

The Impact of Firework Ban Relaxation on Variations in SO₂ Emissions in China During the 2023 Chinese New Year

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Abstract: During the 2023 Chinese New Year (CNY), many city governments temporarily relaxed firework restrictions, leading to increased sulfur dioxide (SO₂) emissions from the combustion of sulfur-containing fireworks. This study employed the four-dimensional variational (4DVar) assimilation system to examine variations in SO₂ emissions in China by assimilating hourly ground-based observations. Two experiments were conducted during CNY in 2022 and 2023 to quantify the variations in SO₂ emissions. On CNY's Eve in 2023, following the relaxation of the firework ban, SO₂ emissions surged by 8.22 Gg nationwide compared to the previous day with significant increases in the Energy Golden Triangle (2.037 Gg), the North China Plain (1.709 Gg), and northeast China (0.945 Gg). Emissions peaked on CNY's Eve and rapidly declined in the following two days but remained elevated compared to the pre-CNY period, indicating lingering effects of firework burning. Compared to the forecasts using the prior emissions, the optimized emissions markedly improved the model forecasts of SO₂ during the 2023 CNY period, with an increase in the correlation coefficient (R) from 0.13 to 0.64 and a reduction in the root mean square error (RMSE) by 49.2%, demonstrating the effectiveness of the optimized emissions. These findings will be useful for local governments in formulating strategies for firework burning during CNY.

Keywords: firework burning; SO₂ emissions; 4DVar assimilation; firework ban



Citation: He, X.; Hu, Y.; Li, Y.; Zang, Z.; You, W.; Liu, L. The Impact of Firework Ban Relaxation on Variations in SO₂ Emissions in China During the 2023 Chinese New Year. *Remote Sens.* **2024**, *16*, 4191.

<https://doi.org/10.3390/rs16224191>

Academic Editor: Sang-Hyun Lee

Received: 12 September 2024

Revised: 26 October 2024

Accepted: 8 November 2024

Published: 10 November 2024



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1. Introduction

Setting off fireworks and firecrackers to celebrate Chinese New Year (CNY) has been a traditional Chinese folk culture for over a millennium, symbolizing the transition from the old to the new [1,2]. Fireworks primarily consist of black powder, which contains chemicals like sulfur (S), charcoal (C), and potassium nitrate (KNO₃). When the firework was burned, it can release substantial amounts of pollutant gases like SO₂ and NO_x into the atmosphere [3–8]. Therefore, the extensive firework burning nationwide during the CNY has the potential to result in notable short-term adverse effects on air quality [9–13]. Moreover, the emissions from fireworks pose a significant risk to human health, particularly by increasing the likelihood of respiratory diseases and lung cancer [14–16].

Since December 2017, a near-sweeping ban on fireworks has been implemented in the main urban areas across China. As the scope continued to expand, nearly 160 prefecture-level cities had implemented the firework ban by the end of 2018 [17,18]. Several studies have examined the positive impact of firework bans on controlling air pollution [19–23]. Before the arrival of the 2023 CNY, the debate surrounding whether firework burning should be reinstated has once again become a topic of public concern, with an intensity exceeding that in previous years. Many local governments have relaxed their firework restrictions, allowing the public to set off fireworks in designated areas and at specified times. Given that firework burning is an important source of SO₂ emissions, it is essential to assess variations in SO₂ emissions during this period.

SO₂ emissions are generally estimated using a “bottom-up” approach, relying on activity data and emission factors from multiple sources [24]. However, the “bottom-up” approach is susceptible to uncertainties stemming from inaccurate and infrequently updated statistics [25–27]. Data assimilation methods, including four-dimensional variational assimilation (4DVar) and ensemble Kalman filter (EnKF), provide a “top-down” methodology for improving emissions in chemical transport models (CTMs) by integrating observations to revise the prior emissions [27–29]. Additionally, probabilistic methods have been explored to address uncertainties, such as the models proposed by Kamińska et al. [30] and Catalano et al. [31] to estimate the probability of peak pollutant concentrations based on meteorological data. These methods complement traditional deterministic models by providing insight into the likelihood of short-term pollution events exceeding specific concentration thresholds. Emissions based on the data assimilation method provide a more precise estimation for specific events compared to traditional methods [32]. Hu et al. [33] developed a 4DVAR system that assimilated hourly surface observational data of SO₂ concentrations to optimize SO₂ emissions during the COVID-19 lockdown and found that the average SO₂ emissions in central China were 21.0% lower in 2020 than in 2019. Kong et al. [34] developed a multi-air-pollutant inversion system based on the EnKF algorithm to concurrently estimate the emissions of several pollutants in China, including NO_x, SO₂, CO, PM_{2.5}, and PM₁₀, and found that the emissions of these pollutants quickly returned to normal levels within a week after the CNY.

Although a number of works have explored the level of SO₂ emissions from various events [35–37], studies specifically on firework burning have primarily focused on the environmental consequences and health risks associated with SO₂ emissions [10,38–40]. These studies have often analyzed the SO₂ emissions in the context of the strict enforcement of the firework ban [41–44]. To date, there is a lack of studies on the variation in SO₂ emissions after the relaxation of firework restrictions in different regions of China during the CNY in 2023. The results of this study will help evaluate the environmental impacts caused by pollutant gases and offer reasonable recommendations for suitable policy adjustments in the future.

2. Materials and Methods

2.1. WRF-Chem Model

In this study, meteorological and chemical fields were simulated using the WRF-Chem v3.9.1 model with meteorological data from the National Centers for Environmental Prediction (NCEP) Final Operational Global Analysis dataset. The modeling domain (Figure 1) was centered at 37.5°N, 101.5°E, containing 169 × 211 grid points with a horizontal resolution of 27 km and 40 vertical layers extending up to an altitude of 50 hPa. The WRF-Chem configurations (Table S1) adhered to those of Hu et al., with details provided in their work [45].

