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## Key Points:

- COVID  $\text{NO}_x$  reductions reveal a two-phase climate response from rapid ozone cooling to methane driven warming
- Methane driven forcing dominates the net effect producing a global warming of about  $18 \text{ mW/m}^2$
- South and Southeast Asia (excluding China) contributes most to rapid radiative forcing change due to strong emissions changes and efficient upper tropospheric export

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## Abstract

The COVID-19 response provided a natural experiment to quantify the climate forcing efficiency of short-lived pollutants. Using satellite-constrained reanalysis and chemistry-climate simulations, we isolate the radiative impacts of anthropogenic  $\text{NO}_x$  reductions through two modes: a rapid ozone decrease and a slower methane-driven adjustment that dominates the net effect. Globally, these responses produce a net radiative forcing of  $+17.87 \pm 3.83 \text{ mW m}^{-2}$ , indicating that methane-driven warming outweighs the initial ozone cooling. The rapid response is strongly regional: South and Southeast Asia (excluding China) contributes most by  $-2.96 \pm 0.78 \text{ mW m}^{-2}$ , driven by large emission reductions, efficient convective export, and high upper-tropospheric radiative sensitivity, with North and South America secondary. Because our experiment isolates the gas-phase  $\text{NO}_x\text{--O}_3\text{--OH--CH}_4$  pathway, it is an upper bound on the methane-mediated warming; co-reduced CO and volatile organic compounds and lower nitrate aerosol would offset part of it.  $\text{NO}_x$  mitigation alone can cause delayed warming unless methane is concurrently controlled.

## Plain Language Summary

During the COVID-19 pandemic, global activity dropped sharply, leading to reduced air pollution. This created a rare opportunity to study how short-lived air pollutants affect climate. We show that reducing nitrogen oxides ( $\text{NO}_x$ ) leads to two competing effects: a fast decrease in ozone that cools the climate, and a slower increase in methane that causes warming. Over time, the methane effect becomes stronger, resulting in a net warming impact. The largest contribution comes from South and Southeast Asia, where emissions changed most and atmospheric processes efficiently transport pollutants to high altitudes where they strongly absorb radiation. Our results highlight an important trade-off: reducing  $\text{NO}_x$  alone may not cool the climate unless methane is also reduced. This finding has important implications for designing dual benefits for air quality and climate policies together.

## 1 Introduction

To align with the objectives of the Paris Agreement, which aims to cap global temperature increases to well below  $2^\circ\text{C}$ , preferably to  $1.5^\circ\text{C}$ , countries must implement robust and comprehensive strategies to decrease greenhouse gas (GHG) emissions (Schleussner et al., 2016). Most nations have pledged specific reduction goals by 2030 via their Nationally Determined Contributions (NDCs). Achieving these goals necessitates a broad array of policies and measures that target the principal sources, sinks, and reservoirs of GHGs (Chlela & Selosse, 2023; Kuramochi et al., 2021).

Long-lived GHGs, such as carbon dioxide ( $\text{CO}_2$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride ( $\text{SF}_6$ ), are well-understood in terms of their direct effects on Earth’s radiative balance (Sovacool et al., 2021). Due to their long atmospheric lifetimes, these gases are well-mixed and have been the target for emissions reduction initiatives, such as the Kyoto Protocol, in support of the UN Framework Convention on Climate Change (UNFCCC) (Ramaswamy et al., 2001).

In contrast, short-lived climate forcers (SLCFs) such as tropospheric ozone ( $\text{O}_3$ ) and methane ( $\text{CH}_4$ ) pose intricate challenges for climate policy.  $\text{O}_3$ , a secondary air pollutant, forms from photochemical production involving nitrogen oxides ( $\text{NO}_x$ ), volatile organic compounds (VOCs), carbon monoxide (CO), and  $\text{CH}_4$  (Monks et al., 2015), and its precursors influence the lifetime of  $\text{CH}_4$  by modulating the oxidative capacity through reactions that generate and deplete the hydroxyl radical (OH). The lifetime of tropospheric  $\text{O}_3$  spans days to weeks, giving a spatially and temporally uneven distribution (Young et al., 2013; Naik et al., 2005). The short lifetimes of  $\text{O}_3$  precursors and the nonlinear dependence of  $\text{O}_3$  production on  $\text{NO}_x$  complicate the attribution of  $\text{O}_3$  to specific sources,

and transport across regions further complicates quantifying each region’s contribution at the surface and in the free troposphere. Unlike long-lived GHGs, whose emission-to-forcing relationship is readily parameterized, the climate impact of  $\text{O}_3$  depends on both the location of precursor emissions and the distribution of  $\text{O}_3$  formation and transport, so its radiative-forcing attribution demands more nuanced approaches (Bowman & Henze, 2012).

To curb the spread of COVID-19, many countries implemented lockdowns that restricted movement and reduced anthropogenic activity. These measures were intended to relieve healthcare systems (Cash & Patel, 2020) but also swiftly reduced air-pollutant emissions (Le et al., 2020; Yang et al., 2021). A large body of COVID-era modelling (Gettelman et al., 2021; Reifenberg et al., 2022; Steinbrecht et al., 2021) and observational studies has documented the complex, regionally variable ozone response to these abrupt changes, including satellite and in-situ process diagnostics over Europe (Fan et al., 2021; Grange et al., 2020; Nussbaumer et al., 2022; Pimlott et al., 2025), a hemispheric ozone-sonde synthesis (Steinbrecht et al., 2021), and high-elevation observations across North America and Europe (Putero et al., 2023). Others have linked oxidant perturbations during 2020 to 2021 to the contemporaneous methane rise (Ciais et al., 2026; Feng et al., 2023; Peng et al., 2022; Stevenson et al., 2022) and shown that air-pollution controls modulate methane variability on climate-relevant timescales (Zhao et al., 2025).

Despite these advances, the  $\text{NO}_x$ -driven radiative forcing pathway that links emission reductions to both the rapid  $\text{O}_3$  change and the slower methane-mediated adjustment has previously been quantified only for idealized, sustained regional perturbations in global chemistry–climate models (Wild et al., 2001; Naik et al., 2005), and not for an observationally constrained, real-world emission shock. Here we address this gap by combining satellite-constrained chemical reanalysis with chemistry–climate simulations to isolate the  $\text{NO}_x$  perturbation against a business-as-usual counterfactual. We emphasize that the observational constraint enters through the satellite-derived  $\text{NO}_x$  emission anomaly; the subsequent  $\text{O}_3$ , OH,  $\text{CH}_4$ , and radiative-forcing responses are computed with the chemistry–climate model.

