlands, Portugal and Switzerland due to visibility constraints. MLO Mauna Loa Baseline Atmospheric Observatory, SD standard deviation

(411.31 ppm). Similarly, compared with March 2019 (409.41 ppm), the GOSAT XCO_2 signature showed an increase of 2.11 ppm across land worldwide in March 2020 (411.52 ppm). Compared with March 2019, a remarkable increase in the GOSAT XCO_2 signature in Europe (2.59 ppm) and China (2.74 ppm) was observed in March 2020.

The CO_2 measured by the GAW station in Europe tended to increase after the lockdown (Fig. 6). Zeppelin Observatory, a global GAW station located in the Arctic, shows that the CO_2 concentration is still rising compared with the same months of the previous year (April 2020 versus April 2019: 3.88 ppm, March 2020 versus March 2019: 3.54 ppm). Another global GAW station located on Monte Cimone (CMN) near the Mediterranean coast in Italy has also shown a steady upward trend compared with the previous year. Furthermore, no CO_2 reduction trend has been observed after the COVID-19 outbreaks in the five GAW stations distributed over long distances (> 4000 km) from the northernmost to southernmost parts of Europe, ranging from 44.16°N to 78.90°N in latitudinal bands.

In April 2020, the CO_2 concentration observed at ZEP was 419.84 ppm, which is 3.63 ppm higher than that of the MLO (416.21 ppm). There are several reasons why ZEP in the same hierarchy (global) as GAW station shows higher concentrations than MLO. MLO is located at the midpoint of the Pacific Ocean, where there are no CO_2 emission sources. On the other hand, ZEP is located in the northernmost of Europe, where CO_2 emission sources are intensively concentrated. The two stations in terms of latitude are located at completely different points. ZEP is located in the polar climate zone of the northern hemisphere (latitude: N78°), the coldest zone in the world due to the least amount of solar radiation. MLO is located close to the southern hemisphere (latitude: N19°), closest to the equator with the highest solar radiation in the world, which is classified as a tropical climate. In the Northern Hemisphere, carbon concentrations are highest in spring and lowest in summer due to the photosynthetic CO_2 absorption (Hwang & Um, 2017b; Piao et al., 2007; Stephens et al., 2007; Tan et al., 2015). ZEP shows a higher concentration than MLO because photosynthetic CO_2 uptake in March and April 2020 was not as active as in the summer of the Northern hemisphere. Further, much lower altitude (475 m) than MLO (3397 m) makes ZEP unavoidable from the influences of CO_2 emission sources transported from Europe.

The IPR contributing station recorded a CO_2 concentration of 426.8 ppm in April 2020, whereas the same contributing station TOH recorded 417.45 ppm



	a	b	c	d	e
2020.04 vs. 2019.04*	2.29	2.33	2.12	1.89	1.79
2020.03 vs. 2019.03*	2.19	2.11	2.59	1.46	2.74
2019.03 vs. 2018.04*	2.44	2.32	2.2	3.03	1.83
2020.04	411.4	411.99	413.43	413.69	413.5
2020.03	410.2	411.52	413.13	412.93	413.27
2019.04	409.11	409.66	411.31	411.8	411.71
2019.03	408.01	409.41	410.54	411.47	410.53
2018.03	405.57	407.08	408.34	408.44	408.7

2020.04 vs. 2019.04* 2020.03 vs. 2019.03* 2019.03 vs. 2018.04*
2020.04 2020.03 2019.04 2019.03 2018.03

Fig. 5 Annual variations of GOSAT XCO_2 concentrations worldwide before and after the COVID-19 outbreak (unit: ppm): **a** worldwide including ocean; **b** worldwide land; **c** Europe; **d** USA; **e** China (*$p < 0.001$; unpaired *t* test)

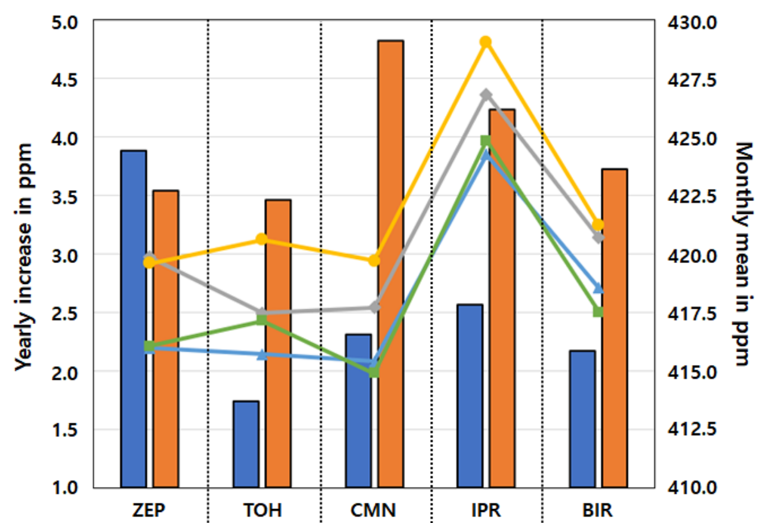
in the same month. There is a large difference of 9.35 ppm between the two contributing GAW stations. The IPR station is located at low altitudes (210 m) in a small town on the eastern coast of Lake Maggiore, whereas most of the other stations are distributed in the forest. The local population, traffic and a small fraction of green areas could be the main factors that lead to higher CO_2 emissions at IPR compared with TOH and BIR.

