30 Years of the Clean Air Act Amendments: Impacts on haze in remote regions of the U.S. 1990-2018

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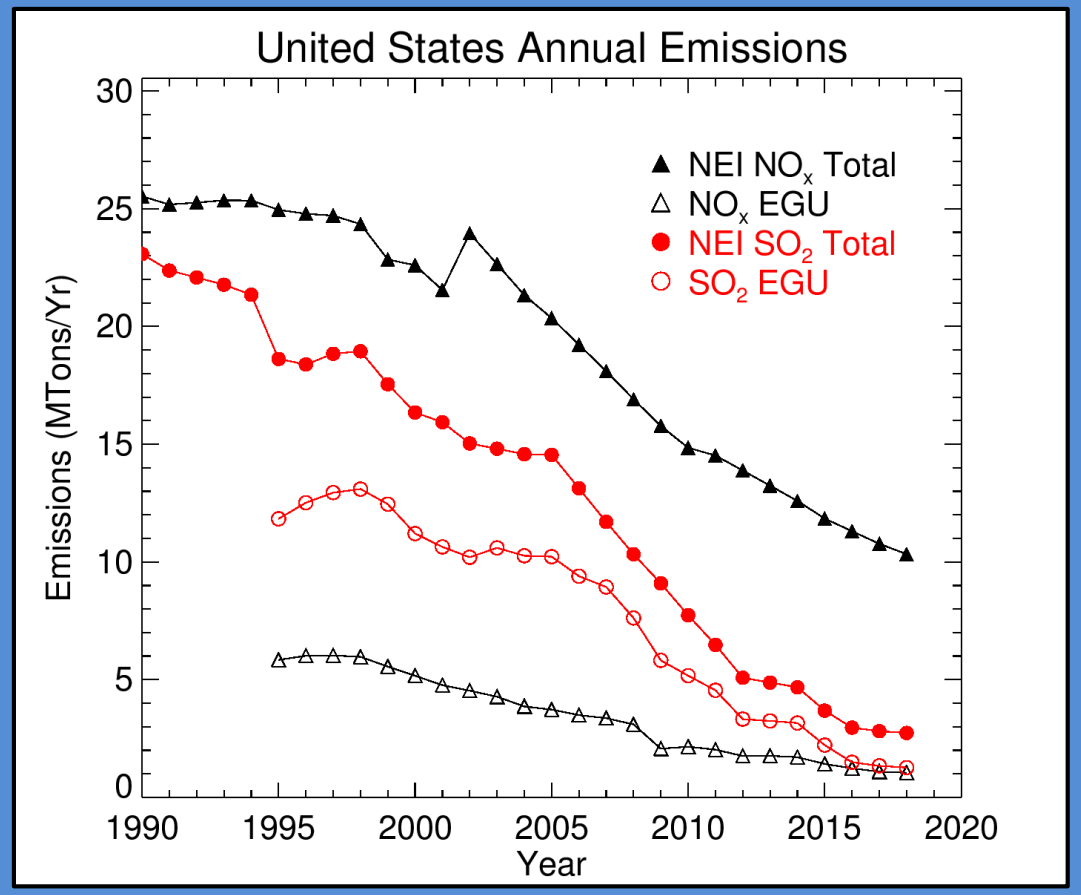
1990 Great Smoky Mountains NP, TN 2017

MOTIVATION

- 30th Anniversary of the Clean Air Act Amendments
- Reductions in SO_2 and NO_x emissions and impacts on haze



EPA National Emission Inventory (NEI)*

SO_2: Nearly 10-fold decrease in emissions
(EGUs 65% to 48% of emissions since 1995)

NO_x: Reduced by over half
(EGUs: 25% to 10% since 1995)
(Mobile: 63% to 58% since 2002)

* https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data

MOTIVATION

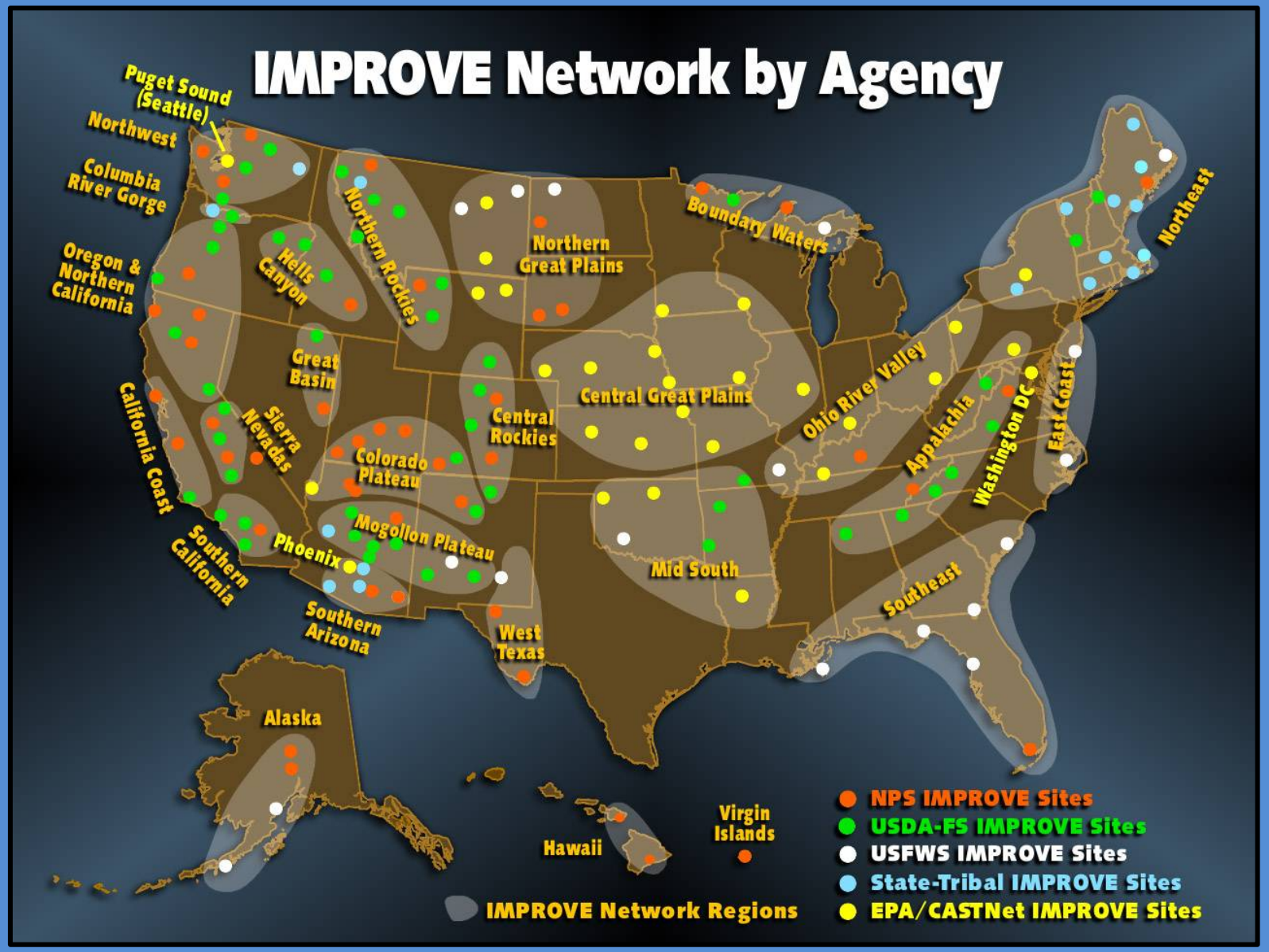
- Particulate sulfate and nitrate concentrations in the atmosphere and precipitation have decreased since the early 1990s.