2.2. 4DVar

In this study, we used the 4DVar assimilation system originally developed by Hu et al. [33]. The cost function of this system can be formulated as

$$J = \frac{1}{2}(c_0 - c_0^b)^T B_{c_0}^{-1}(c_0 - c_0^b) + \frac{1}{2} \sum_{k=0}^{n-1} (e_k - e_k^b)^T B_{e_k}^{-1}(e_k - e_k^b) + \frac{1}{2} \sum_{k=0}^n (y_k^0 - H_k c_k)^T R_k^{-1}(y_k^0 - H_k c_k). \quad (1)$$

Here, c_0 and c_0^b are the initial concentration and background concentration at the start of the assimilation window; and e_k , e_k^b , y_k^0 , and c_k denote the posterior emission, prior emission, observation vector, and concentrations at time k , respectively. The SO₂ increment can be defined as $\delta e_k = e_k - e_k^b$. The innovation vector is defined as $d_k \equiv y_k^0 - H_k(c_k)$, which represents the difference between the observed values and the model equivalent

state. Then, the cost function in Equation (1) can be expressed in its incremental form as follows:

$$J = \frac{1}{2}(\delta c_0^T)B_{c0}^{-1}(\delta c_0) + \frac{1}{2}\sum_{k=0}^{n-1}(\delta e_k)^T B_{ek}^{-1}(\delta e_k) + \frac{1}{2}\sum_{k=0}^n(d_k - H_k\delta c_k)^T R_k^{-1}(d_k - H_k\delta c_k). \quad (2)$$

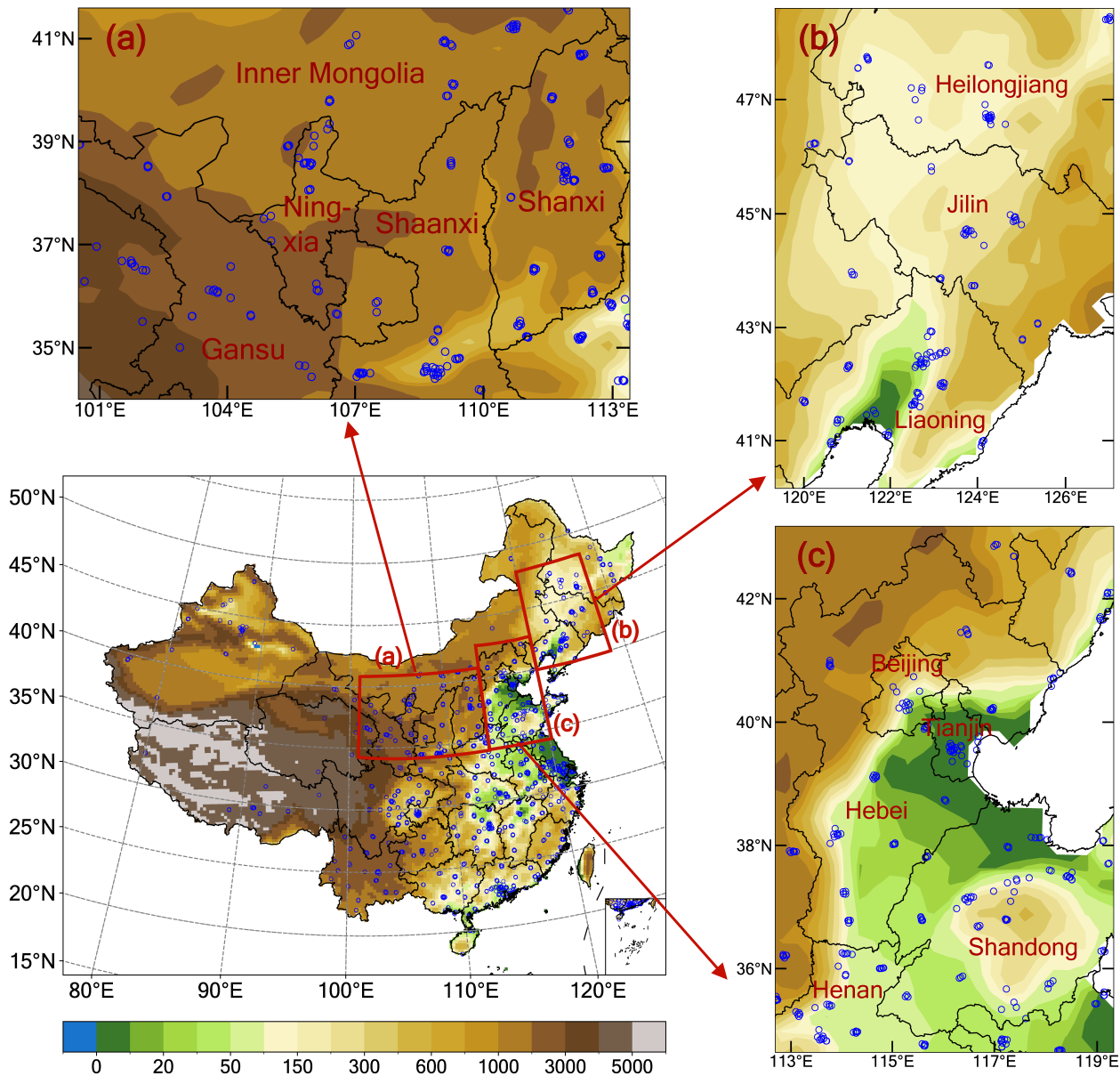


Figure 1. Model domain featuring terrain altitude (filled colors) and spatial distributions of the observation stations (blue circles). The three subregions defined in red rectangles are (a) Energy Golden Triangle (EGT), (b) northeastern China (NEC) and (c), North China Plain (NCP). The solid black lines are province boundaries, and the names of the provinces are marked in red. Units: m.

