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Timely estimates of India's annual and monthly fossil CO_2 emissions

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Abstract

India is the world's third-largest emitter of carbon dioxide and is developing rapidly. While India has pledged an emissions-intensity reduction as its contribution to the Paris Agreement, the country does not regularly report emissions statistics, making tracking progress difficult. Moreover, all global estimates of India's emissions are for its financial year, not aligned to the calendar year used by almost all other countries. Here I compile monthly energy and industrial activity data allowing the production of estimates of India's CO_2 emissions by month and calendar year. Emissions show clear seasonal patterns, and the series allows the investigation of short-lived but highly significant events, such as the near-record monsoon in 2019 and the COVID-19 crisis in 2020. Data are available at https://doi.org/10.5281/zenodo.3894394 (Andrew, 2020).

Keywords: India, CO_2 emissions, Covid-19, seasonality

Introduction

As the world rapidly approaches the temperature limits set in the Paris Agreement (CONSTRAIN, 2019), timely estimates of greenhouse gas emissions are critical for steering policy and scientific understanding of the global carbon cycle (Le Quéré et al., 2020). India, although having low per-capita emissions, is the world's third-largest emitter of carbon dioxide (Friedlingstein et al., 2019), yet its most recent official report of emissions covers the single year 2014 (GOI, 2018).

According to available estimates, India's CO_2 emissions have grown by about 4.9%/yr over 2010–2018 (Crippa et al., 2019). This growth has mainly been driven by expansion of the economy as, among other things, the country's labour pool grows and much-needed energy supply is increased (Karstensen et al., 2020), and much of this energy is supplied by coal and petroleum products. Countering these upward pressures on CO_2 emissions, India's recent development of small renewables, particularly solar and wind, has exerted a downward pressure on emissions growth, assisted by a sharp decline in prices for these technologies and ambitious goals for renewables growth that have been repeatedly strengthened (Khanna, 2010; MNRE, 2015; Varadhan, 2019).

India does publish a great deal of energy data, but it is scattered across many documents, often not in machine-readable form, occasionally containing errors, and generally without much documentation. The country's official estimates of CO_2 emissions are infrequent and never for more than a single year (GOI, 2004, 2012, 2015, 2018). Moreover, these reported emissions are for India's financial year, running from April to March, so that they do not align with the calendar-year estimates provided by almost every other country (Andrew, *accepted*). This gap in official reporting has been filled by third parties estimating emissions largely based on available financial-year publications, whether directly or via intermediate sources (e.g., IEA, 2019a; Gilfillan et al., 2019; EIA, 2020; Hoesly et al., 2018).

Given the rapid pace both of India's development and of the change in global context, emissions estimates at a frequency greater than annual are also of interest. Higher-frequency data open up opportunities to analyse the relationships between emissions and policy shifts, economic cycles, weather, and more. The ability to explain why emissions have changed is critical to developing effective emissions policies.

Much of India's energy data is not available in formats that are readily machine-readable. In many cases, tables must be copied from PDF-format reports, either automatically using 'scraping' scripts, or by hand. On some occasions, reports posted on official websites are low-quality scans of signed documents, further reducing the availability of these data for analysis.

The International Energy Agency in 2020 stated that the "Government of India should … Improve the collection, consistency, transparency and availability of energy data across the energy system at central and state government levels" (IEA, 2020, p. 18). While government ministries responsible for publishing these data are making moves to improve the availability of more recent data, there are still obvious examples of copy-and-paste errors in spreadsheets, random misspellings, filename glitches, and even incorrect units given in the Energy Yearbook. During the Covid-19 lockdown in India, CEA stopped publishing daily generation reports for four weeks. Clearly much data work is still manual, and further automation will significantly improve India's ability to produce robust and timely estimates of fossil CO_2 emissions.

Monthly emissions estimates are also a core input to atmospheric inversion models (Oda et al., 2018). The standard approach taken in the literature to produce monthly emissions estimates is to use a temporal profile based on partial monthly activity data to temporally downsample annual emissions estimates. Three examples of this downsampling approach in the literature are the very first seasonal estimates made by Rotty (1987), CDIAC's gridded estimates (Andres et al., 2011) and EDGAR's temporal profiles (Crippa et al., 2020). Rotty (1987) and Andres et al. (2011), for example, used coal-fired power generation as a proxy for all coal consumption in India, while Crippa et al. (2020) used a proprietary database of activity data.