Implication and outlook

A precise estimation of global vertical mixing from the ground surface owing to COVID-19 is almost impossible because the residence time of CO_2 in the atmosphere could be hundreds of years and widely dispersed by atmospheric transport (Kutsch et al., 2020). There is no reliable record of CO_2 measurements prior to the 1950s (Wigley, 1983). The MLO has the longest CO_2 measurement record in the world (Keeling, 2001) and confirms that there has been a 98.76 ppm increase over the past 62 years, from 317.45 ppm in April 1958 to 416.21 ppm in April 2020 (Fig. 7). The measurement record from three GAW stations (ZEP, SSL, CMN) in Europe shows a steady increase in CO_2 concentrations since 1972 when the observational records began. The overall concentration trend of the GOSAT and GAW data is similar, although the latter show higher concentrations than satellite data. No unusual trend caused by the lockdown exists during the first wave of COVID-19 pandemic. This study confirms that the CO_2 concentration in the atmosphere, which accumulated over a long period of time, was not reduced by a short-term lockdown. This study plays a key role as an objective reference to properly frame the reality for various previous studies (WMO, 2020) that have claimed that the global CO_2 concentration decreased owing to the COVID-19 pandemic.

Previous studies estimated the amount of CO_2 emission reduced during the first wave of COVID-19 pandemic, using energy use statistics derived from major CO_2 emission sources (aviation, residential, industry, ground transportation, power station etc.). There is no global observation on atmospheric CO_2 concentrations due to energy use reduced during the COVID-19 lockdown period, to the best of our knowledge. Atmospheric CO_2 of 1 ppm can be converted with the conversion factor of 2.124 Gt C ppm^{-1} (Ballantyne et al., 2012). One mole CO_2 of atomic mass is 44.01, calculated by

Fig. 7 Global mean (unit: ppm) of GOSAT XCO_2 and CO_2 ▶ concentrations measured at WMO/GAW stations located in the USA and Europe since 1958, including the COVID-19 pandemic period (unit: ppm). **a** Global mean (unit: ppm) of GOSAT XCO_2 and CO_2 concentrations measured at WMO/GAW stations before and after COVID-19 pandemic period. This is a magnified portion from Fig. 6b*. **b** Global mean (unit: ppm) of GOSAT XCO_2 and CO_2 concentrations measured at WMO/GAW stations since 1958. This trend indicates that CO_2 concentrations keep accelerating since 1958, even after the COVID-19 pandemic period. MLO Mauna Loa Baseline Atmospheric Observatory (USA), SSL Schauinslan (Germany), CMN Monte Cimone (Italy), ZEP Zeppelin mountain (Norway)

