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Open Access Earth System Science Data Discussions

Daily CO2 emission for China's provinces in 2019 and 2020

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Abstract

Tracking China's national and regional CO_2 emission trends is becoming ever more crucial. The country recently pledged to achieve ambitious emissions reduction targets, however, high-resolution datasets for provincial level CO_2 emissions in China are still lacking. This study provides daily CO_2 emission datasets for China's 31 provinces, including for the first time, the province of Tibet. The inventory covers the emissions from three industrial sectors (power, industry and ground transport) during 2019 to 2020, with its temporal resolution at a daily level. In addition, the variations in CO2 emissions for seasonal, weekly and holiday periods have been uncovered at a provincial level for the first time. This new data was added to further analyze the impact that weekends and holidays have on China's CO_2 emissions. Over weekend periods, carbon emissions are shown to reduce by around 3%. Spring Festival meanwhile, has the greatest impact on the reduction of China's CO_2 emissions. This detailed and time-related inventory will facilitate a more local and adaptive management of China's CO_2 emissions during both the COVID-19 pandemic's recovery and the ongoing energy transition. The data are archived at https://doi.org/10.5281/zenodo.4730175 (Cui et al., 2021).

1. Introduction

China has the largest CO_2 emission worldwide, accounting for about 28% of global CO_2 emissions in 2019 (Friedlingstein et al., 2020). China is also the fastest growing country in

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

terms of CO_2 emissions (IEA, 2020). China's energy consumption and CO_2 emissions have been relatively stable since 2013 (Friedlingstein et al., 2019; Liu et al., 2015; Guan et al., 2018). However, since 2018, China's energy consumption and CO_2 emissions have shown a new upward trend. The annual growth rates of China's Carbon emissions have exceeded 2% between 2018 and 2019 (Friedlingstein et al., 2019; Friedlingstein et al., 2020). In contrast, the growth rate of global carbon emissions is only 0.1%. China, therefore, faces considerable pressure from the international community to reduce emissions. The estimates of China's CO_2 emissions carry significant uncertainties, and the differences in estimates of China's carbon emissions between inventories from EDGAR, CDIAC, and CEADs approach 15% (Liu et al., 2015). Having timely and accurate CO_2 emission estimates based on fossil fuel combustion and cement production is therefore fundamental prerequisite to designing evidenced-based policies for reducing China's CO_2 emissions.

The achievement of China's national CO_2 mitigation target will rely on the implementations of certain actions and policies at provincial levels. Previous studies have compiled the provincial emission inventories, which generally include the annual carbon emissions from energy- and industry- related sectors in 30 provinces (except for Tibet) in mainland China (Shan et al., 2018). However, these studies are based on provincial energy statistics and often have a time lag of one or more years.

The timely updating of CO_2 emissions data is a critical step for China's provinces to achieve the carbon neutrality plans. Moreover, the outbreak of the COVID-19 pandemic has resulted in extra uncertainties regarding China's future CO_2 emissions trajectory (Liu et al., 2020a; Liu et al., 2020b). During the outbreak of the COVID-19 pandemic (January-June 2020) in China, the national CO_2 emissions were reduced by 3.7% (-187.2 Mt CO_2) compared to the same period in 2019. Therefore, there is an urgent need to obtain a timely CO_2 emission dataset at provincial level (Liu et al., 2020c) so that the post-COVID emission dynamics can be tracked accordingly.

In a recent study, Liu et al. (2020a; 2020b) described the *Carbon Monitor* of Fossil Fuel CO_2 Emissions dataset, which provides daily CO_2 emissions data up till December 31st, 2020, for 6 sectors and 12 largest emitting countries, plus the rest of the world as an aggregate. The global fossil fuel CO_2 emissions was separated into sectors of power generation (~40% globally), industrial production (~30%), transportation (~20%, categorized as ground, air and shipping) and residential consumption (~10%). This product is evaluated against preliminary national energy usage data for all or part of the year 2020, thereby providing a full picture of all the CO2 emission drivers, including the pandemic (seasonality, working days and holidays, weather and the economy). By acknowledging the uncertainties more than just the inventories, such a dataset can provide more up-to-date information than official inventories (UNFCCC, 2020a, b, c) and international CO_2 emissions datasets (BP, 2020; Crippa et al., 2020; Friedlingstein et al., 2020 ; Gilfillan et al., 2020; IEA, 2020), which have a time lag of 6 to 16 months after the last month of reported emissions.

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

In this study, based on China's daily emissions at the national scale, which are taken from the *Carbon Monitor* and provincial sectoral weight factors related to CO2 emissions, we estimate mainland China's daily CO_2 emissions from electricity, industry and ground transport sectors in all 31 provinces. The full names of these 31 provinces and their corresponding abbreviations are shown in Table 1. CO_2 emissions from Tibet are included in this dataset for the first time. This detailed and timely inventory will facilitate a more local and adaptive management of CO_2 emissions in the process of cutting carbon emissions and achieving carbon neutrality.

2. Materials and Methods

This dataset accounts for the daily changes in provincial CO_2 emissions in mainland China for the years 2019 and 2020. Daily provincial CO_2 emissions are estimated from three sectors: power, industry, and ground transport. It considers CO_2 emissions estimates based on administrative territories, while the emissions from international aviation and shipping are excluded (Shan et al., 2017). The estimates of national CO_2 emissions from 2019 to 2020 is derived from the *Carbon Monitor* dataset (data available at https://carbonmonitor.org).

2.1 National daily CO_2 emissions in 2019 and 2020

China's daily CO_2 emissions estimates are based on a near-real-time daily dataset of the global CO_2 emissions from fossil fuel and cement production since January 1, 2019, as published by the *Carbon Monitor* (data available at https://carbonmonitor.org/) (Liu, Ciais et al. 2020). Emission estimates from the Carbon Monitor are calculated on a national basis and by sectors, thereby gaining from past experiences in constructing annual inventories and newly compiled activity data (Liu, Ciais et al. 2020).

The *Carbon Monitor* has calculated China's daily CO_2 emissions since January 1, 2019. It is separated into several key emission sectors: power sector, industrial production, residential consumption, ground transport, air transport and ship transport. For the first time then, China's daily emission estimates are produced for these sectors based on regularly updated dynamic activity data.

China's near real-time activity data includes daily data for electricity generation, and monthly production data for cement, steel and other energy-intensive industrial sectors. In addition, it includes hourly traffic congestion data for 22 cities, daily maritime and aircraft transportation activity data, and previous-year fuel usage data for both residential and commercial buildings that has been corrected for air temperature.

2.2 Provincial distribution of daily CO_2 emissions

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Daily provincial CO_2 emissions are estimated by daily national CO_2 emissions multiplied by the provincial weight factor. The sectoral provincial daily CO_2 emission can be obtained as follows:

$$\sum_{i,p} E_{pro} = E_{i,China} \times R_{i,p} \tag{1}$$

where E_{pro} represents daily provincial emissions, $E_{i,china}$ refers to daily national CO_2 emissions, and $R_{i,p}$ denotes the weight factor of province p from i sector.
Due to the lack of either daily or monthly provincial energy consumption data, we used alternative indicators that reflect the provincial activity data of the corresponding sector in place of the provincial activity data.

The weight factors for each province equal the amount of provincial alternative indicators divided by the national amount of alternative indicators. The equation is as follows:

$$R_{i,p} = \frac{P_{i,p}}{P_{i,n}} \tag{2}$$

where $P_{i,\,p}$ and $P_{i,n}$ represent the provincial and national amount of alternative indicators for sector i, respectively. For the power, industry and ground transport sectors, the alternative indicators are thermal power generation, cement production and vehicle ownership. The data on provincial thermal power generation, cement production and vehicle ownership were obtained from China's National Bureau of Statistics of China (NBSC).

2.3 Provincial weight factor estimation

The provincial dataset constructed in this study includes daily CO_2 emission data from the three main polluting sectors (power, industry and ground transport) in China, which together account for more than 90% of the total emissions. CO_2 emissions from residential consumption and aviation are not considered in the provincial dataset for three reasons. Firstly, residential and aviation totally accounted for less than 9% of China's average daily CO2 emissions (Table 2). Secondly, currently there is no suitable statistical indicator that can be used as a provincial weight factor to divide residential sector emissions from the national level into the provincial level. Thirdly, it is very difficult to count aviation emissions within provincial territories.

For the power sector, we collected monthly data on thermal power generation from 31 provinces in the Chinese mainland from January 2019 to December 2020. Due to the limitations on daily thermal power generation, we assumed that the change in ratio from provincial thermal power generation to national thermal power generation is negligible when looked at on a monthly scale. We therefore used this ratio of provincial thermal generation to national generation on a monthly scale as the provincial weight factor for the daily scale of

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

the power sector. Provincial weight factors from the power sector during 2019 and 2020 were shown in Table 3.

For the industry sector, CO_2 emissions from steel, cement, chemicals and other industries are calculated on a national scale according to the data provided by the Carbon Monitor. However, at a provincial scale, only the data on cement production was available, with other indicators from the steel, chemical and other industries were missing. Considering the intermediate processes, industrial cement processes have the highest proportion of emissions in the industrial sector. The ratio of the provincial production of industrial cement to the national production was taken as the provincial weight factor for this industry sector (Table 4).

For the ground transport sector, we used the ratio of provincial vehicle ownership to national vehicle ownership for the year 2018 as the provincial weight factor for the ground transport sector (Table 5). Due to a lack of monthly and daily data on provincial vehicle ownership after 2018, however, we considered the fact that there have been a change of less than 2.3% in two years in the provincial share of vehicle ownership in the country, and thus assumed the change in the ratio of provincial vehicle ownership to national vehicle ownership to be negligible.

2.4 Provincial emissions over the weekdays, weekends and holidays

In this dataset, we add two attributions – week and holiday – to provincial daily emissions. The attribution of "week" includes seven values: Monday, Tuesday, Wednesday, Thursday, Friday, Saturday and Sunday. The attribution of "holiday" includes: New Year, Spring Festival, Qingming Festival, Labour Day, Duanwu Festival, Mid-Autumn Festival, and National Day. Among them, New Year, Qingming, Duanwu Festival and Mid-Autumn Festival are generally 3-day holidays, Labour Day is a 5-day holiday, and Spring Festival and November are 7-day holidays. It is worth noted that Labour Day in 2019 was four days long, from 1st May to 4th May, and in 2020, due to COVID-19, Spring Festival was extended to 10 days (24th January to 2nd February). Since the Mid-Autumn Festival holiday overlapped with the National Day holiday, in 2020 the Mid-Autumn Festival and National Day together were an 8-day holiday (1st October to 8th October). Table 6 shows the date and duration of these holidays in 2019 and 2020.

We calculated the average daily emissions over the weekdays, weekends and holidays from power, industry, and ground transport in 31 provinces. For weekdays, we averaged the daily emissions from Monday to Friday; for weekends, we averaged the daily emissions from Saturday to Sunday; and for holidays, we calculated the average daily emissions for New Year, Spring Festival, Qingming, Labour Day, Dragon Boat Festival and Mid-Autumn Festival, respectively.
The formula for calculating the reduced emissions over the weekends is as follows:

$$E_{rowe} = E_{ad\_Mo2Fr} - E_{ad\_Sa2Su}$$

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

where E_{rowe} represents reduced emissions over the weekend, E_{ad_Mo2Frr} and E_{ad_Sa2Su} refer to the average daily emissions from Monday to Friday, and average daily emissions from Saturday to Sunday, respectively.

