Impact and rebound of near real-time United States fossil fuel carbon dioxide emissions from COVID-19 and large differences with global estimates

Kevin R. Gurney[1*], Bhaskar Mitra[1], Geoffrey Roest[1], Pawlok Dass[1], Yang Song[1], Taha Moiz[1]

Affiliations:
[1]School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, AZ, USA

*Correspondence to: School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, AZ, 86011 USA. Phone: (928) 523-3638. Email: kevin.gurney@nau.edu

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Abstract. The COVID-19 pandemic has altered energy use and greenhouse gas (GHG) emissions globally and continues to evolve in the U.S. as the politics of COVID-19 change. Here we report on a new near-real-time fuel consumption data-driven, week-resolved estimate of national U.S. fossil fuel carbon dioxide ($FFCO_2$) emissions, Vulcan-NRT. We explore the impact and rebound from the COVID-19 pandemic in the US. We find that the weekly total U.S. $FFCO_2$ reached a maximum departure of -19.4% (-18.1%/-21.6%) during the week ending April 3, 2020, consistent with the initiation of state-scale COVID-19 lockdown orders. The total $FFCO_2$ emissions decline for the sum of April and May, the two-month period with the largest persistent decline, was -15.7% (-14.2%/-17.7%), led by gasoline-fueled transportation (-29.4%), followed by electricity generation (-15.1%), aviation (-60.3%), and industrial activity (-8.5%). Since reaching its nadir in early April, U.S. total $FFCO_2$ emissions have returned to pre-COVID levels. However, jet fuel consumption remains -16.0% below long-term weekly values for the April/May 2021 time period. We compare our fuel consumption-driven results to two previous global studies that use indirect proxy approaches. We find large disagreement in sector-specific $FFCO_2$ emissions for the US suggesting that the use of indirect proxy data for estimating near-real-time GHG emissions may contain significant bias.

Introduction

On January 19, 2020, a Washington state resident became the first person in the United States with a confirmed case of COVID-19 after returning from Wuhan, China (Holshue et al., 2020). On January 31, 2020, the U.S. declared the COVID-19 spread a public health emergency (HHS, 2020). On March 11, 2020, the World Health Organization declared COVID-19 a global pandemic (Keith and Gharib, 2020). One week later, California became the first state to issue a "stay-at-home" order which was quickly followed by similar policies in states across the U.S. (Johnson and Morena, 2020). The collective result of the mounting alarm and sub-national policies was an alteration in daily human activity including changes such as the temporary closure of businesses, reduced vehicle travel, and a limit on "non-essential" commercial activity.

Among the many impacts of these policy decisions and the independent response of individuals to the COVID-related risks associated with human activity, is the impact on energy consumption and resulting CO_2 emissions. The COVID-19 pandemic highlights the advantages to having a near-real-time assessment of health, economic, and energy information. Timely information offers the possibility of rapid response to changing conditions. In the case of energy consumption and related CO_2 emissions, near-real-time information can provide policymakers with the ability to quickly change course on emissions mitigation activities and better understand the interactions between changes in human activity and emissions, providing insight into the most effective mitigation options at any given point in time. Reliable assessment of CO_2 emissions has traditionally had latencies of years due to reporting delays in the underlying data.

Three recent studies have examined the global response of fossil fuel carbon dioxide ($FFCO_2$) emissions COVID-related changes in human activity (LeQuere et al., 2020; Liu et al., 2020a; 2020b; Forster et al., 2020). All of these studies used relative metrics based primarily on proxy or indirect measures of $FFCO_2$ emissions such as traffic/mobility data samples and industrial production indices, often extrapolated from one or a few countries to the globe. LeQuere (2020) estimated that by early April 2020, daily global $FFCO_2$ emissions had declined by -17%. They further estimated that global emissions for the entire year of 2020 could range from -4% to -7%

of the 2019 values, depending upon how the COVID-19 response and general economic activity evolved for the remainder of 2020.

Liu et al. (2020a; 2020b) estimated that global $FFCO_2$ emissions declined -8.8% in the aggregated January 1st to June 30th, 2020 time period relative to 2019. Mean daily global emissions during this same period declined by -10% with daily declines in the month of April achieving a drop of -16.9%, roughly consistent with the reductions reported in LeQuere et al. (2020).

However, indirect proxy measures of $FFCO_2$ emissions require numerous assumptions and approximations, understandable given the lack of globally available near-real-time data on more direct measures such as fossil fuel consumption statistics. What little direct fuel consumption is available in individual countries, generally contains latencies of a year or more, making the ability to rapidly respond to, or understand, changing $FFCO_2$ emissions impossible. However, such direct near-real-time data is now available in the United States and makes possible a more direct estimate of $FFCO_2$ emissions. This near-real-time data provides insights into the sector-specific dynamics of $FFCO_2$ emissions potentially delivering rapid policy adjustment to emissions disruptions such as seen in the ongoing COVID pandemic in addition to better understanding structural versus ephemeral changes in emitting activities. This direct near-real-time data can be compared to estimates based on indirect emission proxies to assess how accurate indirect proxy use is for estimating $FFCO_2$ emissions.

Here, we present a new U.S. $FFCO_2$ emissions data product, referred to as "Vulcan-NRT", that provides near-real-time estimates of national emissions using direct fuel consumption data at weekly time resolution across the U.S. economy. The output from this approach is continuously updated and is available online with, at most, a one-week latency. We use Vulcan-NRT to investigate how the activity reductions due to COVID-19 and related policies impacted the $FFCO_2$ emissions of different sectors of the U.S. economy. We compare the 2020 emissions to the long-term (2005-2019) detrended $FFCO_2$ emissions in the U.S. and past emissions disruptions. We examine to what extent $FFCO_2$ emissions have returned to pre-COVID levels, offering insight into what, if any, structural changes may have occurred from the declines in 2020. Finally, we compare the results here to both the LeQuere et al. (2020) and Liu et al. (2020a; 2020b) estimates in the U.S., highlighting the ways in which direct fuel consumption data differs from indirect proxies in estimating $FFCO_2$ emissions, informing the robustness of proxy-based estimates for future analysis.

Methods

Input data and processing: The $FFCO_2$ emissions data product produced here relies on collection of fuel supply/consumption data from the U.S. Department of Energy, Energy Information Administration (EIA) and the U.S. Environmental Protection Agency (EPA). It is used to generate weekly estimates of $FFCO_2$ emissions between January 2005 and the week ending May 28, 2021. The input data includes all petroleum fuel consumption by fuel type, natural gas consumption by sector, and coal consumption by sector. These are organized into six fossil fuel consumption sectors: 1) gasoline-fueled transportation; 2) commercial surface transportation (i.e. land and water); 3) aviation; 4) electricity generation; 5) industrial energy consumption; and 6) residential/commercial energy consumption. Standard CO_2 emission factors are applied to the individual fuel types to achieve $FFCO_2$ emissions (Gurney et al., 2020).

The weekly petroleum fuel consumption was collected from the EIA petroleum fuel archive (https://www.eia.gov/dnav/pet/pet_cons_wpsum_k_w.htm), which classifies the petroleum "supplied" to the U.S. economy from the refining process and disaggregates this into six different petroleum fuel types: "finished motor gasoline", "Kerosene-Type Jet Fuel", "Distillate Fuel Oil", "Residual Fuel Oil", "Propane and Propylene", and "Other Oils" (https://www.eia.gov/dnav/pet/TblDefs/pet_cons_wpsup_tbldef2.asp). The onset of the individual fuel time series varies depending upon the petroleum sub-category. Weeks were defined as Saturday – Friday and this start/end pattern was used for the other fuel classes in this study. Weekly petroleum supplied by the EIA is interpreted as an approximation to consumption or "implied demand" as it measures the disappearance of fuel in the primary supply chain (http://www.eia.gov/petroleum/supply/weekly/pdf/appendixb.pdf). $FFCO_2$ emissions are estimated from these weekly fuel consumption accounts by applying a CO_2 emission factor and a heat content value (see Supplementary Information, Table S1).

Because the petroleum fuel data was reported according to fuel type while natural gas and coal consumption data were disaggregated according to consumption sector, it was necessary to categorize the petroleum fuels into consumption sectors. Roughly 92% of EIA "finished motor gasoline" is used in cars, SUVs, light trucks and motorcycles with the remaining 8% spread across recreational vehicles/boats, small aircraft, construction tools and generators (https://www.eia.gov/energyexplained/gasoline/use-of-gasoline.php). Hence, this fuel constituted the entirety of the gasoline transportation category used here. The aviation category reported in this study was entirely comprised of the EIA "kerosene-type jet fuel" category though small amounts of other petroleum fuels (e.g. gasoline) are used in aviation. The commercial surface transportation category is comprised of the sum of the EIA distillate and residual fuel oil categories and natural gas consumed in the onroad vehicle category (next subsection). While there is some consumption of distillate and residual fuel oils in applications other than transportation, it is relatively small. For example, in 2018, 84.3% of distillate fuel oil was consumed in transportation applications, the remainder was evenly divided between industrial, residential, and non-transport commercial applications (http://www.eia.gov/dnav/pet/pet_cons_821dsta_dcu_nus_a.htm). For residual fuel oil, the transportation share is equally large (84.6%) with the remainder divided between industrial and electricity production (http://www.eia.gov/dnav/pet/pet_cons_821rsda_dcu_nus_a.htm). Given that this study emphasizes relative changes over time, the assignment of these fuels to the commercial surface transportation consumption sector was considered an acceptable approximation.