B_{c0} and B_{ek} represent the background error covariance associated with the initial concentrations and background emissions, respectively. R_k is the observation error covariance matrix, and H_k is the observation operator. The concentration c_k can be expressed by the equation $c_k = f_{k,k-1}(c_{k-1}, e_{k-1})$, where $f_{k,k-1}$ denotes the model integration operator over

a time step from time $k - 1$ to time k . With the use of a linear approximation and time integration, this equation can be written in an incremental format:

$$\delta c_k = L_{k,0} \delta c_0 + \sum_{j=0}^{k-1} L_{k,j} \Gamma_j \delta e_j, \quad (3)$$

where $L_{k,0}$ represents the CTM tangent model operator for δc_0 , and Γ_j is the operator that converts emissions to concentrations. Various numerical algorithms can be employed to minimize the cost function, many of which depend on calculating the gradient of the cost function [46,47]. In Equation (2), the first term, which accounts for the initial background concentration field, was omitted in our experiments since we focused solely on emissions. The gradient for δe_k can be written as

$$\frac{\partial J}{\partial \delta e_k} = B_{ek}^{-1}(\delta e_k) + \sum_{j=k+1}^n \Gamma_k^T L_{j,k}^T H_j^T R_j^{-1}(d_j - H_j \delta c_j) \quad (4)$$

The standard time window was approximately 6 h ($n = 6$), providing sufficient duration to effectively capture the influence of the SO₂ lifetime [48].

2.3. The Prior Emissions and Observation Data

Anthropogenic emissions were obtained from the Multi-resolution Emission Inventory of China (<http://www.meicmodel.org/>, accessed on 6 December 2023) developed by Tsinghua University, with a base year of 2016 (MEIC_2016). The MEIC_2016 provides detailed information on the major chemical species (SO₂, NO_x, CO, NMVOC, PM₁₀, PM_{2.5}, BC, and OC), with a high-resolution of $0.25^\circ \times 0.25^\circ$ and takes into account emissions from various sectors such as power, industry, residential, transportation, and agriculture [24].

Hourly concentrations of SO₂ were published by the China National Environmental Monitoring Center network (<http://www.cnemc.cn/en/>, accessed on 6 December 2023). The spatial distribution of the observation stations is shown in Figure 1, with a total of 1641 observation stations covering the majority of China. This expansive coverage allows for a comprehensive understanding of the spatial distribution of SO₂ across China.

2.4. Experimental Design

Two sets of data assimilation (DA) experiments (Emi_2022 and Emi_2023) were designed (Table 1) to obtain the 2022 and 2023 optimized emissions utilizing the 4DVar DA system and by assimilating hourly observations of SO₂ concentrations. The MEIC_2016 was employed as the prior emissions for both Emi_2022 and Emi_2023. We selected specific study periods based on consistent lunar calendar dates: 30 January to 2 February 2022 and 20 to 23 January 2023. Figure 2 illustrates the flowchart of the assimilation process. The initial assimilation procedures for the two sets of experiments commenced at 00:00 UTC on 30 January 2022 and 20 January 2023, respectively. First, observation data from the 00:00–06:00 UTC time window were assimilated to obtain optimized SO₂ emissions for the 00:00–05:00 UTC interval. In the following DA window, the assimilation continued by assimilating the observations from 01:00 to 07:00 UTC to generate the optimized emissions for the 01:00–06:00 UTC interval. All observations within the same DA window can be used to establish constraints on emission e_0^b , and observations from the third to the sixth hour can be used to establish constraints on emission e_1^b . For emission e_5^b , only the sixth hour observation was available as a constraint. This led to a lack of constraints on emissions for later hours within the DA window. To address this issue, the 4DVar DA system was conducted at each hour, and only the initial hour's assimilation result within the DA window was updated as the optimized emission for that time.

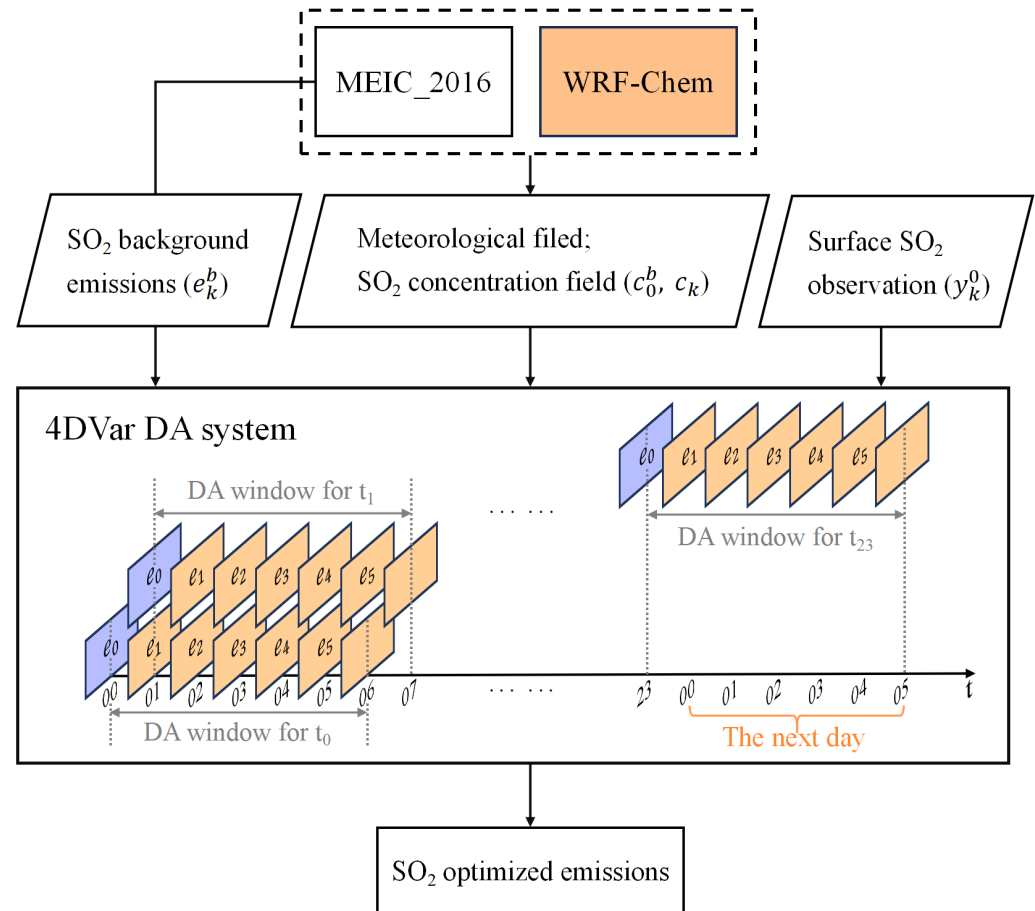


Figure 2. Flowchart for optimization of SO₂ emissions by assimilating SO₂ observations (purple boxes represent updated optimized emissions).