3. Results

3.1 Trends in provincial daily CO2 emissions

Trends in total emissions

For most provinces, there is a valley shape in average daily emission in February (Table 7). For the year 2019, BJ province has its minimum monthly average emissions in April. The minimum monthly average emissions of 5 provinces (SH, FJ, CQ, GX and SC) occur between May to July. YN province has its minimum monthly average emission in September. The minimum monthly average emissions for TJ, HEN and HUB provinces meanwhile, occur in October. Tibet province has its minimum average monthly emission in December. In 2020 however, the minimum monthly average emissions for all provinces was in February, except for BJ (April), SH (October) and HUB (March).

The highest average daily emissions are mainly found in summer (June to August) or/and winter (November to January), and these are called summer peak and winter peak, respectively (Fig. 1). The provinces that follow this pattern for the summer peak emissions are HEB, SX, IM, LN, JL, HLJ, HEN, Tibet, QH, NX and XJ. The remaining provinces, including BJ, TJ, SH, JS, ZJ, AH, FJ, JX, SD, HUB, HUN, GD, GX, HAN, CQ, SC, GZ, YN, SAX and GS, follow the winter peak emissions pattern (Table 7).

Referring to minimum daily emissions (Table 8), this day fell on the 5th February for 25 provinces (except for BJ, SH, HEN, CQ, SC and Tibet), which was the first day of the seven-day holiday for the Spring Festival in 2019. From those that did not follow this trend, BJ and SH province emitted their minimum value of CO_2 on the 1st May, which is the first day of the four-day holiday of Labour Day in 2019; for HEN, CQ and SC it was on the 1st October in 2019, the first day of the seven-day holiday of National Day; and for Tibet it was on the 1st December in 2019. In 2020, 14 provinces, including TJ, HEB, LN, JL, HLJ, JS, ZJ, SD, HEN, GD, QH and Tibet emitted their minimum amount of emissions on the 9th February; 9 provinces, including SX, IM, AH, FJ, JX, SAX, GS, NX, AND XJ, had their minimum daily emission day on the 13th February; 8 provinces (SH, HUN, GX, HAN, CQ, SC, GZ, YN), had it on the 2nd October, which was the second day of the joint Mid-Autumn Festival and National Day holidays; for BJ province it was on the 4th April; and for HUB province, it was the 1st March.

Referring to maximum daily emissions, in 2019, the daily emissions in 20 provinces, including BJ, TJ, SH, JS, ZJ, AH, JX, SD, HUB, HUN, GD, GX, HAN, CQ, SC, GZ, YN, SAX, GS, QH, and XJ, reached their maximum value on a day between November to January (Table 8); for 8 provinces, including HEB, SX, IM, LN, HEN, Tibet and NX were on the 26th

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Open Access Earth System Science Data Discussions

July; and HLJ, FJ and QH were all on the 9th September. In 2020, maximum daily emissions occurred on a day between November and January in all provinces except for IM, JL, FJ, HEN, Tibet, HLJ and QH provinces. IM, JL, FJ, HEN and Tibet provinces emitted their maximum CO_2 on a day between June and August, and HLJ and QH emitted their maximum CO_2 on the 22nd October.

Trends in emissions from the power sector

Provincial daily CO_2 emissions from mainland China's power sector show two trends during an annual period: the "W" shape trend and the "U" shape trend. In most Chinese provinces (25 provinces, except for the six provinces of Tibet, QH, SAX, GS, SC and GZ), daily CO_2 emissions show two peaks and two valleys during an annual period, which we called the "W" trend (Fig. 2, a-aa). The two peaks occur in July-August and December-January, and we refer to them as the summer peak and the winter peak, respectively. The summer peak in the power sector is due to the widespread use of air conditioning, whereas the winter peak is due to heating. The valleys occur during the Spring Festival period and the National Day holiday, which are the two most important seven-day holidays in China.

The remaining six provinces (Tibet, QH, SAX, GS, SC and GZ), which are all western provinces, daily CO_2 emissions show the pattern of one peak and one valley during an annual period, which we call the "U" trend (Fig. 2, ab-ae). These western provinces have lower average summer temperatures and therefore have no summer peak of emissions. However, the winter peaks can be seen as daily CO_2 emissions from the power sector in these provinces.

Trends in emissions from industry sector

Provincial daily CO_2 emissions from the industry sector in mainland China show two trends during an annual period: the "inverted-U" shape trend and the "line" shape trend.
In 16 northern provinces of China, including LN, HLJ, JL, HEN, IM, GS, SX, SD, HEB, SAX, NX, XJ, QH, Tibet, TJ, and BJ, daily CO_2 emissions remain high from June to November, and then drop down from December to January, which we called the "inverted-U" shape trend (Fig. 3).
In 15 southern provinces of China, including YN, JX, FJ, GX, JS, HUB, GZ, GD, HAN, SH, CQ, AH, ZJ, SC, and HUN, daily CO_2 emissions reach their lowest point during the Spring Festival holiday, then slowly rise and reach the peak at the end of the year, which we call the "line" shape trend (Fig. 4).

Trends in emissions from ground transport

The impact that holidays have on daily CO_2 emissions trends is more pronounced in the ground transportation sector (Fig. 6). For the year 2020 however, COVID-19 has had a more

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Open Access Earth System Science Data Discussions

lasting impact on the CO_2 emissions from the transportation sector than on those from the power and industry sectors, which is consistent with previous studies (Liu et al., 2020a; Liu et al., 2020b; Liu et al., 2020c). CO_2 emissions from the ground transportation sector reached the same level until September in 2020 for the same period in 2019.

Trends in sectoral contribution

Fig. 6 shows the trends in the contribution rate of emissions from power, industry and ground transportation. In some provinces, such as in SD, JS, GD, ZJ, AH, SC, HUB, GX, GZ, FJ, HUN, JX, YN, CQ and HAN, the contribution of sectoral emissions varies little within one year. However, in HEB, IM, HEN, SX, XJ, SAX, LN, NX, JL, HLJ, GS, SH, TJ, BJ, QH and Tibet, the contribution of sectoral emissions shows a large variation within one year. Among the provinces that show large changes in sectoral emission contribution trends, except for SH, BJ and Tibet, all the emissions-contributing trends show that the largest contribution from the power sector is during winter, there is an increased share from the industry sector in summer, and the contribution from the transportation sector is relatively stale year-round.

In GS and QH provinces, the power sector accounts for more than 70% of the total daily emissions in winter and less than 30% of the total daily emissions in summer, while the industry sector accounts for more than 60% of the total daily emissions in winter. In the provinces of HLJ, JL, LN, SAX and HEB, the power sector contributes around 60% of the total daily emissions in winter, while in summer, the contribution from the industry sector reaches over 40%, which is close to or exceeds the contribution of daily emissions from the power sector. In SH and BJ, the contribution to total daily emissions from the power sector reaches its maximum in winter, and its minimum in the periods of April-May and September-October. The ground transportation sector is the sector that contributes the second largest volume of emissions in the period of April-May and September-October. This is especially true in BJ, where the transportation sector accounts for about 40% of total emissions in April-May and September-October, which is close to the emissions from the power sector during that period. Meanwhile, CO_2 emissions in Tibet are mostly contributed by the industry sector. In summer, the industry sector contributes over 90% of the daily CO_2 emissions, while in winter, it decreases to around 80% with the rest of the daily emissions mainly coming from ground transport.

3.4 The effect of the weekend on CO2 emissions

In a week, the lowest average daily emissions are observed on Saturday and Sunday (Fig. 7). Emission reductions over the weekend were seen to exceed 50 thousand tons of CO_2 per day in the provinces of SD, GD and JS (Fig. 8a). Among 28 of China's 31 provinces, a substantial decrease in CO_2 emissions can be seen over the weekend: the 17 provinces of HEB, HEN, ZJ, IM, AH, SX, SC, XJ, FJ, GX, HUB, HUN, SAX, JX, LN, YN and GZ, have a weekend emissions reduction that ranges from 20-40 thousand tons CO_2 (Fig. 8a), while the remaining 11 provinces of CQ, NX, GS, HLJ, JL, SH, TJ, BJ, HAN, QH and Tibet, show a weekend emissions reduction of less than 12 thousand tons of CO_2 (Fig. 8a).

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Out of the 31 provinces, BJ has the most prominent reduction of emissions on weekends, accounting for 4.03% of the average daily emissions on weekdays. GZ meanwhile, has the lowest reduction of emissions on weekends, accounting for only 2.35% of average daily CO_2 emissions on weekdays. In the remaining provinces, the reduction of emissions over the weekend is equivalent to around 3% of average daily CO_2 emissions on weekdays (Fig. 8b).

The decreased emissions from the power, industry and ground transport sectors on weekends vary across provinces. However, for the provinces of XJ, SX, NX, SD, JS, AH, TJ, GS, SAX, and IM, we see that the main reduction in emissions comes from the power sector (Table 9), because the power sector is also the main contributor to those emissions generally (Fig. 6). For the provinces of Tibet, HUB, JX, HUN, YN, GZ, FJ, GX, HAN, CQ and SC, the industrial sector is also both the main driver of CO_2 emissions and the sector with the highest reductions on weekends. For China's northeast region, GD, ZJ, HEN, HEB, as well as for BJ and SH, the reduction of CO_2 emissions on weekends mainly comes down to ground contribution sector, which, especially in BJ and SH, is responsible for over 70% and nearly 50% of the emissions reduction on weekends, respectively.

3.5 The effect of holidays on CO_2 emissions

China has seven major holidays, including New Year, Spring Festival, Qingming Festival, Labour Day, Duanwu Festival, Mid-Autumn Festival and National Day. The dates and durations of the holidays we mentioned above in 2019 and 2020 are shown in Table 6. During the period of 2019-2020, the average daily emissions on holidays (dark blue lines in Fig. 9) can be seen to be less than average daily emissions on normal days (light blue lines in Fig. 9), which means that CO_2 emissions are reduced on holidays.

In 2019, compared to other holidays, the largest reduction in average daily CO_2 emissions was recorded during Spring Festival (Fig. 10a). The maximum reduction of average daily CO_2 emissions in that period reached 375.08 thousand tons of CO_2 in JS province, while the minimum reduction of average daily CO_2 emissions in that period reached 5.5 thousand tons of CO_2 in Tibet. Considering the durations of China's national holidays (Table 6), the cumulative reduction of CO_2 emissions on Spring Festival are the largest compared to other holidays (Fig. 10c). During the 2019 Spring Festival, the cumulative reduction of CO_2 emissions reached 30075.89 thousand tons, which is equivalent to 0.33% of the total national emissions in 2019. The cumulative holidays in China during the year 2019 resulted in a total reduction of 67450.21 thousand tons of CO_2, which represents 0.75% of China's annual emissions. Between them, the provinces of JS and SD had a total reduction of more than 5000 thousand tons of CO_2 during these holidays in 2019, thereby contributing 15.87% of the total reductions in that period.

