Supplementary Information for

Nuclear and Coal Power Generation Phaseouts Redistribute U.S. Air Quality and Climate Related Mortality Risk

Lyssa M. Freese, Guillaume P. Chossière, Sebastian Eastham, Alan Jenn, Noelle E. Selin

Corresponding Author Lyssa Freese.
E-mail: lyssamfreese@gmail.com

This PDF file includes:

Supplementary text
Figs. S1 to S23
Tables S1 to S11
SI References

Supporting Information Text

Energy Grid Optimization Model

As described in the Methods and Materials Section, the United States Energy Grid Optimization model (US-EGO) uses data from the National Electric Energy Data System (NEEDS) to perform a cost optimization to meet energy demand in every one of 64 NEEDS regions at every hour of the year. There is transmission between regions, and we have isolated the Texas (ERCOT), Eastern and Western Interconnections in order to represent the limitation on transmission between these regions, and to better match the real-world generation and emissions data (1), meaning that there is no transmission between these regions. We limit hydro-power to maximum capacity factors based on region (Southwest at 56%, Midwest at 68%, Southeast at 49% and Northeast at 73%) (2), aside from the Northwest, for which the model under-predicts hydro-power generation, so we allow it to use 100% of available hydro-power. Finally, we adjust the fuel price of refined coal to be $3 less than the listed price in order to better match refined coal use in the real-world data (based on the fact that refined coal is subsidized (3)).

Constraints for generation in the optimization are:

$$gen_{solar} - capacity_{solar} * pattern <= 0 \tag{1}$$

$$gen_{wind} - capacity_{wind} * pattern * 0.85 <= 0 \tag{2}$$

$$gen_{nuclear} - capacity_{nuclear} * 0.95 <= 0 \tag{3}$$

and for all other fuel types:

$$gen_{fuel} - capacity_{fuel} <= 0 \tag{4}$$

Where gen is generation, capacity is the maximum capacity of the EGU, and the *pattern* is the renewable capacity pattern, taken from NEEDS.

Constraints setting $generation + imports = load + exports$ for region, i at time, t:

$$(\sum(gen_i) + trans_{to_i} - trans_{from_i} - load >= 0)_t \tag{5}$$

Constraints on transmission:

$$trans_i - trans_{capacity} <= 0 \tag{6}$$

Comparison to EPA Data. We evaluate US-EGO by comparing our generation and emissions output from our 2016 baseline (*Base*) US-EGO scenario to the generation and emissions data from our *eGRID* scenario. To evaluate the model, we use annual mean generation and emissions for SO_2, NO, NO_2, and CO_2 by fuel type (biomass, coal, fossil waste, geothermal, hydro, landfill gas, municipal solid waste, natural gas, non-fossil waste, nuclear, oil, petroleum coke, solar, waste coal, and wind) and NEEDS region (64 regions) (4), as seen in Figure S1. We calculate the Pearson correlation coefficient between the annual model generation and *eGRID* generation across both region and fuel types of 0.99 and 1.0, respectively. Correlations for the emissions averaged by region and fuel type vary between 0.82 and 1.0. We do not evaluate methane (CH_4) emissions in our paper because the model largely under-estimates the emissions by region and fuel type (see Figure S1, e). As shown in the results, many oil and gas plants that are the highest emitters have little to no generation in our *Base* and *No Nuclear* scenarios– this is consistent with the generation for these specific EGUs in the *eGRID* generation data. The majority of the high emissions plants in the *Base* scenario have annual generation within a 200 MWh range of *eGRID*, and a few have larger or smaller generation.

Generation Closure. In both shutdown scenarios, *No Nuclear* and *No Nuclear-No Coal*, the demand in various regions exceeds possible supply at certain points in the year. In the nuclear shutdown, the demand in the NEEDS' ERC REST region, located in south eastern Texas, exceeds possible supply for a total of 20 hours in the month of May. Almost 20% of Texas' energy supply is from nuclear power, and we have constrained transmission to stay within the Texas Interconnection (ERCOT), which limits the ability of transmission to take on the shortage. In *No Nuclear-No Coal*, 35 regions have demand that exceeds supply throughout various times of the year. We close these gaps by adding generators that have prohibitive costs such that they are only utilized when the optimization cannot close. The generators have zero emissions, so that we do not impact our estimates on changes in emissions.

Limitations. Our multi-system model uses EGU specific data for explicit interpretation of spatial and temporal variation. However, our choice to use EGU-specific data introduces some tradeoffs relative to more complex energy grid models. We do not include ramp up or reserves for generation, and we do not account for investment into new electricity generation, beyond including emissions free generators without specific locations or limitations on capacity. More complex models incorporate quantification of where this type of investment would occur. The lack of ramp up and reserves have an impact on the amount of generation capacity and the speed with which new plants come on and offline, reducing the amount of capacity available when nuclear and coal power are shut down. This reduces the impact of estimations of future build out on our results. Future research could explore related questions combining chemical transport models with complex energy grid models.

GEOS-Chem

In addition to the comparisons between the *Base* and our two shutdown scenarios (*No Nuclear* and *No Nuclear-No Coal*), we have included the $PM_{2.5}$ and ozone summer (JJA) and winter (DJF) seasonal mean concentrations for each of our five scenarios in summer and winter time (Figures S15 and S16).

Comparison to Observations. We compare 2016 observational data from the IMPROVE network (5) and the EPA's Air Quality System (AQS) monitoring network (6) to our base model, *NEI 2011*, *NEI 2016* and *eGRID* GEOS Chem output. We use AQS daily average observations for $PM_{2.5}$, NO_2, SO_2 and ozone and IMPROVE observations for $PM_{2.5}$, sulfate, and nitrate. We interpolate our model data onto the locations of monitors using xarray's nearest method (7). We calculate the R-value based on interpolated values of our model runs compared to the observations from IMPROVE and AQS (Figures S9 and S10). We also calculate the normalized mean bias (NMB) of ozone and $PM_{2.5}$ for our base model and the observations. The NMB is calculated as $\frac{\sum(M_i - O_i)}{\sum(O_i)} \times 100\%$, where i denotes the seasonal mean at each observational site. The results can be seen in Tables S2 and S3. For ozone, our largest bias shows that the model is high compared to observations during the summer months in the Midwest, Northeast, and Southeast. For $PM_{2.5}$, we find biases during the winter in the Northeast and Southeast (where the model is biased high), and the Northwest, and Southwest (where the model is biased low), as well as being biased low during the summer in the Southwest. Our NMB and R-values are of similar magnitude to previous work (8–11). In S11, we compare the observational data for each of our pollutants with the model output by regional annual mean. The resulting concentrations from our *Base* and *eGRID* scenarios are within a similar range of the observational data as the typical GEOS-Chem emissions inventory, the *NEI 2011* scenario, which shows again that US-EGO does capture similar ranges of pollutant concentrations. We also can see that for the sulfate, $PM_{2.5}$, and SO_2, *NEI 2016* falls closer within the range of the observations than *NEI 2011*.

Ozone Regimes

We calculate a proxy to estimate whether or not a region is NO_x abundant, limited, or transitional by using the formaldehyde (CH_2O):NO_2 ratio (12). We define CH_2O):NO_2 of less than .5 as VOC limited, between .5 and .8 as Transitional, and as greater than .8 as NO_x limited. Figure S14 shows differences between the regimes for the nuclear shutdown and the coal and nuclear shutdown, particularly during the summer, which lead to differences in ozone formation. There is also a shift between VOC limited regimes dominating during the wintertime and NO_x limited regimes dominating during summertime.

Health Impact Assessments

Detailed information about the mean exposure, and mean mortality and 95% confidence intervals for each Race and Ethnicity are shown in tables S5 and S7. We show the mean exposure for the data aggregated by WONDER data and census data, which show similar trends in Tables S6 and S4. Mortality differences are larger than differences in exposure due to the use of race and ethnicity specific relative risks for mortalities using the WONDER data. Tables S8, S9, S10, and S11 show mean exposure and mean mortality rates for counties adjacent to or non-adjacent to nuclear power plants.

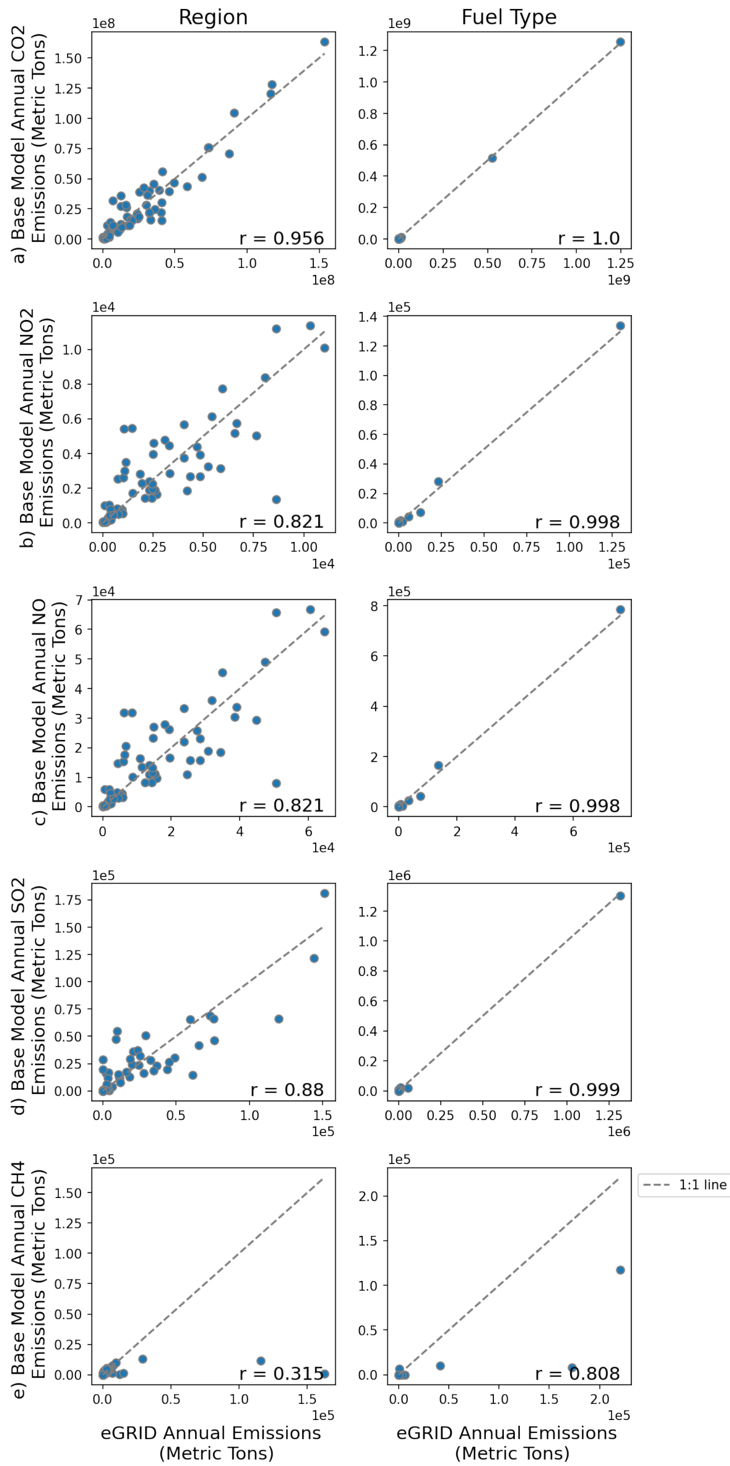

Fig. S1. Scatterplots of the emissions of CO_2 (a), NO_2 (b), NO (c), SO_2 (d), and CH_4 (e) by NEEDS region and fuel type. Pearson correlations (r) are calculated and shown in the bottom right of each plot.

