Climate Change Impacts on Natural Sulfur Production: Ocean Acidification & Community Shifts

Zachary M. Menzo, Scott Elliott, Corinne A. Hartin, Forrest M. Hoffman, Shanlin Wang

Part 1: Background
Part 2: Objectives & Baseline
Part 3: Anthropogenic
Part 4: Ocean Acidifications
Part 5: Community Shifts
Part 6: Conclusion

1. Background: Dimethyl sulfide (DMS)

- Semi-volatile compound containing a central, reduced sulfur atom
- *CLAW* hypothesis (1987):
  - Noted the DMS feedback loop through marine stratus clouds
  - Could act *to reduce* effects of *global warming*
- *Recent* model results:
  - Effect may be positive, *amplifying* effects of *global warming*

1. Background: Sulfur Sources

- *Anthropogenic* Emissions (SO_2): 60-100 TgS/yr
  - Dominates *Northern Hemisphere*
  - Burning of coal & oil
  - Sulfur atoms:
    - Involatile & Short lived
    - Primary cause of acid rain

1. Background: Sulfur Sources

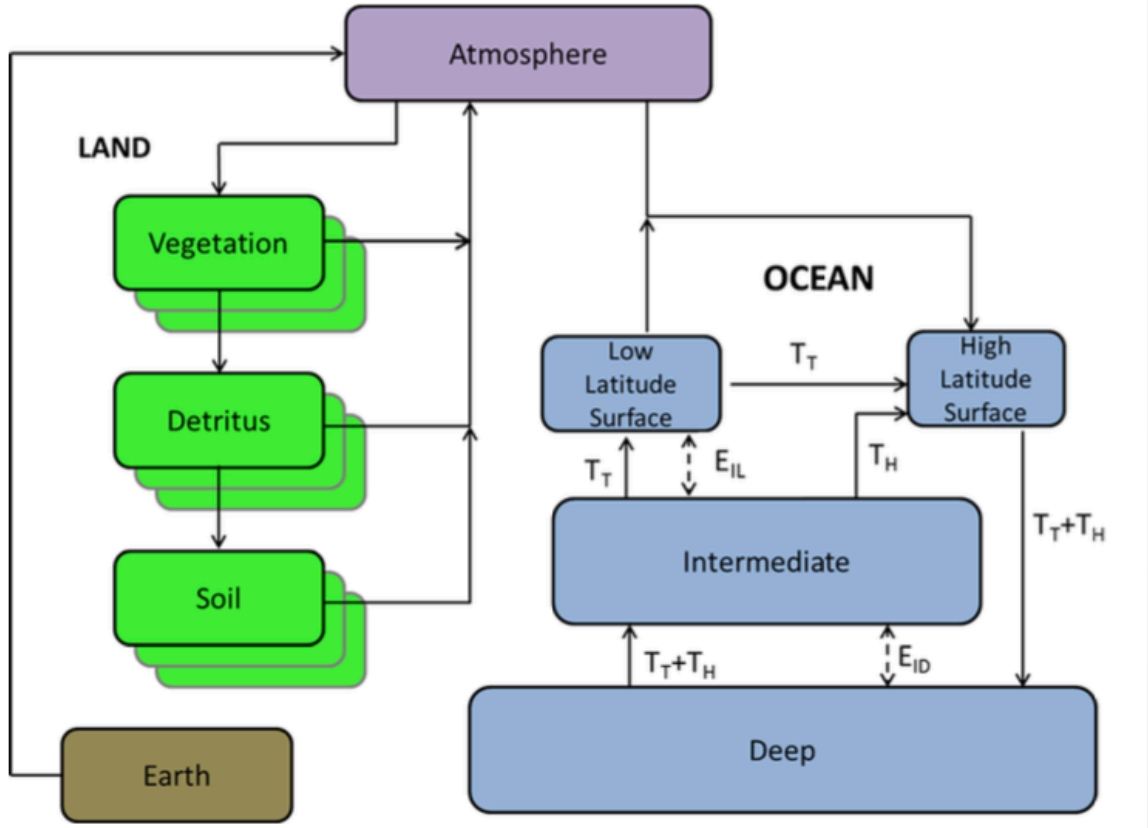
- Anthropogenic Emissions: 60-100 TgS/yr
- *Natural* Emissions: 25-80 TgS/yr
  - Dominates *Southern Hemisphere*
  - Fumaroles, biomass burning, volcanoes & phytoplankton
  - *Phytoplankton*: 50–60% of natural emissions
    - Released: Predation deterrent, Degrade with age, Grazing or viral lysis

1. Background: Air-Sea Exchange

- *DMS* enters atmosphere and *oxidized* → SO_2 , MSA, etc.
- SO_2 reacts with various *HOx oxidants* → SO_4^{2-}
  - Direct: *Scatters* incoming *solar radiation*
  - Indirect: Increases CCN concentration
    - Cloud structure toward smaller water droplets
    - *Increasing albedo* and *lifetime* of clouds

1. Background: Hector

- Joint Global Change Research Institute (JGCRI)
- Reduced-Complexity Model
  - Runs *nearly instantaneously*
  - Critical global-scale processes
- *Reproduces: Historical trends*
  - Atmospheric CO_2
  - Radiative Forcing
  - Surface temperatures
- *Simulates: All four RCPs*
  - MAGICC
  - Models from C^{5}MIP



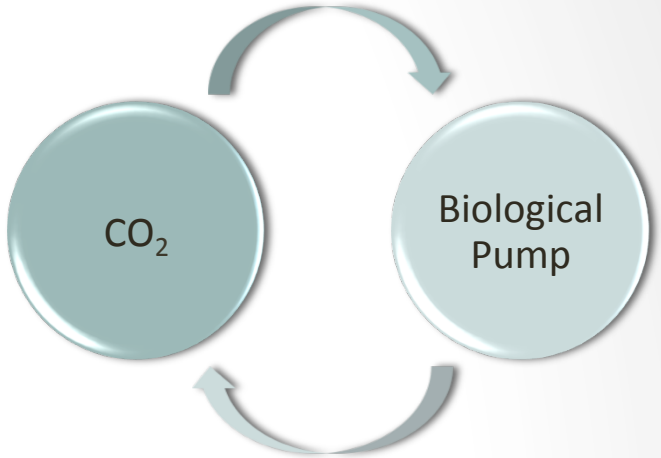
[Hartin et al., 2015]

2. Present Investigation: Objectives

1. Analyze climate change impact on sulfur cycle
   A. Ocean Acidification: [Six et al., 2013]
   B. Community Shifts: [Present & EOC simulations]
      - Nutrient Depletion
      - Increased Sea Surface Temperature
      - Increased Light Availability at the Poles

2. Regional scale perspective:
   - Global
   - Southern High Latitude: (90˚S – 30˚S)
   - Low Latitude: (30˚S – 30˚N)
   - Northern High Latitude: (30˚N – 90˚N)

2. Baseline: *CO_2 Marine Feedback*



- Excel-Hector: Carbon Ocean Component

- Solubility Pump: ocean acidification
  - Represented carbon cycle chemistry
  - Matched historical & projected concentrations in each ocean box

- *Biological Pump*: stratification
  - Biological $Pump_{Surface}$ = Redfield · Nitrogen · (*1-Remineralization*)
  - Biological $Pump_{Int,Deep}$ = Redfield · Nitrogen · (*Remineralization*)

- Radiative Forcing:
  - Equation used by Hector
  - $RF_{CO2} = 5.35 \times \ln(Ca/C0)$

3. Anthropogenic: Forcing & Emissions

- Indirect sulfate aerosol equation

$$RF_{SOx}Indirect = -0.6\,Wm^2\,x\,\frac{\left(\ln\frac{ESN + ESO_{xt}}{ESN}\right)}{\left(\ln\frac{ESN + ESO_{xt0}}{ESN}\right)}$$

