EAPS
Earth, Atmospheric and Planetary Sciences

Selin Group
Pollution, Impacts and Policy at MIT

Black Carbon Reduced Form Modeling through Green's Functions for Policy Scenarios

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MARTIN FAMILY SOCIETY OF FELLOWS FOR SUSTAINABILITY

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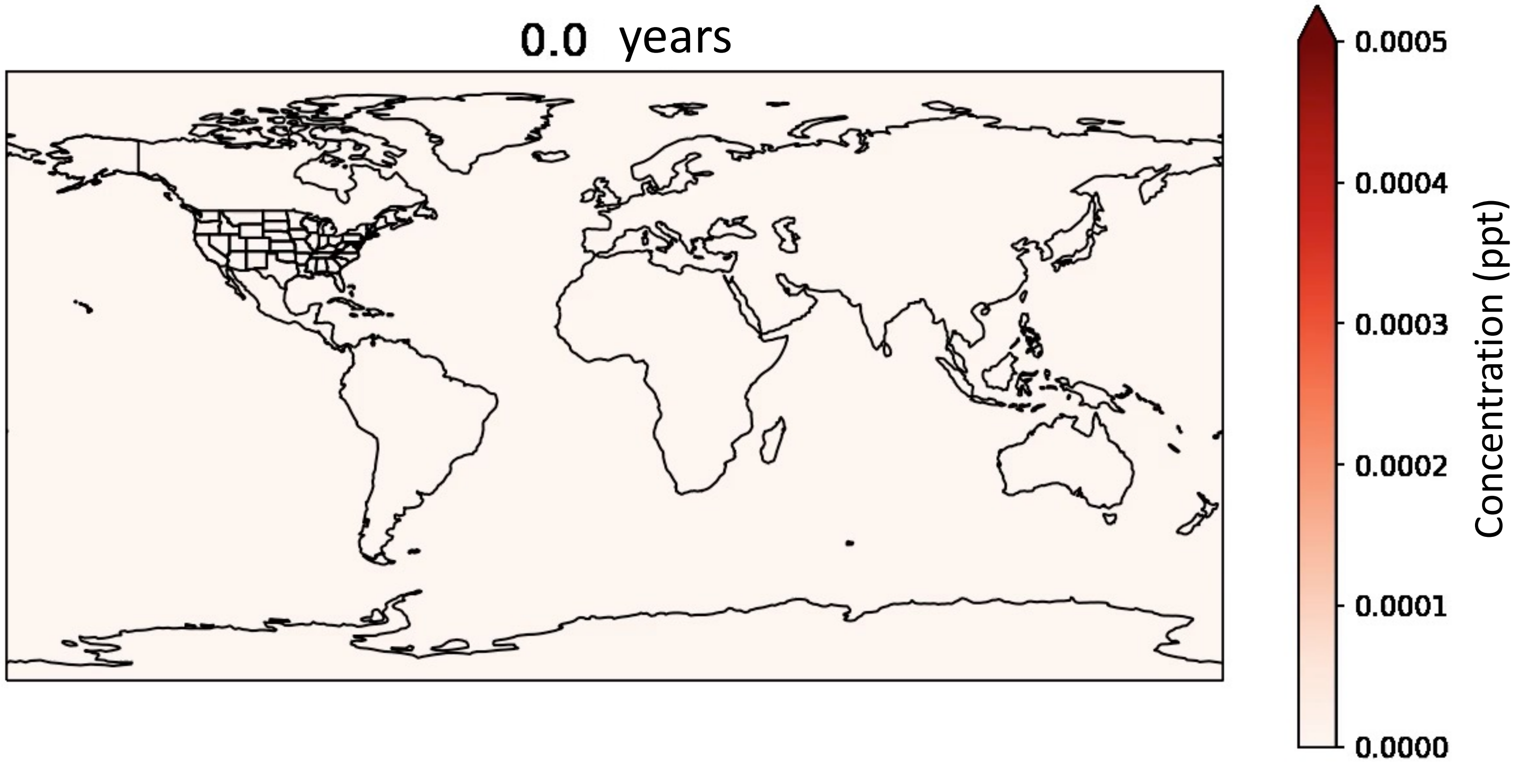
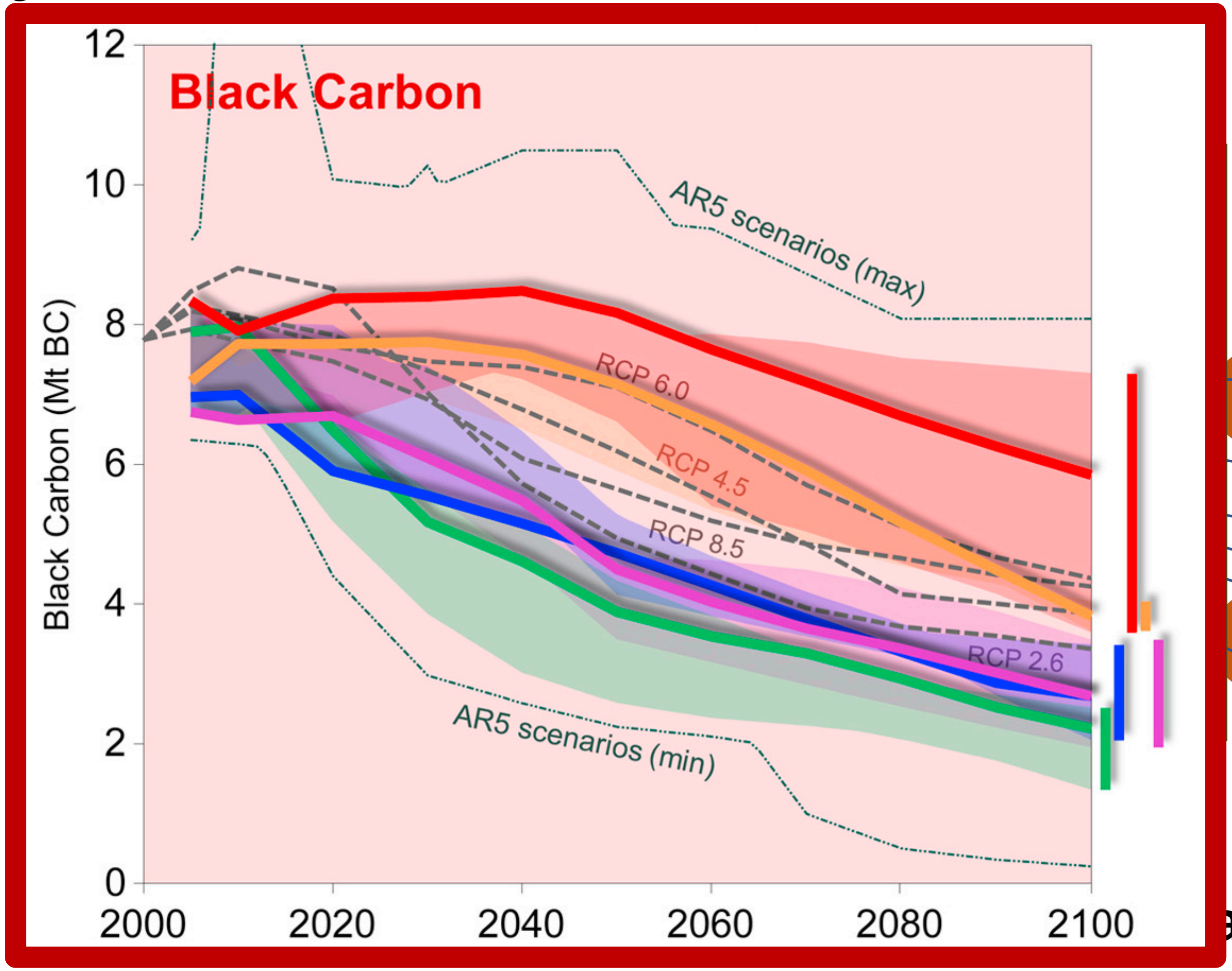
Reduced form model of Black Carbon



- Black carbon concentration from coal power plants in Southeast Asia
- 50 years of simulation
- 3 minutes to simulate in a Jupyter notebook

We need to be able to assess various policy trajectories



We take a few emissions trajectories and use them in a chemical transport model

Missing: Spatial and Temporal variability

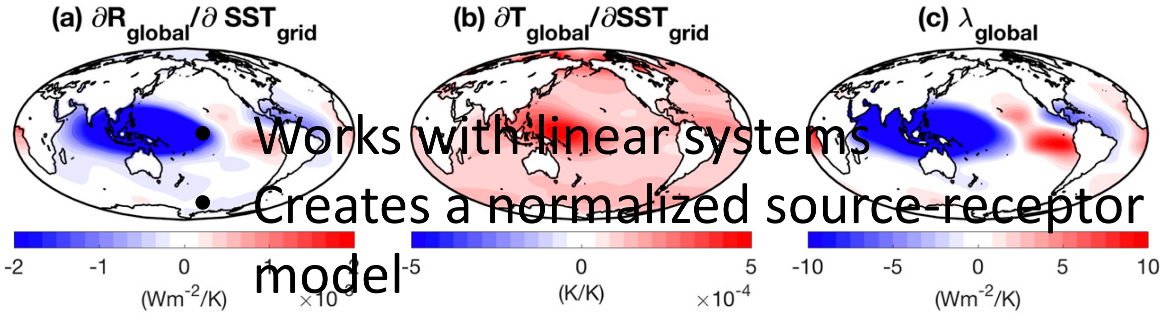
ars Later

Time

Shared Socio-economic Pathways; Riahi, 2017

Using Green's Functions to create patterns of response to a forcing

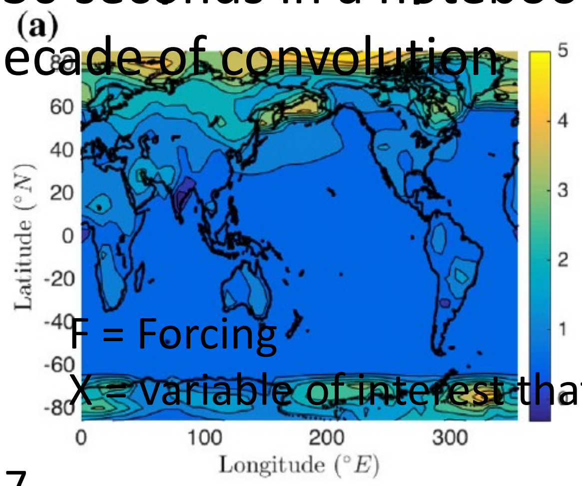
Radiative Feedbacks



Dong et al, 2019

- Works with linear systems
- Creates a normalized source-receptor model
- Convolve with emissions profiles
- ~30 seconds in a notebook for each decade of convolution

