Assessing the recent impact of COVID-19 on carbon emissions from China using domestic economic data

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November 24, 2022

Abstract

The outbreak of coronavirus disease 2019 (COVID-19) has caused tremendous loss to human life and economic decline in China. A timely assessment of COVID-19's impact on provincial CO emission reductions is crucial for accurately understanding the degree of reduction and its implications for mitigation measures. Here, we used gross domestic product (GDP) and an inventory (CEADs) to estimate the reductions in the first quarter (Q1) of 2020. We find a reduction of -257.7 Mt CO (-11.0%) over 2019 Q1. Secondary industry contributed 72.5% of the total reduction, due largely to lower coal consumption and cement reduction. At the provincial level, Hubei contributed the most to reductions. Transportation reduction also made a significant contribution. One policy implication is advocating working from home and holding teleconferences to reduce traffic emissions. We provide provincial reductions as spatial constraints for modeling studies and further support for both the carbon cycling scientists and policy makers.

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Key Points:

- We reported provincial CO_2 decrease for China, and Hubei, the North China Plain and Eastern China provinces have obvious declines;
- National total decrease was -258 Mt (-11.0%). Using GDP as an indicator, our works are easy to be repeated and applied in other areas;
- Working from home and holding teleconferences would reduce traffic emissions. Our results can serve as spatial constraints for modelers.

Abstract

The outbreak of coronavirus disease 2019 (COVID-19) has caused tremendous loss to human life and economic decline in China. A timely assessment of COVID-19's impact on provincial CO_2 emission decrease is crucial for accurately understanding the degree of decrease and its implications for mitigation measures. Here, we used gross domestic product (GDP) and an inventory (CEADs) to estimate the decrease in the first quarter (Q1) of 2020. We find a decrease of -257.7 Mt CO_2 (-11.0%) over 2019 Q1. Secondary industry contributed 72.5% of the total decrease, due largely to lower coal consumption and cement decrease. At the provincial level, Hubei contributed the most to decrease. Transport decrease also made a significant contribution. One policy implication is advocating working from home and holding teleconferences to reduce traffic emissions. We provide provincial decreases as spatial constraints for modeling studies and further support for both the carbon cycling scientists and policy makers.

Plain Language Summary

The outbreak of coronavirus disease 2019 (COVID-19) has caused tremendous loss to human life and economic decline in China and worldwide. It has significantly reduced gross domestic product (GDP), and thus fossil-related carbon dioxide (CO_2) emissions. Due to time delays in obtaining activity data, traditional emissions inventories generally lag real time by 2-3 years. However, a timely assessment of COVID-19's impact on provincial CO_2 emission decrease is crucial for accurately understanding the degree of declines and its implications for mitigation measures. Here, we used GDP and a baseline inventory to estimate the decrease in the first quarter (Q1) of 2020. We find a decline of -257.7 Mt CO_2 (-11.0%) over 2019 Q1. Secondary industry contributed 72.5% of the total decrease, due largely to lower coal consumption and cement production. At the provincial level, Hubei contributed the most to decrease. Moreover, transport contributed significantly. One policy implication is advocating working from home and holding virtual conferences to reduce traffic emissions. Our provincial estimates can serve as spatial disaggregation

constraints for modelers and further support for both the carbon cycle scientists and policy makers.

1 Introduction

China's fossil fuel combustion and industrial processes contributed more than 25% of the global total CO_2 emissions [*Friedlingstein et al.*, 2019]. Due largely to the rapid increase in gross domestic product (GDP), China's CO_2 emissions experienced a period of rapid increase prior to 2013, and it has decreased afterwards except for 2017 [*Guan et al.*, 2018; *Shan et al.*, 2020]. The traditional method for developing an emissions inventory generally has a 2-3 year time lag, due to the delayed availability of activity data [*Friedlingstein et al.*, 2019; *Le Quéré et al.*, 2020]. This is a major obstacle in situations where near-real time emissions estimates are needed.

An alternative method is to use the GDP change rate to reflect CO_2 emissions [*Asumadu-Sarkodie and Owusu*, 2017; *Jenny and Sara*, 2016; *Tucker*, 1995; *Wang et al.*, 2019]. GDP data are more available as a near-real time index than fuel consumption data, especially at the subnational level, where there is a greater lag in publishing statistical data. Since CO_2 emissions mainly come from secondary industry, the growth rate of secondary industry plays an important role in shaping the total changes in CO_2 emissions.

Coronavirus (COVID-19) has caused great loss of human life and has impacted all other social-economic-environmental aspects of life, including global CO_2 emissions [*Epidemiology Team*, 2020; *Le Quéré et al.*, 2020]. Since the Wuhan lockdown on January 23rd, 2020, China has implemented a series of strict measures, including temporarily stopping public transport, restricting the free flow of workers, and confining residents to their homes, to combat the virus. These measures also represent a great economic sacrifice, and thus, CO_2 emissions are certainly dropping compared to the same period in the previous year.

However, few studies have been conducted on China's CO_2 emission decrease associated with the COVID-19, especially at the provincial level [IEA, 2020; Le Quéré et al., 2020; Liu et al., 2020]. A few studies or news reports indicate that the decrease might have temporarily reached 25% [IEA, 2020; Myllyvirta, 2020]. In this study, we collected national and provincial GDP and transport data and used the GDP method to calculate the emission decrease for China at both the national and provincial levels for the first quarter of 2020. We then used a point, line, and area sources method to test this approach. The data can help to understand the magnitude of emission decrease due to the COVID-19 lockdowns and provide information to help policy makers promote the local economy and develop emission reduction policies.