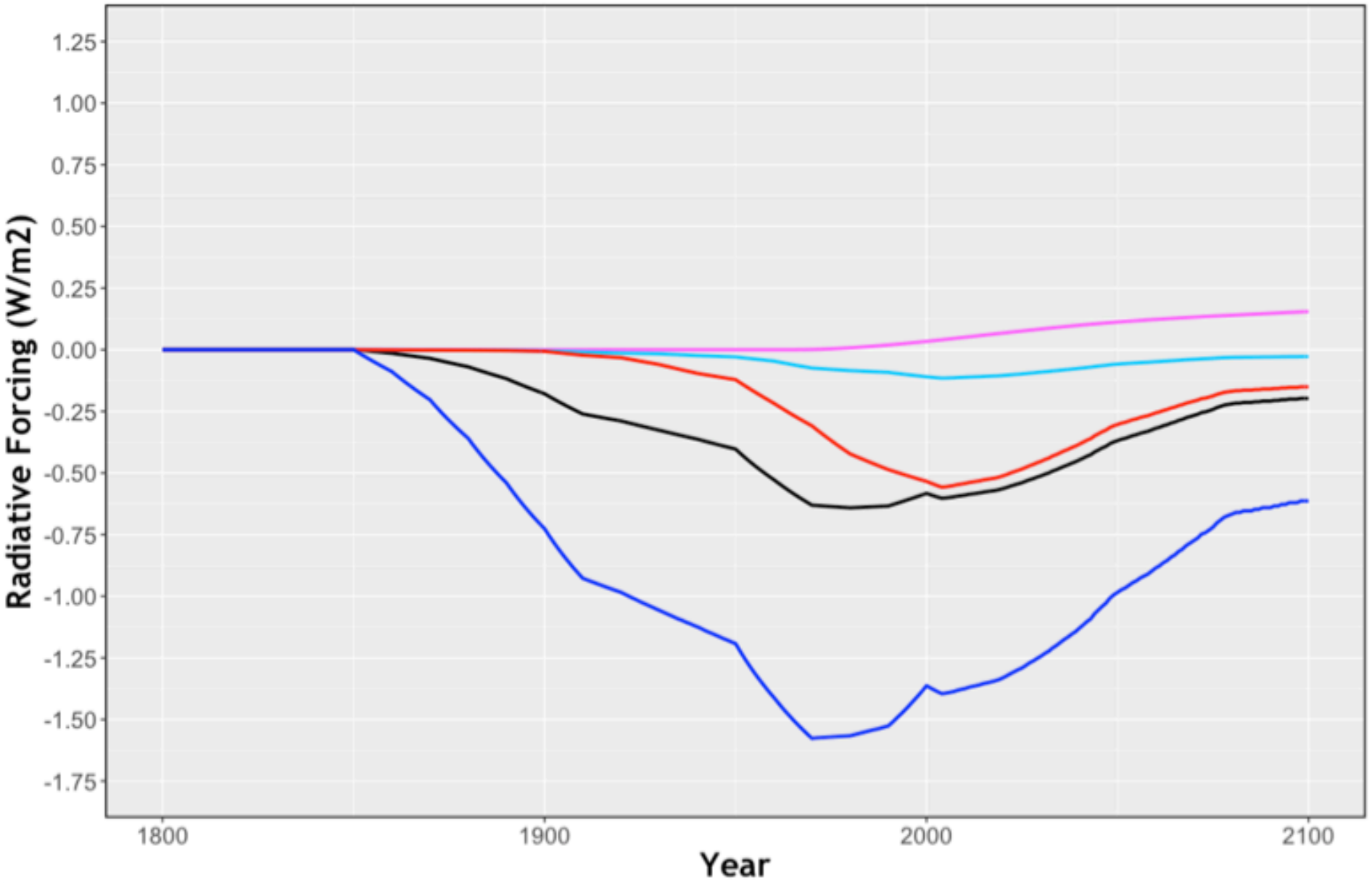
  - *Constants:*
    - Natural sulfur emission: *ESN*
      - *Fixed concentration* (42 TgS)
    - Anthropogenic emissions in 2000: ESO_{xt0}
  - Variables:
    - Anthropogenic emissions: ESO_{xt}

3. Anthropogenic: Forcing & Emissions

- Indirect sulfate aerosol equation: $RF_{SO_X}\text{Indirect} = -0.6 \times (ln\frac{ESN+ESO_{x_t}}{ESN}) \cdot (ln\frac{ESN+ESO_{x_{t0}}}{ESN})^{-1}$
- *Regional:* [Smith et al., 2011]
  - Southern High Latitude: (90˚S – 30˚S)
  - Low Latitude: (30˚S – 30˚N)
  - Northern High Latitude: (30˚N – 90˚N)
- Temporal:
  - 1850-2000: [Smith et al., 2011]
  - 2000-2100: RCP8.5

Location	ESOx in 2000 (TgS)	Percent Total	$RF_{ESOx}(Wm^{-2})$
Southern High Latitudes	4.83	4.52%	-0.11
Low Latitudes:	23.59	22.08%	-0.54
Northern High Latitudes:	68.67	64.26%	-1.57
International Shipping:	9.78	9.15%	-0.22
Global Total:	106.87	-	-0.61

Anthropogenic Sulfur Dioxide (Original Equation)



CO_2: Global
Sulfur: Global
Sulfur: SHL (90˚S – 30˚S)
Sulfur: LL (30˚S – 30˚N)
Sulfur: NHL (30˚N – 90˚N)

4. Natural: Ocean Acidification

- Secondary term added:
  - *Ocean Acidification impact on DMS producing phytoplankton*

$$RF_{SOx}Indirect = RF_{ESO}\,Wm^2\,x\,\frac{\left(ln\frac{ESN + ESO_{xt}}{ESN}\right)}{\left(ln\frac{ESN + ESO_{xt0}}{ESN}\right)} + RF_{ESN}\,Wm^2\,x\,\frac{\left(ln\frac{ESN_{xt65} + \Delta ESN_{xt}}{ESN_{xt65}}\right)}{\left(ln\frac{ESN_{xt65} + \Delta ESN_{xt100}}{ESN_{xt65}}\right)}$$

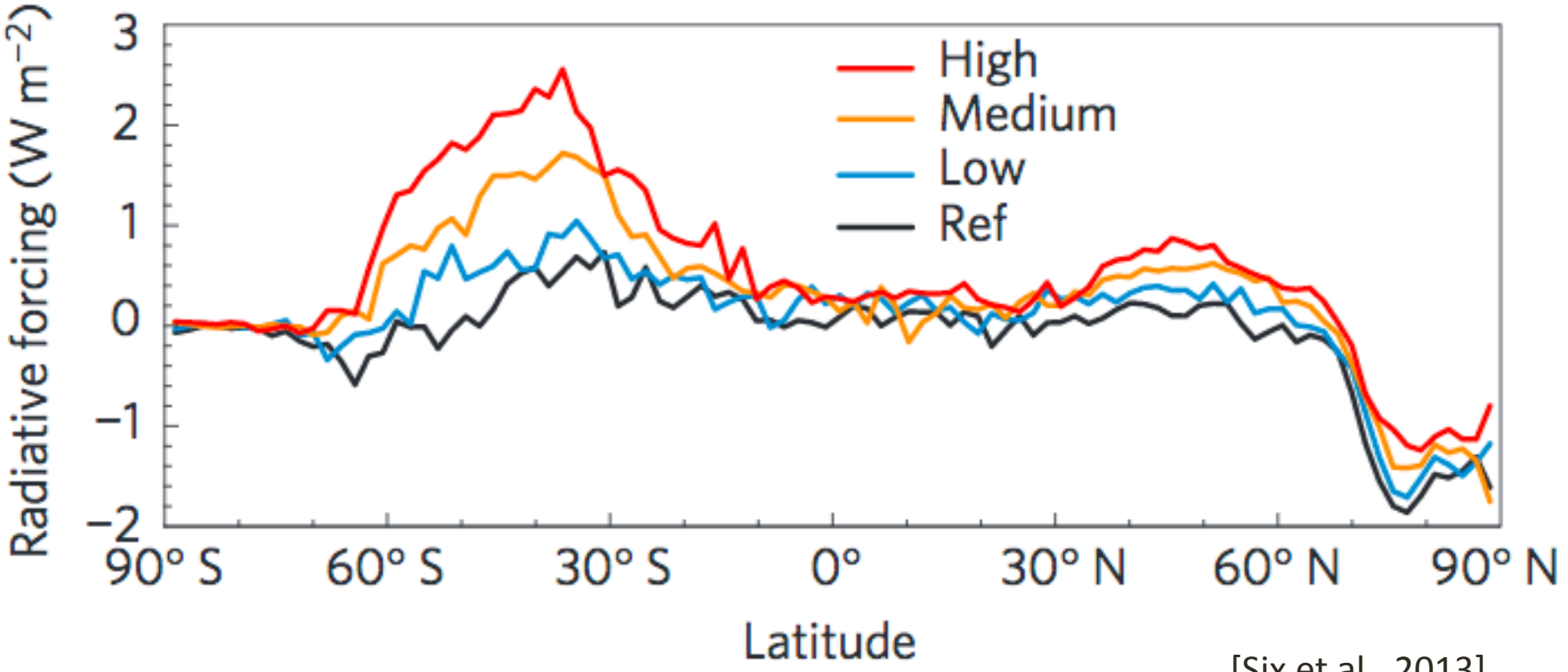
- Constants:
  - ESN_{xt65} : Natural Sulfur Emissions in 1865
  - ΔESN_{xt100} : Change in Natural Sulfur Emission in 2100
- Variables:
  - ΔESN_{xt} : Change in Natural Sulfur Emission

