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Global patterns of daily CO_2 emissions reductions in the first year of COVID-19

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Day-to-day changes in CO_2 emissions from human activities, in particular fossil-fuel combustion and cement production, reflect a complex balance of influences from seasonality, working days, weather and, most recently, the COVID-19 pandemic. Here, we provide a daily CO_2 emissions dataset for the whole year of 2020, calculated from inventory and near-real-time activity data. We find a global reduction of 6.3% (2,232 $MtCO_2$) in CO_2 emissions compared with 2019. The drop in daily emissions during the first part of the year resulted from reduced global economic activity due to the pandemic lockdowns, including a large decrease in emissions from the transportation sector. However, daily CO_2 emissions gradually recovered towards 2019 levels from late April with the partial reopening of economic activity. Subsequent waves of lockdowns in late 2020 continued to cause smaller CO_2 reductions, primarily in western countries. The extraordinary fall in emissions during 2020 is similar in magnitude to the sustained annual emissions reductions necessary to limit global warming at 1.5 °C. This underscores the magnitude and speed at which the energy transition needs to advance.

Emissions of CO_2 from fossil-fuel combustion and cement production ('fossil CO_2')—the main sources of anthropogenic greenhouse gas emissions—were unprecedentedly variable during the COVID-19 pandemic, presenting an opportunity to investigate their underlying drivers[1,2]. With decades of development of emissions estimates, fossil CO_2 emissions are often estimated by activity data (for example, the amount of fossil energy consumption) and emissions factors (for example, the amount of CO_2 emissions per unit of energy consumption). The uncertainty (ranging from ±6% to ±10%) of global fossil CO_2 emissions is generally much lower than that of other species of anthropogenic air pollutants[3]. Current satellite observations have provided consistency checks with inventories for a few large point sources and cities[4,5]. With lockdown restrictions aimed at preventing the spread of coronavirus globally[6], the COVID-19 pandemic has had huge impacts on human activity and the Earth system[7–9], leading to notable declines in air pollution (NO_x, $PM_{2.5}$, SO_2 and so on)[10–14] and in CO_2 emissions[15–22].

Given the apparent lack of low-latency, direct activity data for estimating global CO_2 emissions, the effect of the pandemic on CO_2 emissions can instead be estimated by combining those activity data that are available with proxy data that represent the amount and the change of activities over time. For example, estimating the CO_2 reduction during three levels of forced confinement on the basis of government policies[16] or estimating the greenhouse gas changes on the basis of mobility data[19]. With various sources of proxy data available through different sectors, some proxy data can be obtained at daily, hourly or sub-hourly frequencies, suggesting the possibility of a near-real-time dataset presenting CO_2 emissions with high temporal resolution.

To address this gap, we provide daily CO_2 emissions for the whole year of 2020 calculated from inventories (Methods) and near-real-time activity data (Carbon Monitor project: https://carbonmonitor.org) developed by authors[17,18] for power generation (for 29 countries), industry (for 73 countries), ground transportation (for 406 cities), aviation and maritime transportation and residential fuel-use sectors (which we estimate for 206 countries). On the basis of these methodologies, the Carbon Monitor CO_2 emissions dataset with daily resolution is updated in this study for the entire

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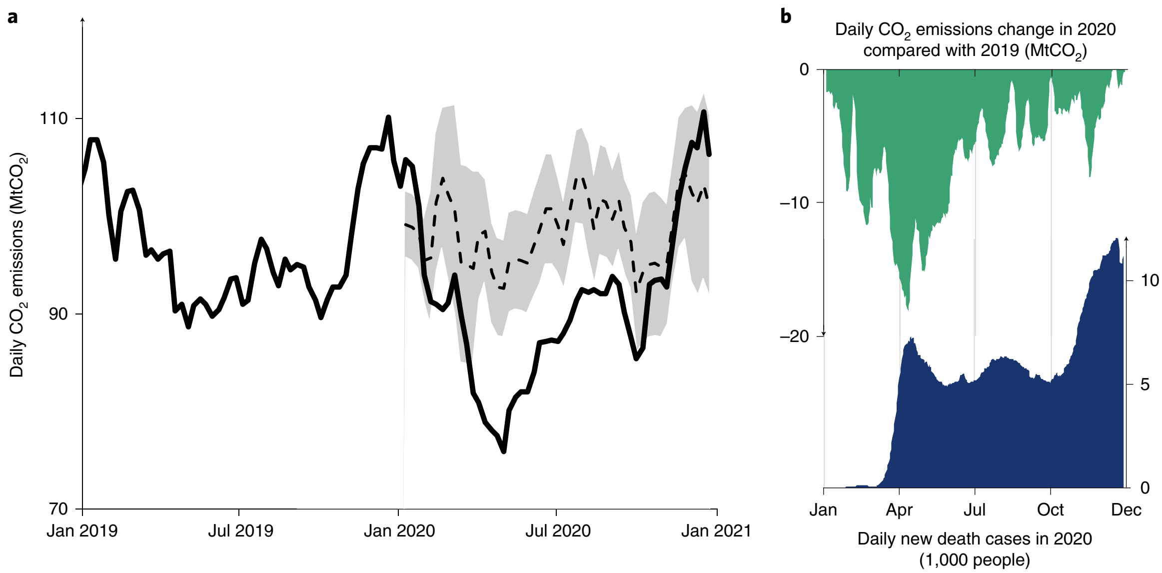

Fig. 1 | Global daily emissions changes in 2019 and 2020. a, Daily global CO_2 emissions trends in 2019 and 2020. Real emissions data are shown as solid black lines in the form of a seven-day running mean. The dotted line represents simulated baselines in 2020 (see Methods for more details). **b**, Global daily CO_2 reduction in 2020 compared with 2019 and the global daily new death cases of COVID-19 in 2020. The green area shows the seven-day running mean of daily CO_2 emissions change in 2020 compared with 2019. The daily new death numbers of COVID-19 (ref. [38]) are shown in blue areas and are used as indicators for the progress of the COVID-19 pandemic.

year 2020. This helps us to evaluate preliminary national energy-use data for all or part of 2020[23], providing a full picture of all the drivers of CO_2 emissions, including the pandemic (seasonality, working days and holidays, weather and the economy). Acknowledging higher uncertainties than inventories, such a dataset provides more up-to-date information than official inventories[24–27] and international CO_2 datasets[2,28–31], which have a time lag of between 6 and 16 months after the last month of reported emissions.