2 Data and Methods

2.1 Data

Statistical GDP data at the national and provincial levels were derived from databases and news releases provided by the National Bureau of Statistics of China (NBS) and provincial bureau statistics agencies (see Table S1 for details). Sectoral growth rate data were derived from the Beijing, Tianjin and Hebei statistics bureaus. The provincial transportation data (freight and passenger distance traveled and change rates) were obtained through the Ministry of Transport of the People's Republic of China (MOT) [*MOT*, 2020], and the Hubei data were derived from the Department of Transportation of Hubei Province. Quarterly GDP deflator data were from both the NBS [*National Bureau of Statistics of the People's Republic of China. NBS*, 2020a] and the World Bank. And GDP (deflator) is calculated using method of price index deflation [*National Bureau of Statistics of the People's Republic of China. NBS*, 2013]. This method means directly deflating value-added at current price by using relevant price index, and calculating value-added at constant price, which is as follows:

Value-added at constant price of some industry = value-added at current price of the industry÷ price index of the industry.

Daily coal consumption for six main power groups from 2011 to 2020 was derived from Wind (https://www.wind.com.cn/).

Along with the change in quarterly GDP (deflator) for the three industry categories, we also need a baseline inventory of CO_2 emissions with the same classification. We used 2017 annual provincial CO_2 emissions data from China Emission Accounts and Datasets (CEADs) because it offers local optimized emission factors for coal and timely updates [*Shan et al.*, 2020; *Shan et al.*, 2017], and we used the GDP deflator scaling factor (0.25, the ratio of 2019 Q1 to 2017 full year), to obtain the 2019 Q1 baseline emissions (Table S4, S5). CEADs provides emissions data for 51 subsector for 2017, and its classification is presented in Table S2. We treat the urban, rural and other subsectors (mainly residential and commercial emissions) as tertiary industry due to their similarities.

2.2 Methods

2.2.1 GDP scaling method

Previous studies have demonstrated that per capita CO_2 emissions have a positive linear relationship with per capita GDP, especially in developing countries [*Jenny and Sara*, 2016; *Wang et al.*, 2019], as shown in Figure S1. In a short time span of two years or several quarters, assuming the population does not change drastically, CO_2 emissions show a good relationship with GDP (Eq. 1) [*Jenny and Sara*, 2016]. We assumed that the emission factor for each of the industry categories remains unchanged from the 2019 level in 2020. Using the “Industrial Classification for National Economic Activities” (GB/T 4754-2017) [*National Bureau of Statistics of the People's Republic of China. NBS*, 2017] and considering the actual situation in China, the first level of classification directly adopts the Three Industries Classification Regulations enacted in 2003 by the NBS, with the division into primary industry, secondary industry and tertiary industry. Primary industry refers to farming, forestry, animal husbandry and fishery, Secondary industry refers to the mining industry, manufacturing industry, electricity, heat, gas and water production and supply industry and construction, and tertiary industry refers to industries other than primary and secondary industry.

$$CO_2 \text{ emissions}=\Sigma[\text{Activity data(GDP)}_i \times EF_i] \quad \text{(Eq. 1)}$$

where i equals the three major sectors: primary industry, secondary industry, and tertiary industry. See the detailed classification in the references [*National Bureau of Statistics of the People's Republic of China. NBS*, 2013; 2019];

GDP refers to the gross domestic product of industry i;

EF refers to the emission factors of industry i.

Assuming the EF_i is maintained at the same level, CO_2 decrease can be calculated as follows:

$$\Delta CO_2 \text{ emissions} =\Sigma[\text{Change rate of } GDP_i \times CO_2 \text{ emissions}_i] \quad \text{(Eq. 2)}$$

We further separate tertiary industry into two subsectors: transport and non-transport due to their different emissions features, and a drastic decline in the transport sector [*Le Quéré et al.*, 2020; *MOT*, 2020] and detailed distance traveled data can be obtained from the MOT. For the non-transport sector, we used the GDP method described above.

2.2.2 Transport scaling method

For the transport sector, we used the change rates in provincial total distance traveled data from the MOT as scaling factors.

$$\Delta CO_2 \text{ emissions}_{\text{Transport}} = \text{Change rate of distance traveled} \times CO_2 \text{ emissions}_{\text{Transport}} \quad \text{(Eq. 3)}$$

The transport-reduced emissions are combined with the non-transport results to yield the final estimate.

2.2.3 Test the GDP method using a point, line and area sources method (PLAS)

We next used the point, line and area sources method to test the results estimated with the GDP method. The validation data for the Beijing-Tianjin-Hebei region inventory are from the Energy Research Institute of the National Development and Reform Commission. This inventory provides emissions shares of point, line and area sources for Beijing, Tianjin and Hebei, respectively. We reclassified the sector growth rate into the PLAS from the Beijing, Tianjin and Hebei statistics based on data availability. We assumed industry as point sources and the statistical traffic data from the MOT as line sources, and we treat tertiary industry as area sources.

$$\Delta CO_2 \text{ emissions} = \Sigma[\text{Change rate of emissions}_{\text{type } i} * CO_2 \text{ emissions}_{\text{type } i}] \quad \text{(Eq. 4)}$$

where type i represents the three major types: the point, line and area sources, which here refer to power and industry; traffic; and the service industry, residential activities and commercial activities, respectively.