Table 1. The design of the 4DVar DA experiments.

Name	Background Emissions	Optimized Emissions	Study Period
Emi_2022	MEIC_2016	EMI_2022	30 January to 2 February 2022
Emi_2023	MEIC_2016	EMI_2023	20 to 23 January 2023

Prior to conducting the DA experiment, 30 h forecasts were generated using the WRF-Chem model for each day of the study period. Each forecast started at 00:00 UTC and ended at 06:00 UTC the next day. The initial concentrations of SO₂ at 00:00 UTC on 30 January 2022 and 20 January 2023 were obtained from 10-day spin-up forecasts. These forecasts not only provided the necessary physical and chemical parameters for the DA experiment but were also used to offer the corresponding chemical initial conditions for the subsequent day.

Two sets of forecast experiments (Table 2) were conducted concurrently using the prior emission MEIC_2016 and 4DVar optimized emission EMI_2023. The 24 h predictions were carried out daily, spanning from 20 to 23 January 2023. The initial chemical conditions at 00:00 UTC on 20 January 2023 were consistent for both forecast experiments. But for 21 to 23 January 2023, the initial chemical conditions were derived from the predictions of the preceding day.

Table 2. The design of the experiments.

Name	Emissions	Study Period
Sim_MEIC_2016	MEIC_2016	20 to 23 January 2023
Sim_EMI_2023	EMI_2023	20 to 23 January 2023

3. Results

3.1. Observation Analysis

Figure 3a illustrates the hourly average SO_2 concentrations during the CNY in 2022 and 2023. The data show that the peak SO_2 concentrations occurred at 17:00 UTC on CNY's Eve and 02:00 UTC on lunar January 1st, which coincided with the custom of celebrating the New Year by setting off fireworks at midnight and in the morning to celebrate the new year. Figure 3b shows the spatial distribution of surface SO_2 concentrations in China at 17:00 UTC on CNY's Eve in 2023, with high-concentration areas mainly concentrated in northern China. In some cities in Jilin, Liaoning, Inner Mongolia, and Gansu, SO_2 concentrations exceeded $200 \mu\text{g}/\text{m}^3$. Figure 3c depicts the distribution of daily average SO_2 concentrations at monitoring stations. On CNY's Eve 2023 (Day 2), there was a notable increase in SO_2 concentrations, with 66% of stations recording daily average exceeding $10 \mu\text{g}/\text{m}^3$, of which 28% ranged between 15 and $20 \mu\text{g}/\text{m}^3$, and 31% exceeded $20 \mu\text{g}/\text{m}^3$. By 23 January 2023 (Day 4), more than 75% of the stations recorded daily averages below $10 \mu\text{g}/\text{m}^3$, which was lower than the pre-holiday levels (Day 1). This decrease was primarily due to favorable weather conditions controlled by cold high pressure at the surface (Figure S1) and increasing north winds (Figure S2) that promoted the dispersion of pollutants. These findings indicate that fireworks have a significant effect on SO_2 pollution, with this effect becoming more pronounced after the relaxation of the firework ban for CNY in 2023.

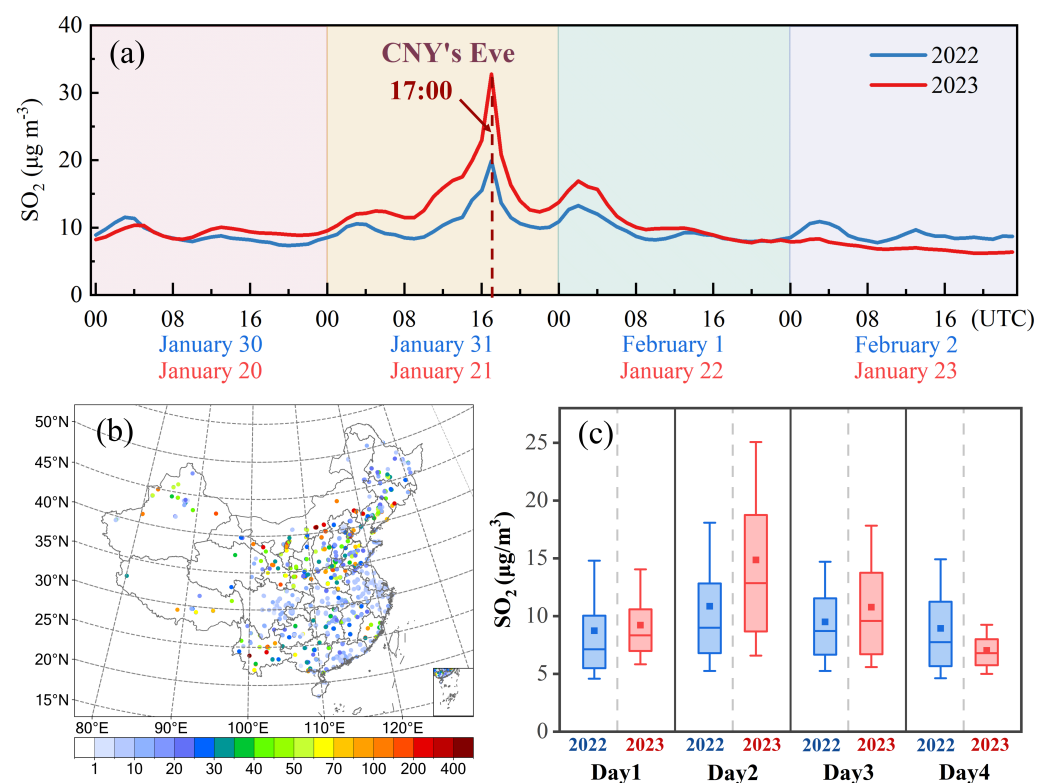


Figure 3. Hourly average SO_2 concentrations in China: (a) during the CNY periods in 2022 (blue) and 2023 (red), (b) at 17:00 UTC on 21 January 2023. (c) Daily average SO_2 concentrations during the 2023 CYN period (20–23 January Day 1~Day 4, red block) and comparison with the same period in 2022 (blue block).