Temperature Response



F = Forcing

X = variable of interest that responds to the forcing

Lucarini et al, 2017

Green's Function

$$G(t\text{-}t') = \frac{1}{\Delta F_0}\frac{d}{dt}(\Delta X_0)$$

unitless

Convolution

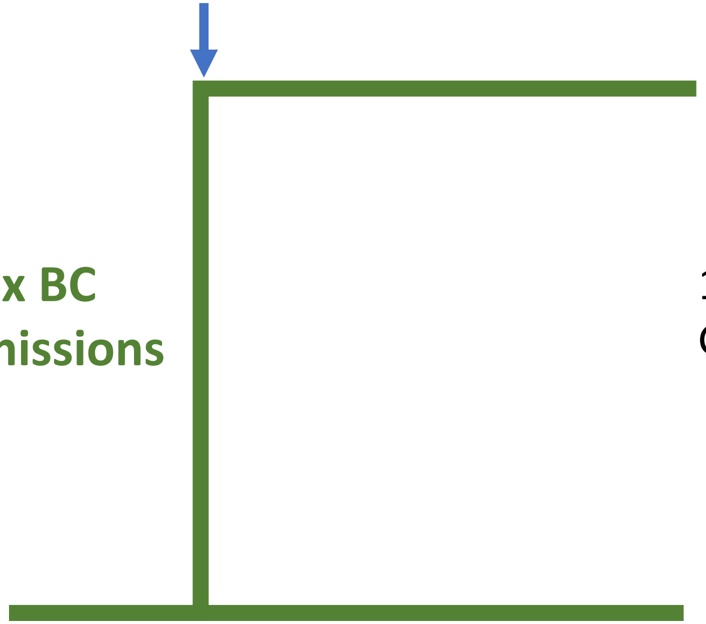
$$\Delta X = \int_{t_0}^{t_f}\int_{x_0}^{x_f} F(t')G_{(t-t',x-x')}dt'x'$$

$$\approx \sum_{t_0}^{t_f}\sum_{x_0}^{x_f} F(t')G_{(t-t',x-x')}\Delta t$$

units of, eg: ppb

Using GEOS Chem High Performance to Diagnose the Green's Functions

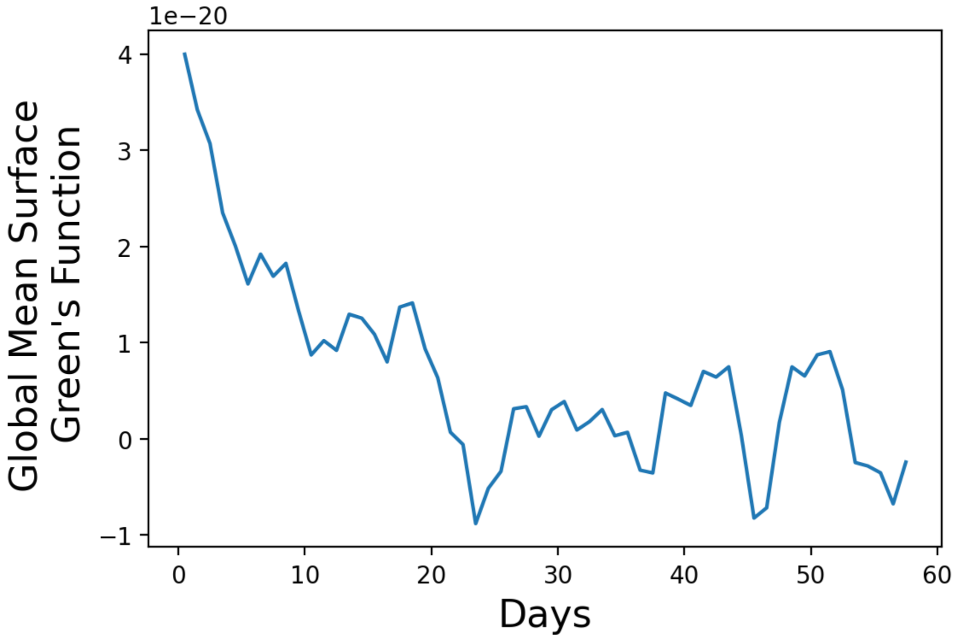
- January, April, July, October
- 2000 and 2016

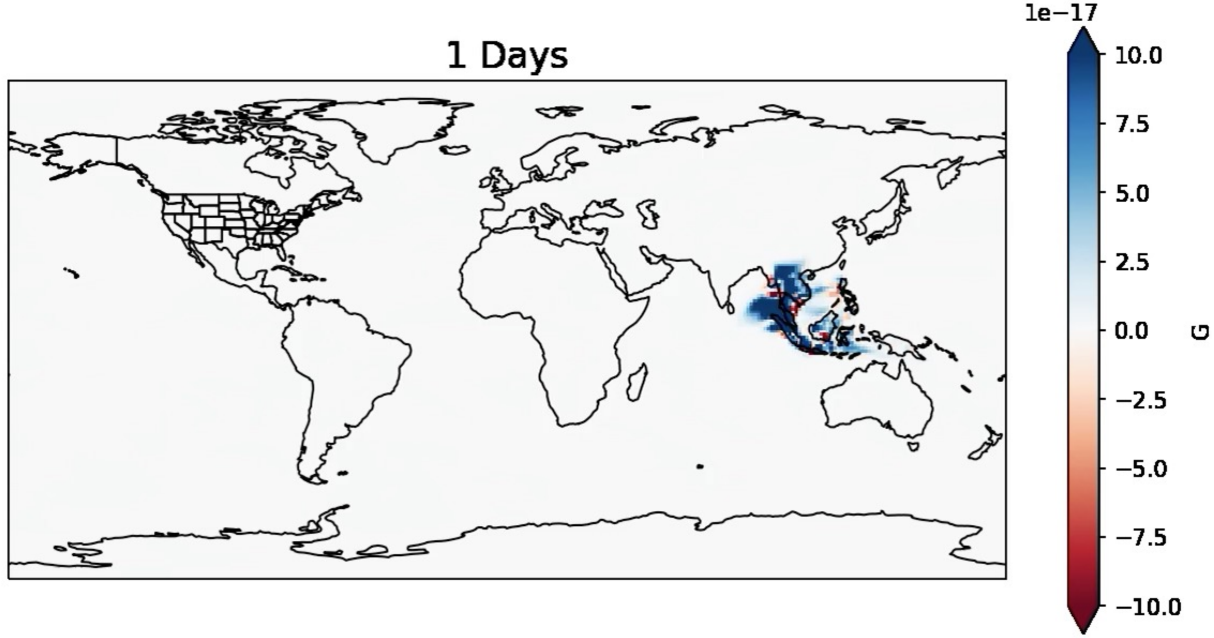


12 two month simulations per region in GEOS Chem High Performance

GCHP v13.3.4
CEDS Emissions Patterns
Resolution: C90 (~1°x1°)– Also testing stretch grid and C180

Black Carbon Green's Function over Southeast Asia (Jan 2016 run)

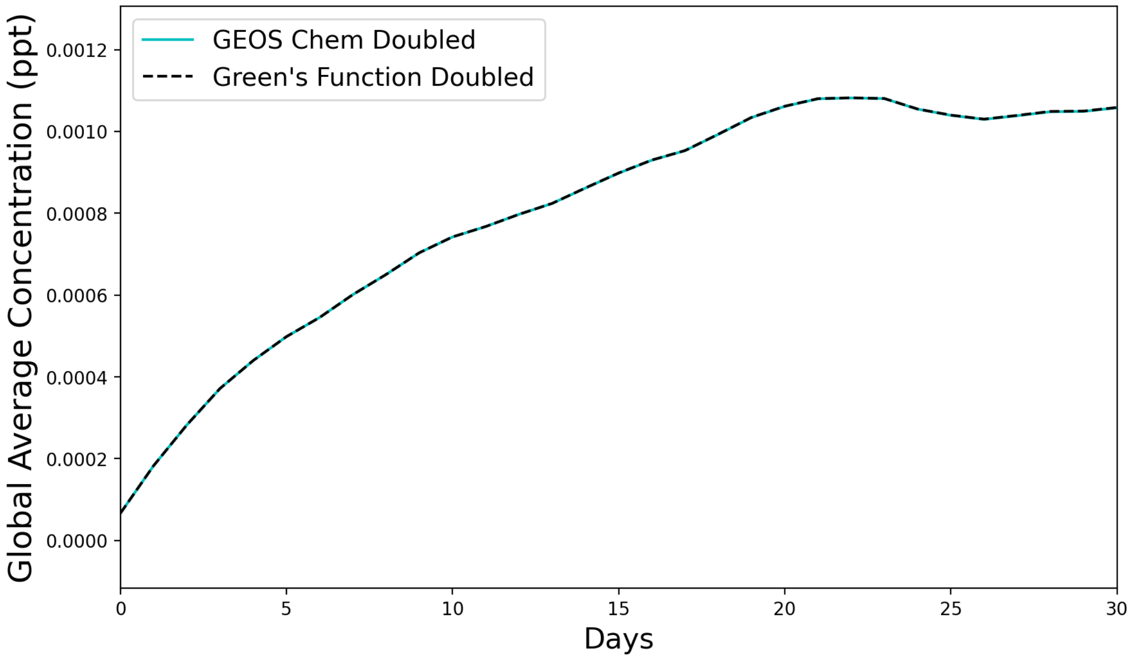




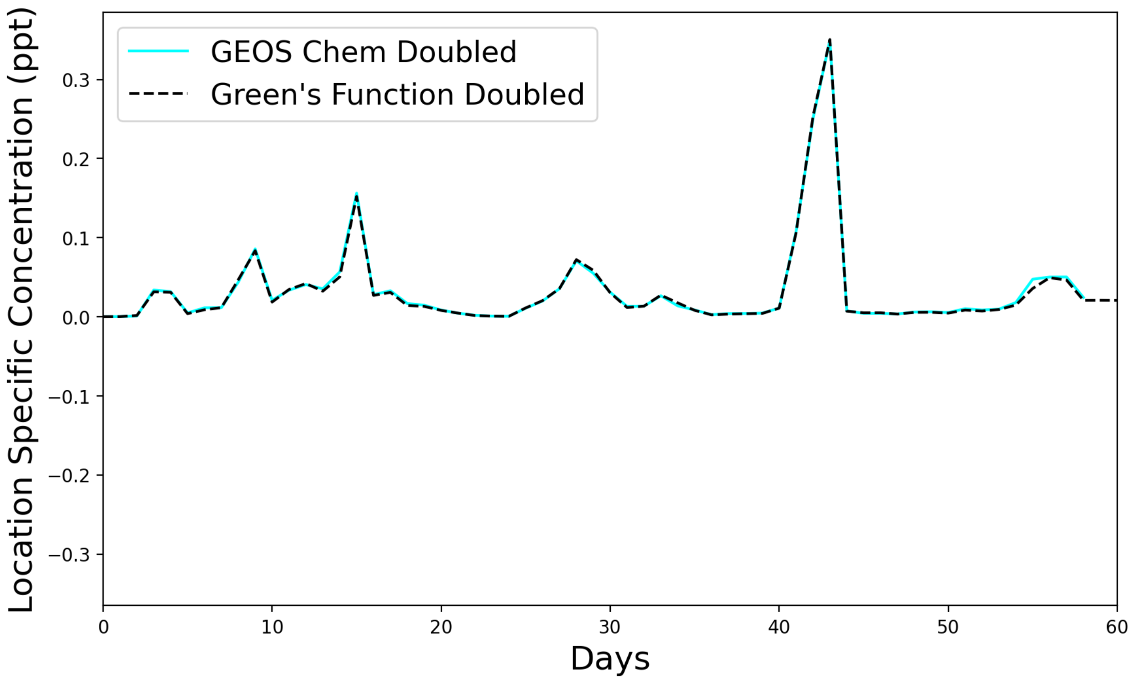
Validation of our Green’s Function with a 2x SEA Black Carbon Simulation

Using Green’s Function from one experiment to recreate a doubled GEOS Chem output

Global Average



One individual grid box (Guangzhou, China)