4. Natural: Ocean Acidification

- Secondary term added:

$$\mathrm{RF}_{\mathrm{SO}_x}\mathrm{Indirect} = \mathrm{RF}_{\mathrm{ESO}} \times \left(ln\frac{ESN+ESO_{x_t}}{ESN}\right) \cdot \left(ln\frac{ESN+ESO_{x_{t0}}}{ESN}\right)^{-1} +$$

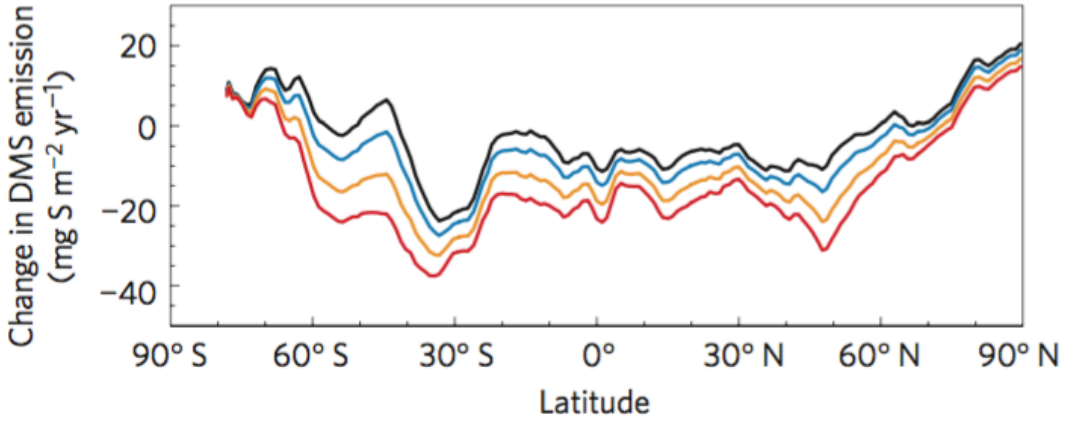
$$\mathrm{RF}_{\mathrm{ESN}} \times \left(ln\frac{ESN_{x_{t65}}+\Delta ESN_{x_t}}{ESN_{x_{t65}}}\right) \cdot \left(ln\frac{ESN_{x_{t65}}+\Delta ESN_{x_{t100}}}{ESN_{x_{t65}}}\right)^{-1}$$



[Six et al., 2013]

4. Natural: Ocean Acidification

- *Point:* [Simo & Dachs, 2002]
  - Average 3 annual emissions
  - *~ Year 2000*
- *Slope:* [Six et al., 2013]
  - *Change in DMS emissions* from:
    - (1865-1874) to (2090-2099)
  - Varying pH sensitivity scenarios:
    - High - Reference

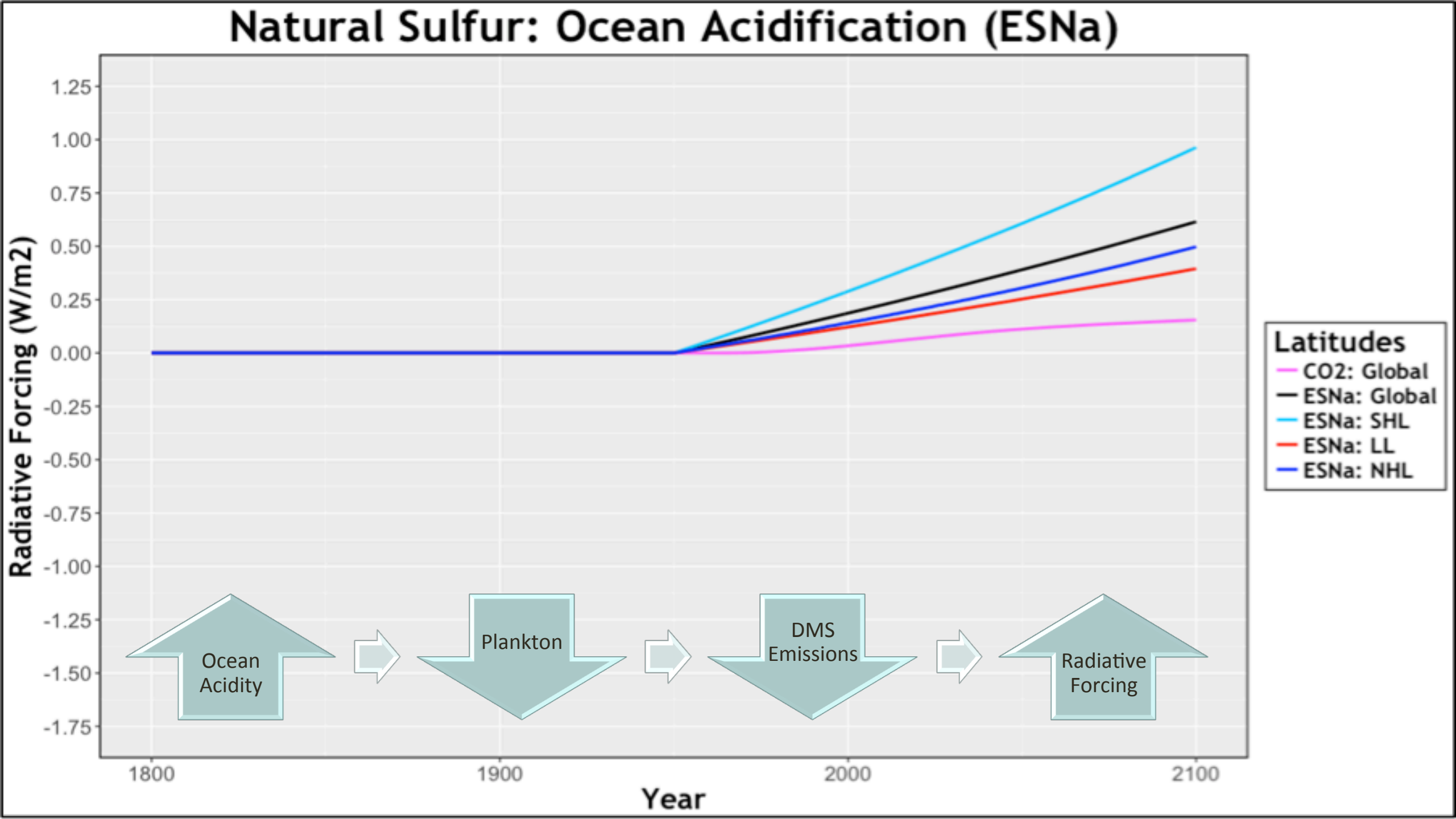


[Six et al., 2013]