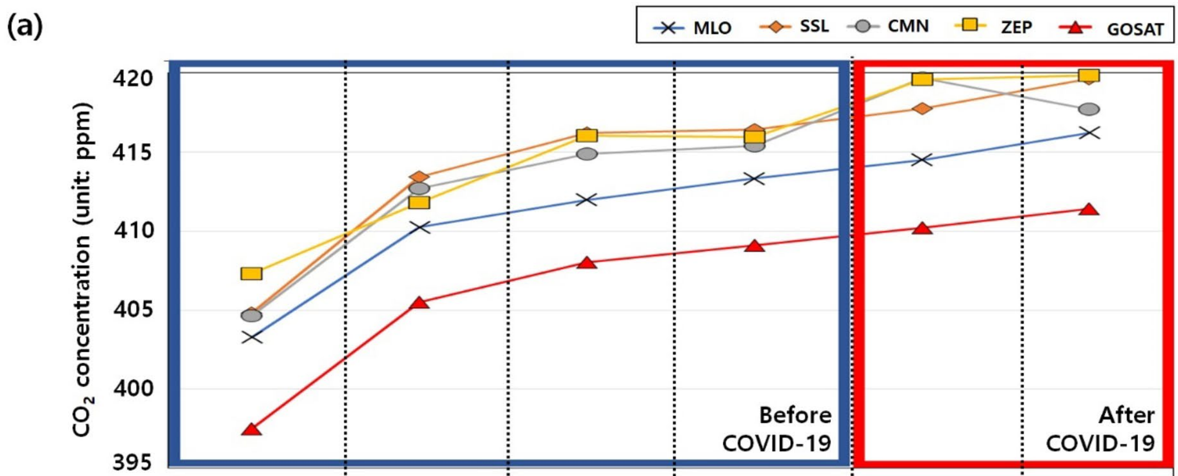


	ZEP	TOH	CMN	IPR	BIR
2020.04 vs. 2019.04*	3.88	1.74	2.31	2.56	2.17
2020.03 vs. 2019.03*	3.54	3.46	4.82	4.23	3.72
2020.04	419.84	417.45	417.7	426.8	420.69
2020.03	419.58	420.59	419.7	429.05	421.21
2019.04	415.96	415.71	415.39	424.24	418.52
2019.03	416.04	417.13	414.88	424.82	417.49

2020.04 vs. 2019.04* 2020.03 vs. 2019.03* 2020.04 2020.03
2019.04 2019.03

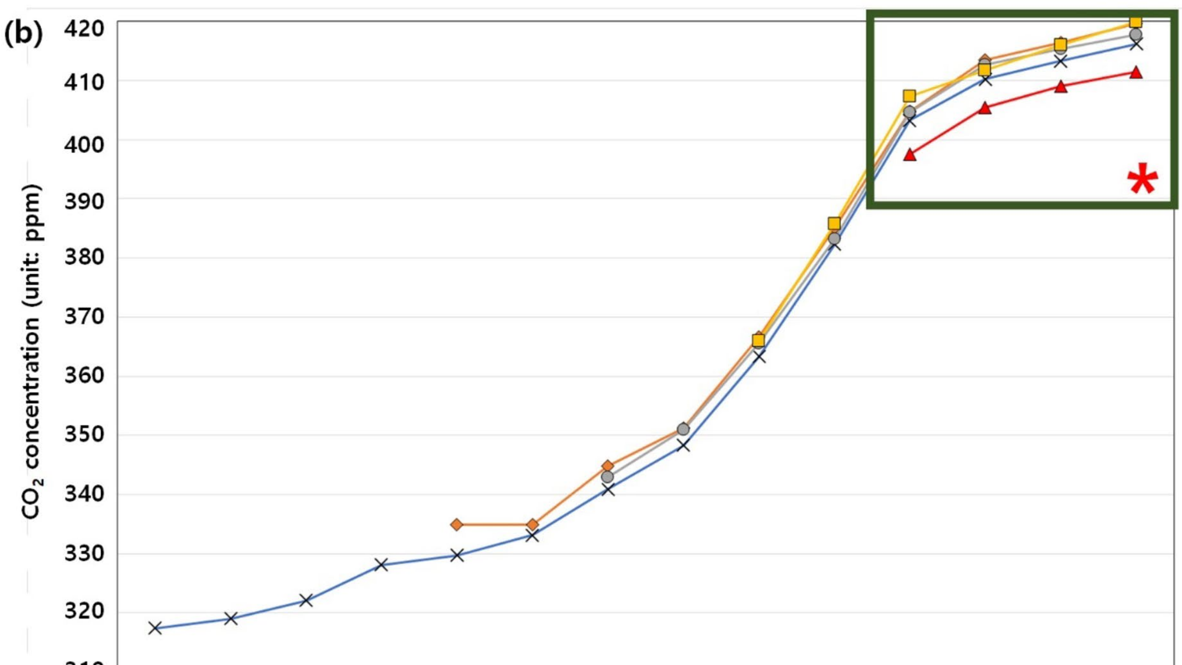
Fig. 6 Annual variations of CO_2 concentrations measured at the WMO/GAW stations before and after the COVID-19 outbreak (unit: ppm): Zeppelin mountain (ZEP), Norway; Torfhaus (TOH), Germany; Monte Cimone (CMN), Italy; Ispra (IPR), Italy; and Birkenes Atmospheric Observatory (BIR), Norway (*$p < 0.001$; unpaired t test)

(a)



	2015.4	2018.4	2019.3	2019.4	2020.3	2020.4
MLO	403.28	410.24	411.97	413.33	414.51	416.21
SSL	404.82	413.44	416.20	416.42	417.74	419.63
CMN	404.63	412.69	414.88	415.39	419.70	417.70
ZEP	407.28	411.79	416.04	415.96	419.58	419.84
GOSAT	397.50	405.50	408.01	409.11	410.20	411.40