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Open Access Earth System Science Data Discussions

In 2020, the joint Mid-Autumn Festival and National Day holidays led to an 8-day holiday whose impacts on CO_2 emissions exceeded that of the Spring Festival (Fig. 10b). The possible reason for this is that CO_2 emissions on normal days had been reduced due to the COVID-19 pandemic, and thus 2020's Spring Festival, which fell during the COVID-19 pandemic, had a less impressive reduction rate. However, by October 2020, China's daily emissions had already recovered from the COVID-19 pandemic and exceeded the level for the same period of 2019. Thus, compared to the Spring Festival period, average daily emissions were able to show a greater reduction compared to normal days when reaching the joint holidays of Mid-Autumn and National Day. Average daily emissions did show their second largest reduction during Spring Festival however. The impact of the other four holidays on average daily emissions meanwhile, these being New Year, Qingming Festival, Labour Day and Duanwu Festival, are less than the combined reduction from the joint Mid-Autumn Festival and National Day, and Spring Festival.

During the joint holidays of the Mid-Autumn Festival and National Day, the reduction of average daily emissions in JS, SD and GD provinces exceeded 400 thousand tons of CO_2 (Fig. 11b); for the 18 provinces of AH, ZJ, HN, IM, HUB, HEB, SC, GZ, SX, FJ, SAX, HUN, XJ, YN, JX, CQ and LN, it ranged from 100 to 310 thousand tons of CO_2; and for the remaining provinces of NX, GS, SH, HLJ, TJ, JL, BJ, HAN, QH and Tibet, it was between 18 and 92 thousand tons of CO_2. During the period of the joint holidays of Mid-Autumn Festival and National Day (8 days, Table 6), the cumulative reduction of CO2 emissions at a national level reached 44447.45 thousand tons of CO2, which is close to 0.5% of the national emissions for 2020. The total reduction of CO2 emissions over the 7 holidays was 91350.96 thousand tons of CO2, which is equivalent to 1.01% of national annual emissions. The provinces of SD, JS and GD contribute the highest reduction of emissions during holiday periods, accounting for 8.90%, 7.43% and 7.53% respectively, of China's total reduction of emissions on holidays.

4. Comparison with CEADs dataset

Although the time range of the CEADs (Carbon Emission Accounts & Datasets, https://www.CEADs.net.cn/) dataset and this study do not match up, the proportion of provincial emissions changed little in those two years. The most recent available data in the CEADs inventory is for the year 2018, and thus this was used for comparison with the sectoral provincial data in this study for the year 2019. In addition, our inventory estimates CO_2 emissions in Tibet, while the CEADs dataset does not include them. In order to carry out a comparison with the CEADs's provincial contributions, this inventory only considers the provincial contributions from 30 provinces (which excludes Tibet). Fig. 11 shows the provincial contribution differences between the inventories from the CEADs and those from this study for the power, industry and ground transportation sectors.

When studying the power sector, the provincial emission contributions shown in the CEADs dataset and those in this study show similar values. For the power sector, the provincial emissions in this study (Fig. 11d) are also consistent with those in the CEADs (Figs. 11a and

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

11d). The top 10 CO_2 emission contributors are the provinces of SD, IM, JS, GD, SX, HEB, XJ, HEN, ZJ and AH, both in the CEADs dataset and in this inventory. For the industry sector (Figs.11b and 11e), a large difference in the emissions contribution rate can be seen for HEB province between the CEADs dataset and this study. The CEADs inventory states that HEB province accounts for nearly 15% of the national CO_2 emissions coming from the power sector, while our inventory considers it to be only 4.34%. HEB province is the largest emissions emitter in the CEADs dataset, while our inventory ranks it as the 13^{th}. This difference may be due to the fact that emissions from cement production processes are not the main emissions driver in HEB's industry sector. Regarding ground transportation, according to the CEADs dataset, SH contributes around 7%, while this inventory states that it only contributes 1.70%. However, the contribution ratio for the provinces of SD, JS, ZJ, HEN and HEB, were higher in this inventory than in CEADs's estimates.

The likeliest cause for the discrepancies of sectoral provincial contributions between the CEADs dataset and this study, is the method used in each inventory. The CEADs calculates provincial emissions based on energy consumption during sectoral processes. However, it is difficult to estimate daily emissions based on energy-related methods due to a lack of daily energy consumption data. To calculate the provincial weight factor, estimate the daily provincial weight factors and improve the time precision of the emission inventory to a daily level, this inventory uses high temporal resolution alternative indicators, such as thermal power generation for the power sector, cement production for the industry sector and vehicle ownership for ground transportation. However, some uncertainties will still be introduced due to the poor consistencies between alternative indicators and actual emission processes in some provinces.

5. Source of uncertainty

The uncertainties in this inventory come from two sources: the uncertainties of near-real national CO_2 emissions from the *Carbon Monitor*, and the uncertainties from the estimates of each provincial weight factor. The uncertainties of near-real national CO_2 emissions from the Carbon Monitor have been discussed in detail in (Liu et al, 2020a, b). The uncertainties from the emissions from the power and industry sectors come from monthly statistical data of thermal power generation and cement production. Uncertainties from the monthly statistics were derived from 10,000 Monte Carlo simulations carried out to estimate a 68% confidence interval (1 sigma) for provincial thermal power generation and cement production in China. The uncertainties of the ground transportation sector mainly come from the inter-annual variability of provincial vehicle ownership, which are based on the estimates in the annual data of vehicle ownership from the China Bureau of Statistics within (±2.3%).

6. Conclusions

Estimating China's provincial CO_2 emissions is fraught with problems, such as data availability and the time lag of one or more years in the data itself. In the context of a

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Open Access Earth System Science Data Discussions

sustained COVID-19 pandemic and China's commitment to achieve its peak carbon emissions before 2030 and then drop to carbon neutrality before 2060, annual provincial emission inventories have become untenable. The provincial daily CO_2 emissions dataset presented here increases the temporal resolution of the emissions inventory and estimates the daily CO_2 emissions from the power, industry and ground transportation sectors in 31 provinces of mainland China. This study also notably includes the CO_2 emission estimates for Tibet for the first time; something which was not done previously due to the lack of available energy-related statistic data. This dataset adds the two attributes of the "week" and "holiday" to provincial daily emission, which can be used to analyse the impact of weekends and holidays on China's CO_2 emissions.

The provincial emissions based on the estimates in this inventory are in good agreement with those in the *CEADs* dataset. However, this inventory improves the temporal resolution to a daily level compared to only annual emissions estimates provided in the *CEADs* dataset. This dataset will be near-real time updated (may be one month behind the actual time). However, more work is still required in order to improve the provincial daily CO2 emission estimates from the lower emitting sectors, such as the residential, aviation and shipping sectors.

7. Data available

The national daily CO_2 emissions from Carbon Monitor, provincial weight factor from China Bureau of Statistics, provincial daily CO2 emissions in 31 provinces of mainland China from 2019 to 2020, and Yearly comparison results of CEADs and This inventory can be accessed at https://doi.org/10.5281/zenodo.4730175 (Cui et al., 2021).

Competing interests

The author declares that they have no conflict of interest.

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Figures

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Open Access Earth System Science Data Discussions

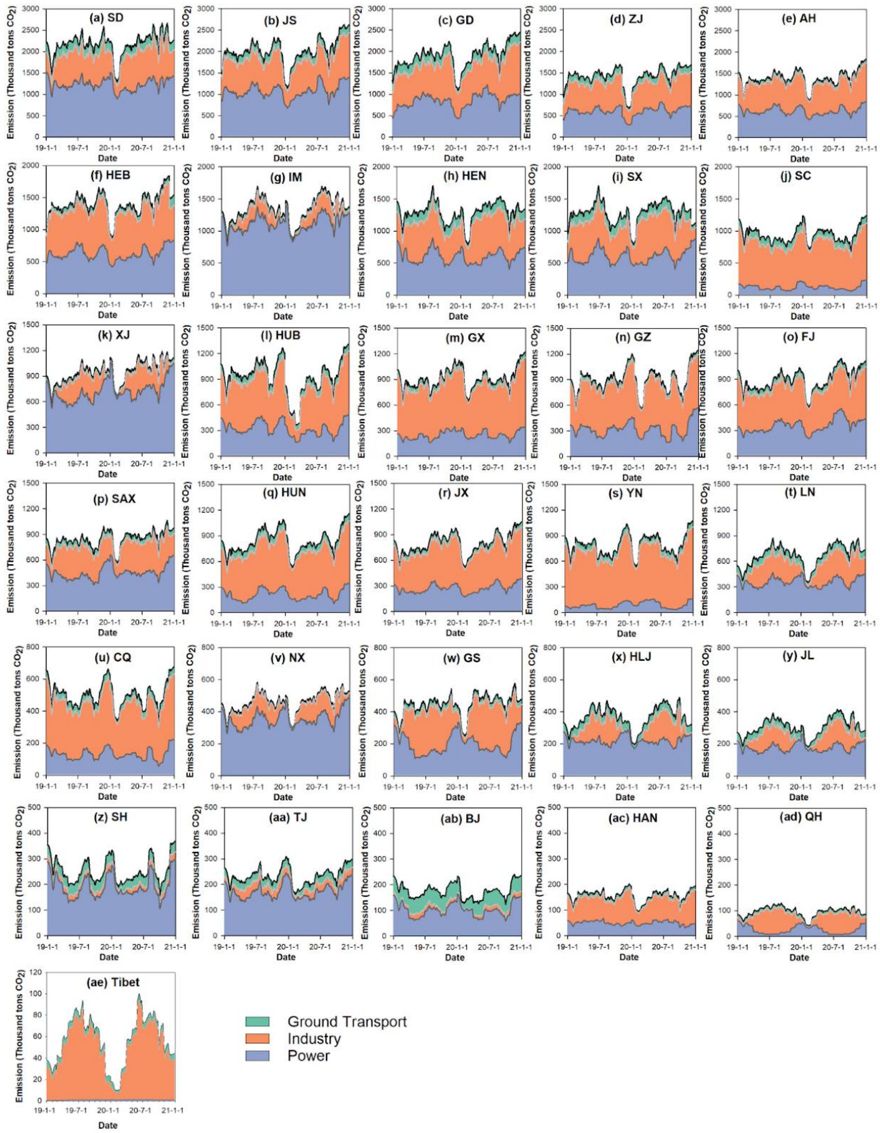

Figure 1. Total daily CO_2 emissions from the Chinese mainland's 31 provinces from 2019 to 2020. Total emissions cover 3 sectors: electricity (green), industry (orange) and ground transport (blue). SD, JS, GD, ZJ, AH, HEB, IM, HEN, SX, SC, XJ, HUB, GX, GZ, FJ, SAX, HUN, JX, YN, LN, CQ, NX, GS, HLJ, JL, SH, TJ, BJ, HAN, QH and Tibet are abbreviations of the names of the 31 provinces. The full names corresponding to these abbreviations are shown in Table S1.