We show that the daily CO_2 reduction (differences between daily CO_2 emissions in 2019 and 2020) is caused by multiple factors but most importantly by the impact of the COVID-19 pandemic starting in early 2020. With the baseline stimulation in 2020 (for details, see Methods), we analyse the impact of COVID-19 on global and national emissions after removing historical emissions trends and taking into account year-over-year variability.

Global daily CO_2 emissions for 2020

The global daily CO_2 emissions for 2020 were 33.1 $GtCO_2$ (Fig. 1). Compared with 2019, the global CO_2 emissions in 2020 decreased by an estimated 2,232 $MtCO_2$ (±304 $MtCO_2$; hereafter, the uncertainty provided refers to a 2-sigma error unless otherwise specified), which represents a relative change of −6.3% (from −7.2% to −5.5%). Mean daily emissions were 90.5 $MtCO_2$ per day in 2020 (with the leap day in 2020), which is 6.6% lower than the daily average emissions in 2019 (96.8 $MtCO_2$ per day). The decrease in CO_2 emissions in 2020 (2,232 $MtCO_2$) is the largest absolute annual decline in emissions, larger than the emissions decrease of the 2009 financial crisis (380 $MtCO_2$) (ref. [31]) and even larger than the decrease reconstructed at the end of World War II (814 $MtCO_2$) (ref. [30]). Simultaneously, the world's gross domestic product dropped by 3.6% in 2020 compared with 2019.

The dramatic decrease in CO_2 emissions is linked to the impact of complex responses to the COVID-19 pandemic, including stay-home orders, closure of factories, collapse of air traffic and perturbations of supply chains. The largest weekly decline was found on week 15 of 2020 (6 April–12 April), by 17% in 2020 compared with the same week in 2019. Importantly, we found that global CO_2 emissions gradually recovered from late April with global partial reopening. The second and third waves of pandemics in autumn and early winter 2020 and the corresponding new lockdowns reduced CO_2 emissions further in Western countries but to a much lesser extent than the declines in the first wave. Global emissions were strongly reduced by the first wave of COVID-19, dropping most pronouncedly in April by 16.3% compared with the same month in 2019. However, although hit by further waves of infections in many countries, global CO_2 emissions dropped by only 0.5% in December 2020 compared with December 2019.

Although dramatic declines in CO_2 emissions have been observed in 2020, which can be attributed mainly to the impact of the pandemic, other effects may have played a role, such as prevailing warmer winter temperatures over most northern industrialized regions during the first months of 2020. Comparing with the stimulated baseline emissions (see Methods for details), we found a larger annual reduction of 6.5% caused by COVID-19 impacts in 2020 after accounting for historical trend.

Country-specific daily CO_2 emissions in major countries/regions in 2020

We found that the national emissions fell by 9.7% in Brazil, 9.5% in the United States, 8.0% in Russia, 7.9% in India, 7.3% in the European Union and United Kingdom (United Kingdom: 8.8%, France: 9.0%, Germany: 7.2%, Italy: 7.1%, Spain: 12.7%) and 4.7% in Japan. Conversely, China's CO_2 emissions in 2020 increased slightly by 0.9% (Figs. 2 and 3). The national shares of global CO_2 emissions show different structures in 2019 and 2020 (Extended Data Fig. 1) due to different emissions trends in each country. Obvious changes were found in China and international bunkers. Although China's CO_2 emissions had only a slight increase (0.9%) in 2020, the proportion of China's CO_2 emissions increased from 29.6% in 2019 to 31.9%, contributing a larger share (+2.3%) to the global total emissions.

The contributions of major emitters to global CO_2 reduction in different stages during 2020 are shown in Supplementary Fig. 1. During the first quarter of 2020, China was the largest contributor (41%) to global CO_2 reduction, followed by the United States (20%) and EU27 & UK (12%). China was the first country to suffer