Latitude Band	Mean Concentration, nM	Mean Annual Flux, μmol m^{-2} d^{-1}		Annual Emission, Tg S yr^{-1}		
		N00	W99	LM86	N00	W99
80°–90°N	0.9	0.9	4.1	0.00	0.00	0.01
70°–80°N	4.5	8.9	13.6	0.13	0.18	0.29
60°–70°N	4.0	5.8	8.3	0.10	0.13	0.21
50°–60°N	3.8	5.9	10.7	0.34	0.41	0.75
40°–50°N	2.7	5.8	9.7	0.57	0.75	1.18
30°–40°N	2.4	6.6	9.6	0.94	1.26	1.69
20°–30°N	2.4	6.5	8.9	1.16	1.56	1.97
10°–20°N	2.7	9.3	14.7	1.96	2.68	3.94
0°–10°N	2.9	10.6	14.8	2.45	3.38	4.33
0°–10°S	2.7	8.2	11.3	2.05	2.81	3.59
10°–20°S	2.1	7.8	11.3	1.85	2.51	3.42
20°–30°S	2.1	6.7	9.1	1.63	2.22	2.86
30°–40°S	1.9	5.9	8.5	1.51	2.05	2.82
40°–50°S	1.4	5.6	9.4	1.36	1.88	2.86
50°–60°S	1.0	3.8	6.7	0.72	1.04	1.58
60°–70°S	1.4	3.2	5.0	0.26	0.38	0.48
70°–80°S	1.5	1.9	2.3	0.01	0.02	0.02
80°–90°S	0.0	0.0	0.0	0.00	0.00	0.00
Global mean flux	5.7	8.8				
Global emission				17.0	23.3	34.6

[Simo & Dachs, 2012]

Natural Sulfur: Ocean Acidification (ESNa)



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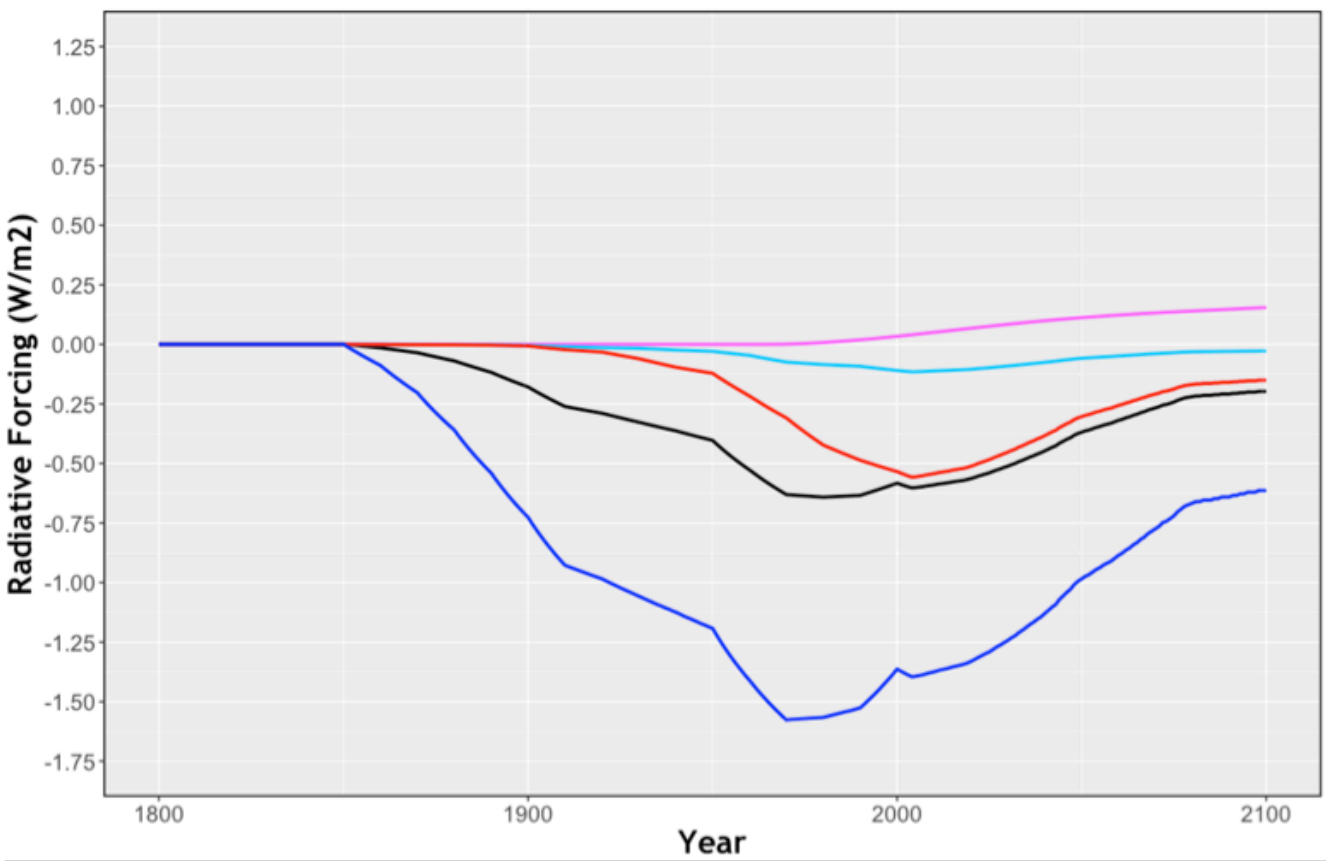
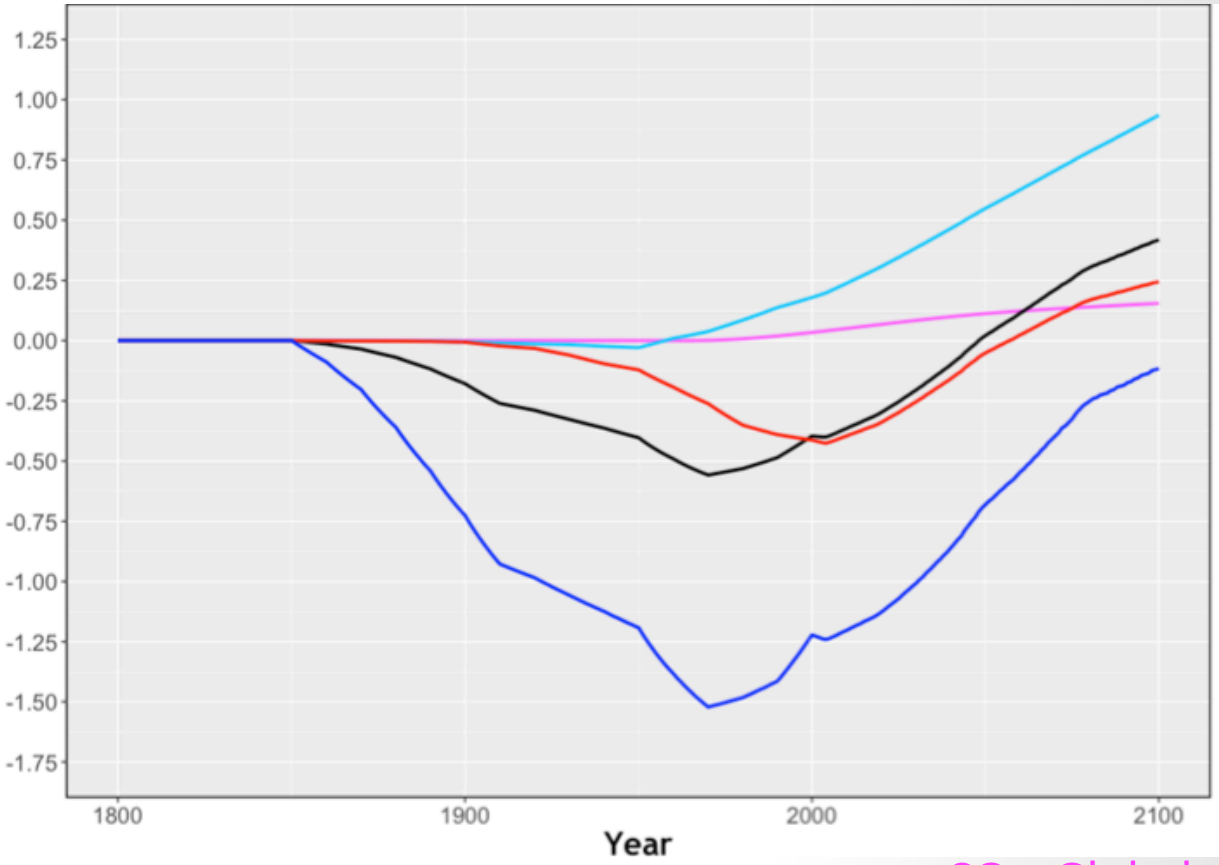