Two petroleum fuel types remain after the foregoing assignments: propane and propylene, and other oils. Propane/propylene consumption is not dominated by a single sector but spread across the residential, commercial, and industrial sectors (https://www.eia.gov/energyexplained/hydrocarbon-gas-liquids/uses-of-hydrocarbon-gas-liquids.php). Hence, temporal variations could not be reliably allocated to the sector-based categories used here. It is therefore not included in any of the sector-specific statistics. It is, however, used in the total category designated as "all total".

Similarly, the "other oils" as reported by the EIA include a wide assortment of fuel types including fossil fuel that is not incorporated into combustion but is used, for example, in the production of plastics. Allocation to the sectors used in this study is not possible and hence, this fuel type is not included in our analysis. The combustion share (78.8%), however, is used in the total category designated as “all total”.

Natural gas fuel consumption is archived by the EIA at monthly (https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_m.htm) and weekly (https://www.eia.gov/naturalgas/weekly/) temporal resolution. The monthly resolution consumption data has an approximate 3-month latency, is reported in 8 sub-categories (lease and plant fuel consumption, pipeline & distribution use, residential, commercial, industrial, vehicle use, electricity generation) and starts in January 2001. The lease and plant fuel consumption and the pipeline & distribution consumption were incorporated into the industrial sector total.

The weekly data must be extracted from an EIA webpage and was begun so as to include weekly data starting in January 2020. The weekly “demand table” data was used to generate a Saturday-Friday weekly total by calculating weighted averages of the two weeks contributing to the Saturday-Friday data week used here. This data included 3 sector sub-categories (power, industrial, and residential/commercial). The weekly data provided the same sector sub-categories with the addition of an onroad natural gas consumption category. The weekly data listed “Pipeline fuel use/losses” and “LNG pipeline receipts” were incorporated into the industrial total. As with petroleum fuel, a heat content and CO_2 emission factor were applied to the natural gas consumption (irrespective of sector) data.

The monthly and weekly natural gas consumption data had a significant amount of temporal overlap (roughly 4 months in 2020) and this was used to ensure harmonization (weekly data was adjusted to sum to the monthly values) across the 2 time series. This was performed by transforming the monthly data to daily data characterized by constant daily values within a given month. This was smoothed with a 45-day moving average (box) window. Then, the daily data aggregated to weekly totals. These were compared to the weekly data and the weekly data adjusted. Adjustments to the weekly data amounted to 1% or less on a weekly basis.

Coal consumption in the U.S. is dominated by use in the production of electricity accounting for 91.8% of total coal consumption. The remainder, other than 0.15% of the total, is consumed in the industrial sector. Hence, we divide total coal consumption into that consumed for electricity generation and that consumed in the commercial/industrial sector.

Coal consumed for electricity generation is composed of monthly and hourly data. The monthly data (https://www.eia.gov/totalenergy/data/browser/xls.php?tbl=T07.02A&freq=m) has a latency of roughly 4 months and is reported in units of million kilowatt hours per month. The hourly coal consumed for electricity generation (megawatt hours) covering the 48 contiguous states and the District of Columbia (https://www.eia.gov/opendata/qb.php?category=3390105&sdid=EBA.US48-ALL.NG.COL.H) was aggregated to weekly sums for use here.

As with the natural gas consumption, the monthly coal consumption for electricity generation is translated to a daily total, followed by smoothing and aggregation to weekly sums. The adjustment of the true weekly data is performed and here the adjustment will subsume both accounting errors and the lack of Alaska and Hawaii reporting in the true weekly data.

Conversion of the electricity generation coal data is performed by application of a CO_2 emission rate (tCO_2/MWhr). Emission rates were derived from statistics on CO_2 emissions from electricity generation in the U.S. using the eGRID datasets for the years 2009, 2010, 2014, and 2018 (https://www.epa.gov/egrid/emissions-generation-resource-integrated-database-egrid). The total CO_2 emissions and electricity generation from coal-fired powerplants was used to estimate a time-dependent CO_2 emission rate.

Coal consumed in the combined industrial and commercial sector is based on the difference between coal production in the U.S. (https://www.eia.gov/coal/production/weekly/) and coal consumed for electricity production. To estimate a complete historical time series of weekly coal production requires the use of monthly coal production data (https://www.eia.gov/totalenergy/data/browser/xls.php?tbl=T06.02&freq=m) which begins January 1973. Once again, the monthly production data is translated to a weekly value via application of a subsampling (constant value for each month) followed by a 45 day smoother and finally, aggregation to weekly sums.

Detrending: The previous processing achieves a weekly dataset of $FFCO_2$ emissions in the US disaggregated into 6 sector divisions with a common start date of the week ending January 7, 2005 up to the week ending May 28, 2021. In order to compare the anomalous values during the COVID-19 lockdown period, the historical time series is detrended using a linear time trend fit across the entire time series (Jan 1, 2005-May 28, 2021). The fit was used to 'rotate' the original time series about the temporal midpoint. The detrended weekly composites of all years (2005 to 2019) were compared to the corresponding 2020/2021 weekly composite values. Day-of-the-week integrity was maintained such that all weeks represented Saturday through Friday in each year.

Comparison statistics: For estimating the difference between the long-term detrended weekly values and the weekly values in 2020, a relative difference was calculated as the difference between the long-term median and the 2020 value normalized to the long-term median value. The upper and lower bounds of the relative differences used the maximum/minimum of the long-term detrended weekly 15-member ensemble distribution. Statistical significance is defined by departures that exceed a) the $1^{st}/3^{rd}$ quartile of the weekly ensemble distributions from 2005-2019, referred to as "partly significant" and b) the maximum/minimum distributions of the same weekly ensembles, referred to as "significant". The latter criteria are considered akin to a 2-sigma boundary for gaussian statistics.

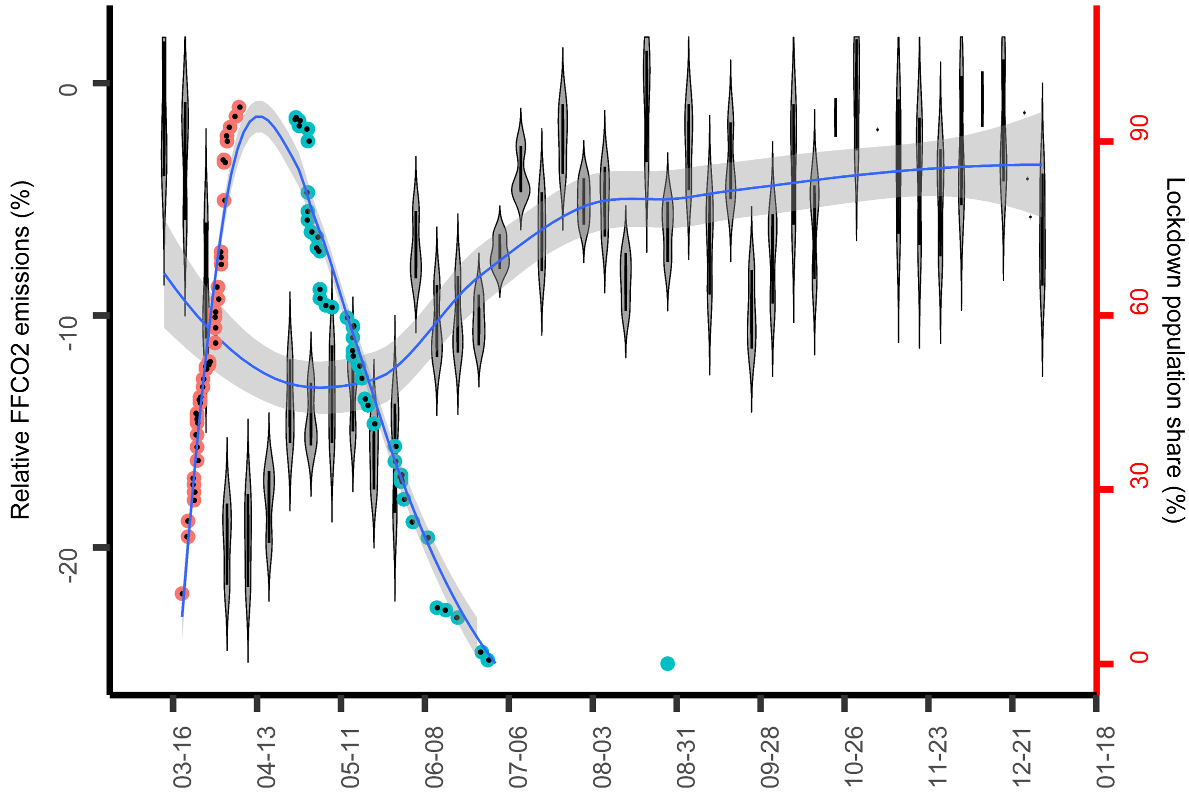

Figure 1. *Weekly total FFCO₂ emissions in the U.S. relative to detrended long-term (2005-2019) median values (left axis) with long-term ensemble distribution (violin symbols). The gray shading represents the locally weighted scatterplot smoothing (LOESS) curve. LOESS was used to depict the non-linear change of the weekly median values of the relative emissions as a function of 'date'. Share of U.S. population (right-axis) included in the initiation of state-scale lockdown orders (red) and the end of the state-scale lockdown orders (light blue) with LOESS curve (Lockdown population share (%) ~ date) plotted to highlight the non-linear increase and decline trend of lockdown population as a function of time.*