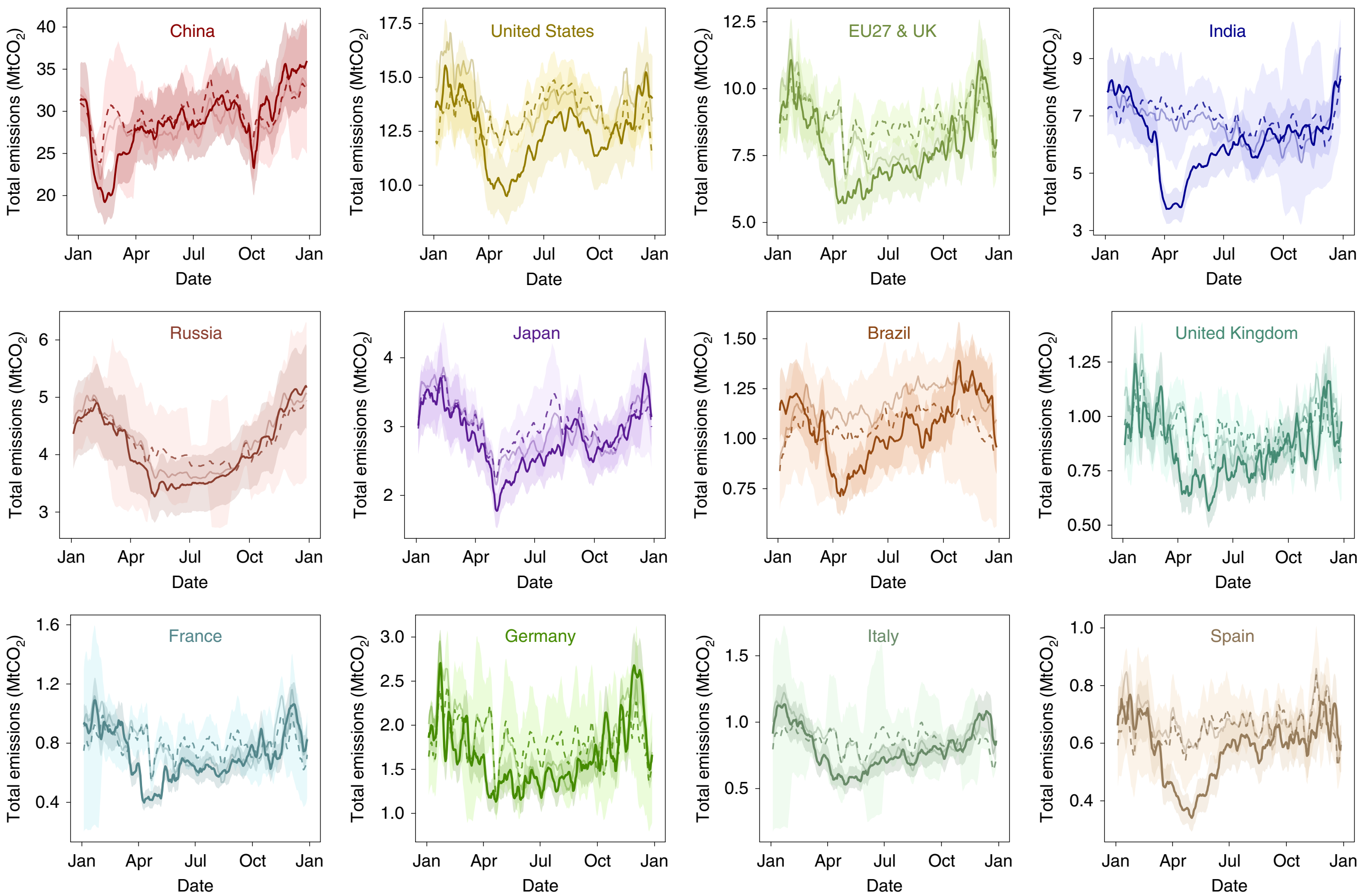

Fig. 2 | Country-specific daily CO_2 emissions in 2019 and 2020. The thick solid lines show the seven-day running mean of daily CO_2 emissions in 2020, and the results in 2019 are shown by thin solid lines. The simulated baselines, which combine the daily variation from 2019 with historical sector-specific and country-specific emissions trends, are shown as dashed lines. The ranges of uncertainty (95% confidence interval; 2-sigma errors) associated with the simulated baselines and daily estimates in 2020 are shown in light and dark shaded areas, respectively.

the impact of COVID-19 and the corresponding lockdown policies. However, China's contribution has become positive since the start of the second quarter of 2020, indicating a fast recovery of CO_2 emissions and even an increase over the 2019 level. By contrast, CO_2 emissions in ROW (rest of world) countries, the United States and India dropped dramatically in the second quarter. ROW countries and the United States remained the two largest contributors to the global CO_2 reduction in the third and fourth quarters of 2020, while the other countries declined only slightly or even increased.

Sectoral daily CO_2 emissions in 2020

The global decrease in CO_2 emissions is due mainly to mobility-related emissions, with the largest contributions to the global decrease in emissions in 2020 coming from ground transportation (709 $MtCO_2$, down 10.9% and 32% of the total decrease). The very large drops were also shown in other mobility-related sectors, such as the domestic aviation sector (112 $MtCO_2$, down 30.8% and 5% of the total decrease) and international bunkers (including international aviation and international shipping, 503 $MtCO_2$, down 36.9% and 23% of the total decrease). Somewhat smaller decreases were observed from the power sector (554 $MtCO_2$, down 4.1% and 25% of the total decrease) and the industry sector (265 $MtCO_2$, down 2.6% and 12% of the total decrease), and relatively small decreases in residential sector emissions (89 $MtCO_2$, down 2.5% and 4% of the total decrease). Details of national emissions changes by sector are shown in Supplementary Fig. 2.

Decreases in mobility-related emissions seem to be more persistent than decreases from other sectors: emissions from ground transportation were 10.9% lower in 2020 than in 2019, with the largest monthly decreases occurring in April and May (33.7% and 26.2%, respectively), while monthly declines were much smaller in November and December (9.7% and 6.8%). Emissions from the power sector and the industry sector decreased most dramatically in April by 10.0% and 9.9%, respectively, but recovered to their 2019 levels from August, with average growth rates of 1.0% and 2.5%, respectively, from August to December. However, emissions still decreased cumulatively by 2.5% and 1.4% for the whole year of 2020 compared with 2019 in the power sector and the industry sector.

As a result, the shares of the power sector and the industrial sector to the global totals were 39.2% and 29.4% in 2020, larger than 38.3% and 28.3% in 2019 (Extended Data Fig. 2). The contribution of CO_2 emissions from transportation sectors dropped largely, from 18.4% in 2019 to 17.5% of the ground transportation sector, from 2.8% to 1.6% of the aviation sector, and from 2.1% to 1.6% of the international shipping sector. The proportion of the residential sector had only a very slight change, from 10.1% to 10.5%.

Relationships between CO_2 reduction and factors of COVID-19

Compared with March to May 2020, there were similar numbers of COVID-19 deaths but fewer CO_2 emissions reductions from October to December 2020. On average, in 2020, for the aggregate of ten countries (the United States, India, the United Kingdom, France,