Anthropogenic Sulfur Dioxide + *Natural Sulfur: Ocean Acidification*



CO_2: Global

Sulfur: Global

Sulfur: SHL (90˚S – 30˚S)

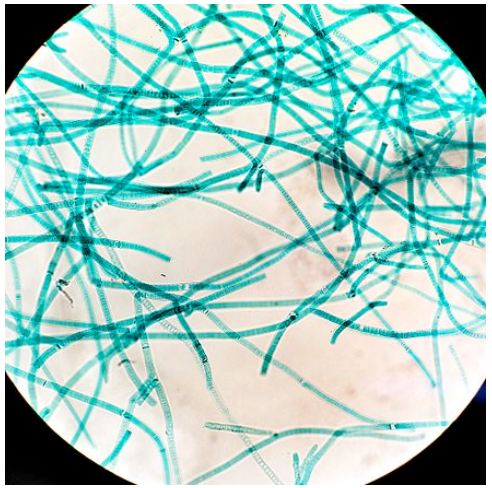
Sulfur: LL (30˚S – 30˚N)

Sulfur: NHL (30˚N – 90˚N)

5. Natural: Community Shifts

- DMS Non-Producers:
  - Diatoms
  - Cyanobacteria

- DMS Producers:
  - Coccolithophorids (EHUX)
  - Dinoflagellates et al.
  - *Phaeocystis*



Cyanobacteria

Phaeocystis

5. Natural: Community Shifts

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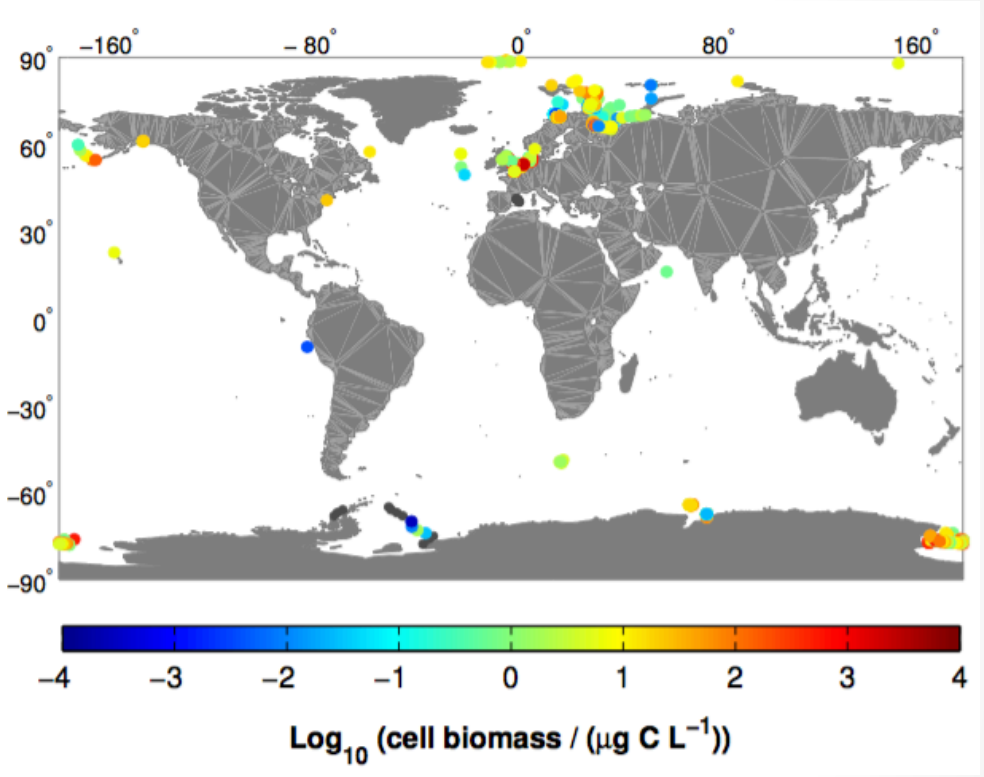
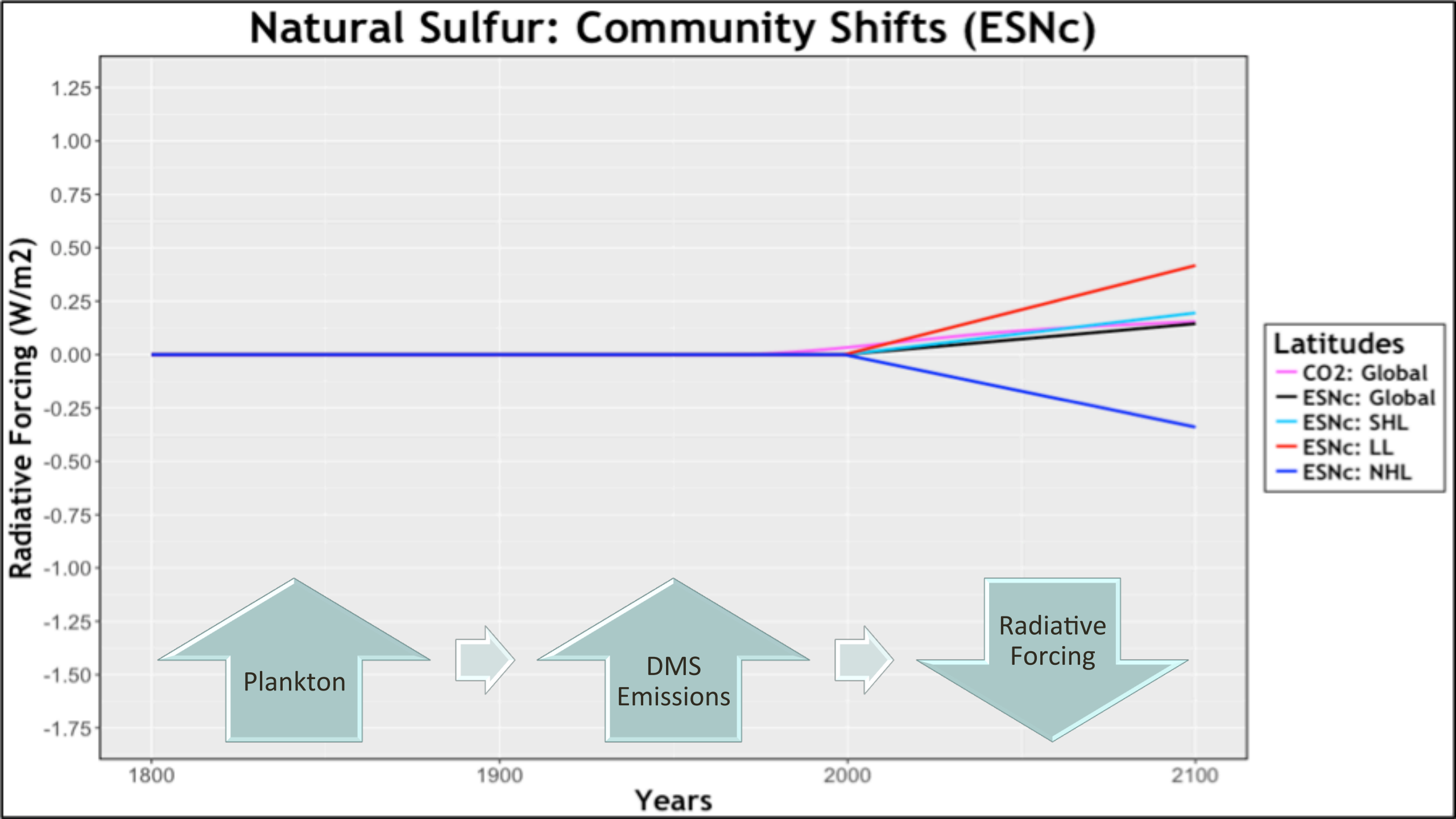