- How have these reductions affected haze across the U.S.?

- How has the composition of haze changed?

1990 Shenandoah, VA 2017

Interagency Monitoring of Protected Visual Environments



IMPROVE website: http://vista.cira.colostate.edu/Improve/

Revised IMPROVE Algorithm

Reconstructed b_{ext} =

Sulfate: $2.2*f_S(RH)*[AS]_S + 4.8*f_L(RH)*[AS]_L$

Nitrate: $+ 2.4*f_S(RH)*[AN]_S + 5.1*f_L(RH)*[AN]_L$

Sea Salt: $+ 1.7*f_{ss}(RH)*[SS]$

Hygroscopic species

Particulate Organics: $+ 2.8*[POM]_S + 6.1*[POM]_L$

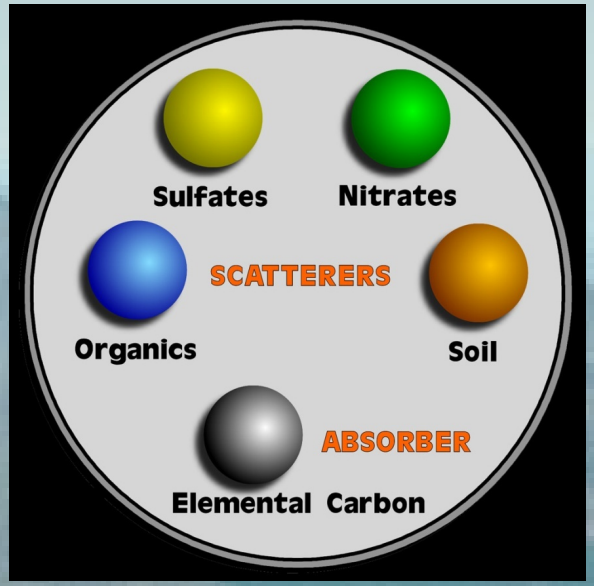
$+ 10*[\text{Elemental Carbon}]$

$+ 1*[\text{Fine Soil}]$

$+ 0.6*[\text{Coarse Mass}]$

$+$ Rayleigh scattering (site specific)

$+ 0.33*[NO_2\ (ppb)]$



"S" refers to 'small' mode; "L" refers to 'large' mode
Pitchford et al., 2007, JAWMA

Mm^{-1}, 550 nm

The equation underestimates reconstructed b_{ext}, especially in the East where sulfate and POM have experienced the strongest reductions. (Prenni et al., 2019)

This could lead to an uncertainty in trends of up to 1% yr^{-1} in the East and 0.5 % yr^{-1} in the West.

Download data: http://vista.cira.colostate.edu/fed

1995 Shining Rock, NC 2017

METHOD

- Annual mean b_{ext}

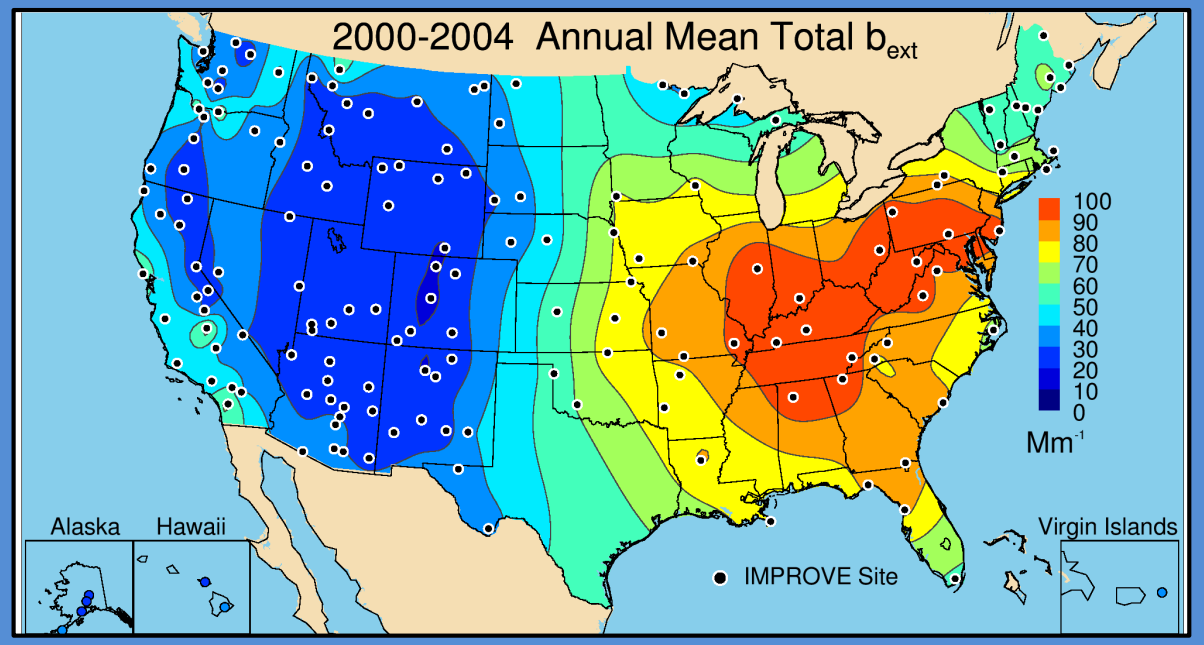
- Trends in reconstructed b_{ext} using Theil regression, significance ($p<0.10$)