3 Results and discussion

3.1 National-level CO_2 emission decrease

The estimated total CO_2 emissions decreased by -257.7 million tons (Mt) (-11.0%) for the first quarter of 2020, which is consistent with *Le Quéré et al.* [2020] (-242 Mt) and *Liu et al.* [2020] (-260 Mt); both of these two studies concentrated on global and national estimates and time disaggregation into daily using proxy data. Secondary industry contributed the majority of the decrease (-186.8 Mt), and tertiary industry and primary industry contributed -70.0 Mt and -0.9 Mt to the decrease, respectively (Figure 1, a). Their contributions are largely determined by the emissions characteristics and thus the emissions shares of each major sector. In the CEADs account, secondary industry contributes 83.7% of total emissions, while tertiary industry and primary industry contribute 15.2% and 1.1%, respectively. Secondary industry includes power and cement production, both of which are large emissions sectors, contributing ~40% to total emissions [*Lei et al.*, 2011; *F Liu et al.*, 2015; *Z Liu et al.*, 2015; *Liu et al.*, 2020; *Shan et al.*, 2020], and these two sectors saw decreases in production of -8.4 and -23.9% for 2020 Q1 [*National Bureau of Statistics of the People's Republic of China. NBS*, 2020a], and -13.5% and -29.5% for the first two months, respectively [*National Bureau of Statistics of the People's Republic of China. NBS*, 2020b]. And this is consistent with results from *Le Quéré et al.* [2020], *Myllyvirta* [2020] and *Liu et al.* [2020], that power and industry coal consumptions decreased -6.8% and -23.6~-30%, respectively. The GDP change rate for secondary industry was -9.6% for 2020 Q1, despite the total GDP change rate being -6.8%

(Figure 1, b), which may be why the calculated CO_2 decrease were higher than the mean GDP change rate, indicating that COVID-19 mainly influenced industry production through “safer at home” orders from governments. This situation is different from the 2008 financial crisis, when GDP decreased by -1.7% in 2009 [*World Bank*, 2020], while CO_2 emissions only reduced by -1.4% [*Friedlingstein et al.*, 2019]; the financial crisis mainly impacted finance-related sectors that do not release the same level of CO_2 as secondary industry, and after the crisis emissions rebounded quickly [*Le Quéré et al.*, 2020]. As for the uncertainty, the activity data of GDP for the NBS has a difference of 0.1-7.4% for provincial total and national total (NBS, 2020), and thus the maximum error derived from GDP can reach 7.4% or 19.1 Mt CO_2. The assumption that emission factors for three major sectors would introduce slight uncertainties too, which is hard to be quantified but is likely to be smaller than the uncertainty derived from GDP.

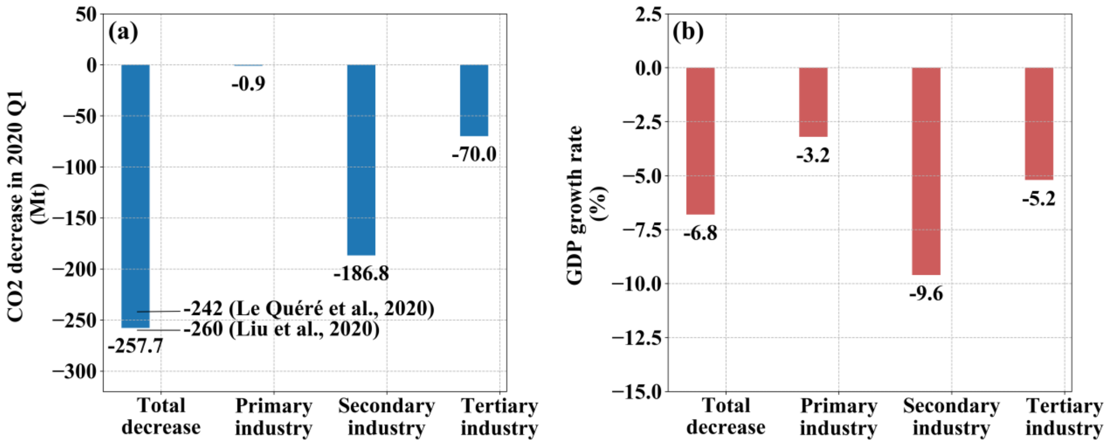


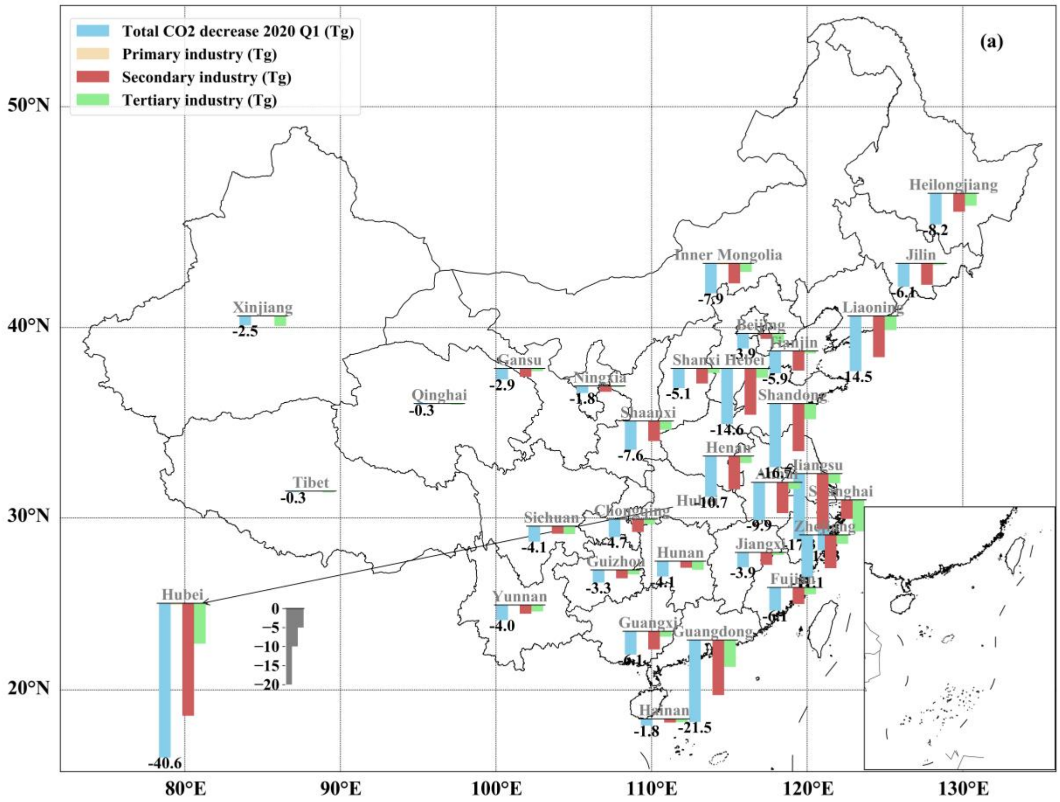
Figure 1 China’s CO_2 emission decrease in 2020 Q1 (a) and GDP growth rate (b) compared to 2019 Q1.