[Vogt et al., 2012]

$$Phaeocystis_{2100} = Concentration_{Present}\ x\ \left(\frac{Phaeocystis\ DMS\ Emissions_{2100}}{Phaeocystis\ DMS\ Emissions_{Present}}\right)$$

Natural Sulfur: Community Shifts (ESNc)



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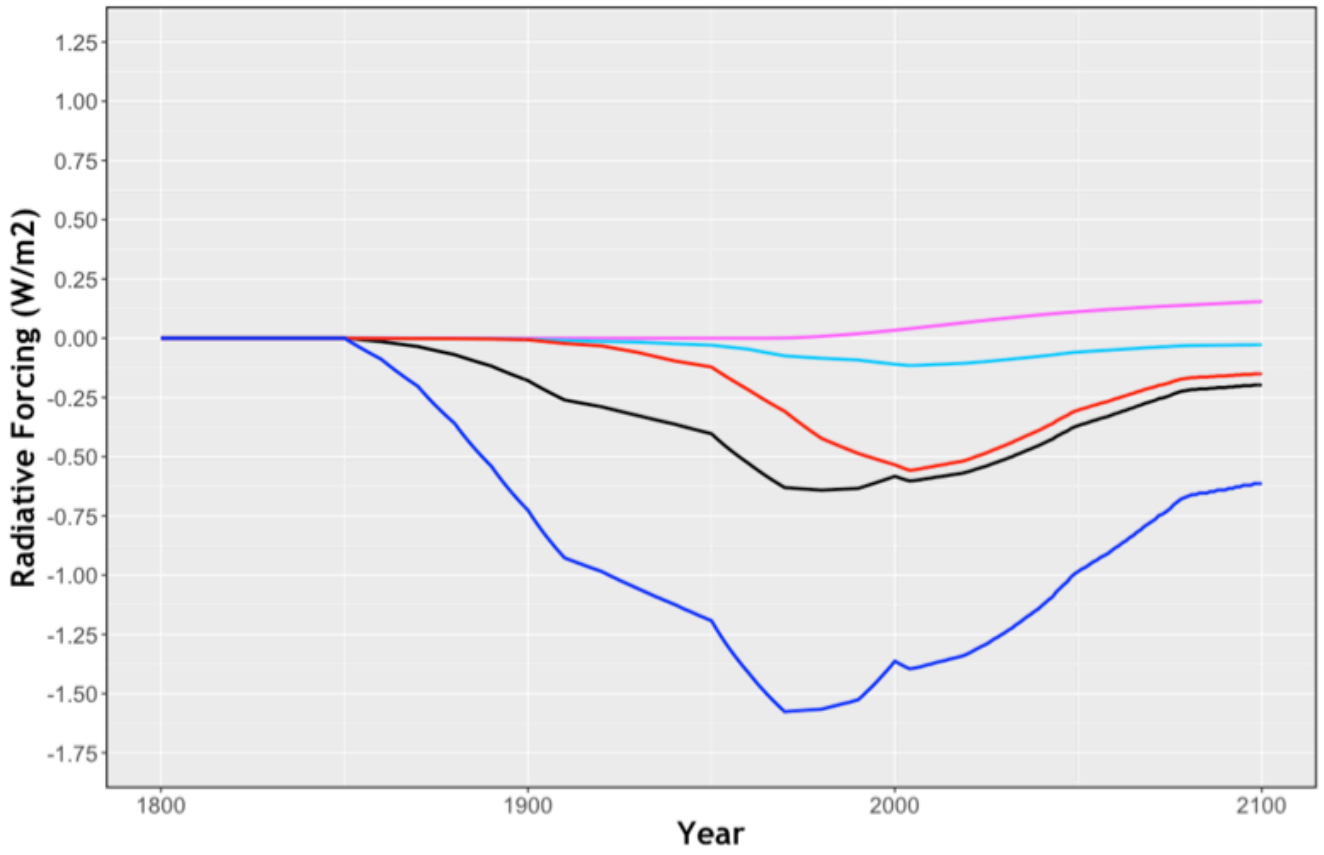
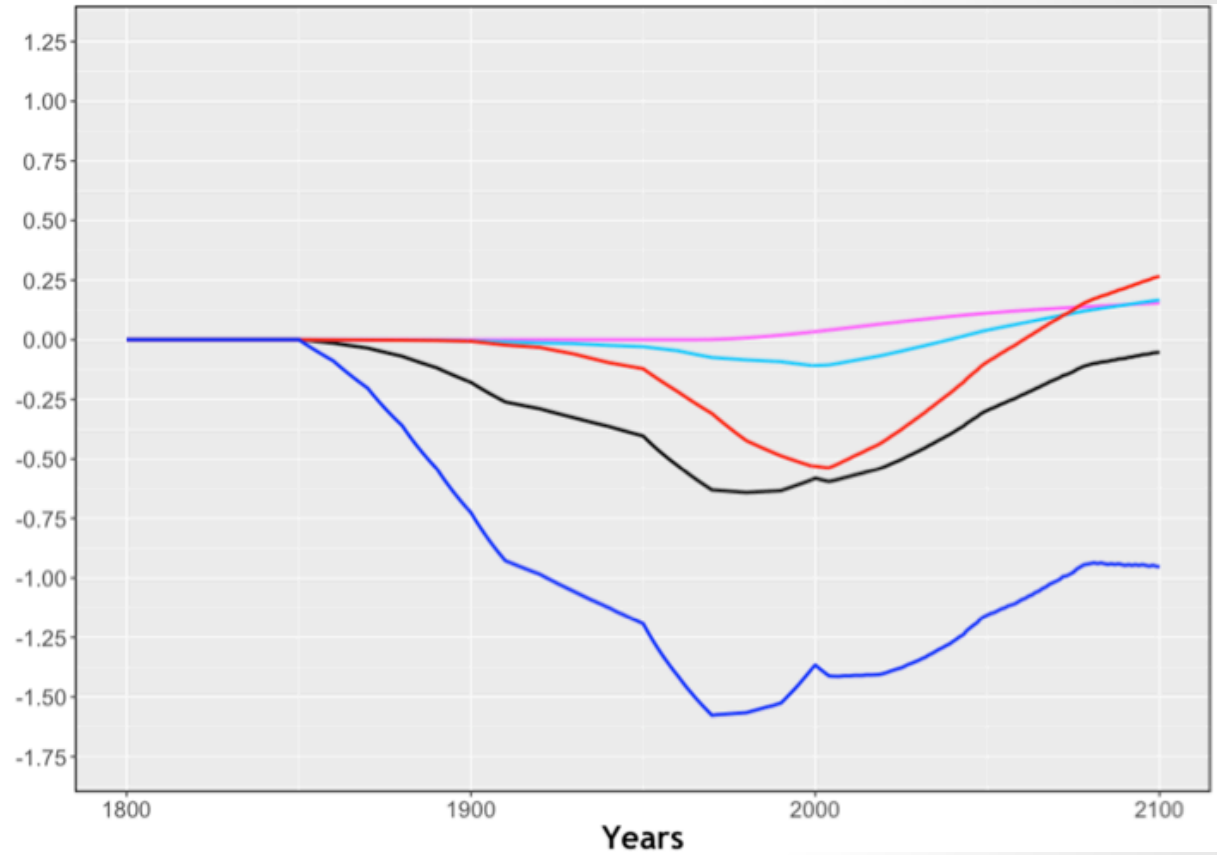


