CALIPSO-inferred aerosol direct radiative effects: bias estimates using ground-based Raman lidars

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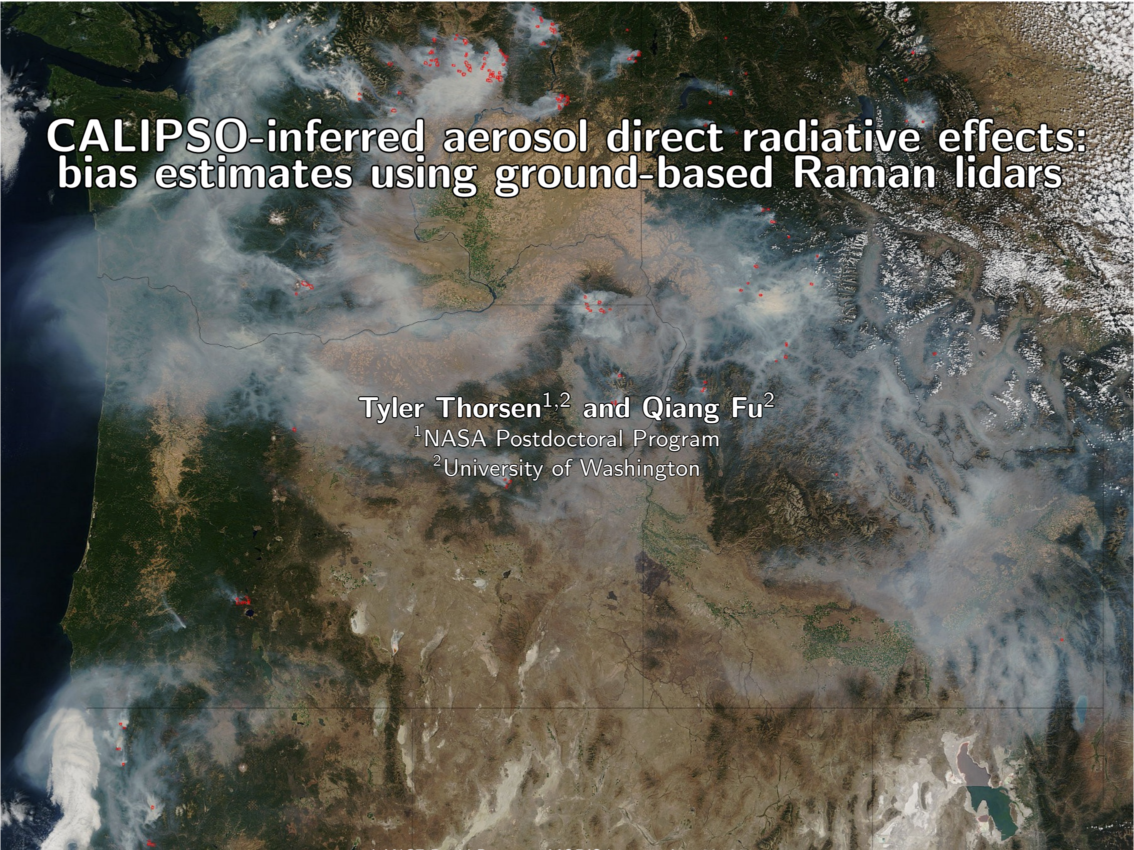

Aerosol direct radiative effect (DRE)

- The change in radiative flux caused by the presence of aerosols (both natural and anthropogenic)
  - How aerosol affects the Earth's radiation balance in the present climate
  - Estimation of aerosol radiative forcing (i.e. anthropogenic aerosols)

  (Bellouin et al. Nature 2005, Kaufman GRL 2005, Su et al. JGR 2013)

Satellite estimates of aerosol DRE

- Many estimates of the shortwave (SW) aerosol DRE have been made using passive remote sensors (Yu et al. ACP 2006 and references therein)
    - Longwave aerosol DRE is usually much smaller
    - Mostly MODIS-based