Here I present a new dataset collating available information on India's monthly energy production and consumption, as well as cement production, and use this dataset directly to estimate India's monthly and calendar-year CO_2 emissions. In contrast to downsampling techniques, the method used here provides accurate estimates of monthly CO_2 emissions in India.

Materials and Methods

Fossil CO_2 emissions can be divided into four main source categories: coal, oil, natural gas, and carbonates (Friedlingstein et al., 2019). For the fossil fuels, estimates of monthly consumption are required, while for carbonates, production statistics are needed. In all cases, apparent energy consumption approximates true consumption, omitting some minor changes in stocks. For example, reported consumption of petroleum products is most likely supply to the market, with stocks at petrol stations and in vehicles not accounted for. A

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summary of the methodology is presented here, while full details are provided in the Supplementary Information.

Since India does not report sub-annual coal consumption, apparent consumption must be calculated using data on production, imports, exports, and stock changes. While these data are incomplete, they are sufficient to produce a reasonable estimate of monthly coal consumption. Importantly, the goal of this analysis is CO_2 emissions from all oxidation of solid fossil fuels, rather than the more limited emissions from combustion for energy purposes, and this means it is unnecessary to separate out, for example, coking coal used in steel manufacture, which is oxidised rather than combusted.

The energy data sources used include revised, historical data from the Indian Bureau of Mines (2019), Ministry of Coal (various years-c), UN Statistics Division (2020); provisional and revised data from CIL (various years), SCCL (various years), Ministry of Coal (various years-b, various years-a), and Ministry of Mines (Ministry of Mines, various years); power station stocks from CEA (various years-b, various years-a); and international trade from DGCIS (2020) and DOC (2020), supplemented by recent provisional estimates reported by the media. While these data sources combined allow a good estimate of production and stock changes of hard coal with a lag of less than one month, lignite production data has a slightly longer lag, and simple extrapolation is used to complete the picture for the most recent month or two (SI Fig 15). It is assumed that the share of consumed coal that is not oxidised is negligible.

Monthly data on production and consumption of petroleum products are available from the Petroleum Planning and Analysis Cell of the Ministry of Petroleum and Natural Gas In all four categories, revised data are always used when available in preference to provisional data. Since consumption data are available, the apparent consumption approach used for coal is not required for petroleum products. All products except for bitumen and lubricants are assumed to be fully oxidised; while it is known that some naphtha is used for production of durable commodities, this share is not known.

PPAC also publishes monthly data on production, import, and supply of natural gas (PPAC, various years-a, b). Some data on consumption by sector are also published, and this is used to estimate the proportion of natural gas that is oxidised.

For carbonates, monthly data on clinker production are not available, so monthly cement production statistics are combined with a time-varying estimate of the clinker ratio to produce an estimate of monthly clinker production. Data on production of lime, glass, and ceramics were not available, and emissions from these carbonate sources are therefore omitted; India's second Biennial Update Report indicates these emissions combined contributed 1.9% of fossil CO_2 emissions in 2013-14 (GOI, 2018).

Once monthly energy consumption and clinker production estimates are available, these are converted to estimates of CO_2 emissions. For fossil fuels this requires first converting the consumption in physical units to energy units using information from IEA for coal and petroleum products (IEA, 2019b, c) and PPAC (no date) for natural gas, and then applying emission factors from the IPCC's 2006 guidelines (Gómez et al., 2006). For clinker

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production, the method of Andrew (2019) is followed to estimate emissions from physical production in tonnes.

For complete details of the methodology, data sources used, comparisons of provisional and revised energy data, comparisons of energy data from different sources, and more, see the Supplementary Information. The monthly energy and cement data collated here are available at https://doi.org/10.5281/zenodo.3894394 (Andrew, 2020).

Results and Discussion

Following the described methods, I have assembled monthly CO_2 emissions estimates for coal, oil, natural gas, and cement for India (Figure 1). The available data and methodology allow estimation of emissions from coal from January 2009, oil from April 1998, natural gas from April 2009, and cement from April 2004.