Anthropogenic Sulfur Dioxide + *Natural Sulfur: Community Shifts*



CO_2: Global

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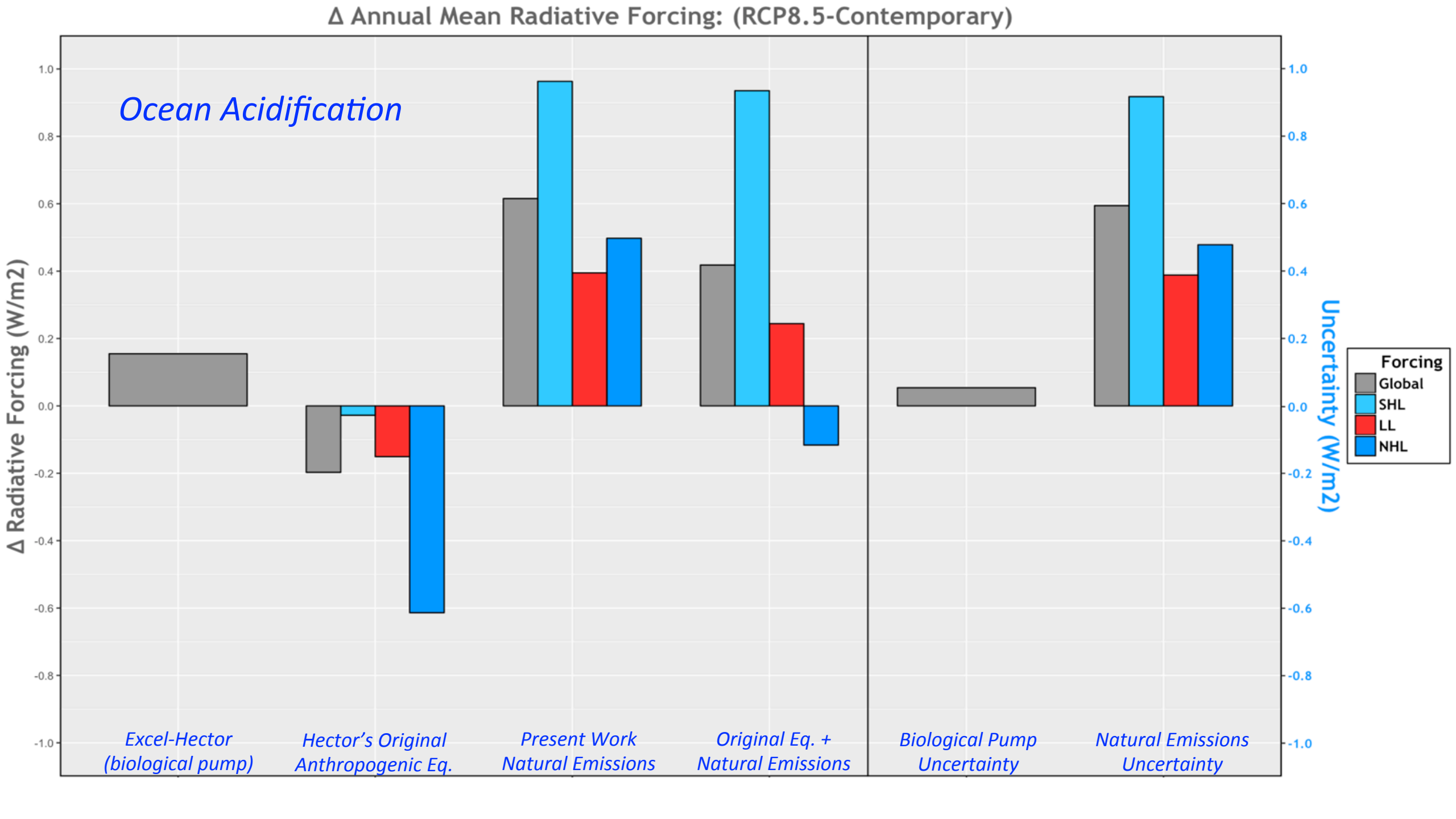
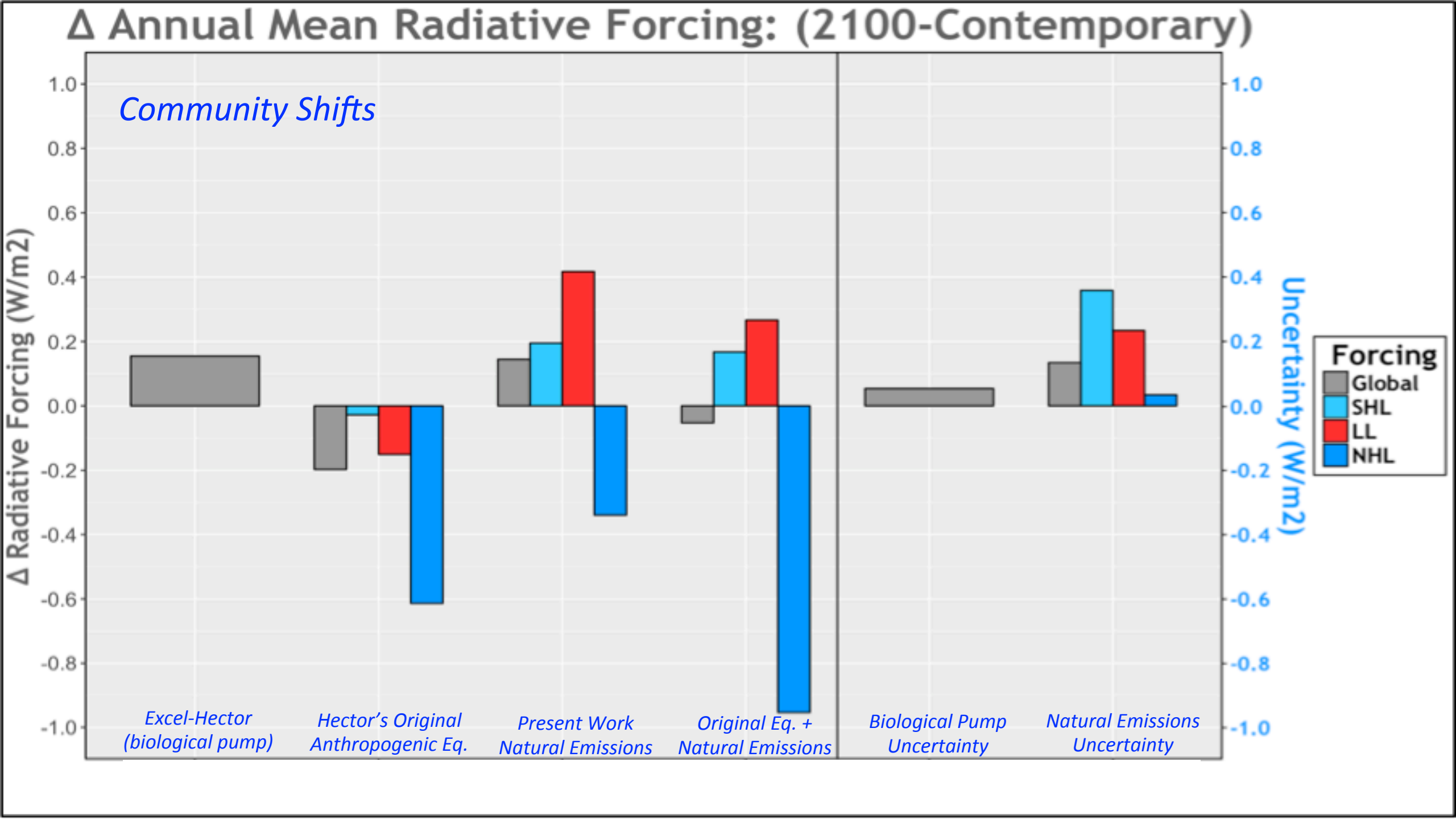
Sulfur: NHL (30˚N – 90˚N)


Δ Annual Mean Radiative Forcing: (RCP8.5-Contemporary)
Ocean Acidification
Δ Radiative Forcing (W/m2)
Uncertainty (W/m2)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Forcing
Global
SHL
LL
NHL
Excel-Hector (biological pump)
Hector's Original Anthropogenic Eq.
Present Work Natural Emissions
Original Eq. + Natural Emissions
Biological Pump Uncertainty
Natural Emissions Uncertainty