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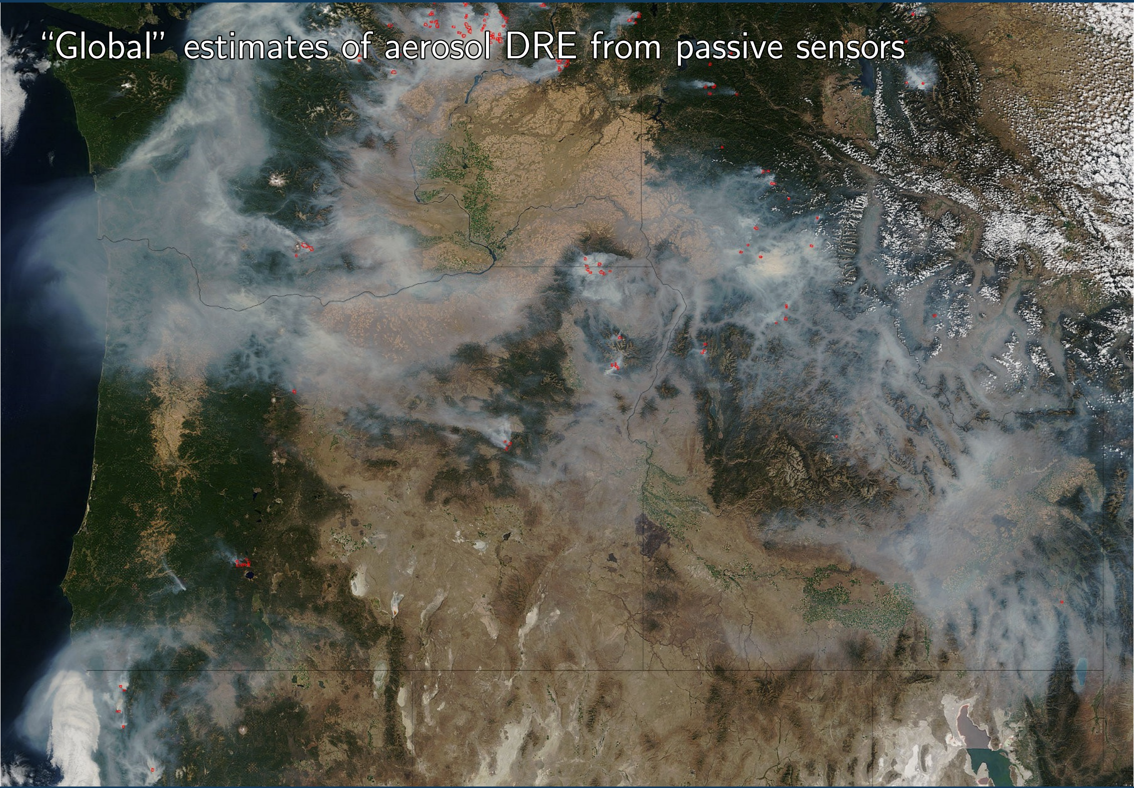
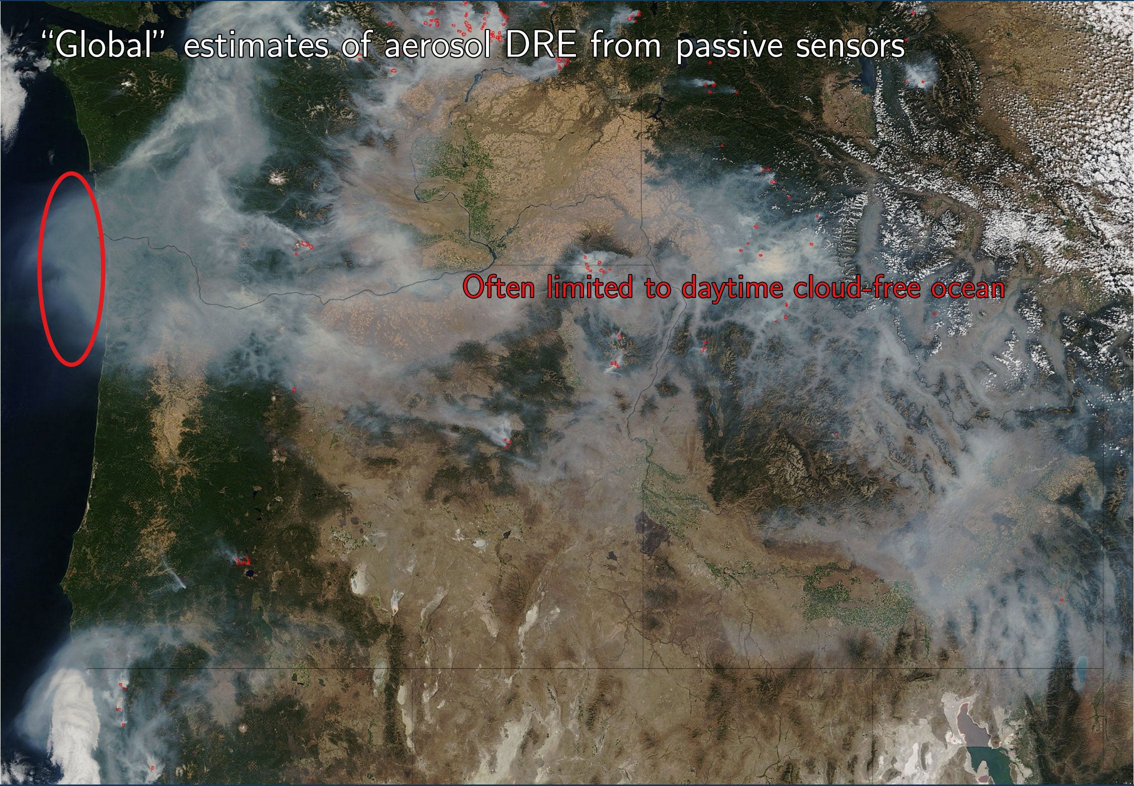
- The global-mean SW aerosol DRE at the TOA is about $-5.0\ Wm^{-2}$
  - The presence of aerosols increases the amount of reflected SW by $5.0\ Wm^{-2}$