Results

2020 decline: Total U.S. $FFCO_2$ emissions in 2020 reflect the impact of diminished human activity beginning the last week of March 2020 and extending up to early July (Figure 1). The onset of the emissions decline occurred shortly after some of the larger U.S. states enacted lockdown orders (https://ballotpedia.org/States_that_issued_lockdown_and_stay-at-home_orders_in_response_to_the_coronavirus_(COVID-19)_pandemic,_2020). For example, by the end of March 2020, approximately 50% of the U.S. population was under state lockdown orders of varying severity. The largest persistent $FFCO_2$ emission declines are notable in April and May with partial return to pre-COVID emission levels beginning in June 2020 when the share of U.S. population under lockdowns declined to below 50%. Hence, we use the sum of April-May $FFCO_2$ emissions as an integrated metric of the emissions decline from the 2005-2019 median value, also taking note of single-week maximum departure values and timing in each of the six fossil fuel consumption sectors (Table 1).

Table 1. *United States $FFCO_2$ emission statistics for weeks in 2020 relative to detrended 2005-2019 median values for six fossil fuel consumption sectors, the sector total and the U.S. total. An asterisk denotes departures exceeding the 1st/3rd quartile ensemble distribution boundaries; Two asterisks denote departures exceeding the minimum/maximum ensemble distribution boundaries; NS denotes departures that are not statistically significant (do not exceed the 1st/3rd quartile ensemble distribution boundaries). The maximum decline week date shows the end day for the weekly interval.*

Fossil fuel consumption sector	April-May abs decline (tC)	April-May relative decline (%)	Share of sector total April-May abs decline (%)	Share of sector total emissions in 2019 (%)	Max weekly relative decline (%)	Max decline week (end date)
Gasoline transportation	-15,092,559	-27.9%**	38.7%	25.2%	-43.0%**	10-Apr
Commercial surface transportation	-4,597,769	-14.5%*	11.8%	14.0%	-26.5%**	29-May
Aviation	-6,119,012	-59.7%**	15.7%	5.4%	-74.3%**	29-May
Electricity generation	-11,343,148	-14.0%**	29.1%	34.3%	-20.7%**	15-May
Industrial	-2,065,878	-8.7%**	5.3%	11.5%	-13.2%**	24-Apr
Residential/ Commercial	-470,879	-3.0%[NS]	1.2%	9.7%	-26.8%**	13-Mar
Sector Total†	-41,654,625	-18.1%**	100.0%	100.0%	-23.1%**	10-Apr
All Total‡	-39,587,294	-15.6%**			-19.4 %**	3-Apr

† The Sector total does not include “propane and propylene” and “other oils”. See Methods for details.
‡ The All total includes a small amount of petroleum feedstock not used for combustion. This is estimated to be less than 1% of the emissions total and hence, no adjustment was made.

The largest share of the total $FFCO_2$ emissions decline was due to gasoline-fueled transportation (39.3%). The gasoline transportation $FFCO_2$ emissions shows significant departures from the long-term median values starting in the last week of March, reaching a maximum value of -43.0% (-41.3%/-44.2%) in the week ending April 10, 2020 (Figure 2a; Table 1). All of the values in April through June are smaller than the long-term weekly minimum. The emissions sum of April and May is -27.9% (-26.3%/-29.3%) below the long-term median value. The first two months of 2021 show gasoline transportation $FFCO_2$ emissions remaining outside the 3rd quartile boundary but far from the large declines of March and April 2020. Beginning in March of 2021, however, gasoline transportation emissions returned to within the long-term mean envelope of variability and can be said to have returned, therefore, to “pre-COVID” values.

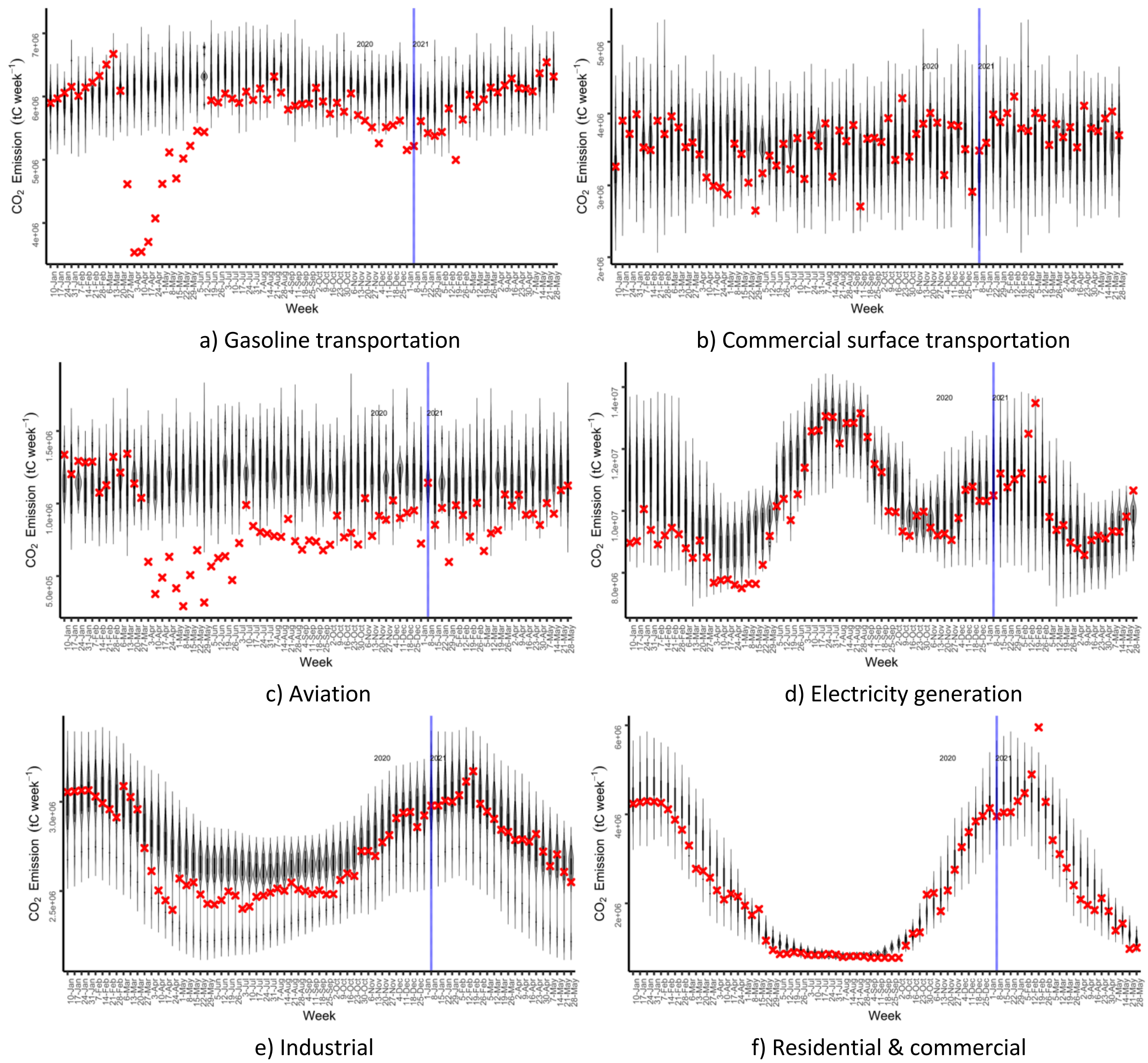

Figure 2. *Comparison of weekly long-term (2005-2019), detrended U.S. fossil fuel $FFCO_2$ emissions (black) to weekly $FFCO_2$ emissions from January 2020 to June 2021 (red "X") by six fossil fuel consumption sectors. The violin plots (Hintze and Nelson, 1998) illustrate the distribution and dispersion (minimum, 1st quartile, median, 3rd quartile and maximum) of the long-term detrended emission data across the ensemble of weekly values. The density trace plotted symmetrically around the boxplot, provides a graphical illustration of the shape of the distribution of weekly detrended data for each $FFCO_2$ emissions category. Vertical blue line denotes the transition from 2020 to 2021. Units: tC/week.*