Emissions from oxidation of coal form the largest share of the total, rising from about 61% in 2010 to 66% in 2014, before levelling off to about 65% in 2019. Peak monthly emissions to date were in May 2019 with 157 Mt CO_2 in the month. While emissions from coal grew at an average rate of 5.5%/yr over 2009–2018, in 2019 they grew only 0.3%, as electricity demand dropped dramatically (SI Fig 39).

Emissions from oxidation of oil (petroleum products) are the next-largest source with about 25% of the total, reaching 50–60 Mt CO_2 per month in recent years. Emissions from natural gas and cement production are both about 5% of the total.

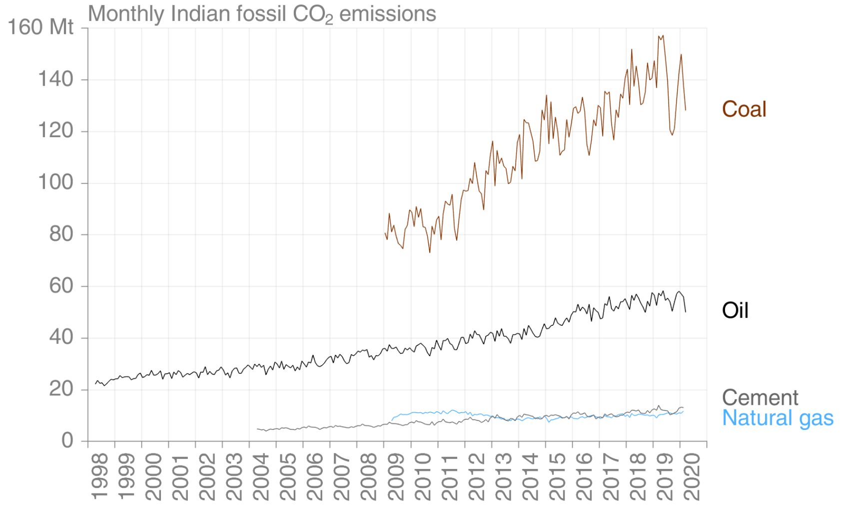

Figure 1: Final monthly CO_2 emissions by category. Source: Own calculations.

While the monthly emissions series appear quite volatile, X-11 seasonality analysis (Darné et al., 2018; Shiskin et al., 1967; summarised in SI) reveals strong, underlying seasonal patterns (Figure 2). Coal emissions reach a peak in March through May, before declining by up to 10% below the trend line for the typical southwest monsoon months of June through August and then picking up again towards the end of the year, and emissions from both oil and cement show similar though somewhat less smooth patterns. In addition, oil emissions exhibit a consistent dip in January and also in March–April. Natural gas emissions show a substantially lower amplitude of seasonality, under ±5%, with recent years showing a peak during the monsoon, perhaps being used as peaking plants. The seasonality of natural gas emissions is also less stable over time, as supply constraints have changed considerably. Despite relatively clear derived seasonal signals, considerable volatility is superimposed on this seasonality in all emissions series (Figure 1).

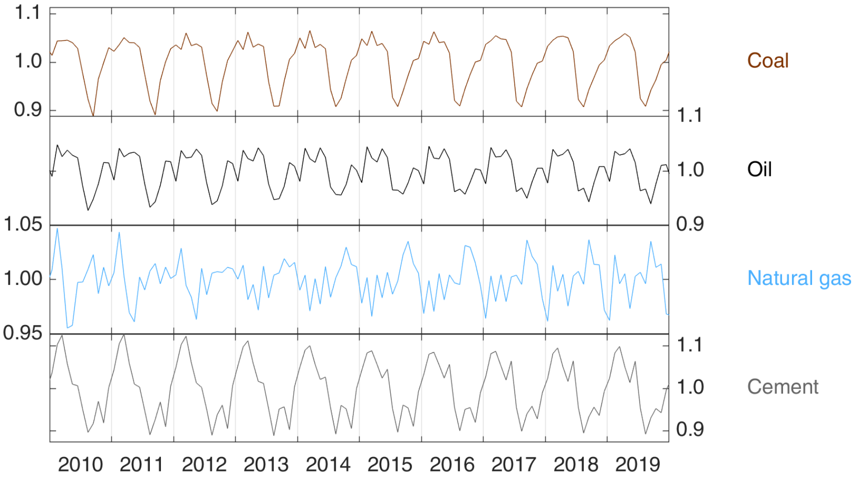

Figure 2: Seasonality of the four emissions categories, derived using the X-11 method.

