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# Observational estimates of the aerosol direct radiative effect: improving CALIPSO-based estimates and the role of lidar observations

# Introduction

- Aerosols continue to be responsible for the largest uncertainty in determining the anthropogenic radiative forcing of the climate
- Aerosols influence anthropogenic forcing **indirectly** via modifications to cloud properties as well as **directly** through the scattering and absorption of solar radiation— the aerosol direct radiative forcing (DRF, aka $\mathrm{RF}_{\mathrm{ari}}$)

- IPCC AR5: aerosol DRF ($\mathrm{RF}_{\mathrm{ari}}$) $= -0.35 \pm 0.5\ Wm^{-2}$ (95% confidence)
  - There is evidence that the IPCC assessment underestimates the true uncertainty... (Loeb and Su, 2010; Samset et al., 2014)

# Uncertainty in observational estimates of the aerosol DRF (Thorsen et al. 2021)

Consider a hypothetical global observing system with AERONET-like accuracy (similar exercise as Loeb and Su, 2010)

- Global constraints only possible with satellite remote sensing + AERONET uncertainty $<<$ satellite uncertainty = **Lower-bound on the current observational uncertainty**
  - DRF uncertainty $= 0.31\ Wm^{-2}$ $(1\sigma)$
  - Dominated by the contribution from the single scattering albedo (SSA) uncertainty

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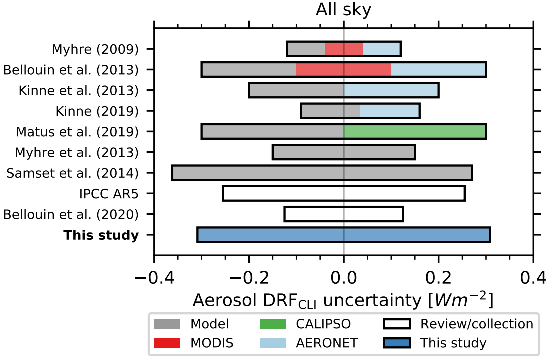
How does this lower-bound compare to other uncertainty estimates?

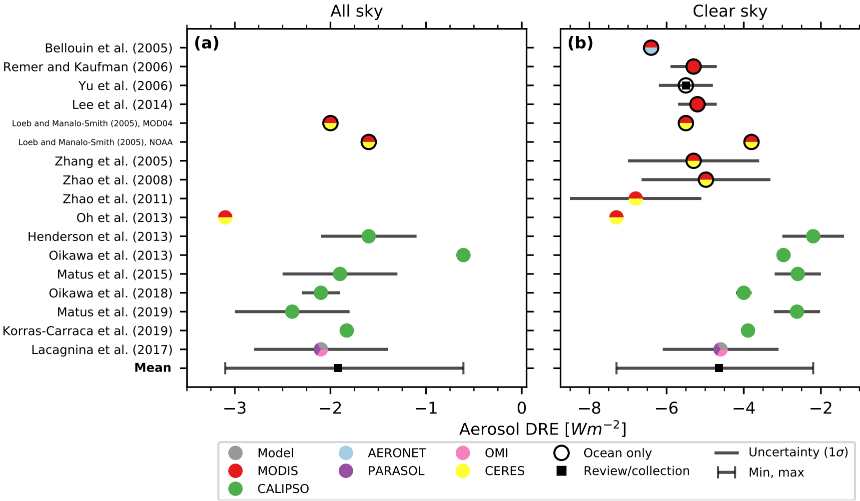
- Past estimates of the aerosol DRF uncertainty are smaller (on average) than our optimistic observational estimate, including the uncertainty given in the IPCC AR5
- Past studies have underestimated the uncertainty → the aerosol DRF has been constrained to a point beyond that possible with current observational accuracies