We distinguish two responses: a short-lived mode, defined as the rapid ozone adjustment to  $\text{NO}_x$  changes on timescales of weeks to months, and a primary mode, representing the slower, chemically integrated response mediated by  $\text{CH}_4$ –OH– $\text{O}_3$  coupling, evolving over years to decades. Using a decade-long reanalysis constrained by satellite observations, we diagnose COVID-19-related  $\text{NO}_x$  emission anomalies and quantify the associated changes in  $\text{O}_3$  and  $\text{CH}_4$  radiative forcing under fixed meteorological conditions, enabling a mechanistic attribution.

## 2 Materials and Methods

We initially investigated the COVID-induced  $\text{NO}_x$  perturbation through chemical reanalysis, constrained by multiple satellite measurements. Subsequently, we evaluate the  $\text{NO}_x$  perturbation as the sole catalyst for  $\text{O}_3$  production, incorporating meteorological factors to simulate  $\text{O}_3$  perturbation using the chemical transport model (CTM). We then calculate the  $\text{O}_3$  radiative effect during COVID by applying the Model for Interdisciplinary Research on Climate Earth System Model (MIROC-ESM).

### 2.1 $\text{NO}_x$ Perturbation

To estimate COVID-related  $\text{NO}_x$  emission anomalies, we followed Miyazaki et al. (2021), comparing top-down satellite-constrained anthropogenic  $\text{NO}_x$  emissions for 2020 against a business-as-usual (BAU) baseline from the 2010 to 2019 chemical reanalysis. The relative temporal changes are climatological daily emission cycles computed at the model-grid level from ten years of satellite-informed anthropogenic  $\text{NO}_x$  emissions and

applied to the 2020 baseline to reconstruct the emissions expected without COVID-19 restrictions. They capture typical seasonality and weekday-weekend patterns, not climate-driven  $\text{NO}_x$  sources such as lightning, soil, or biomass burning, which were excluded in Miyazaki et al. (2021). Thus only anthropogenic activity-driven deviations are attributed to COVID-19, while meteorology-driven variability is handled by the transport model and data-assimilation system. The reconstructed counterfactual reflects anthropogenic  $\text{NO}_x$  only; co-emitted CO and VOC changes are not included (see Section 4).

## 2.2 Tropospheric $\text{O}_3$ , OH, and $\text{CH}_4$ Modeling

We use the MIROC-CHASER chemical general circulation model (Sekiya et al., 2018; Watanabe et al., 2011), the same model and configuration used to derive the COVID-19 ozone response in Miyazaki et al. (2021), to simulate the changes in  $\text{O}_3$ , OH, and  $\text{CH}_4$  induced by  $\text{NO}_x$  emission reductions. The model resolves tracer transport, emissions, deposition, and gas-phase chemistry of the  $\text{O}_3$ - $\text{HO}_x$ - $\text{NO}_x$ - $\text{CH}_4$ -CO-NMVOC system at  $0.56^\circ$  resolution. Meteorological fields are generated by the MIROC atmospheric general circulation model and nudged to six-hourly ERA-Interim reanalysis, so the runs are driven by observed meteorology rather than a fully coupled or Atmospheric Model Intercomparison Project (AMIP) configuration. Methane is prescribed as a surface lower-boundary mixing ratio, so the primary-mode  $\text{CH}_4$  response is diagnosed offline from the simulated OH change (Section 2.4) rather than from an interactive  $\text{CH}_4$  tracer;  $\text{N}_2\text{O}$  is likewise prescribed. Integrations were run for February to June 2020, each initialized monthly from a continuous BAU simulation following Miyazaki et al. (2021): a global BAU control, a global COVID run using the 2020 satellite-constrained emissions, and eight regional sensitivity runs in which the 2020 emissions are applied over one target region while BAU emissions are retained elsewhere.  $\Delta\text{O}_3$  and  $\Delta\text{OH}$  are computed as COVID minus BAU, and regional contributions come from the eight regional runs. We define the global ozone response efficiency as the ratio of the tropospheric ozone burden change (Tg) to the global  $\text{NO}_x$  emission reduction (Tg N), which, unlike local production-efficiency metrics, captures coupled chemical and transport feedbacks at the global scale:

$$\text{OPE} = \frac{\text{O}_3 \text{ produced}}{\text{NO}_2 \text{ lost (or converted)}} \quad (1)$$

## 2.3 Climate Model to Calculate Radiative Forcing

We use MIROC-ESM to calculate the short-lived  $\text{O}_3$  radiative forcing. The MIROC-ESM radiative-transfer module computes the net top-of-atmosphere (TOA) radiative flux for the BAU and COVID scenarios. These are instantaneous radiative-forcing estimates, derived with fixed (climatological) meteorology and pre-computed instantaneous tropospheric-ozone radiative kernels, and they do not include adjustments such as the stratospheric-temperature response or cloud feedbacks. The kernel approach follows that used for ozone radiative forcing by Skeie et al. (2020): the kernels map a vertically resolved ozone perturbation to the TOA flux change and therefore explicitly retain the vertical dependence of the ozone radiative efficiency. Radiative forcing is calculated as:

$$\text{O}_3 \text{ RF Reduction} = \text{Net radiation (baseline)} - \text{Net radiation (COVID-19 scenario)} \quad (2)$$

Our results for the methane-related forcing components are expressed in terms of time-integrated radiative forcing (TIRF), integrated over 20 years (analogous to GWP20), in line with the methodology applied in prior studies (Myhre et al., 2013; Wild et al., 2001).

## 2.4 Primary Mode Change Estimation

To estimate methane changes via the primary-mode response, we first diagnose the change in the global-mean tropospheric OH concentration from the model simulations

with and without  $\text{NO}_x$  emission reductions. The methane lifetime is evaluated as a global effective lifetime, defined as the ratio of the global  $\text{CH}_4$  burden to the total tropospheric sink (primarily oxidation by OH). The “primary mode” denotes the longest-lived eigenmode of the coupled  $\text{CH}_4$ –OH– $\text{O}_3$  chemical system; because of the positive  $\text{CH}_4$ –OH feedback its e-folding timescale ( $\sim 12$  yr) exceeds the perturbation lifetime of  $\text{CH}_4$  itself, and it represents the chemically integrated, steady-state adjustment first formalized by M. J. Prather (1994, 1996) and applied to regional  $\text{NO}_x$  perturbations by Naik et al. (2005). The primary atmospheric sink of methane is its oxidation by the hydroxyl radical (OH), represented by the reaction:



This reaction controls the global lifetime of methane and is highly sensitive to OH concentration, which in turn is influenced by  $\text{NO}_x$ , CO, and other precursors.