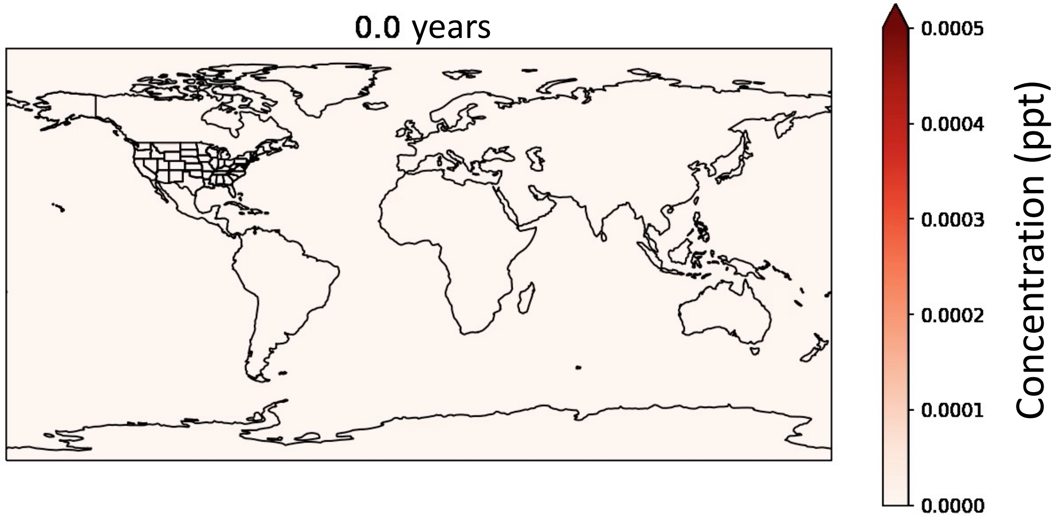


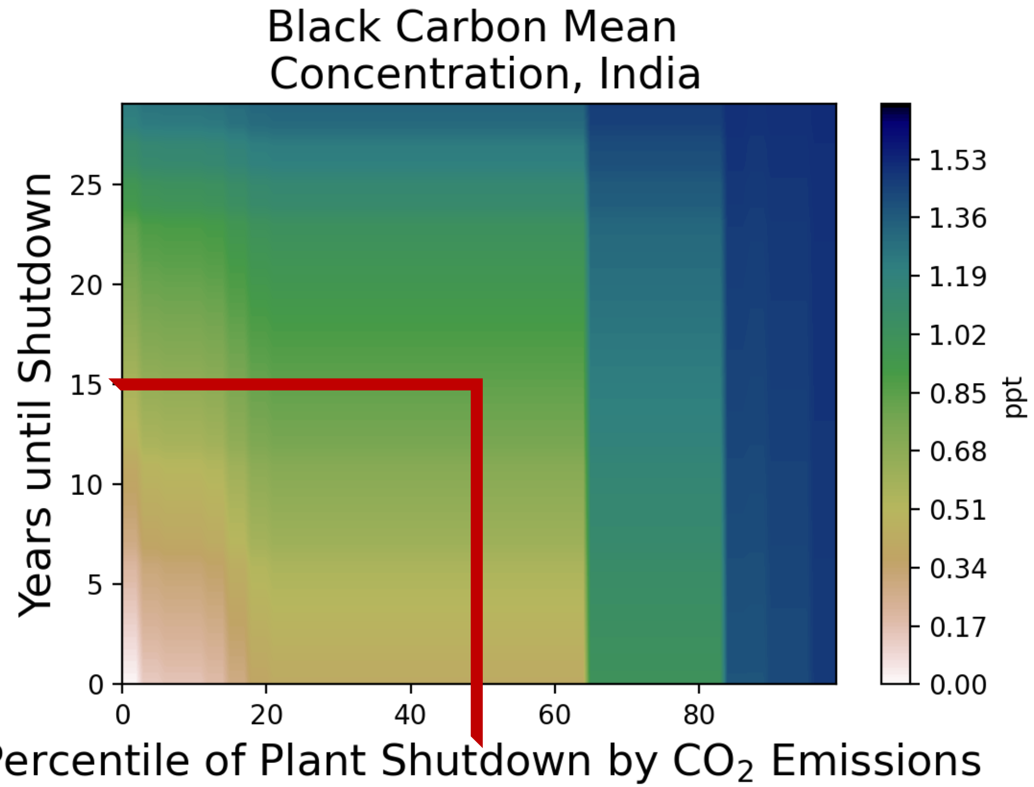
Early Retirement of Coal Power in Southeast Asia

Closures in Southeast Asia driven by three key reasons:

1. CO_2 emissions factors
2. Plant Age
3. Local air pollution policies

Early Retirement After 20 Years





This can and will be applied to other important black carbon sources, such as wildfires and residential coal burning

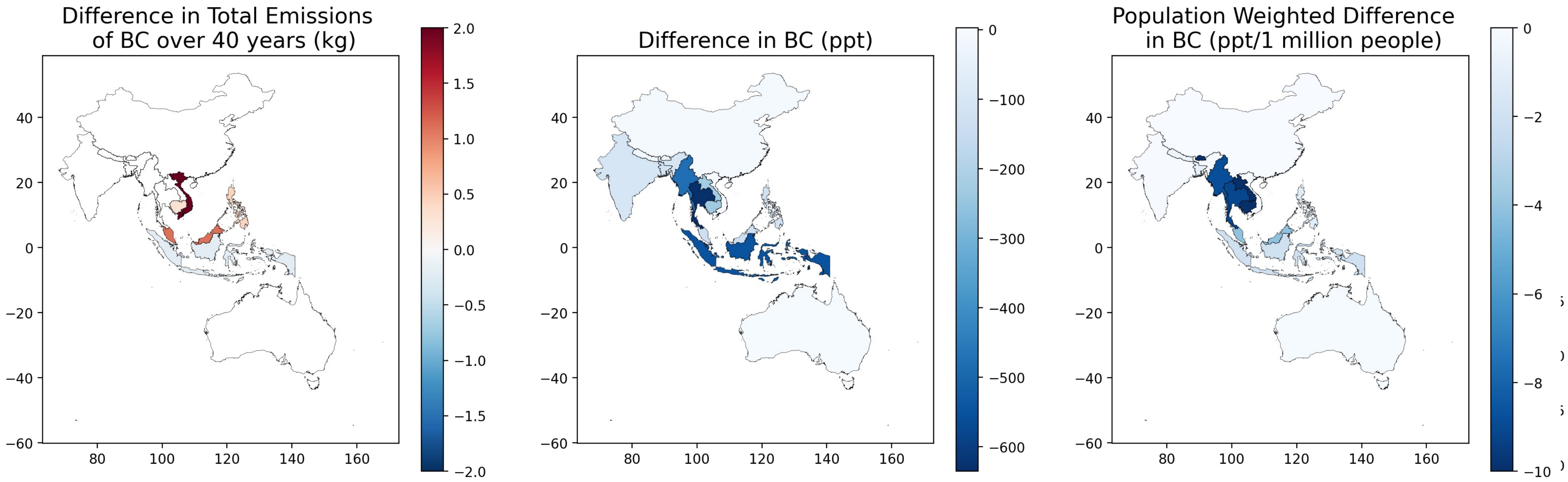
Today's takeaways

1. Emission and pollution trajectories over space and time determine cumulative impacts
2. We can use Green's functions for reduced form Black Carbon modeling with low computational load
3. Applying Green's functions across dozens of coal early retirement trajectories in Southeast Asia informs us of cumulative impacts, policies to prioritize, and transboundary pollutant transport
4. Future aspects: applying this to Hg and CO_2

Contact me: emfreese@mit.edu https://lfreese.github.io/ @lyssafreese

Cumulative impacts over time– comparing across policies

Scenario 1: Shutdown all plants after 20 years of operation
Scenario 3: Shutdown top 50% of CO_2 emitters after 5 years, all other plants have 40-year lifetime
Scenario 3 < Scenario 1



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Green’s Functions in Chemical Transport Modeling

Transport **Production** **Loss**

$$\frac{\delta n}{\delta t} = -\boldsymbol{\nabla}\cdot\left(n\tilde{U}\right) + P(n) - L(n)$$

Continuity Equation

$$E(s) = \frac{\delta n}{\delta t} + \boldsymbol{\nabla}\cdot\left(n\tilde{U}(s)\right) - C(n,s) + L_C(n,s) + L_D(n,s)$$

Emissions **Chemical Production** **Chemical Loss** **Deposition**

s is any combination of x, y, t

Green’s Functions in Chemical Transport Modeling

$$E(s) = \mathcal{L}n$$

Linear operator = continuity equation

$$\mathcal{L}G(s-s') = \delta(s-s')$$

Definition of a Green’s Function

Delta Function

1

$$\int \mathcal{L}G(s-s')E(s')ds = \int \delta(s-s')E(s')ds$$

$$\mathcal{L}\int G(s-s')E(s')ds = E(s)$$

$$\int G(s-s')E(s')ds = n$$

Taking the relationship between the linear operator acting on n and the Emissions

Green’s Functions in Chemical Transport Modeling

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Definition of a Green’s Function

Delta Function

$$\int \mathcal{L}G(s-s')E$$

If we have G, we now know we can convolve that with Emissions to find our concentration

$$\mathcal{L}\int G(s-s')E(s')ds = E(s)$$

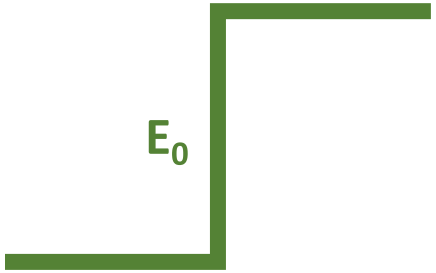
$$\int G(s-s')E(s')ds = n$$

Taking the relationship between the linear operator acting on n and the Emissions

How do we get G from a step increase in emissions?

$$\mathcal{L}c = H(t)E_0$$

Continuity equation acting on a specific pollutant in a given location



$$\frac{\delta}{\delta t}\mathcal{L}c = \frac{\delta}{\delta t}H(t)E_0$$

Time derivative of the Heaviside function = delta function

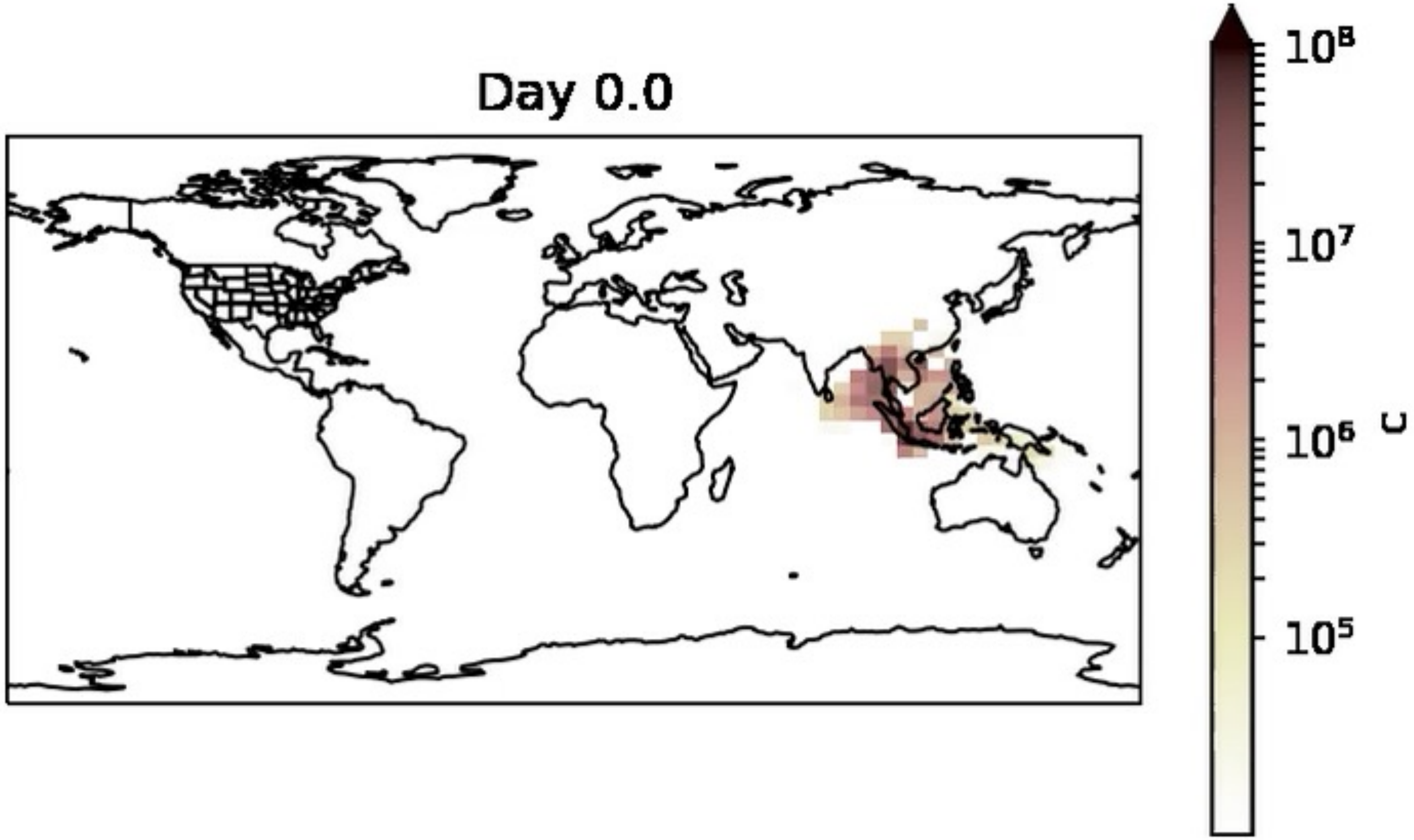
$$\mathcal{L}\frac{\delta c}{\delta t} = \delta(t)E_0$$

$$\mathcal{L}\boxed{\left(\frac{\delta c}{\delta t}\frac{1}{E_0}\right)} = \delta(t)$$