3.2 Spatial pattern of CO_2 emission decreases at the provincial level.

The spatial distribution of CO_2 emission decrease was closely related to the severity of COVID-19 impacts (Figure 2 and Figure S2, S3). As expected, Hubei Province showed the largest CO_2 decrease of -40.6 Tg (or -44.4%) (Figure 2, Figure S4, Table S3), which corresponds to the GDP recession of -48.2% for secondary industry. The lockdown from January 23rd to April 8th caused by COVID-19 was not limited to Wuhan, and all prefectural cities in Hubei Province were locked down before January 25th. CO_2 emission decreases in Guangdong, Jiangsu, and Shandong were -21.5, -17.3 and -16.7 Tg, respectively (Figure 2, a). Correspondingly, the GDP change rates were -8.8%, -7.1% and -14.1% for secondary industry, respectively (Figure 2, b). These three provinces were all high emissions contributors [*Shan et al.*, 2020]. The provinces in the North China Plain and Eastern China also had noticeable declines of 10-15 Tg (Figure 2, a), resulting from a -10% ~ -20% decrease in GDP for secondary industry (Figure 2, b). In contrast, the central and southern provinces mostly saw decreases in CO_2 emissions of 0-5 Tg at a rate of less than 10% for secondary industry. In Western China, where COVID-19's impact was small, the influence on economic and industrial production was also slight, with Qinghai Province dropping by only 0.3 Tg (or -1.0%). Moreover, at provincial level, there was a significant linear relationship (p value<0.001) between CO_2 emissions decrease and $\log_{10}$ of total confirmed cases (Figure S3). Although *Le Quéré et al.* [2020] and [*Liu et al.*, 2020] reported national and major sectors decrease, here we presented spatial decreases at provincial level. Considering the homology of CO_2 with NO_2, our results were consistent in spatial patterns with *Bauwens et al.* [2020] and *Huang et al.* [2020], both of which showed -40~-60% reductions in NO_2 from TROPOMI, OMI and ground based monitoring for North China Plain and Eastern China. However, the decrease signals may be too weak to be detected by ground based CO_2 concentration [*Kutsch et al.*, 2020; *Ott et al.*, 2020] and satellite based column CO_2 observations [*Schwandner et al.*, 2017], due to the mask of natural variability from a 'noisy' global carbon cycle and meteorology [*Ballantyne et al.*, 2012; *Kutsch et al.*, 2020; *Le Quéré et al.*, 2020; *Peters et al.*, 2017].

Moreover, we tested the GDP estimation results by the PLAS. We take the Beijing-Tianjin-Hebei regions as an example. The PLAS estimated CO_2 emission decreases for Beijing, Tianjin and Hebei were 5.8, 4.9, and 11.0 Tg (total 21.8 Tg), respectively (Figure S5), while the GDP method estimated them as 3.9, 5.9, and 14.6 Tg (total 24.4 Tg), respectively, for differences of -32.4%, 18.5%, and 32.6% (total 12.0%). Specifically, the decreases in point, line and area sources for Beijing were 2.2, 3.1, and 0.5 Tg; for Tianjin, 4.1, 0.4, and 0.5 Tg; and for Hebei, 8.9, 1.0, and 1.2

Tg. Although these two methods used different assumptions and data, they produced reasonably consistent results, with a mean difference of 12.0%. Moreover, due to the lack of a detailed change rate for PLAS sector data (e.g., power and industry data) for 2020 Q1, Beijing showed a larger difference than Tianjin and Hebei.