  - Long-term (LT): 1990-2018
  - Short-term (ST): 2000-2018

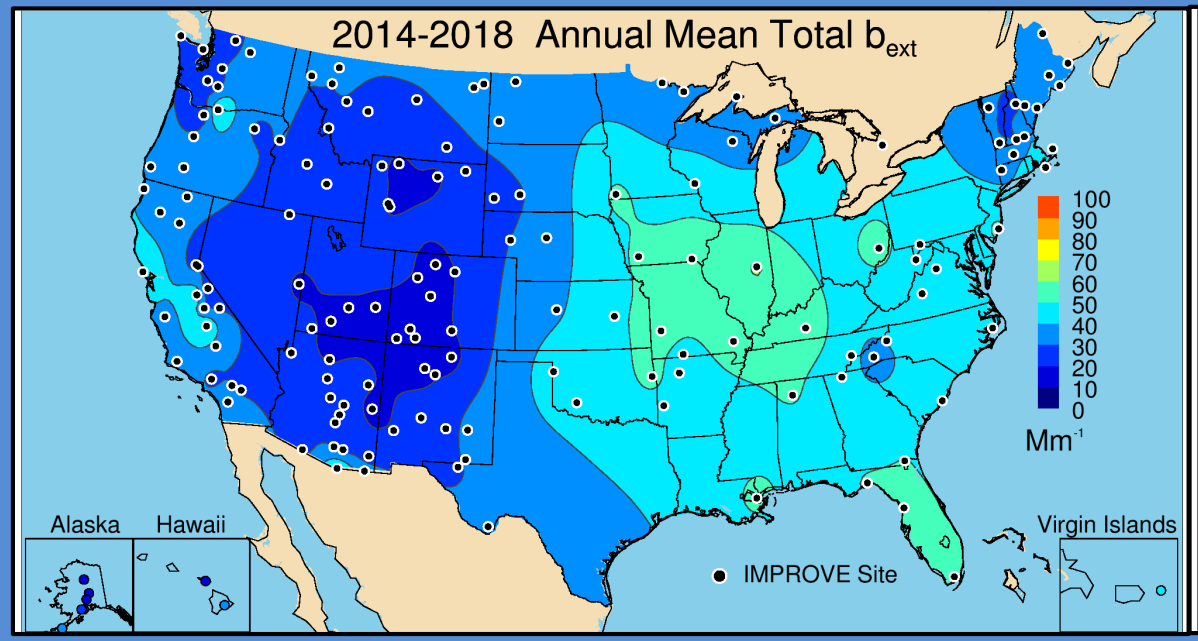
1990 Acadia NP, ME 2017

Annual Mean b_{ext}

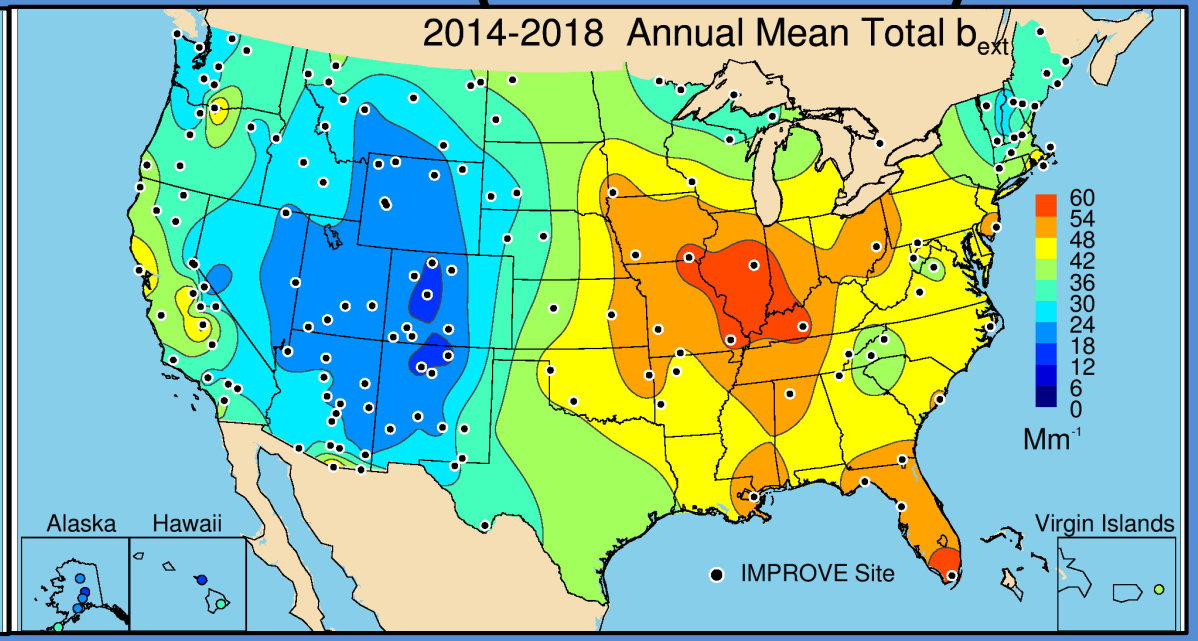
2000-2004



2014-2018

