COVID-19 lockdown NOx emission reductions can explain mover halfost of the coincident increase in global atmospheric methane

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Abstract. Compared to 2019, measurements of the global growth rate of background (marine air) atmospheric methane - rose by about 50%5.5 ppb/yr in 2020, reaching 15.2 ppb/yr. Models of gGlobal atmospheric chemistry models have previously shown that reductions in nitrogen oxide (NOx) emissions reduce levels of the hydroxyl radical (OH), and lengthen the methane lifetime. Acting in the opposite sense, reductions of carbon monoxide (CO) and non-methane volatile organic compound (NMVOC) emissions increase OH and shorten methane's lifetime. Using estimates of NOx, CO and NMVOC emission reductions associated with COVID-19 lockdowns around the world in 2020, together with model-derived regional and sectoral aviation sensitivities of methane to theseNOx emissions, we find that NOx emissions reductions led to a 4.3 (3.6 to 5.0) ppb/yr increase can fully explain the observed surge in the global methane growth rate. Reductions in CO and NMVOC emissions partly counteracted this, changing (reducing) the methane growth rate by -1.1 (-0.5 to -1.5) ppb/yr (CO) and -0.1 (0.0 to -0.3) ppb/yr (NMVOC). Uncertainties refer to ±1 standard deviation model ranges in sensitivities. Whilst changes in NOx anthropogenic emissions related to COVID-19 lockdowns are probably not the only important factor that has influenced methane since the beginning of 2020during 2020, it is clearthese results indicate that they have had a large impact are a key factor that will need to be included within any attribution study, and that the net effect of NOx, CO and NMVOC emissions changesy may well be the dominant drivercan explain over half of the observed 2020se recent methane changes. Large uncertainties remain in both emissions changes during the lockdowns and methane's response to them; nevertheless, this analysis suggests that further research into how atmospheric composition changed over the lockdown periods will help us to interpret past methane changes and to constrain future methane projections. The major global scale changes in composition of the Earth's atmosphere measured during lockdown provide unprecedented constraints on the sensitivity of the atmospheric chemical system to changes in emissions, and are of great utility for evaluating policy-relevant models.

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1 Introduction

Methane is a powerful greenhouse gas and important precursor of tropospheric ozone; both are key air pollutants and short-lived climate forcers (SLCFs). The 2013 Intergovernmental Panel on Climate Change assessment estimated methane's Global

~~Warming Potential (GWP) over a 100 year time horizon to be 28 (Myhre et al., 2013); updates to its short-wave radiative forcing have increased this value by 14% (Etminan et al., 2016). Advances in our understanding of how GWP metrics relate to climate change indicate that it is not only the magnitude of emissions, but also the rates of change of SLCFs like methane that strongly influence near-term global temperature changes (Allen et al., 2018; Cain et al., 2019).~~ Several factors in addition to rising anthropogenic methane emissions have influenced the evolution of atmospheric methane from its pre-industrial level of ~700 ppb to its present-day value of over 1900 ppb. The Intergovernmental Panel on Climate Change's Sixth Assessment Report (Szopa et al., 2021) assessed how changes in emissions of NOx, CO, and NMVOCs have contributed to historical changes in methane, through their impacts on OH, the main sink for methane. A range of modelling studies have explored these indirect impacts on methane (e.g., Shindell et al., 2005, 2009; Stevenson et al. 2013; Thornhill et al., 2021). For example, the Atmospheric Chemistry and Climate Model Intercomparison Project found that 1850-2000 increases in anthropogenic NOx emissions had reduced year 2000 methane levels by 955 ppb, whilst growing emissions of CO and NMVOCs had increased methane by 150 ppb and 59 ppb, respectively (Table 7 of Stevenson et al., 2013). These results have quite large uncertainties (at least ±10%, based on the model range in Stevenson et al. 2013), but indicate that non-methane (especially NOx) emissions have had very significant impacts on methane. ~~These post-2013 updates increase the importance of~~Better understanding of what controls methane and its evolution is vital for progress towards~~in the context of~~ the Paris Climate Agreement target that seeks to limit warming to 1.5°C above pre-industrial levels.