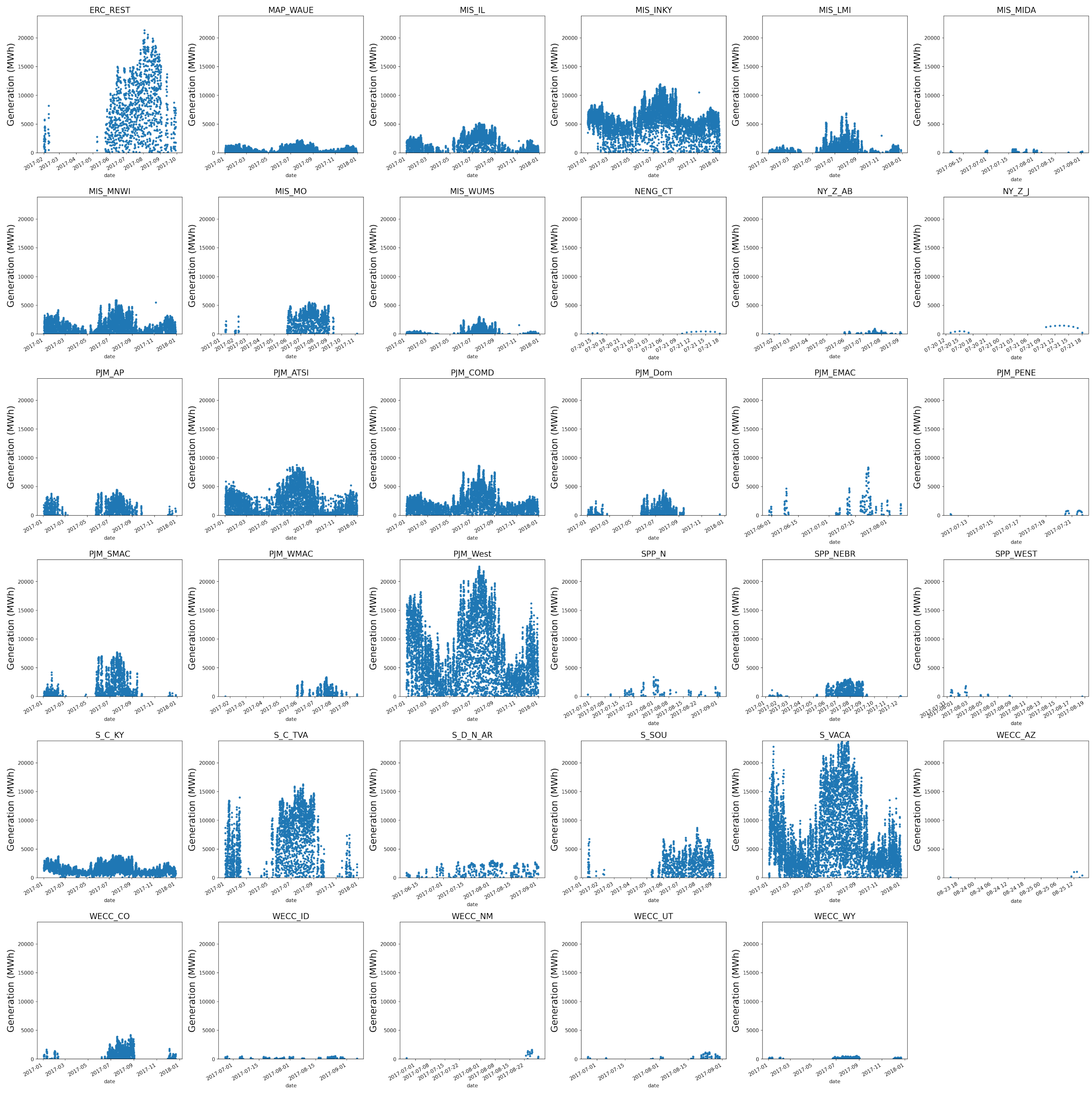

Fig. S2. Generator use by region throughout the year in the *No Nuclear-No Coal* scenario.

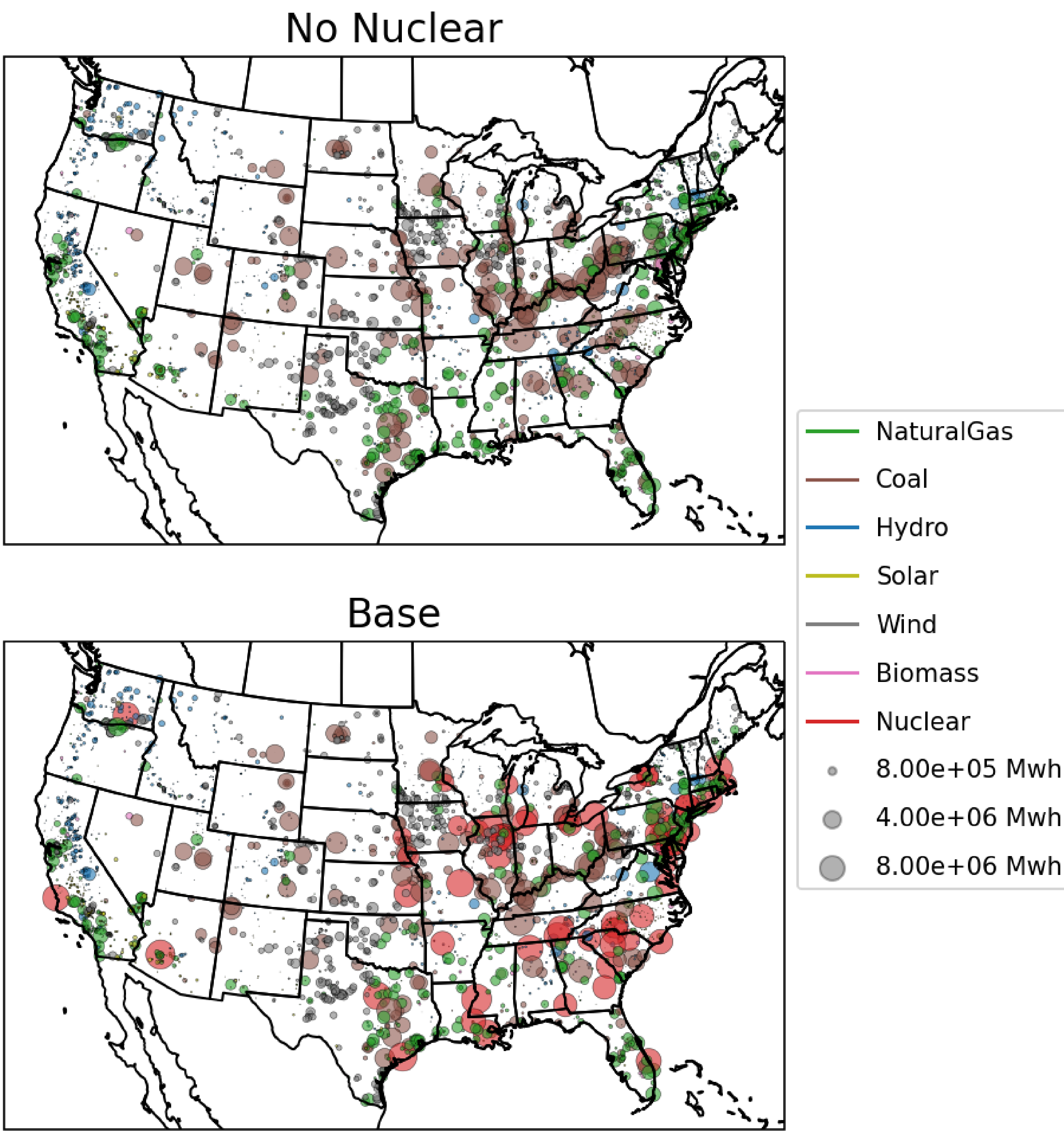

Fig. S3. Map of plants in the *Base* (top) and *No Nuclear* (bottom) scenarios, sized by their annual generation.

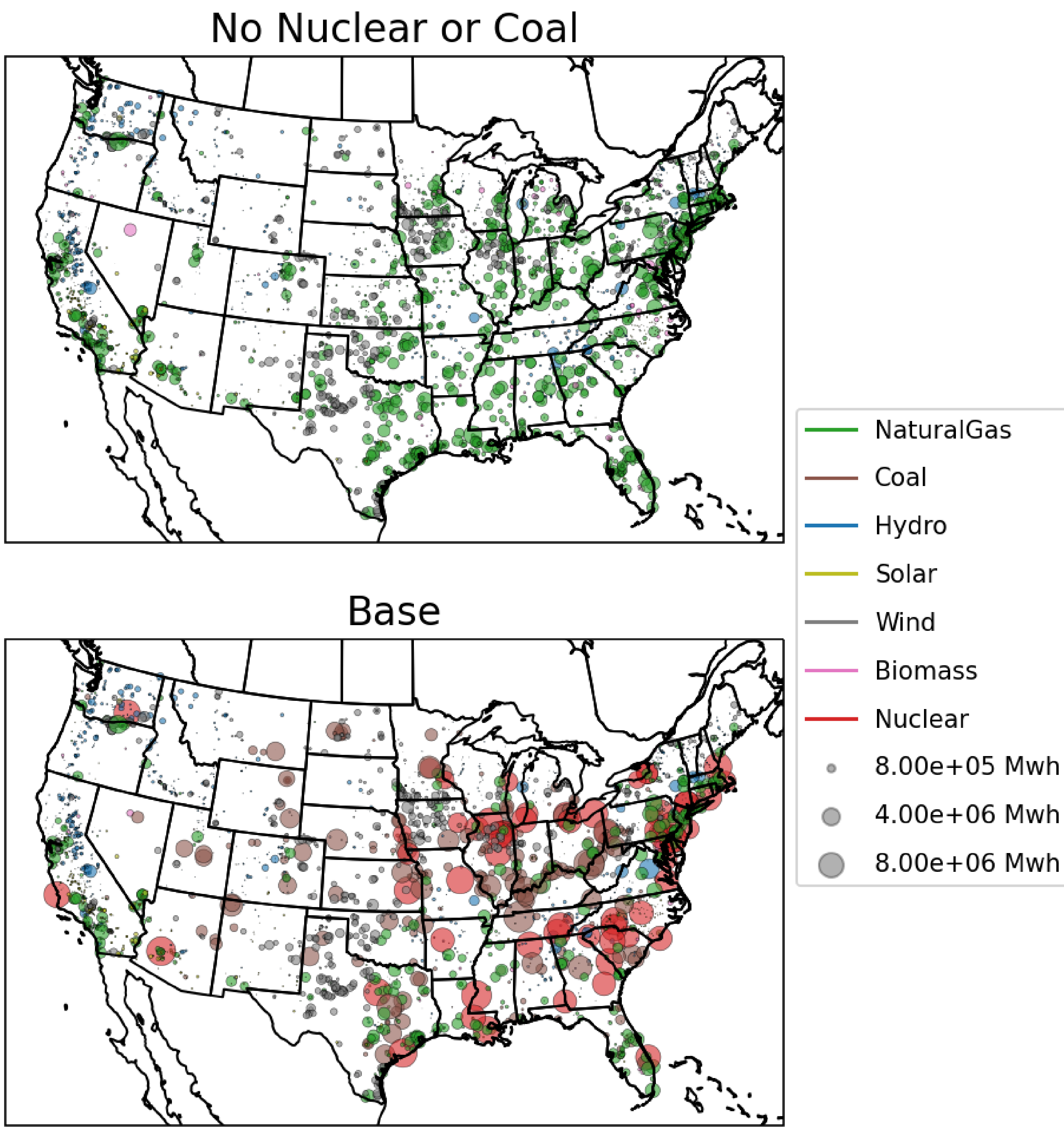

Fig. S4. Map of plants in the *Base* (top) and *No Nuclear-No Coal* (bottom) scenarios, sized by their annual generation.