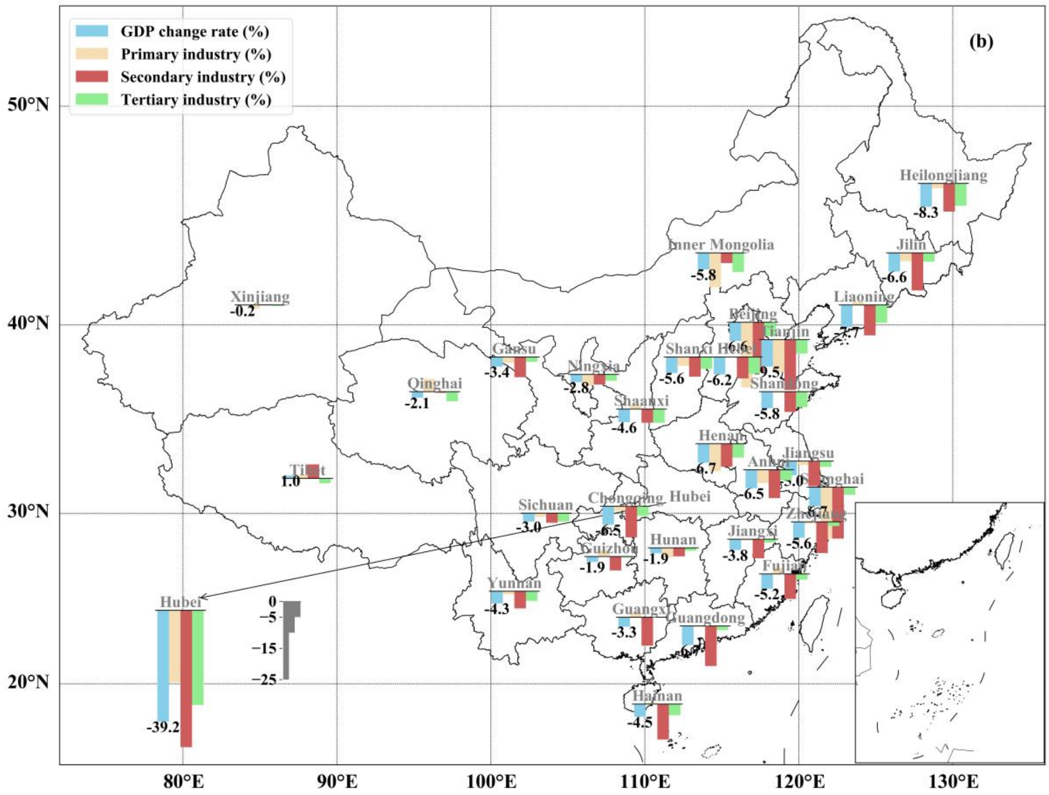
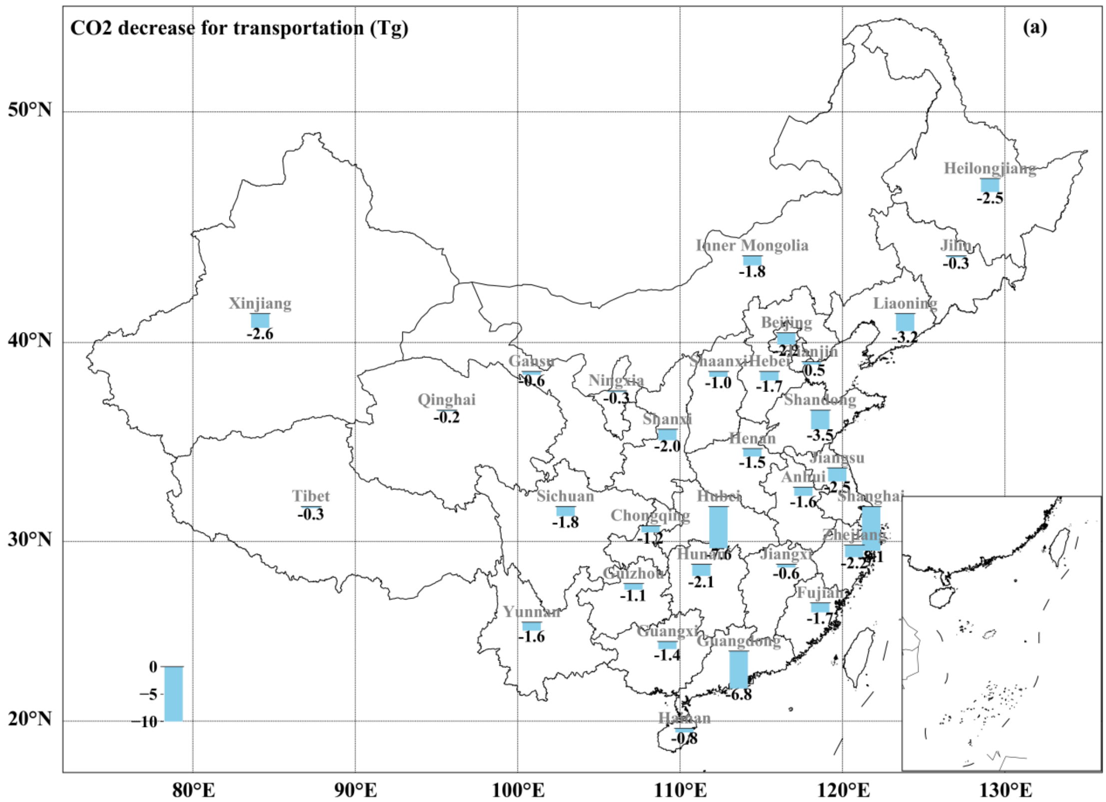


Figure 2 Provincial CO_2 emission decrease in 2020 Q1 (a) and GDP change rate (b) compared with 2019 Q1.