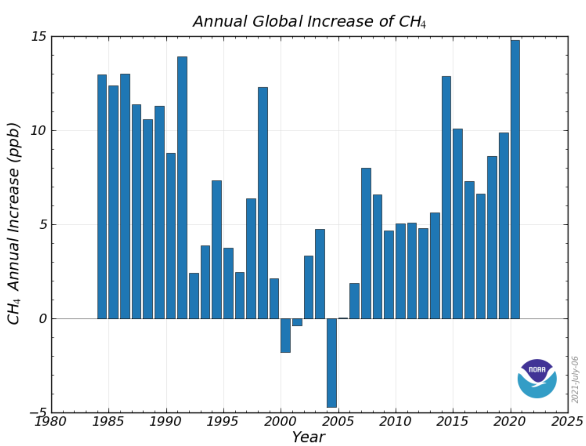
Following the onset of the COVID-19 pandemic in early 2020, the trace gas composition of the global atmosphere changed~~has shown~~ substantially~~ changes~~. Atmospheric nitrogen oxide~~ (NOx)~~ levels ~~have~~ reduced as surface and aviation NOx emissions fell (Bauwens et al., 2020; Cooper et al., 2022), whilst the measured growth rate of methane (CH_4) rose~~has risen~~ sharply in 2020 (Laughner et al., 2021). The observed NOx changes are clearly linked to falls in emissions resulting from lockdowns, but the driver of the methane increases is less clear, with some studies discussing causes related to decreases in OH (e.g., Weber et al., 2020; Laughner et al., 2021) while others suggest rises in sources (e.g., Feng et al., 2022).~~remain unexplained (e.g., Vaughan, 2021).~~ Methane, ~~and~~ NOx, CO and NMVOCs are linked ~~through~~ via the oxidising capacity of the atmosphere, specifically by the abundance of the hydroxyl (OH) radical. The response of global atmospheric chemistry to the large lockdown perturbation since early 2020 provides an opportunity to explore the sensitivity of the NOx-CO-NMVOC-OH-CH_4 system, and compare models and observations. Here we use model-derived sensitivities of global methane to NOx, CO and NMVOC emissions~~s~~, together with estimated changes in anthropogenic ~~NOx~~ emissions of these species related to the COVID-19 lockdowns, to calculate estimated~~the~~ impacts from lockdown emissions changes on the growth rate of global methane, and compare this to ~~methane~~ observations.

2 Measurements of atmospheric methane and nitrogen oxides

Recent methane measurements from the US National Oceanographic and Atmospheric Administration (NOAA) show that the atmospheric (marine air background) methane growth rate rose sharply from 9.7~~9~~ ppb/yr in 2019 to 15.2~~14.8~~ ppb/yr in 2020,

~~the~~ higher~~est~~ than any preceding annual value in the ~~37-year~~ NOAA record, that started in 1984 (~~Figure 1;~~ Dlugokencky, 2022~~1~~). Many of the earlier large year-to-year jumps in methane's growth rate relate in part to variability in climate and emissions associated with El Niño Southern Oscillation (ENSO), and in part~~icular~~ because of modulation of methane's main sink, oxidation by OH (Turner et al., 2018; Zhao et al., 2020). ~~ENSO indices have not shown strong variations over 2019-2020 (WMO, 2021).~~ The start of 2020 marked the onset of a La Niña that has persisted into 2022. Past La Nina's have not always shown clear links with methane's growth rate, and the influence of the current ENSO phase on methane is uncertain.

Measurements of nitrogen dioxide (NO_2) from satellite instruments and nitrogen monoxide (NO) and NO_2 from surface sites show that levels of atmospheric NOx (NO + NO_2) dramatically fell globally during 2020 (Bauwens et al., 2020; Laughner et al., 2021; Cooper et al., 2022). This was driven by ~~as~~ COVID-19 lockdowns around the world that reduced emissions, mainly from transportation (Venter et al., 2020; Lamboll et al., 2021; Doumbia et al., 2021).



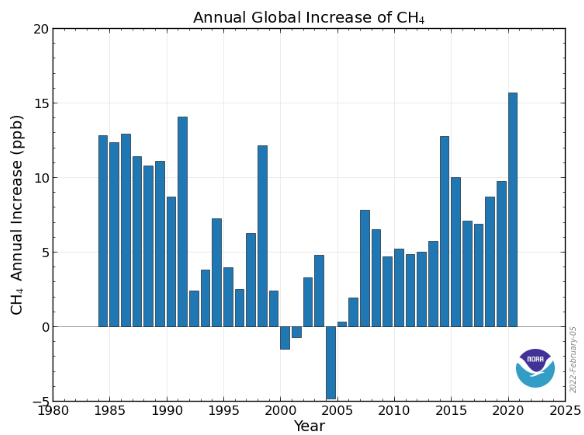


Figure 1: Global annual changes in surface atmospheric methane mole fraction (ppb) 1984-2020 (Dlugokencky, 20221).