Δ Annual Mean Radiative Forcing: (2100-Contemporary)
Community Shifts
Δ Radiative Forcing (W/m2)
Uncertainty (W/m2)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Forcing
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Hector's Original Anthropogenic Eq.
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Original Eq. + Natural Emissions
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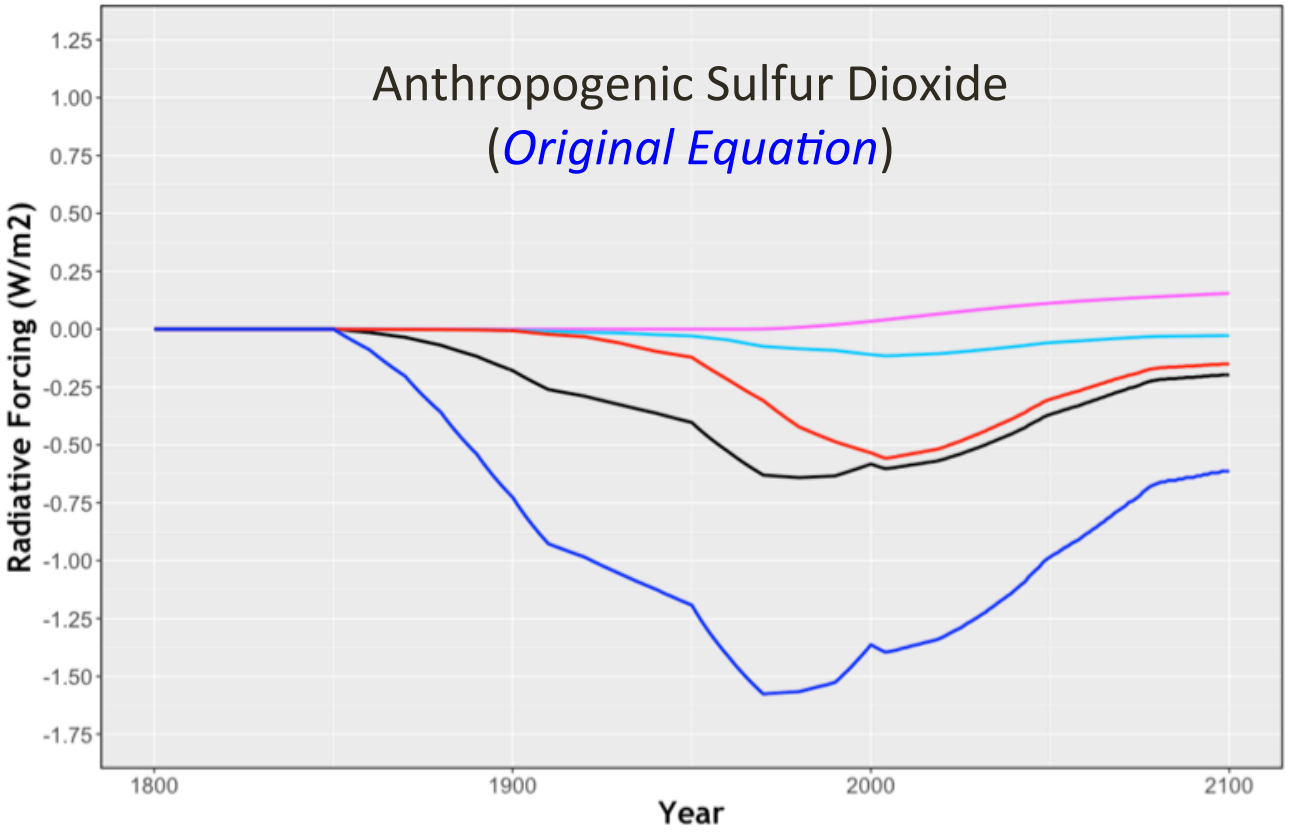
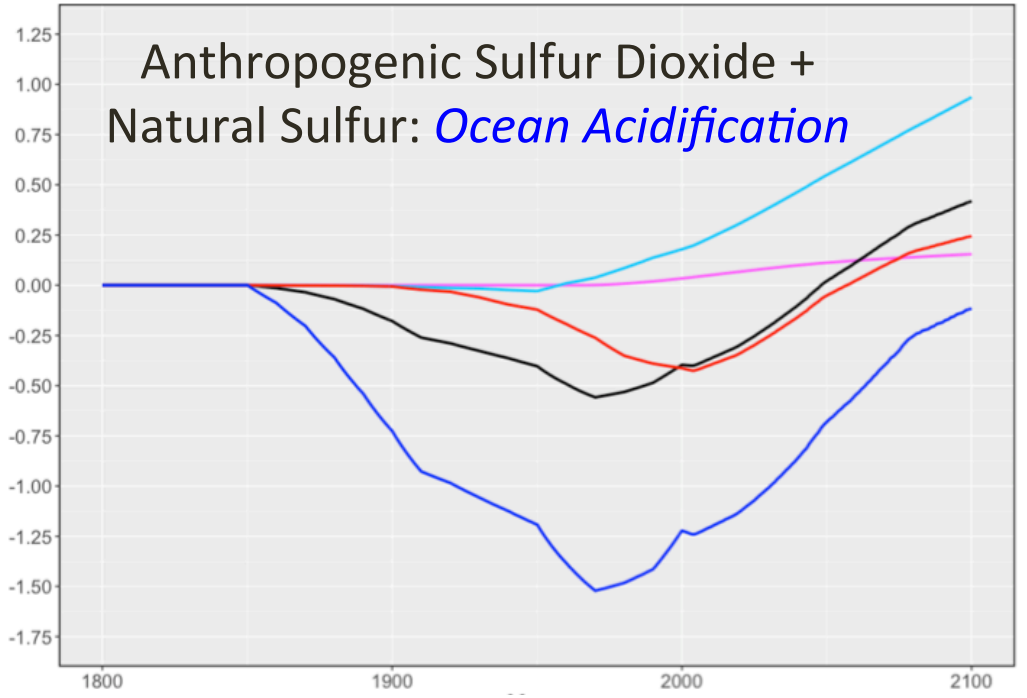
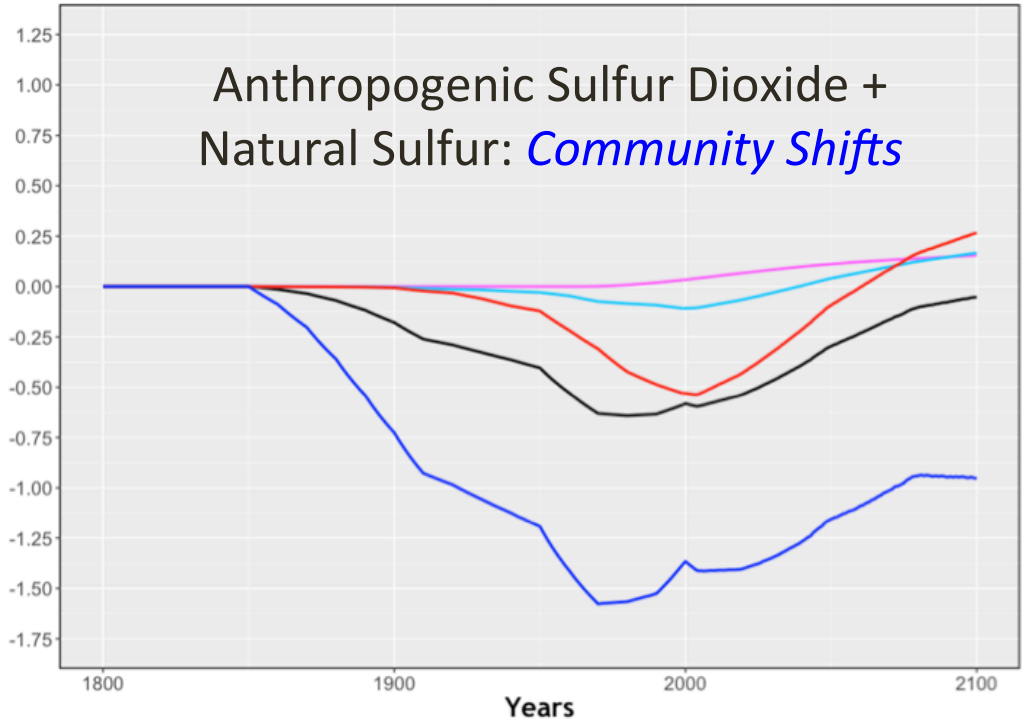
6. Conclusion:







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