# Satellite observations

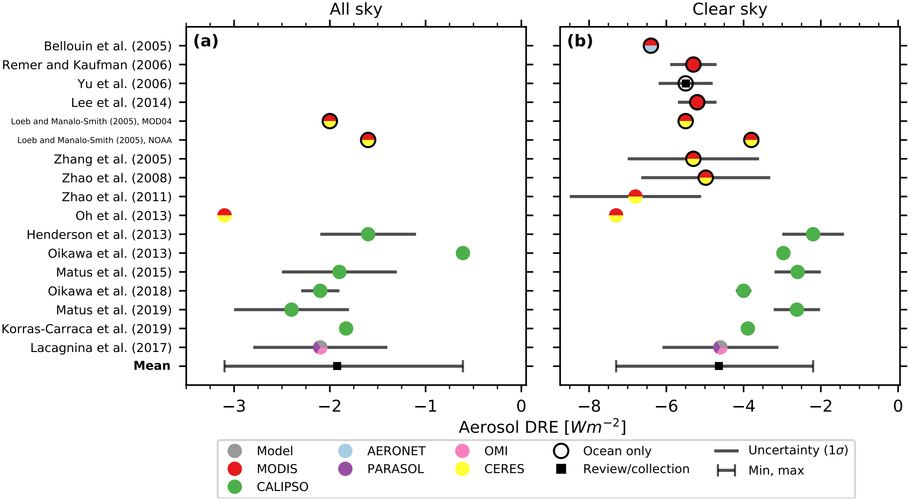
- Aerosol DRF: can only observe proxies (e.g. fine mode fraction) for anthropogenic aerosols, those proxies are uncertain (Kaufman et al., 2005; Anderson, 2005; Bellouin et al., 2005; Christopher et al., 2006; Yu et al., 2006, 2009)
- The aerosol direct radiative effect (DRE)— the radiative effect of all aerosols both natural and anthropogenic— is more readily quantifiable

# Review of aerosol DRE estimates



- Summary in the bottom row: **Mean** of past studies (square) and the min/max values (error bars)
- These DRE estimates produce a wide range of values:
  -3.1 to -0.61 $Wm^{-2}$ in the all-sky; -7.3 to -2.2 $Wm^{-2}$ in the clear-sky
- Estimates often don't agree within their stated uncertainties

# Review of aerosol DRE estimates



- Many of these estimates are clear-sky (right panel) ocean-only (black circles) using MODIS (red); remainder use CERES or CALIPSO
- CALIPSO enables all-sky global estimates, passive estimates often limited to clear-sky ocean
- Clear-sky MODIS/CALIPSO offset:

  ❶ MODIS cloud contamination: possible bias of 0.5 to 1.0 $Wm^{-2}$ (Yu et al., 2006; Remer and Kaufman, 2006)
  ❷ CALIPSO sensitivity...

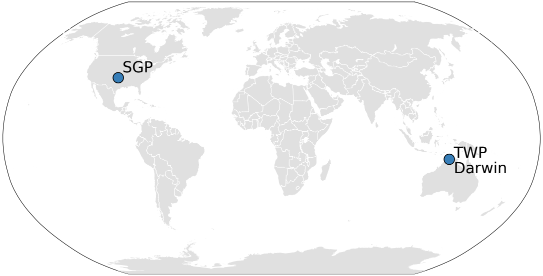
# Impact of CALIPSO detection sensitivity

(Thorsen and Fu 2015, Thorsen et al. 2017)

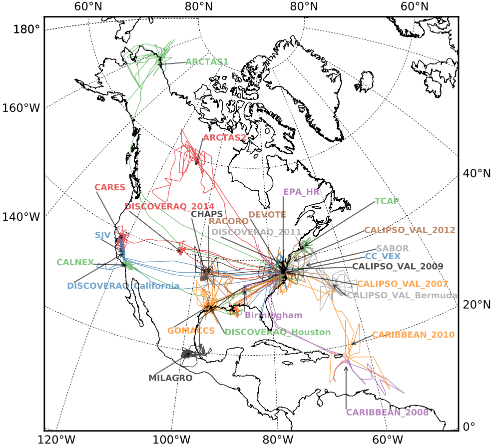
Tested the ability of CALIPSO to detect all radiatively significant aerosol using the ARM Raman lidars and the NASA Langley Airborne HSRL as a reference