Definition of a Green's Function

$$\mathcal{L}G(s - s') = \delta(s - s')$$

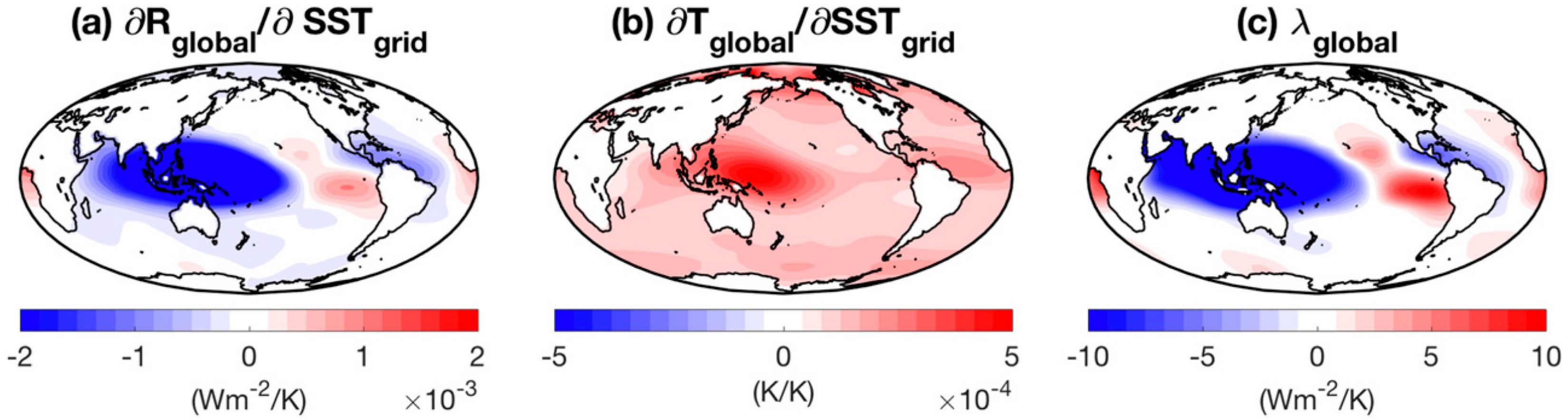
Green’s Functions in Chemical Transport Modeling



Application of Green's Functions in Sea Surface Temperature Perturbations and Climate Science

Radiative feedback, λ in response to sea surface temperature

$$\lambda(t) = \frac{\overline{\mathbf{R}}}{\overline{\mathbf{T}}},$$



Dong et al, 2019

Criteria for Applying Green's Functions to Atmospheric Chemistry

Similar to previous work, we need a variable that:

1. Changes as a function of time
2. Is linearizable
3. Is a direct output or can be indirectly calculated from outputs of a complex model

And is relevant to our scientific research questions:

1. Emitted from coal power
2. Has climate/air quality impacts

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Black Carbon

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Using a step increase to calculate the Green's Function

1. Two Chemical Transport model simulations are needed:
   1. A base scenario where emissions are normal
   2. A step increase scenario where emissions are increased by **x** amount in the region of interest
2. Normalize this by the emissions forcing

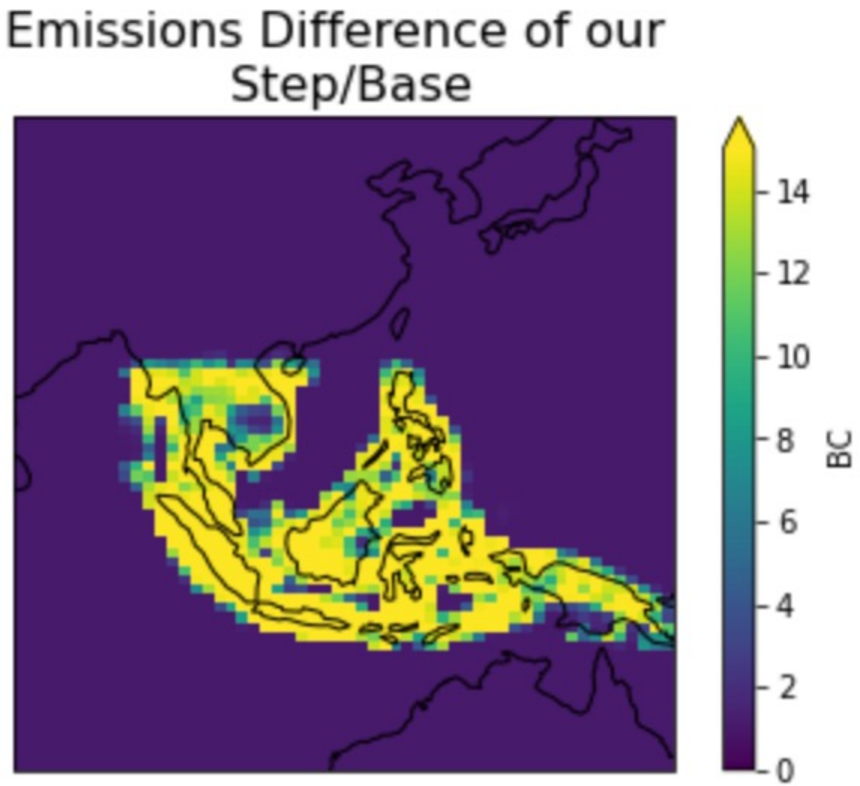
The outcome of this is our Green's Function, which we can convolve with an emissions profile to estimate the spread of a pollutant from the region of interest

$$G(t) = \frac{\left(\frac{d\,C_{step} - C_{base}}{dt}\right)}{\left(E_{step,t=0} - E_{base,t=0}\right)}$$

Method based on Lucarini, 2017

1. Simulation details– Base and Step increase

- GEOS-Chem High Performance
- Black Carbon
- Two 60 day simulations
  - Base scenario uses BC emissions from CEDS
  - Step increase uses BC emissions from CEDS increased across all sectors in the region of interest by **15x**



1.2: Three potential types of step increases:

1. Pure step (one value added to all grid boxes)

T = 0 T >1

2. Weighted by existing emissions (% of current emissions added to each grid box)

T = 0 T >1

3. Sin weighted (reduces the impact of the boundaries on spread)

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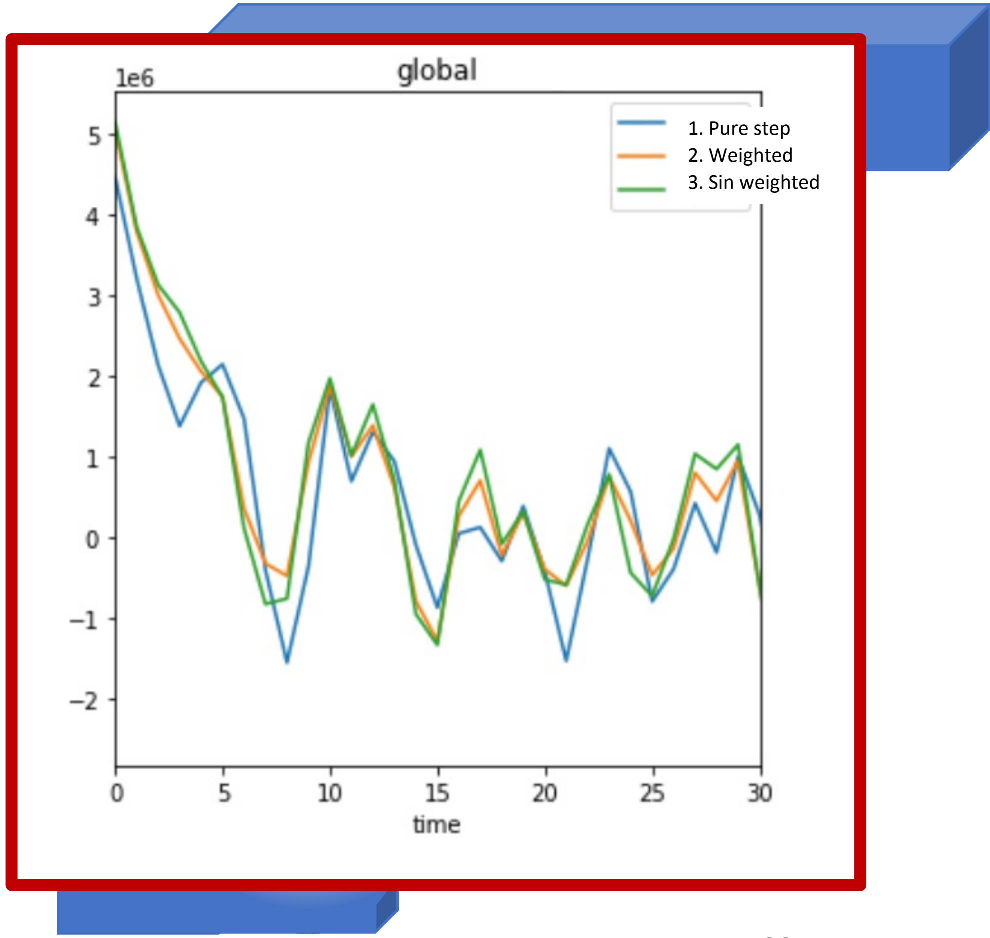