The lifetime  $\tau_{\text{CH}_4}$  due to OH is calculated as follows:

$$\tau_{\text{CH}_4} = \frac{1}{k \cdot [\text{OH}]} \quad (4)$$

Where  $k$  is the reaction rate,  $[\text{OH}]$  is the OH concentration can be represented by the Arrhenius expression:

$$k(T) = 2.45 \times 10^{-12} \cdot \exp(-1775/T) \quad (5)$$

Here  $T$  is the temperature in a given grid box and vertical layer. The change in  $\text{CH}_4$  lifetime due to the OH change during COVID is obtained from the difference in  $\text{CH}_4$  lifetime between the COVID and BAU simulations. Following M. J. Prather (1994, 1996) and Naik et al. (2005), and taking the 2019 global-mean  $\text{CH}_4$  mixing ratio to be 1888 ppb (NOAA Global Monitoring Laboratory), the perturbed steady-state (primary-mode)  $\text{CH}_4$  change is estimated as:

$$\Delta[\text{CH}_4] = F_{\text{CH}_4} \cdot [\text{CH}_4]_0 \frac{\Delta\tau_{\text{CH}_4}}{\tau_{\text{CH}_4 0}} \quad (6)$$

Here  $F$  is a model-dependent feedback factor that quantifies the positive  $\text{CH}_4$ –OH feedback. We adopt  $F = 1.30$ , consistent with recent multi-model constraints on the  $\text{CH}_4$  lifetime feedback (Holmes, 2018; Stevenson et al., 2020; Thornhill et al., 2021), which update the value of 1.4 used by Naik et al. (2005);  $\Delta\tau$  is the  $\text{CH}_4$  lifetime change between BAU and COVID,  $\tau_0$  is the  $\text{CH}_4$  lifetime in BAU, and  $[\text{CH}_4]_0$  is the  $\text{CH}_4$  mixing ratio in 2019. The relative  $\text{CH}_4$  lifetime change (%) between BAU and COVID is given in Table S2, and the primary-mode  $\text{CH}_4$  change (in ppb) is given in Table S4. The primary-mode  $\text{O}_3$  change (Naik et al., 2005), in Dobson units (DU), due to the primary-mode  $\text{CH}_4$  change is calculated as:

$$[\Delta\text{O}_3]_{\text{primary}} = \frac{\Delta[\text{CH}_4]}{[\text{CH}_4]_0} \cdot \frac{0.64}{0.1} \quad (7)$$

The resulting primary-mode  $\text{O}_3$  change is given in Table S4. The factor 0.64/0.1 DU converts a fractional  $\text{CH}_4$  change into a tropospheric ozone-column change: it is the 0.64 DU increase in global tropospheric ozone per 10% (i.e., 0.1) increase in  $\text{CH}_4$  diagnosed by the OxComp multi-model experiment (M. Prather et al., 2001; Naik et al., 2005). Throughout, the tropospheric ozone column (in Dobson units) is integrated from the surface to the tropopause, defined as the model level at which the ozone mixing ratio equals 150 ppbv in the BAU simulation (M. Prather et al., 2001), consistent with Naik et al. (2005).

The radiative effect from the primary mode  $O_3$  was calculated as:

$$[\Delta F_{O_3}]_{\text{Primary}} = \frac{\partial F_{\text{TOA}}}{\partial O_3} \cdot (\Delta O_3)_{\text{Primary}} \quad (8)$$

The primary-mode  $O_3$  radiative forcing is obtained by multiplying the primary-mode tropospheric-ozone column change (in DU) by the global-mean normalized tropospheric-ozone radiative efficiency of  $42 \text{ mW m}^{-2} \text{ DU}^{-1}$  derived from the ACCMIP multi-model ensemble (Stevenson et al., 2013; Miyazaki et al., 2021); this normalization already embeds the ensemble-mean vertical distribution of the ozone response, whereas the short-lived  $O_3$  forcing (Eq. 2) is computed from the fully vertically resolved MIROC-ESM radiative kernel. The result is given in Table S4. The primary-mode  $CH_4$  radiative forcing (Etminan et al., 2016) was calculated as:

$$\Delta F_{CH_4} = (a_3 \bar{M} + b_3 \bar{N} + 0.043)(\sqrt{M} - \sqrt{M_0}) \quad (9)$$

Here  $M$  and  $M_0$  are the perturbed and unperturbed  $CH_4$  concentrations (in ppb),  $\bar{M} = 0.5(M + M_0)$  is the mean  $CH_4$  concentration, and  $N$  is the  $N_2O$  concentration (in ppb).  $N_2O$  is not simulated interactively; it is prescribed at its 2019 global-mean value of  $\bar{N} = 332$  ppb (NOAA Global Monitoring Laboratory), and  $CH_4$  is referenced to  $M_0 = 1888$  ppb. The coefficients  $a_3 = -1.3 \times 10^{-6} \text{ W m}^{-2} \text{ ppb}^{-1}$  and  $b_3 = -8.2 \times 10^{-6} \text{ W m}^{-2} \text{ ppb}^{-1}$  are the polynomial-fit parameters of Etminan et al. (2016). This expression supersedes the simplified formula of Myhre et al. (1998) and captures the shortwave methane band omitted in earlier parameterizations; we apply it consistently to both the short-lived and primary-mode  $CH_4$  changes.