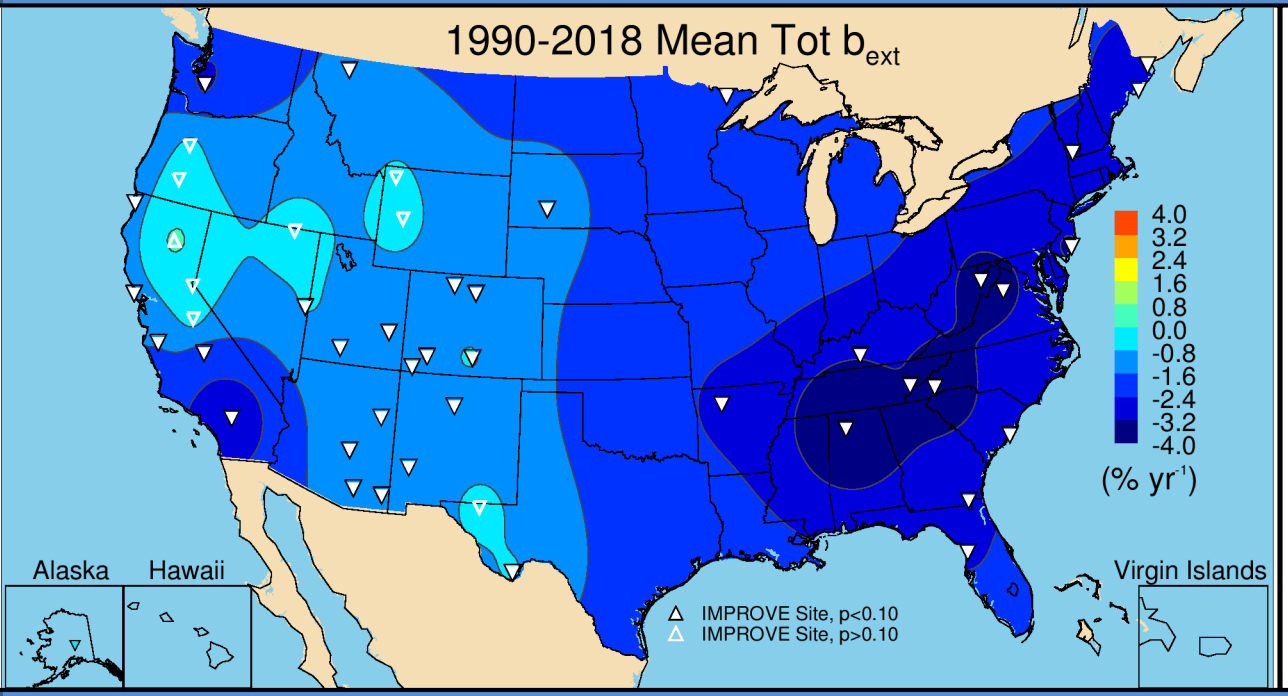


(Different Scale)



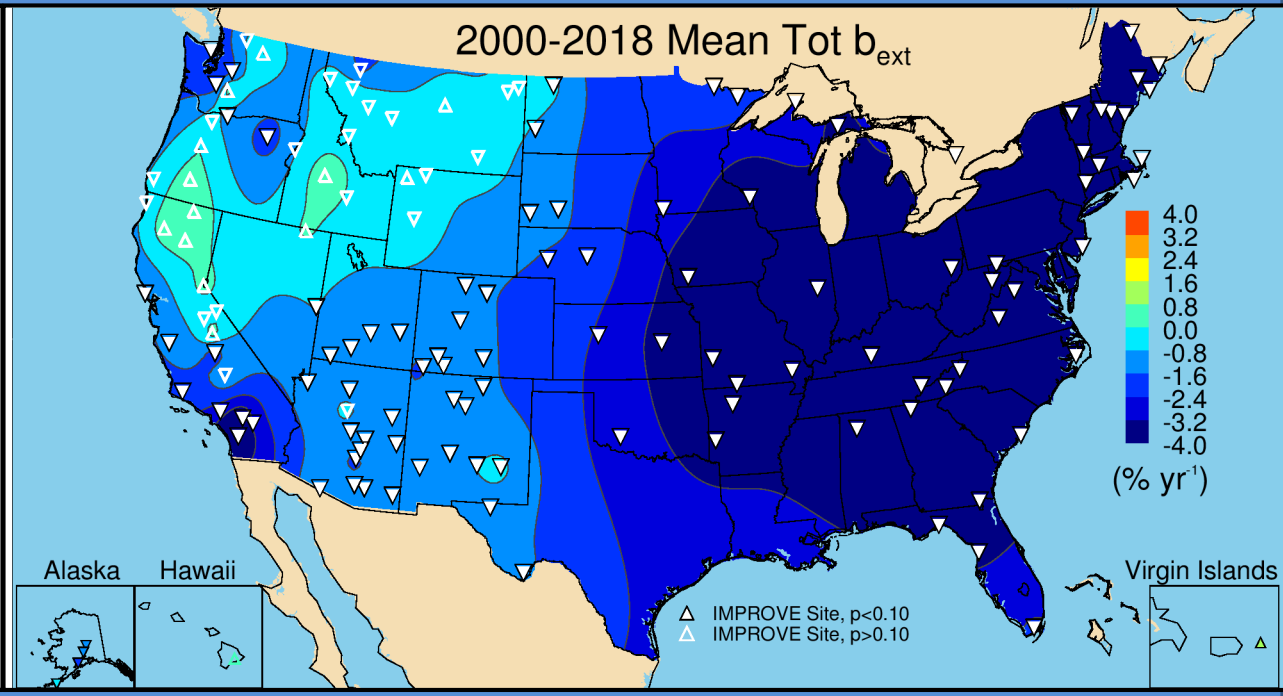
Trends in Annual Mean b_{ext}

1990-2018



Average CONUS annual mean b_{ext} decreased by -1.8 % yr^{-1} (p<0.001)