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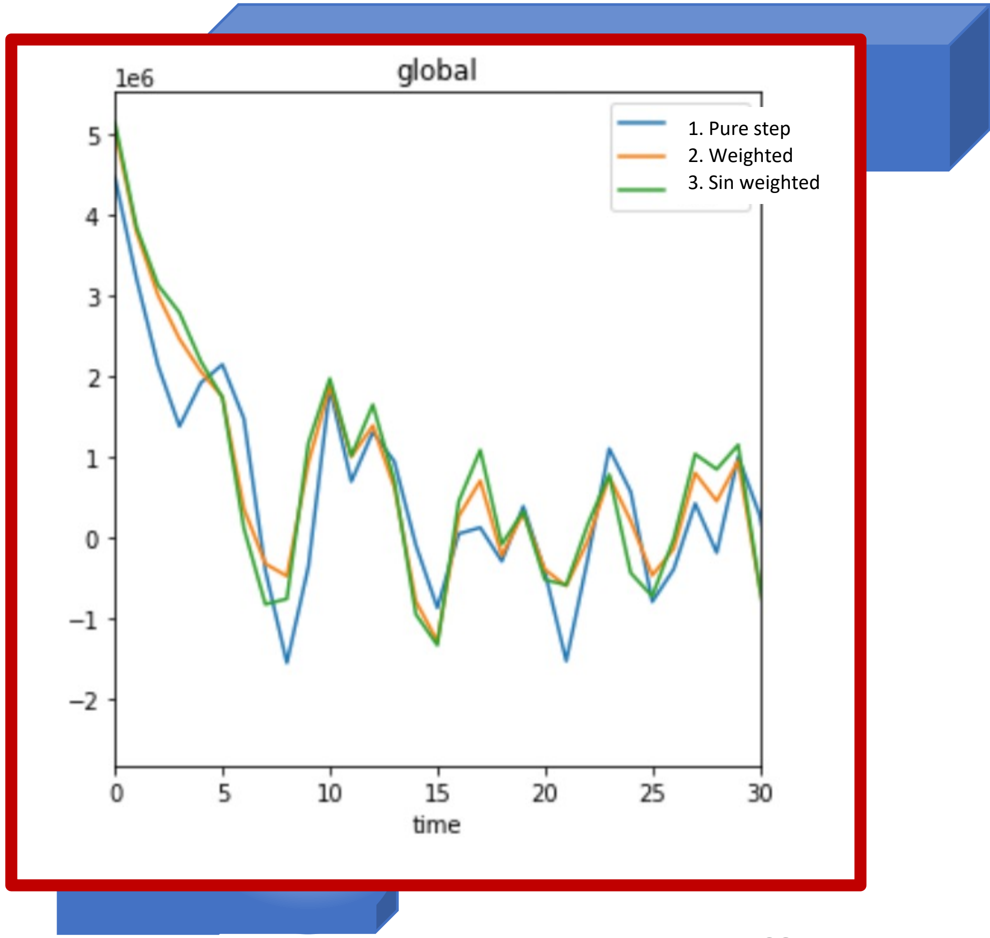
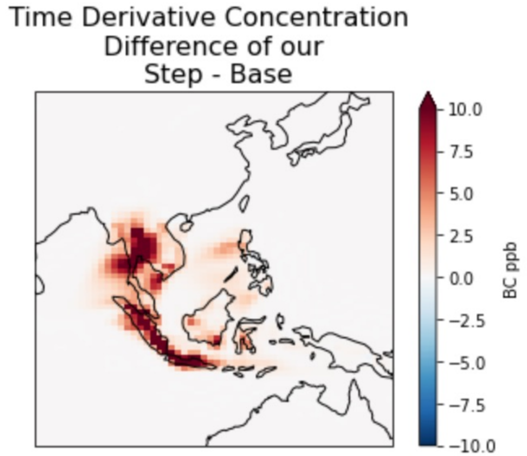


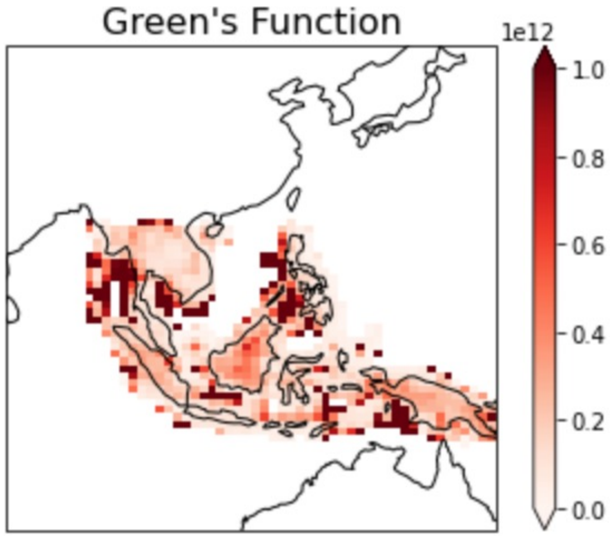
T = 0 T >1

2. Normalizing our Green's Function by the emissions forcing

$$G(t) = \frac{\left(\frac{d\,C_{step} - C_{base}}{dt}\right)}{\left(E_{step,t=0} - E_{base,t=0}\right)}$$



E_0



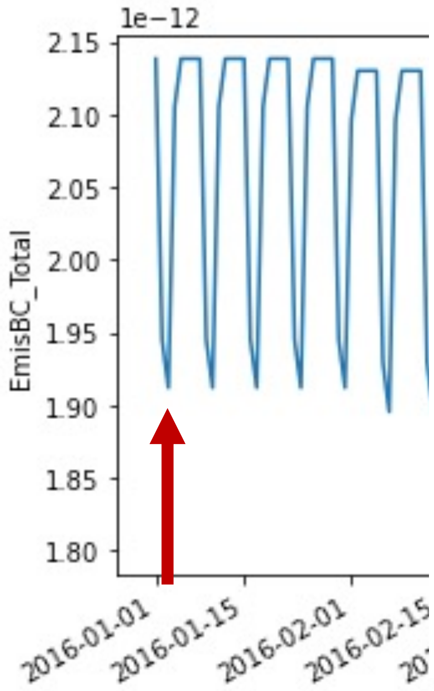
Convolution of our Green's Function with the Emissions Profile

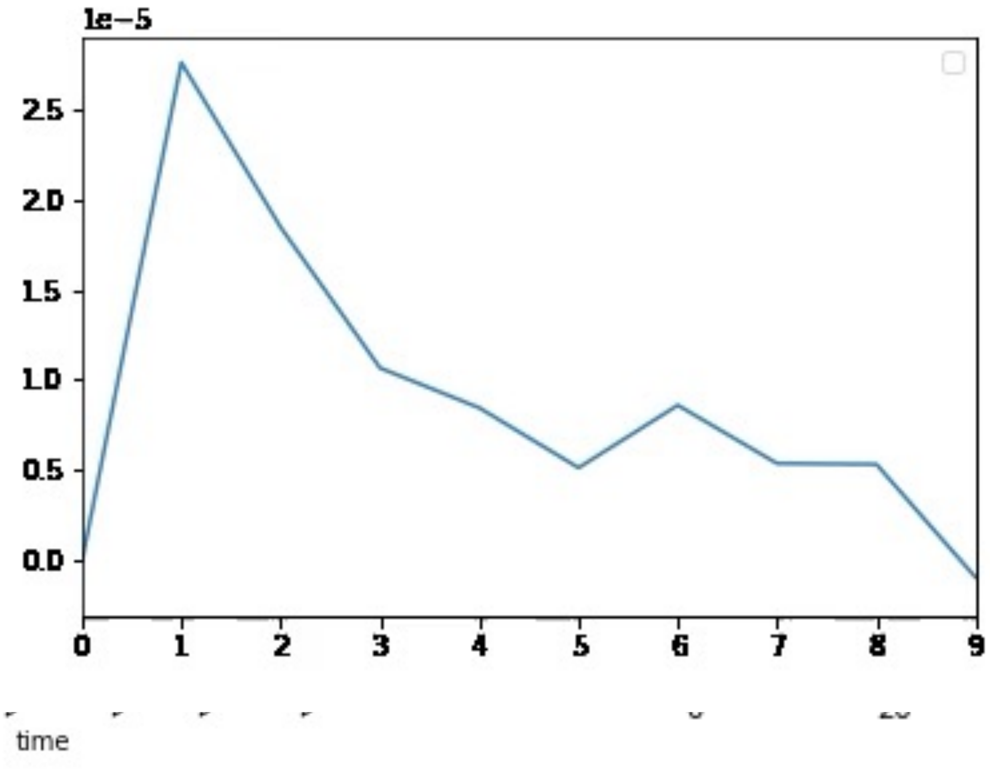
1. Convolve the Emissions in each location with the Green's Function
2. Sum over time (and space if looking for a global response)

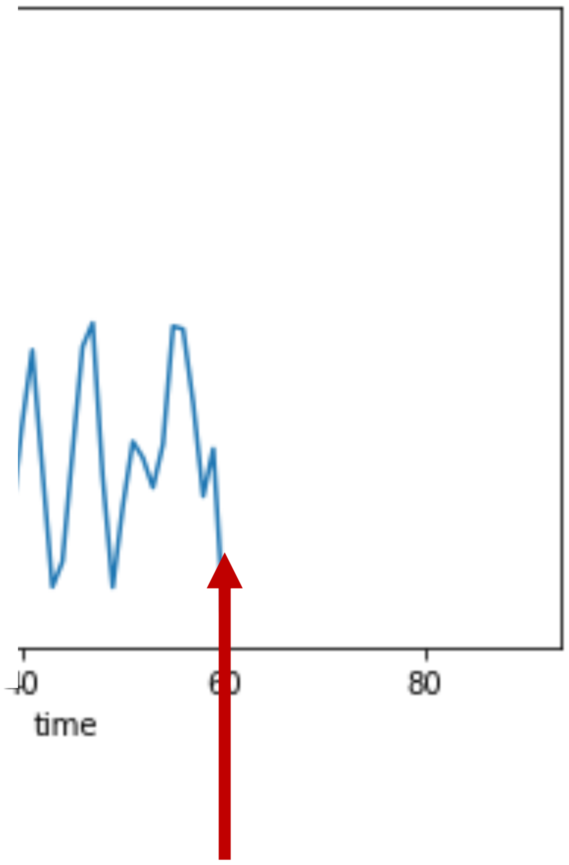
$$\Delta[X] = \int_{t_0}^{t_f} \int_{x_0}^{x_f} E(t')G_{(t-t',\, x-x')} dt'x' \approx \sum_{t_0}^{t_f} \sum_{x_0}^{x_f} E(t')G_{(t-t',\, x-x')} \Delta t$$