3.2. Spatial Variations in Emissions

Figure 4 shows the spatial distribution of SO_2 emissions for the prior and optimized emissions at 00:00 BJT (Beijing Time) on lunar 1st January in 2022 and 2023. The MEIC_2016 represents the average monthly emissions, and optimized emissions were obtained from the Emi_2022 and Emi_2023 experiments described above. Figure 4a shows that emissions in most regions of China were below $30 \text{ mol}/\text{km}^2/\text{h}$ at 00:00 BJT. However, as shown in

Figure 4b, SO₂ emissions in EMI_2022 were higher in the EGT and NEC with individual areas exceeding 80 mol/km²/h. Compared to EMI_2022, the scope of high-emission areas in EMI_2023 was obviously larger, and SO₂ emissions exceeded 200 mol/km²/h in some cities in Inner Mongolia, Ningxia, and Gansu Provinces (Figure 4c).

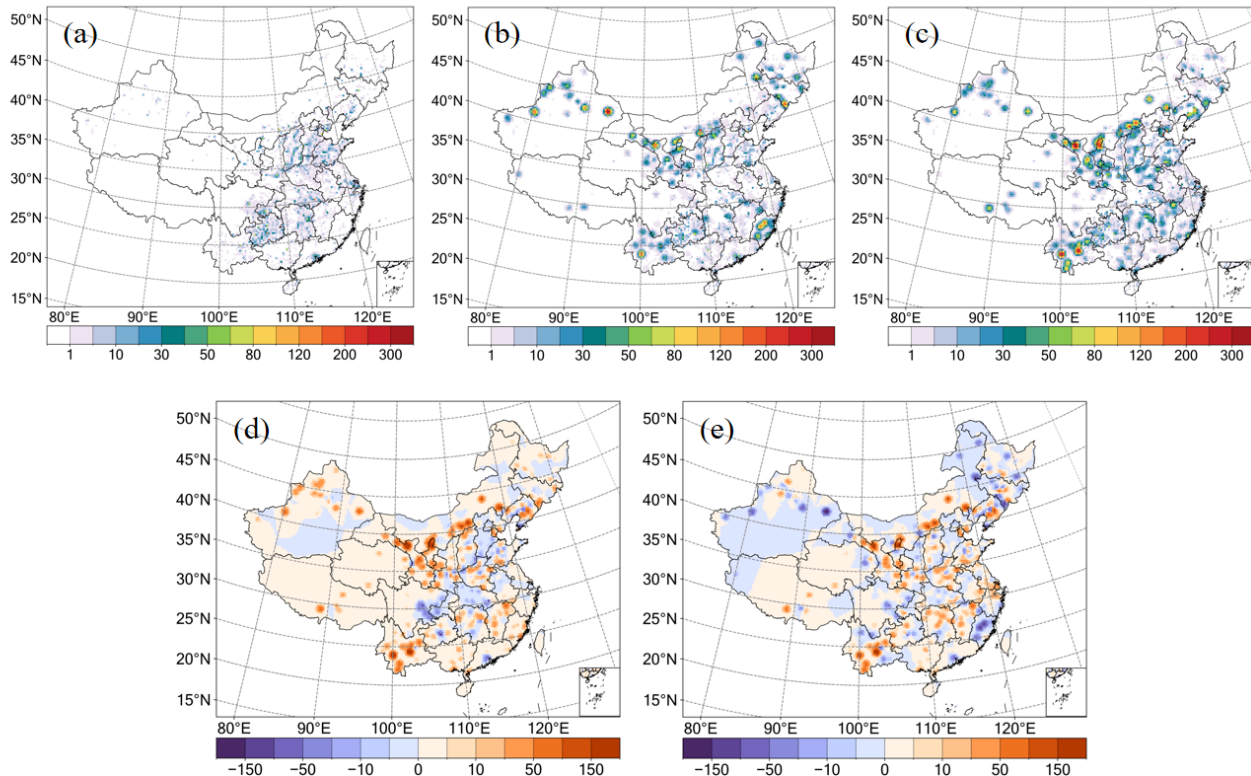


Figure 4. Spatial distribution of SO₂ emission at 00:00 BJT on the lunar January 1st. (a) MEIC_2016, (b) EMI_2022, (c) EMI_2023, (d) EMI_2023 minus MEIC_2016, (e) EMI_2023 minus EMI_2022. Units: mol/km²/h.

In Figure 4d, there are some significant increases in SO₂ emissions in northern China, except for Beijing and Hebei regions. The main reason for the surge in SO₂ emissions was the firework burning, which typically occurred during the initial hour of lunar 1st January [49,50]. Figure 4e illustrates the variations in SO₂ emissions that arose from the CNY fireworks at 00:00 BJT on the lunar 1st January. SO₂ emissions increased across most of China in 2023 compared with those in 2022, and the areas with an emission increment exceeding 30 mol/km²/h were mainly located in provincial capitals or large cities. This was different from previous years, when fireworks were permitted to be set off mainly in suburban or rural areas during CNY. However, regions like Hebei and Beijing, nearly the entire province, exhibited a decrease in SO₂ emissions. The variation was primarily due to these regions being designated as high-priority areas for rigorous environmental air pollution control, and the prohibition on firework burning was still strictly enforced during CNY in 2023.