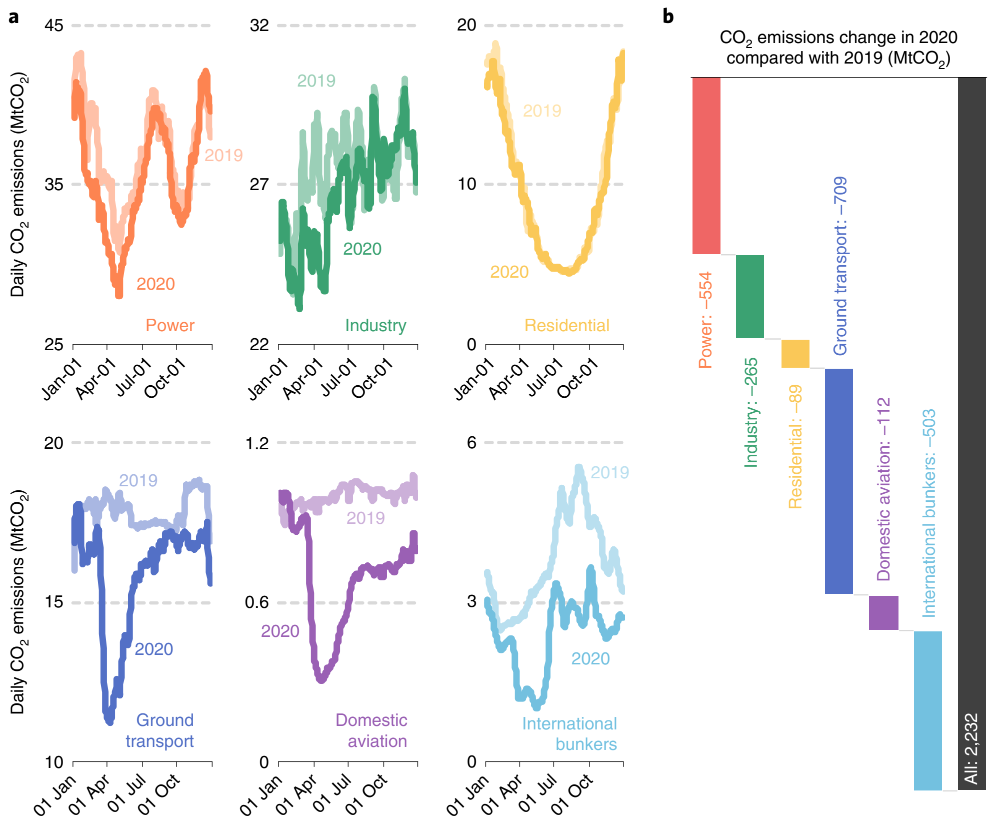

Fig. 3 | Sector-specific daily CO_2 emissions in 2019 and 2020. a, Global daily CO_2 emissions by sector in 2019 and 2020 in the form of a seven-day running mean. **b**, The contribution of each sector to the total emissions change in 2020 compared with 2019. 'International bunkers' includes the emissions from the international aviation sector and the international shipping sector.

Germany, Italy, Spain, Russia, Brazil and Japan), the daily deaths were approximately 3,120 from March to May and approximately 4,694 from October to December (+50%). However, their total CO_2 emissions dropped 5.7 $MtCO_2$ per day, compared with only 0.5 $MtCO_2$ per day during the last three months of 2020 (−91%). Later waves of COVID-19 infections in late 2020 and corresponding lockdowns (October to December) have caused further CO_2 emissions reductions, particularly in Western countries, but to a much smaller extent than the declines in the first wave (March to May).

The correlation test further shows the relation of CO_2 reduction and other factors (daily deaths, level of government response, human mobility and energy demand).

The large drop in CO_2 from March to May 2020 showed a strong correlation with the number of daily deaths due to COVID-19 ($r=0.9$) as well as the level of government response ($r=0.9$), human mobility ($r=0.8$) and energy demand ($r=0.8$). To prevent the spread and reduce deaths, governments tightened their policies and even implemented closure measures regionally or nationwide. Accordingly, lives and livelihoods were confined to some extent as people spent more time at their residences, and the demand for energy was reduced. Thus, the duration people spent at home and the reduction of energy demand show a very strong relationship with the stringency index of government response, for example, a longer duration people spent at home and larger reduction of energy demand along with the harsher government measures. As a result, fewer human activities resulted in a large drop in CO_2 during this period.

However, from October to December 2020, the changes in human mobility show weaker or even no relationship with the daily deaths of COVID-19 and the stringency of government response, although the strong relationship ($r=0.8$) between the deaths of COVID-19 and the stringency index reflects that governments tend to maintain a high level of confinement measures to cope with the new wave of COVID-19. It could be explained that as people resumed their lives and livelihoods to a limited extent with a deeper understanding of COVID-19, governments partially restored their economy, although governments were still maintaining high-pressure measures to respond to the pandemic. As a result, the relationship between the duration people spent at residences and the stringency index of government responses was weaker ($r=0.6$) compared with March–May 2020 ($r=0.8$), and the relationship between energy demand and the stringency index of government responses was even negligible ($r=0.1$), while it was strongly correlated during March–May 2020 ($r=-0.8$). In addition, the relationship between daily CO_2 changes and duration at residences was also weaker ($r=-0.1$) during this period. Consequently, the daily CO_2 changes show no relationship with the level of government responses. However, daily CO_2 changes still show a strong relationship with energy demand ($r=0.9$) when the decrease in energy demand was much smaller during the second wave (11.3 GWh per day) compared with the first wave (1,877.6 GWh per day), indicating a lower reduction in energy demand and a correspondingly smaller CO_2 reduction during the second wave.

Implications for future climate mitigation

Our results show the best estimate of a decline of 6.3% (from 7.2% to 5.5%) with a global CO_2 emissions reduction of 2,232 $MtCO_2$ in 2020 compared with 2019, which is approximately five times larger than the annual emissions decline at the peak of the Global Financial Crisis of 2008 (380 $MtCO_2$). The countries with the largest contributions to this global decline were the United States (480 $MtCO_2$, down 9.5%), EU & UK (226 $MtCO_2$, down 7.3%) and