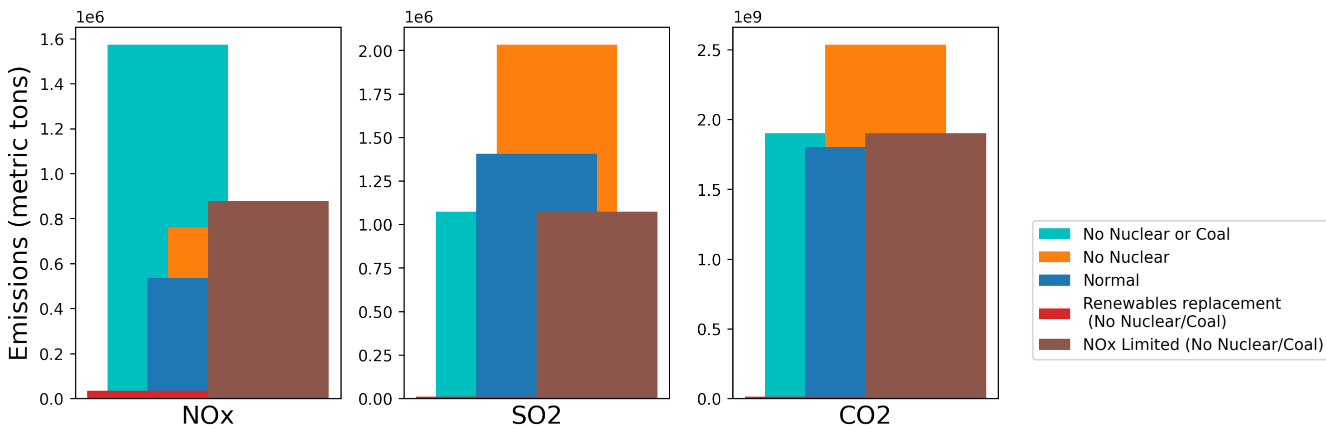

Fig. S5. Emissions of NO_x, SO_2 and CO_2 for the US-EGO simulations for our *No Nuclear-No Coal*, *No Nuclear*, *Base*, and two sensitivity tests of A) renewables replacement in *No Nuclear-No Coal* and B) CSAPR regulations in *No Nuclear-No Coal*

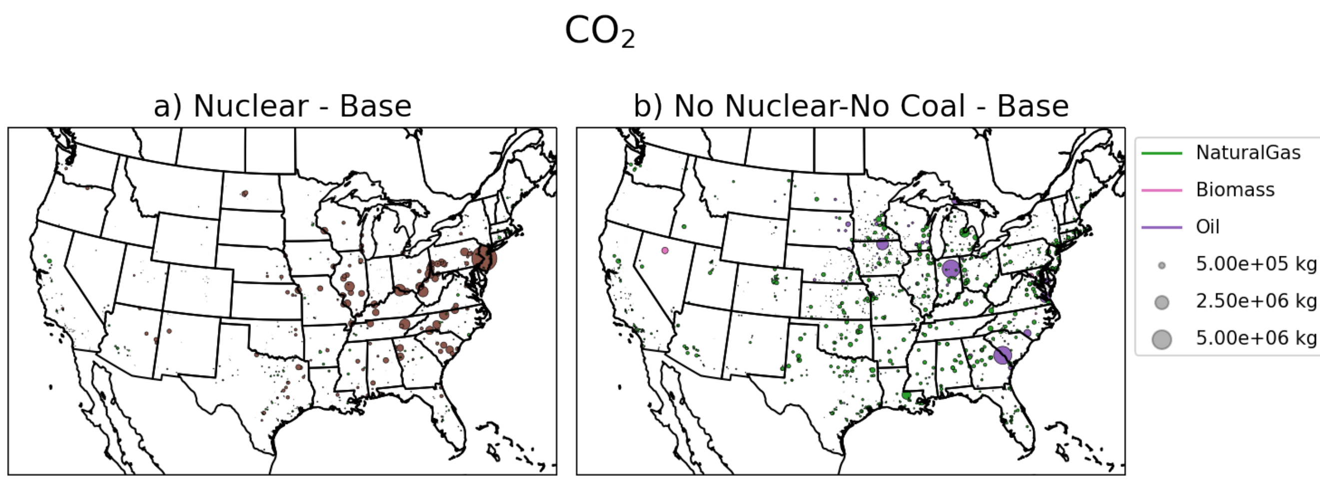

Fig. S6. *No Nuclear - Base* and *No Nuclear-No Coal - Base* annual emissions of CO_2 by each EGU.

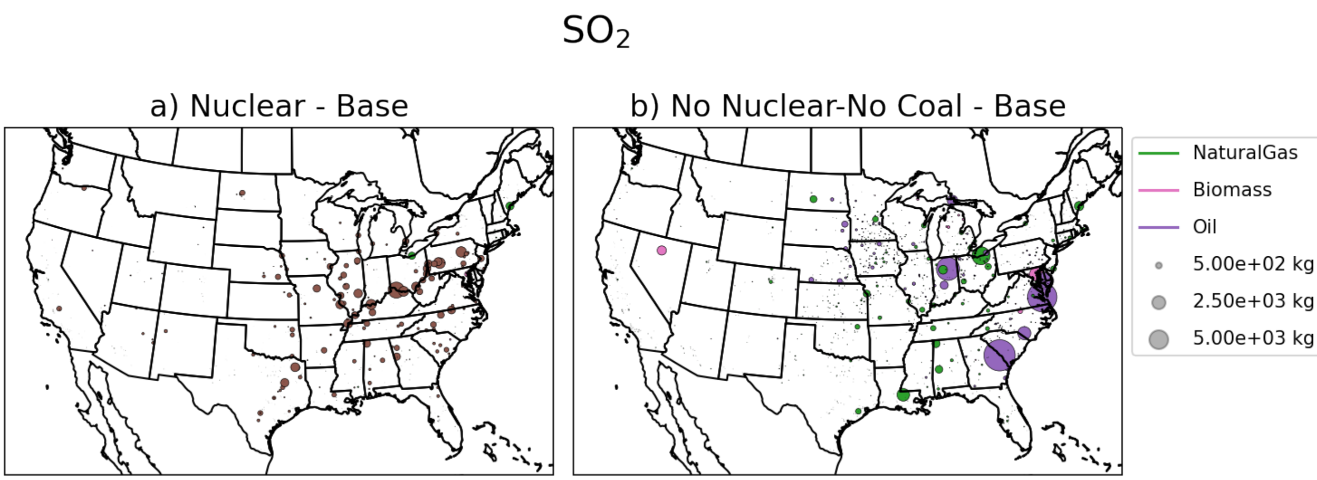

Fig. S7. *No Nuclear - Base* and *No Nuclear-No Coal - Base* annual emissions of SO_2 by each EGU.

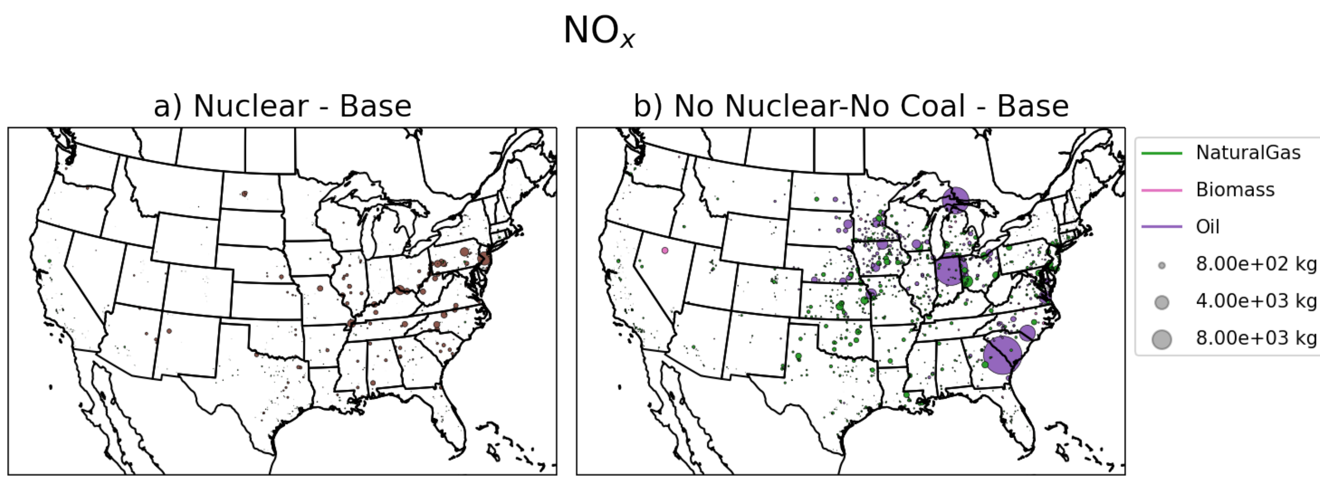

Fig. S8. *No Nuclear - Base* and *No Nuclear-No Coal - Base* annual emissions of NO_x by each EGU.

Table S1. GEOS-Chem Simulations

Name	Data
NEI 2011	National Emissions Inventory, 2011
NEI 2016	National Emissions Inventory, 2016
eGRID	Emissions and Generation Resource Integrated Database
No Nuclear	US-EGO No Nuclear Scenario
No Nuclear- No Coal	US-EGO No Nuclear-No Coal Scenario
Base	US-EGO Base Scenario

Table S2. GEOS-Chem AQS Observation Comparison for Ozone, and the Normalized Mean Bias (NMB) between interpolated GEOS-Chem data and the observational data

Region	Season	NMB (%)
Midwest	DJF	-6.6
Midwest	JJA	36.3
Northeast	DJF	-18.5
Northeast	JJA	34.4
Southeast	DJF	8.1
Southeast	JJA	60.8
Northwest	DJF	13.6
Northwest	JJA	13.7
Southwest	DJF	13.1
Southwest	JJA	12.1

Table S3. GEOS-Chem AQS Observation Comparison: $PM_{2.5}$, and the Normalized Mean Bias (NMB) between interpolated GEOS-Chem data and the observational data

Region	Season	NMB (%)
Midwest	DJF	11.4
Midwest	JJA	-7.4
Northeast	DJF	41.3
Northeast	JJA	13.2
Southeast	DJF	28.3
Southeast	JJA	-4.2
Northwest	DJF	-42.1
Northwest	JJA	-12.0
Southwest	DJF	-37.3
Southwest	JJA	-31.3