2000-2018



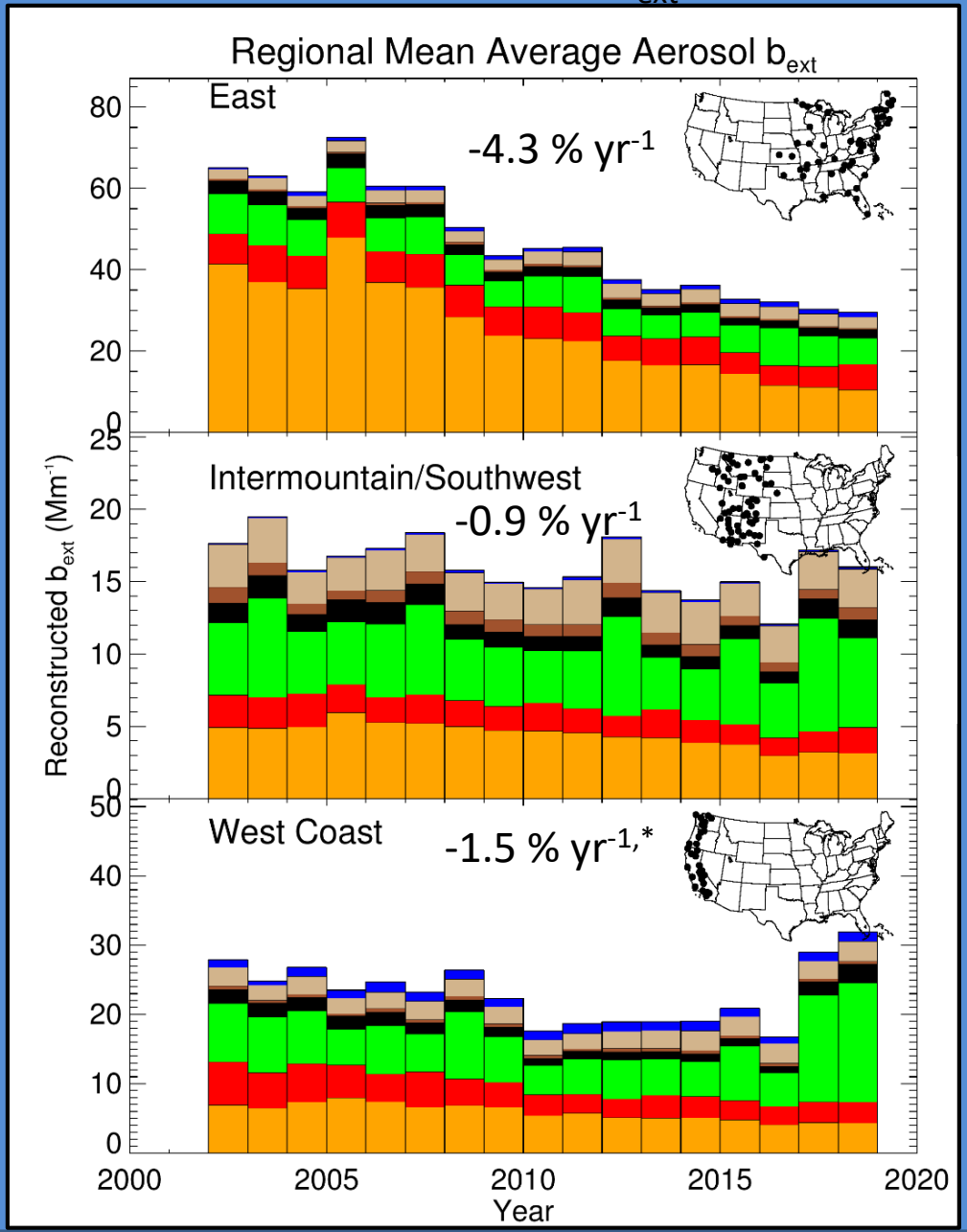
Average CONUS annual mean b_{ext} decreased by -2.8 % yr^{-1} (p<0.001)

Hand et al. (2020)

Regional Mean: Changes in Annual Mean Speciated b_{ext} (2002-2018)

Absolute aerosol b_{ext}

Extinction from:
- Ammonium Sulfate (AS)
- Ammonium Nitrate (AN)
- Particulate Organics (POM)
- Elemental Carbon (EC)
- Fine Dust (FD)
- Coarse Mass (CM)
- Sea Salt



% Change over 17 years

East:

AS (↓ 148%) and AN (↓ 53%).

POM (↓ 44%) and EC (↓ 69%)

FD (↓ 33%) and CM (↑ 18%)

IMW/SW:

AS (↓ 61%) and AN (↓ 49%).

POM (↓ 16%) and EC (↓ 43%)

FD (↓ 17%) and CM (↔,no change)

WC:

AS (↓ 67%) and AN (↓ 100%).

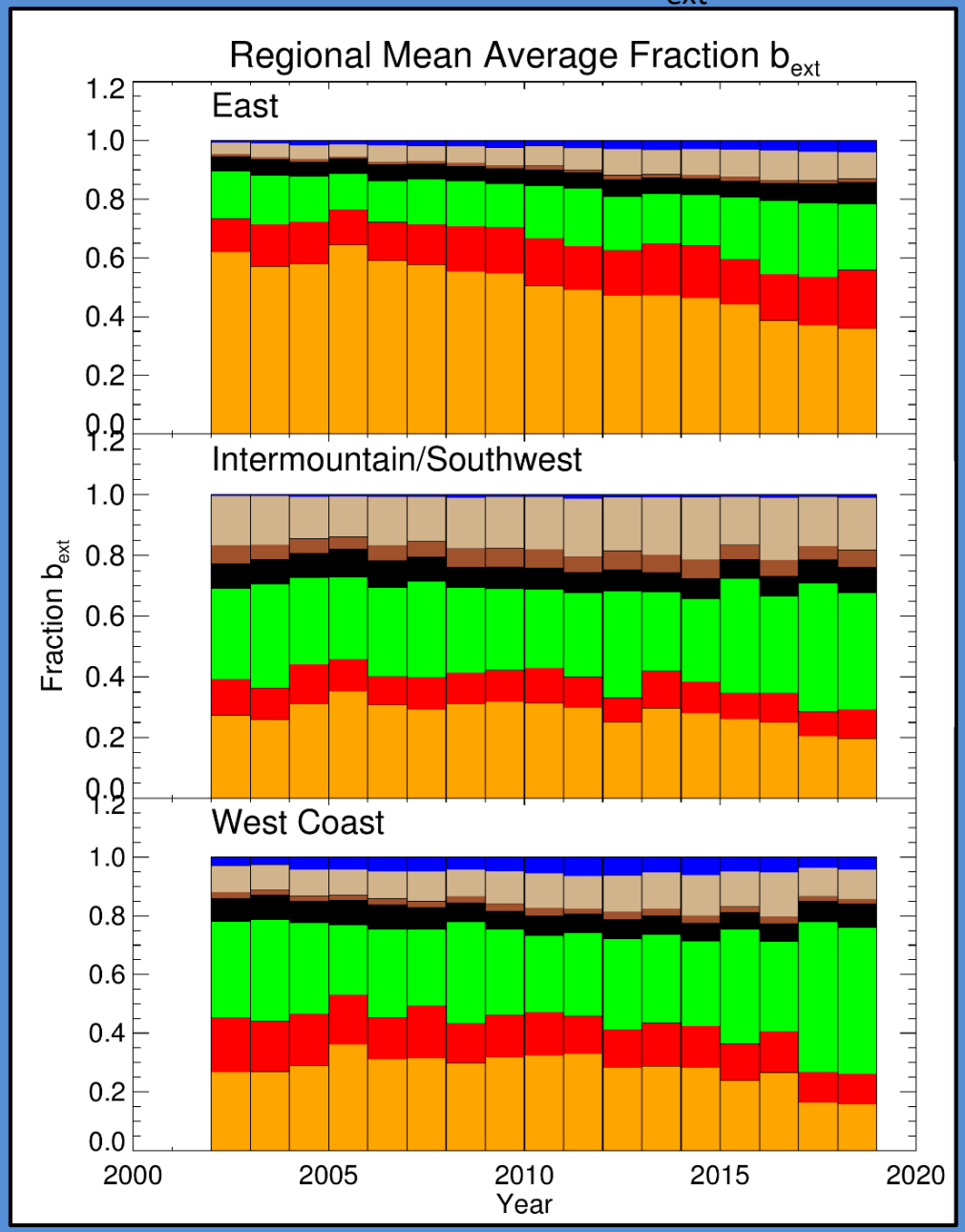
POM (↓ 11%) and EC (↓ 64%)

