Analysis and updates to the IMPROVE Equation for estimating light extinction

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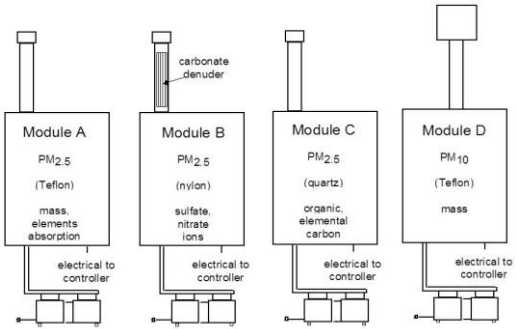
IMPROVE Steering Committee Fall 2025 Meeting

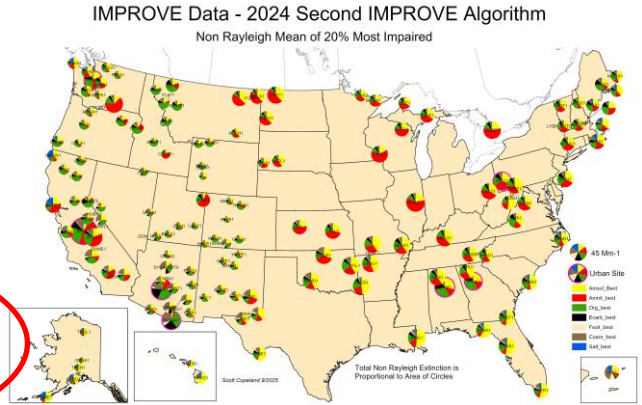
Visibility metrics for the RHR are calculated from mass composition measurements in the IMPROVE network



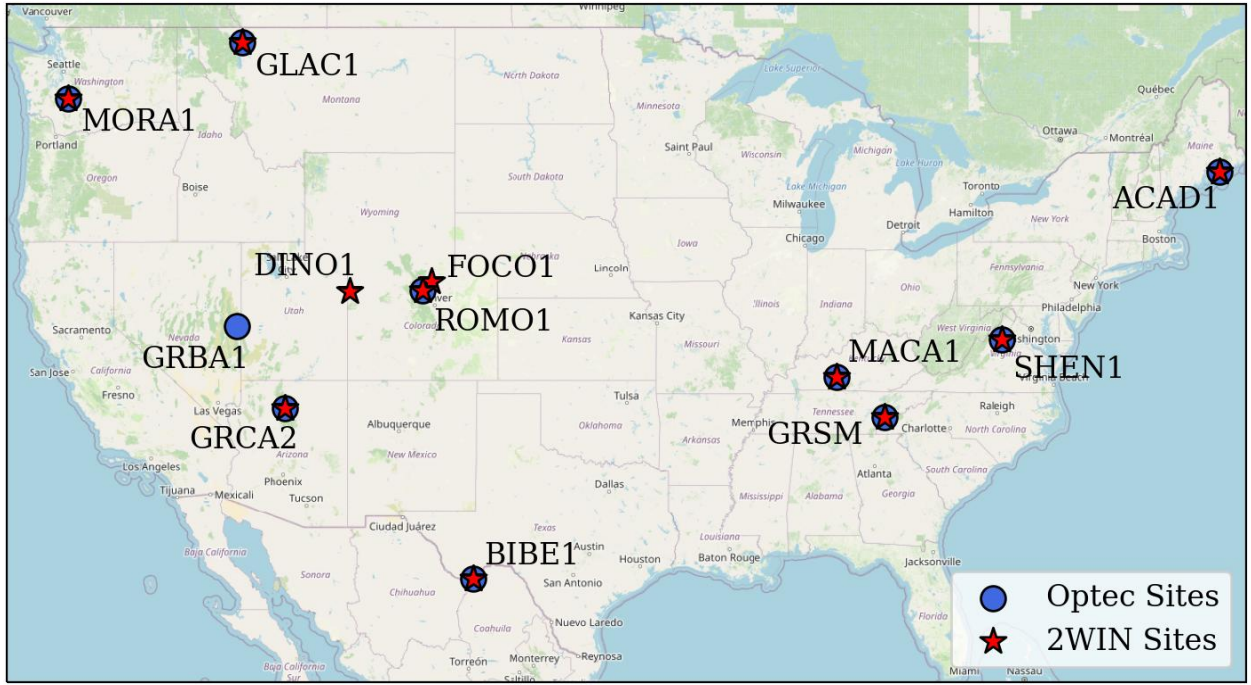
Converting measurements to mass concentrations

Converting mass concentrations to extinction values using IMPROVE equation

Impairment framework



The IMPROVE equations were developed and evaluated using co-located nephelometer measurements



Main Points

- The 2nd IMPROVE Equation worked well for the period for which it was developed.
- Performance has decreased over time compared to measurements.

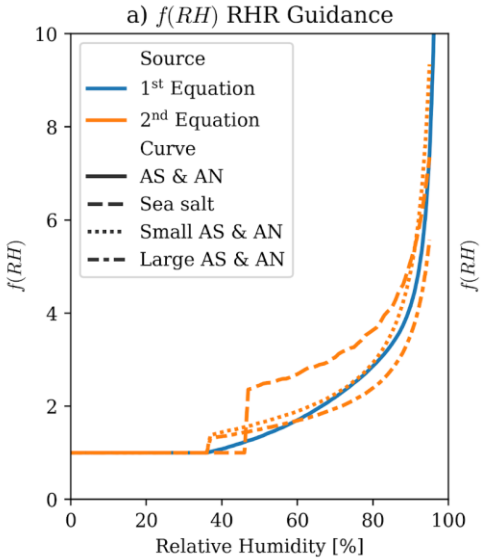
- We should return to the form of the 1st Equation with some updates.