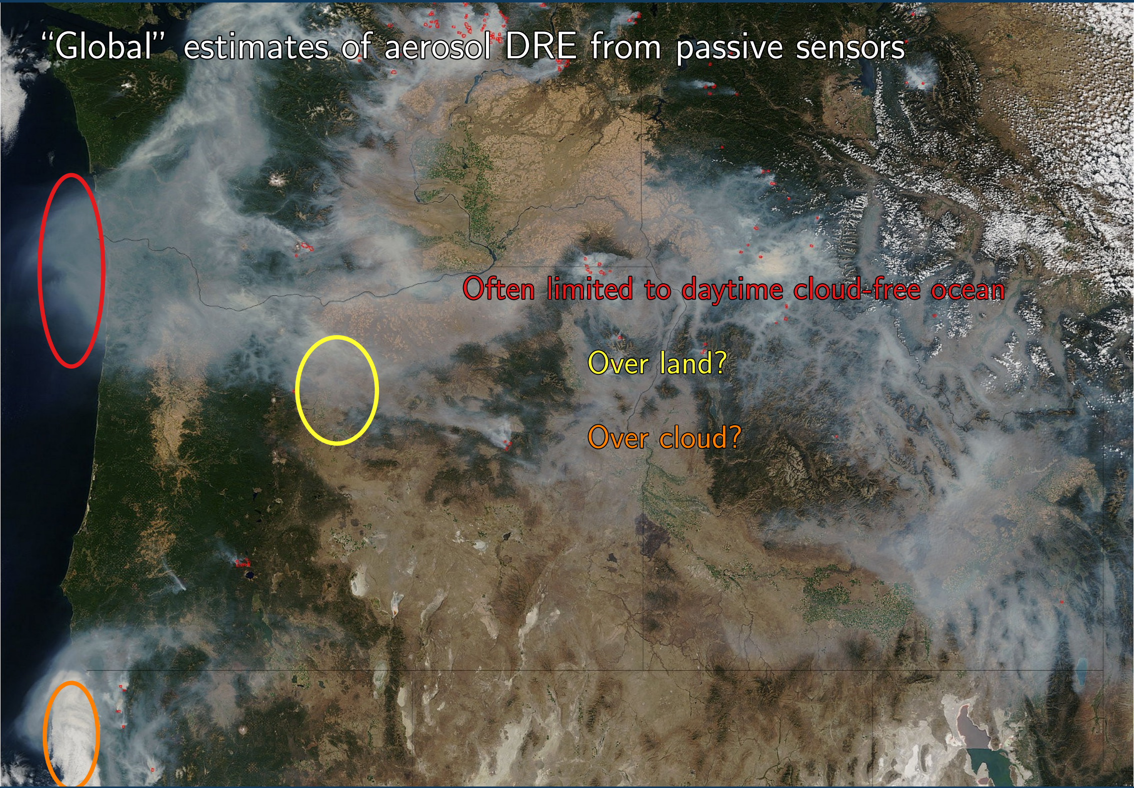
"Global" estimates of aerosol DRE from passive sensors