t is our time of interest, t' is all times prior

1. Convolution of Emissions



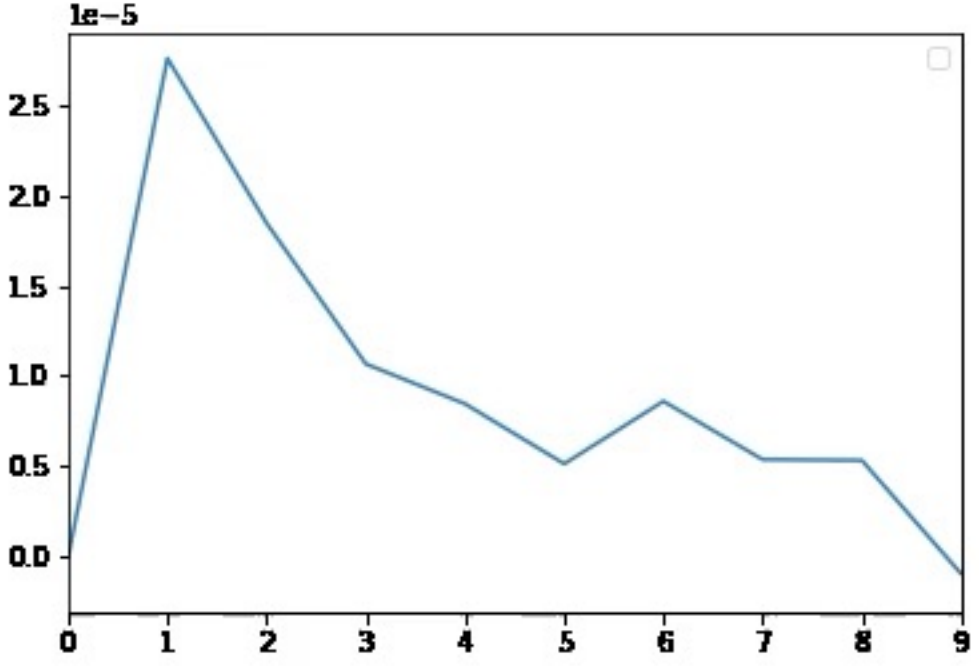


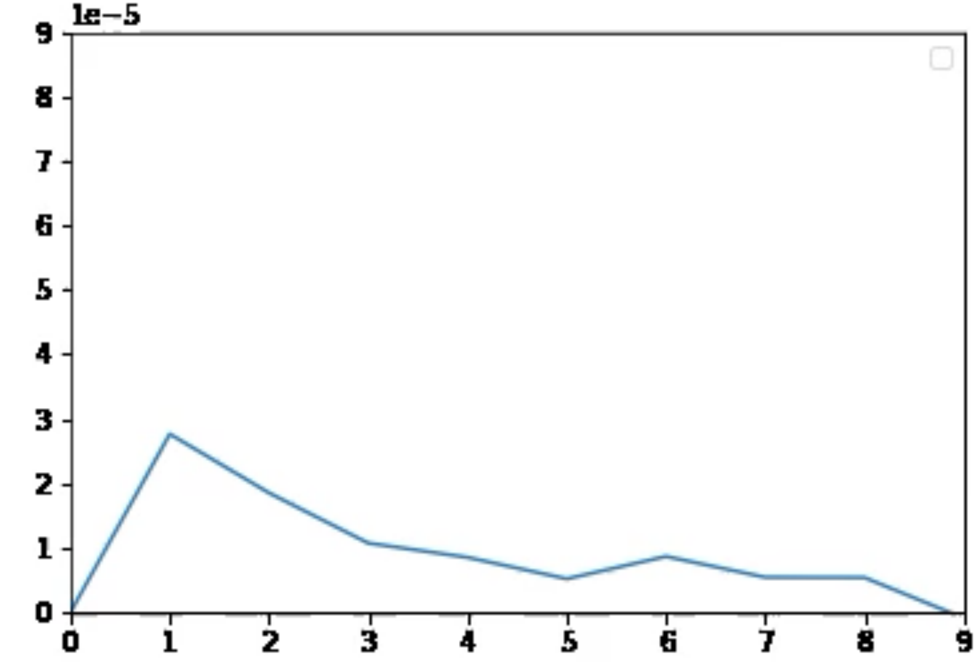


$E(t')G(t-t')$

After 60 days I am treating it as 0

2. Sum over time

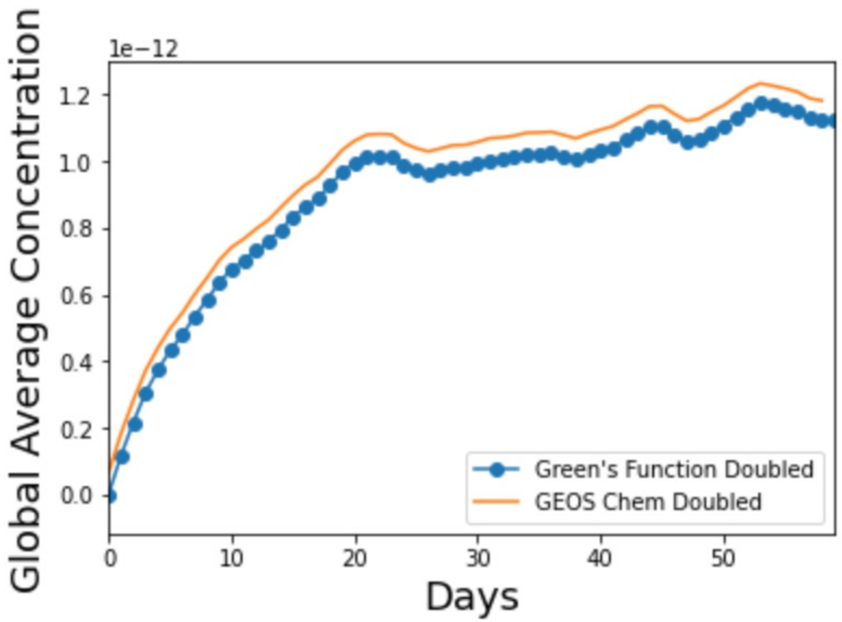




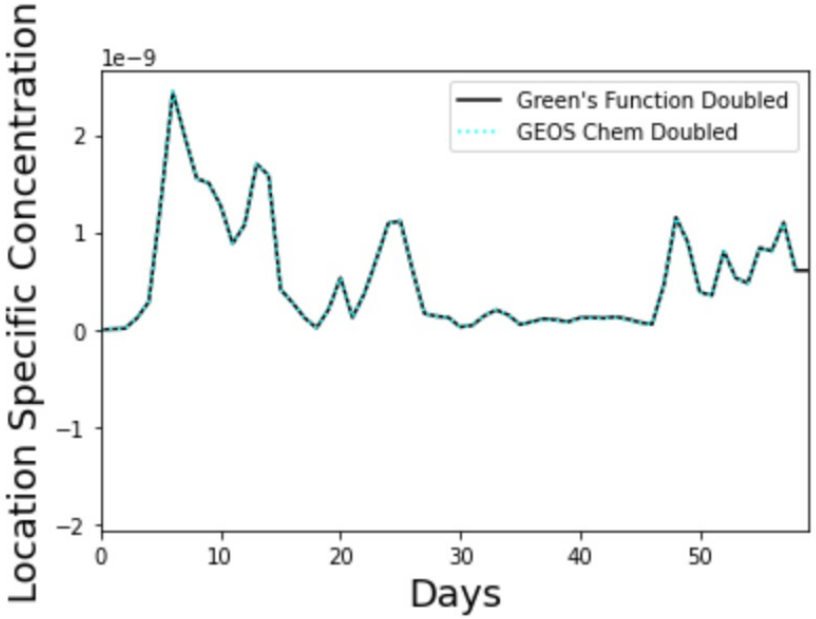
Validation of our Green's Function with a 2x Simulation

Use Green's Function from one experiment to recreate a doubled GEOS Chem output

Global Average



One individual grid box



Research Questions and Scenario Application

What are the impacts of trajectories of coal plant retirements in Southeast Asia on a black carbon?

Simulation Setup across Southeast Asia

Locations of step changes:

Southeast Asia

Indonesia

Singapore

Malaysia

Vietnam

Cambodia

Execution time: 15-30 seconds per every 10 years (in an interactive notebook)

In GEOS Chem High Performance it takes 48 days to run one year on 60 cores (50 years of simulations for one scenario would take longer than my PhD)

Times of step changes:

January

April

July

October

2016

2000

Coal Early Retirements due to four key reasons

1. Location based

2. CO_2 emission factors

3. Plant Age

4. Funding type

Coal Early Retirements due to four key reasons

1. Location based → Country specific policies
2. CO_2 emission factors → Dirtiest plants shut down to meet climate goals
3. Plant Age → Least efficient/oldest plants shut down (lowest marginal loss)
4. Funding type → Foreign Direct Investment vs. Policy Banks

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Coal Early Retirements due to four key reasons

1. Location based → Country specific policies

Policy Driven

2. **CO_2 emission factors** → **Dirtiest plants shut down to meet climate goals**

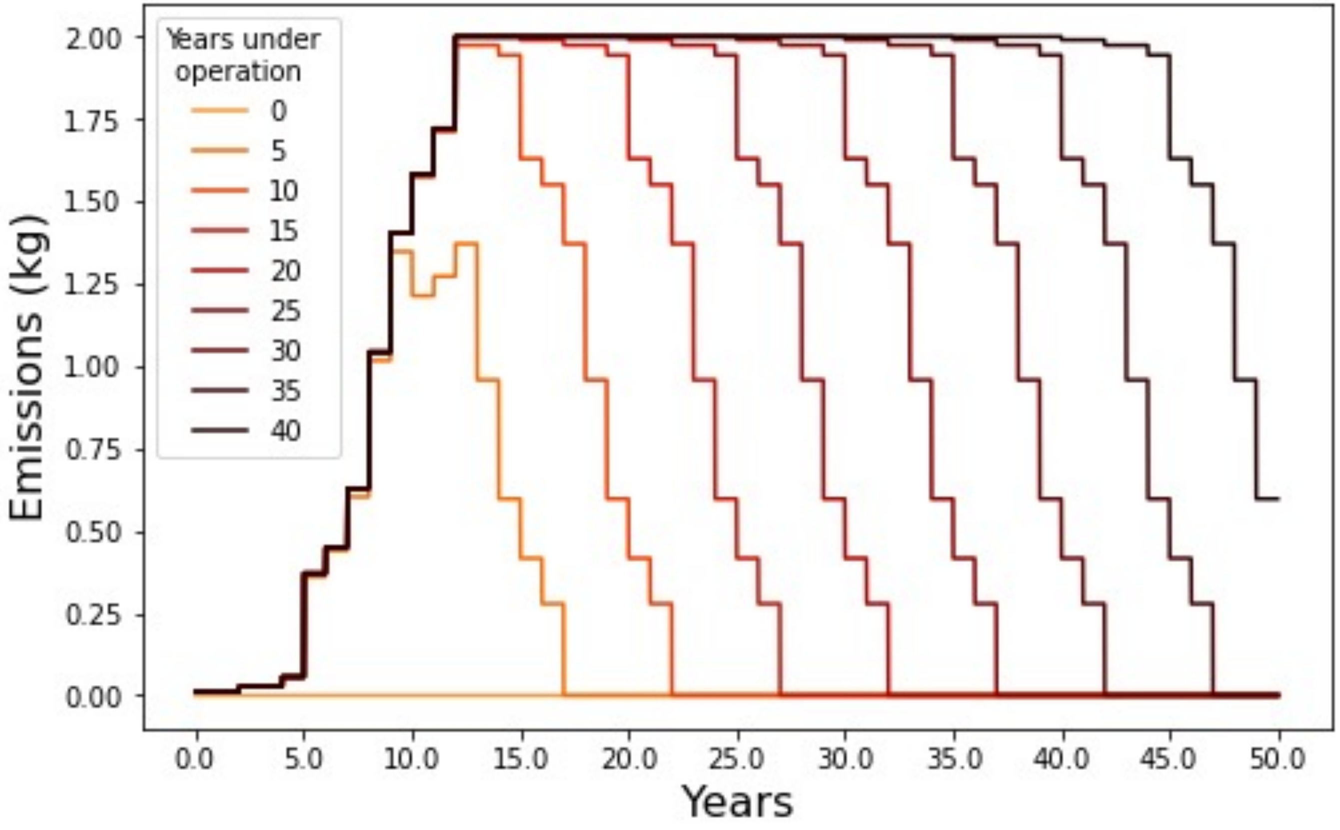
Market Driven

3. **Plant Age** → **Least efficient/oldest plants shut down (lowest marginal loss)**

4. Funding type → Foreign Direct Investment vs. Policy Banks

In collaboration with Cecilia Han Springer, BU China Global Development Center

Early Retirement based on plant age: Trajectories



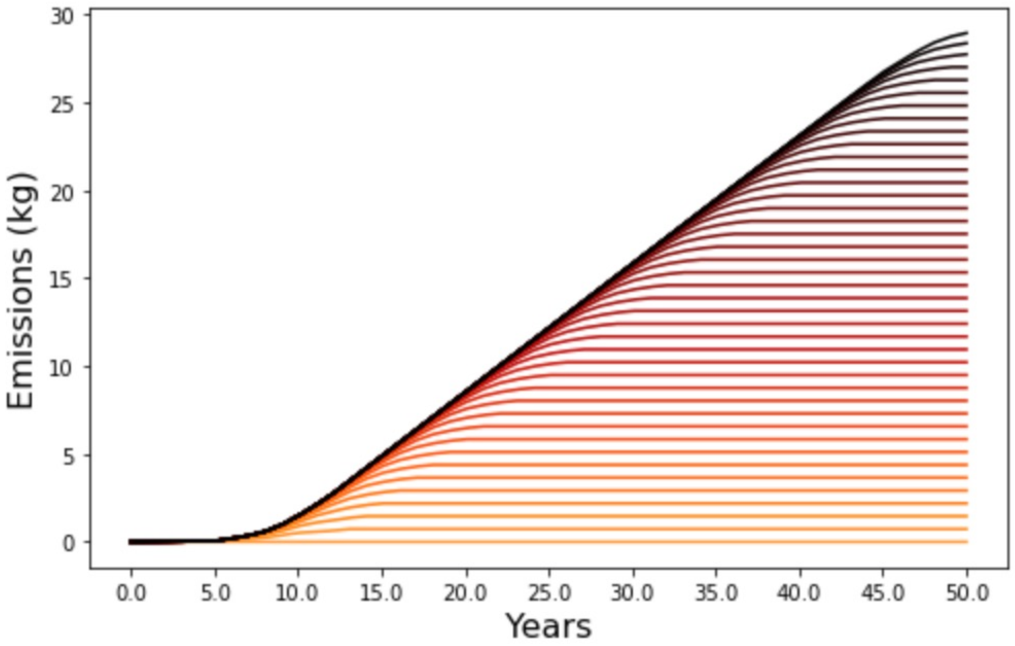
Emissions of black carbon from all Chinese funded Southeast Asian coal plants

Assuming emission factor is constant at .026 g/kg of coal burned, assuming a 22.51 GJ/t conversion factor

Wang et al, 2012 and National Research Council

National Academies of Sciences, Engineering, and Medicine. 2000. Cooperation in the Energy Futures of China and the United States. Washington, DC: The National Academies Press. https://doi.org/10.17226/9736.