1st IMPROVE Equation

$$b_{ext} \approx \mathbf{3} \times f(RH) \times [\textit{Ammonium Sulfate}] + \mathbf{3} \times f(RH) \times [\textit{Ammonium Nitrate}] + \mathbf{4} \times [\textit{Organic Mass}] + \mathbf{10} \times [\textit{Elemental Carbon}] + \mathbf{1} \times [\textit{Fine Soil}] + \mathbf{0.6} \times [\textit{Coarse Mass}] + \textit{Rayleigh scattering}$$

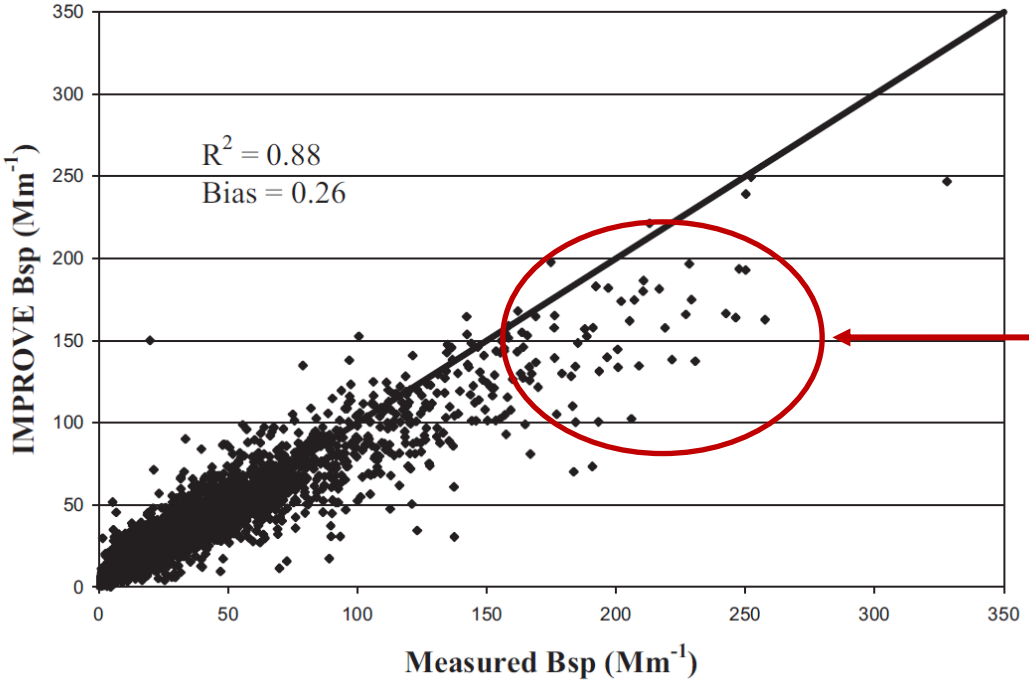
Assumptions:

- No sea salt
- Only AS and AN are hygroscopic (same curve)
- Mass scattering efficiencies (MSE) constant



(~ Malm et al., 1994)

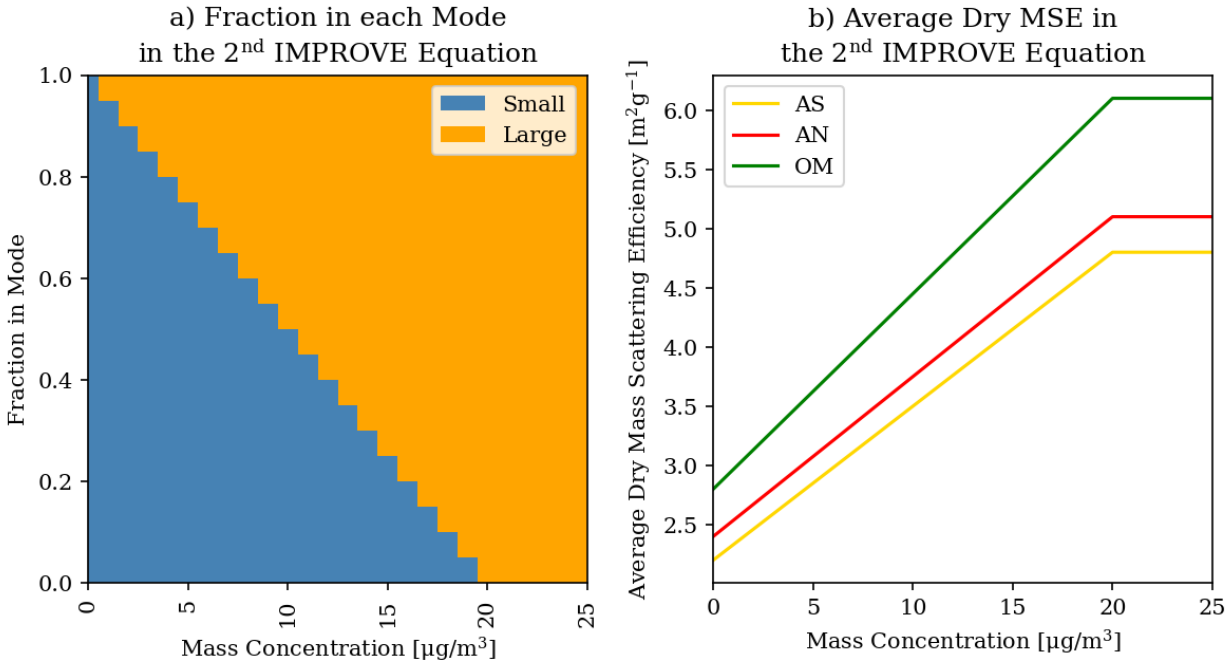
Comparison with nephelometer data suggested a revised algorithm was necessary



Haziest Days

(Pitchford et al., 2007)

2nd IMPROVE Equation ("split mode") uses 2 modes to scale MSE



2nd IMPROVE Equation

$b_{ext} \approx$ **2.2** × *f*S(*RH*) × [*Small Ammonium Sulfate*] + **4.8** × *f*L(*RH*) × [*Large Ammonium Sulfate*] +

2.4 × *f*S (*RH*) × [*Small Ammonium Nitrate*] + **5.1** × *f*L(*RH*) × [*Large Ammonium Nitrate*] +

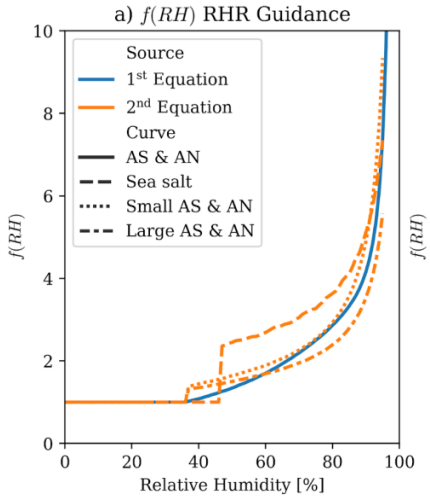
2.8 × [*Small Organic Mass*] + **6.1** × [*Large Organic Mass*] +