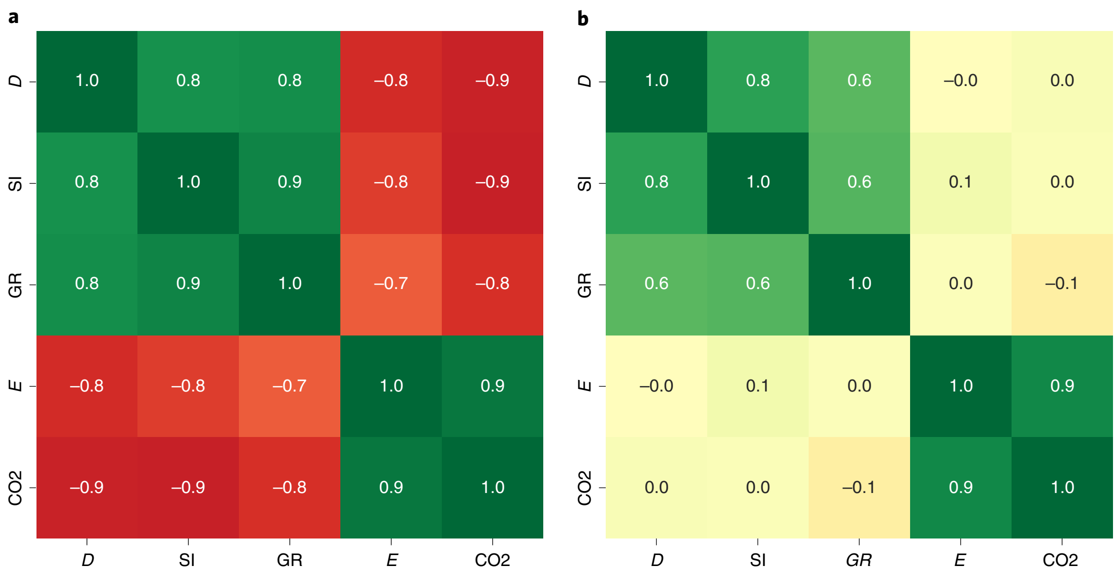

Fig. 4 | Correlation matrixes of five indicators during 1 March~31 May 2020 and 1 October~31 December 2020. a, 1 March–31 May 2020. **b**, 1 October–31 December 2020. CO2, daily CO_2 changes in 2020 compared with the simulated baseline emissions, which combine the daily emissions patterns in 2019 and historical sectoral trends; *D*, the daily new death cases of COVID-19[38]; SI, the stringency index of government responses to COVID-19[39]; GR, the duration spent at places of residence[40]; *E*, the daily changes of power demand in 2020 compared with the same day in 2019. These five indicators are the averages of the United States, India, the United Kingdom, France, Germany, Italy, Spain, Russia, Brazil and Japan. The daily averages of the five indicators during these two periods are shown in Extended Data Table 1. Gradient colors indicate negative strong relationship (red) through no relationship (yellow) to positive strong relationship (green).

India (195 $MtCO_2$, down 7.9%). Although China underwent the earliest lockdowns in response to the pandemic, China's emissions increased by 0.9% (89 $MtCO_2$) in 2020 owing to the relatively short duration of lockdowns, fast rebound of the economy and rapid recovery of industrial activities and power production back to and exceeding the 2019 level.

The large emissions decline is attributed to emissions decreases from ground transport (down 10.9%, 709 $MtCO_2$), power (down 4.1%, 554 $MtCO_2$), international aviation and shipping (down 36.9%, 503 $MtCO_2$), industry (down 2.6%, 265 $MtCO_2$), domestic aviation (down 30.8%, 112 $MtCO_2$) and residential consumption (down 2.5%, 89 $MtCO_2$). The largest contribution to COVID-related decreases in emissions was from the ground transport sector (32%), followed by power (25%), international aviation (16%), industry (12%), international maritime transport (7%), domestic aviation (5%) and residential consumption (4%).

The correlation analysis shows the differing relationships between CO_2 reduction and other indicators during different periods (Fig. 4). During the first wave of the pandemic, governments generally adopted stricter confinement measures to prevent the spread of the coronavirus. Following the experience of the first lockdowns, with hard-hit economies, subsequent lockdowns were less strict, and although later waves caused wider spread of infection, governments and citizens resumed part or more of their activities. This reveals the urgent need to restore the economy, which is also reflected by the difference in the degree of CO_2 reduction in the different periods. In addition, in the post-COVID era, there are still huge conflicts between economic recovery and the control and reduction of greenhouse gas emissions.

Importantly, although the global pandemic outbreak is still under way, global daily CO_2 emissions rebounded in the second half of 2020 and through 2021 to 2019 levels. There has been some discussion about possible 'green' or 'brown' recoveries from the emissions decline in 2020[32–36] to orient fiscal stimulus packages in the post-COVID period with climate targets and limit the increase in global average temperatures close to 1.5 °C. However, stimulus packages are still dominated by fossil-fuel investments, although they have become more green with time[37]. Current data availability is still not enough to fully capture the ongoing dynamics of CO_2 emissions under the COVID-19 pandemic and other world disruptions. Further monitoring, observation, data collection and improved methods are urgently needed. The ability to monitor trends in daily emissions in near real time, which we demonstrate here, could contribute to timely policy actions with implications for climate change mitigation and Earth system management.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-022-00965-8.

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Methods

We calculate daily CO_2 emissions since January 2019, drawing on hourly datasets of electricity production and CO_2 emissions in 29 countries (including the substantial variations in carbon intensity associated with electricity production), three different indexes of daily vehicle traffic/mobility in 416 cities worldwide, monthly production data for cement, steel and other energy-intensive industrial products in 73 countries, daily aircraft transportation activity data and proxies for residential and commercial building emissions.

Daily emissions estimates. Carbon dioxide emissions (Emis) can be estimated by multiplying the activity data (AD, such as energy consumption) with their respective emissions factors (EF, CO_2 emissions per unit of activity data)[41,42]:

$$\mathrm{Emis} = \sum\sum\sum \mathrm{AD}_{r,s} \times \mathrm{EF}_{r,s} \quad (1)$$

Here, *r* and *s* reflect the regions and sectors, respectively. In our calculation, *r* covers countries, and *s* covers six sectors: power generation, industry, ground transportation, aviation, international shipping and residential consumption (Extended Data Table 2). Due to data availability, we assume that the emissions factors remain unchanged during 2019 and 2020; thus, the daily emissions are directly proportional to the daily activity data. For example, the ratio of daily emissions on day *i* (Emis′) to daily emissions on day *j* (Emis) is equal to the ratio of daily activity data on day *i* (AD′) to daily activity data on day *j* (AD):

$$\frac{\mathrm{Emis}'}{\mathrm{Emis}} = \frac{\mathrm{AD}'}{\mathrm{AD}} \quad (2)$$