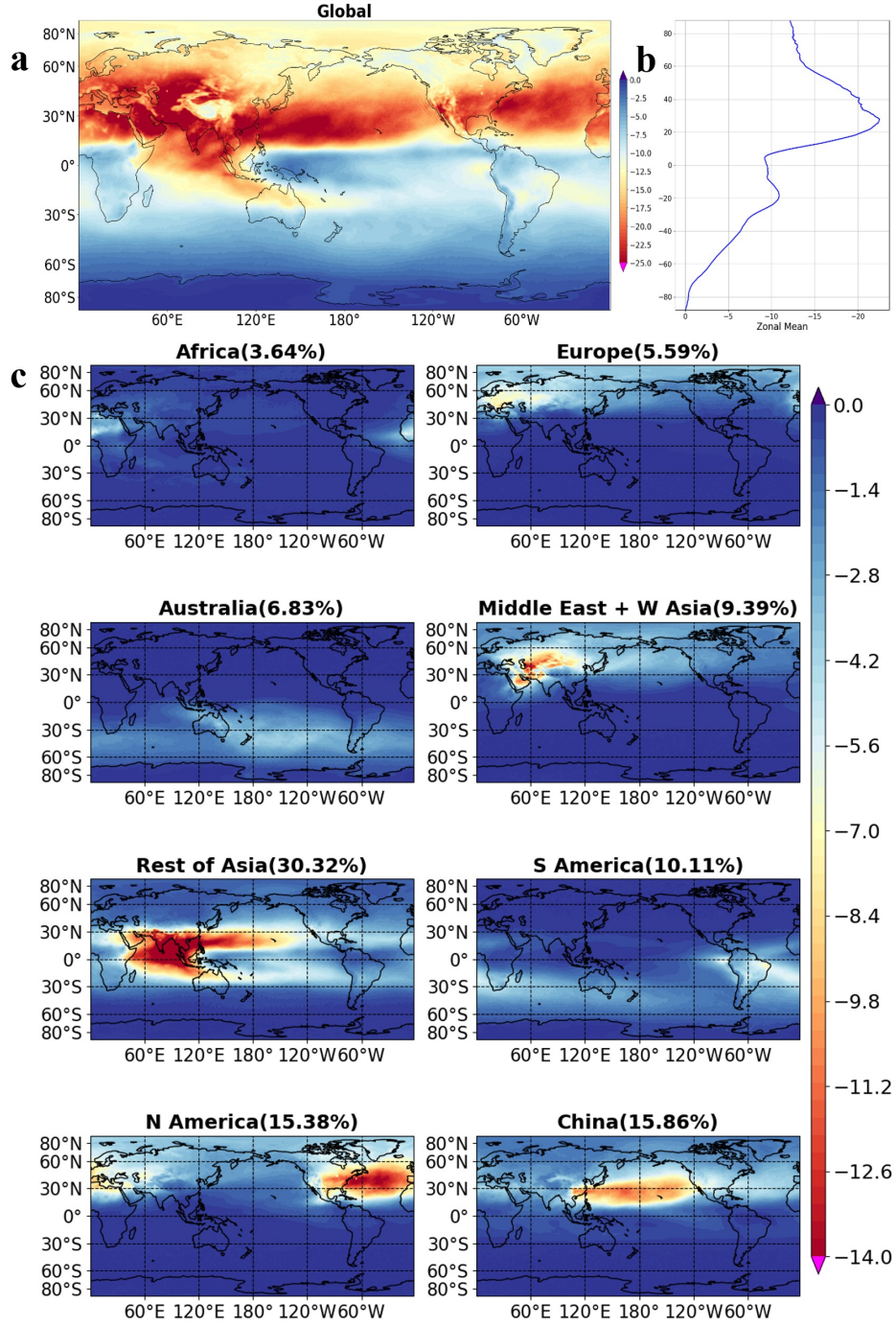
### 3 Results

#### 3.1 Short-lived $O_3$ and $CH_4$ responses

The abrupt reduction in anthropogenic activity during the COVID-19 lockdowns led to marked decreases in  $NO_x$  emissions and a fast re-adjustment of tropospheric oxidant chemistry, expressed first through ozone. Short-lived  $O_3$  burdens declined globally (Fig. S1), with the largest decreases over high-emission continental corridors and in the major outflow regions of East Asia, North America, and South America. These  $O_3$  reductions extend downstream along mid-latitude westerlies into the remote Pacific, illustrating rapid chemical adjustment in polluted boundary layers followed by efficient advective export into the free troposphere. Particularly strong anomalies over South and Southeast Asia and their monsoonal outflow zones emphasize the role of deep convection in vertically redistributing precursors, thereby amplifying the radiative leverage of  $O_3$  perturbations in the upper troposphere. In contrast, more modest changes in Europe, Africa, and Australia reflect weaker regional emission reductions and more persistent oxidant regimes.

Globally, we diagnose a  $-4.07 \pm 0.55 \text{ Tg}$  decrease in short-lived  $O_3$ , corresponding to an instantaneous cooling of  $-11.94 \pm 1.63 \text{ mW m}^{-2}$  (Table 1) (see Materials and Methods). Regionally, the “Rest of Asia”, defined as South and Southeast Asia excluding China, contributes the largest fraction of the global  $O_3$  reduction ( $-0.82 \pm 0.17 \text{ Tg}$ ;  $-3.62 \text{ mW m}^{-2}$ ), followed by North America ( $-0.68 \pm 0.19 \text{ Tg}$ ;  $-1.84 \pm 0.51 \text{ mW m}^{-2}$ ) and China ( $-0.58 \pm 0.55 \text{ Tg}$ ;  $-1.89 \pm 0.49 \text{ mW m}^{-2}$ ). South America also exhibits substantial cooling ( $-1.21 \pm 0.33 \text{ mW m}^{-2}$ ), reflecting strong photochemical sensitivity and large-scale transport. The zonal-mean pattern (Fig.1b) shows peak cooling in the subtropical and midlatitude upper troposphere, consistent with the high radiative efficiency of  $O_3$  at these altitudes and with enhanced export from continental source regions.

In parallel, the  $NO_x$  reductions suppress OH, producing a short-lived methane increase of  $+7.21 \pm 0.98$  ppb and an associated warming of  $+3.14 \pm 0.43 \text{ mW m}^{-2}$  (Table 1). The largest  $CH_4$  increases occur in the Rest of Asia, South America, and North



**Figure 1.** Calculated monthly averaged  $\text{O}_3$  radiative effects ( $\text{mW}/\text{m}^2$ ) from February to June 2020, resulting from reduction in surface anthropogenic  $\text{NO}_x$  emissions from global and each of the 8 regions. a. Global Map. displays the global spatial distribution of monthly column averaged short-lived  $\text{O}_3$  radiative effects ( $\text{mW}/\text{m}^2$ ). b. Zonal Mean Plot. shows the zonal mean of monthly column averaged short-lived  $\text{O}_3$  radiative effects ( $\text{mW}/\text{m}^2$ ) as a function of latitude. c. Regional map depicts regional distribution of monthly column averaged short-lived  $\text{O}_3$  radiative effects ( $\text{mW}/\text{m}^2$ ) in 8 different regions.