## ❶ ARM Raman lidars

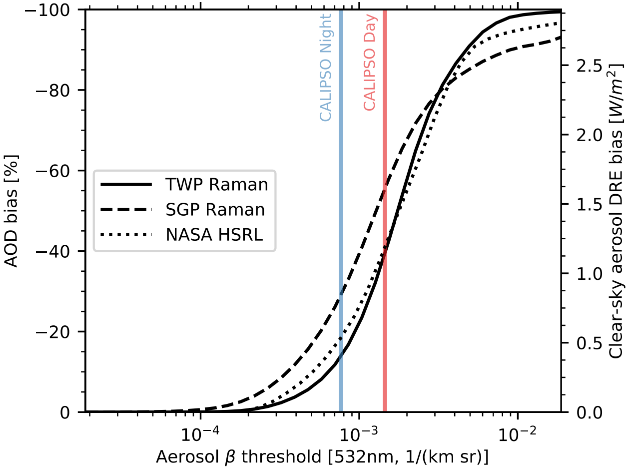
(Thorsen et al.; Thorsen and Fu JTECH 2015)



## ❷ NASA HSRL campaigns (Hair et al. AO 2008)

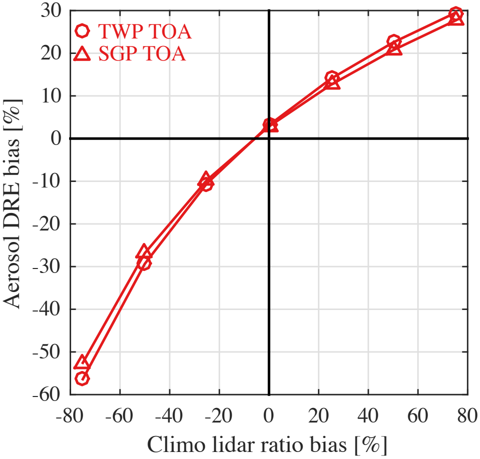


# Detection sensitivity and AOD/DRE bias



- Impose backscatter thresholds on the Raman/HSRL data → compute AOD/DRE bias
- Estimates of global mean nighttime and daytime CALIPSO detection thresholds (from extrapolating the Raman comparisons globally)
  - CALIPSO's daytime threshold implies a missing $\sim 1.5 Wm^{-2}$ of aerosol

# Lidar ratio



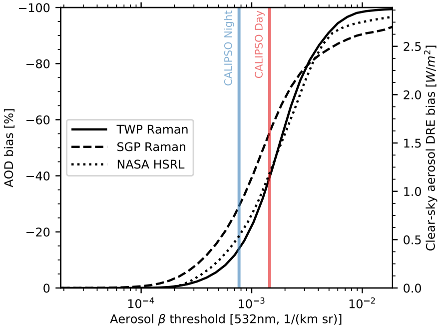
- Did not directly assess potential lidar ratio biases (these Raman lidars are 355nm)
- Instead, we test how well one needs to resolve the variability of the lidar ratio: i.e the impact of a bias in the climatological mean lidar ratio
- Rogers et al. (2014): about +20% bias in CALIPSO's lidar ratio → +10% bias in the DRE

# Reducing uncertainty

Some things are "beyond CALIPSO":

1. Need better detection sensitivity (higher daytime SNR)
2. Higher accuracy absorption (SSA) measurements (likely from combined lidar+polarimeter)

- Recommended ACCP architecture: the HSRL has a *daytime* SNR considerably higher than CALIOP *nighttime* SNR. The backscatter lidar has better daytime SNR than CALIOP.



But there are pathways to unlocking CALIOP's full potential:

1. More advanced detections algorithms, de-noising techniques
2. Column optical depth retrievals (SODA, ocean surface). Constraints for "clear-air" aerosol extinction profile retrievals?

- Will there be enough SNR to do extinction retrievals?

# Reducing uncertainty

- Using aerosol optical properties directly with AERONET-like accuracy (Thorsen et al 2021):
  - Aerosol DRF uncertainty $= 0.31 \ Wm^{-2}$
  - Aerosol DRE uncertainty $= 1.1 \ Wm^{-2}$
- Possible 40% reduction in uncertainty by leveraging both ❶ aerosol typing and ❷ vertically resolved optical properties

❶ An identification of aerosol type + a pre-determined optical model to avoid using directly-retrieved SSA in situations when it is difficult to retrieve (e.g. when there is little absorption)

❷ Vertically-resolved aerosol optical properties (after absorption, this is the next leading source of uncertainty): retrieve optical properties in 2 layers instead of a column-average

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