Early Retirement based on plant age: Cumulative Emissions



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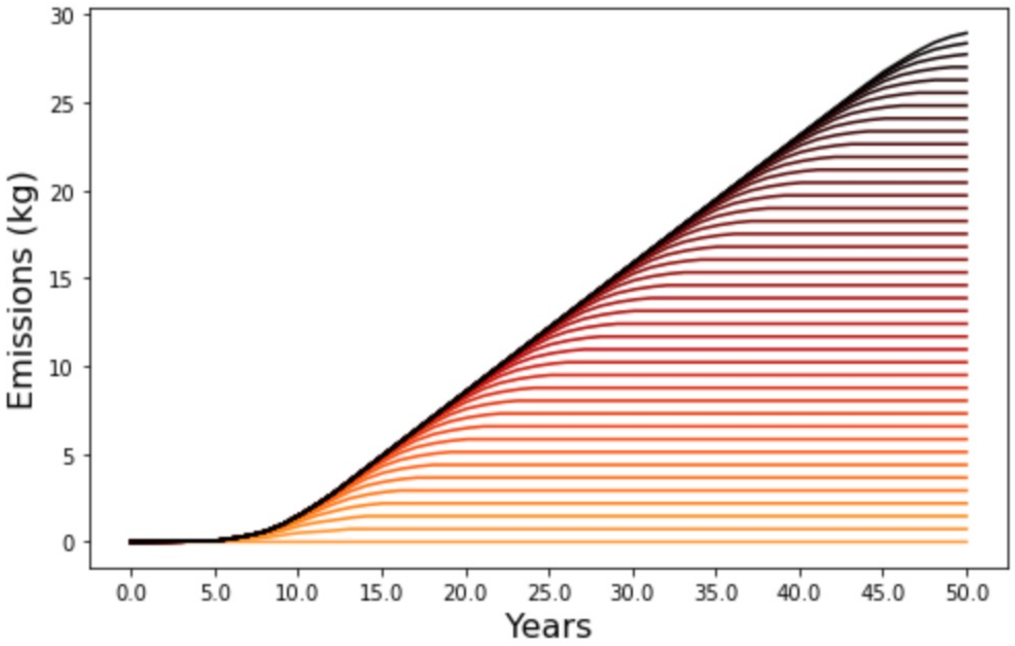
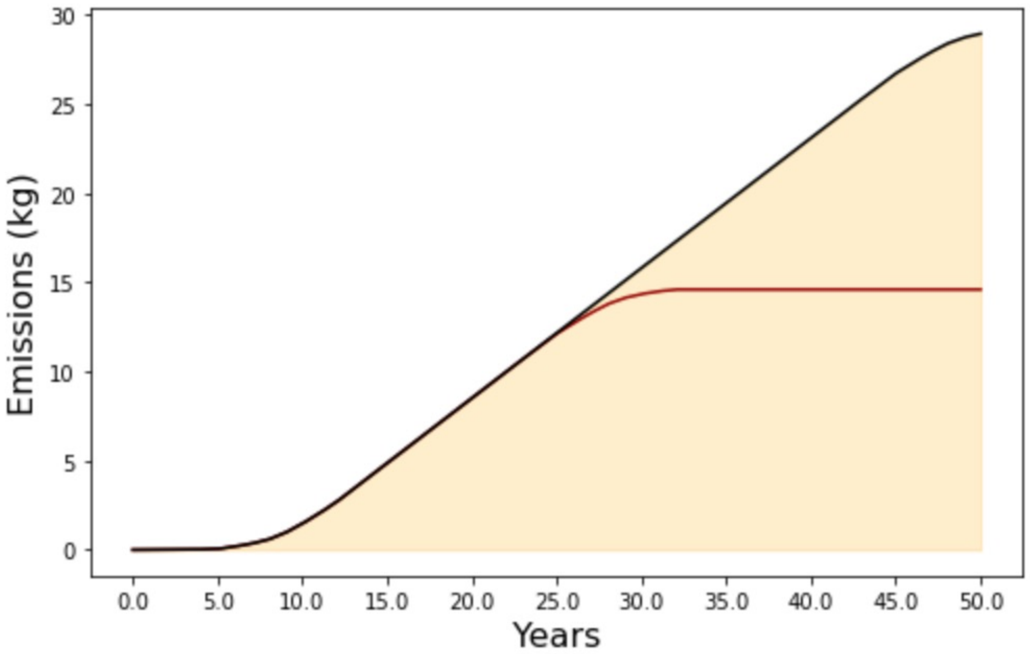
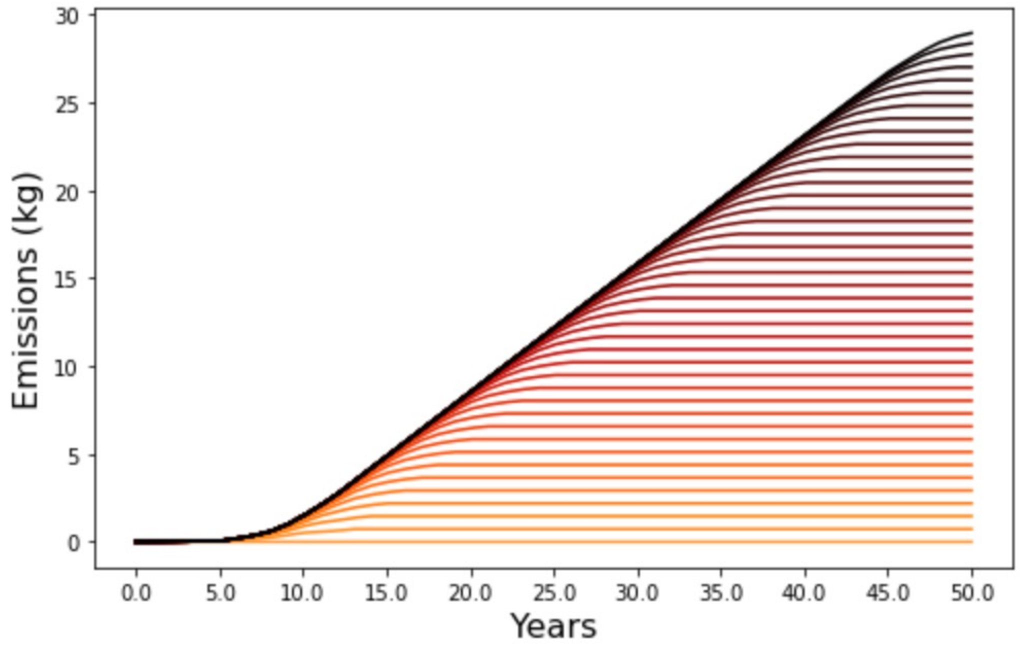