America, mirroring the regions with the strongest  $\text{NO}_x$  perturbations and the largest oxidant decreases. This tight spatial covariance highlights the sensitivity of the global oxidizing capacity to regional anthropogenic  $\text{NO}_x$  perturbations on short timescales.

Taken together, these rapid chemical adjustments yield a net short-lived radiative effect of  $-8.81 \pm 1.68 \text{ mW m}^{-2}$ , dominated by  $\text{O}_3$ -driven cooling that is only partially offset by  $\text{CH}_4$ -driven warming. The COVID-19 lockdowns thus reveal, at the global scale, the immediate climate expression of sudden  $\text{NO}_x$  emission reductions through the coupled  $\text{NO}_x\text{--O}_3\text{--OH--CH}_4$  system, highlighting the strong but transient cooling induced by suppressing short-lived  $\text{O}_3$ .

### 3.2 Primary-mode $\text{O}_3$ and $\text{CH}_4$ adjustments

In addition to the fast perturbation of ozone and the short-lived radiative response, the COVID-19-related  $\text{NO}_x$  reductions also altered the slower oxidative balance of the atmosphere, giving rise to a primary-mode adjustment, which has longer characteristic timescale and e-folding decay time (M. J. Prather, 1996). This response reflects the coupling between  $\text{NO}_x$ , OH,  $\text{CH}_4$ , and secondary  $\text{O}_3$ : reduced  $\text{NO}_x$  lowers OH, lengthening the methane lifetime, and the resulting increase in  $\text{CH}_4$  subsequently enhances tropospheric  $\text{O}_3$  over multi-month to annual timescales. This feedback, distinct from the immediate photochemical ozone loss, represents the chemically integrated and dynamically adjusted component of the  $\text{NO}_x$  perturbation.

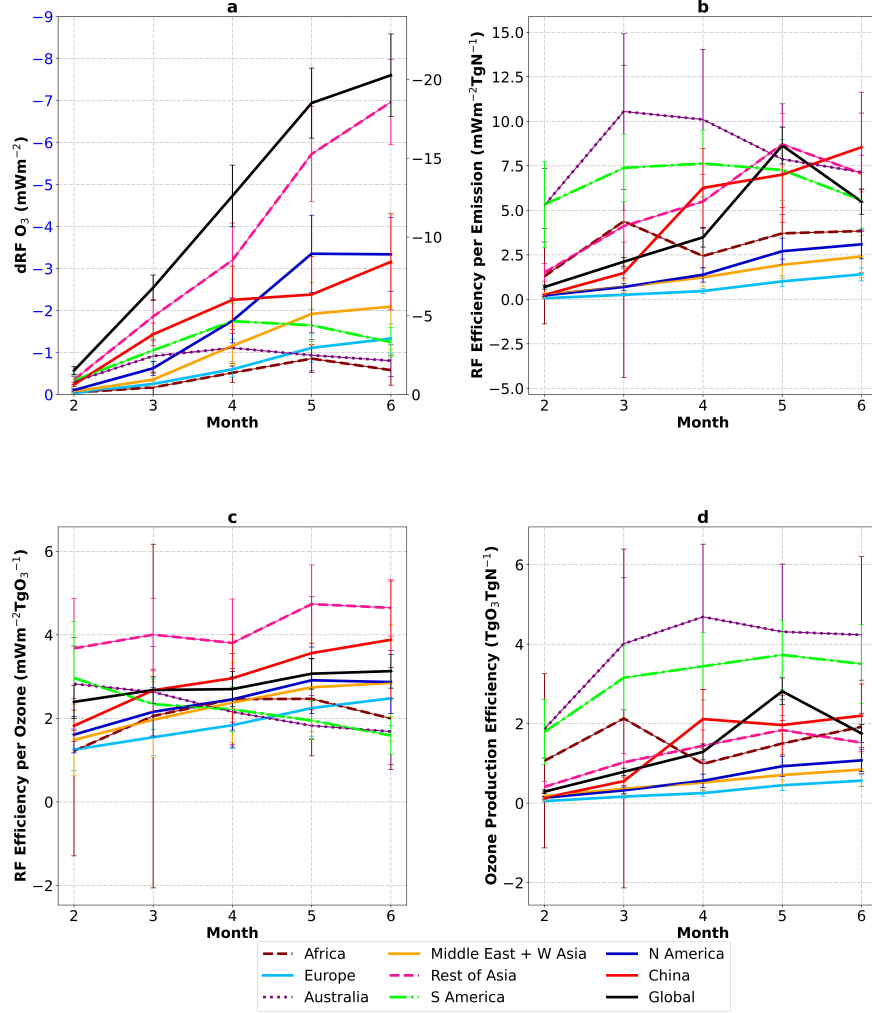
We find a global increase of  $+2.17 \pm 0.30 \text{ Tg}$  in primary-mode  $\text{O}_3$ , associated with  $+1.44 \pm 0.20 \text{ mW m}^{-2}$  of positive radiative forcing (Table 2). Concomitantly, the extended methane lifetime drives a large  $\text{CH}_4$  enhancement of  $+58.48 \pm 7.96 \text{ ppb}$ , producing  $+25.23 \pm 3.43 \text{ mW m}^{-2}$  of warming. Together, these adjustments yield a net primary-mode radiative forcing of  $+26.67 \pm 3.44 \text{ mW m}^{-2}$ , substantially larger in magnitude than the short-lived cooling and reflecting the dominant role of methane in the oxidative response to  $\text{NO}_x$  perturbations.

The largest primary-mode  $\text{CH}_4$  contributions originate from North America ( $+11.75 \pm 3.25 \text{ ppb}$ ), the Rest of Asia ( $+10.83 \pm 2.29 \text{ ppb}$ ), and the Middle East and West Asia ( $+8.94 \pm 3.96 \text{ ppb}$ ), consistent with the regions experiencing the sharpest reductions in  $\text{NO}_x$  emissions. These anomalies translate into regional radiative forcings exceeding  $+4 \text{ mW m}^{-2}$  in North America ( $+5.11 \pm 1.41 \text{ mW m}^{-2}$ ) and the Rest of Asia ( $+4.71 \pm 1.00 \text{ mW m}^{-2}$ ), and reaching  $+3.89 \pm 1.72 \text{ mW m}^{-2}$  in the Middle East and West Asia and  $+2.93 \pm 0.76 \text{ mW m}^{-2}$  over China. The spatial coherence between  $\text{NO}_x$  decreases, OH suppression,  $\text{CH}_4$  build-up, and  $\text{O}_3$  formation underscores the tight chemical control of the climate system by anthropogenic  $\text{NO}_x$  emissions, even outside traditional heavy-emission regions.