FD (↓ 17%) and CM (↑ 18%)

* Insignificant

Regional Mean: Changes in Annual Mean Speciated b_{ext} (2002-2018)

Relative aerosol b_{ext}



Extinction from:
- Ammonium Sulfate (AS)
- Ammonium Nitrate (AN)
- Particulate Organics (POM)
- Elemental Carbon (EC)
- Fine Dust (FD)
- Coarse Mass (CM)
- Sea Salt

Percent of aerosol b_{ext}

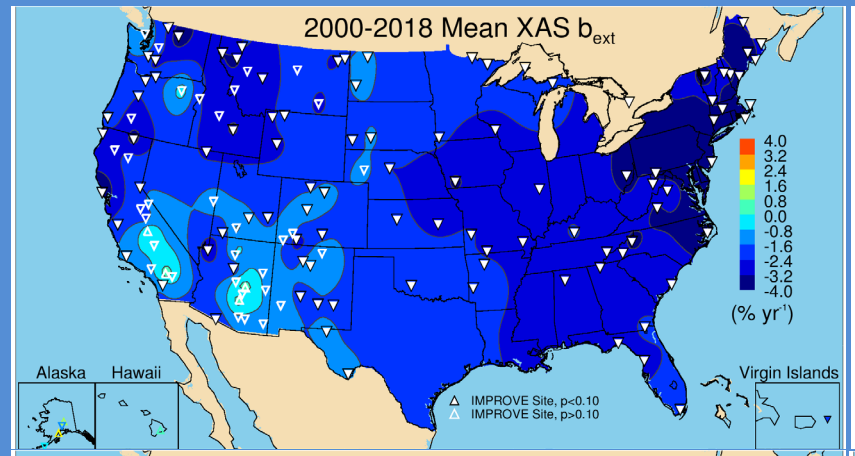
East	AS+AN	Carbon	Crustal
2002-2004:	72%	21%	5%
2016-2018:	55%	31%	14%

IMW/SW	AS+AN	Carbon	Crustal
2002-2004:	40%	39%	21%
2016-2018:	31%	45%	24%

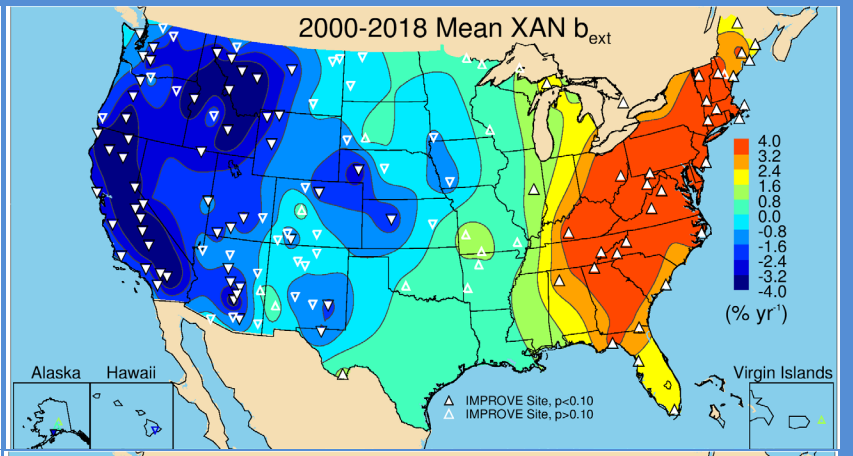
WC	AS+AN	Carbon	Crustal
2002-2004:	45%	41%	14%
2016-2018:	31%	51%	18%