The emissions associated with electricity generation show statistically significant declines relative to the long-term median from late-April to late-May with a maximum departure of -20.7% (-17.3%/-22.3%) during the week ending May 15, 2020 (Figure 2d, Table 1). Accounting for the second-largest share of the total $FFCO_2$ emission decline in April-May (29.1%), the emissions sum of April and May were -14.0% (-10.7%/-16.6%) below the long-term median value. Examination of the underlying contribution to electricity generation from coal and natural gas indicates that the decline was primarily driven by coal, which is principally used for baseload electricity generation as opposed to peak load generation which relies mostly on natural gas. The electricity generation sector exhibits statistically significant departures in weeks spanning the January through March 2020 time period. This is driven by the coal contribution to the electricity generation total (see SI). Furthermore, the natural gas contribution to electricity generation shows positive departure anomalies during this time period but given the relative magnitudes of the two fuels in the electricity generation total, the coal contribution drives the combined behavior. These countervailing anomalies in the first two months of 2020 are likely unrelated to COVID-19 activity changes but, rather, are related to the substitution of natural gas for coal in electricity production which could not be eliminated by the linear detrending approach taken here (de Gouw et al., 2014).

Not surprisingly, aviation $FFCO_2$ emissions exhibited a precipitous decline starting in the week ending April 3, 2020 reaching -73.9% (-73.3%/-76.4%) below the long-term median level during the week ending May 29, 2020 (Figure 2c, Table 2). The emissions sum of April and May was -59.7% (-56.4%/-62.2%) below the long-term median value, making it the third largest contribution to the total $FFCO_2$ emissions decline though it only constitutes 5.4% of total 2019 $FFCO_2$ emissions. Though some rebound from the large declines began in early June, aviation $FFCO_2$ emissions remain -12.3% below the long-term value for the four weeks of May 2021. U.S. passenger throughput data at checkpoints in U.S. domestic airports from the Transportation Security Administration (TSA) shows declines beginning mid-March 2020 with the maximum departure from 2019 same-day values in mid-April, slightly leading the aviation $FFCO_2$ emissions decline by 1-2 weeks (TSA 2020).

The industrial $FFCO_2$ weekly values show persistent significant declines starting in the week ending March 27, 2020 continuing to early October 2020 (Figure 2e, Table 2). The emissions sum of April and May is -8.7% (-6.0%/-9.7%) below the long-term median value with a peak decline of -13.2% (-10.3%/-14.0%) during the week ending April 24, 2020. By early November 2020, industrial $FFCO_2$ emissions returned to levels consistent the long-term mean.

Two of the six sectors reported here show little to no significant declines during the weeks in 2020. Commercial surface transportation $FFCO_2$ emissions (Figure 2b, Table 2) show some weeks in the April to May time period departing significantly from the long-term mean same-week values but less so compared to other sectors. Furthermore, this sector shows a large amount of historical variance relative to the 2020 declines. The residential/commercial emissions (Figure 2f, Table 2) exhibit a single week of significant decline (week ending March 13, 2020) during the April-May 2020 time period. Significant declines also occur in late May/early June and throughout the month of September. Due to the relationship between external temperature and residential/commercial energy consumption (not corrected for here), large short-term departures may be due to anomalously warm/cold temperatures in enough of the U.S. to result in the observed departures. The week of February 11, 2021 is another example, whereby historically low temperatures persisted from Texas to the Great Lakes, placing over 170 million Americans under a winter weather alerts (NWS, 2021).

These results suggest that the primary impact to April-May 2020 U.S. $FFCO_2$ emissions from the activity changes due to COVID-19 activity constraints were largely confined to gasoline and aviation transportation fossil fuel consumption (combined 54.3% of decline) and electricity generation (29.1% of the decline) with small contributions from commercial surface transportation (11.8%) and industrial fossil fuel consumption (5.3%).

When all the fossil fuel consumption sectors are combined, the peak decline in total $FFCO_2$ emissions reach -23.1% (-20.9/-24.7%) during the week ending April 10, 2020. The emissions sum of April and May are -18.1% (-16.4%/-19.4%) below the long-term median value. The total $FFCO_2$ emissions (which include propane/propylene and "other petroleum" consumption) see a single-week peak decline of -19.4% (-18.1%/-21.5%) and an April-May mean decline of -15.1 (-13.6%/-17.1%). Towards the end of November 2020, the $FFCO_2$ emissions were within the envelope of historic variability, thereby returning to pre-COVID emissions.

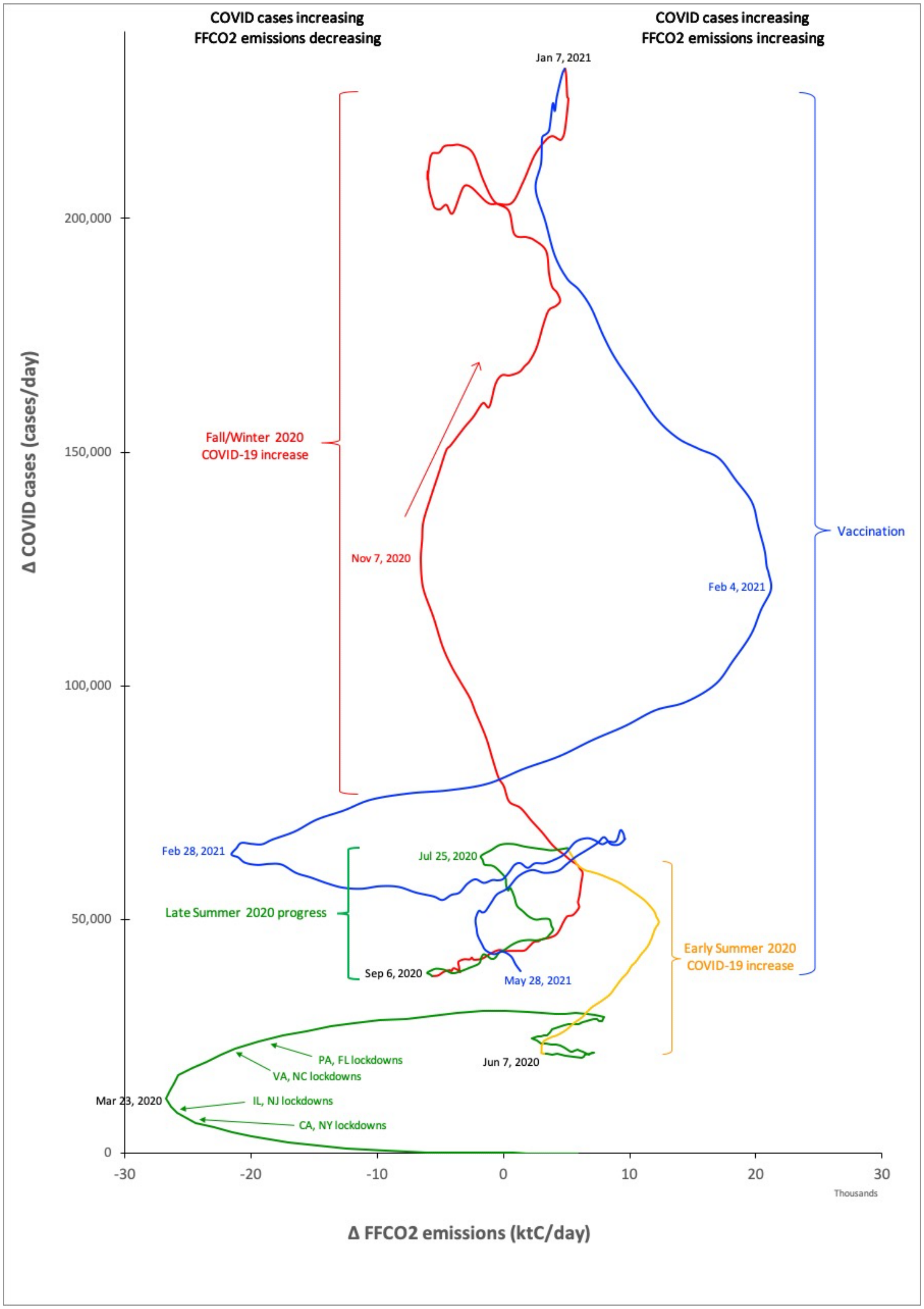

Figure 3. *Phase diagram of the daily change in U.S. COVID-19 cases versus U.S. total $FFCO_2$ emissions, January 2020 to May 28, 2021. Notable dates and time periods are identified.*