Turning to calendar-year emissions, Table 1 summarises emissions by category and total CO_2 emissions for India from 2009 to 2019. Each category has grown by about 4% per year over the last five years, although growth from year to year has not been smooth, with coal emissions growing only 0.3% in 2019. Total CO_2 emissions in India have grown from 1.7 Gt in 2011 to 2.6 Gt in 2019, at an annual growth rate of 4.2%.

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Table 1: Calendar-year CO_2 emissions in India by category, million tonnes.

Year	Coal	Oil	Natural gas	Cement	Total
2009	975	429	-	81	-
2010	1007	435	134	86	1662
2011	1065	455	136	91	1748
2012	1201	485	126	100	1911
2013	1286	492	106	108	1991
2014	1411	507	107	116	2141
2015	1445	551	107	118	2221
2016	1494	609	113	123	2340
2017	1555	627	118	121	2420
2018	1673	648	123	139	2583
2019	1678	666	127	144	2614
CAGR 2015-19*	4.1%	4.4%	4.2%	4.1%	4.2%

* Continuous compounding and adjusted for leap years.

The monthly Indian fossil CO_2 emissions dataset produced here includes all but about 2% of anthropogenic fossil sources in the country, excluding emissions from decomposition of fossil carbonates in the production of lime, glass and ceramics. The time lags of the emissions estimates are at most two months, and under one month for coal, the most important emissions source.

Comparison with existing emissions estimates

To compare the emissions estimates produced here with other datasets, I aggregate monthly emissions to annual emissions against the Indian financial year, April–March. Figure 3 compares the emissions estimates produced here with those of the IEA (2019a) and CDIAC (Gilfillan et al., 2019), and also EDGAR (Crippa et al., 2019) for cement, noting that all three of these datasets report emissions in 2017–18 as 2017 emissions.

For coal the method produces one series of oxidation emissions, and this is largely similar to the estimates from both IEA and CDIAC (Figure 3a). In the final two years 2017-18 and 2018-19, however, IEA has lower estimates. Close investigation has revealed potential errors in IEA's reported stock changes in both years, amounting to about 30 Mt in 2018-19 (detailed in SI section 2); IEA's 2018-19 estimate is indicated as being preliminary.

For oil there are two series: combustion and oxidation (Figure 3b). The combustion series lies very close to that of the IEA – which specifically includes only energy uses of oil products – over the entire period. Oxidation emissions are on average about 50 Mt CO_2/yr higher throughout the period, largely reflecting emissions from oxidised naphtha and petroleum coke. CDIAC's series exhibits quite a different trend.

The natural gas emissions series includes three estimates: combustion, oxidation, and full oxidation (Figure 3c). The last of these assumes that all natural gas is oxidised, merely to present a bounding case. The combustion series agrees well with IEA's estimates, but again the CDIAC series exhibits a very different trend, diverging sharply from 2013-14. The oxidation series is significantly higher, largely reflecting the emissions from production and use of nitrogen-based fertilisers. Emissions show a very prominent peak in 2010–2012, a result of the rapid development of offshore gas field KG D6, but while this led to the construction of a number of gas-fired power stations, production from this field dropped substantially leading to substantially reduced domestic supplies and stranded power assets (MoP, 2019)(SI Fig 31).

For cement process emissions, the series is much lower than that of CDIAC, for reasons that have been explained elsewhere (Andrew, 2019). EDGAR's series appears to be reasonable up until 2010-11, when national clinker production data are readily available, but thereafter the trend appears unrealistic.