10 × [*Elemental Carbon*] + 1 × [*Fine Soil*] + 1.7 × *f*SS(*RH*) × [*Sea Salt*] +

0.6 × [*Coarse Mass*] + *Rayleigh Scattering* (*Site Specific*) + 0.33 × [*NO2 (ppb)*]

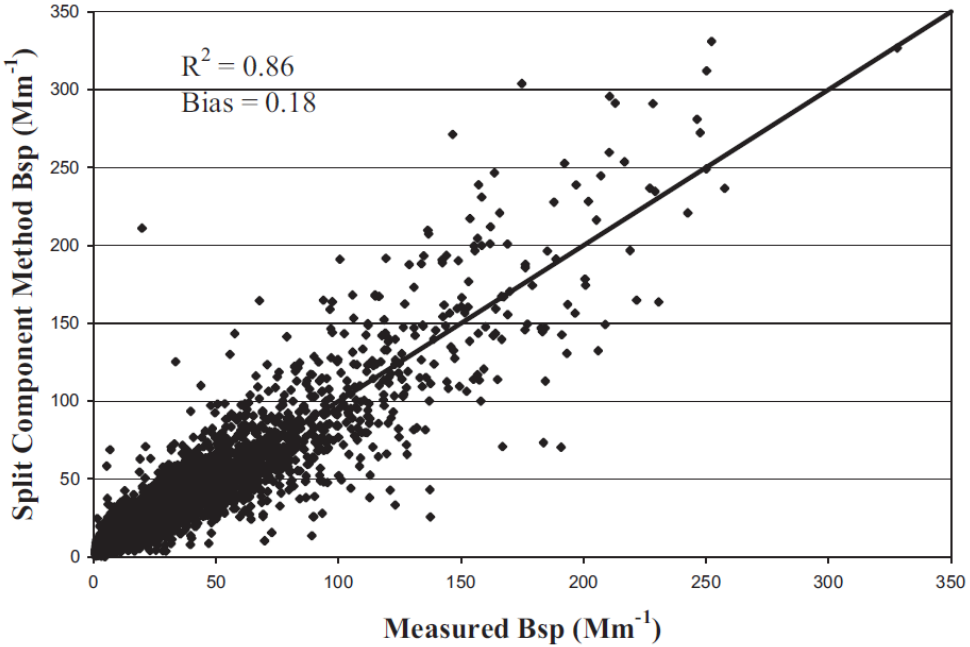
Assumptions:

- Large and small mode fractions
  - Mass of component < **20 µg/m^3**, large mode fraction is mass/20
  - Mass of component > **20 µg/m^3**, all mass of component is large mode
- Different water growth curves for small and large mode fractions
- OM is not hygroscopic
- Ratio of OM to OC (R_{oc}) is 1.8



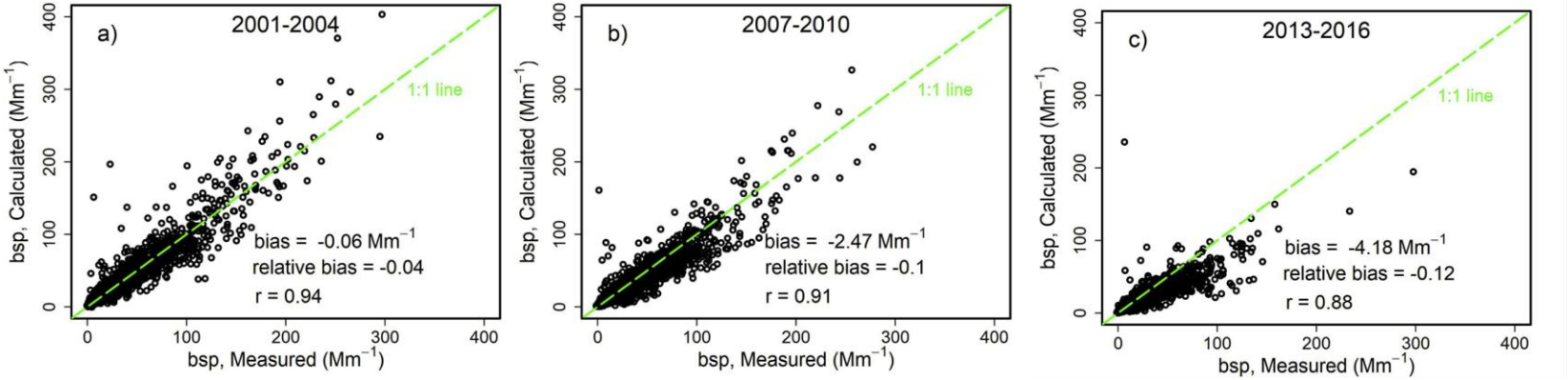
(Pitchford et al., 2007)

2nd IMPROVE Equation compared better to measurements in the early 2000s, specifically at highest and lowest values



(Pitchford et al., 2007)

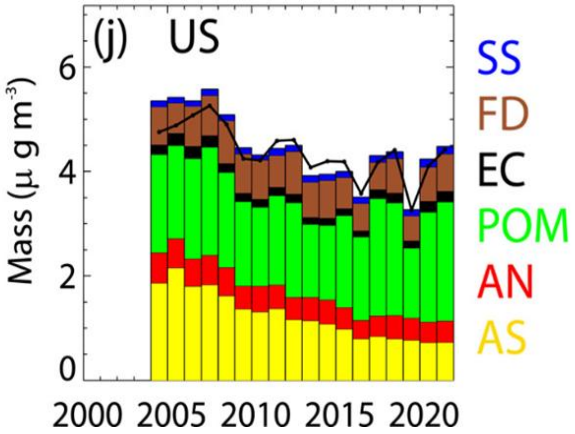
Agreement between measured and calculated scattering with 2nd IMPROVE Equation has deviated over time



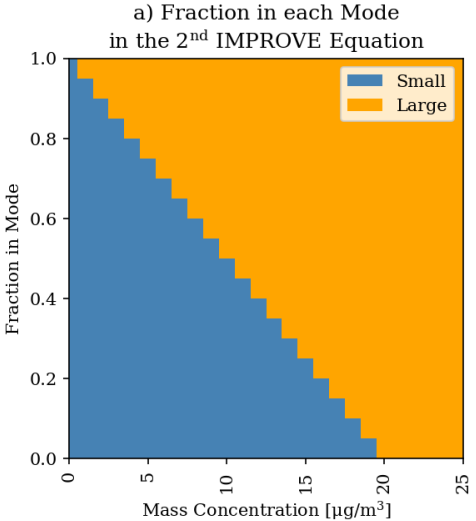
(*Prenni et al.*, 2019)