(b)



	1958.4	1960.4	1965.4	1970.4	1972.4	1975.4	1980.4	1985.4	1995.4	2005.4	2015.4	2018.4	2019.4	2020.4
MLO	317.45	319.02	322.13	328.13	329.72	333.17	340.93	348.34	363.3	382.29	403.28	410.24	413.33	416.21
SSL					334.96	334.96	344.79	351.26	366.6	385.11	404.82	413.44	416.42	419.63
CMN							343	351.03	365.55	383.21	404.63	412.69	415.39	417.7
ZEP									365.94	385.72	407.28	411.79	415.96	419.84
GOSAT											397.5	405.5	409.11	411.4

one carbon atom (14.01) + 2 oxygen atoms (15.999). To convert from Gt C to Gt CO_2, a 3.664 conversion factor (3.664 = CO_2 atomic mass [44.01]/C atomic mass [12.011]) has to be multiplied. In other words, 1 Gt C equals the 3.664 Gt CO_2. Therefore, atmospheric CO_2 of one ppm equals approximately 7.782 Gt CO_2 (Le Quéré et al., 2018). According to CO_2 concentration data at the MLO from 2010 to 2019, the annual mean growth rate of atmospheric CO_2 is about 2.39 ppm per year. It means that an additional 18.69 Gt CO_2 is added annually to the global atmosphere. Le Quéré et al., (2020a, 2020b) (Le Quéré et al., 2020a) state that the global CO_2 emissions decrease 1.524 (0.795 to 2.403) Gt CO_2 from April to June 2020.

As we convert it in the ppm of atmospheric CO_2, it is about 0.35 (0.13 to 0.61) ppm. Liu et al. (2020) (Liu et al., 2020) reported that 1.551 Gt CO_2 (0.20 ppm) was decreased in the first half of 2020 compared to the same period in 2019. This decline in global CO_2 emission is similar to the El Niño dilution effect in 2015–2016, which constrains CO_2 outgassing (0.35 ppm) from the tropical Pacific Ocean (Chatterjee et al., 2017). The previous studies may cause confusion in exploring the changing scenario of the global carbon budget caused by COVID-19 lockdown, which is the most important in establishing climate change policies. This study empirically confirmed through observations from the GOSAT and GAW monitoring stations that reducing energy use due to the first wave of COVID-19 pandemic does not decrease atmospheric CO_2 concentration. The global CO_2 concentration will not be reduced even if the COVID-19 pandemic is longer than expected, and CO_2 emissions will continue at the current level for a long time. This study is of great significance because it provided policy implications to estimate a changing scenario on the global carbon budget after the post-COVID-19 era.

The most powerful lockdown has been implemented during the first wave of the COVID-19 pandemic (March–April 2020) all around the world (more than 100 countries in the world) (Haug et al., 2020). According to the "COVID-19 Community Mobility Reports," regional mobility is dramatically decreased up to 40% during the first wave of the COVID-19 pandemic (Google, 2020). Therefore, the first wave of the COVID-19 pandemic could become the representative interval timing in exploring the global decrease in CO_2 concentration caused by the COVID-19 pandemic. However, this study does not cover the "non-contact" lifestyle period established as the new-normal shifted from the first wave period of the COVID-19 pandemic (Grinberga-Zalite et al., 2021; Lamptey & Serwaa, 2020; Puriwat & Tripopsakul, 2021). To generalize the results of this study, further study is required to monitor the whole period from the first wave of COVID-19 pandemic to the non-contact lifestyle period established as the new-normal.

Conclusions

This study is the first attempt to explore a global decrease in CO_2 concentration during the COVID-19 pandemic by utilizing measurements from the GOSAT and GAW monitoring stations. The global background CO_2 concentration observed in the MLO and GOSAT shows a steady increase during the COVID-19 outbreak. North America, Europe, and East Asia in the northern hemisphere, where countries with a large number of COVID-19 confirmed cases are concentrated, also show an increasing trend in annual variations of CO_2 concentrations. The annual variations of CO_2 concentration among the global top 20 countries in terms of the confirmed COVID-19 patients increased or remained similar, during the COVID-19 pandemic, excluding Sweden.

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Data availability This study used Landsat data that were publicly available from Japan Aerospace Exploration Agency (JAXA), National Institute for Environmental Studies (NIES) and Ministry of the Environment Japan (MOE) (https://data2.gosat.nies.go.jp/index_en.html) and World Data Centre for Greenhouse Gases (WDCGG) (https://gaw.kishou.go.jp/search).

Declarations

Conflict of interest The authors declare no competing interests.

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