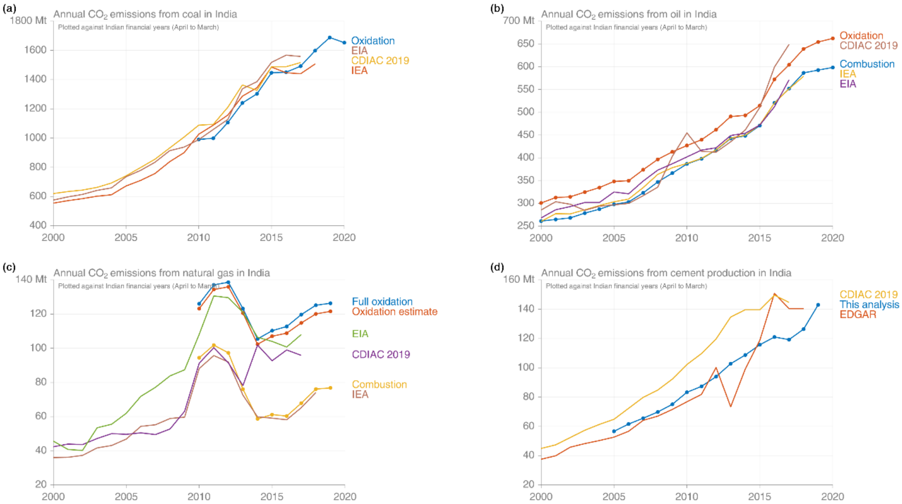

Figure 3: Comparison of financial-year emissions estimates with other datasets. Sources: (Gilfillan et al., 2019; IEA, 2019a; Crippa et al., 2019; EIA, 2020), own calculations.

The most recent Indian official estimate of total CO_2 emissions was presented in India's second biennial update report to the UNFCCC, with 1.998 Gt in the financial year 2013-14 (GOI, 2018). In the analysis here, total CO_2 emissions in India in 2013-14 are estimated to be 2.000 Gt (coincidentally almost exactly 2 Gt). While this is strikingly close, this is not a true measure of the accuracy of the method since some errors have cancelled: it is known that the emissions estimates generated here exclude some carbonate sources, and there are other assumptions in various factors used here that introduce uncertainty. Nevertheless, this match with the official total is encouraging.

Deviations from forecasts

If official forecasts of growth in hard coal demand had played out, demand would have been more than 20% higher in 2019–20, with consequently higher emissions (Figure 4). These forecasts were based on assumptions of underlying growth in the economy of as much as 10%/yr (Ministry of Coal, 2011). In fact, the report on coal and lignite for the 12th five-year plan included a second scenario with much higher demand growth, reaching 1200 Mt already in 2016–17. While growth in demand followed the projection reasonably closely until 2014–15, it has since slowed markedly.

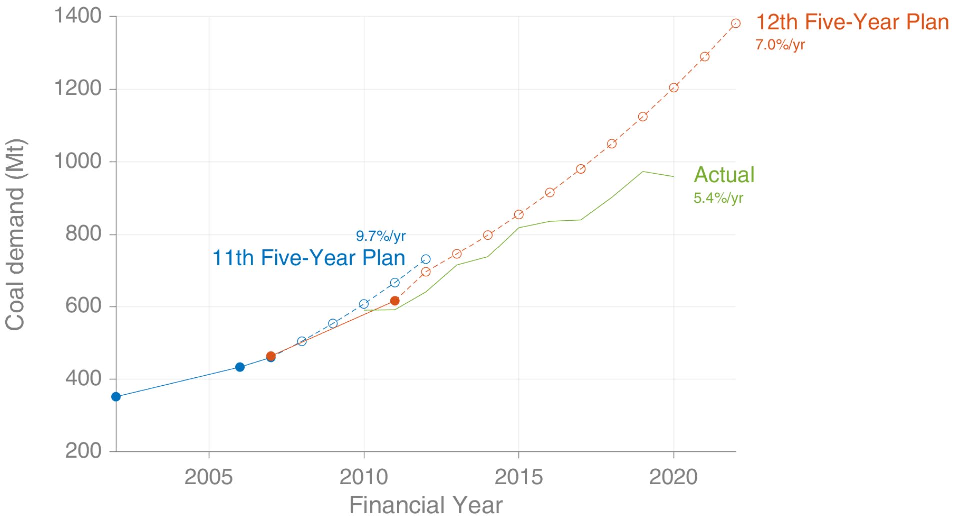

Figure 4: India's hard coal demand. Filled circles and hollow circles show reported and projected demand in two five-year plans, while the green line shows actual demand, and annual growth rates are indicated. Demand does not equal consumption because of changes of stocks at power stations and industry. Source: Ministry of Coal (2006, 2011), own calculations.