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

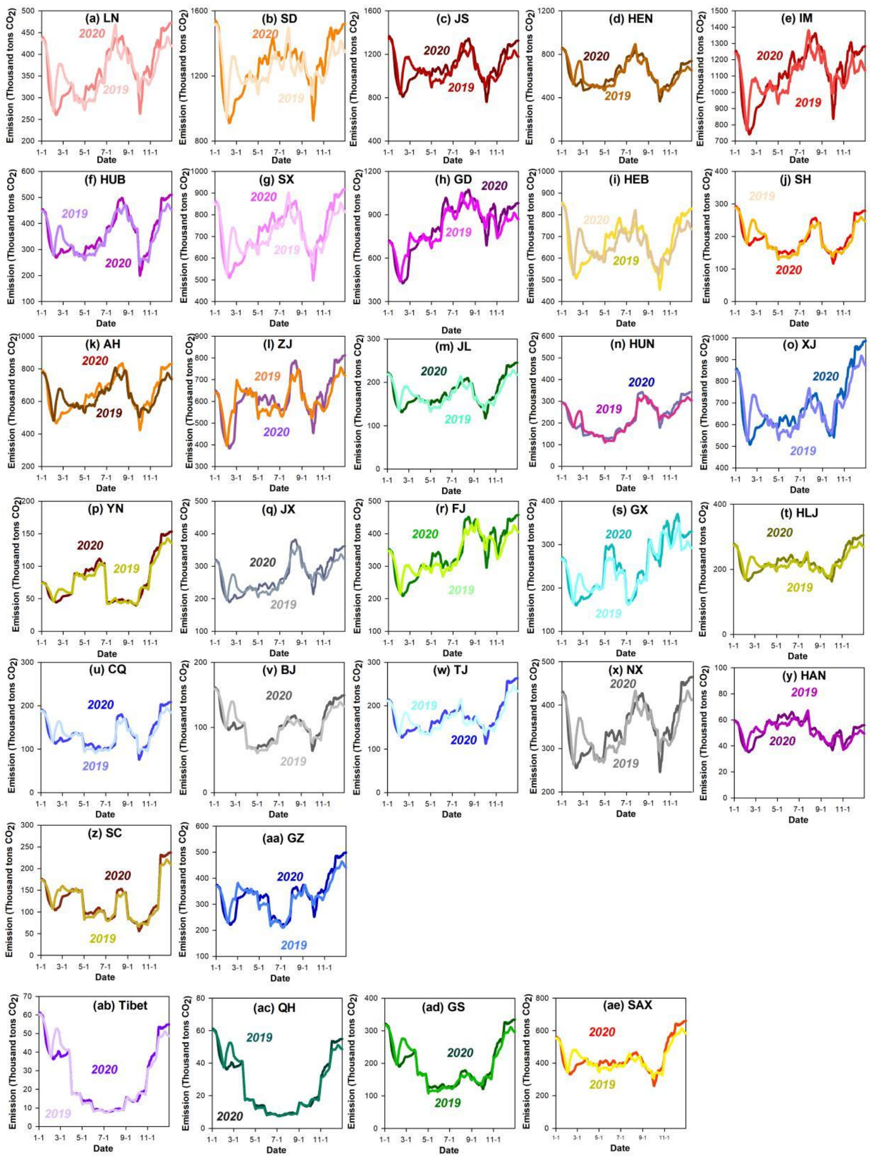

Figure 2. Daily CO_2 emissions from the power sector in China's 31 provinces from 2019 to 2020. LN, SD, JS, HN, IM, HUB, SX, HLJ, HEB, GX, AH, ZJ, GD, HUN, YN, JL, JX, FJ, NX, XJ, CQ, BJ, TJ, SH, HAN, Tibet, QH, SAX, GS, SC and GZ are abbreviations for the names of these 31 provinces. The full names corresponding to these abbreviations are shown in Table 1.

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

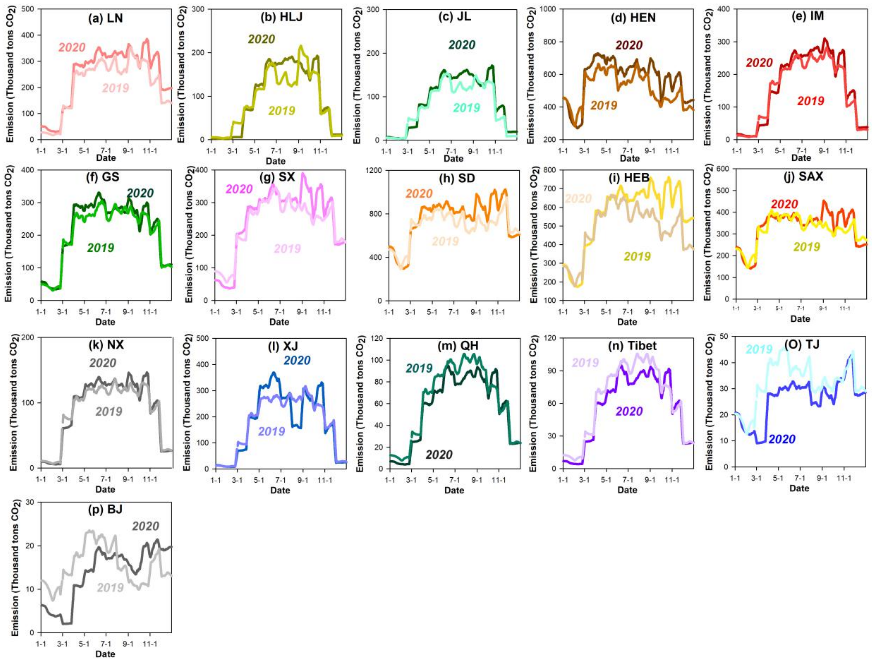

Figure 3. Daily CO_2 emissions from the industry sector in 16 of China's provinces from 2019 to 2020. LN, HLJ, JL, HEN, IM, GS, SX, SD, HEB, SAX, NX, XJ, QH, Tibet, TJ, and BJ are abbreviations of the names of 16 provinces in northern China. The full names corresponding to these abbreviations are shown in Table 1.

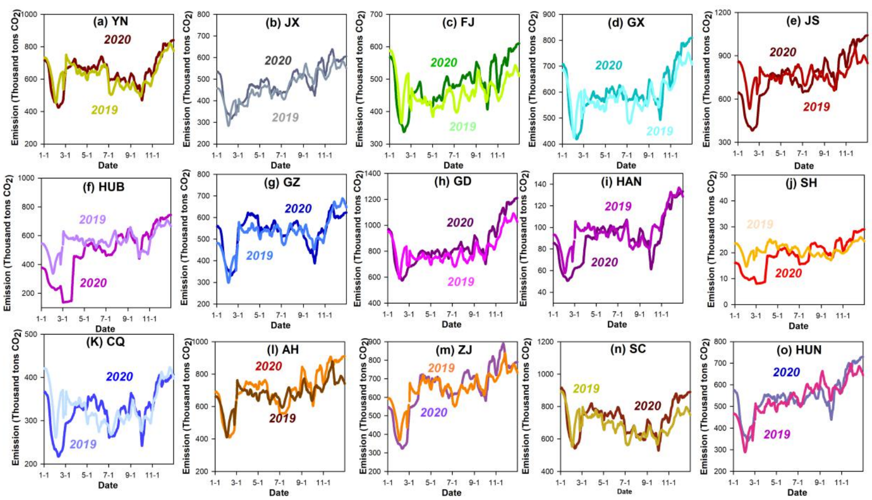

Figure 4. Daily CO_2 emissions from the industry sector in 15 of China's provinces from 2019 to 2020. YN, JX, FJ, GX, JS, HUB, GZ, GD, HAN, SH, CQ, AH, ZJ, SC, and HUN are

abbreviations of the names of these 15 provinces in southern China. The full names corresponding to these abbreviations are shown in Table 1.

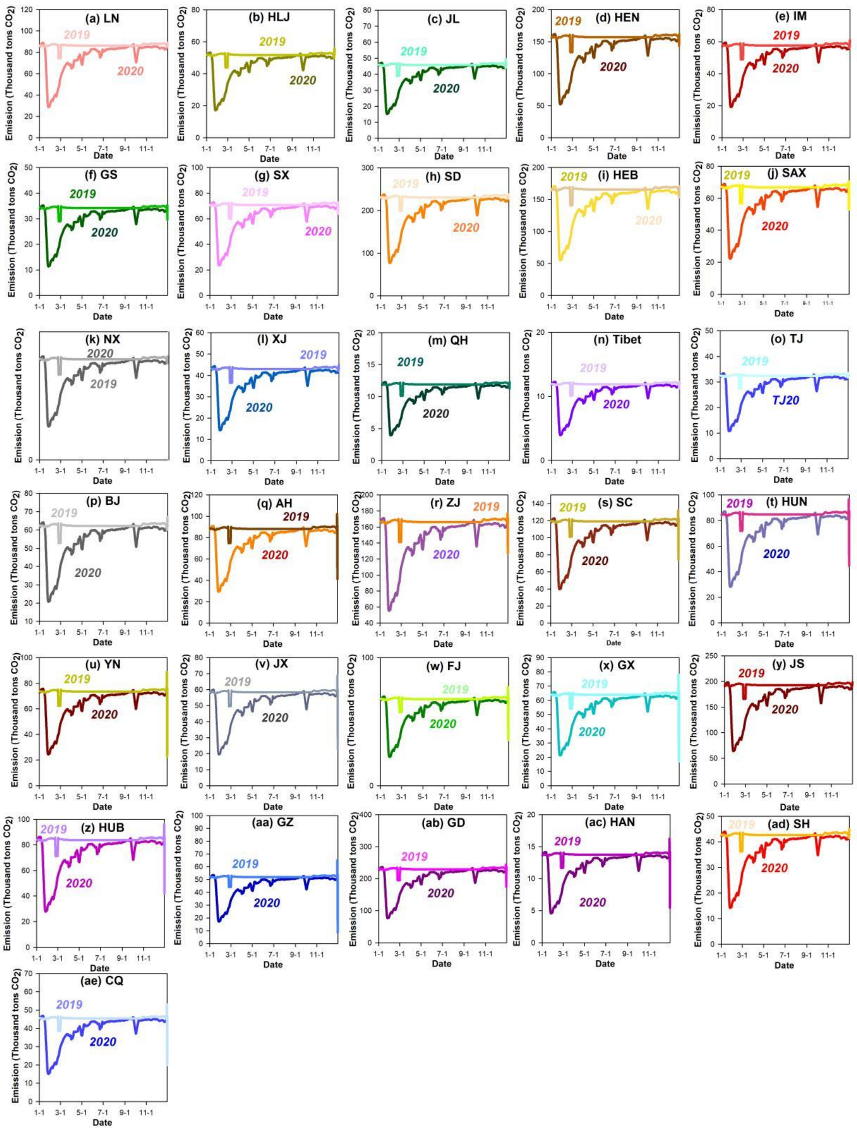

Figure 5. Daily CO_2 emissions from the ground transportation sector in China's 31 provinces from 2019 to 2020. YN, JX, FJ, GX, JS, HUB, GZ, GD, HAN, SH, CQ, AH, ZJ, SC, and HUN are abbreviations of the names of these 31 provinces in southern China. The full names corresponding to these abbreviations are shown in Table S1.