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3 Sensitivity of global methane to NOx, CO and NMVOC emissions

Global atmospheric chemistry model simulations indicate that decreases in NOx emissions lead to reductions in OH and increases in the global methane lifetime (Prather, 1994; Derwent et al., 2001; Wild et al., 2001; Stevenson et al., 2004; Weber et al., 2020). Similarly, decreases in CO and NMVOC emissions lead to increases in OH and decreases in methane lifetime (Derwent et al., 2001; Wild et al., 2001). Multi-model studies have calculated methane effects for NOx emissions from specific world regions (Fry et al., 2012) and the aviation sector (Lee et al., 2021). Although methane has an atmospheric lifetime of about 10 years, the models show that its peak response occurs within a few months of the cessation of a sudden short-lived (month- or year-long) pulse of extra NOx emissions (Derwent et al., 2001; Wild et al., 2001; Stevenson et al., 2004). This indicates that the impacts on methane from the sudden changes in emissions associated with lockdowns will have had rapid impacts on methane's growth rate. Multi-model studies have calculated methane effects for NOx emissions from specific world regions (Fry et al., 2012) and the aviation sector (Lee et al., 2021).

We first illustrate the basis of our approach by describing the model experiments performed by Derwent et al. (2001), who conducted a series of experiments simulations with the global tropospheric chemistry model STOCHEM to quantify the impact of NOx emissions on methane. They compared a 4-year long base simulation with a perturbation simulation that was identical apart from an enhancement in NOx emissions of magnitude 1 Tg(NO_2), added during the first month with the Northern Hemisphere surface anthropogenic NOx emissions distribution. The extra NOx produced a short-lived increase in OH, and this led to a rapid depletion of global methane, which peaked with a magnitude of~~at~~ around 0.39 Tg(CH_4) after about six months. The methane deficit then exponentially decayed with an e-folding timescale of about 12 years (the methane perturbation lifetime, τ), with methane levels returning towards their base values. Wild et al. (2001) conducted similar experiments, with year-long emissions perturbations using a different model (UCI CTM), and found very similar behaviour but with slightly larger sensitivities: 1 Tg(NO_2) from global fossil fuel sources yielded a 0.55 Tg depletion of CH_4. These studies also investigated the impact of CO and NMVOC emissions. Changes in global methane burden (Tg) are converted to changes in tropospheric mole fraction (ppb) using the total atmosphere mass of 5.113 x 10^9 Tg and a fill factor of 0.973 for conversion of a total atmosphere abundance to a tropospheric abundance (Prather et al., 2012). We assume the troposphere is well mixed, so surface changes will be the same as whole troposphere changes.

More recently, Fry et al. (2012) analysed results from ~~multi~~11 global ~~-~~models that took part in~~ experiments from~~ the Hemispheric Transport of Air Pollutants (HTAP) study ~~that~~ in order to isolate~~d~~ the impacts on methane of~~of~~ surface NOx, CO and NMVOC emissions from Europe (EU), North America (NA)~~, and~~ South Asia (SA) and East Asia (EA). We utilise that ensemble of ~~11~~ model results here;~~ these~~ model~~s~~ ~~are~~ descriptions are given~~bed~~ in Fiore et al. (2009). Models performed a base simulation, and a series of further repeat simulations with 20% lower anthropogenic emissions f~~F~~or~~ each region~~ and each species for each region~~, Fry et al. (2012) compared each model performed a~~~~a base simulation and to others~~~~one with 20% lower regional anthropogenic NOx emissions from that region~~. In addition to the 20% regional emission reduction experiments, some models also performed global 20% emission reduction experiments (Wild et al., 2012). Four models include results from all the regional and global perturbation simulations: FRSGCUCI-v01, GISS-PUCCINI-modelE, MOZARTGFDL-v2, and TM5-JRC-cy2-ipcc-v1. We calculate a 'four model mean' (4MM) based on these model results. We also show results from the other models to illustrate the range of model behaviour, and show 'multi-model mean' (MMM) results from all available simulations. In t~~T~~he HTAP~~se~~ simulations~~, had~~ methane was fixed as a prescribed boundary condition, precluding direct diagnosis of changes in methane. However, methane changes can be~~ but~~ diagnosed indirectly, by analysing the~~ change in~~ methane lifetime associated with the~~ changes in~~ tropospheric OH sink in each run. We convert these to whole atmosphere lifetimes by assuming fixed lifetimes for methane loss to soils (160 yr) and in the stratosphere (120 yr) (Prather et al., 2012). The HTAP experiments also included a global methane perturbation simulation – allowing the methane feedback factor and perturbation lifetime to be calculated (Prather, 1994; Holmes, 2018). Figure 1 shows whole atmosphere and perturbation methane lifetimes for the~~ six~~ HTAP models, with typical values of~~,~~ around 10 years and 12 years, respectively.