FFCO$_2$ Emissions and COVID-19. Energy consumption and resulting FFCO$_2$ emissions are a useful reflection of broad economic activity which can now be produced with little temporal latency. With statistics on the number of daily cumulative cases of COVID-19, we can contrast these two important measures for insights into the timing and potential cause/effect of their relationship. Figure 3 presents the daily change in COVID-19 cases plotted against the daily change in total FFCO$_2$ emissions relative to the long-term (2005-2019) detrended daily mean. At all times shown here (January 1, 2020 to May 28, 2021), the daily change in COVID-19 cases has been a positive value but varying in magnitude. The change in daily FFCO$_2$ emissions, however, changes sign from a negative value (declining emissions) to positive values (increasing emissions). The period from January 1, 2020 to mid-April 2020 coincides with the series of state-scale lockdown orders, starting with California on March 19, 2020. Between mid-April and early June 2020, the relationship between the COVID case rate and the daily change in FFCO$_2$ emissions was complicated with both measures increasing and decreasing alternatively (though the change was always positive). This corresponds to a time period when a mix of states began to ease lockdown measures at different times. From early June 2020 to approximately mid-July, both COVID-19 cases and FFCO$_2$ emissions show persistent increases, consistent with the COVID-19 summer 2020 increase. From mid-July to early September, COVID-19 case increases slowed while daily FFCO$_2$ increased slowly, shifting to daily declines towards the end of August 2020. From early September to the January 7, 2021, COVID-19 show day-to-day increases similar to the Summer surge period with a relatively steady daily change in FFCO$_2$ emissions. Starting in early January 2021 to the end of May 2021, new COVID cases decline as vaccination incidence increases (CDC, 2021). Over this time period FFCO$_2$ emissions alternate between increasing and decreasing values more consistent with the FFCO$_2$ seasonality as the emissions return to pre-COVID levels.

Comparison to indirect proxy-based estimates. The 2020 emissions declines reported here contrasts with previously published results which relied primarily upon indirect proxy-based information (LeQuere et al., 2020; 2021; Liu et al., 2020a; 2020b). While the total US FFCO$_2$ decline reported for the first half of 2020 relative to 2019 is similar for Vulcan-NRT (-12.9%), LeQuere et al. (-12.5%), and Liu et al. (-13.3%), the declines in individual sectors show large differences (Table 2). For example, in the electricity generation or “power” sector, the estimated half-year decline ranges from -0.8% for LeQuere et al. (2020; 2021) to -7.7% for Liu et al. (2020a; 2020b) to a -17.9% decline in Vulcan-NRT. A similarly wide range exists for the full-year estimate (Liu et al. report only to July 31, 2020) with LeQuere reporting a -0.4% decline while Vulcan-NRT reports an -10.8% decline, or roughly 26x the decline of LeQuere et al. (2020; 2021) and far outside the scenario range reported.

Table 2. *Comparison of percentage decline in CO_2 emissions in 2020 relative to 2019 across three studies: LeQuere et al. (2020) ("Med" results with "lo" and "high" in parentheses), Liu et al. (2020a; 2020b), and this study (Vulcan-NRT). Note: The results presented in this table do not use detrended values and are relative to 2019 (as opposed to the 2005-2019 long-term median comparison metric used in this study) and hence, differ from the results presented in Table 1. †: The residential/commercial sector for the LeQuere et al. study is the sum of the residential and "public" sectors. The LeQuere et al. emissions for the electricity generation and residential sector were adjusted for heating degree day (HDD) differences between 2019 and 2020. This was not done in either Vulcan-NRT or Liu et al.*

Time period	Study	All Total	Electricity Generation	Ground Transport	Industrial	Residential/ Commercial	Aviation
Jan-Jun, 2020	LeQuere et al. (2020; 2021)	-12.5% (-(6.5 to -19.0%)	-0.8% (0 to -3.2%)	-19.5% (-11.8 to -28.1%)	-17.5% (-5.7 to -26.3%)	-4.8% (-2.1 to -7.5%)	-39.5% (-26.7 to -59.6%)
	Liu et al. (2020a;b)	-13.3%	-7.7%	-22.9%	-8.9%	-4.5%	-31.2%
	Vulcan-NRT	-12.9%	-17.9%	-14.1%	-5.4%	-10.5%	-37.6%
Jan-Dec, 2020	LeQuere et al. (2020)	-11.0% (-4.3 to -17.4%)	-0.4% (0 to -1.6%)	-15.3% (-6.8 to -24.3%)	-19.0% (-3.1 to -28.4%)	-3.7% (-1.2 to -6.2%)†	-37.8% (-27.7 to -58.2%)
	Vulcan-NRT	-10.9%	-10.8%	-11.6%	-5.4%	-9.8%	-39.7%

The industrial sector also exhibits large differences with half-year declines of -17.5%, -8.9%, and -5.4% for LeQuere, Liu, and Vulcan-NRT, respectively. Full-year declines are -19.0% and -5.4% for LeQuere and Vulcan-NRT, slightly greater than ¼ of the LeQuere decline. Residential/commercial sector half-year declines are -4.8%, -4.5%, and -10.5% for LeQuere, Liu, and Vulcan-NRT, respectively. The full-year decline shows a similar span with Vulcan-NRT estimating over 2x the decline found in LeQuere et al. (2020; 2021). The ground transportation and aviation sectors show more consistency with both half- and full-year results within the ranges given.

Discussion

The reduced $FFCO_2$ emissions as a result of the reduced activity during the lockdowns in the U.S. raises the prospect of what might be learned about the relationship between emissions and human activity in tackling GHG emissions policy in the U.S.. An important question for climate change is whether or not the lower $FFCO_2$ emissions seen in the COVID pandemic have long-term impacts on structural issues associated with emissions. Thus far, there is no conclusive evidence that the $FFCO_2$ emissions reductions recounted here are the result of structural changes to emitting activity but are, rather, a short-term behavioral response. However, the shift in working location and the related commuting as more individuals establish work-at-home routines and employers become adjusted to those arrangements, may lead to a long-term change in gasoline transportation emissions in particular and possibly lead to alterations in the amount of commercial workspace required and the emissions associated with commercial building space (Lebanon, 2020). The evidence for that type of structural change is yet to emerge but is a key task for future analysis.

Similarly, the amount and need for airborne business-related travel may see changes that last beyond the current pandemic response as businesses re-evaluate the costs and benefits associated with business travel. Like daily vehicle commuting, employees and employers have had an opportunity to experience a strong contrast between normal travel activity and significantly reduced travel activity and that may offer insights into potential efficiencies for the future.

The limited decline in the commercial surface transportation sector in 2020 stands in contrast to the precipitous decline in gasoline transportation emissions. This may reflect conditions in which personal transportation was limited (e.g. reduced community and local non-essential trips) during the various state-scale stay-at-home periods but consumption of goods and services were not similarly limited (e.g. home delivery, container ship activity). This could be consistent with the limited decline in the residential and commercial sector $FFCO_2$ which is defined here by natural gas consumption in those sectors. This, in turn, is dominated by natural gas consumption for interior climate control (e.g. heating). While workplace occupancy was reduced during the state-scale lockdowns, many workers were simply displaced to home occupancy and the resulting energy consumption not altered in the net.

The annual total $FFCO_2$ emissions for 2020 was 1358 MtC, -10.7% below the 2019 annual emissions. Gasoline transportation, aviation, and electricity generation account for 88.3% of the annual reduction. The last year for which annual $FFCO_2$ emissions were at this reduced level occurred in the year 1990 (LeQuere et al., 2018). For additional context, the Global Financial Crisis (GFC) was the last large perturbation to the U.S. economy that had repercussions on $FFCO_2$ emissions. We estimate the decline in 2009 relative to 2008 as -7.8%, suggesting that 2020 exhibits an annual decline 37% greater than that resulting from the GFC.

However, as of June 2021, nearly every sector has returned to pre-COVID emission levels with the except of the aviation sector where $FFCO_2$ emissions remain slightly below the detrended long-term same-week mean.

The comparison to indirect proxy-based emissions estimation methods suggests that proxy measures may miss the linkage to CO_2 emissions. While the total decline reported here was close to both LeQuere et al. (2020; 2021) and the Liu et al. (2020a) estimate, the large differences within each of the sectors raises questions about whether the agreement on the total emissions is coincidental. Caveats remain. The fuel consumption data used in this study can reflect delayed consumption when fuel stockpiling or temporary storage occurs. Furthermore, the Vulcan-NRT fuel consumption data is based on surveys which contain potential sampling errors. Finally, while every attempt has been made to similarly define the six sectors compared, there may be differences arising from sector definitions across the three studies (see Supplementary Information for more details). Plus, the issue of HDD adjustment may make a difference.

Further comparison of fuel consumption and activity data in other countries would provide additional evidence regarding how well these indirect proxy measures can capture the true dynamics of CO_2 emissions.