Specifically, the daily emissions for day *d* in sector *s* were generally calculated by the following steps: (1) we disaggregated the annual emissions in 2019 into daily levels by following equation (3); (2) then, we calculated the daily emissions in 2020 by the daily activity changes as equation (4) on the basis of the assumption of the linear relationship between activity data and emissions.

$$\mathrm{Emis}_{\mathrm{d},2019} = \frac{\mathrm{AD}_{\mathrm{d},2019}}{\mathrm{AD}_{2019}} \times \mathrm{Emis}_{\mathrm{d},2019} \quad (3)$$

$$\mathrm{Emis}_{\mathrm{d},2020} = \frac{\mathrm{AD}_{\mathrm{d},2020}}{\mathrm{AD}_{\mathrm{d},2019}} \times \mathrm{Emis}_{\mathrm{d},2019} \quad (4)$$

Detailed methodologies have been discussed in our previous study[17,18]. Note that in this study, we update the baseline emissions in 2019 of each country and each sector on the basis of the latest emissions data release from the Emissions Database for Global Atmospheric Research (EDGAR): EDGARv5.0_FT2019[31].

In addition, due to data availability, we updated our data sources and methodologies in some sectors compared with our previous releases (full data sources are listed in Supplementary Table 1):

In the power sector, we followed equations (3) and (4) by using daily national thermal production to estimate daily CO_2 emissions from the power sector. Since September 2020, we use the daily coal consumption of the Zhedian Company to disaggregate the monthly thermal generation data from China's National Bureau of Statistics to estimate daily thermal generation in China. In addition, we updated the daily power emissions in Russia by using a new proxy of hourly thermal production from SO-UPS[43].

In the industry sector, we primarily use industrial production data or the industrial production index to calculate monthly emissions. However, in some countries, due to the delay of data release by one month (China, the United States, Russia and Japan) to two months (Brazil, India and European countries), we use the monthly prediction data of industrial production from the Trading Economics website (https://tradingeconomics.com/) to predict the changes in monthly CO_2 emissions. First, we calculate the monthly emissions from the industry sector in 2019 by following the disaggregation equation (3) and then estimate the monthly emissions in 2020 on the basis of the year-on-year rates of industrial production by following equation (4). Then, we disaggregate monthly emissions using daily thermal electricity generation due to the lack of daily industrial data.

In the ground transportation sector, the activity data we used in this study (the traffic congestion level) were not directly proportional to emissions. However, the traffic congestion level is correlated with car counts, which is positively associated with emissions from ground transportation. Thus, we further develop a sigmoid model to describe the daily relationship between the congestion level and the car counts. Detailed information can be found in our previous paper[17,18].

In the aviation sector, we estimate both domestic and international aviation emissions on the basis of real-time flight distance (https://flightradar24.com). In the international shipping sector, we used a daily Baltic dry index to estimate the daily emissions changes.

US daily emissions estimates. Annual total state-level CO_2 emissions by sector in 2017 are obtained from the US Energy Information Administration (EIA)[44] and then updated to 2018 on the basis of EIA's latest comprehensive state-level annual estimates of energy consumption by sector and source[45]. We disaggregate the annual emissions in 2018 into the monthly level for each sector using state-level monthly energy consumption data from EIA (Supplementary Table 2). We also estimate monthly emissions by sector in 2019 and 2020 on the basis of the change in monthly energy consumption data in 2019 and 2020 compared with the same period in 2018 by assuming that the emissions factors remain unchanged. The monthly emissions are then allocated to each day using state-level daily indicators for each sector (Supplementary Table 2). For the last two months in 2020, due to the lack of monthly energy data, we directly estimate daily emissions on the basis of the change of daily indicators for each sector (Supplementary Table 2), as well as scale factors that reflect potential change of carbon intensity of indicators in 2020 compared with the same period of 2019 (based on the change in the previous month).

Daily emissions estimates in ROW countries. According to the Oxford COVID-19 Government Response Tracker Workplace Closing Index, the degree of workplace closure is divided into four levels. We calculated the average value of emissions reductions (percentage) in India, the United States, Europe, Brazil, Russia and Japan for each level and used those values to characterize the impact of different levels on emissions reduction (Supplementary Table 3). Then, on the basis of the Oxford index (*CI*) in each ROW country (*c*), we calculate the weighted daily CO_2 in 2020 and 2021 of the ROW:

$$\mathrm{ROW_d} = \mathrm{ROW}_{2019,\mathrm{d}} \times \frac{\sum_c (\mathrm{CO}_{2_c} \times (1 + \mathrm{CI}_c))}{\sum_c \mathrm{CO}_{2_c}} \quad (5)$$

Daily emissions baseline simulation in 2020. We simulated the daily emissions baseline with data from the latest emissions data release from EDGARv5.0_FT2019[31] and from our previously estimated daily emissions data for 2019. For the power and industry sector, we compiled a monthly emissions dataset for 2015–2019 and fitted a linear regression model with this dataset. The model is as follows:

$$E_{s,m,c} = \alpha_{s,m,c} + \beta_{s,m,c} \times Y \quad (6)$$

where a linear relationship between monthly total emissions ($E_{s,m,c}$) and year (*Y*) is established per sector (*s*), per month (*m*) and per country (*c*), with α being the intercept and β being the slope. The regression coefficients are found by fitting the model with a previously explained dataset (with data from 2015–2019) with the least-squares method. This fitted model is used to simulate the monthly baseline emissions for 2020 (Simulated-EB_{2020}) for each sector (s) for each month (M). This E-sim is then combined with previously calculated daily emissions data for 2019 ($Emis_{2019}$) to simulate the daily emissions baseline (Simulated-EB_{2020}). For each day (*D*) of month (*M*), the calculation is expressed as the following equation:

$$\mathrm{Simulated} - \mathrm{EB}_{2020,s,M,D} = \mathrm{Emis}_{2019,s,M,D} \times \frac{\mathrm{Simulated} - \mathrm{EB}_{2020,s,M}}{\sum_M \mathrm{Emis}_{2019,s,M,D}} \quad (7)$$

where sectors are denoted by *s*. For sectors such as ground transportation, residential and domestic aviation, the functions are applied for the yearly emissions dataset instead of the monthly dataset. For international aviation and international shipping, the baseline simulation was not applied due to data limitations.