"Global" estimates of aerosol DRE from passive sensors



"Global" estimates of aerosol DRE from passive sensors



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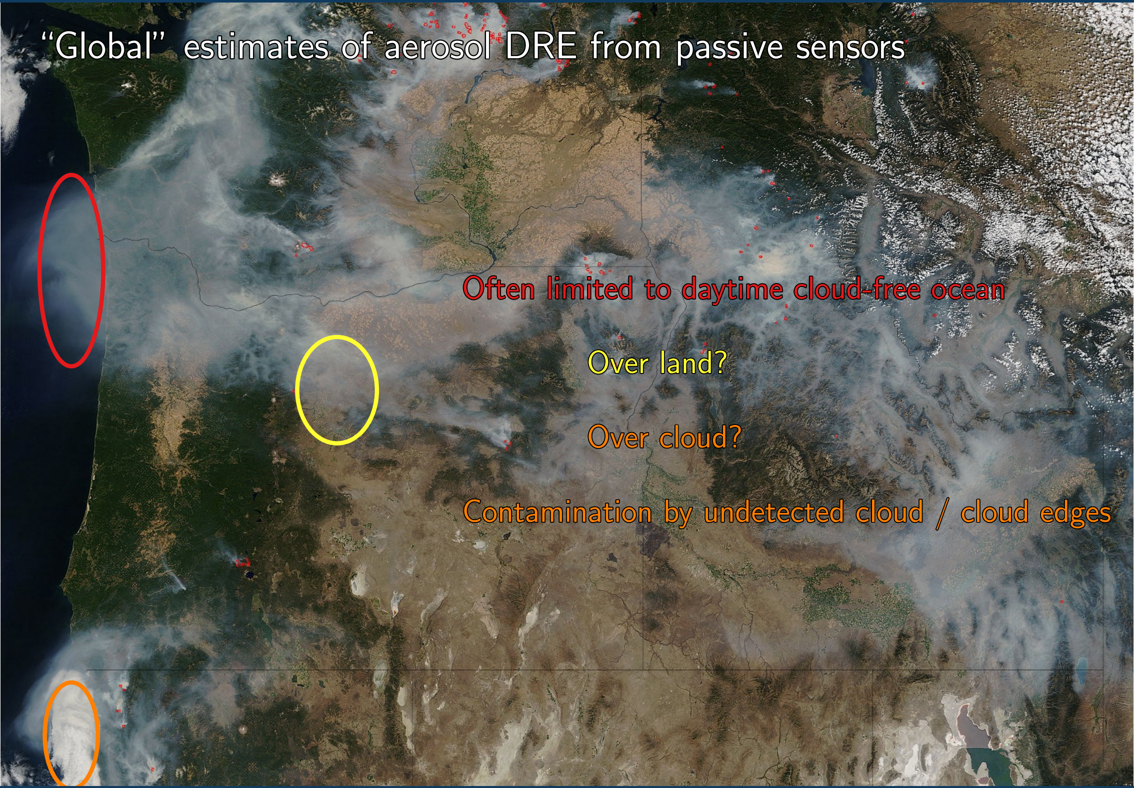
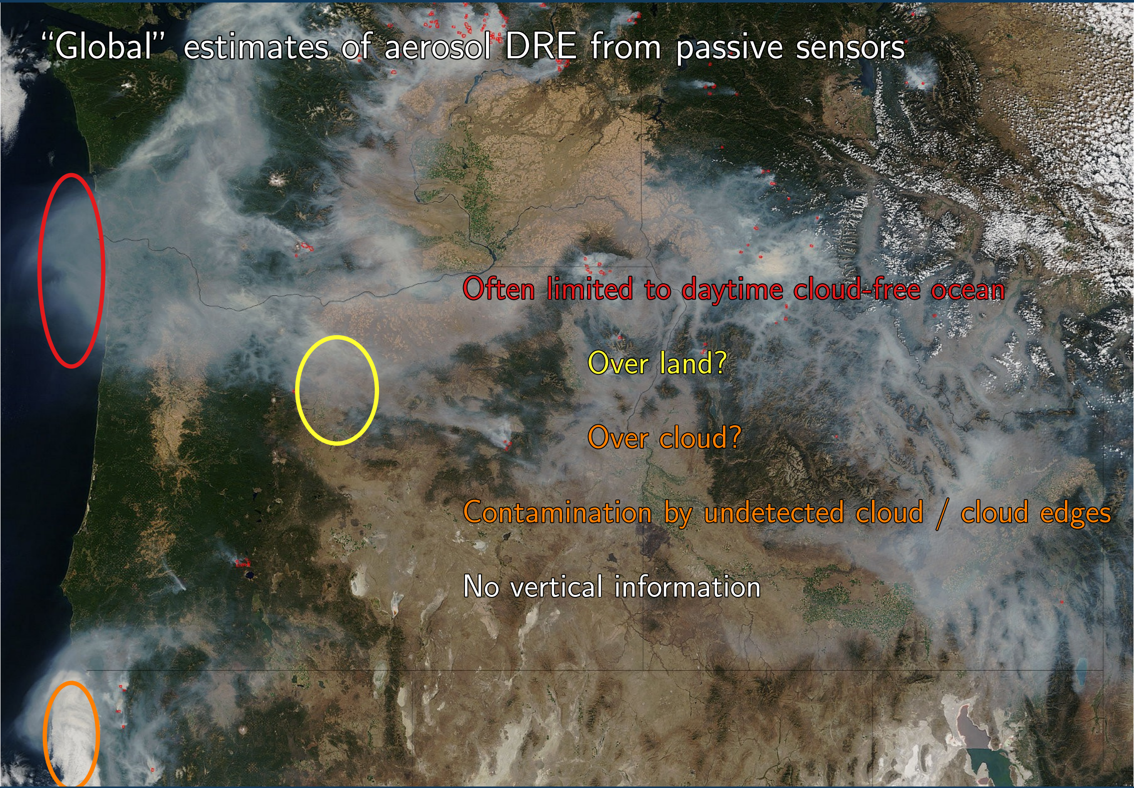