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Open Access Earth System Science Data Discussions

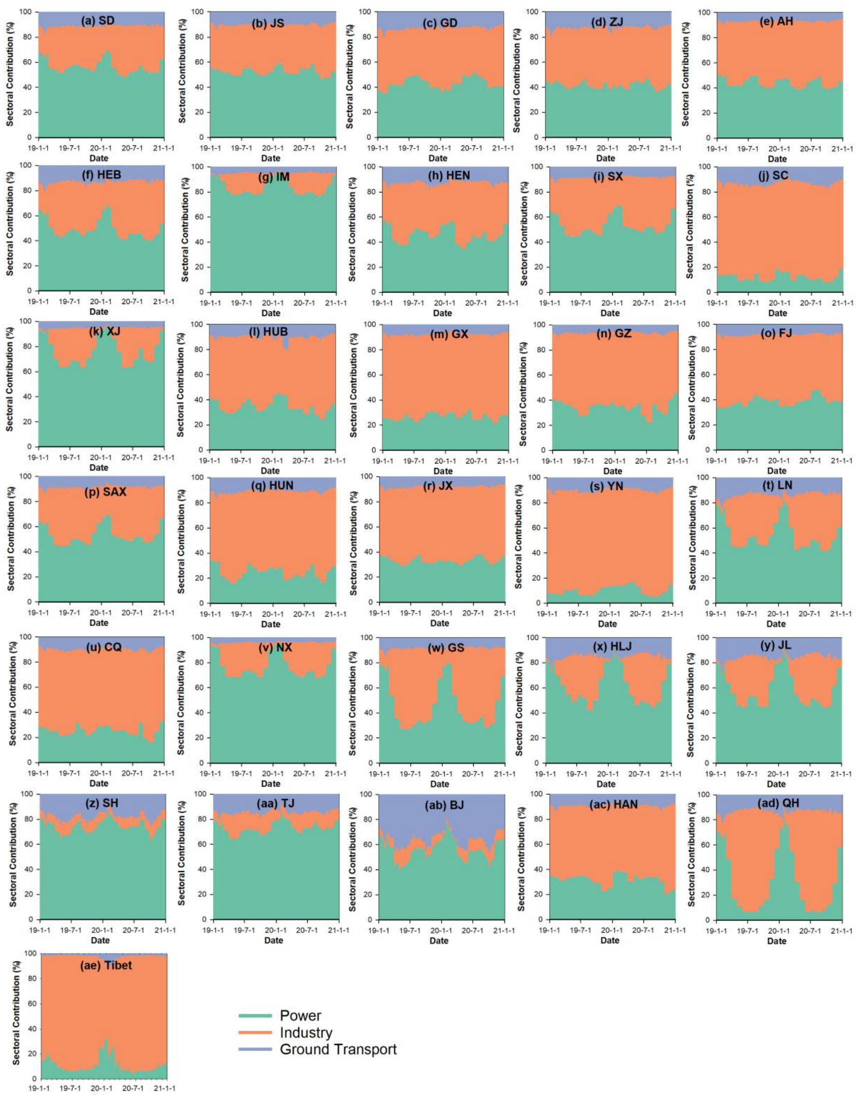

Figure 6. sectoral contribution to provincial daily CO_2 emissions in 31 provinces in China. Green, orange and blue refer to the power, industry and ground transport sectors, respectively. SD, JS, GD, ZJ, AH, HEB, IM, HEN, SX, SC, XJ, HUB, GX, GZ, FJ, SAX, HUN, JX, YN, LN, CQ, NX, GS, HLJ, JL, SH, TJ, BJ, HAN, QH and Tibet are abbreviations for the names of these 31 provinces. The full names corresponding to these abbreviations are shown in Table 1.

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Preprint. Discussion started: 21 May 2021

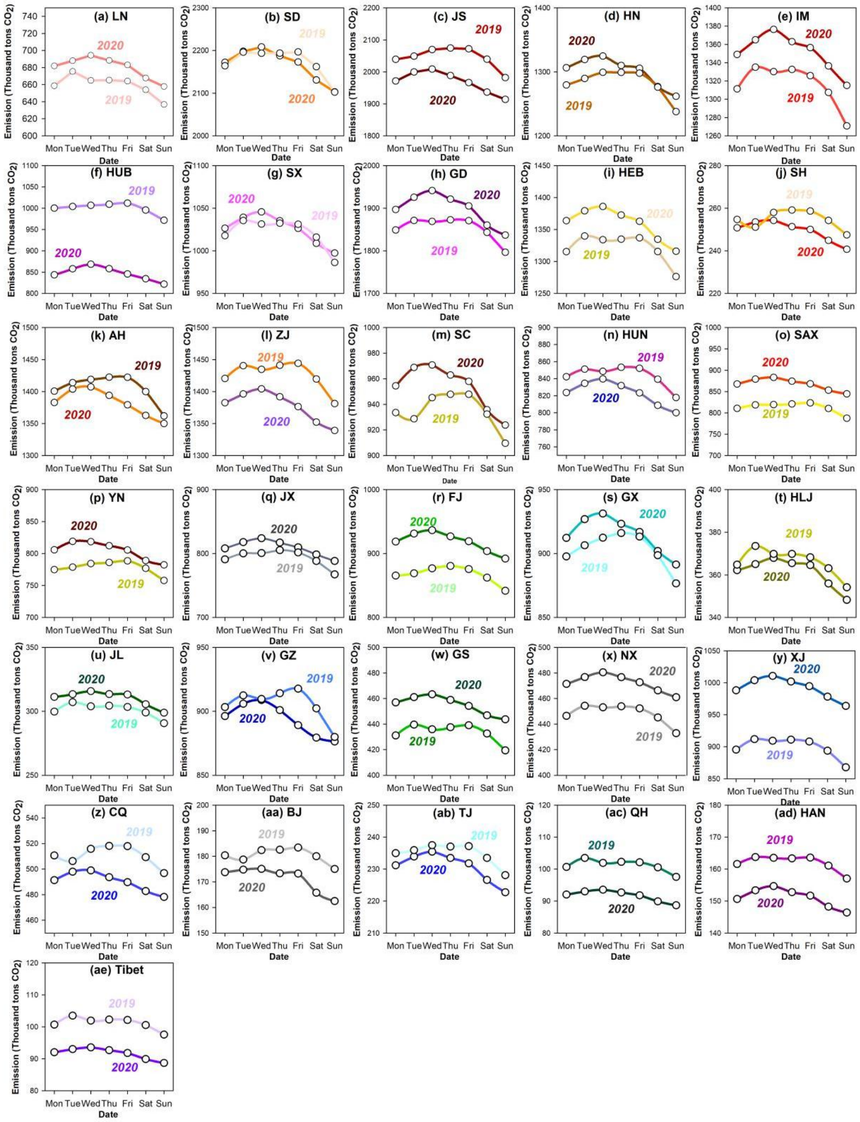

Figure 7. Average daily CO_2 emissions from Monday to Sunday. SD, JS, GD, ZJ, AH, HEB, IM, HEN, SX, SC, XJ, HUB, GX, GZ, FJ, SAX, HUN, JX, YN, LN, CQ, NX, GS, HLJ, JL, SH, TJ, BJ, HAN, QH and Tibet are abbreviations of the names of 31 Chinese provinces. The full names corresponding to these abbreviations are shown in Table 1.

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

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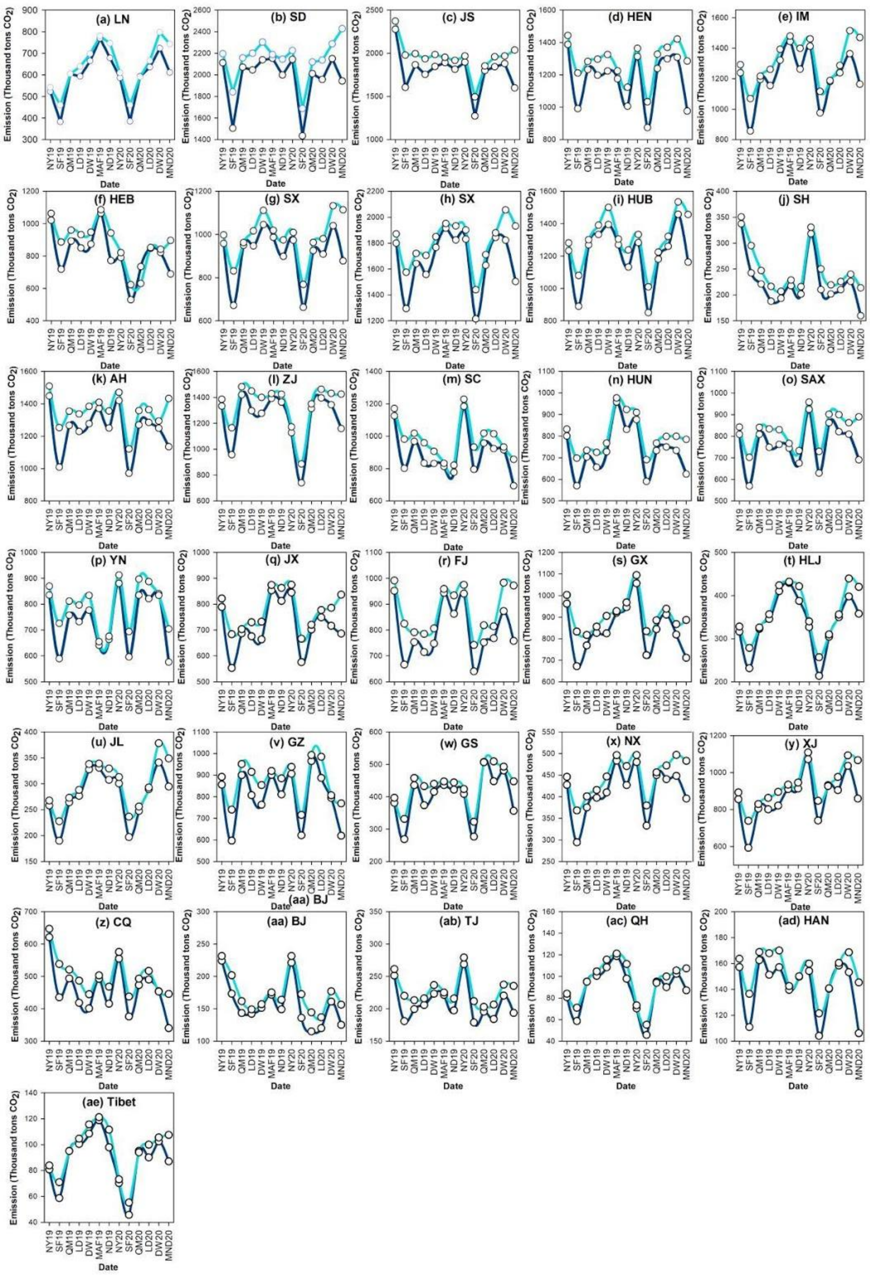

Figure 9. Average daily CO2 emissions in 31 provinces during holiday periods. Dark blue lines represent the average daily emissions on holidays, while light blue lines represent the average daily emissions for the periods of 15 days both before and after these holidays. SD, JS, GD, ZJ, AH, HEB, IM, HEN, SX, SC, XJ, HUB, GX, GZ, FJ, SAX, HUN, JX, YN, LN,

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

CQ, NX, GS, HLJ, JL, SH, TJ, BJ, HAN, QH and Tibet are all abbreviations of the names of these 31 Chinese provinces. The full names corresponding to these abbreviations are shown in Table S1. NY, SF, QM, LD, DW, MAF, and ND represent the Chinese holidays of New Year, Spring Festival, Qingming, Labour Day, Duanwu, Mid-autumn Festival and National Day, respectively. 19 and 20 refer to 2019 and 2020. MND20 stands for the joining of Mid-Autumn Festival and National Day in 2020.