3.3. Temporal Variations in Emissions

Figure 5 shows the hourly variation in SO₂ emissions in China and different regions on CNY's Eve. The monthly average emissions of the MEIC inventory in January 2016 were considered as corresponding to the emissions on CNY's Eve. As shown in Figure 5a, MEIC_2016 peaked at 1:00 UTC (9:00 BJT) and 9:00 UTC (17:00 BJT), reflecting the highest emissions during the day [45,51]. In terms of the overall national emissions, EMI_2022 and EMI_2023 emissions were both lower than those of MEIC_2016 before 12:00 UTC. EMI_2023 emissions were consistently higher than those in the other two emissions after 13:00 UTC,

and the difference with EMI_2022 was the largest at 16:00 UTC, exceeding 913.1×10^3 kg. This was mainly due to the firework burning for CNY's Eve celebrations, along with an increase in human activities compared to usual.

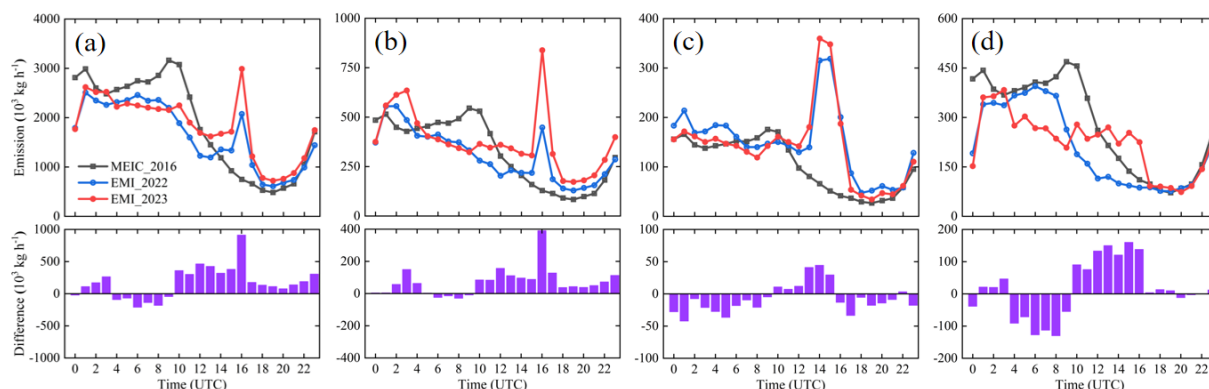


Figure 5. Hourly SO₂ emissions for MEIC inventory in January 2016, and hourly SO₂ emissions on CNY's Eve for the EMI_2022 and EMI_2023 in different regions: (a) China, (b) EGT, (c) NEC, (d) NCP. The bars represent emission differences between EMI_2023 and EMI_2022 (units: 10^3 kg).

For EGT (Figure 5b), EMI_2023 emissions exceeded EMI_2022 for most of the CNY's Eve. In particular, at 16:00 UTC, the peak emission of EMI_2023 was significantly higher than that of EMI_2022, with a maximum difference of 390.9×10^3 kg. The spike in SO₂ emissions reflected the fact that the scale of fireworks displayed in the region on CNY's Eve in 2023 was much larger than that in 2022. In contrast, for NEC (Figure 5c), both EMI_2022 and EMI_2023 emissions surpassed those of MEIC_2016 emissions after 11:00 UTC, peaking at 14:00 UTC (22:00 BJT). However, the difference between the EMI_2022 and EMI_2023 emissions was not significant, as the emissions in 2022 were already high. This was related to traditional customs and less stringent control strategies in NEC, where many cities still allowed fireworks to be set off in urban areas during CNY [50].

For NCP (Figure 5d), the EMI_2022 emissions were lower than those of the MEIC_2016 for the entire day of CNY's Eve. This trend was not only attributable to the factory shutdown during the CNY but was also influenced by the region's pivotal role as a key area for air quality governance [21,52,53]. Over the past few years, China has implemented a series of proactive control strategies that have significantly improved air quality in this region [54]. During CNY in 2023, Beijing and Hebei continued to implement the strict firework ban, while Tianjin and several cities in Henan and Shandong adjusted their regulations to allow fireworks for a limited period of time. As a result, SO₂ emissions in the region increased after 10:00 UTC compared with EMI_2022, with the largest increase occurring at 15:00 UTC, reaching 160×10^3 kg.

Table 3 shows the daily emissions for China and the three regions. The cumulative daily SO₂ emissions for each region were calculated by summing the emissions from the corresponding model grids. The highest daily emissions for both EMI_2022 and EMI_2023 occurred on CNY's Eve. The emissions for EMI_2022 on CNY's Eve increased by 4.701 Gg compared to those on lunar 29 December, with NEC accounting for most of the increase of 0.921 Gg. EMI_2023 emissions experienced a substantial surge of 8.22 Gg on CNY's Eve compared to the emissions on lunar 29 December. Of this increment, 2.037 Gg was contributed by EGT, 1.709 Gg by NCP, and 0.945 Gg by NEC, collectively accounting for 57.07% of the total national increment on that day, with their respective shares being 24.78%, 20.79%, and 11.5%. The difference in SO₂ emissions between CNY's Eve in 2023 and the day before was nearly twice the difference between CNY's Eve in 2022 and its preceding day, highlighting the impact of a relaxed firework ban. In the two days after CNY's Eve in 2022, SO₂ emissions rapidly declined to normal levels, even falling below pre-holiday levels in EGT and NCP, likely influenced by the decrease in industrial production during CNY. Conversely, after CNY's Eve in 2023, although SO₂ emissions also decreased a lot,

they were still above pre-holiday levels, with the exception of EGT. This was probably due to the fact that there was still small-scale firework burning after CNY's Eve, resulting in emissions remaining higher than usual. If the period corresponds to static meteorological conditions, it may continue to lead to deterioration in air quality [55]

Table 3. SO₂ emissions in China for the EMI_2022 and EMI_2023 (units: Gg). Lunar 29 December to lunar 2 January correspond to the 4DVar DA experimental study period.