### 3.3 Total $\text{O}_3$ and $\text{CH}_4$ radiative effects and efficiency metrics

The combined fast and chemically adjusted (primary-mode) responses to COVID-19  $\text{NO}_x$  reductions reveal a spatially heterogeneous but globally positive radiative effect (Fig. 2 & Table 3). Across regions, the total ozone radiative forcing (short-lived plus primary-mode) remains negative but small in magnitude, reflecting the transient  $\text{O}_3$  loss followed by gradual  $\text{O}_3$  recovery driven by methane oxidation chemistry. Conversely, methane dominates the sign of the climate response, producing strong and persistent warming as the  $\text{NO}_x$ -induced OH suppression lengthens  $\text{CH}_4$  lifetime and enhances its global background concentration.

Figure 2a shows a progressive strengthening of ozone-related cooling from February to early summer, with the largest magnitudes in the Rest of Asia, North America, and China, consistent with the regions exhibiting the steepest  $\text{NO}_x$  perturbations and most efficient export of  $\text{O}_3$  anomalies into the free troposphere. However, by May–June,



**Figure 2.** Monthly variation in global a) instantaneous  $O_3$  radiative forcing ( $mW m^{-2}$ ), blue scale (left axis) in panel a) represents scale for each region while the black scale (right axis) in panel a) represents scale for global trend. b) instantaneous radiative forcing efficiency per unit  $NO_x$  emission ( $mW m^{-2} TgN^{-1}$ ), c) instantaneous radiative forcing efficiency per unit ozone ( $mW m^{-2} TgO_3^{-1}$ ), d) ozone production efficiency ( $TgO_3 TgN^{-1}$ ). These results reflect short-lived  $O_3$  perturbations arising from reductions in surface anthropogenic  $NO_x$  emissions across eight regions during the COVID-19 lockdowns.

the slope of ozone forcing anomalies flattens, signaling the rise of methane-driven ozone production that compensates the initial cooling. When normalized per unit  $\text{NO}_x$  reduction (Fig. 2b), radiative forcing efficiency increases in all regions, peaking in Rest of Asia and North America, where meteorological conditions, frequent deep convection, and strong precursor supply favor rapid oxidant adjustment and high radiative leverage.

Radiative forcing efficiency per unit ozone change (Fig. 2c) further highlights the disproportionate climate influence of  $\text{O}_3$  removal aloft, particularly over monsoonal Asia and the mid-latitude storm-track regions, where perturbations in the upper troposphere exhibit high longwave and shortwave radiative efficiency. The ozone production efficiency metric (Fig. 2d) rises steadily through spring in the northern hemisphere, peaking in late boreal spring, reflecting both seasonal photochemistry and the re-emergence of methane-driven ozone formation. Collectively, these efficiency diagnostics demonstrate that rapid  $\text{NO}_x$  reductions modulate atmospheric chemistry in a way that first cools the climate via  $\text{O}_3$  loss, then transitions toward warming as methane accumulates.

Table 3 quantifies these combined effects. Globally, the total  $\text{O}_3$  forcing is  $-10.50 \pm 1.64 \text{ mW m}^{-2}$ , while the total methane forcing reaches  $+28.37 \pm 3.46 \text{ mW m}^{-2}$ , yielding a net warming of  $+17.87 \pm 3.83 \text{ mW m}^{-2}$ . Regionally, the largest net warming emerges from North America ( $+4.02 \pm 1.51 \text{ mW m}^{-2}$ ), the Middle East and West Asia ( $+3.25 \pm 1.80 \text{ mW m}^{-2}$ ), and South America ( $+2.26 \pm 0.82 \text{ mW m}^{-2}$ ), followed by Europe ( $+2.13 \pm 0.79 \text{ mW m}^{-2}$ ) and the Rest of Asia ( $+2.11 \pm 1.27 \text{ mW m}^{-2}$ ). By contrast, Africa, Australia, and China show smaller magnitudes, consistent with lower  $\text{NO}_x$  emission perturbations or a weaker oxidant disruption. These results are qualitatively consistent with Naik et al. (2005), who reduced anthropogenic  $\text{NO}_x$  by 10% and likewise found that North America produced the highest net radiative forcing from the combined effects of  $\text{O}_3$  and  $\text{CH}_4$ . They illustrate how a globally synchronous emissions shock produces a geographically structured radiative fingerprint, governed by regional  $\text{NO}_x$  sensitivities, seasonal chemistry, and large-scale atmospheric transport pathways.

Our net positive (warming) forcing for  $\text{NO}_x$ -only reductions agrees in sign with Naik et al. (2005), who found that for  $\text{NO}_x$  alone the long-term  $\text{CH}_4$  warming offsets, and in several regions exceeds, the short-lived ozone cooling. Our larger magnitude reflects three factors: the COVID-19  $\text{NO}_x$  reductions (9 to 15% globally, up to  $\sim 25\%$  regionally; Miyazaki et al., 2021) exceed the uniform 10% regional cuts of Naik et al. (2005); we evaluate the methane forcing with the Etminan et al. (2016) expression, about 20% more efficient per unit  $\text{CH}_4$  than Myhre et al. (1998) and now applied consistently to both modes; and our forcing is integrated over the pandemic rather than annually averaged. These results do not conflict with the IPCC finding that the net effective  $\text{NO}_x$  forcing is negative (Szopa et al., 2021): that estimate also includes the strongly negative nitrate-aerosol forcing and co-varying precursors under sustained emissions. Here we isolate the transient gas-phase  $\text{NO}_x$ - $\text{O}_3$ -OH- $\text{CH}_4$  pathway and exclude aerosols; adding the nitrate-aerosol cooling and CO/NMVOC co-reduction would restore the IPCC sign, while the isolated pathway is what the COVID-19 experiment lets us observe.

Together, the total-effect diagnostics in Fig.2 and Table 3 reveal a characteristic two-phase chemical response: rapid  $\text{O}_3$  cooling followed by methane-driven warming that dominates the net radiative balance. These results confirm that while short-lived  $\text{O}_3$  reductions initially cool the climate, the chemically integrated perturbation to methane dominates the long-term radiative balance. The primary-mode response thus represents the climate legacy of transient  $\text{NO}_x$  reductions, revealing how rapid improvements in air quality can mask a delayed warming driven by methane chemistry. This behavior, expressed during an unprecedented global emission shock, highlights the central role of OH control pathways and the need to consider coupled  $\text{NO}_x$ - $\text{O}_3$ -OH- $\text{CH}_4$  feedbacks when designing short-lived climate forcer mitigation strategies.