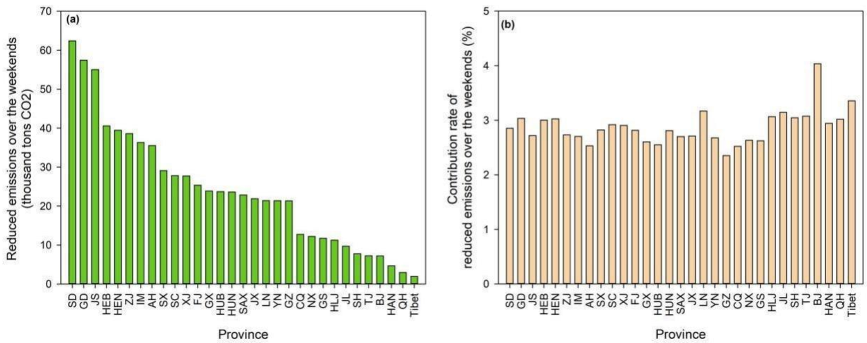

Figure 8. Reduced emissions over the weekends (a), and contribution rate of reduced emissions over the weekends (b). SD, JS, GD, ZJ, AH, HEB, IM, HEN, SX, SC, XJ, HUB, GX, GZ, FJ, SAX, HUN, JX, YN, LN, CQ, NX, GS, HLJ, JL, SH, TJ, BJ, HAN, QH and Tibet are abbreviations of the names of the 31 Chinese provinces. The full names corresponding to these abbreviations are shown in Table 1.

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

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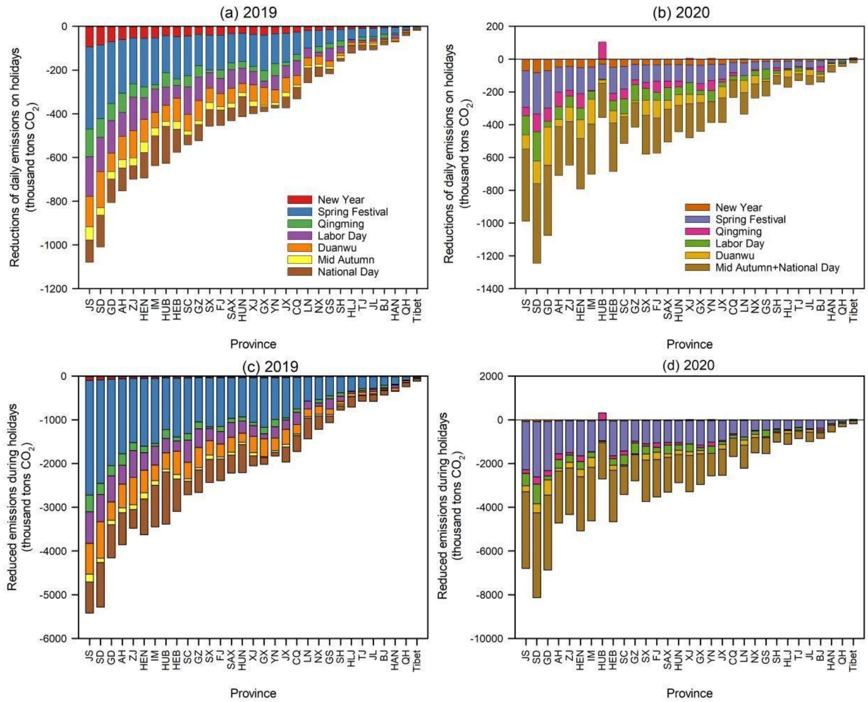
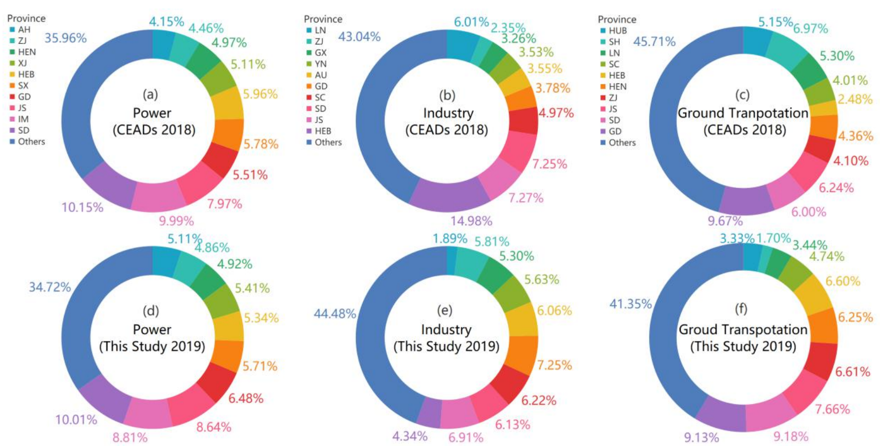


Figure 10. Reductions of daily emissions on holidays (a and b) and reduced emissions during holidays (c and d). SD, JS, GD, ZJ, AH, HEB, IM, HEN, SX, SC, XJ, HUB, GX, GZ, FJ, SAX, HUN, JX, YN, LN, CQ, NX, GS, HLJ, JL, SH, TJ, BJ, HAN, QH and Tibet are abbreviations of the names of the 31 Chinese provinces. The full names corresponding to these abbreviations are shown in Table S1. New Year, Spring Festival, Qingming Festival, Labour Day, Duanwu Festival, Mid-Autumn Festival and National Day refer to holidays in China.



https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Figure 11. Comparison of the provincial contributions to national emissions in this study to those reported by the CEADs dataset

Tables

Table 1. The abbreviation of provincial names in mainland China

Abbr	Full name	Abbr	Full name	Abbr	Full name
LN	Liaoning	IM	Inner Mongolia	HUB	Hubei
SD	Shandong	SH	Shanghai	NX	Ningxia
JS	Jiangsu	HAN	Hainan	XJ	Xinjiang
HN	Henan	FJ	Fujian	SX	Shanxi
CQ	Chongqing	GX	Guangxi	HLJ	Heilongjiang
BJ	Beijing	AH	Anhui	HEB	Hebei
TJ	Tianjin	ZJ	Zhejiang	GD	Guangdong
HUN	Hunan	YN	Yunnan	JL	Jilin
JX	Jiangxi	Tibet	Tibet	QH	Qinghai
SAX	Shaanxi	GS	Gansu	SC	Sichuan
GZ	Guizhou				

Table 2. National average daily emissions from the residential and aviation sectors for the years 2019 and 2020.

Year	Total	Residential		Aviation	
		Emissions (Mt CO2)	contribution rate (%)	Emissions (MtCO2)	contribution rate (%)
2019	28.66	0.17	0.60	2.20	7.69
2020	28.73	0.14	0.49	2.21	7.69

Table 3. Provincial monthly weight factor from the power sector in 2019 (a) and 2020 (b).

Province	(a) 2019 (%)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BJ	1.06	1.06	0.92	0.60	0.59	0.63	0.80	0.78	0.82	0.71	0.92	0.90
TJ	1.40	1.40	1.33	1.21	1.34	1.43	1.46	1.16	1.32	1.24	1.38	1.59
HEB	5.60	5.60	5.38	5.33	5.81	5.96	5.58	4.95	4.74	5.03	5.22	4.99
SX	5.63	5.63	5.34	5.82	6.08	6.14	6.13	5.70	5.39	5.51	5.67	5.53
IM	8.20	8.20	8.51	9.07	9.10	9.48	9.38	8.99	9.42	9.26	8.66	7.72
LN	2.87	2.87	2.86	2.59	2.67	2.78	3.18	2.92	3.02	2.91	2.87	2.85
JL	1.45	1.45	1.45	1.37	1.29	1.34	1.46	1.39	1.26	1.29	1.43	1.48
HLJ	1.82	1.82	1.78	1.87	1.91	1.85	1.72	1.45	1.52	1.80	1.90	1.83
SH	1.91	1.91	1.78	1.45	1.25	1.20	1.44	1.70	1.31	1.29	1.35	1.68
JS	8.93	8.93	9.09	9.07	8.72	8.37	8.85	8.87	8.34	8.41	8.27	7.99

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Open Access Earth System Science Data Discussions

ZJ	4.24	4.24	5.56	5.59	5.07	4.76	4.36	5.20	4.77	5.02	4.69	4.89
AH	5.15	5.15	4.94	5.00	5.24	5.40	5.49	5.50	4.88	4.69	4.74	5.01
FJ	2.30	2.30	2.35	2.61	2.78	2.40	2.49	2.98	3.34	3.27	2.72	2.75
JX	2.09	2.09	1.89	2.03	2.00	1.89	2.03	2.52	2.32	2.37	2.17	2.18
SD	10.06	10.06	9.92	10.44	10.70	10.86	10.17	9.01	10.10	10.24	9.92	9.16
HEN	5.61	5.61	4.42	4.40	4.62	5.28	6.07	5.33	4.76	4.07	4.24	4.44
HUB	2.97	2.97	2.71	2.46	2.55	2.62	3.02	3.29	3.22	2.22	2.73	3.07
HUN	1.93	1.93	1.34	1.24	1.07	1.33	1.55	2.26	2.29	1.97	1.97	2.06
GD	4.72	4.72	6.15	6.50	6.57	7.72	7.16	7.08	7.49	7.62	6.23	5.91
GX	1.76	1.76	1.64	1.77	2.42	1.95	1.33	1.58	2.34	2.77	2.45	1.99
HAN	0.39	0.39	0.44	0.51	0.52	0.50	0.46	0.36	0.35	0.41	0.31	0.34
CQ	1.25	1.25	1.11	1.18	0.91	0.81	0.80	1.19	1.11	0.84	1.08	1.26
SC	1.15	1.15	1.28	1.31	0.80	0.83	0.65	1.01	0.66	0.62	0.76	1.43
GZ	2.44	2.44	3.04	3.04	2.73	1.93	1.73	2.42	2.81	2.79	2.89	3.00
YN	0.49	0.49	0.51	0.76	0.78	0.85	0.35	0.32	0.35	0.57	0.85	0.92
Tibet	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
SAX	3.66	3.66	3.69	3.45	3.37	3.16	3.11	3.08	2.99	2.87	3.88	3.97
GS	2.10	2.10	2.07	1.46	1.05	1.03	1.00	1.18	1.18	1.34	1.82	2.01
QH	0.40	0.40	0.35	0.15	0.11	0.07	0.06	0.06	0.12	0.15	0.26	0.33
NX	2.82	2.81	2.67	2.42	2.76	2.59	2.95	2.82	2.91	2.72	2.64	2.80
XJ	5.61	5.61	5.50	5.29	5.17	4.83	5.22	4.91	4.83	5.99	5.97	5.93
Province	(b) 2020 (%)											
	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BJ	1.07	1.07	0.93	0.62	0.55	0.80	0.76	0.71	0.68	0.64	1.04	0.93
TJ	1.49	1.50	1.34	1.35	1.18	1.39	1.34	1.35	1.39	1.55	1.47	1.43
HEB	5.80	5.80	5.16	4.78	4.74	5.76	5.24	4.94	5.03	5.23	5.15	5.03
SX	5.79	5.79	5.73	5.50	5.08	5.60	6.05	5.32	5.85	6.15	5.88	5.27
IM	9.17	9.17	8.74	9.09	8.75	9.04	9.93	8.90	9.47	10.03	8.66	7.76
LN	3.12	3.12	2.78	2.40	2.63	2.84	3.26	2.77	2.51	2.87	2.97	2.71
JL	1.72	1.72	1.46	1.29	1.28	1.35	1.59	1.36	1.24	1.46	1.40	1.32
HLJ	1.88	1.88	2.01	1.87	1.73	1.60	1.77	1.52	1.47	1.93	1.72	1.56
SH	1.80	1.79	1.52	1.44	1.41	1.47	1.35	1.82	1.38	1.16	1.34	1.80
JS	7.52	7.52	8.01	8.54	8.56	8.90	8.03	9.58	8.95	8.34	7.58	8.42
ZJ	3.07	3.07	4.67	4.78	5.58	5.27	4.79	5.45	4.86	4.73	4.60	4.40
AH	4.62	4.62	5.03	4.57	4.68	4.82	4.43	5.17	4.90	4.92	4.71	5.07
FJ	2.27	2.27	2.64	2.68	2.75	3.06	3.90	3.69	3.54	3.16	2.83	2.63
JX	1.90	1.90	1.91	1.94	2.20	2.13	2.40	2.52	2.29	2.28	2.29	2.33
SD	9.91	9.91	10.15	9.50	8.68	9.65	9.29	9.25	10.81	11.14	9.37	8.64
HEN	4.99	4.99	4.49	4.11	4.77	5.10	4.91	4.99	4.68	4.49	4.48	4.49
HUB	2.41	2.40	1.54	2.27	2.54	2.34	1.75	2.50	2.20	1.89	2.50	2.93
HUN	1.69	1.69	1.24	1.40	1.59	1.35	1.65	1.98	1.40	1.19	1.87	2.08
GD	4.71	4.71	6.30	6.61	8.34	7.68	8.89	6.84	7.66	6.59	6.46	6.09
GX	2.19	2.19	2.00	2.25	2.67	1.73	1.64	1.80	1.92	1.73	2.10	2.10
HAN	0.41	0.41	0.43	0.40	0.50	0.43	0.47	0.35	0.46	0.36	0.25	0.28