2000-2018 Trends in the annual mean speciated extinction fraction

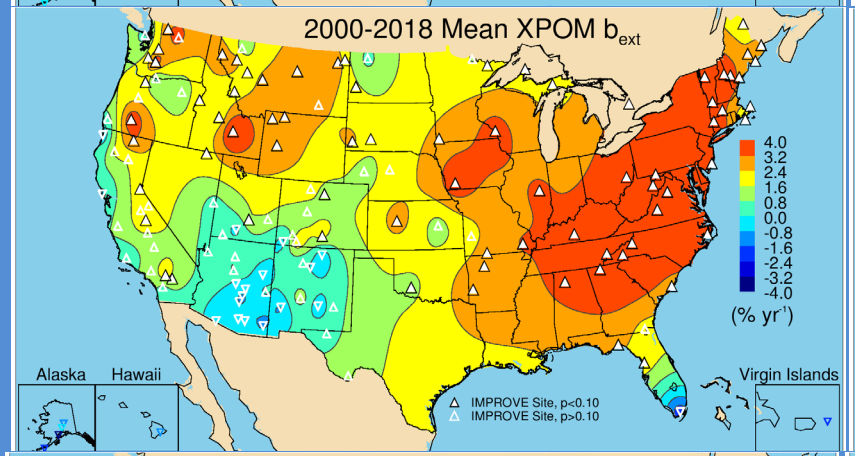
AS b_{ext} fraction



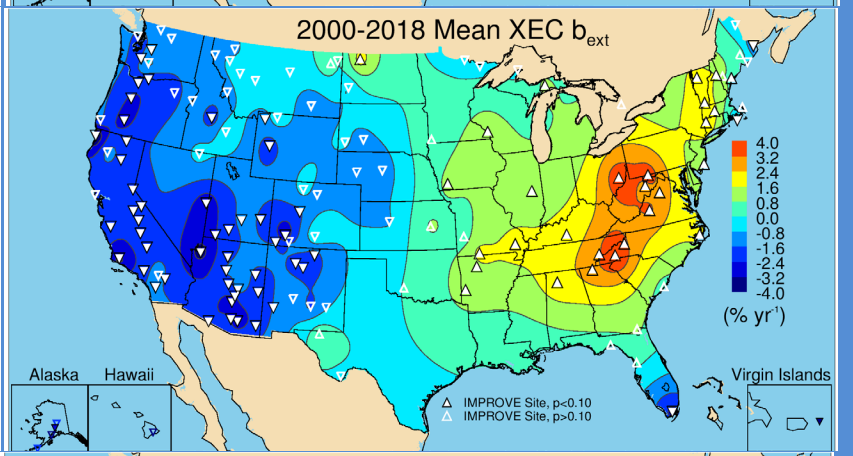
AN b_{ext} fraction



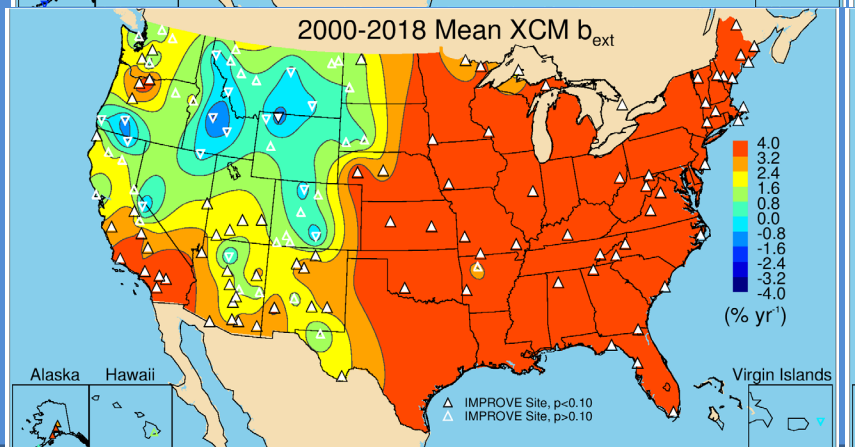
POM b_{ext} fraction



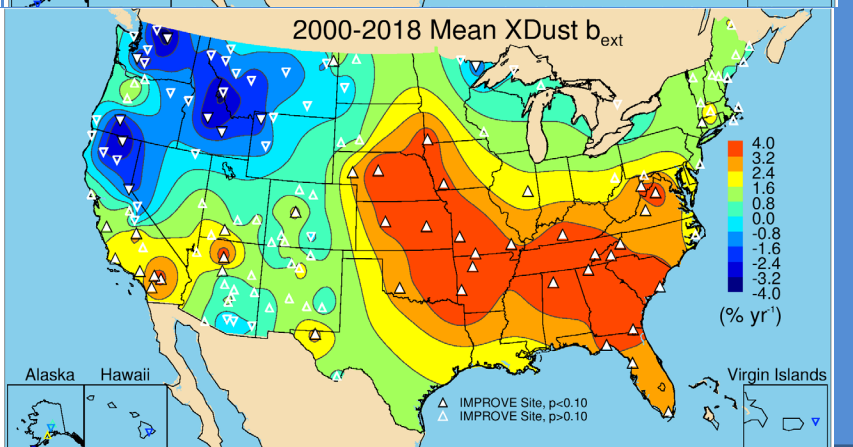
EC b_{ext} fraction



CM b_{ext} fraction

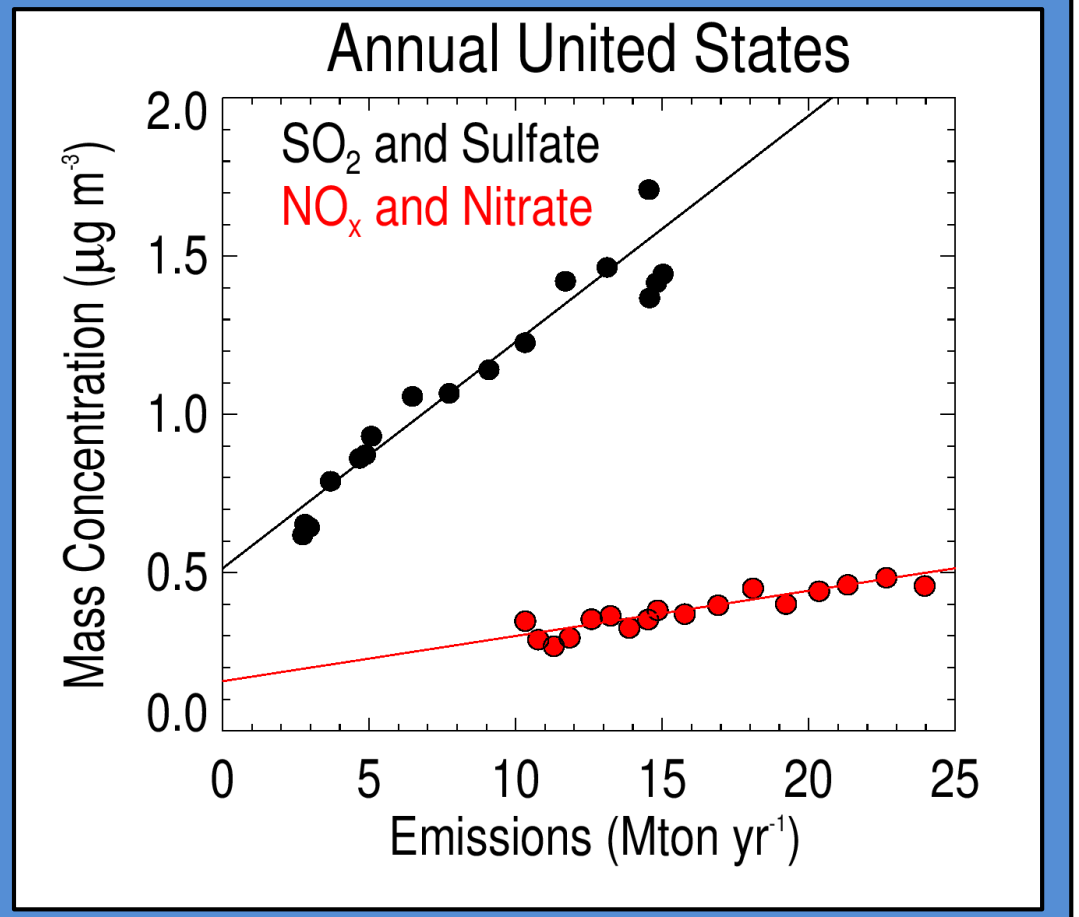


Dust b_{ext} fraction



How are these changes related to emission reductions?