We assume that ROW countries follow the same development patterns as the other countries for which we have detailed data. Therefore, the sectoral trends for ROW are simulated by applying the same trends estimated for all other countries combined. The total emissions for each country were computed by aggregating all sectoral emissions (except for the international aviation and international shipping sectors). The total emissions for the world were computed by aggregating all national emissions (including the international aviation and international shipping sectors).

The uncertainty of the baseline simulation was provided as a 95% confidence interval (2-sigma errors), which was estimated by combining the uncertainties in regression coefficient estimations.

Uncertainty estimates. The uncertainty analysis is conducted sector by sector (a normal distribution is assumed for the activity data and emissions factors used; uncertainty between countries and between sectors is assumed to be uncorrelated when conducting the error propagation method; unless specified, the same uncertainty applied for all countries/regions per sector and the quantity of uncertainty is presented as a 2-sigma error):

1. For the power sector (38% of the global CO_2 emissions), we use the daily statistics of actual thermal production as the activity data, which are collected from the national-level or company-level reporting authorities (see the list of data sources in Supplementary Table 1). When no uncertainty information is available, the uncertainty of the power activity data here is assumed to be ±5% according to the Intergovernmental Panel on Climate Change recommended default uncertainty range of energy statistics. In addition, for the emissions factors, the uncertainties come mainly from the interannual variability of coal emissions factors (as coal has a wide range of emissions factors of different coal types) and changes in the mix of generation fuel in

thermal production. We calculate the emissions factors on the basis of the annual thermal production[46] and the annual power industry emissions[31], and the uncertainty range of emissions factor is estimated as ±13%. For the uncertainty in ROW countries, we used the uncertainty range of ±10% from ref. [16] to estimate the uncertainties of confinement level. We used the error propagation equations to combine the uncertainties of each part (including the combined uncertainty from activity data and emissions factors for non-ROW countries and uncertainty for ROW countries) and quantified the uncertainties of the power emissions as ±10%.

2. For the industry sector (28% of the global CO_2 emissions), the 2-sigma uncertainty (±30%) of CO_2 from industry and cement production comes from monthly production data and sectoral emissions factors. The uncertainty of industrial output data is assumed to be ±20% in the industrial sector[47]. For the sectoral emissions factor uncertainty, we calculate the national emissions factors in 2010–2012 in the United States, France, Japan, Brazil, Germany and Italy according to the data availability of monthly emissions data[48] and industrial production index (IPI) data, and their 2-sigma uncertainties vary from ±14% to ±28. Thus, we adopt a large uncertainty of ±30%.
3. For the ground transport sector (18% of the global CO_2 emissions), we quantify the 2-sigma uncertainty of ±9.3% from the prediction interval of the regression model we built in Paris to estimate the emissions from this sector. Note that the regression model in Paris between car counts and the TomTom congestion index we built was based on assuming a relative magnitude in car counts; thus, emissions follow a similar relationship with the TomTom congestion index in Paris. However, due to the lack of car count data from other cities, the uncertainty of applying such a regression model to all 416 cities across the world is still not quantified in this study, when car counts in other cities are likely to have a different relationship with the TomTom congestion index.
4. For the residential sector (10% of the global CO_2 emissions), we compare the estimates by using our methodology with the estimates by using the publicly available natural gas daily consumption data by residential and commercial buildings for France[49], and the 2-sigma uncertainty of the daily emissions estimations is further quantified as ±40%.
5. For the aviation sector (3% of the global CO_2 emissions), we compare the estimates by using two different types of activity data, that is, the flight route distance (what we used in this study) and the number of flights, and calculate the average difference to quantify the uncertainty of ±10.2% in the aviation sector.
6. For the international shipping sector (2% of the global CO_2 emissions), we used uncertainty analysis from the International Maritime Organization (IMO) as our uncertainty estimate for shipping emissions. According to the Third IMO Greenhouse Gas Study 2014[50], the uncertainty in shipping emissions was ±13% based on bottom-up estimates.

By combining the uncertainty of sectoral emissions estimates and the uncertainty of the emissions in 2019 we used from EDGAR[51] (of ±7.1%), the overall uncertainty of annual CO_2 emissions changes in 2020 compared with 2019 is quantified as ±13.6%. The uncertainty of baseline simulation in 2020 is discussed in the previous section and listed in the Supplementary Information.

As a result, the CO_2 emissions in 2020 decreased by 2,232 ± 304 $MtCO_2$, a reduction of 6.3% (from 7.2% to 5.5%). Our estimate of the annual CO_2 decreases in 2020 of 6.3% is comparable to other studies' estimates of 5.4% (ref. [52]), 5.8% (ref. [2]), 5.8% (ref. [53]), 6.3% (ref. [46]), 7.2% (ref. [16]) and 13% (ref. [2,19]), and most of them fall into the uncertainty ranges of each other.

Correlation analysis. The daily deaths of COVID-19 by country were collected from Worldometers[38]. The stringency index is collected from the Oxford COVID-19 Government Response Tracker project[39], ranging between 0 and 100 to indicate the level of government response (mainly closure measures and containments). The mobility trend of places of residence is collected from Google Mobility Report[40], which shows the relative changes of duration people spent at residential places. Then, we calculate the Pearson correlation coefficients to measure the linear correlation of every two sets of data. The coefficient is calculated as follows:

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2}\sqrt{\sum(y-\bar{y})^2}} \quad (8)$$

Data availability

The dataset is available at https://doi.org/10.6084/m9.figshare.13685839 (ref. [54]). Country-specific and sector-specific emissions data are also available from the Carbon Monitor (https://carbonmonitor.org and http://carbonmonitor.org.cn).

Code availability

The code generated and/or analysed during the current study is available from the corresponding author upon reasonable request.

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Author contributions

Z.L., Z.D., P.C. and S.J.D. designed the paper. Z.D., J.T. and B.Zhu coordinated the data processing. Z.L., Z.D., P.C., J.T., B.Zhu, S.J.D., R.M.A., O.B., S.D.A., J.G.C., X.D., P.F., P.G., R.G., C.H., R.B.J., C.K., D.M.K., P.K., C.L.Q., C.M., G.J.-M., G.P.P., K.T., Y.W., B.Zheng, H.Z., T.S., and H.J.S. contributed to writing and revising the paper.