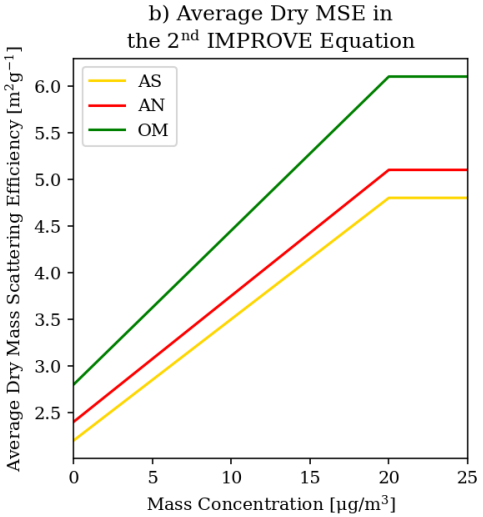
"bias" = mean (bias) error, "relative bias" = median normalized bias

With the 2nd IMPROVE Equation, too much mass is being apportioned to the small mode

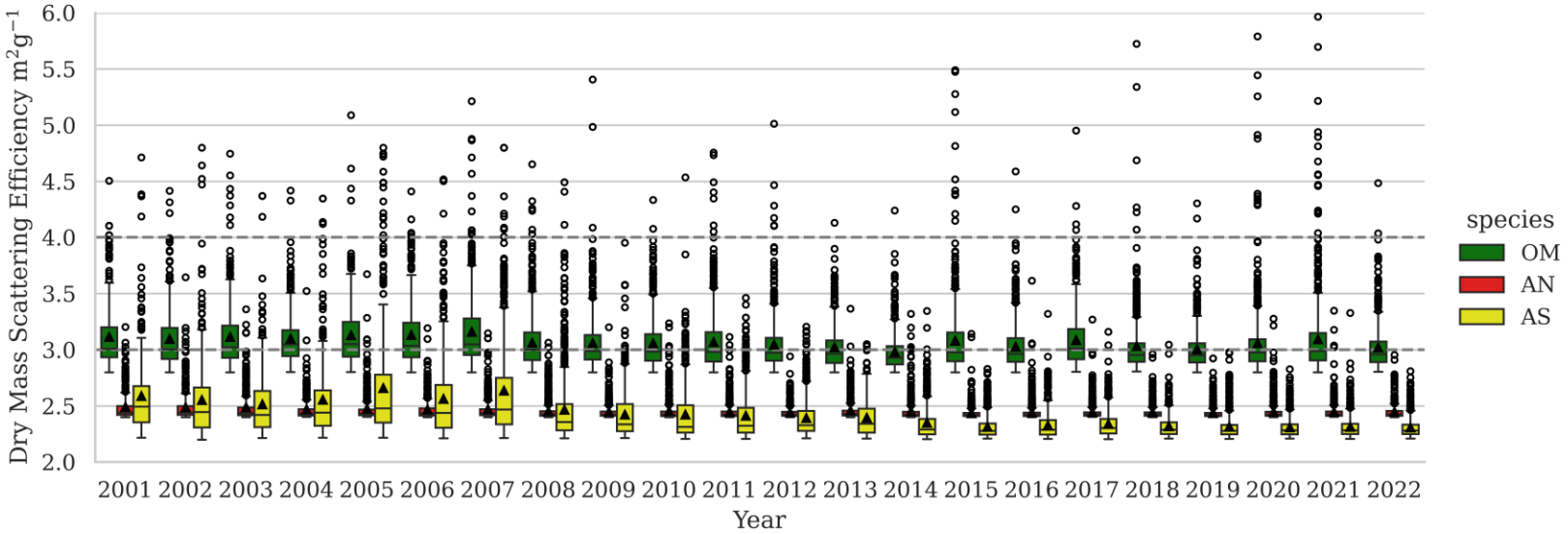


(*Hand et al.*, 2024)





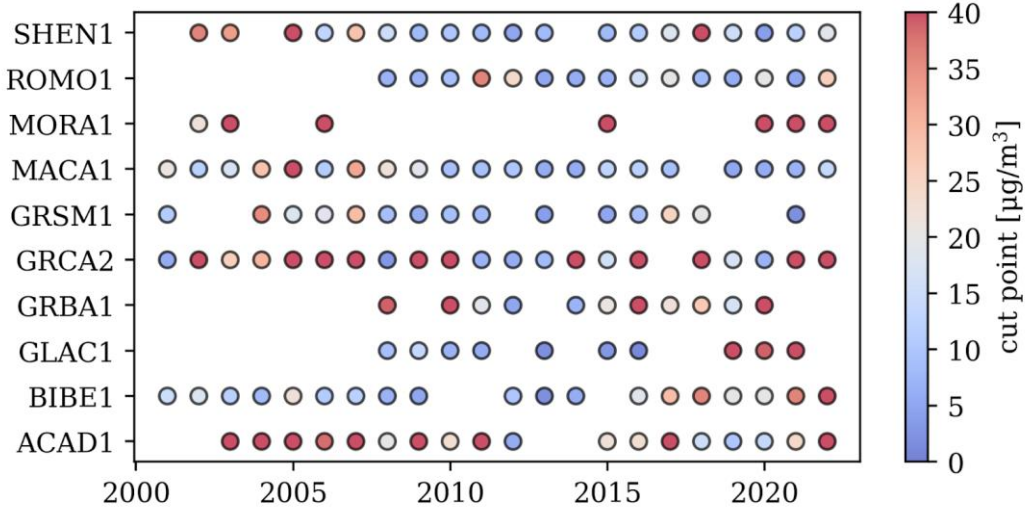
With the 2nd IMPROVE Equation, average dry MSEs used in the 2nd Equation are decreasing over time.