3.3 Provincial CO_2 decreases in road transport

Transport is the sector seeing the most influence on CO_2 emissions from the lockdown. Only two days after the Wuhan lockdown on January 23rd, 2020, all other prefectural cities in Hubei Province were locked down. During the 76-day lockdown period, public transport, including urban public transport, subways, ferries, and long-distance passenger transport, was shut down, and airports and railway stations were temporarily closed [*WCNCPCCC*, 2020]. People were ordered to stay home as much as possible except for essential needs, and all these measures suddenly and substantially decreased on-road transport. Consequently, the carbon dioxide decrease was -7.6 Mt (Figure 3 a), and the corresponding distance-weighted transport turnover change rate was -83.9%. More specifically, according to the statistics of the Department of Transport of Hubei Province, in the first quarter, freight and passenger turnover volume decreased -93.4% and -70.1% compared to the same period in 2019, respectively (Figure S6). Shanghai, Guangdong and Shandong provinces had emission decreases of -8.1, -6.8 and -3.5 Mt CO_2 (Figure 3 a), with a distance-weighted decreases of -63.4%, -40.2% and -32.1% in transport turnover volume (Figure 3 b). The transport change rates for Hainan, Xinjiang and Heilongjiang were also high (nearly -50%), but the decreases were relatively small (-0.8 ~ -2.6 Tg) due to the low total baseline emissions. Other provinces mostly had decreases of -1 ~ -2 Tg (or -20% ~ -30%). In total, ground-based transport CO_2 decrease for the 30 provinces were -65.1 Mt (or -32.7%), which is comparable to the estimate (-79.8 Mt or -36.2%) from [*Liu et al.*, 2020], and *Le Quéré et al.* [2020] estimated that surface transport contributed ~50% of the global decrease. The policy implications are that advocating working from home and changing communication channels by holding virtual video conferences over the Internet can reduce traffic emissions.



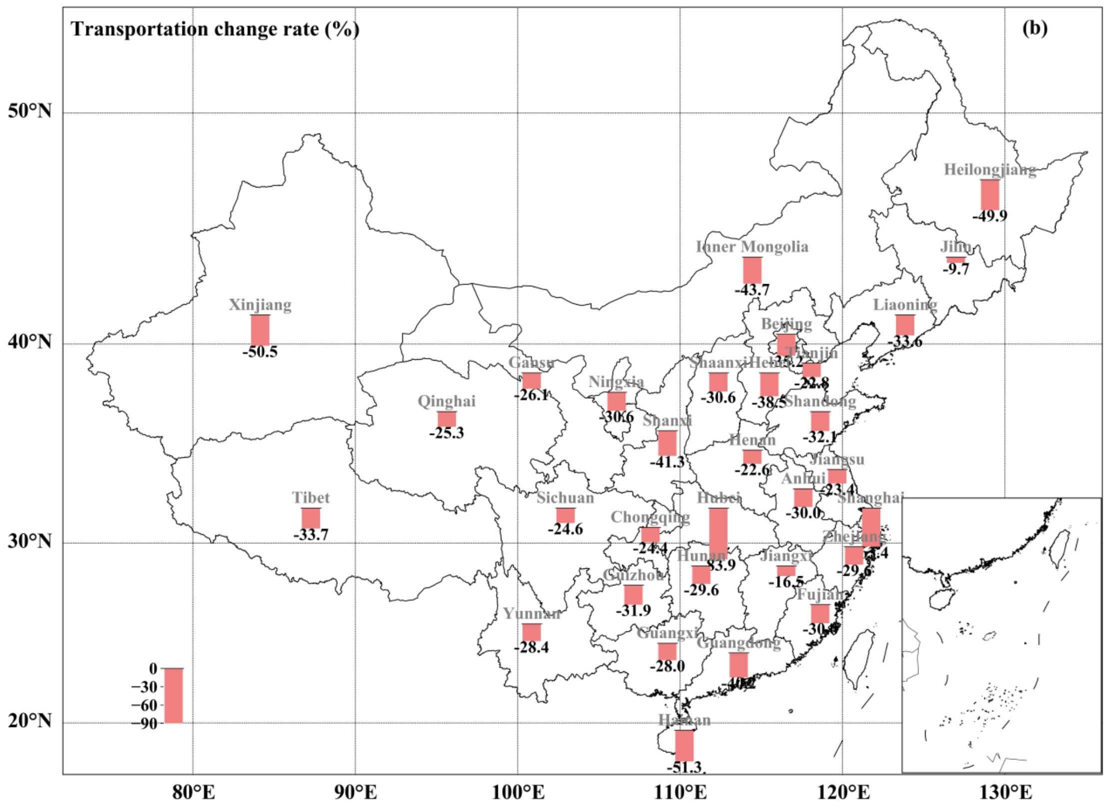


Figure 3 Transport emission decrease in 2020 Q1 (a) and distance-weighted freight and passenger turnover growth rate (b) compared with 2019 Q1.

3.4 Daily coal consumption at six main power groups and implications

Calculating CO_2 emission decrease for all of 2020 depends on the duration of the lockdown and the recovery of energy and economic activity. Using the daily coal consumption at six power generation groups as an indicator, the mean decreases were estimated at -13.4% for 2020 Q1 compared with 2019 Q1 (Figure 4 and Figure S7), with a peak decrease of -25%, which strongly corresponds to the confirmed cases reported by the Chinese Center for Disease Control and Prevention; for the first four months, the decrease was -12.6%, and for April alone, it was -9.9%. With the alleviation of coronavirus impacts and the economic stimulus package, CO_2 emissions are rebounding, although they have not yet returned to prepandemic levels (~10% lower than previous 10 years mean, Figure 5). By simply extrapolating the rate to the whole year, the decreases were estimated at a low bound of –3.9% if pre-pandemic conditions return by July and a high bound of –7.4% if impacts remain until the end of 2020. And this prediction is consistent with estimates by *Le Quéré et al.* [2020] (-2.6 ~ -5.6%). As has been advocated by China and the UK governments, we must strengthen international solidarity to address global environmental and climate challenges through taking green and low-carbon road for economic recovery [*MEE*, 2020].