There were certainly significant tailwinds in support of high growth, such as strong political will, the 25%/yr annual average growth in coal imports 2011–2014, the rapid construction of new coal-fired capacity 2010–2016 (SI Fig 37), high targets for coal mining, the opening up of coal mining to competition, and significant expansion of the labour pool, among others. But these faced an array of headwinds constraining growth, including difficulty in acquiring land and environmental permits, local protests, difficulty obtaining finance (CEA, 2019), rail under-capacity, debt, subdued demand, unpredictable monsoon rains, "Coalgate" (illegal government coal block allocations; Gilbert and Chatterjee, 2020), the dramatic fall in renewables prices, and large economic shocks such as 2016's demonetisation, 2017's GST introduction and 2020's COVID-19 pandemic. In comparison, China's much larger consumption of coal grew by almost 9% over 2000–2010 (NBS, 2019).

As suggested by Figure 5, growth in electricity generation from coal – recently about 75% of all coal consumption – has been more linear than exponential in the last ten years.

Figure 5 also shows how significant the deviation in coal generation was in the latter half of calendar-year 2019, also clear in Figure 1. From 2008 to 2018, the largest deviation of monthly electricity generation with seasonality removed from the trend line is 110 GWh/day, while in 2019 it peaked at over 390 GWh/day. Generation from hydropower was 17% higher in 2019 than in 2018, partly a result of a very heavy southwest monsoon (IMD, 2019). But total electricity demand was down by almost 3% in the second half of 2019 compared to the same period in 2018, and more than 13% down in October 2019 (POSOCO, 2020), probably driven by a stalling economy, with value-added growth in the manufacturing sector below zero in the period July to December 2019 (MOSPI, 2020).

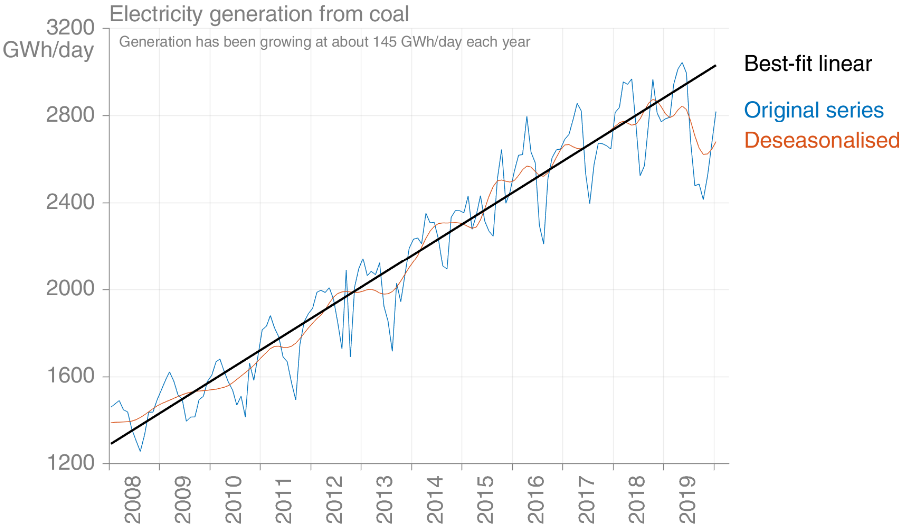

Figure 5: Average daily electricity generation from coal by month, divided by month length, deseasonalised, and a best-fit linear regression. Source: CEA, own calculations.

The seasonal patterns of emissions generally follow the monsoon, particularly with less electricity generation from coal. Rather than being due to decreased demand or difficulty producing electricity from coal during the monsoon, the reason for this is higher generation from both hydro and wind, both of which peak during the monsoon season. In fact, electricity demand is highest through summer and lowest in winter (SI Fig 39), with energy required in India for summer cooling substantially higher than energy required for winter heating (Gaur et al., 2016).