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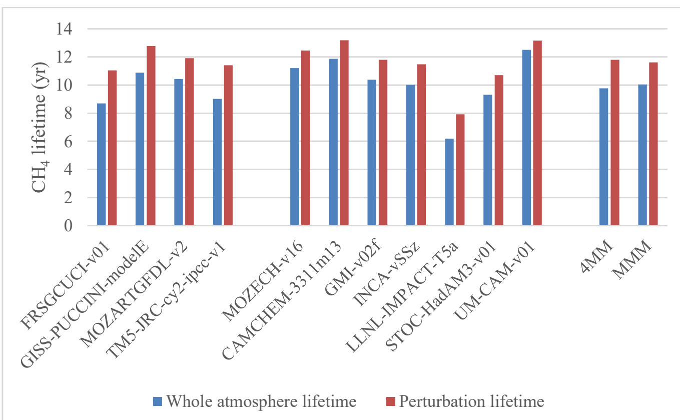

Figure 1. Whole atmosphere and perturbation methane lifetimes (years) for the HTAP models, together with the four model mean (4MM) of the core models (four models on the left), and the multi-model mean (MMM).

-Differences between simulations yielded the change in methane lifetimes due to changes in regional emissions. From these changes in methane lifetime, the equilibrium change in methane was calculated; , that is the change in methane that would have been achievedoccurred if methane levels had been free to respond (e.g., see Stevenson et al., 2013). In model simulations whereith methane is not prescribed, methaneit adjustss towards equilibrium with an e-folding timescale given by the methaneits perturbation lifetime (τ) (Derwent et al., 2001; Wild et al., 2001; Holmes, 2018). WeTo convert equilibrium methane changes derived from sustained changes in emissions to the equivalent methane response for a pulse of emissions for each experiment. , we We use each model'se the perturbation lifetime to calculate the fraction of the equilibrium response that would have been reached after one year; e.g., for the multi-model mean (MMM)a methane perturbation lifetime of 1112.684 years (Holmes, 2018Figure 1) this fraction is $(1-e^{-1/\tau})$ = 87.217%. This method is appropriate because we compare to changes in the observed annual growth rate, and is justified by the rapid response of global methane seen in transient model simulations where methane is free to respond, and because the largest lockdown emissions' perturbations occurred in the first half of 2020. -We normalise results to produce global methane sensitivities per Tg of gas emitted for each HTAP region and globally for each model. Figures 2, 3 and 4 show global methane sSensitivities for NOx, CO and NMVOC emissions are shown in Figures 2, 3 and 4, respectively.

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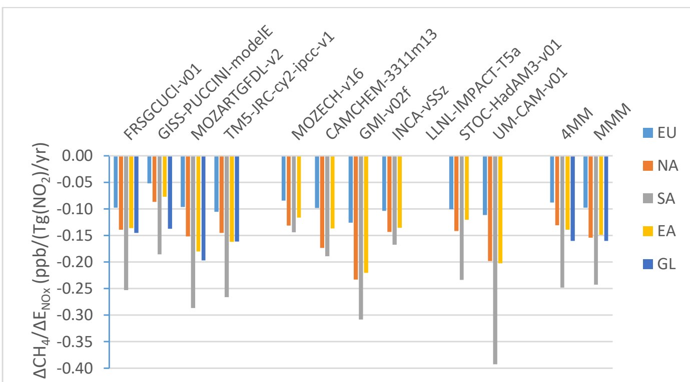

Figure 2. Sensitivity of global methane (ppb) to changes in surface anthropogenic NOx emissions (Tg(NO_2)/yr) for the HTAP models for four regions (Europe, EU; North America, NA; South Asia, SA; and East Asia (EA), and globally (GL). Global results are~~for~~ ~~just~~only available for the four core models, shown on the left of the figure. Also shown are the 4MM and MMM. There are no results for the LLNL-IMPACT-T5a model for NOx; it is included to maintain consistency with Figures 3 and 4.

Figure 2 shows relatively consistent responses to NOx emissions, with all models least sensitive to EU NOx emissions and most sensitive to SA, with NA and EA in between. The 4MM sensitivities are slightly lower than the MMM.

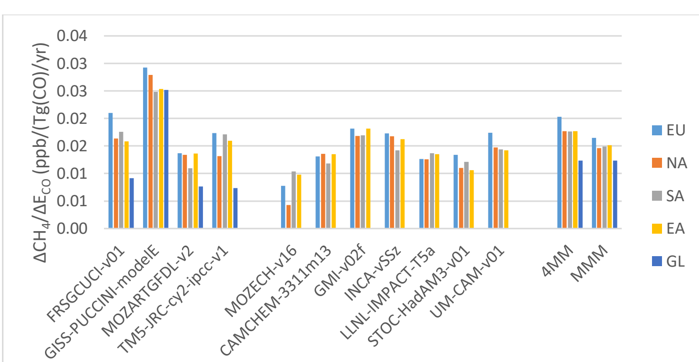

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Figure 3. As Figure 2, but methane sensitivities for changes in surface anthropogenic CO emissions (Tg(CO)/yr).