Prenni et al. (2019) showed that measurements do not support a size dependence on mass over time

Main questions to consider

- Can we “fix” the 2nd IMPROVE Equation?
  - Lower the “cut point”? i.e., Lowenthal and Kumar, 2016
  - Vary the “cut point”? i.e., Prenni et al., 2019

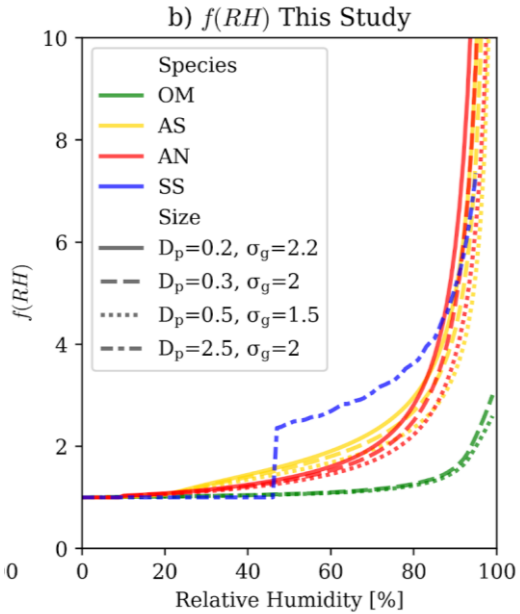


- Should we return to 1st IMPROVE Equation?

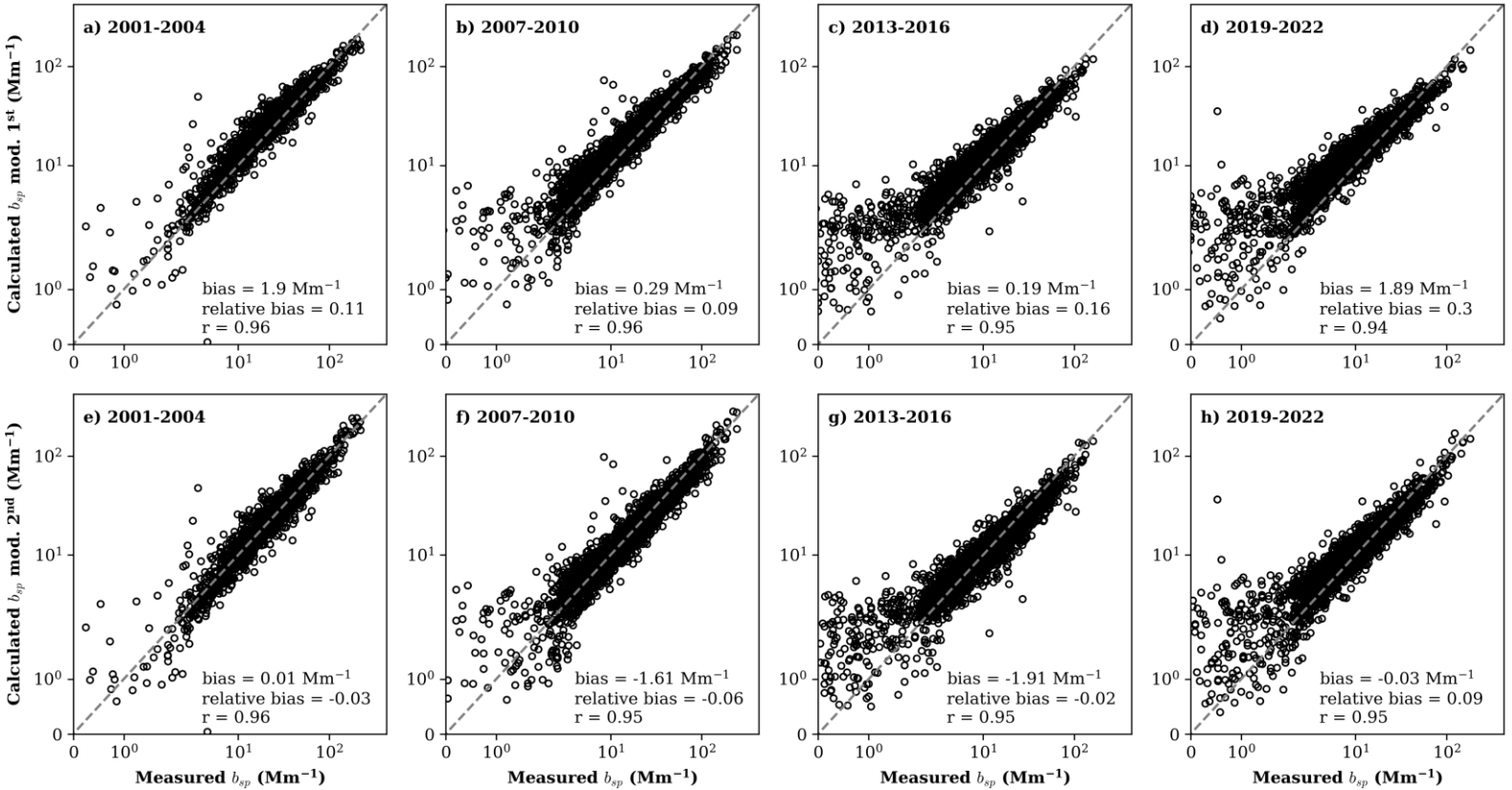
We use “modified” IMPROVE Equations for comparisons

- In Prenni et al. (2019): “Potential biases with the reconstructed mass algorithm first must be understood and corrected before any changes to the second IMPROVE equation are proposed.”

- Updated dust/soil equation (Hand et al., 2019)
- Monthly OM/OC ratios (Hand et al., 2019; 2024)
- OM slightly hygroscopic
- Updated *f(RH)* curves for AS and AN