COVID-19 effects

March would usually be one of the highest coal emissions months of the year (Figure 2), but in 2020 this was affected by Covid-19 measures. India introduced a nationwide lockdown (curfew) on March 25th, although some areas introduced lockdowns in the days before (Roy and Phartiyal, 2020; Varadhan, 2020). Initially the lockdown was to be for three weeks, but was extended in April to at least May 3rd (Miglani and Jain, 2020). Largely as a result of substantially reduced activity, and despite the lockdown only affecting about one-third of the month, CO_2 emissions from coal in March 2020 were over 18% lower than in March 2019. This drop is likely to be even more significant in April, since the entire month will be affected by lockdown, and early data show a sharp decline in the consumption of petroleum products (Reuters, 2020).

Sources of uncertainty

There are several sources of uncertainty in these emissions estimates, which can be divided into four categories. First is the omission of some emissions sources. This analysis has excluded emissions from some carbonates, estimated to be equivalent to less than 2% of India's total CO_2 emissions. Further, some imported non-energy goods containing fossil carbon are excluded. While the case of Iceland shows clearly that imports of carbon anodes used in aluminium manufacture can be important (Andrew, *accepted*), these are not imported by India (DGCIS, 2020). India does import urea from China, and the approach used here will not capture emissions from its use in agriculture; however, the amount is likely to be below 2 Mt/yr (see SI).

Second is use of provisional data and extrapolation before revised data are available. Revisions of coal, the most important emissions source, are in general relatively minor, and use of provisional data along with the methods used here to fill gaps are unlikely to introduce significant error (see SI). Lignite production is relatively small and stable, so its extrapolation is not expected to introduce significant uncertainty. Moreover, if monthly press releases of mineral production have indeed recommenced, the lignite uncertainty will be largely removed in future.

Third is that of the revised data, effectively measurement error. While energy and emissions data in China serve as a cautionary example (Korsbakken et al., 2016), and India's economic production data face heavy revisions (SI Fig 38), these issues are not expected to affect India's energy and emissions data. One of the reasons for China's high data uncertainty is the very large number of enterprises involved, but in India energy and cement production are highly concentrated and closely monitored. As examples, two coal-mining companies, both state-owned, account for close to 90% of all coal production, and three state-owned fuel retailers account for about 90% of India's retail fuel sales (Reuters, 2020). While there have recently been claims of official tampering with economic statistics in India (Nadeem, 2019; The Telegraph, 2019), there is as yet no evidence of manipulation of energy or industrial production data.

The final category of uncertainty is in the emission factors, energy contents, and oxidised fractions used. The largest of these may be the assumption that all naphtha is oxidised, which potentially leads to an overestimate in the order of 1–2 MtCO$_2$/month.

The combination of data availability and assumptions made mean that coal emissions can be estimated with the shortest lag, within a week of the end of the month. Oil, natural gas, and cement emissions are usually delayed an additional month. There are two main reasons that coal emissions have a short lag. Firstly, coal-fired power stations have faced critical shortages at times and are monitored very closely, and secondly, the two largest mining companies, which report within a day of the month closing, make up the great majority of production. While short-lag emissions estimates require extrapolation of some components (e.g., lignite production), and use provisional data, as reported and revised data become available, these are incorporated into the estimation procedure used here.

While there are some identified deficiencies in the emissions estimates here, including the exclusion of emissions from use of limestone apart from in cement clinker production, comparisons with annual estimates from other sources, and in particular India's official reporting to the UNFCCC, suggests relatively good accuracy and therefore a high level of usefulness.

Conclusions

The monthly, short-lag estimates of India's CO_2 emissions produced here will likely prove useful for tracking the country's progress against its nationally determined contribution under the Paris Agreement, but will also be useful for analysis of the drivers of India's emissions both historically and in future. Calendar-year estimates derived from these are also better aligned to the global datasets into which India's emissions are incorporated.

The future pathway of India's CO_2 emissions is highly uncertain. But India is developing rapidly in a world that – largely because of emissions in other countries – is carbon constrained. As India's population grows, as roads, railways and houses are built, as both vehicles and houses are electrified, as solar panels and wind turbines are installed, and as new coal mines are opened, tracking CO_2 emissions monthly will allow a closer observation on the consequences of these changes.

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Data Availability

All monthly input data used in the analysis, in addition to the monthly emissions estimates and seasonality analysis results, are available at https://doi.org/10.5281/zenodo.3894394 (Andrew, 2020).

Code Availability

Scripts to reproduce the figures in this article are included in the Supplementary Information, while other scripts used in this study are available from the corresponding author upon reasonable request.

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