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As for NOx, Figure 3 shows relatively consistent behaviour across the models for CO, with less variation between regions, reflecting the longer lifetime of CO, which makes the location of emissions less important. The 4MM sensitivities for CO are slightly larger than the MMM values.

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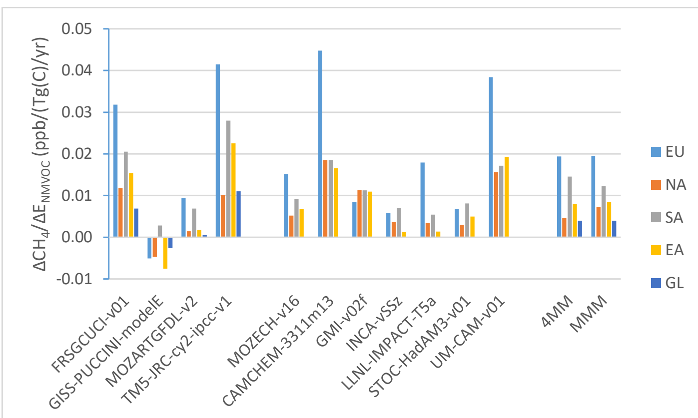

Figure 4. As Figure 2, but methane sensitivities for changes in surface anthropogenic NMVOC emissions (Tg(C)/yr).

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Figure 4 shows more divergence in model response to NMVOC emissions, with one model (GISS-PUCCINI-modelE) displaying an opposite sensitivity to the other models (apart from for SA emissions), and some models showing quite large sensitivities, whilst others are small. This probably reflects differing methods of representing NMVOCs in each model, in terms of both the number of species, grouping together of species, and the sophistication of their oxidation chemistry. Somewhat fortuitously, the 4MM and MMM are similar.

The HTAP experiments used 2001 as their base year, prescribing global methane to be 1760 ppb~~v~~, and each model used their own best estimates of global 2001 emissions. In 2020, surface level background global mean methane was ~1870 ppb~~v~~, and emissions of NOx, CO and NMVOCs had changed relative to 2001. Sensitivities of methane to emissions derived from the HTAP results will differ somewhat from those that would be found if 2020 conditions were used, and this represents an important caveat to our results. However, these differences are unlikely to be substantial, and no more up-to-date multi-model study of the impacts of regional NOx, CO and NMVOC emissions on methane has been published to date, so it represents our best source of information in the literature.

~~***Revised to here 13/07/22***~~

~~and for NOx from aviation (Lee et al., 2021)~~

Similar model simulations have calculated the sensitivity of methane to aviation NOx emissions. Wild et al. (2001) and Stevenson et al. (2004) conducted pulse experiments adding NOx using the global aviation NOx emission~~s~~ distribution, and found a peak impact on global methane of about 2.5-2.6 Tg (equivalent to mole fractions of 0.88-0.92 ppb) for a 1 Tg(NO_2) emission perturbation. Stevenson and Derwent (2009) also found spatial variation in sensitivity for aviation NOx, with the more sensitive regions tending to have lower background NOx levels. The most up-to-date study of aviation NOx is Lee et al. (2021), who assessed multi-model results~~ for aviation NOx emissions~~ using sustained emissions changes, similarly to the HTAP study. Lee et al. (2021) report (their Table 3) a methane radiative forcing sensitivity to aviation NOx emissions of -15.8 mW m^{-2} (Tg(N) yr^{-1})$^{-1}$. We convert this to a methane mole fraction sensitivity to NOx emissions using the relationship between changes in mole fraction and radiative forcing given by Myhre et al. (1998), and then~~. W~~~~which we convert these~~, using a similar methodology to that~~as~~ described above, to the equivalent response for a pulse of emissions. This yields a sensitivity of methane to a pulse change in aviation NOx emissions of 1.12 ppb (CH_4)/Tg(NO_2) yr^{-1}, ~~and find a~~ similar to, but slightly higher than~~sensitivity~~ results from~~to~~ the earlier studies. Lee et al. (2021) also report a 95% likelihood range on the radiative forcing sensitivity, which translates to a standard deviation of 0.21 ppb (CH_4)/Tg(NO_2) yr^{-1}, which we take to be a representative uncertainty for the mole fraction sensitivity to aviation NOx emissions.~~.~~