2nd IMPROVE Equation is not consistently better than 1st Equation



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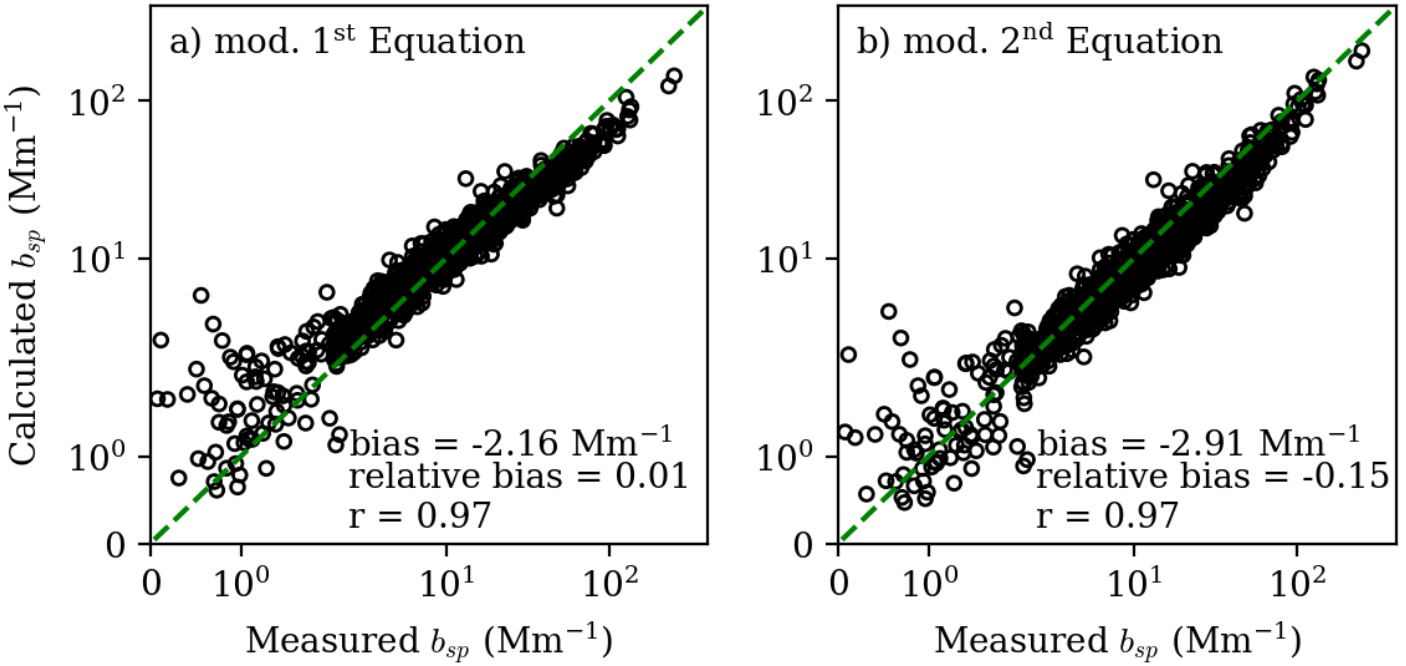
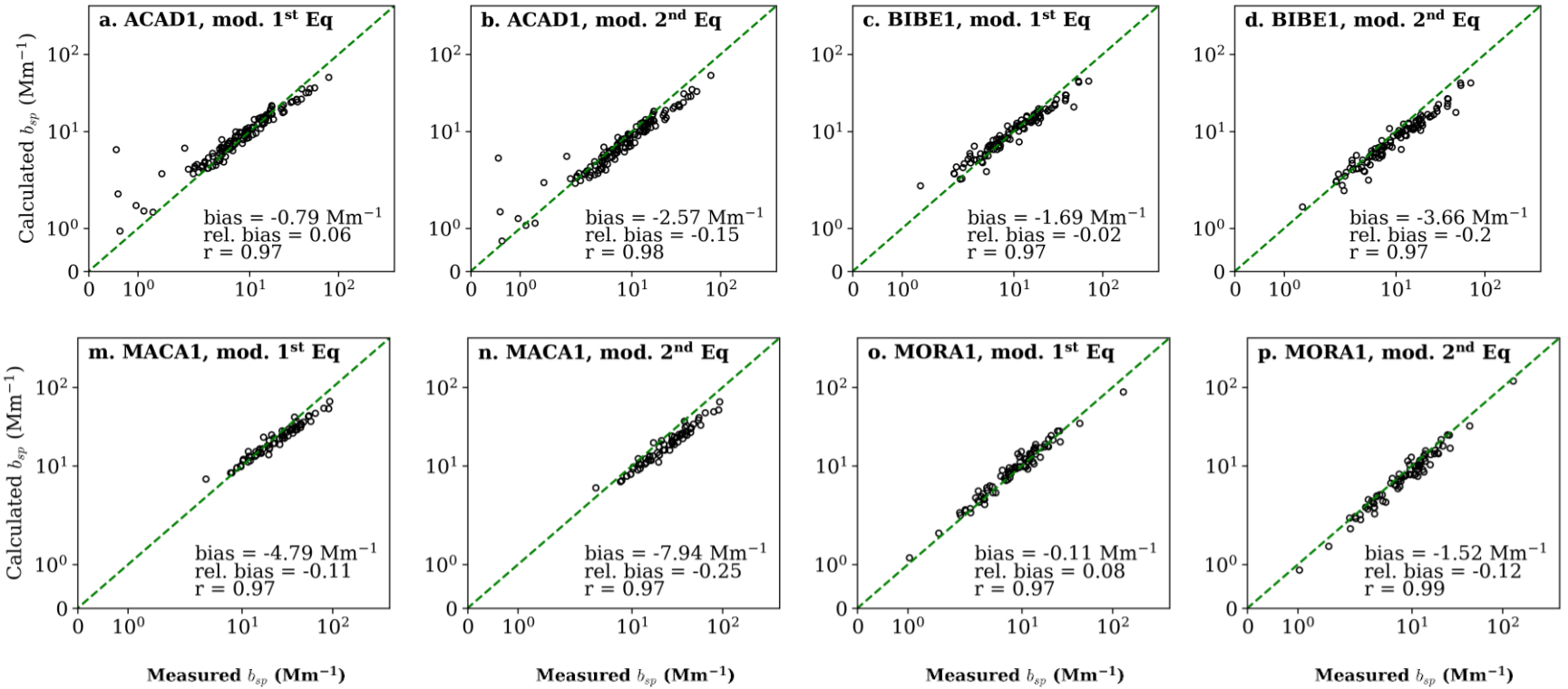
2-WIN data also suggests that 2nd Equation is not clearly better