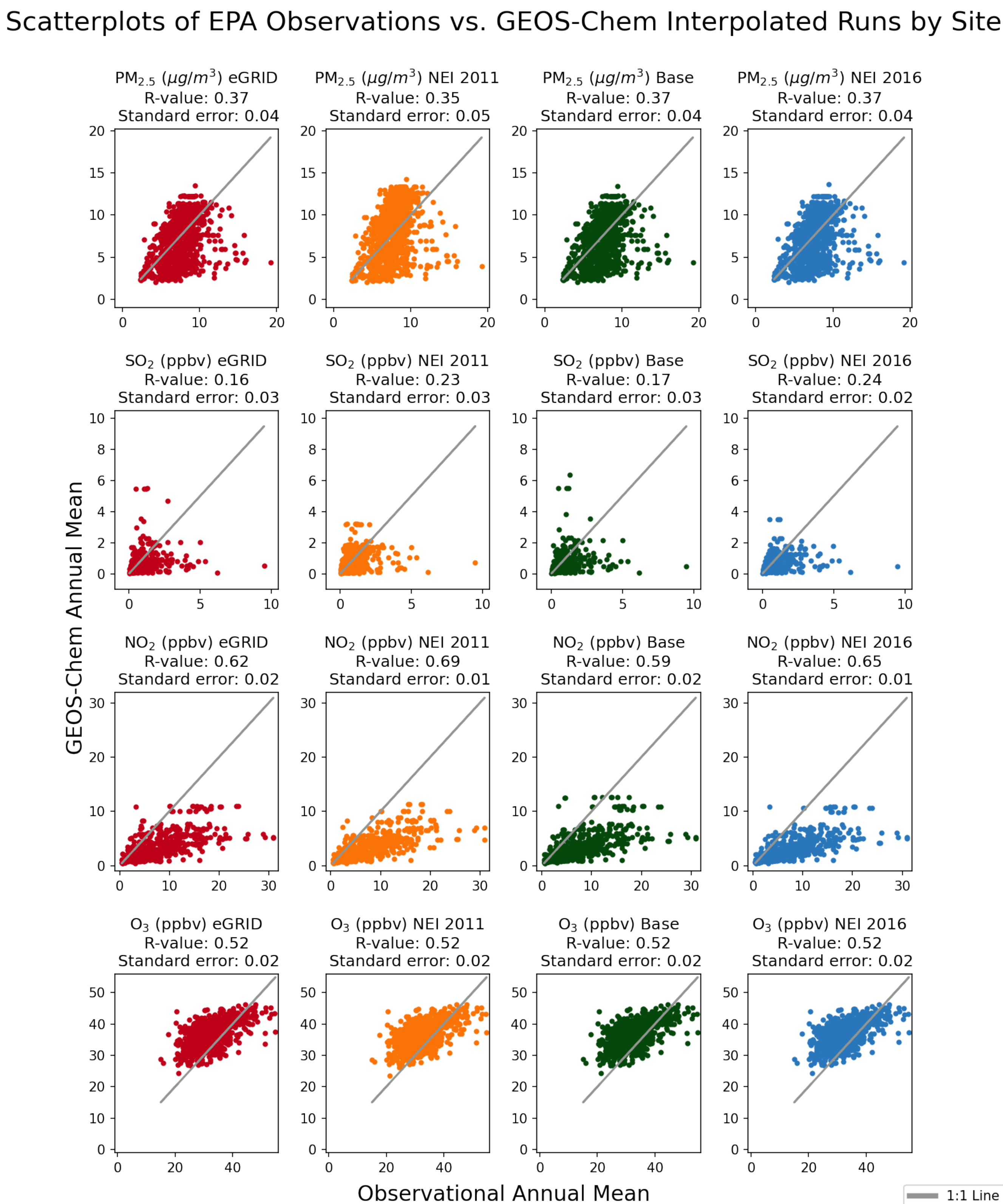

Fig. S9. Scatter plot of the interpolated annual mean GEOS-Chem data as compared to the AQS observational annual mean for the *eGRID*, *NEI 2016*, *Base*, and *NEI 2011*.

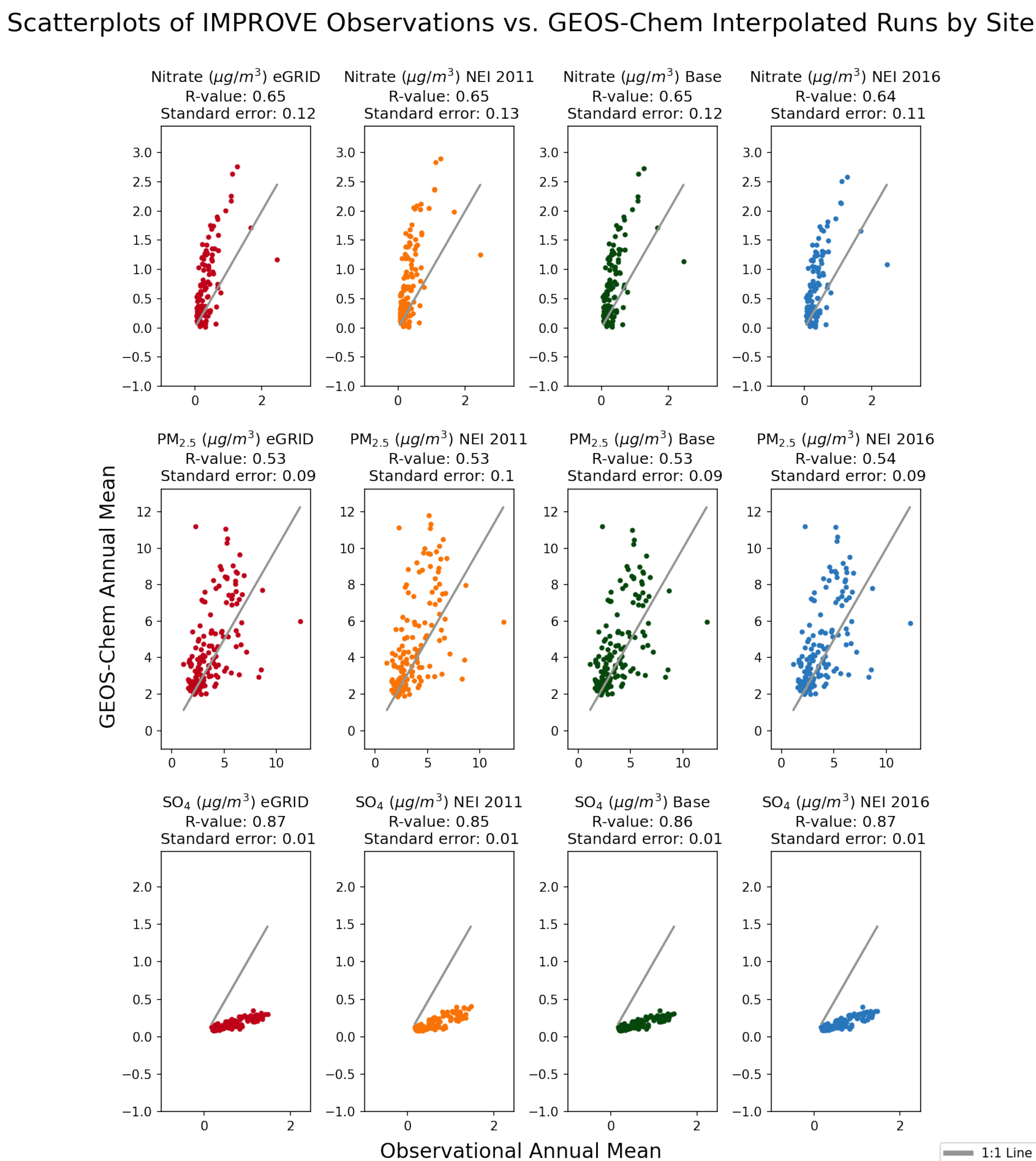

Fig. S10. Scatter plot of the interpolated annual mean GEOS-Chem data as compared to the IMPROVE observational annual mean for the *eGRID*, *NEI 2016*, *Base*, and *NEI 2011*.

Lyssa M. Freese, Guillaume P. Chossière, Sebastian Eastham, Alan Jenn, Noelle E. Selin

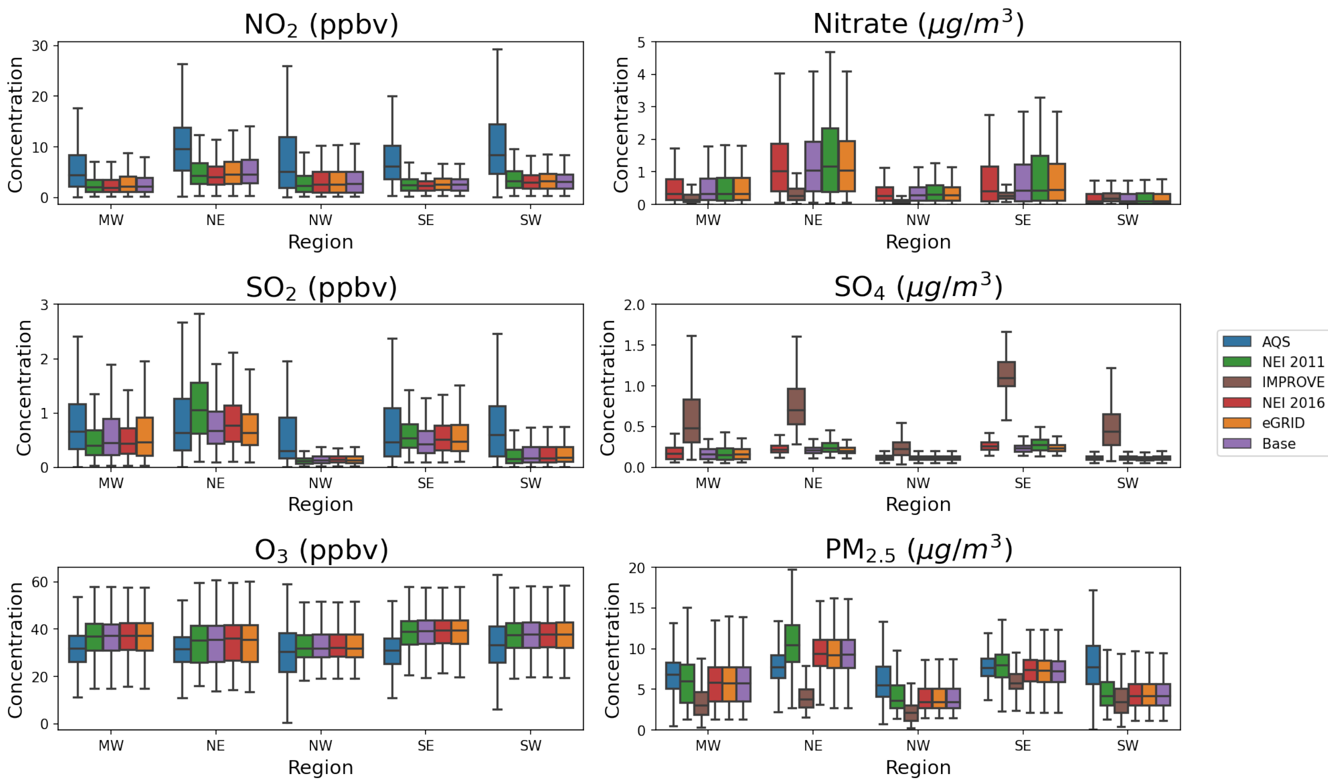

Fig. S11. Boxplots of the observational data from IMPROVE and AQS as compared to the eGRID, NEI 2016, NEI 2011, and normal model data. We split each pollutant into five regions for comparison.

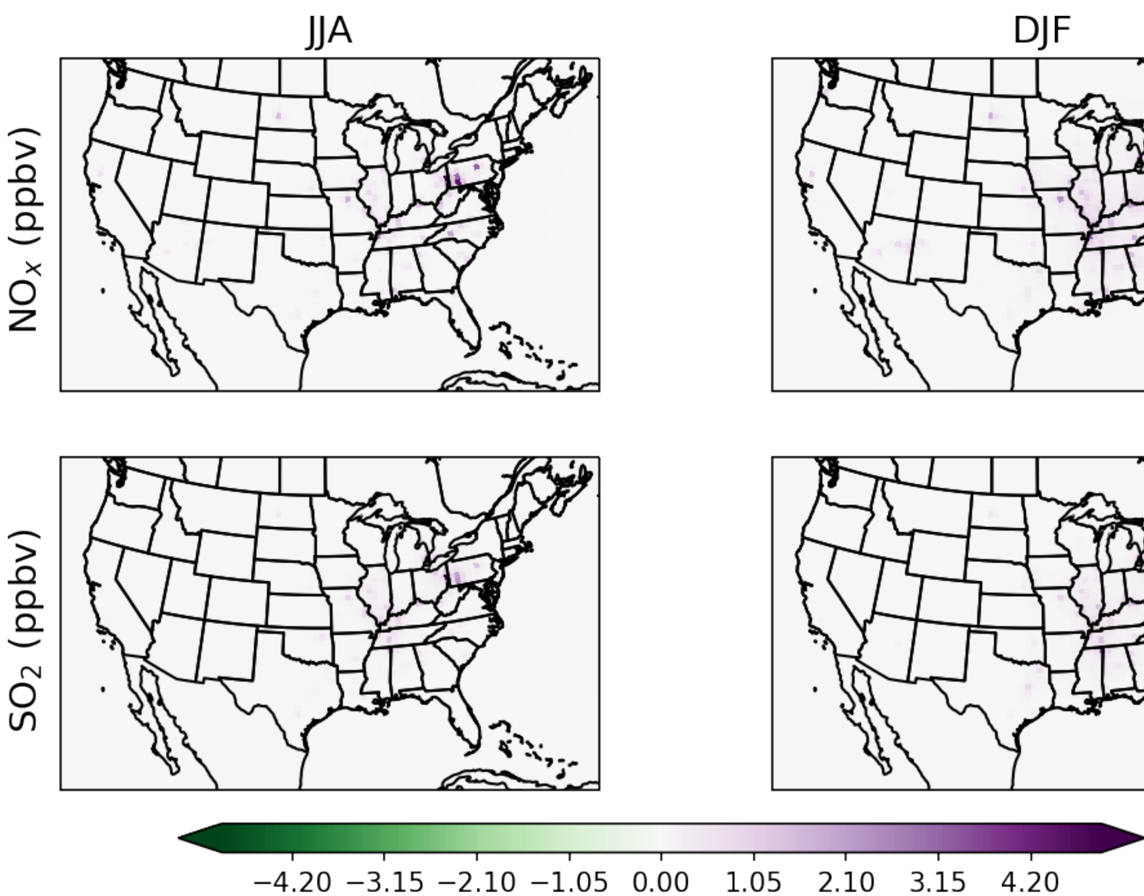

Fig. S12. NO_x and SO_2 concentrations in summer and winter for *No Nuclear* compared to the *Base*