~~Table 1 summarises results from all these existing studies. For surface NOx emissions reductions of 1 Tg(NO_2) over one year, models find peak increases in global methane burden of about 0.5 Tg, with about five times higher sensitivities for reductions in aviation NOx. There is significant variation in sensitivity between regions for surface NOx emissions, with South Asia about twice as sensitive as North America and East Asia, and three times as sensitive as Europe (Fry et al., 2012). Stevenson and Derwent (2009) also found spatial variation in sensitivity for aviation NOx, with the more sensitive regions tending to have lower background NOx levels.~~

~~NOx emission region/sector~~	~~$\Delta CH_4/\Delta E_{NOx}$ Tg(CH_4)/Tg(NO_2) yr^{-1}~~	~~2020-2019 ΔE_{NOx} Tg(NO_2) yr^{-1}~~	~~ΔCH_4 Tg(CH_4)~~
~~*Surface emissions*~~			
~~Global~~	~~-0.55~~[a]	~~-19.38~~	
~~N. Hemisphere~~	~~-0.39~~[b]	~~-16.72~~	
~~S. Hemisphere~~	~~-1.1~~[b]	~~-2.66~~	~~2.93~~
~~Europe~~	~~-0.28~~[c]	~~-2.65~~	~~0.74~~

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N. America	-0.47[e]	-2.55	1.20
E. Asia	-0.44[e]	-4.40	1.94
S. Asia	-0.88[e]	-3.78	3.33
NH minus 4 regions	-0.39[b]	-3.34	1.30
Aviation emissions			
Global	-2.6[a]	-0.83	
Global	-2.5[d]	-0.83	
Global	-2.3[e]	-0.83	1.91
Various 10° x 10° model grid-boxes	-1.9 to -15[f]		

Table 1: Sensitivity of changes in the global methane burden (ΔCH_4; units $Tg(CH_4)$) to changes in NOx emissions (ΔE_{NOx}; units $Tg(NO_2)\ yr^{-1}$) from several modelling studies, calculated for a variety of surface and aviation emissions from different regions. Also shown are COVID-19 lockdown impacts on NOx emissions ($Tg(NO_2)\ yr^{-1}$) between 2019 and 2020 from Lamboll et al. (2021) for regions and global aviation, and the corresponding contributions to the change in global methane burden ($Tg(CH_4)$; values only given for contributions used in Section 4). References for the sensitivity values: (a) Wild et al. (2001); (b) Derwent et al. (2001); (c) Fry et al. (2012); (d) Stevenson et al. (2004); (e) Lee et al. (2021); and (f) Stevenson and Derwent (2009).

4 COVID-19 lockdown impacts onn NOx emissions

Lamboll et al. (2021) compiled estimates of the impact of COVID-19 lockdowns on global anthropogenic NOx, CO and NMVOC emissions, as monthly mean time series, with spatial resolution 0.5° latitude by 0.5° longitude. We use these data to calculate the difference in surface NOx emissions between 2019 (pre-lockdown) and 2020 for the four HTAP regions, as well as globally, and hence for the 'Rest of the World' (ROW) region (i.e. everywhere beyond the four HTAP regions)for the Northern and Southern Hemispheres. The annual reduction in global surface NOx emissions from 2019 to 2020 was about 19.38 $Tg(NO_2)$, or 15%. Lamboll et al. (2021) also compiled data on aviation emissions, estimating a global reduction of about 0.83 $Tg(NO_2)$, or 25%. Global and rRegional annual changes in NOx, CO and NMVOC emissions are summarised in Table 1.

	NOx $Tg(NO_2)$	CO Tg(CO)	NMVOC Tg(C)

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Global surface emissions (GL)	-19.38	-73.38	-15.65
Europe (EU)	-2.65	-6.09	-1.71
North America (NA)	-2.55	-7.49	-1.56
South Asia (SA)	-3.78	-16.76	-4.34
East Asia (EA)	-4.40	-24.58	-2.41
Rest of the World (ROW)	-6.00	-18.46	-5.63
Global aviation	-0.83	-	-

Table 1. Changes in global and regional annual anthropogenic emissions from 2019 to 2020, assumed to be associated with COVID-19 lockdowns. Derived from data in Lamboll et al. (2021).

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5 Impacts of reduced lockdown ~~NOx~~ emissions on global methane

To calculate an approximate impact of the lockdown~~NOx~~ emission reductions on global methane, we simply multiply the regional/aviation sensitivities and emissions changes and sum over the globe. To calculate ROW contributions, we assume that the global sensitivity values can be linearly constructed from the four regions and the ROW, weighting each region by its emissions.

Figure 5 shows calculated regional contributions to the global methane growth rate from changes in surface NOx emissions for each of the HTAP models, together with the 4MM and MMM values. Equivalent results for CO and NMVOCs are shown in Figures 6 and 7, respectively. Table 2 summarises the regional and aviation components for all emissions, using results from the 4MM.