	Lunar 29 December		CNY's Eve		Lunar 1 January		Lunar 2 January	
	2022	2023	2022	2023	2022	2023	2022	2023
China	35.052	35.163	39.753	43.383	38.34	38.39	36.916	38.335
EGT	6.893	7.037	7.378	9.074	6.765	7.683	6.399	7.052
NEC	2.658	2.454	3.579	3.399	3.036	2.65	3.31	2.693
NCP	4.524	3.643	5.0	5.352	4.881	4.473	4.071	4.629

Here, a day refers to the period from 00:00 UTC of one day to 00:00 UTC the next day, which corresponds to 08:00 BJT of one day to 08:00 BJT the next day.

3.4. Forecast Performance

Figure 6 shows hourly average SO₂ concentration forecasts for both Sim_MEIC_2016 and Sim_EMI_2023 experiments. Compared to the control experiment, the forecasts in the Sim_EMI_2023 experiment were closer to the observed concentrations (Figure 6a). As given in Table 4, the correlation coefficient (CORR) of the Sim_EMI_2023 experiment increased from 0.13 to 0.64, the root mean square error (RMSE) decreased by 49.2% from 21.15 to 10.74 µg/m³, and BIAS decreased from 4.37 to −0.20 µg/m³. The simulated concentrations in Sim_EMI_2023 showed an underestimation of both the observed peak concentration at 17:00 UTC on 21 January 2023 and the secondary peak at 02:00 UTC on 22 January 2023. These over- and underestimations can be explained by the theory of variational assimilation, which is the balance between the observed and background fields according to their respective errors. Therefore, the assimilated emissions necessarily contain information from the background field, potentially leading to inaccurate estimates of SO₂ concentrations.

For EGT (Figure 6b) and NEC (Figure 6c), the peak concentration forecasts in the Sim_EMI_2023 experiment showed improved agreement with observations, especially in EGT, where the CORR improved from 0.07 to 0.65 and RMSE decreased by 42.5% from 29.36 to 16.88 µg/m³. For NCP (Figure 6d), compared to the Sim_MEIC_2016, SO₂ forecasts from the Sim_EMI_2023 significantly mitigated the extent of overestimation, with the BIAS decreasing from 11.52 to 1.63 and the RMSE reducing by 57.9%. Notably, despite the insignificance of emissions in NCP during CNY's Eve, the Sim_EMI_2023 results were still able to capture these characteristics effectively. However, the Sim_EMI_2023 experiment still manifested overestimation, especially during the daily 10:00–12:00 UTC time period. This is because the prior emission in the 4DVar DA experiments was MEIC_2016, which had the highest SO₂ emission at 9:00 UTC, leading to an excessive estimation of concentrations in subsequent time periods.

Table 4. Statistical indicators of the simulated SO₂ concentrations in Sim_MEIC_2016 and Sim_EMI_2023 experiments and observations during CNY in 2023.

	Sim_MEIC_2016			Sim_EMI_2023		
	CORR	RMSE (µg/m ³)	BIAS (µg/m ³)	CORR	RMSE (µg/m ³)	BIAS (µg/m ³)
China	0.13	21.15	4.37	0.64	10.74	−0.20
EGT	0.07	29.36	4.44	0.65	16.88	1.03
NEC	0.12	19.63	−2.81	0.64	14.67	−1.86
NCP	0.30	24.55	11.52	0.80	10.33	1.63