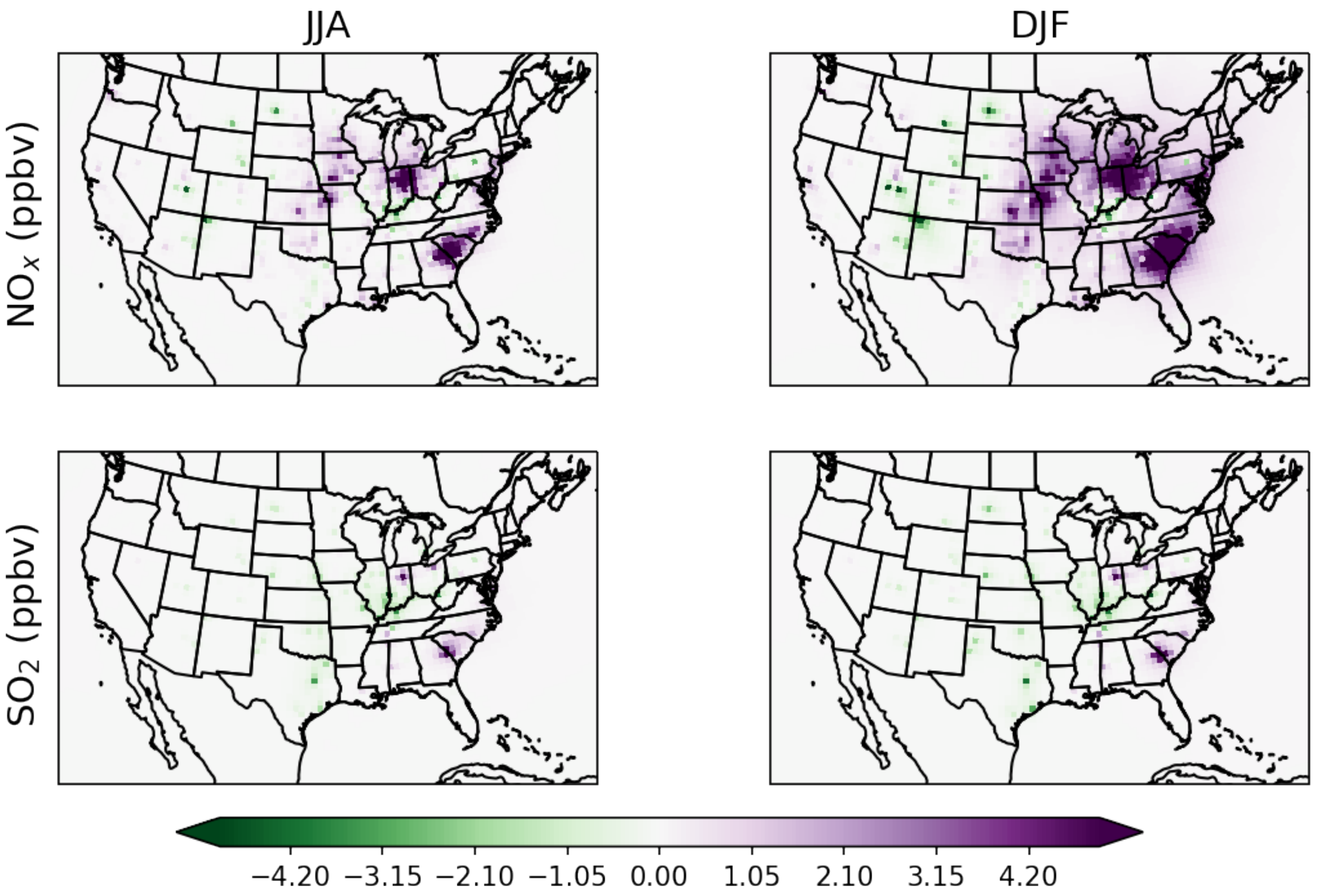

Fig. S13. NO_x and SO_2 concentrations in summer and winter for *No Nuclear-No Coal* compared to the *Base*.

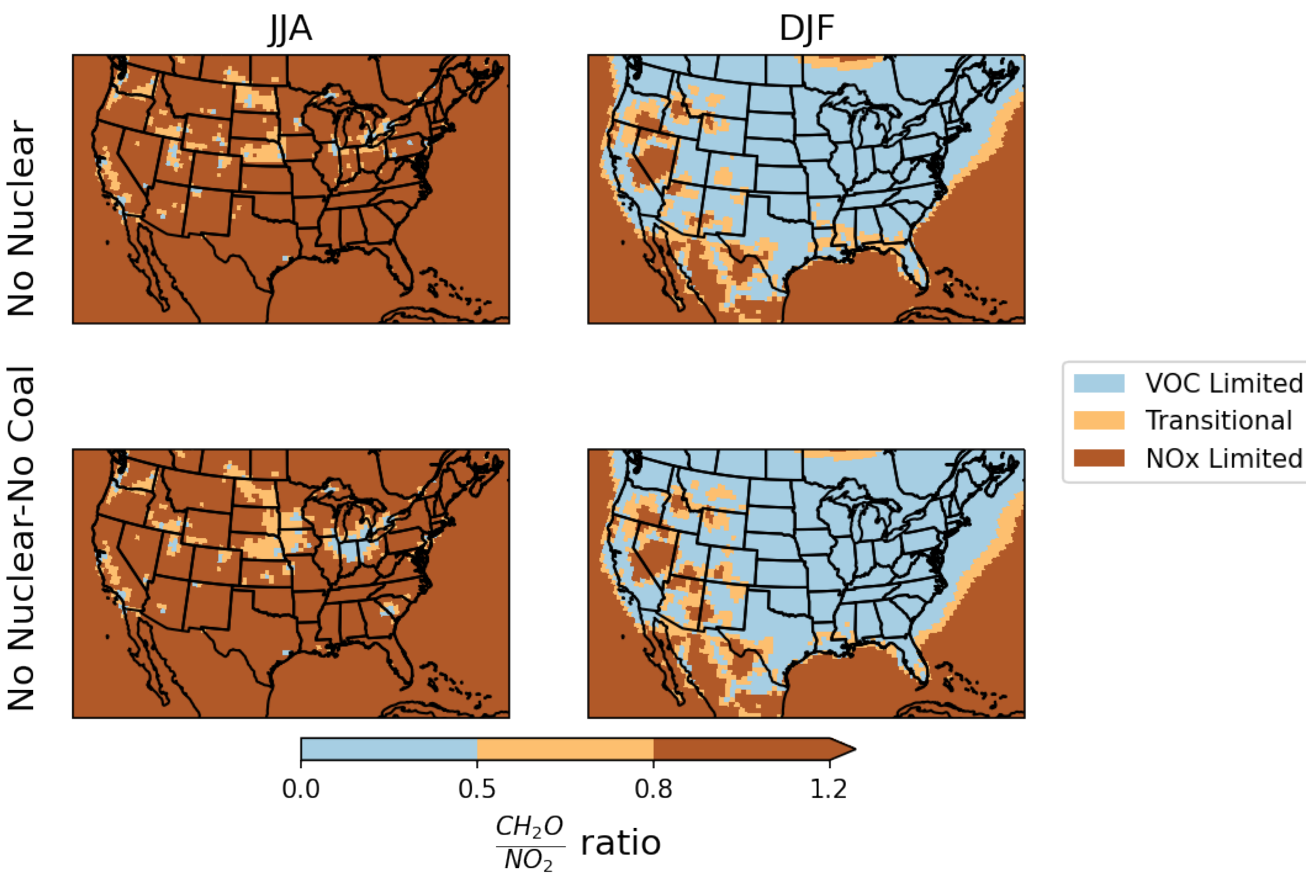

Fig. S14. Summertime and wintertime CH_2O/NO_2 regimes.

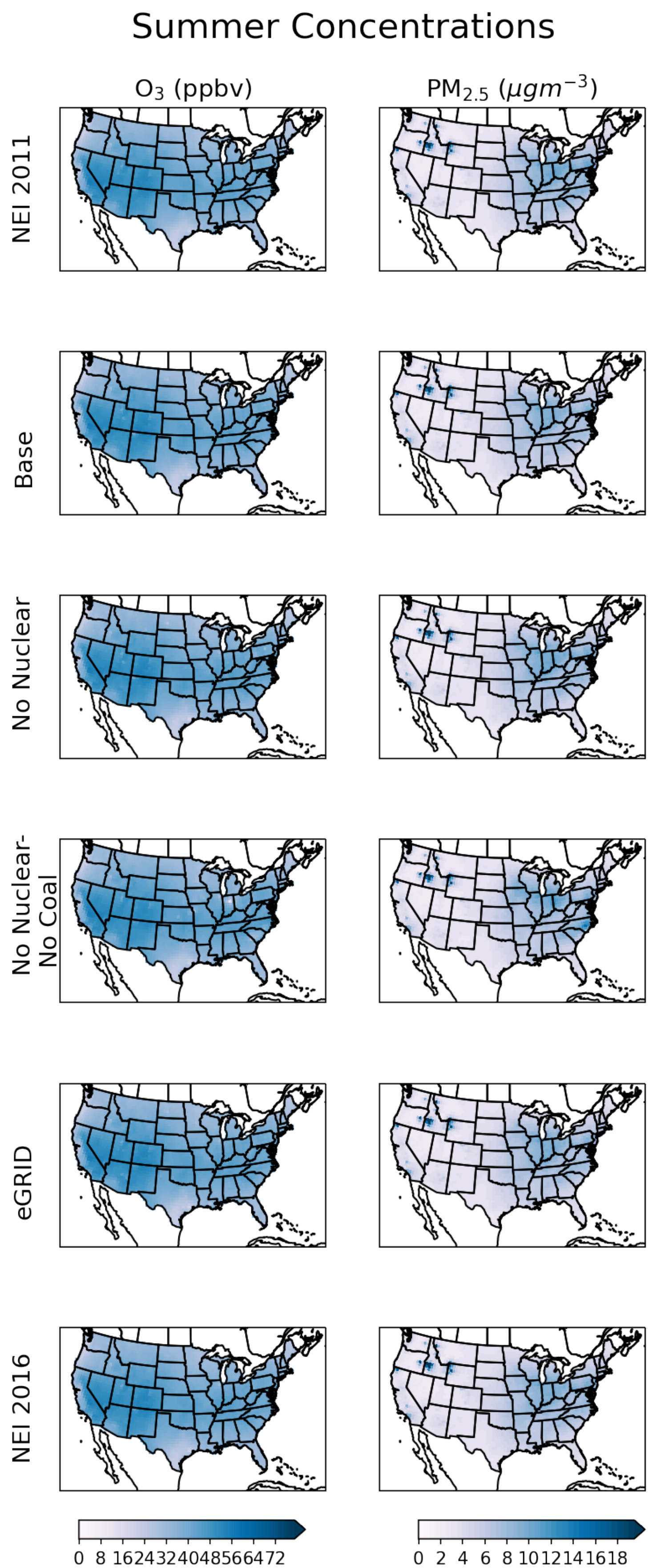

Fig. S15. Mean summer (JJA 24-hour) concentrations of ozone and $PM_{2.5}$ for all six scenarios.