We find that reduced NOx emissions during lockdown increased the methane growth rate in total by 4.3 ± 0.7 ppb/yr (4MM; a slightly larger impact of 4.4± 0.8 ppb/yr is found for the MMM). South Asia is the largest contributing HTAP region, although this is exceeded by the impact from NOx emissions changes from outside the four HTAP regions. Aviation NOx is also an important contributor. Reduced CO emissions partly counteracted this positive impact on the methane growth rate, with an overall impact of -1.1 ± 0.5 ppb/yr (4MM; a slightly smaller impact of -1.0 ± 0.4 ppb/yr is found for the MMM). East Asia, followed by South Asia, are the largest contributing regions. Reduced NMVOC emissions had a small additional effect in the same sense as CO, but about one order of magnitude smaller, and with a large uncertainty. The overall impact from NMVOC was -0.13 ± 0.15 ppb/yr (4MM; very similar value for MMM: -0.13 ± 0.10 ppb/yr).

We find a net total impact on methane of 3.0 ± 0.8 ppb/yr (4MM; 3.2 ± 0.9 ppb/yr MMM), with the largest contributing region overall being ROW, followed by South Asia. Aviation NOx changes make up about 30% of this net total.

Table 1 shows calculated regional and aviation components of the methane change. We calculate a total methane burden change of 13.36 Tg(CH_4), comprising 11.44 Tg(CH_4) from surface NOx changes, with a further 1.92 Tg(CH_4) from aircraft. The more sensitive regions (South Asia, the Southern Hemisphere) and aviation make proportionally larger contributions to the total methane change. We convert the overall change in global methane burden (Tg) to a change in tropospheric mole fraction (ppb) using the total atmosphere mass of 5.113 x 10^9 Tg and a fill factor of 0.973 for conversion of a total atmosphere abundance to a tropospheric abundance (Prather et al., 2012). This yields a global mean increase in tropospheric methane mole fraction of 4.9 ppb associated with the NOx reductions. Since the troposphere is well mixed, this is also the change at the surface.

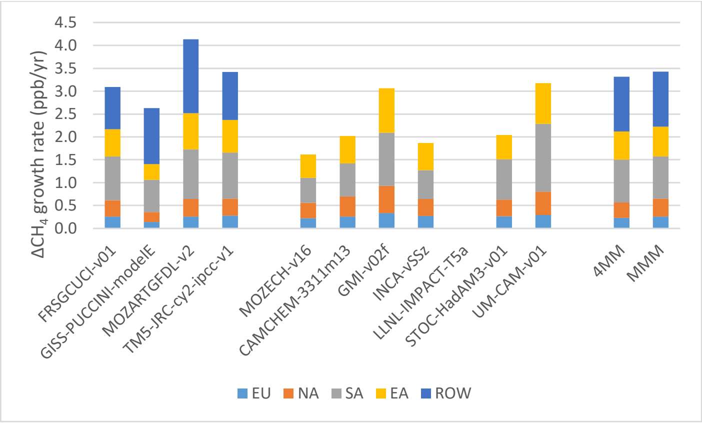

Figure 5. Calculated changes in global methane growth rate from changes in surface NOx emissions during the 2020 lockdown, for each of the HTAP models. Also shown are values for the mean of the four core models (shown on left) (4MM) that reported results for all simulations, together with multi-model mean (MMM) results based on all available models.

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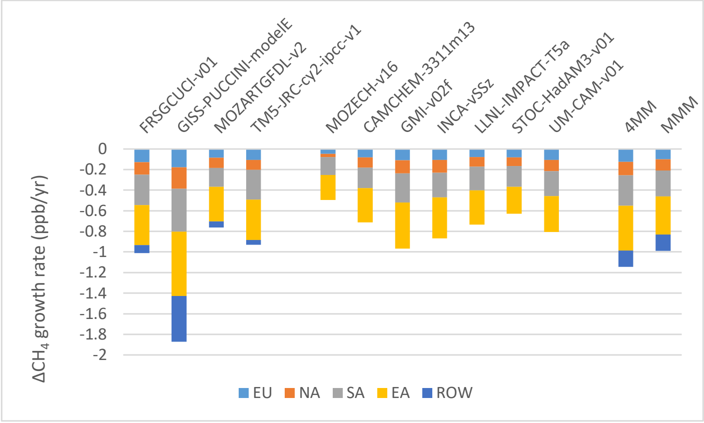

Figure 6. As Figure 5, but for CO emissions.