Competing interests

The authors declare no competing interests.

Additional information

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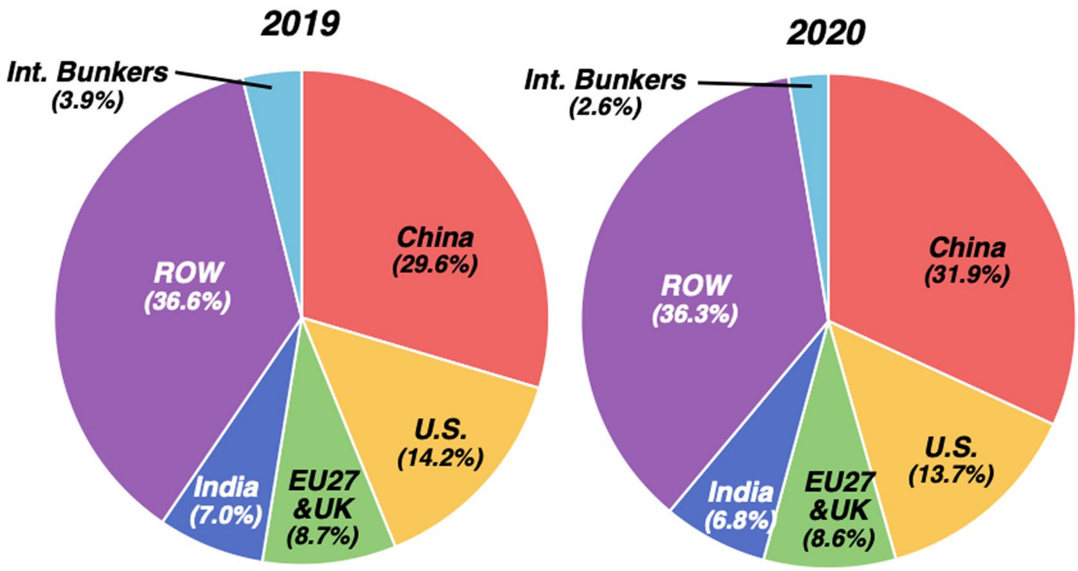
Extended Data Table 1 | Daily average of the five indicators during March 1st ~ May 31st, 2020 and October 1st ~ December 31st, 2020

	CO_2(Mt CO_2/day)	D (person/day)	SI (%)	GR (%/day)	E (GWh/day)
March-May, 2020	−5.7	3,120	67.9	15.7	−1877.6
October-December, 2020	−0.5	4,694	62.6	8.7	−11.3

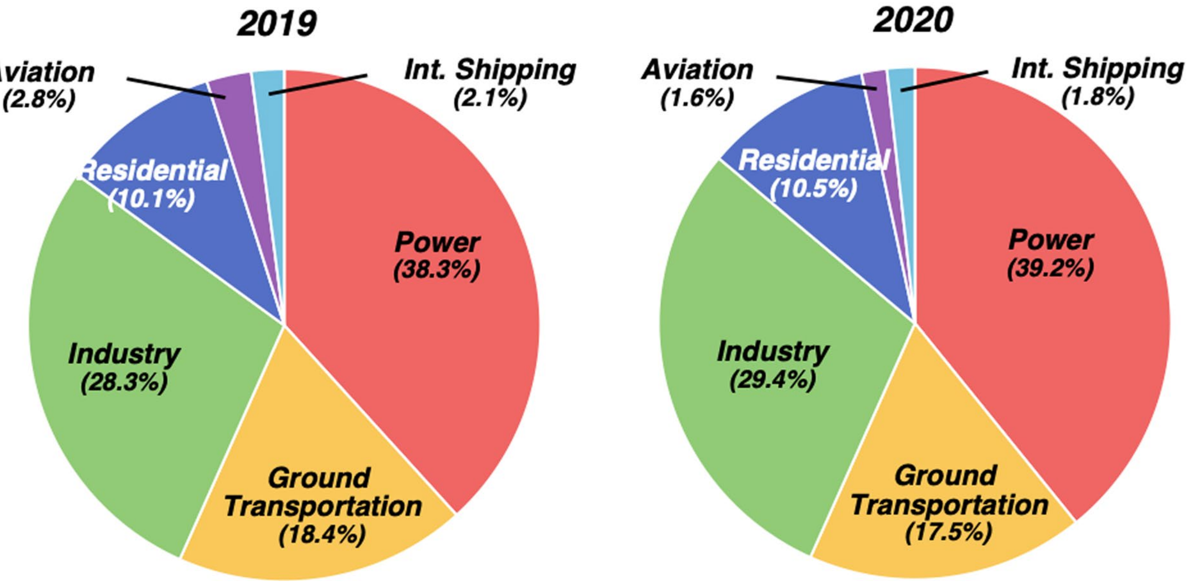
CO2 denotes daily CO_2 changes in 2020 compared to the simulated baseline emissions, which combine the daily emission patterns in 2019 and historical sectoral trends, *D* denotes the daily new death cases of COVID-19[38], *SI* denotes the stringency index of government responses to COVID-19[39], *GR* denotes the duration spent at places of residence[40], and *E* denotes the daily changes of power demand in 2020 compared to the same day in 2019.

Extended Data Table 2 | Mapping table of sectors in this study and IPCC category

IPCC code	IPCC category	this study
1A1	Energy Industries	Power
1A2	Manufacturing Industries and Construction	Industry (incl. Cement Process)
2A1	Cement production	
1A3a	Domestic aviation	Domestic aviation
1A3b	Road transportation no resuspension	Ground Transport
1A3c	Other transportation	
1A4	Residential and other sectors	Residential
1C2	Memo: International navigation	International shipping
1C1	Memo: International aviation	International aviation



Extended Data Fig. 1 | Contribution by major emitters in 2019 and 2020.



Extended Data Fig. 2 | Contribution by sectors in 2019 and 2020.