The near-real-time $FFCO_2$ emissions data product described in this study is available online and updated on a weekly basis. The rapid updates in the coming months will offer a better understanding of how the relationship between reduced activity and $FFCO_2$ emissions can guide future GHG emissions reductions and whether or not permanent behavioral or infrastructural change has resulted. The continually updated $FFCO_2$ emissions data product will also serve to complement new GHG information systems that use atmospheric measurements and “bottom-up” emissions as dual constraints to plan, monitor, and evaluate GHG emissions mitigation (Mueller et al., 2020).

Conclusion

In contrast to global studies that have used a collection of indirect proxy metrics to estimate the decline in GHG emissions due to the COVID-19 pandemic, we have retrieved all of the United States fossil fuel consumption data to estimate fossil fuel carbon dioxide ($FFCO_2$) emissions in near-real-time. We find dramatic declines in almost all sectors of U.S. economic activity except for the residential/commercial and commercial surface transportation. Among the remaining sectors, gasoline transportation, aviation, and electricity generation show the largest declines and account for 83.4% of the total sector-based decline in the April to May 2020 time period. When examined for the whole year, 2020 $FFCO_2$ emissions were -10.7% below 2019 values and 10.5% below the detrended long-term annual median value. This represents a year-over-year decline 37% greater than experienced during the 2008 Global Financial Crisis.

While the overall decline in U.S. $FFCO_2$ emissions should not come as a surprise given the impact the COVID-19 pandemic has had on human activity, the sector composition suggests that the impact is not cross-sector or economy-wide. This is both good news for economic recovery but potentially bad news for the trajectory of U.S. $FFCO_2$ emissions and climate change. There are opportunities for structural change, particularly in emissions from commercial building, aviation, and personal vehicle emissions as the impact of the pandemic eases, but as of early 2021, US $FFCO_2$ emissions have returned to pre-COVID levels with the exception of the aviation sector. Whether or not the US returns to previous long-term trends in individual sectors or in the aggregate and whether this indicates some long-term behavioral or structural changes, remains to be seen.

The use of fuel consumption data to estimate the $FFCO_2$ emission impacts of the COVID-19 pandemic shown here are also dramatically different from the studies that have attempted the same emissions impact using indirect proxy data. Though the total $FFCO_2$ emissions decline in 2020 relative to 2019 across the three studies are similar, individual sectors show large countervailing differences. For example, in the electricity generation sector, Vulcan-NRT estimates a -10.8% decline compared to a -0.4% decline for LeQuere et al. (2020; 2021). When comparing to Liu et al. (2020a; 2020b), the January-to June decline is -7.7% compared to a 0=-17.9% decline for Vulcan-NRT. While it cannot be avoided when estimating global emissions in near-real-time, these results suggest that direct fuel consumption data should be used where it is available.

The availability of a near-real-time $FFCO_2$ emissions estimation even for the U.S.-whole domain provides insight into behavioral and economic dynamics that can provide numerous benefits, particularly as the U.S. considers re-engagement of the international climate change policy process. A rapid feedback to climate or economic policies can be useful for rapid course-correction or confirmation of policy effectiveness. Combining this near-real-time effort with existing high-resolution $FFCO_2$ results, can bring these feedback advantages to local and regional policies.

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Author Contributions: K.R.G conceived and designed the project. K.R.G. and B.M. collected, processed and analyzed the data. K.R.G. and B.M. wrote the paper. B.M. built the online retrieval system. G.R. assisted with figures. All authors contributed to the interpretation of the results.

Data availability: Weekly updated $FFCO_2$ emissions in all fuel/sector and consumption categories are available at https://vulcan.rc.nau.edu/realtime.html. Weekly time series span 2005 to most recent week available. Updates to the time series are made every Saturday, noon Pacific time.

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Supplementary Materials for

Impact and rebound of near real-time United States fossil fuel carbon dioxide emissions from COVID-19 and large differences with global estimates

Kevin R. Gurney[1*], Bhaskar Mitra[1], Geoffrey Roest[1], Pawlok Dass[1], Yang Song[1], Taha Moiz[1]

[1]School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, AZ, USA

*Correspondence to: School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, AZ, 86011 USA. Phone: (928) 523-3638. Email: kevin.gurney@nau.edu

This PDF file includes:

Supplementary Text

Tables S1 to S2

Figures S1 to S3

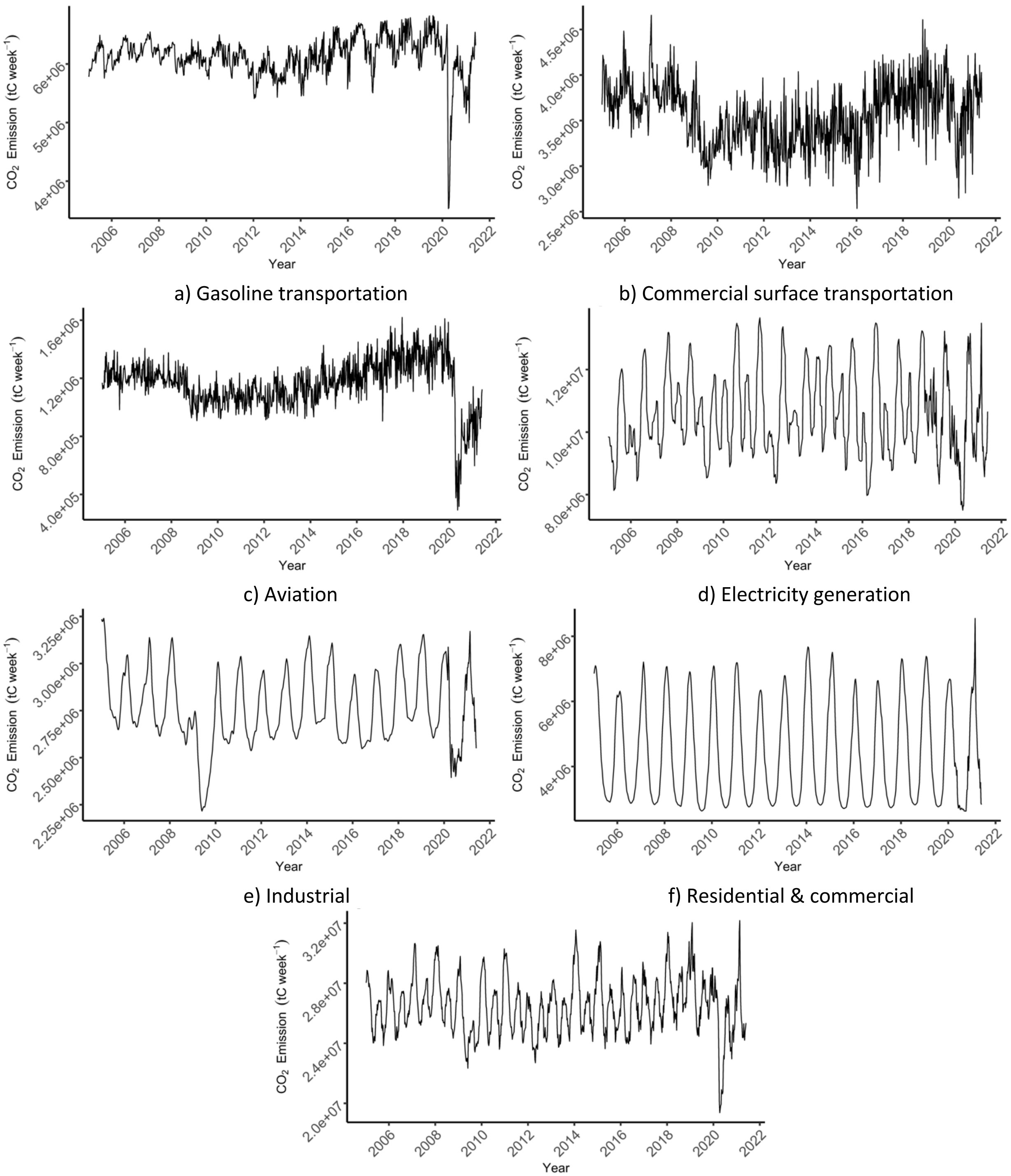
Supplementary Text

Table S1 provides all of the heat content and CO_2 emission factors used for all of the fuel/sector categories used in this study. The heat content values are defined as heating values per either volume or mass, depending upon fuel. The CO_2 emission factors are all defined as mass carbon per unit heat.

Figure S1 provides the detrended $FFCO_2$ emissions from 2005 to the last week available by each of the six aggregate consumption categories and Figure S2 provides the same but in the original fuel/sector categories.