"Global" estimates of aerosol DRE from passive sensors



Often limited to daytime cloud-free ocean

Over land?

Over cloud?

Contamination by undetected cloud / cloud edges

No vertical information

CALIPSO

- Vertically-resolved aerosol properties over all surface types during both day and night
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- Recent studies have made new estimates of the global-mean aerosol DRE using CALIPSO:

	Clear-sky ocean	All-sky global
Passive sensor-based (Yu et al. *ACP* 2006)	$-5.0\ Wm^{-2}$	N/A
CALIPSO-based (Oikawa et al. *JGR* 2013)	$-3.21\ Wm^{-2}$	$-0.61\ Wm^{-2}$
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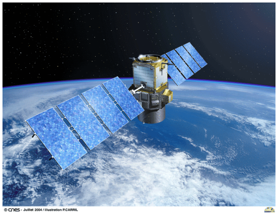
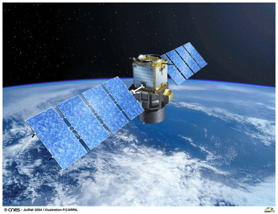
Why are CALIPSO-based estimates significantly smaller in magnitude than the passive sensor-based ones?

CALIPSO



ARM Raman lidars (RL)

CALIPSO



1. Radiative flux → aerosol extinction → assumed lidar ratio (ratio of extinction-to-backscatter)

ARM Raman lidars (RL)

1. Direct extinction measurements

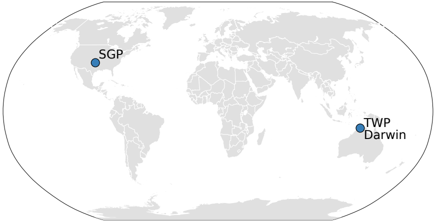
   (no critical assumptions)

CALIPSO

❶ Radiative flux → aerosol extinction → assumed lidar ratio (ratio of extinction-to-backscatter)

❷ Is all radiatively-significant aerosol detected? (Kacenelenbogen et al. 2014, Rogers et al. 2014, Thorsen et al. 2015)

ARM Raman lidars (RL)



❶ Direct extinction measurements (no critical assumptions)

❷ Strong signals from aerosols (it's closer)

Methodology

- Collocate ($\pm$200 km, $\pm$2 hr) CALIPSO aerosol products (VFM, ALay) and ARM RL-FEX product over a 5 year period at SGP, 4 year period at TWP
- Calculate aerosol DRE using the NASA Langley Fu-Liou radiative transfer model:

$$DRE(TOA) = [F^{\downarrow}(TOA) - F^{\uparrow}(TOA)]_{\text{aerosol}} - [F^{\downarrow}(TOA) - F^{\uparrow}(TOA)]_{\text{no aerosol}}$$

$$DRE(SFC) = [F^{\downarrow}(SFC) - F^{\uparrow}(SFC)]_{\text{aerosol}} - [F^{\downarrow}(SFC) - F^{\uparrow}(SFC)]_{\text{no aerosol}}$$

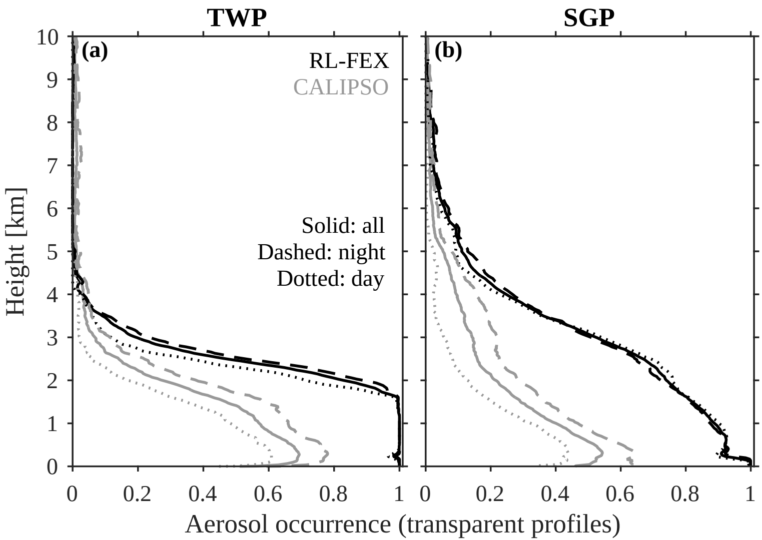
- *Modify RL retrievals to mimic CALIPSO to test the effect of
  ❶ lidar ratio assumptions and
  ❷ detection sensitivity

*Avoiding using the CALIPSO data directly because of wavelength difference between the lidars