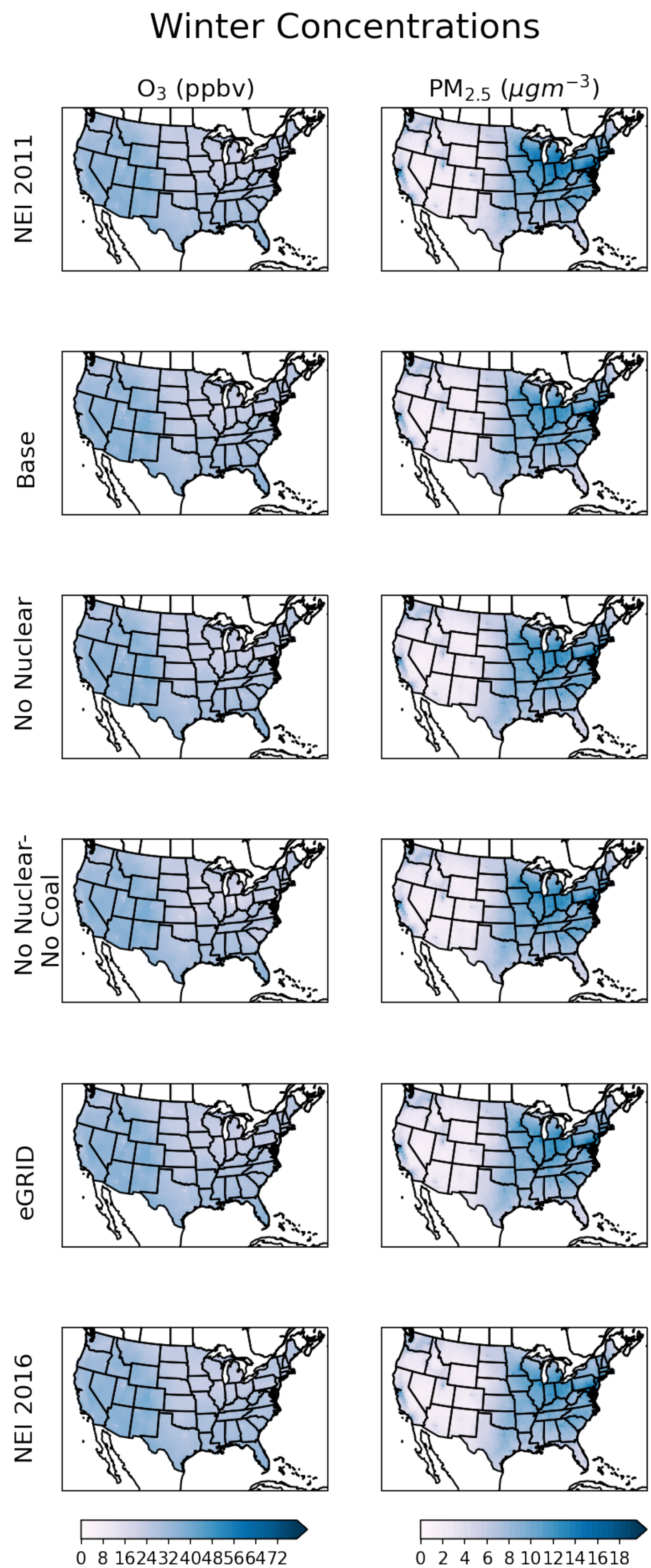

Fig. S16. Mean winter (DJF 24-hour) concentrations of ozone (top) and $PM_{2.5}$ (bottom) for all six scenarios.

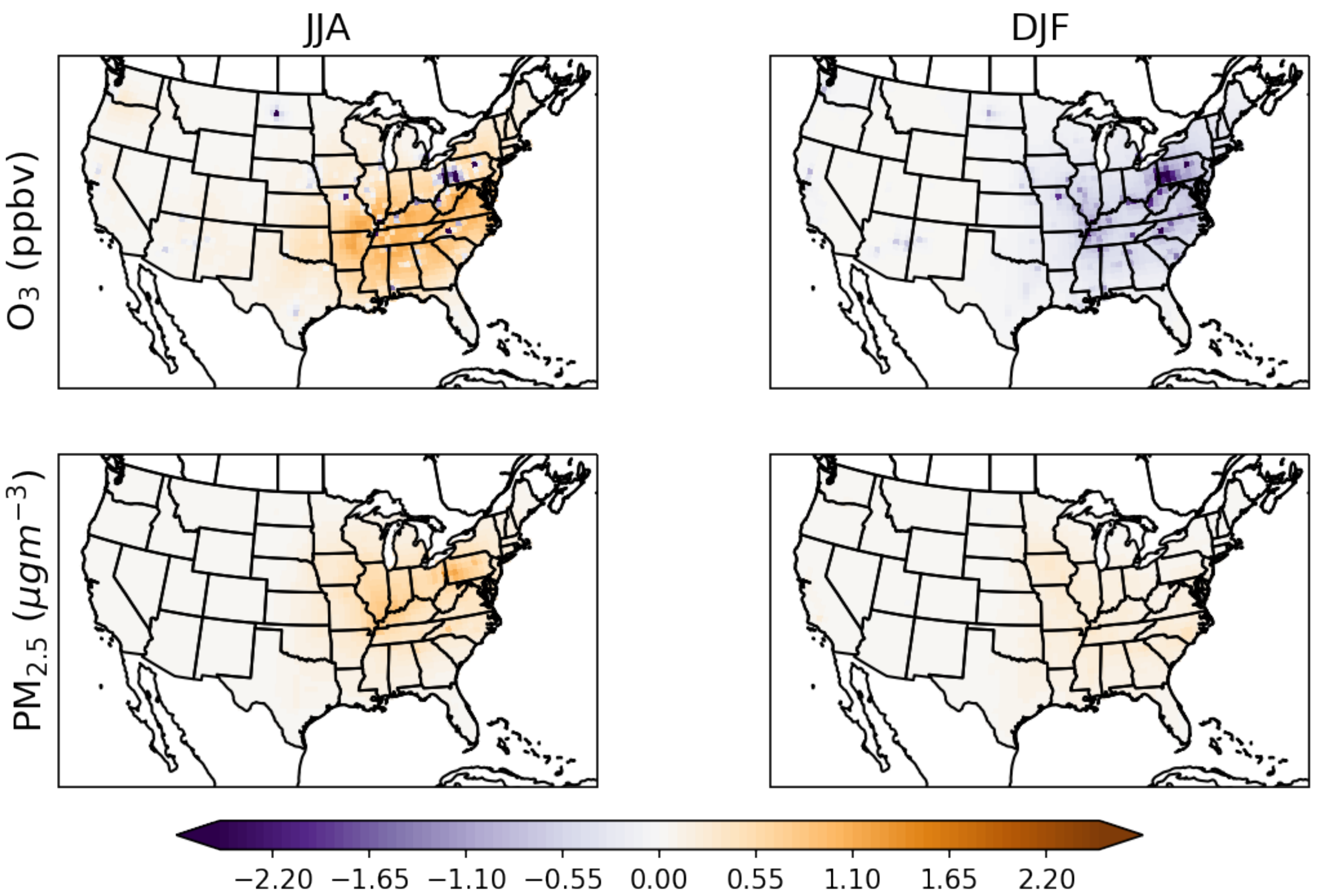

Fig. S17. Differences in summer (JJA) and winter (DJF) mean $PM_{2.5}$ and differences in summer afternoon (JJA 10 A.M.-6 P.M.) and winter (DJF) mean ozone between *No Nuclear* and the *Base*.

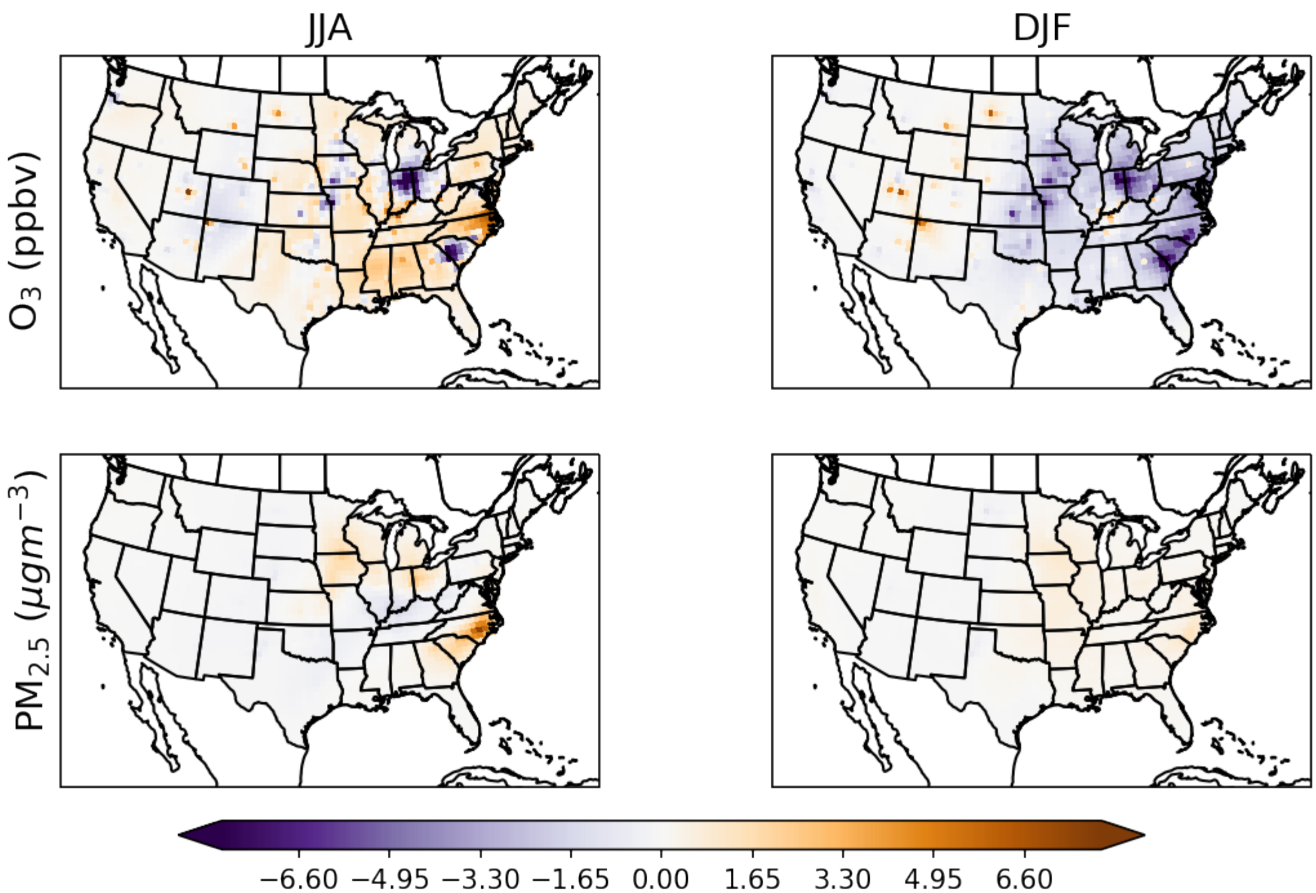

Fig. S18. Differences in summer (JJA) and winter (DJF) mean $PM_{2.5}$ and differences in summer afternoon (JJA 10 A.M.-6 P.M.) and winter (DJF) mean ozone between *No Nuclear-No Coal* and the *Base*.