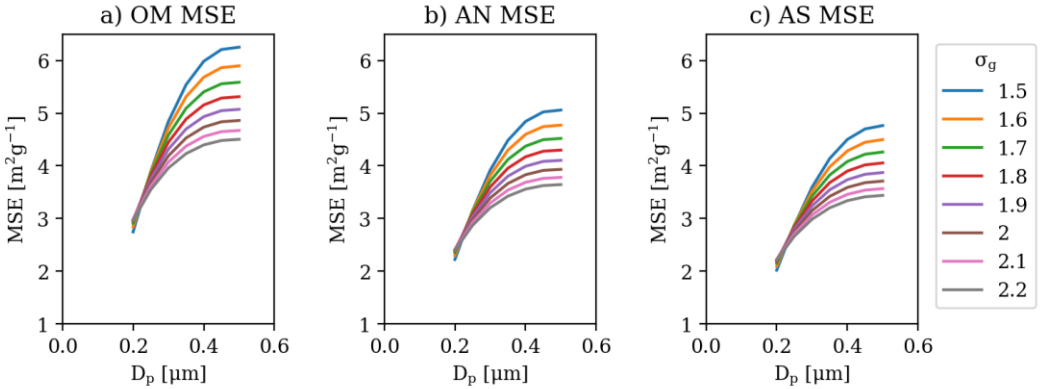


True for 2-WIN sites in the eastern and western US

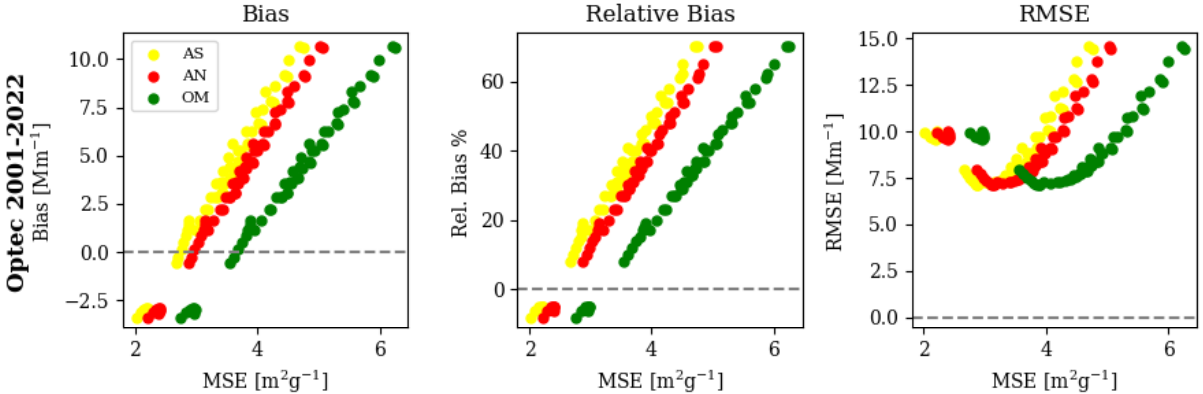


Are the MSE values in 1st IMPROVE Equation appropriate?