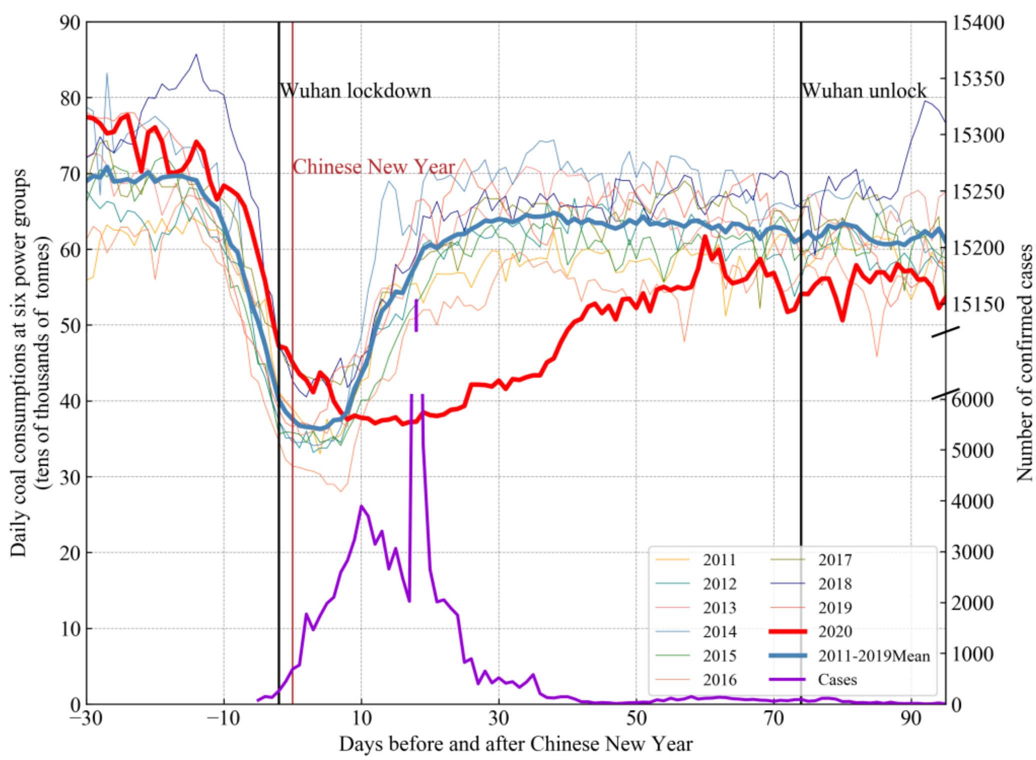


Figure 4 Daily coal consumption at six main power groups from 2011 to 2020 (left y-axis) and number of confirmed cases (right y-axis). Coal consumption data were derived from https://www.wind.com.cn/. Daily confirmed cases were from http://www.chinacdc.cn/, accessed on June 3rd 2020.

4 Conclusions

Using national and provincial GDP in three major sectors, transport statistical data and a bottom-up inventory as a baseline, we conducted an analysis of China's CO_2 emission decrease in the first quarter of 2020 related to the COVID-19 mitigation measures. The overall decrease was estimated as -257.7 Mt (-11.0%), and Hubei contributed the most (15.6%) to this decrease. In terms of sectoral contribution, ground transport contributed significantly (25.0%). The estimates from the GDP method were reasonably consistent with those from the point, line and area sources method. The estimated decrease helps to explain the impacts of COVID-19 on China's CO_2 emissions and is useful for understanding local economic recovery and developing reduction strategies for policy makers.

Data availability. Data is available through Shan et al., (2020). GDP data is available through http://data.stats.gov.cn/english/easyquery.htm?cn=B01.

Author contributions. PFH and YLS conceived and designed the study. PFH and QXC collected and analyzed the data sets. PFH, TO and NZ led the paper writing with contributions from all coauthors.

Competing interests. The authors declare that they have no conflicts of interest.

Acknowledgments This work was supported by the National Key R&D Program of China (No. 2017YFB0504000). We thank Mr. Meng Zhao from Energy Research Institute, National Development and Reform Commission for kindly providing PLAS information on Beijing-Tianjin-Hebei inventory. We thank Ms. Xiaoli Zhou and Mr. Zhe Hu for help in data collection and processing.

References

Asumadu-Sarkodie, S., and P. A. Owusu (2017), Recent evidence of the relationship between carbon dioxide emissions, energy use, GDP, and population in Ghana: A linear regression approach, *Energy Sources, Part B: Economics, Planning, and Policy*, *12*(6), 495-503.

Ballantyne, A. P., C. B. Alden, J. B. Miller, P. P. Tans, and J. W. C. White (2012), Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years, *Nature*, *488*(7409), 70-72.

Bauwens, M., et al. (2020), Impact of coronavirus outbreak on NO2 pollution assessed using TROPOMI and OMI observations, *Geophysical Research Letters*, *n/a*(n/a), e2020GL087978.

Epidemiology Team, T. N. C. P. E. R. (2020), The epidemiological characteristics of an outbreak of 2019 novel coronavirus diseases (COVID-19) in China, *China CDC Weekly*, *41*(2), 145-151.

Friedlingstein, P., et al. (2019), Global Carbon Budget 2019, *Earth Syst. Sci. Data*, *11*(4), 1783-1838.

Guan, D., J. Meng, D. M. Reiner, N. Zhang, Y. Shan, Z. Mi, S. Shao, Z. Liu, Q. Zhang, and S. J. Davis (2018), Structural decline in China's CO 2 emissions through transitions in industry and energy systems, *Nature Geoscience*, *11*(8), 551-555.