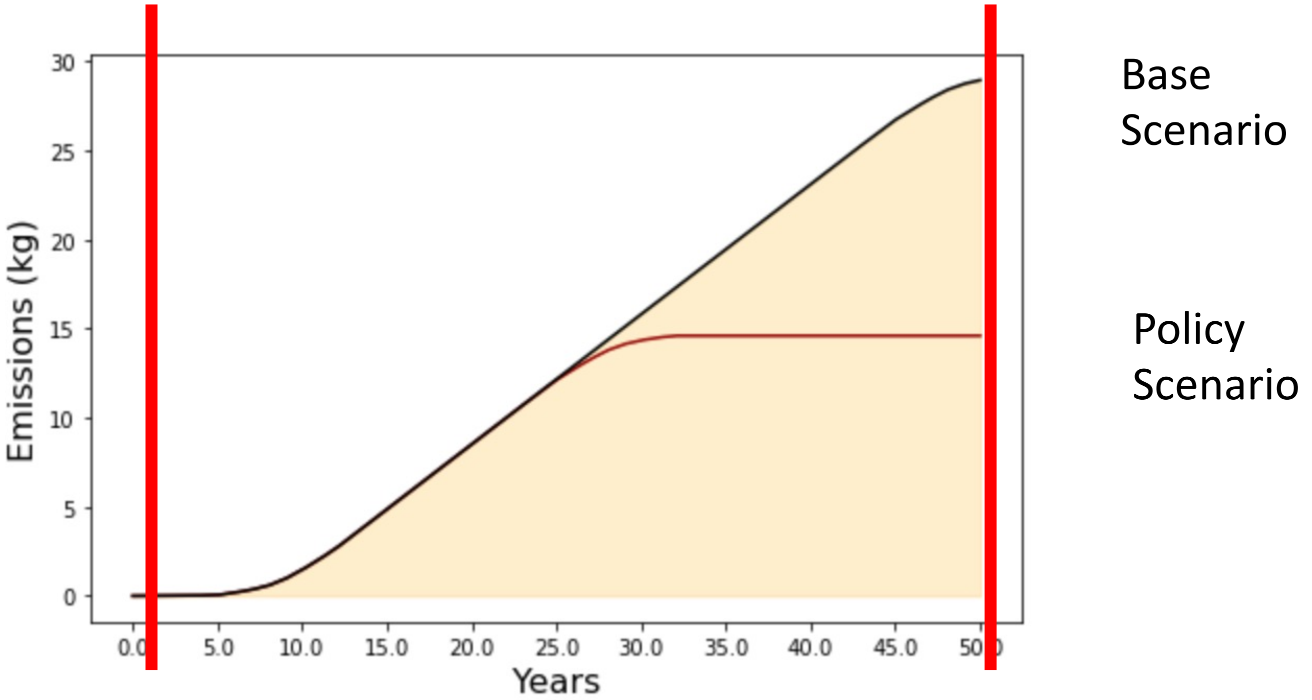


Base Scenario

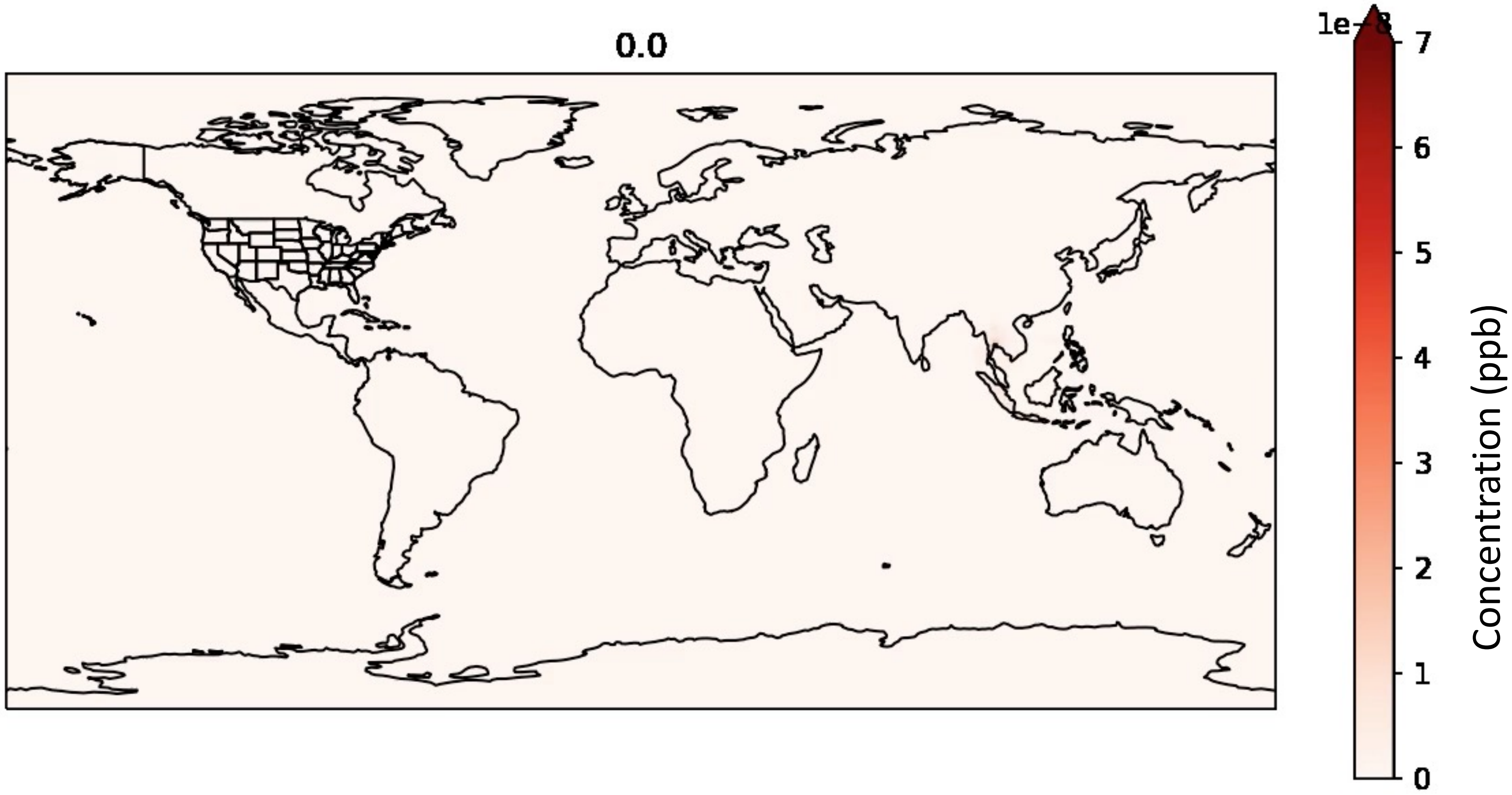
Policy Scenario

Early Retirement based on plant age: Cumulative Emissions

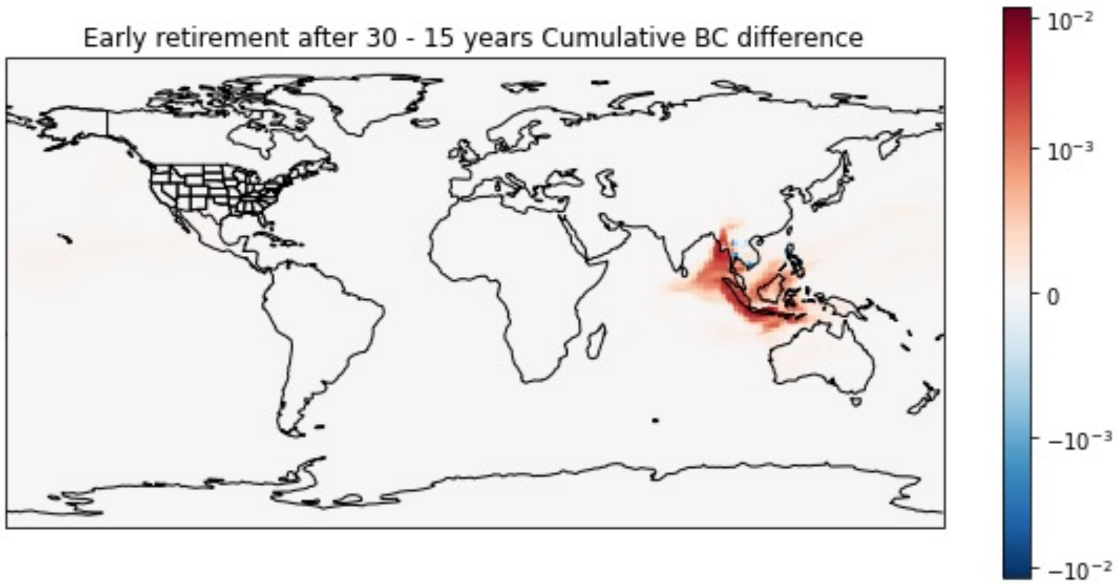


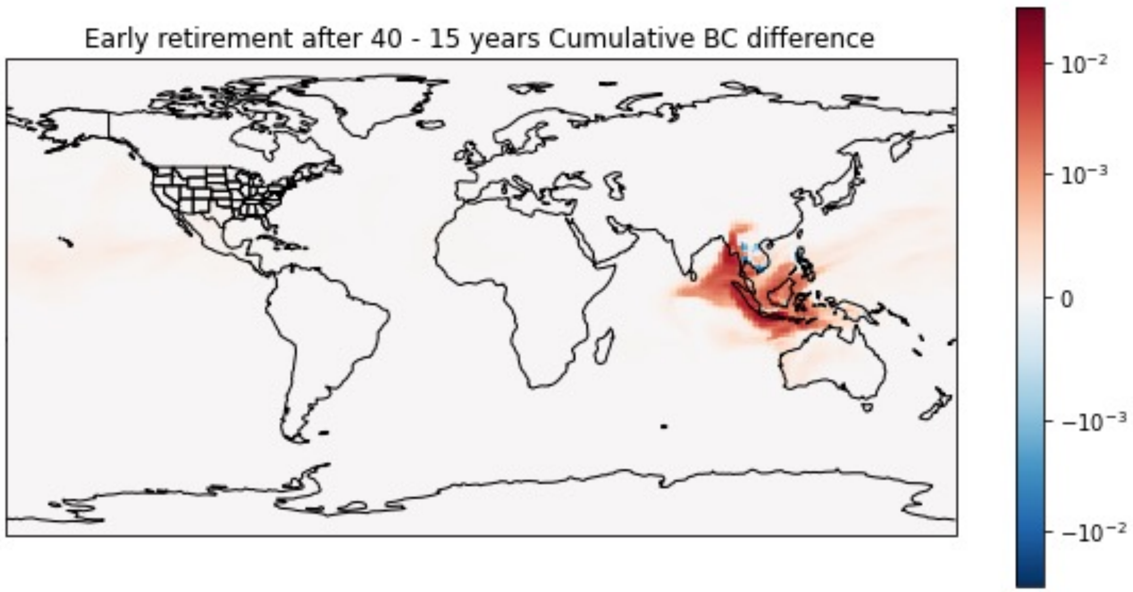


Closing plants after 15 years of operation

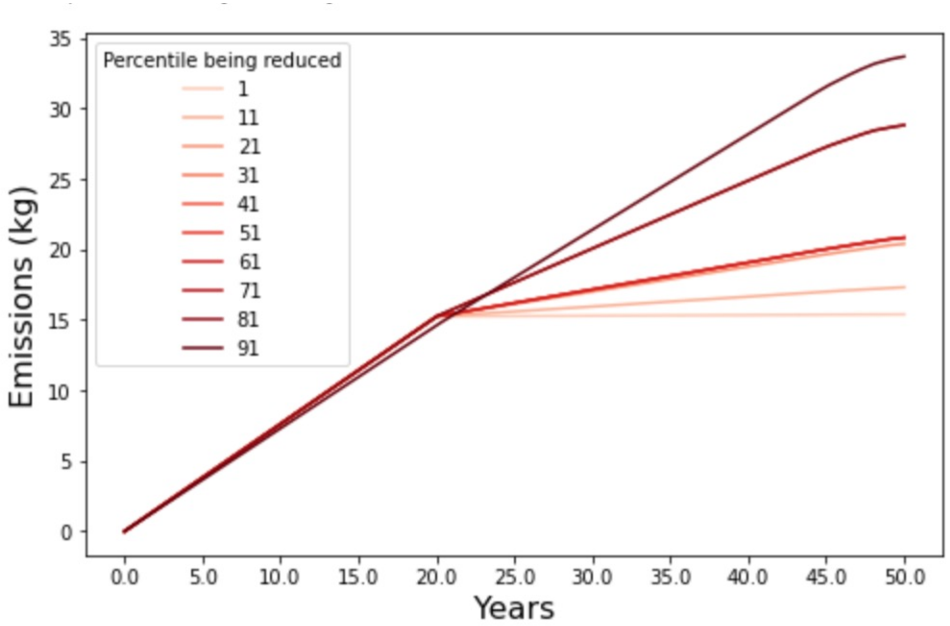


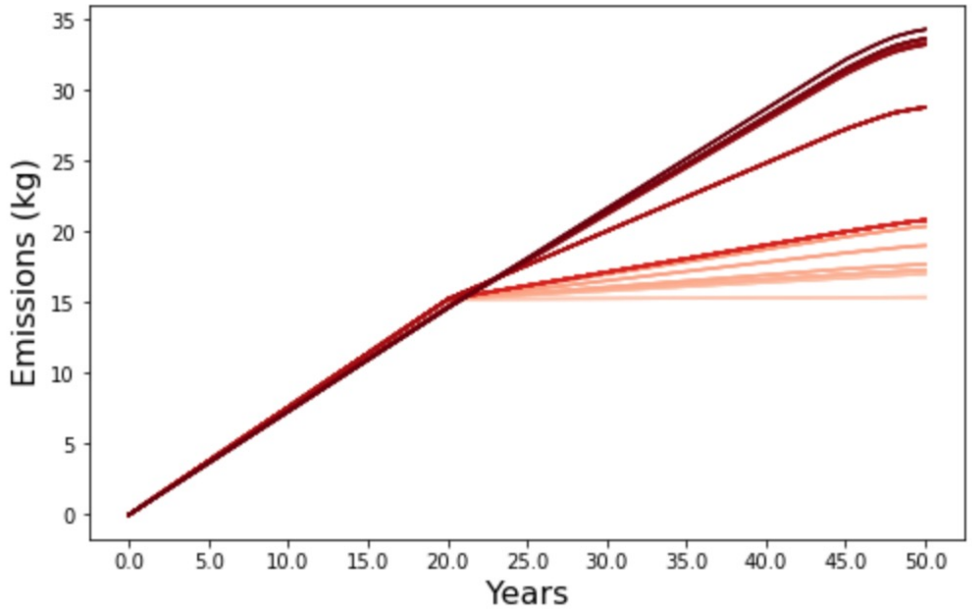
Early Retirement Cumulative Differences





Shutting down high emitters by percentile after 20 years





Shutting down high emitters vs. early retirement