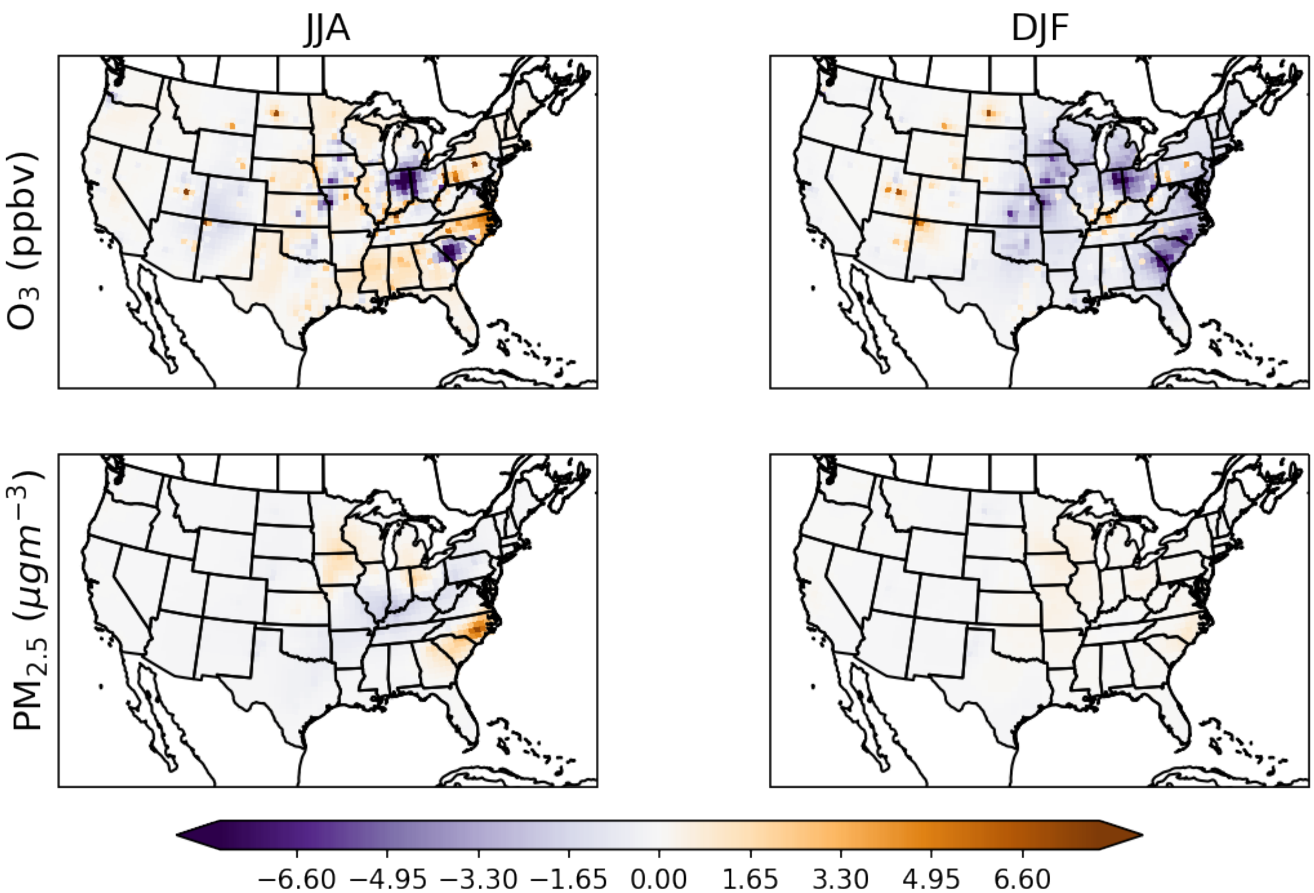

Fig. S19. Differences in summer (JJA) and winter (DJF) mean $PM_{2.5}$ and differences in summer afternoon (JJA 10 A.M.-6 P.M.) and winter (DJF) mean ozone between *No Nuclear-No Coal* and *No Nuclear*.

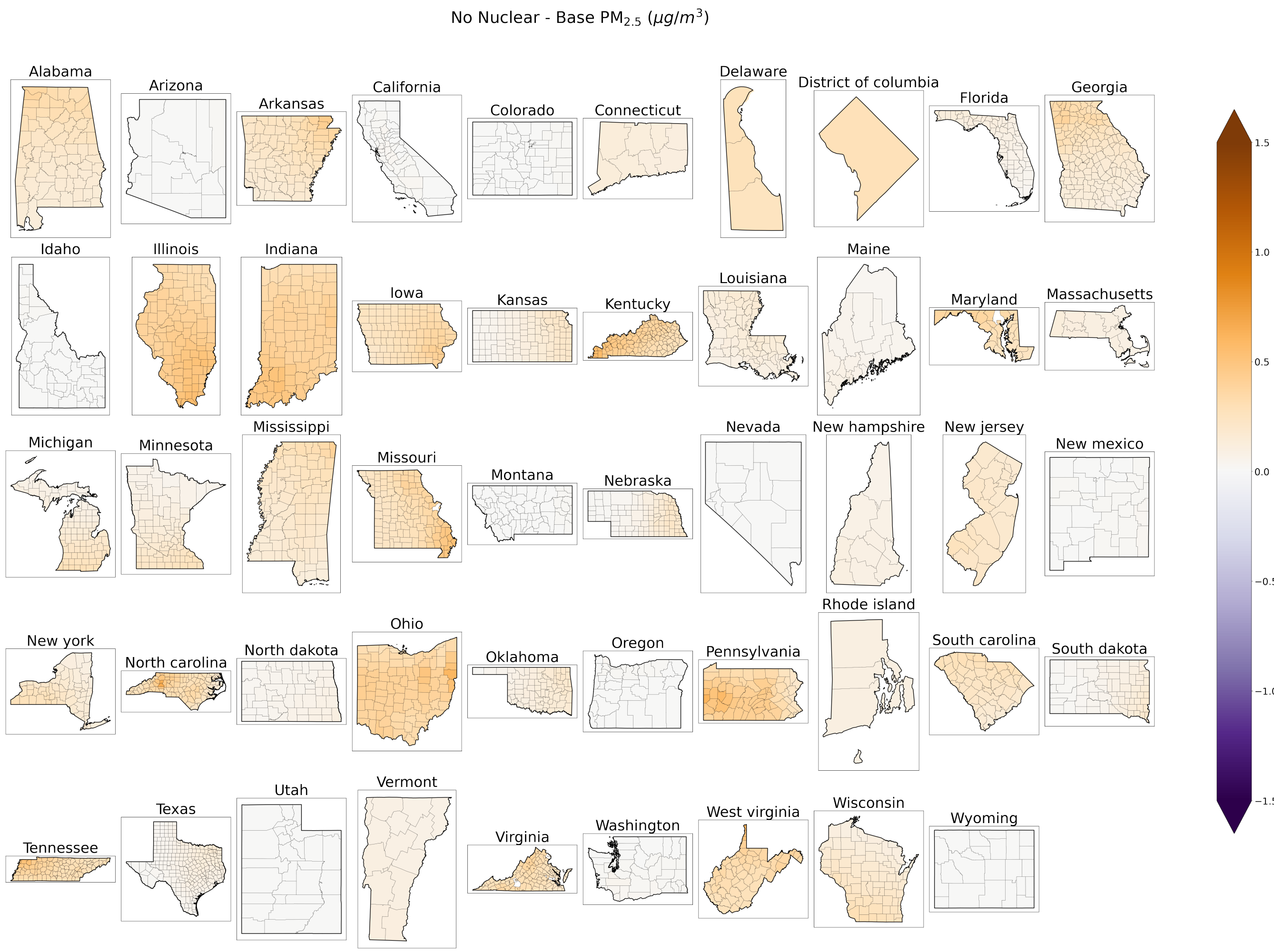

Fig. S20. State specific differences in $PM_{2.5}$ between *No Nuclear* and *Base*

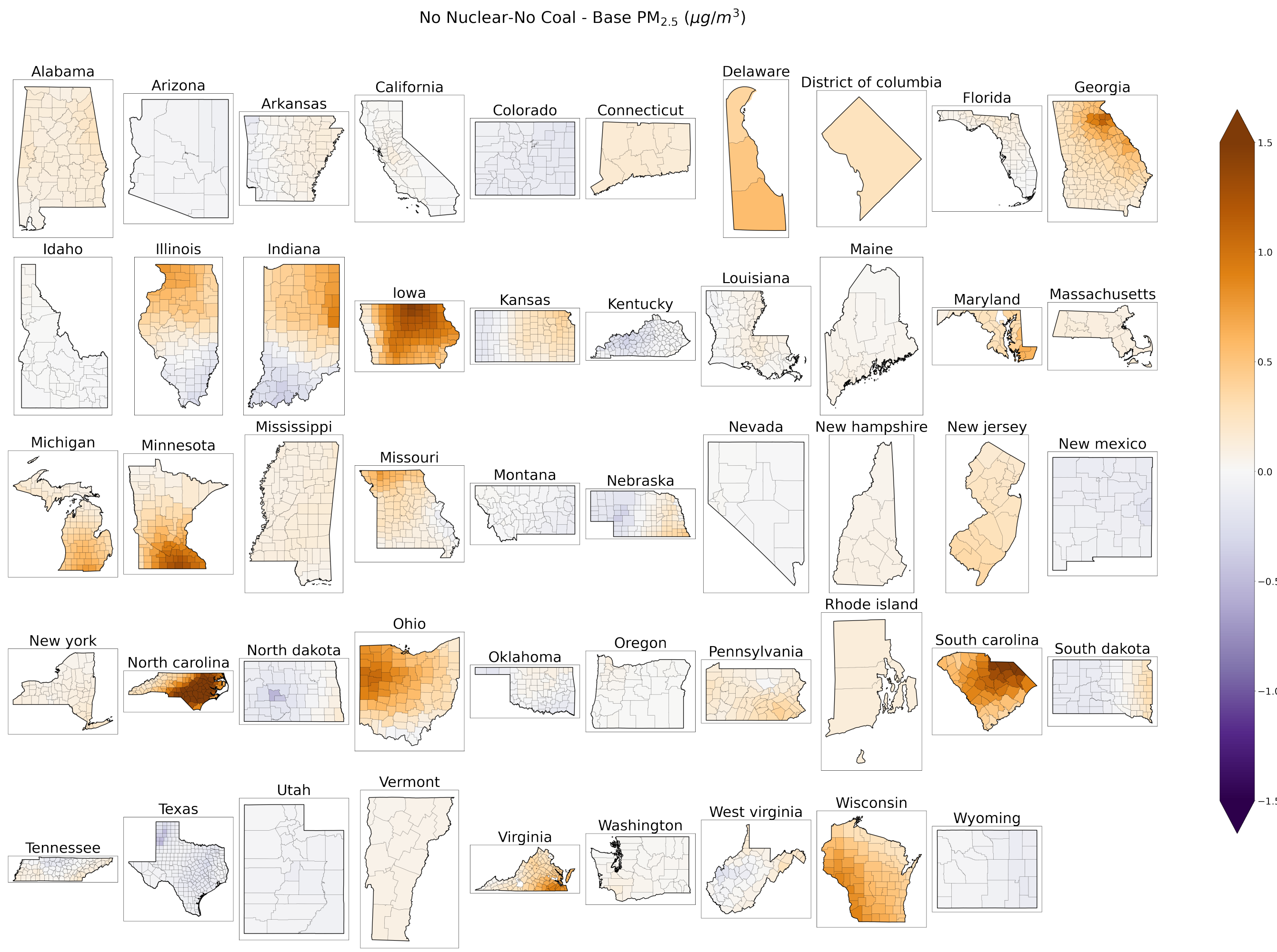

Fig. S21. State specific differences in PM$_{2.5}$ between *No Nuclear-No Coal* and *Base*

Fig. S22. State specific differences in $PM_{2.5}$ between *No Nuclear* and *Base*