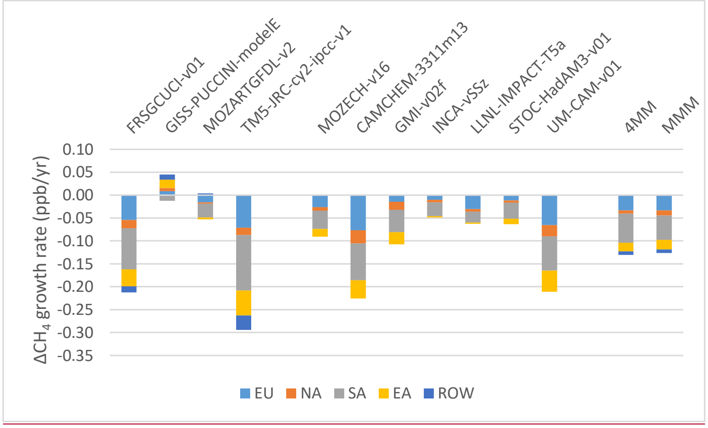

Figure 7. As Figure 5, but for NMVOC emissions.

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	NOx	CO	NMVOC	Total
Europe	0.23 ± 0.06	-0.12 ± 0.04	-0.03 ± 0.04	0.08 ± 0.08
N America	0.33 ± 0.08	-0.13 ± 0.05	-0.01 ± 0.01	0.19 ± 0.09
S Asia	0.94 ± 0.17	-0.30 ± 0.09	-0.06 ± 0.05	0.58 ± 0.20
E Asia	0.61 ± 0.20	-0.44 ± 0.13	-0.02 ± 0.03	0.16 ± 0.24
ROW	1.20 ± 0.30	-0.16 ± 0.19	-0.01 ± 0.02	1.04 ± 0.36
Aviation	0.93 ± 0.18			0.93 ± 0.18
Total	4.25 ± 0.66	-1.14 ± 0.50	-0.13 ± 0.15	2.97 ± 0.84

Table 2. Summary of impacts on the 2020 global methane growth rate (ppb/yr) relative to 2019 due to COVID-19 lockdown emission reductions based on 4MM results.

6 Discussion and Conclusions

These model-derived results can be compared to the observed increase in methane growth rate from 2019 to 2020 of 5.5 ppb/yr, and suggest that lockdown emission changes in NOx, CO and NMVOCs can explain 54-58% of this increase. Uncertainties estimated from the standard deviation of the HTAP (Fry et al., 2012) and aviation NOx (Lee et al. 2021) model's sensitivity results are about ±30%. No uncertainty estimate is included here for the magnitude of lockdown emissions changes, which is probably similar in magnitude. ~~This model-derived estimate of the extra methane expected due to the reductions in NOx emissions exactly matches the observed extra growth in methane seen during lockdown from 2019 to 2020 (4.9 ppb), suggesting that the NOx changes can account for all or most of the observed methane changes.~~

Refinements to this relatively simply derived~~e~~ estimate will need to account for several additional complications. The ~~NOx~~ emission changes have temporal structure (Lamboll et al., 2021), as do the sensitivities of methane to NOx, CO and NMVOCs ~~(e.g., Stevenson et al., 2004)~~, and these will interact. One study has reported a reduction in lightning during 2020 (Vasquez, 2022), which may contribute much like reductions in aircraft NOx. The regional sensitivities derived here are based on emissions changes with the spatial distributions and base magnitudes of the 2001 anthropogenic emissions, rather than a 2020 emissions baseline and the actual changes during lockdown, so the real sensitivities are likely to be slightly different. ~~In addition, we have ignored any spatial variations in aircraft emissions, but Stevenson and Derwent (2009) found that NOx emissions into cleaner environments had larger effects; there are also likely spatial variations within the large regions we have used for the surface NOx emissions.~~ Detailed modelling of the lockdown period is starting to explore these effects (Weber et al., 2020; Miyazaki et al., 2021). There is also spatio-temporal structure in the observed methane changes (e.g., Laughner et al., 2021; Feng et al., 2022) that will yield further information. There are undoubtedly several other factors, in addition to changes in anthropogenic NOx, CO and NMVOC emissions that influenced methane during 2020. Nevertheless, it seems likely that the dramatic reductions in theseNOx emissions, especially NOx, brought about by the COVID-19 lockdowns can explain a large component of the surge in methane growth rate seen duringsince early 2020. These influences on methane related to changes in OH need to be carefully accounted for in any attribution study that attempts to explain the recent observed dramatic changes in methane..

Author contributions

DSS wrote the text and performed the main analysis. OW and WJC performed additional analysis and commented on the text. RGD commented on the text.

Competing interests

The authors declare that they have no conflict of interest.

Code/data availability

Original data used here are all freely available in the cited references.

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