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

CQ	1.11	1.11	1.06	1.14	1.15	0.90	0.69	1.18	0.76	0.62	1.03	1.35
SC	1.34	1.34	0.88	1.27	1.21	0.89	0.69	0.68	0.63	0.65	0.92	1.42
GZ	2.20	2.20	2.72	3.12	3.01	1.90	1.30	2.49	2.04	1.99	3.28	3.44
YN	0.86	0.86	1.16	1.29	1.28	0.99	0.43	0.30	0.32	0.43	0.61	0.98
Tibet	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
SAX	4.33	4.33	4.09	4.12	3.71	3.37	3.44	3.20	3.64	3.69	3.87	3.95
GS	2.20	2.20	2.19	1.87	1.36	1.32	1.18	1.26	1.08	1.23	1.94	2.02
QH	0.36	0.36	0.40	0.27	0.13	0.06	0.06	0.05	0.08	0.13	0.21	0.31
NX	3.12	3.12	3.07	3.03	2.76	2.61	2.93	2.72	2.66	3.03	3.02	2.94
XJ	6.95	6.95	6.37	6.47	5.15	5.64	5.82	5.31	6.08	6.39	6.43	6.32

Table 4. Provincial monthly weight factor from the industry sector in 2019 (a) and 2020 (b).

Province	(a) 2019 (%)											
	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BJ	0.12	0.12	0.13	0.15	0.19	0.18	0.17	0.13	0.09	0.09	0.14	0.11
TJ	0.20	0.20	0.27	0.34	0.37	0.30	0.33	0.25	0.26	0.28	0.32	0.25
HEB	2.80	2.80	4.05	4.79	5.38	5.16	4.93	4.87	4.57	3.92	4.30	3.29
SX	0.88	0.88	1.76	2.30	2.49	2.73	2.56	2.46	2.30	2.17	2.21	1.57
IM	0.13	0.13	0.63	1.47	1.77	2.05	2.06	2.14	2.17	1.90	0.90	0.27
LN	0.27	0.27	1.14	2.17	2.20	2.45	2.49	2.24	2.73	2.57	1.82	1.23
JL	0.06	0.06	0.44	0.64	0.93	1.21	1.04	1.02	1.14	1.13	0.40	0.08
HLJ	0.06	0.06	0.36	0.64	0.95	1.39	1.21	1.10	1.66	1.31	0.52	0.08
SH	0.23	0.23	0.19	0.21	0.19	0.18	0.17	0.17	0.15	0.18	0.17	0.21
JS	8.43	8.43	7.20	6.33	6.34	6.62	6.52	6.57	5.96	6.61	6.99	7.44
ZJ	5.84	5.84	5.89	5.90	5.70	5.28	5.20	5.57	5.57	6.06	6.13	6.43
AH	6.50	6.50	6.64	5.79	5.66	5.36	5.60	5.70	5.95	6.08	6.42	6.50
FJ	5.77	5.77	4.11	3.66	3.39	3.74	3.75	3.87	4.06	4.09	3.80	4.47
JX	4.49	4.49	3.56	3.71	3.82	3.57	3.83	4.34	4.41	4.62	4.37	4.82
SD	4.64	4.64	6.59	6.50	6.87	6.46	6.41	5.55	6.07	6.14	6.95	5.49
HEN	4.48	4.48	5.36	5.45	5.30	4.38	5.19	5.04	3.82	3.80	3.82	3.35
HUB	5.34	5.34	5.49	4.92	4.67	4.51	4.94	4.79	5.07	4.15	5.07	5.83
HUN	4.57	4.57	4.47	4.39	4.22	4.45	4.70	5.02	5.11	4.94	5.09	5.65
GD	9.33	9.33	6.99	6.46	6.16	6.21	6.42	6.33	6.73	7.15	7.74	8.99
GX	6.72	6.72	5.31	4.65	4.76	4.90	4.52	4.72	4.92	5.40	5.37	6.20
HAN	0.91	0.91	0.92	0.85	0.78	0.79	0.83	0.71	0.71	0.85	0.97	1.13
CQ	4.13	4.13	3.20	2.90	2.57	2.39	2.52	2.61	2.68	2.58	3.01	3.49
SC	8.76	8.76	6.94	6.40	5.77	5.56	5.30	5.30	5.26	5.47	5.76	6.57
GZ	4.73	4.73	5.04	4.71	4.41	4.47	4.46	4.64	4.37	4.24	4.90	5.67
YN	7.18	7.18	6.54	5.43	5.29	5.46	4.75	4.77	4.48	4.90	5.45	6.78
Tibet	0.31	0.31	0.32	0.45	0.56	0.64	0.68	0.53	0.57	0.52	0.35	0.14
SAX	2.28	2.28	2.92	3.35	3.17	3.13	2.99	2.97	2.72	2.76	2.68	2.37
GS	0.49	0.49	1.63	2.21	2.14	2.40	2.30	2.38	2.22	2.25	1.79	0.90

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Open Access Earth System Science Data Discussions

QH	0.12	0.12	0.30	0.60	0.70	0.79	0.82	0.87	0.79	0.64	0.45	0.21
NX	0.11	0.11	0.71	0.90	0.99	1.00	1.06	1.03	1.01	1.09	0.75	0.24
XJ	0.13	0.13	0.90	1.76	2.24	2.23	2.25	2.30	2.44	2.07	1.36	0.25
Province	(b) 2020 (%)											
	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BJ	0.06	0.06	0.02	0.09	0.11	0.15	0.15	0.14	0.11	0.14	0.15	0.15
TJ	0.21	0.21	0.09	0.23	0.24	0.25	0.26	0.19	0.22	0.24	0.29	0.22
HEB	2.92	2.92	4.09	4.75	5.13	5.40	5.42	5.45	5.44	5.32	5.06	4.19
SX	0.63	0.63	2.11	2.35	2.42	2.69	2.60	2.46	2.80	2.49	2.16	1.38
IM	0.17	0.17	0.45	1.20	1.79	2.06	2.19	2.23	2.22	1.92	1.03	0.29
LN	0.51	0.51	1.25	2.36	2.34	2.67	2.71	2.64	2.62	2.69	2.30	1.53
JL	0.07	0.07	0.30	0.67	0.94	1.21	1.22	1.26	1.05	1.20	0.54	0.15
HLJ	0.03	0.03	0.06	0.57	0.99	1.40	1.49	1.49	1.28	1.35	0.51	0.09
SH	0.16	0.16	0.08	0.15	0.17	0.15	0.13	0.19	0.16	0.18	0.17	0.22
JS	6.42	6.42	6.46	6.33	6.26	5.64	5.56	6.30	6.35	6.58	6.93	8.05
ZJ	5.44	5.44	5.64	5.88	5.48	4.93	5.27	5.84	5.12	5.74	6.09	6.11
AH	6.90	6.90	7.00	6.09	5.89	5.09	4.75	5.60	6.05	5.96	6.21	7.04
FJ	5.68	5.68	4.69	3.55	3.47	3.83	4.08	4.07	3.96	4.02	3.87	4.71
JX	5.33	5.33	3.98	3.87	3.89	3.51	3.74	4.26	3.78	4.18	4.37	4.68
SD	4.98	4.98	6.87	7.05	6.88	6.91	6.93	6.16	7.04	7.13	7.01	4.71
HEN	4.55	4.55	6.53	5.92	5.49	4.85	5.52	4.99	5.00	4.24	4.19	3.42
HUB	3.76	3.76	1.43	3.72	4.25	4.01	3.97	4.77	4.63	4.35	4.87	5.75
HUN	5.73	5.73	5.09	4.51	4.32	4.25	4.36	4.48	4.24	4.34	4.79	5.64
GD	9.66	9.66	7.07	6.53	6.26	6.14	6.95	6.49	6.60	6.92	7.76	9.35
GX	7.05	7.05	5.65	4.76	4.79	4.72	4.86	4.59	4.64	4.87	5.16	6.25
HAN	0.85	0.85	0.65	0.75	0.78	0.77	0.85	0.70	0.71	0.61	0.83	1.03
CQ	3.65	3.65	3.05	2.74	2.78	2.61	2.25	2.61	2.61	2.39	2.78	3.15
SC	9.13	9.13	7.76	6.39	5.93	6.01	5.43	4.96	5.16	5.23	6.02	6.88
GZ	5.58	5.58	5.75	5.03	4.32	4.42	4.38	4.57	3.67	3.83	4.50	4.81
YN	7.15	7.15	6.89	5.55	5.28	5.58	5.09	4.75	4.55	4.64	5.25	6.50
Tibet	0.11	0.11	0.26	0.42	0.48	0.71	0.57	0.60	0.56	0.46	0.32	0.30
SAX	2.38	2.38	3.43	3.13	3.00	2.99	2.89	2.92	3.25	2.90	2.82	1.95
GS	0.58	0.58	1.73	2.40	2.29	2.50	2.29	2.25	2.25	2.10	1.71	0.85
QH	0.07	0.07	0.26	0.49	0.56	0.72	0.66	0.71	0.67	0.64	0.43	0.19
NX	0.10	0.10	0.63	0.90	1.00	1.05	1.09	1.01	1.05	1.02	0.71	0.21
XJ	0.14	0.14	0.72	1.62	2.49	2.79	2.32	1.32	2.20	2.31	1.17	0.20

Table 5. Provincial weight factor from the industry sector. WF represents weight factor.