## 4 Conclusions and Discussion

Our results demonstrate that abrupt reductions in  $\text{NO}_x$  emissions during COVID-19 yielded a two-phase climate response: an immediate decrease in tropospheric ozone that produced short-lived regional cooling, followed by a slower increase in methane due to suppressed OH, ultimately generating a net positive radiative forcing. This behavior highlights the dual role of  $\text{NO}_x$  as both an ozone precursor and the dominant chemical sink for methane via OH control. The time separation between the fast  $\text{O}_3$  response and the slow  $\text{CH}_4$  response underscores the importance of fully accounting for methane's primary-mode adjustment when interpreting short-lived forcing perturbations.

COVID-19 also altered emissions of other ozone and OH precursors, including CO and non-methane volatile organic compounds (NMVOCs), along with aerosols and meteorology. Whereas the  $\text{NO}_x$  reductions were the most globally pronounced and give a clean diagnosis of the  $\text{NO}_x$ – $\text{O}_3$ –OH– $\text{CH}_4$  system, co-reductions in CO and NMVOCs raise OH and would partly offset the simulated methane growth; indeed, Naik et al. (2005) showed the net sign can reverse from warming to cooling once CO and NMVOCs are cut with  $\text{NO}_x$ . The reduction in nitrate aerosol accompanying lower  $\text{NO}_x$  adds a further cooling we do not quantify. Our  $\text{NO}_x$ -only experiment therefore sets a mechanistic upper bound on the methane-mediated warming, and the full real-world response was likely smaller, and possibly negative. Future work integrating co-varying precursor and aerosol emissions, together with concurrent methane mitigation (Chua et al., 2026), will refine the magnitude and sign of the multi-pollutant response.

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## Open Research Section

The Python programming codes and data used for the generation figures of this study are publicly available through the open-access repository: <https://doi.org/10.5281/zenodo.18869360>

## Conflict of Interest Disclosure

The authors declare there are no conflicts of interest for this manuscript.

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**Table 1.** Monthly Average Global and Regional Changes of Short-lived O<sub>3</sub> and CH<sub>4</sub> and their Sensitivity to the Radiative Effects in Anthropogenic NO<sub>x</sub> Emissions during COVID

| Region                  | dO <sub>3</sub><br>Short-lived<br>[Tg] | dFO <sub>3</sub><br>Short-lived<br>[mW/m <sup>2</sup> ] | dCH <sub>4</sub><br>Short-lived<br>[ppb] | dFCH <sub>4</sub><br>Short-lived<br>[mW/m <sup>2</sup> ] | dF<br>Net Short-lived<br>[mW/m <sup>2</sup> ] |
|-------------------------|----------------------------------------|---------------------------------------------------------|------------------------------------------|----------------------------------------------------------|-----------------------------------------------|
| Africa                  | $-0.194 \pm 0.128$                     | $-0.435 \pm 0.288$                                      | $0.71 \pm 0.470$                         | $0.309 \pm 0.205$                                        | $-0.126 \pm 0.353$                            |
| Europe                  | $-0.311 \pm 0.094$                     | $-0.668 \pm 0.201$                                      | $0.42 \pm 0.127$                         | $0.183 \pm 0.055$                                        | $-0.485 \pm 0.208$                            |
| Australia               | $-0.393 \pm 0.162$                     | $-0.816 \pm 0.337$                                      | $0.69 \pm 0.285$                         | $0.300 \pm 0.124$                                        | $-0.516 \pm 0.359$                            |
| Middle East + West Asia | $-0.43 \pm 0.190$                      | $-1.121 \pm 0.496$                                      | $0.66 \pm 0.292$                         | $0.287 \pm 0.127$                                        | $-0.834 \pm 0.512$                            |
| Rest of Asia            | $-0.822 \pm 0.174$                     | $-3.62 \pm 0.767$                                       | $1.52 \pm 0.322$                         | $0.661 \pm 0.140$                                        | $-2.959 \pm 0.780$                            |
| S America               | $-0.597 \pm 0.162$                     | $-1.207 \pm 0.327$                                      | $1.48 \pm 0.401$                         | $0.644 \pm 0.174$                                        | $-0.563 \pm 0.371$                            |
| N America               | $-0.677 \pm 0.187$                     | $-1.836 \pm 0.507$                                      | $1.11 \pm 0.307$                         | $0.483 \pm 0.134$                                        | $-1.353 \pm 0.524$                            |
| China                   | $-0.582 \pm 0.554$                     | $-1.894 \pm 0.490$                                      | $0.3 \pm 0.0776$                         | $0.131 \pm 0.034$                                        | $-1.763 \pm 0.491$                            |
| Global                  | $-4.068 \pm 0.554$                     | $-11.94 \pm 1.625$                                      | $7.21 \pm 0.981$                         | $3.135 \pm 0.427$                                        | $-8.805 \pm 1.680$                            |

*Note.* Columns 2 and 3 show the simulated monthly average changes in global and regional O<sub>3</sub> and its radiative forcing associated with short-lived mode resulting from anthropogenic NO<sub>x</sub> reductions during COVID. Columns 4 and 5 show the simulated changes in global and regional CH<sub>4</sub> and its radiative forcing associated with CH<sub>4</sub> emissions changes during COVID. Column 6 shows the net radiative forcing combined with O<sub>3</sub> and CH<sub>4</sub>, which is the sum of column 3 and column 5. d (Mass Perturbation): Defined as the total change in the global mean tropospheric burden of a specific species (e.g., O<sub>3</sub> in Tg or CH<sub>4</sub> in ppb) resulting from the isolated NO<sub>x</sub> emission reduction during the study period. dF (Radiative Forcing Change): Defined as the change in net top-of-atmosphere (TOA) instantaneous radiative forcing (IRF), expressed in milliwatts per square meter (mW/m<sup>2</sup>). This represents the radiative impact of the mass perturbation (d) for the specific species. Sign Convention: We have clarified that negative values for dF represent a cooling effect (energy loss to space), while positive values represent a warming effect (energy gain by the Earth-atmosphere system).