Table S1. *Heat content and CO_2 emission factors used in this study defined by fuel category. Source: Gurney et al., (2020).*

Fuel	Heat content (units provided)	CO_2 emission factor (tC/e6btu)	notes
Motor gasoline	120.5 (e6btu/e3gal)	0.01915	
Kerosene type jet fuel	135.0 (e6btu/e3gal)	0.01915	
Distillate oil	137.5 (e6btu/e3gal)	0.01978	
Residual fuel oil	149.7 (e6btu/e3gal)	0.02129	
Propane/propylene	91.3 (e6btu/e3gal)	0.01705	Propane entry
Other oil	138.7 (e6btu/e3gal)	0.02013	Unfinished oil
Natural gas	1032 (e6btu/e6ft3)	0.01446	
Coal	22.61 (e6btu/metric ton)	0.02597	Bitum/subbitum



a) Gasoline transportation

b) Commercial surface transportation

c) Aviation

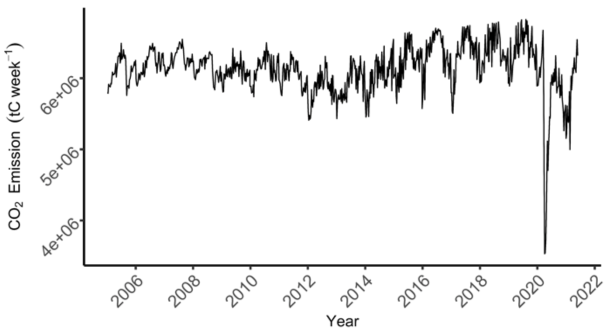
d) Electricity generation

e) Industrial

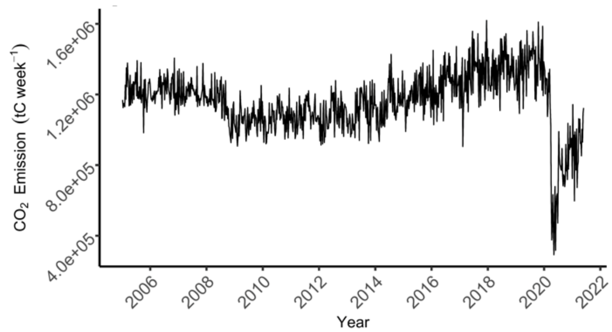
f) Residential & commercial

g) Sector Total

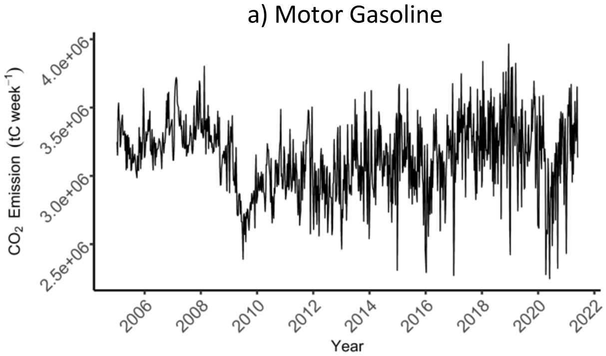
Figure S1. *Detrended weekly time series of U.S. $FFCO_2$ emissions by the six aggregate emission categories and the category total. Timespan is from January 2005 to May 28, 2021.*