- Generated MSE and *f(RH)* curves for different size distributions



- Tested in comparisons with measurements



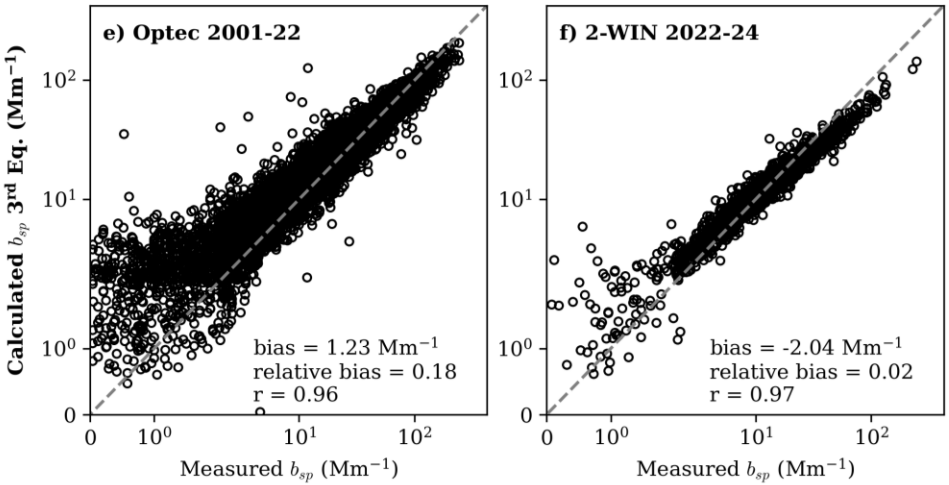
Selected D_p of 300 nm with σ_g of 2.2

Corresponds to MSE
AS 3 m^2g^{-1}
AN 3.2 m^2g^{-1}
OM 4 m^2g^{-1}

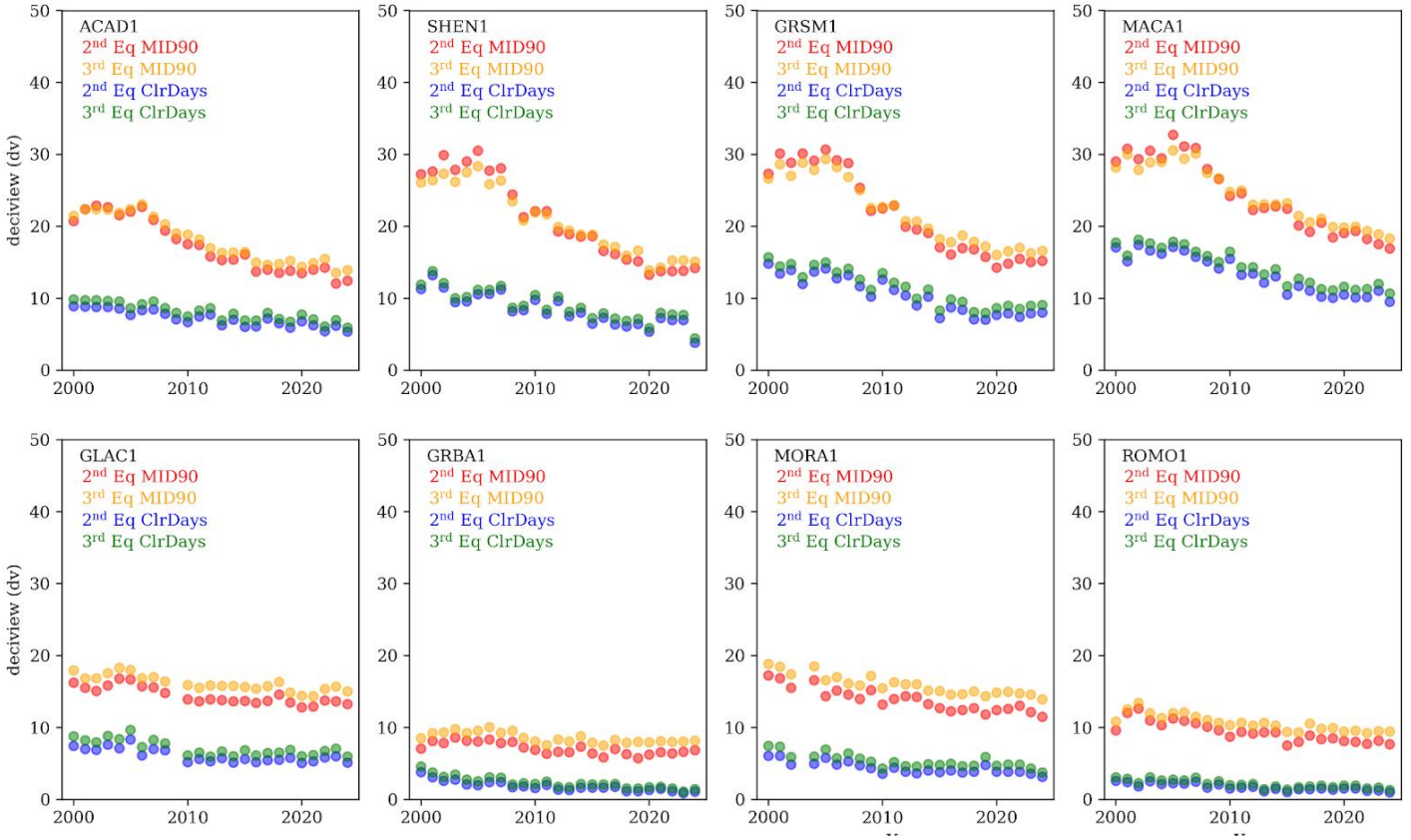
Recommendation

1. Return to the form of the 1st IMPROVE Equation (Assume a single size distribution that does not vary with concentration for AS, AN, and OM)
2. Use the updated equation for estimating soil/dust concentrations and a monthly-varying OM/OC
3. Uses species-specific *f(RH)* curves that correspond to the assumed size distribution of OM, AS, and AN
   - This will require new climatological *f(RH)* values for the RHR

$$b_{ext} = 3 \times f_{AS}(RH) \times [Ammonium\ Sulfate] + 3.2 \times f_{AN}(RH) \times [Ammonium\ Nitrate] + 4 \times f_{OM}(RH)[Organic\ Mass] + 10 \times [Elemental\ Carbon] + 1 \times [Fine\ Soil] + 0.6 \times [Coarse\ Mass] + 1.7 \times f_{SS}(RH) \times [Sea\ Salt] + Rayleigh\ scattering + 0.33 \times [NO_2\ (ppb)]$$



Using the 3rd Equation minimally affects the RHR metrics



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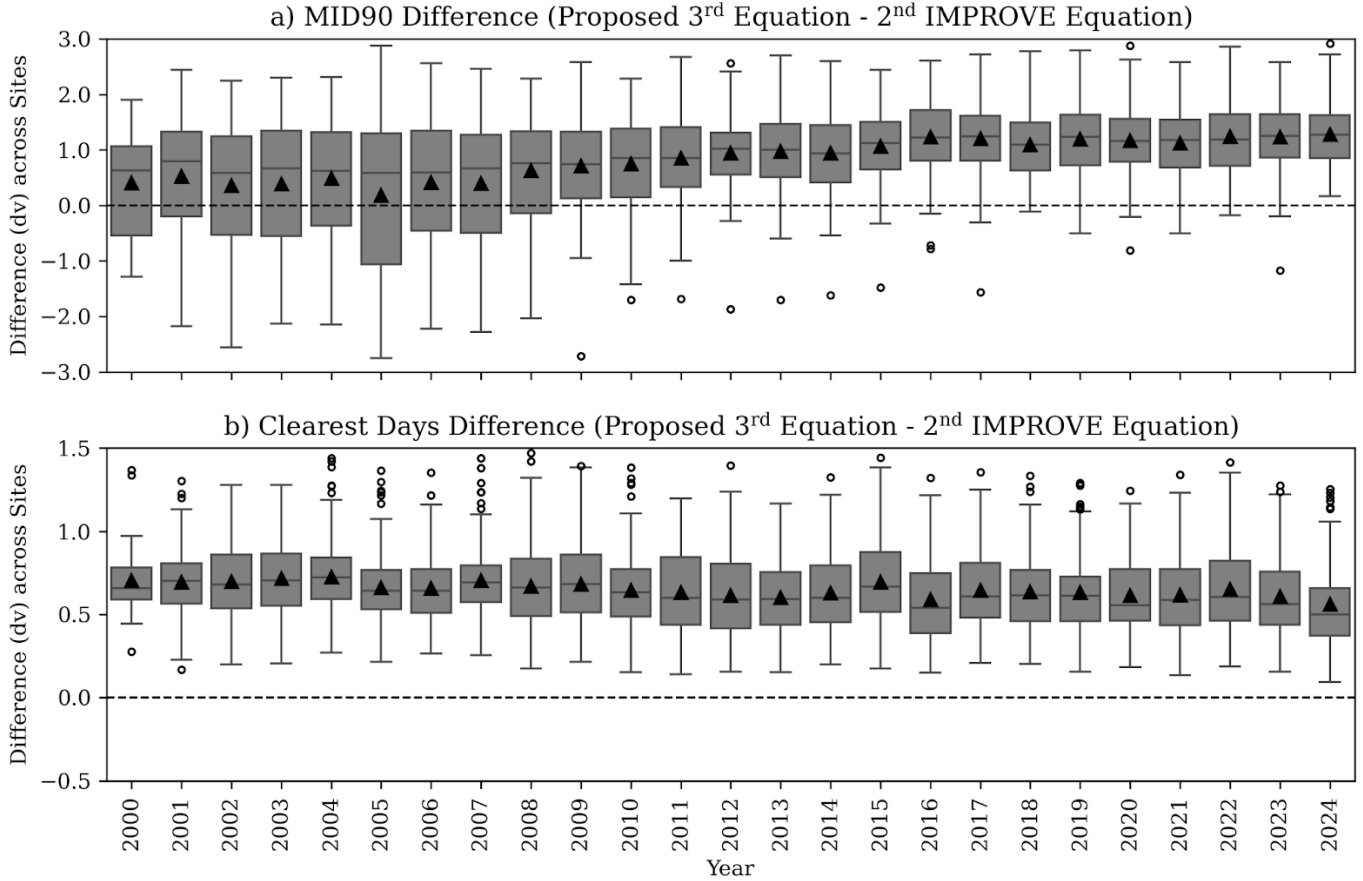

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