**Table 2.** Monthly Average Global Change in Primary O<sub>3</sub> and CH<sub>4</sub> and their Sensitivity to the Radiative Effects

| Region                  | dO <sub>3</sub><br>Primary<br>[Tg] | dFO <sub>3</sub><br>Primary<br>[mW/m <sup>2</sup> ] | dCH <sub>4</sub><br>Primary<br>[ppb] | dFCH <sub>4</sub><br>Primary<br>[mW/m <sup>2</sup> ] | dF<br>Net Primary<br>[mW/m <sup>2</sup> ] |
|-------------------------|------------------------------------|-----------------------------------------------------|--------------------------------------|------------------------------------------------------|-------------------------------------------|
| Africa                  | 0.144 ± 0.096                      | 0.074 ± 0.049                                       | 3.887 ± 2.575                        | 1.691 ± 1.120                                        | 1.765 ± 1.121                             |
| Europe                  | 0.215 ± 0.065                      | 0.105 ± 0.032                                       | 5.779 ± 1.743                        | 2.513 ± 0.758                                        | 2.618 ± 0.759                             |
| Australia               | 0.150 ± 0.062                      | 0.085 ± 0.035                                       | 4.028 ± 1.665                        | 1.752 ± 0.724                                        | 1.837 ± 0.725                             |
| Middle East + West Asia | 0.332 ± 0.147                      | 0.195 ± 0.086                                       | 8.944 ± 3.961                        | 3.888 ± 1.722                                        | 4.083 ± 1.724                             |
| Rest of Asia            | 0.401 ± 0.085                      | 0.359 ± 0.076                                       | 10.828 ± 2.294                       | 4.705 ± 0.997                                        | 5.065 ± 1.000                             |
| S America               | 0.230 ± 0.062                      | 0.123 ± 0.033                                       | 6.210 ± 1.682                        | 2.700 ± 0.731                                        | 2.823 ± 0.732                             |
| N America               | 0.436 ± 0.121                      | 0.271 ± 0.075                                       | 11.751 ± 3.245                       | 5.106 ± 1.410                                        | 5.377 ± 1.412                             |
| China                   | 0.250 ± 0.065                      | 0.180 ± 0.046                                       | 6.735 ± 1.743                        | 2.928 ± 0.758                                        | 3.108 ± 0.759                             |
| Global                  | 2.168 ± 0.295                      | 1.443 ± 0.196                                       | 58.476 ± 7.958                       | 25.231 ± 3.434                                       | 26.674 ± 3.439                            |

*Note.* Columns 2 and 3 show the simulated monthly average changes in global and regional O<sub>3</sub> and its radiative forcing associated with primary mode resulting from OH changes during COVID. Columns 4 and 5 show the simulated changes in global and regional CH<sub>4</sub> and its radiative forcing associated with primary mode. Column 6 shows the net radiative forcing combined with O<sub>3</sub> and CH<sub>4</sub> in primary mode, which is the sum of column 3 and column 5. d (Mass Perturbation): Defined as the total change in the global mean tropospheric burden of a specific species (e.g., O<sub>3</sub> in Tg or CH<sub>4</sub> in ppb) resulting from the isolated NO<sub>x</sub> emission reduction during the study period. dF (Radiative Forcing Change): Defined as the change in net top-of-atmosphere (TOA) instantaneous radiative forcing (IRF), expressed in milliwatts per square meter (mW/m<sup>2</sup>). This represents the radiative impact of the mass perturbation (d) for the specific species. Sign Convention: We have clarified that negative values for dF represent a cooling effect (energy loss to space), while positive values represent a warming effect (energy gain by the Earth-atmosphere system).

**Table 3.** Monthly Average Global Change in Radiative Effects of total O<sub>3</sub>, total CH<sub>4</sub> and Net

| Region                  | dFO <sub>3</sub><br>Total<br>[mW/m <sup>2</sup> ] | dFCH <sub>4</sub><br>Total<br>[mW/m <sup>2</sup> ] | dF<br>Net<br>[mW/m <sup>2</sup> ] |
|-------------------------|---------------------------------------------------|----------------------------------------------------|-----------------------------------|
| Africa                  | $-0.361 \pm 0.292$                                | $2.000 \pm 1.139$                                  | $1.639 \pm 1.175$                 |
| Europe                  | $-0.563 \pm 0.203$                                | $2.696 \pm 0.760$                                  | $2.133 \pm 0.787$                 |
| Australia               | $-0.731 \pm 0.339$                                | $2.052 \pm 0.735$                                  | $1.321 \pm 0.809$                 |
| Middle East + West Asia | $-0.926 \pm 0.503$                                | $4.175 \pm 1.726$                                  | $3.249 \pm 1.798$                 |
| Rest of Asia            | $-3.261 \pm 0.771$                                | $5.367 \pm 1.006$                                  | $2.106 \pm 1.268$                 |
| S America               | $-1.084 \pm 0.329$                                | $3.344 \pm 0.752$                                  | $2.260 \pm 0.820$                 |
| N America               | $-1.565 \pm 0.513$                                | $5.589 \pm 1.416$                                  | $4.024 \pm 1.506$                 |
| China                   | $-1.714 \pm 0.492$                                | $3.059 \pm 0.759$                                  | $1.345 \pm 0.904$                 |
| Global                  | $-10.497 \pm 1.637$                               | $28.366 \pm 3.460$                                 | $17.869 \pm 3.828$                |

*Note.* Columns 2 shows the simulated monthly average changes in global and regional O<sub>3</sub> radiative forcing associated with short-lived mode and primary mode. Columns 3 shows the simulated changes in global and regional CH<sub>4</sub> radiative forcing associated with short-lived mode and primary mode. Column 4 shows the net radiative forcing combined with O<sub>3</sub> and CH<sub>4</sub>, which is the sum of column 2 and column 3. d (Mass Perturbation): Defined as the total change in the global mean tropospheric burden of a specific species (e.g., O<sub>3</sub> in Tg or CH<sub>4</sub> in ppb) resulting from the isolated NO<sub>x</sub> emission reduction during the study period. dF (Radiative Forcing Change): Defined as the change in net top-of-atmosphere (TOA) instantaneous radiative forcing (IRF), expressed in milliwatts per square meter (mW/m<sup>2</sup>). This represents the radiative impact of the mass perturbation (d) for the specific species. Sign Convention: We have clarified that negative values for dF represent a cooling effect (energy loss to space), while positive values represent a warming effect (energy gain by the Earth-atmosphere system).