Rural CONUS 2002-2018



Reflects only the emissions included in the EPA NEI annual total emissions

This study:

"Background" Sulfate:

0.51 ± 0.05 µg m^{-3}

Slope: 0.072 ± 0.005 µg m^{-3} per Mton yr^{-1}

r = 0.96

"Background" Nitrate:

0.16 ± 0.03 µg m^{-3}

Slope: 0.014 ± 0.002 µg m^{-3} per Mton yr^{-1}

r = 0.92

Previous work: "Background" Sulfate:

0.39 ± 0.12 µg m^{-3} CONUS (2002-2010, Hand et al., 2012)

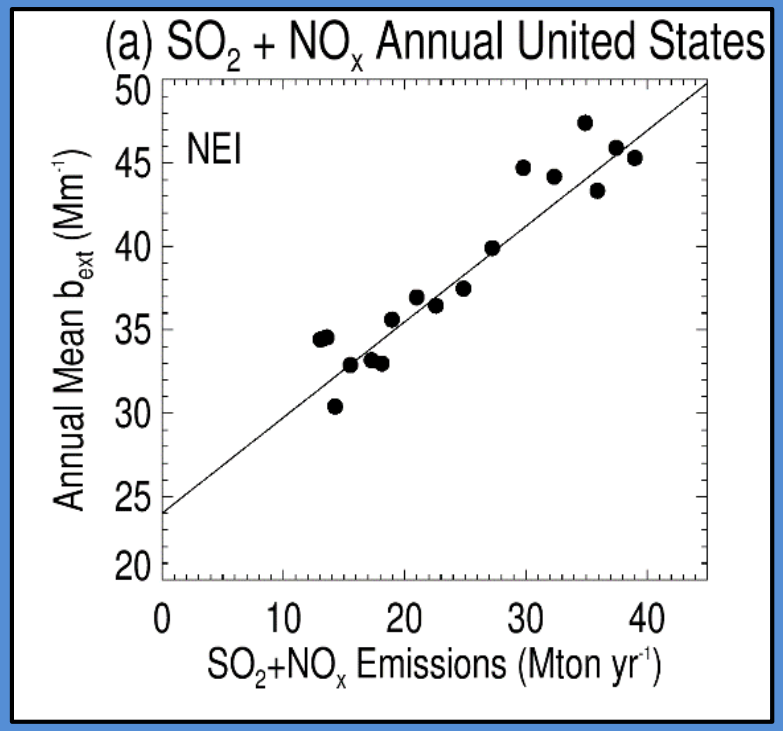
0.31 µg m^{-3} in East and 0.28 µg m^{-3} in the West (Park et al., 2004, modeling study)

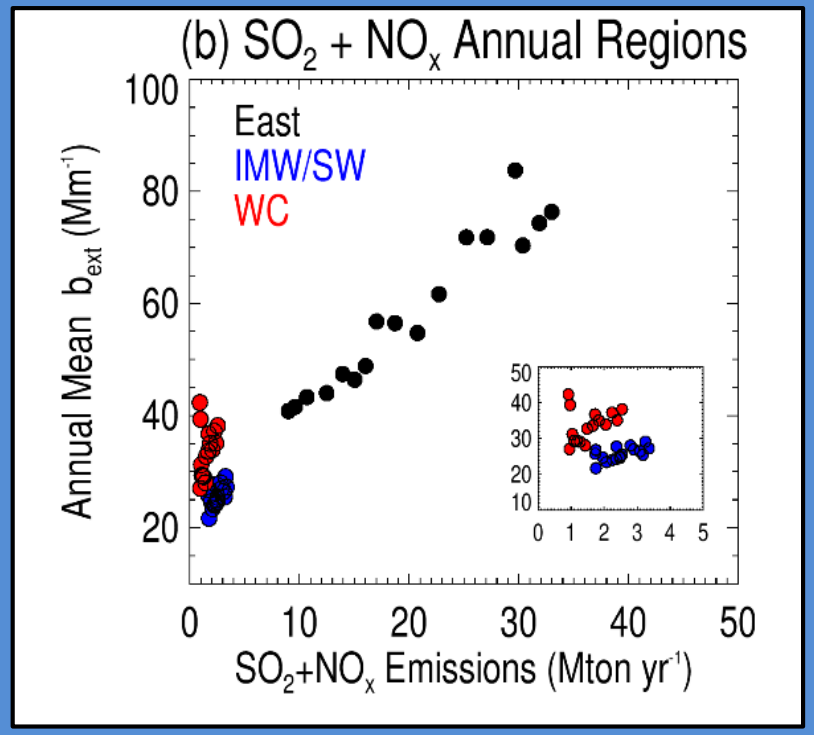
Trijonis Natural Conditions:

Sulfate: 0.17 µg m^{-3} (East) and 0.09 µg m^{-3} (West)

Nitrate: 0.08 µg m^{-3} (East and West)

2002-2018 Total SO_2 + NO_x emissions and annual mean b_{ext}





Region	Correlation (r)	Intercept (Mm^{-1}) ("Background" b_{ext})
CONUS	0.95	24.0 ± 1.3
East	0.96	27.3 ± 2.6
Intermountain West/Southwest	0.59	19.4 ± 1.9
West Coast	0.35	26.9 ± 3.2

Summary

- The Clean Air Act Amendments have been very effective at reducing emissions and particulate haze (by 47%) across the U.S.
- Reductions in haze are highest in the East, mostly due to reduced sulfate, although reductions in nitrate and organic carbon play a role.
- Carbonaceous aerosols are the dominant contributors to b_{ext} in the West (wildfire).
- The absolute and relative contributions of coarse mass to b_{ext} have increased.
- As emissions from regulated sources continue to decline, contributions from other sources to haze have increased, suggesting additional strategies may be needed to protect visibility in the future.

1990 San Gorgonio, CA 2017

Acknowledgments

National Park Service Air Resources Division

IMPROVE

WinHaze

(http://vista.cira.colostate.edu/Improve/winhaze/)

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2002 Cohutta, GA 2017