Huang, X., et al. (2020), Enhanced secondary pollution offset decrease of primary emissions during COVID-19 lockdown in China. https://doi.org/10.31223/osf.io/hvuzy, edited.

IEA, I. E. A. (2020), Global Energy Review 2020: The impacts of the COVID-19 crisis on global energy demand and CO_2 emissions https://www.iea.org/reports/global-energy-review-2020.

Jenny, C., and S. Sara (2016), Is there a relationship between economic growth and carbon dioxide emissions?, Södertörns University, Stockholm, Sweden.

Kutsch, W., A. Vermeulen, and U. Karstens (2020), Finding a hair in the swimming pool: The signal of changed fossil emissions in the atmosphere. https://www.icos-cp.eu/event/917, edited.

Le Quéré, C., et al. (2020), Temporary decrease in daily global CO_2 emissions during the COVID-19 forced confinement, *Nature Climate Change*.

Lei, Y., Q. Zhang, C. Nielsen, and K. He (2011), An inventory of primary air pollutants and CO_2 emissions from cement production in China, 1990–2020, *Atmospheric Environment*, *45*(1), 147-154.

Liu, F., Q. Zhang, D. Tong, and B. Zheng, Li, M., Huo, H., and He, K. B. (2015), High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010, *Atmos. Chem. Phys.*, *15*, 13299-13317.

Liu, Z., D. Guan, W. Wei, S. J. Davis, P. Ciais, J. Bai, S. Peng, Q. Zhang, K. Hubacek, and G. Marland (2015), Reduced carbon emission estimates from fossil fuel combustion and cement production in China, *Nature*, *524*(7565), 335-346.

Liu, Z., et al. (2020), COVID-19 causes record decline in global CO_2 emissions. https://arxiv.org/abs/2004.13614, edited.

MEE, t. M. o. E. a. E. o. t. P. s. R. o. C. (2020), MEE news: Minister of MEE held teleconference with British Minister of Commerce, Energy and Industry Strategy. http://www.mee.gov.cn/xxgk2018/xxgk/xxgk15/202006/t20200603_782344.html.

MOT, t. M. o. T. o. t. P. s. R. o. C. (2020), Statistical data (In Chinese, accessed 25th May 2020). http://www.mot.gov.cn/tongjishuju/, edited.

Myllyvirta, L. (2020), Myllyvirta, L. Coronavirus temporarily reduced China's CO_2 emissions by a quarter. Carbon Brief https://www.carbonbrief.org/analysis-coronavirus-has-temporarily-reduced-chinas-co2-emissions-by-a-quarter, edited.

NBS, N. B. o. S. o. t. P. s. R. o. C. (2013), Annual GDP Accounting Instructions of China. http://www.stats.gov.cn/english/understanding/201311/t20131118_463791.html (Accessed on 6th May 2020), edited.

NBS, N. B. o. S. o. t. P. s. R. o. C. (2017), Industrial Classification for National Economic Activities (GB/T 4754-2017) http://www.stats.gov.cn/tjsj/tjbz/hyflbz/201710/P020180402592793000880.pdf, edited.

NBS, N. B. o. S. o. t. P. s. R. o. C. (2019), National Economy Accounting (In Chinese). http://www.stats.gov.cn/tjsj/zbjs/201912/t20191202_1713058.html, edited.

NBS, N. B. o. S. o. t. P. s. R. o. C. (2020a), National Data. http://data.stats.gov.cn/english/easyquery.htm?cn=A01, edited.

NBS, N. B. o. S. o. t. P. s. R. o. C. (2020b), NBS news: From January to February 2020, the added value of industries above Designated Size will decrease by 13.5%. http://www.stats.gov.cn/tjsj/zxfb/202003/t20200316_1732233.html edited.

Ott, L., G. Peters, and A. Meyer (2020), Special Virtual Panel: Covid-19 and Its Impact on Global Carbon Emissions. https://carbon.nasa.gov/policy_speaker_28052020.html, edited.

Peters, G. P., et al. (2017), Towards real-time verification of CO_2 emissions, *Nature Climate Change*, *7*(12), 848-850.

Schwandner, F. M., et al. (2017), Spaceborne detection of localized carbon dioxide sources, *Science*, *358*(6360), eaam5782.

SCIO, t. S. C. I. O. o. t. P. s. R. o. C. (2020), Fighting Covid-19: China in Action. http://www.scio.gov.cn/ztk/dtzt/42313/43142/index.htm (Accessed on 7th June).

Shan, Y., Q. Huang, D. Guan, and K. Hubacek (2020), China CO_2 emission accounts 2016–2017, *Scientific Data*, *7*(1), 54.

Shan, Y., H. Zheng, D. Guan, C. Li, Z. Mi, J. Meng, H. Schroeder, J. Ma, and Z. Ma (2017), Energy consumption and CO_2 emissions in Tibet and its cities in 2014, *Earth's Future*, *5*, 854-864.

Tucker, M. (1995), Carbon dioxide emissions and global GDP, *Ecological Economics*, *15*(3), 215-223.

Wang, H., X. Lu, Y. Deng, Y. Sun, C. P. Nielsen, Y. Liu, G. Zhu, M. Bu, J. Bi, and M. B. McElroy (2019), China’s CO_2 peak before 2030 implied from characteristics and growth of cities, *Nature Sustainability*, *2*(8), 748-754.

WCNCPCCC, W. C. N. C. P. a. C. C. C. (2020), The No. 1 public notice on novel coronavirus infection prevention (In Chinese). http://www.wuhan.gov.cn/zwgk/tzgg/202003/t20200316_972434.shtml, edited.

World Bank, W. (2020), GDP growth (annual %). https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG (Accessed May 16 2020).