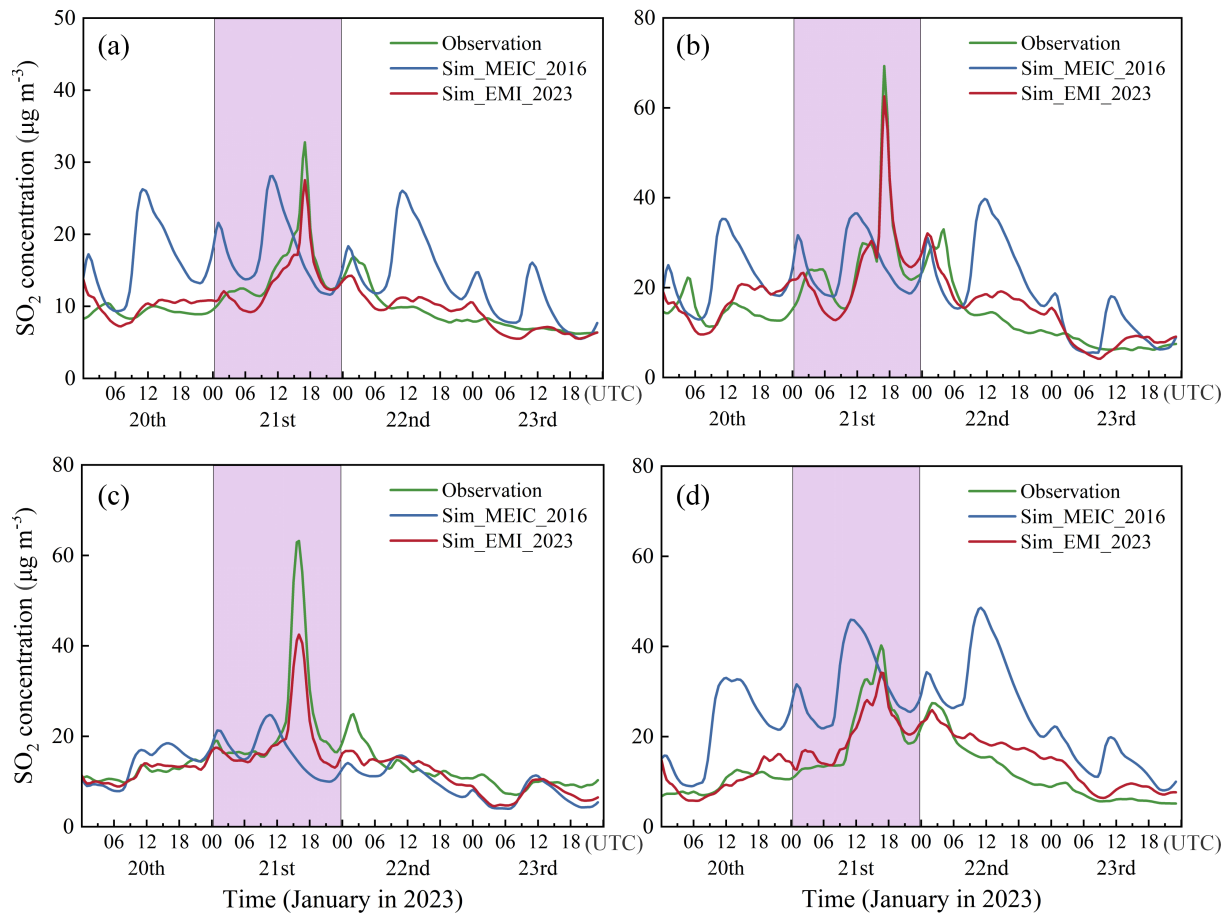


Figure 6. Hourly variations in SO_2 concentration during Spring Festival in 2023 for forecast experiments Sim_MEIC_2016 and Sim_EMI_2023 in different regions: (a) China, (b) EGT, (c) NEC, (d) NCP. The shaded areas represent the day of CNY's Eve.

4. Conclusions and Discussion

In this study, the 4DVar DA system was employed to examine variations in SO_2 emissions in China by assimilating ground-based hourly observation data. Prior emissions were updated, and variations in SO_2 emissions were quantitatively estimated using the optimized emissions. The difference in SO_2 emissions between the CNY in 2023 and 2022 revealed a significant increase in SO_2 emissions at 00:00 BJT on the lunar 1 January 2023, particularly in northern China. This surge was attributed to the relaxation of the firework ban during CNY. The increase in emissions during the 2023 CNY, particularly in provinces such as Inner Mongolia, Ningxia, and Gansu, exceeded $50 \text{ mol}/\text{km}^2/\text{h}$ compared to the same time in the 2022 CNY. We noted a spike in SO_2 emissions on CNY's Eve for the EMI_2023, with an increase of 8.22 Gg from the preceding day—almost double the difference between the CNY's Eve and its preceding day for EMI_2022. The Energy Golden Triangle, North China Plain, and northeastern China regions accounted for 57.07% of the total increment on CNY's Eve.

Two sets of forecast experiments were conducted to assess the improvement in 4DVar optimized emissions in the simulation of SO_2 concentrations. The correlation coefficients for the Sim_EMI_2023 experiment increased from 0.13 to 0.64, and the RMSE decreased by 49.2% compared to the Sim_MEIC_2016 experiment. The results show that the forecast accuracy was greatly enhanced using optimized emissions. This indicates the considerable potential of the 4DVar DA system in examining pollution events triggered by firework burning on CNY, especially in response to a sharp increase in pollutant gas concentrations within a short period of time.

Our analysis of the variation in SO₂ emissions during CNY shows that while there was a significant reduction in SO₂ emissions after CNY's Eve, sporadic emissions still existed. To expedite the recovery to pre-CNY levels, restricting firework displays to CNY's Eve—allowing only intensive activities on that day—could help SO₂ concentrations return to levels close to, or lower than, pre-CNY within two days. Therefore, we recommend that the government further optimize firework display regulations by permitting concentrated firework displays on CNY's Eve and strictly prohibiting them during the rest of the CNY period.

It is important to note that the sustained decrease in SO₂ concentrations during the two days following CNY's Eve was primarily due to meteorological conditions favorable for pollutant dispersion. However, the relaxation of the firework ban may pose greater pollution risks when meteorological conditions are relatively stable. Therefore, such policy adjustments should be carefully considered under unfavorable weather conditions. The goal of this proposal is to mitigate the impact of firework emissions and restore pollutant concentrations to normal levels as quickly as possible. We anticipate that such a policy adjustment would strike a better balance between preserving traditional celebrations and environmental pollution control.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/rs16224191/s1>: Figure S1: Mean sea level pressure from 12:00 UTC on January 22 to 18:00 UTC on January 23, 2023. Figure S2: Surface 10 m wind direction (black arrows) and wind speed (filled colors) from 12:00 UTC on January 22 to 18:00 UTC on January 23, 2023. (unit: m/s). Table S1: WRF-Chem physics and chemistry process configuration. References [56–65] are cited in the Supplementary Materials.

Author Contributions: Conceptualization, Z.Z. and Y.H.; methodology, X.H.; validation, Y.H., Y.L. and Z.Z.; formal analysis, X.H.; investigation, X.H. and L.L.; resources, Y.H., Z.Z. and W.Y.; data curation, X.H.; writing—original draft preparation, X.H.; writing—review and editing, Y.H., Z.Z. and Y.L.; visualization, X.H.; supervision, Y.H. and Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Independent Innovation Science Fund of National University of Defense Technology, grant number 22-ZZCX-081; Postdoctoral Fellowship Program of CPSF, grant number GZC20233525; China Postdoctoral Science Foundation, grant number 2024M754303; the National Natural Science Foundation of China, grant number 42430612; and Key Research and Development Program of Hunan Province of China, grant number 2024AQ2004.

Data Availability Statement: The NCEP FNL reanalysis data can be download at <https://rda.ucar.edu/datasets/ds083.2/>, last access: 6 December 2023. The MEIC 2016 emission sources are available at http://meicmodel.org/?page_id=541&lang=en, accessed on 6 December 2023. The hourly ground SO₂ concentration data can be downloaded at <https://air.cnemc.cn:18007/>, accessed on 6 December 2023.

Conflicts of Interest: The authors declare no conflicts of interest.

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