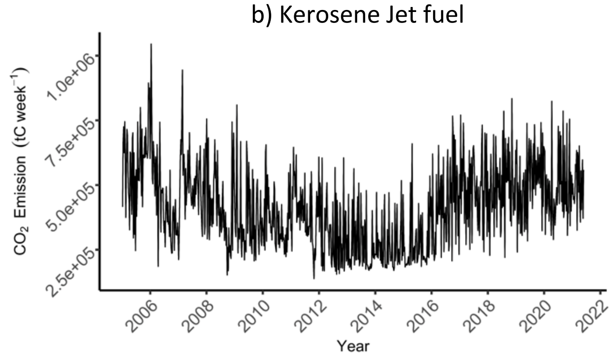
a) Motor Gasoline



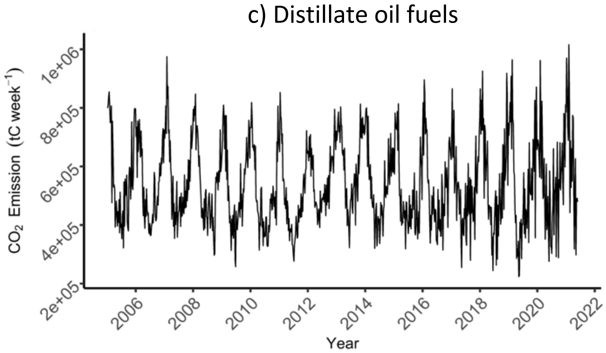
b) Kerosene Jet fuel



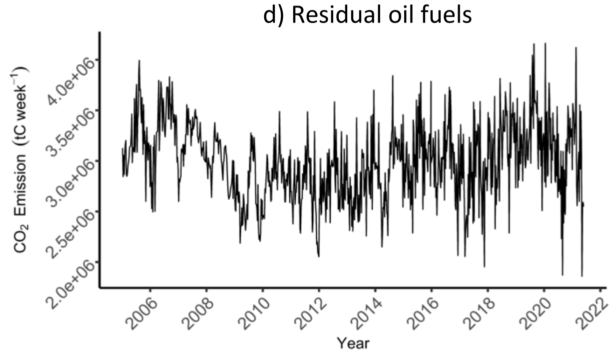
c) Distillate oil fuels



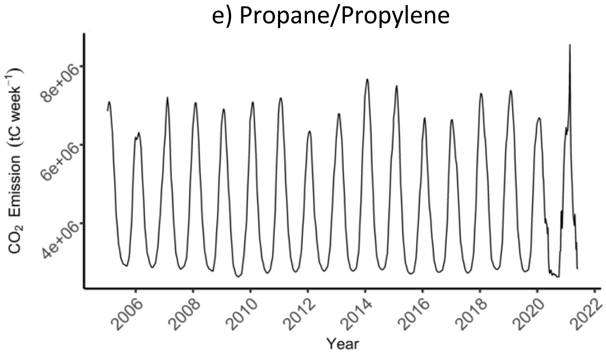
d) Residual oil fuels



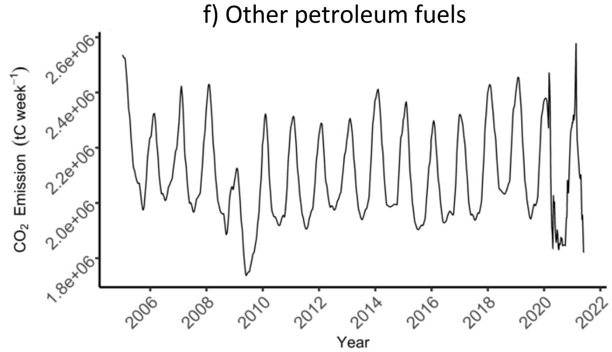
e) Propane/Propylene



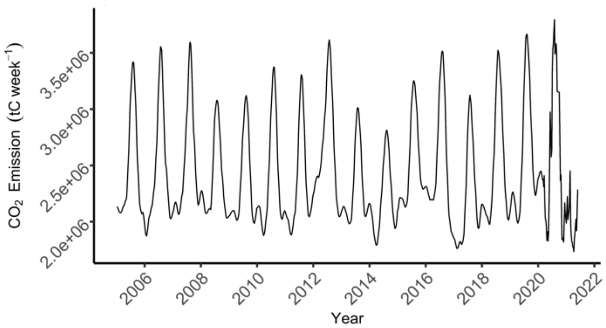
f) Other petroleum fuels



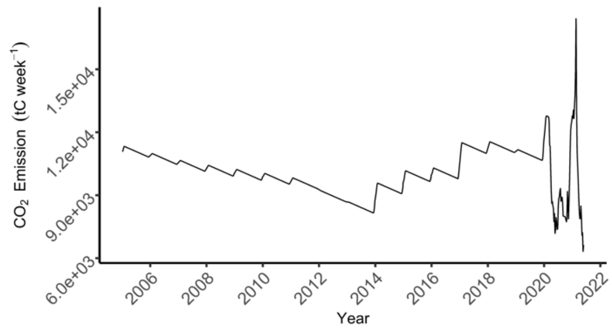
g) Residential & Commercial Natural Gas



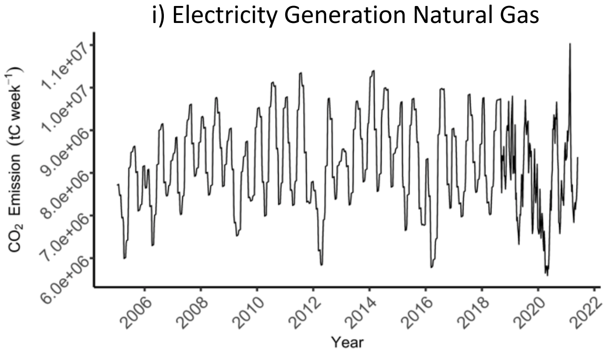
h) Industrial Natural Gas



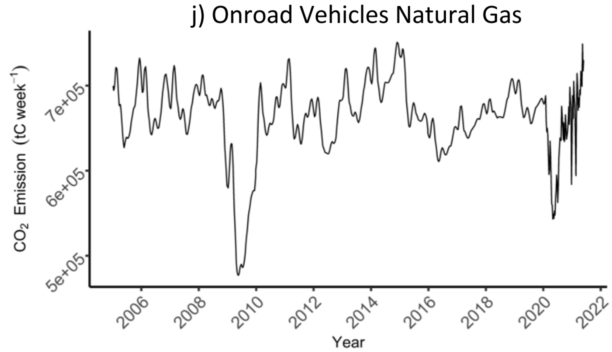
i) Electricity Generation Natural Gas



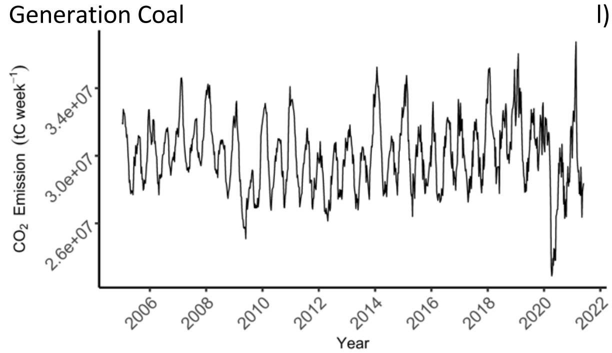
j) Onroad Vehicles Natural Gas



k) Electricity Generation Coal



l) Coal all else



m) Total

Figure S2. *Detrended weekly time series of U.S. $FFCO_2$ emissions by original reported fuel/sector categories and the total $FFCO_2$ emissions. Timespan is from January 2005 to May 28, 2021.*

Table S2 provides the time series statistics as in main text Table 1 but for the originally reported fuel/sector categories from the US Energy Information Administration (EIA).

Table S2. *United States $FFCO_2$ emission statistics for weeks in 2020 relative to detrended 2005-2019 median values for the original fuel/sector categories present in the input data. An asterisk denotes departures exceeding the 1st/3rd quartile ensemble distribution boundaries; Two asterisks denote departures exceeding the minimum/maximum ensemble distribution boundaries; NS denotes departures that are not statistically significant (do not exceed the 1st/3rd quartile ensemble distribution boundaries.*

Fuel/Sector	April-May abs decline (tC)	April-May relative decline (%)	Share of total April-May abs decline (%)	Share of total emissions in 2019 (%)	Max relative weekly decline	Max decline week (date)
Motor Gasoline	-16,357,983	-29.3%**	41.3%	21.7%	-43.0**%	10-Apr
Distillate fuel oil	-4,451,0345	-15.5%**	11.2%	11.0%	-29.9%**	29-May
Kerosene-type Jet fuel	-6,280,924	-59.3%**	15.9%	4.6%	-74.3%**	29-May
Residual fuel oil	82,195	2.2%	-0.2%	1.0%	-31.0%*	3-Apr
Propane & propylene	-178,262	-4.5%	0.5%	1.8%	-32.6%**	29-May
Other oils	1,298,567	4.9%	-3.3%	12.0%	-40.2%*	28-Aug
NG residential & commercial	-700,980	-4.1%	1.8%	8.3%	-26.8%**	13-Mar
NG industrial	-1,164,107	-6.3%**	2.9%	8.2%	-12.1%**	24-Apr
NG electricity generation	-853,845	-4.5%*	2.2%	11.1%	-13.5%**	8-May
NG onroad	-17,548	-19.2%**	0.04%	0.05%	-29.0%**	22-May
Coal other consumption	-823,221	-14.0%**	2.1%	1.7%	-14.8%**	3-Jul
Coal electricity generation	-12,196,579	-18.7%**	30.8%	18.5%	-23.2%**	15-May
Total	-39,587,294	-15.6%**	100.0%	100.0%	-19.4%**	3-Apr

Comparison to Liu et al. (2020a; 2020b) requires some recategorization of the Vulcan-NRT fuel consumption data (Figure S3). For example, for comparison to the Liu et al. ground transportation category, the Vulcan-NRT petroleum consumption categories for gasoline, distillate fuels, and vehicle natural gas were combined (Figure S3a). Though difficult to glean from the Liu et al. (2020a) methodology, it is assumed that the absolute emission magnitude in this sector starts with the EDGAR “TRO” category (Janssens-Maenhout et al. (2019) and no emissions from the “TNR_Other” category. This would create a discrepancy in that the fuel combination for Vulcan-NRT includes distillate fuels which are not solely used in onroad transportation but are used in, for example, rail and off-road transport categories. Notable in the Liu et al. results are a period of nearly constant emissions during the June to October 2019 time period (constant value of 35.04 $MtCO_2$). This can be seen in the original data as a weekly cycle that repeats throughout this time period. The source of this anomaly is unexplained. During

2019, the mean difference between the two estimates is 3.2% with the Vulcan-NRT estimate slightly larger and with greater short-term (weekly) variability. However, in 2020, the mean difference increases to 17.7% with the Liu estimate showing a much larger decline. The source of the difference increase is not clear.

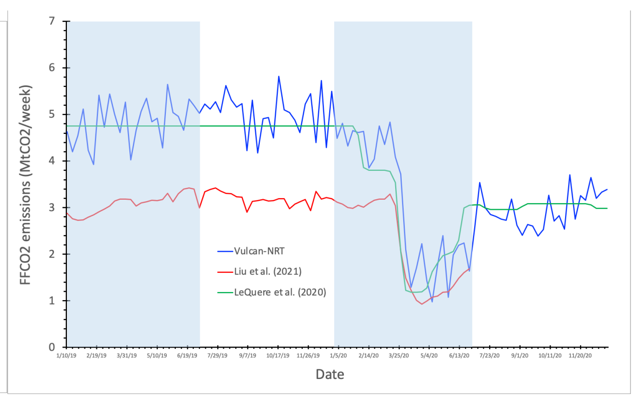
Aviation $FFCO_2$ emissions are significantly larger (mean difference: 33.5%) throughout 2019 and 2020 in the Vulcan-NRT estimate than that found in Liu et al. This discrepancy could be due to how Liu allocated the flight data to individual countries, not described in Liu et al. (2020a). Vulcan-NRT will reflect all jet fuel sales to the retail level and hence, will include any airplane refueling in domestic airports which will include all domestic flights and an unknown percentage of international flights. In spite of the absolute magnitude difference between the two, the percentage decline in 2020 relative to 2019 is comparable.

The Liu et al. power sector exhibits emissions larger than Vulcan-NRT (mean difference: 19.0%) throughout the 2019 to 2020 time period (Figure S3.c) though there is considerable agreement on the shorter-term (weekly) variations. Both studies make reference to the same underlying electricity output data. However, the Vulcan-NRT uses fuel- and time-specific CO_2 emission factors while Liu et al. uses a single value.

Differences in the industry sector are large Liu et al. estimating 43.2% more emissions over the 2019 to 2020 time period (Figure.S3.d). Furthermore, Liu et al. estimates a larger decline in the first half of 2020 compared to Vulcan-NRT. The general offset may be due to the use of EDGAR 2019 from the "IND" sector compared to the U.S.-based fuel consumption data used here (Janssens-Maenhout et al., 2019).

Differences in the residential and commercial sector are similarly large averaging -50.8% with the Liu et al. estimate exceeding the Vulcan-NRT through the entire 2019 to 2020 time period (Figure S3.e). Liu et al. references the 2018 values to residential emissions in the EDGAR data, but the EDGAR sector "RCO" refers to "Energy for buildings" so the assumption is that this Liu et al. sector is the combination of commercial and residential emissions and not residential emissions alone (Janssens-Maenhout et al., 2019). Vulcan-NRT estimates a larger decline in 2020 but does not make any correction for surface temperature as performed by Liu et al. (2020a). This may account for the different decline estimation.

a) Ground Transportation



b) Aviation

c) Power

d) Industry

e) Residential & Commercial

f) Total

Figure S3*. Comparison of weekly, sector-specific Vulcan-NRT $FFCO_2$ emissions to LeQuere et al., (2020; 2021) and Liu et al. (2020a; 2020b). Blue shading denotes the first six months of 2019 and 2020.*

Comparison to LeQuere et al. (2020; 2021) used the estimated emissions which included each countries' share of international transport (as opposed to UNFCCC accounting where international transport is included in the global total only). That was more consistent with the Vulcan-NRT approach in which international transportation fuels that originate as part of the US fuel supply are included. The "medium" scenario results were used, and all sectors used as stated except for comparison to the Vulcan-NRT combined residential and commercial sector, the LeQuere "Public" and "Residential" categories were summed. LeQuere 2019 values consisted of a single daily mean (Figure S3). The LeQuere $FFCO_2$ emissions estimate representing electricity generation and those for the residential sector were adjusted for heating degree days (HDD) to normalize the 2019 and 2020 results. Vulcan-NRT did not similarly perform a normalization (Vulcan-NRT main results were compared to a detrended 2005-2019 mean, thereby averaging out weather-related anomalies). This may partly explain the relatively flat emissions trend over 2020 for these two sectors in the LeQuere results (Figure S3.c, S3.e).