Province	WF (%)	Province	WF (%)	Province	WF (%)
BJ	2.47	ZJ	6.60	HAN	0.55
TJ	1.29	AH	3.50	CQ	1.80
HEB	6.59	FJ	2.68	SC	4.73
SX	2.81	JX	2.31	GZ	2.06

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

IM	2.29	SD	9.16	YN	2.92
LN	3.43	GZ	6.24	Tibet	0.22
JL	1.82	HUB	3.32	SAX	2.66
HLJ	2.06	HUN	3.36	GS	1.36
SH	1.69	GD	9.11	QH	0.47
JS	7.65	GX	2.53	NX	0.62
XJ	1.71				

680

Table 6. The duration of holidays in 2019 and 2020.

	2019	2020
New Year	1 (1st Jan)	1 (1st Jan)
Spring Festival	7 (4th-10th Feb)	10 (24th Jan-2nd Feb)
Qingming Festival	3 (5th-7th Apr)	3 (4th-6th Apr)
Labor Day	4 (1st-4th May)	5 (1st-5th May)
Duanwu Festival	3 (6th-8th Jun)	3 (25th-27th Jun)
Mid-autumn Festival	3 (13th-15th Sep)	
National Day	7 (1st-7th Oct)	
Mid-autumn Festival+National Day		8 (1st-8th Oct)

684 **Table 7. The maximum and minimum average daily CO_2 emissions during a monthly period.** Max-value and Min-value (unit in thousand tons of CO_2) represent the maximum and minimum average daily CO_2 emissions from January to December, respectively. Max-month and Min-month represent the month of Max-value and Min-value, respectively.

Province	2019				2020			
	Max-value	Max-month	Min-value	Min-month	Max-value	Max-month	Min-value	Min-month
BJ	218.76	Jan	148.59	Apr	231.14	Dec	134.11	Apr
TJ	298.01	Dec	208.35	Oct	292.10	Dec	171.46	Feb
HEB	1504.43	Jun	1038.11	Feb	1563.70	Jun	816.01	Feb
SX	1179.77	July	795.24	Feb	1172.00	July	628.09	Feb
IM	1546.09	Aug	1021.28	Feb	1628.95	Aug	918.07	Feb
LN	796.29	July	442.85	Feb	833.84	July	371.05	Feb
JL	358.82	July	219.25	Feb	398.24	July	190.19	Feb
HLJ	442.15	Jun	267.98	Feb	460.07	July	206.40	Feb
SH	327.82	Jan	200.96	May	361.51	Dec	194.01	Oct
JS	2248.65	Dec	1895.21	Feb	2570.50	Dec	1214.57	Feb
ZJ	1644.01	Dec	1119.25	Feb	1675.47	Aug	712.81	Feb
AH	1590.19	Dec	1198.58	Feb	1797.30	Dec	918.42	Feb
FJ	998.65	Dec	775.03	May	1105.20	Aug	606.53	Feb
JX	944.01	Dec	654.71	Feb	1025.60	Dec	545.07	Feb
SD	2379.96	Nov	1766.90	Feb	2477.22	Sep	1370.22	Feb
HEN	1562.23	July	1062.25	Dec	1493.97	Aug	836.75	Feb

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

HUB	1220.24	Dec	817.10	Dec	1282.58	Dec	374.27	Mar
HUN	1050.76	Dec	669.25	Feb	1132.73	Dec	561.96	Feb
GD	2157.74	Dec	1512.92	Feb	2392.54	Dec	1165.01	Feb
GX	1081.54	Dec	762.69	July	1192.86	Dec	683.77	Feb
HAN	195.21	Dec	130.85	Feb	189.20	Dec	98.96	Feb
CQ	639.08	Dec	432.79	Jun	661.45	Dec	357.05	Feb
SC	1097.89	Dec	818.46	July	1215.52	Dec	758.39	Feb
GZ	1158.96	Dec	707.93	Feb	1216.74	Dec	586.51	Feb
YN	1001.56	Dec	653.67	Sep	1050.60	Dec	566.12	Feb
Tibet	85.26	July	22.95	Dec	95.88	Jun	10.27	Feb
SAX	932.69	Dec	672.54	Feb	978.21	Nov	596.12	Feb
GS	491.43	Nov	317.21	Feb	534.28	Apr	262.71	Feb
QH	121.99	Aug	68.17	Feb	109.87	Jun	44.20	Feb
NX	529.20	July	351.58	Feb	536.81	Aug	312.74	Feb
XJ	995.69	July	705.71	Feb	1102.21	Jun	696.57	Feb

Table 8. The maximum and minimum daily CO2 emissions and the date of maximum and minimum daily CO2 emissions for the years 2019 and 2020.

Province	2019				2020			
	max	max-date	min	min-date	max	max-date	min	min-date
BJ	238.47	2nd Jan	136.50	1st May	259.44	25th Nov	108.19	4th Apr
TJ	311.88	23rd Dec	169.37	5th Feb	322.38	25th Nov	157.80	9th Feb
HEB	1644.33	26th Jul	833.74	5th Feb	1833.70	25th Nov	750.25	9th Feb
SX	1321.05	26th Jul	624.80	5th Feb	1390.64	25th Nov	579.48	13rd Feb
IM	1729.28	26th Jul	794.23	5th Feb	1760.15	30th Jul	846.90	13rd Feb
LN	887.56	26th Jul	359.50	5th Feb	947.89	25th Nov	340.47	9th Feb
JL	399.22	26th Jul	178.72	5th Feb	430.42	30th Jul	174.42	9th Feb
HLJ	481.52	9th Sep	217.43	5th Feb	513.57	22nd Jan	189.16	9th Feb
SH	362.96	2nd Jan	177.40	1st May	370.87	30th Dec	133.79	2nd Jan
JS	2462.56	29th Nov	1494.95	5th Feb	2638.44	30th Dec	1120.04	9th Feb
ZJ	1769.28	29th Nov	895.79	5th Feb	1906.72	25th Nov	654.05	9th Feb
AH	1739.33	29th Nov	937.18	5th Feb	1865.33	25th Nov	847.29	13rd Feb
FJ	1064.38	9th Sep	619.51	5th Feb	1189.15	17th Aug	559.58	13rd Feb
JX	1022.51	29th Nov	514.41	5th Feb	1138.33	25th Nov	502.87	13rd Feb
SD	2746.37	29th Nov	1406.35	5th Feb	2910.49	25th Nov	1262.75	9th Feb
HEN	1742.59	26th Jul	901.54	1st Oct	1604.27	17th Aug	770.12	9th Feb
HUB	1279.00	23rd Dec	669.19	5th Feb	1316.63	30th Dec	321.87	1st Mar
HUN	1124.05	29th Nov	532.01	5th Feb	1164.44	25th Nov	510.31	2nd Oct\
GD	2302.20	29th Nov	1212.04	5th Feb	2545.89	25th Nov	1071.58	9th Feb
GX	1216.50	29th Nov	624.59	5th Feb	1240.07	25th Nov	576.60	2nd Oct
HAN	204.60	23rd Dec	103.33	5th Feb	194.20	30th Dec	86.71	2nd Oct
CQ	670.97	2nd Jan	369.71	1st Oct	678.98	30th Dec	277.90	2nd Oct

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

Open Access Earth System Science Data Discussions

SC	1213.74	2nd Jan	695.89	1st Oct	1274.44	9th Oct	571.12	2nd Oct
GZ	1215.89	23rd Dec	553.49	5th Feb	1316.95	25th Nov	501.27	2nd Oct
YN	1049.60	23rd Dec	549.25	5th Feb	1078.43	30th Dec	470.26	2nd Oct
Tibet	95.43	26th Jul	21.42	1st Dec	101.86	15th Jun	9.23	9th Feb
SAX	1043.79	29th Nov	530.14	5th Feb	1160.70	25th Nov	549.98	13rd Feb
GS	569.14	29th Nov	250.69	5th Feb	630.91	25th Nov	242.39	13rd Feb
QH	133.49	9th Sep	55.00	5th Feb	125.07	22nd Oct	40.45	9th Feb
NX	594.27	26th Jul	272.39	5th Feb	629.72	25th Nov	288.48	13rd Feb
XJ	1143.20	29th Nov	549.59	5th Feb	1296.39	25th Nov	642.57	13rd Feb

Table 9. Reduced emissions over the weekend and sectoral contributions to reduced emissions over the weekend.

Province	**Emissions (thousand tons CO2)**			**Contribution rate (%)**		
	Power	**Industry**	**Transport**	**Power**	**Industry**	**Transport**
HLJ	5.38	1.85	6.09	40.39	13.92	45.69
XJ	19.57	4.57	5.06	67.02	15.66	17.33
SX	18.66	5.09	8.32	58.2	15.87	25.93
NX	9.06	1.88	1.85	70.87	14.69	14.44
Tibet	0.02	1.39	0.66	1.05	67.17	31.78
SD	30.81	14.8	27.14	42.35	20.35	37.3
HEN	15.67	13.07	18.49	33.19	27.67	39.14
JS	26.15	16.91	22.65	39.8	25.73	34.48
AH	15.03	14.72	10.38	37.44	36.68	25.87
HUB	7.37	11.13	9.85	25.99	39.26	34.74
ZJ	12.34	14	19.55	26.9	30.51	42.6
JX	6.74	10.95	6.85	27.46	44.6	27.93
HUN	4.99	12.39	9.96	18.26	45.31	36.43
YN	1.92	14.46	8.64	7.68	57.79	34.53
GZ	6.01	11.46	6.11	25.48	48.61	25.91
FJ	9.18	11.7	7.94	31.86	40.59	27.55
GX	5.45	14.25	7.5	20.02	52.39	27.59
GD	19.94	20.52	26.99	29.57	30.42	40.01
HAN	1.35	2.33	1.62	25.54	43.92	30.54
JL	4.44	1.67	5.38	38.63	14.51	46.86
LN	9.02	5.28	10.15	36.88	21.59	41.52
TJ	4.27	0.74	3.81	48.4	8.42	43.18
QH	0.6	1.39	1.4	17.77	40.95	41.27
GS	4.5	4.43	4.02	34.75	34.22	31.03
SAX	10.95	6.95	7.87	42.51	26.97	30.53
IM	28.1	3.67	6.78	72.89	9.52	17.59
CQ	2.8	7.46	5.34	17.94	47.8	34.26

https://doi.org/10.5194/essd-2021-153
Preprint. Discussion started: 21 May 2021

HEB	16.95	11.06	19.51	35.67	23.28	41.05
SH	4.73	0.46	5.02	46.36	4.52	49.12
BJ	2.58	0.36	7.32	25.14	3.47	71.39
SC	2.95	17.42	14	8.58	50.68	40.74