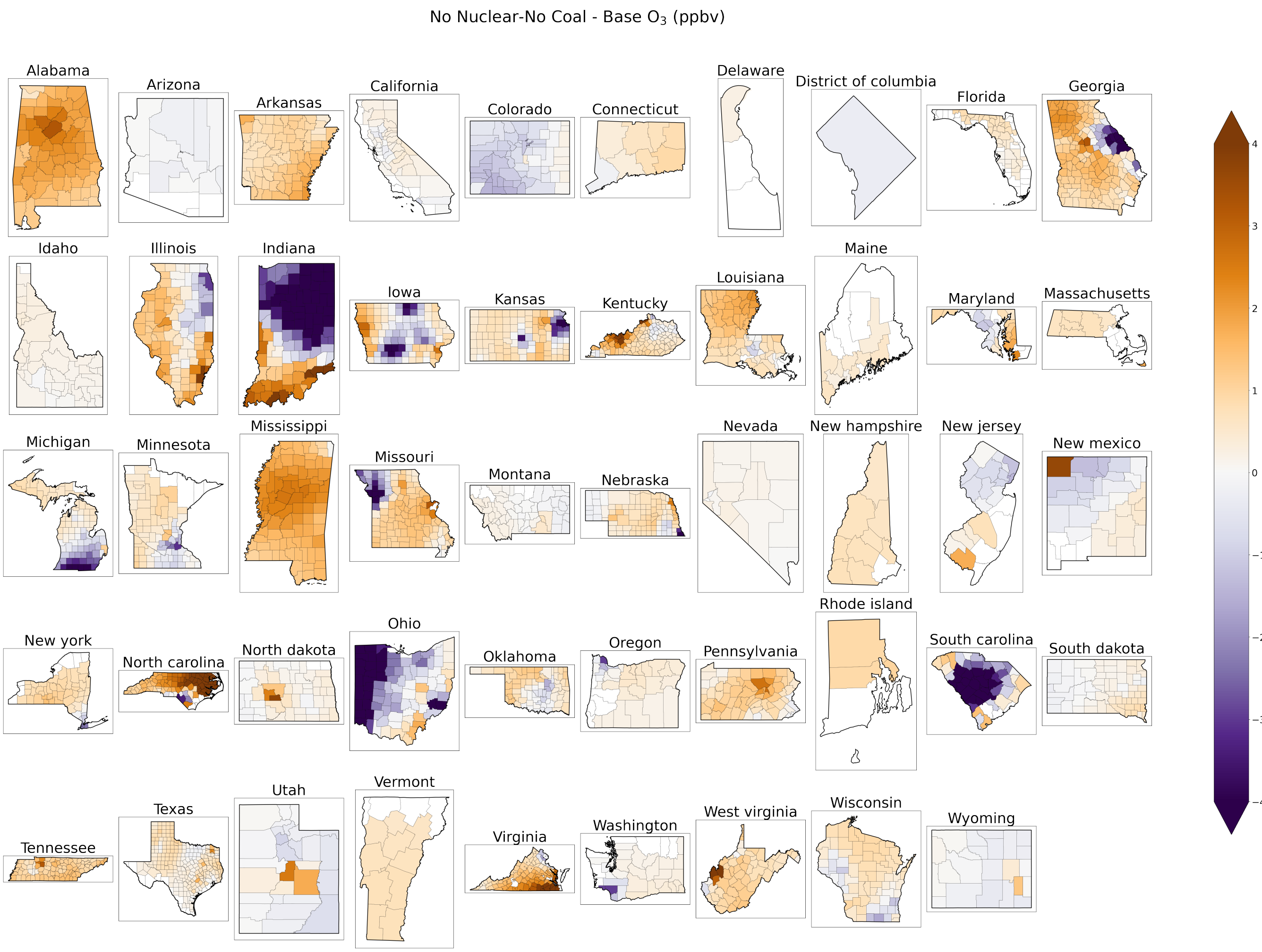

Fig. S23. State specific differences in $PM_{2.5}$ between *No Nuclear-No Coal* and *Base*

Table S4. $PM_{2.5}$ Population Weighted Exposure by Race and Ethnicity, Mean and 95% Confidence Interval

Race and Ethnicity	No Nuclear Change in Exposure WONDER data ($\mu g/m^3$)	No Nuclear-No Coal Change in Exposure WONDER data ($\mu g/m^3$)	No Nuclear Change in Exposure Census data ($\mu g/m^3$)	No Nuclear-No Coal Change in Exposure Census data ($\mu g/m^3$)
Black or African American	0.20	0.26	0.20	0.27
Asian or Pacific Islander	0.12	0.14	0.12	0.15
Hispanic or Latino	0.09	0.08	0.10	0.09
White	0.17	0.18	0.17	0.18
American Indian or Alaska Native	0.07	0.09	0.11	0.13

Table S5. $PM_{2.5}$ Mortality by Race and Ethnicity, Mean and 95% Confidence Interval

Race and Ethnicity	No Nuclear Mortality Rate per 1 million people WONDER (95% CI)	No Nuclear-No Coal Mortality Rate per 1 million people WONDER (95% CI)	No Nuclear Mortality Rate per 1 million people Census Data (95% CI)	No Nuclear-No Coal Mortality Rate per 1 million people Census Data (95% CI)
Black or African American	28.8 (27.6, 29.9)	39.5 (37.9, 41.0)	12.3 (12.0, 12.7)	16.3 (15.9, 16.7)
Asian or Pacific Islander	2.8 (2.2, 3.4)	3.4 (2.7, 4.1)	7.6 (7.4, 7.8)	9.0 (8.8, 9.3)
Hispanic or Latino	2.9 (2.5, 3.3)	1.7 (1.5, 2.0)	6.1 (6.0, 6.3)	5.3 (5.1, 5.4)
White	10.3 (9.8, 10.6)	10.7 (10.2, 11.1)	10.5 (10.3, 10.8)	11.2 (11.0, 11.5)
American Indian or Alaska Native	3.8 (2.3, 0.52)	5.2 (3.2, 7.3)	6.5 (6.4, 6.7)	7.7 (7.5, 7.9)

Table S6. Ozone Population Weighted Exposure by Race and Ethnicity, Mean and 95% Confidence Interval

Race and Ethnicity	No Nuclear Change in Exposure WONDER data (ppb)	No Nuclear-No Coal Change in Exposure WONDER data (ppb)	No Nuclear Change in Exposure Census data (ppb)	No Nuclear-No Coal Change in Exposure Census data (ppb)
Black or African American	0.28	-0.12	0.29	-0.11
Asian or Pacific Islander	0.10	-0.38	0.11	-0.34
Hispanic or Latino	0.08	-0.24	0.09	-0.21
White	0.18	-0.12	0.18	-0.12
American Indian or Alaska Native	0.12	-0.15	0.15	-0.10

Table S7. Ozone Mortality by Race and Ethnicity, Mean and 95% Confidence Interval

Race and Ethnicity	No Nuclear Mortality Rate per 1 million people WONDER (95% CI)	No Nuclear-No Coal Mortality Rate per 1 million people WONDER (95% CI)	No Nuclear Mortality Rate per 1 million people Census data (95% CI)	No Nuclear-No Coal Mortality Rate per 1 million people Census data (95% CI)
Black or African American	2.0 (1.1, 2.6)	-0.8 (-0.5 -1.1)	5.0 (2.5, 9.8)	-1.9 (-1.0, -3.8)
Asian or Pacific Islander	-0.5 (-0.6, -0.3)	2.4 (3.4, 1.4)	1.9 (1.0, 3.8)	-6.0 (-3.0, -11.7)
Hispanic or Latino	-0.3 (-0.4, -0.2)	2.2 (2.8, 1.7)	1.5 (0.8, 3.1)	-3.7 (-1.8, -7.3)
White	2.3 (2.1, 2.4)	-0.7 (-0.6, -0.79)	3.1 (1.6, 6.2)	-2.0 (-1.0, -4.0)
American Indian or Alaska Native	-3.2 (-4.7, -1.8)	1.5 (2.2, 0.85)	2.7 (1.3, 5.3)	-1.7 (-0.9, -3.4)

Table S8. Change in $PM_{2.5}$ Population Weighted Exposure in Nuclear-adjacent and Non-adjacent Counties

Nuclear Adjacent or not	No Nuclear - Base $PM_{2.5}$ exposure WONDER	No Nuclear-No Coal - Base $PM_{2.5}$ exposure WONDER	No Nuclear - Base $PM_{2.5}$ exposure Census Data	No Nuclear-No Coal - Base $PM_{2.5}$ exposure Census Data
Nuclear-adjacent	0.21	0.31	0.21	0.31
Non-adjacent	0.001	0.31	0.14	0.09

Table S9. Change in $PM_{2.5}$ Mortality in Nuclear-adjacent and Non-adjacent Counties

Nuclear Adjacent or not	No Nuclear - Base $PM_{2.5}$ Mean Mortality Rate per 1 million people WONDER	No Nuclear-No Coal - Base $PM_{2.5}$ Mean Mortality Rate per 1 million people WONDER	No Nuclear - Base $PM_{2.5}$ Mean Mortality Rate per 1 million people Census Data	No Nuclear-No Coal - Base $PM_{2.5}$ Mean Mortality Rate per 1 million people Census Data
Nuclear-adjacent	8.2	11.9	13.1	18.9
Non-adjacent	5.1	3.5	8.3	5.7

Table S10. Change in Population Weighted Ozone Exposure in Nuclear-adjacent and Non-adjacent Counties

Nuclear Adjacent or not	No Nuclear - Base ozone exposure WONDER	No Nuclear-No Coal - Base ozone exposure WONDER	No Nuclear - Base ozone exposure census	No Nuclear-No Coal - Base ozone exposure census
Nuclear-adjacent	0.17	-0.29	0.17	-0.28
Non-adjacent	0.004	-0.006	0.21	0.002

Table S11. Change in Population Weighted Ozone Mortality in Nuclear-adjacent and Non-adjacent Counties

Nuclear Adjacent or not	No Nuclear - Base ozone Mean Mortality Rate per 1 million people WONDER	No Nuclear-No Coal - Base ozone Mean Mortality Rate per 1 million people WONDER	No Nuclear - Base ozone Mean Mortality Rate per 1 million people Census Data	No Nuclear-No Coal - Base ozone Mean Mortality Rate per 1 million people Census Data
Nuclear-adjacent	0.9	0.02	2.9	-4.9
Non-adjacent	1.2	0.4	3.6	0.04

References

1. U.S. electric system is made up of interconnections and balancing authorities - Today in Energy - U.S. Energy Information Administration (EIA) (2016).
2. R Uría-Martínez, et al., 2017 Hydropower Market Report, (Oak Ridge National Laboratory), Technical report (2018).
3. Refined coal has made up nearly one-fifth of coal-fired power generation so far in 2017 - Today in Energy - U.S. Energy Information Administration (EIA) (2017).
4. EPA, Power Sector Modeling Platform v.5.15 (2016).
5. WC Malm, JF Sisler, D Huffman, RA Eldred, TA Cahill, Spatial and seasonal trends in particle concentration and optical extinction in the United States. *J. Geophys. Res. Atmospheres* **99**, 1347–1370 (1994).
6. U EPA, Daily summary data for pollutants (2016) Library Catalog: aqs.epa.gov.
7. S Hoyer, J Hamman, xarray: N-D labeled Arrays and Datasets in Python. *J. Open Res. Softw.* **5**, 10 (2017) Number: 1 Publisher: Ubiquity Press.
8. H Simon, KR Baker, S Phillips, Compilation and interpretation of photochemical model performance statistics published between 2006 and 2012. *Atmospheric Environ.* **61**, 124–139 (2012).
9. J Holt, NE Selin, S Solomon, Changes in Inorganic Fine Particulate Matter Sensitivities to Precursors Due to Large-Scale US Emissions Reductions. *Environ. Sci. & Technol.* **49**, 4834–4841 (2015) Publisher: American Chemical Society.
10. JM Walker, S Philip, RV Martin, JH Seinfeld, Simulation of nitrate, sulfate, and ammonium aerosols over the United States. *Atmospheric Chem. Phys.* **12**, 11213–11227 (2012).
11. CL Heald, et al., Atmospheric ammonia and particulate inorganic nitrogen over the United States. *Atmospheric Chem. Phys.* **12**, 10295–10312 (2012).
12. X Jin, et al., Evaluating a Space-Based Indicator of Surface Ozone-NOx-VOC Sensitivity Over Midlatitude Source Regions and Application to Decadal Trends. *J. Geophys. Res. Atmospheres* **122**, 10,439–10,461 (2017).