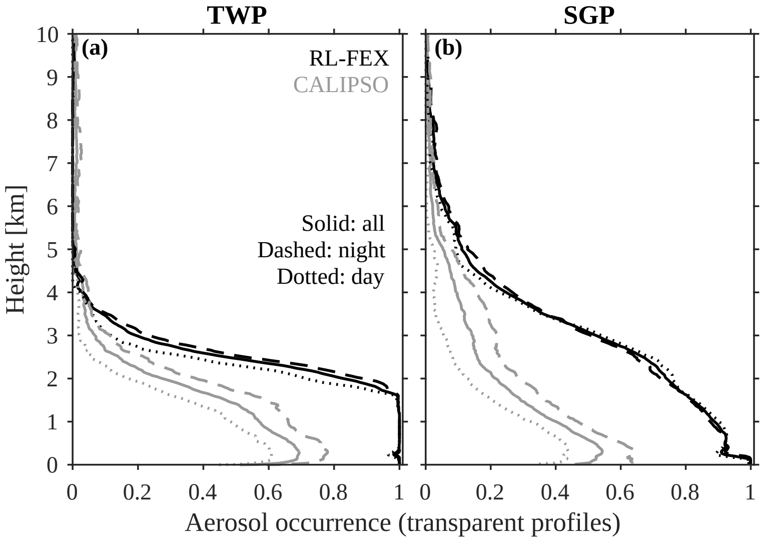
❶ About +10% bias in the aerosol DRE due to the lidar ratio

Detection sensitivity

Detection sensitivity



Detection sensitivity



Is this undetected aerosol radiatively-significant?

Effect of detection sensitivity

- Method to force RL aerosol occurrence profile to match CALIPSO's by removing aerosol in each collocated overpass.

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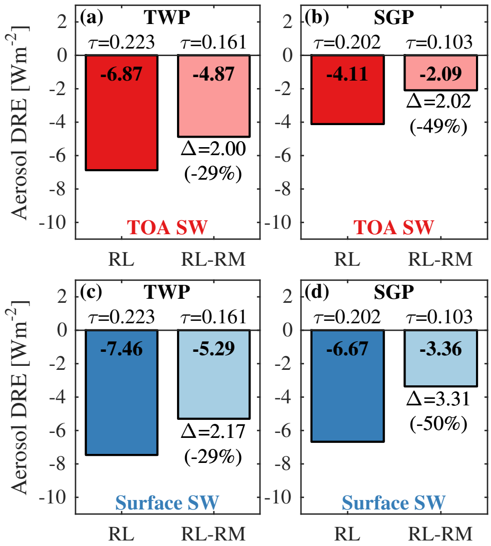
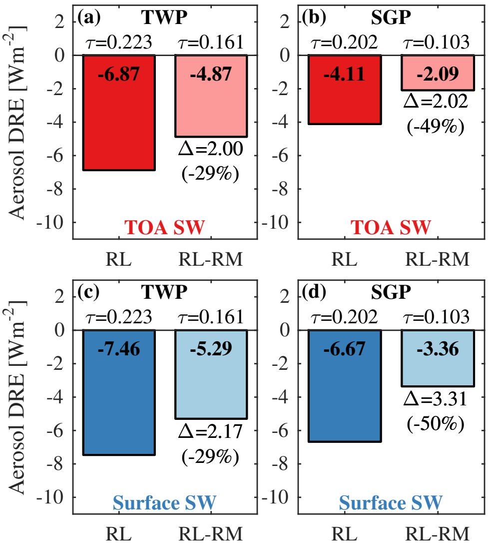
- "RL-RM": RL degraded to CALIPSO's sensitivity



Effect of detection sensitivity



- Method to force RL aerosol occurrence profile to match CALIPSO's by removing aerosol in each collocated overpass.
- "RL-RM": RL degraded to CALIPSO's sensitivity

CALIPSO's lack of sensitivity causes a significant reduction of 30–50% in the magnitude of the aerosol DRE

Global implications

- Aerosol that goes undetected is consistent with random noise considerations
  - CALIPSO's SNR is too low to detect all aerosol during both day and night.

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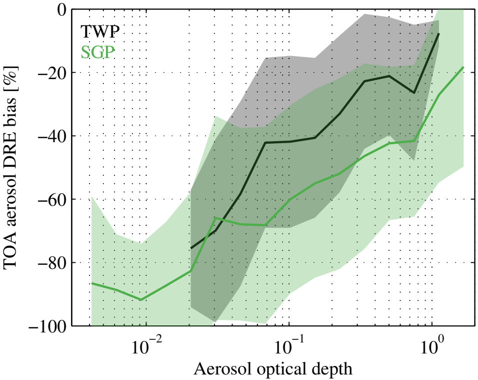
- Even for large aerosol optical depths, the bias remains significant



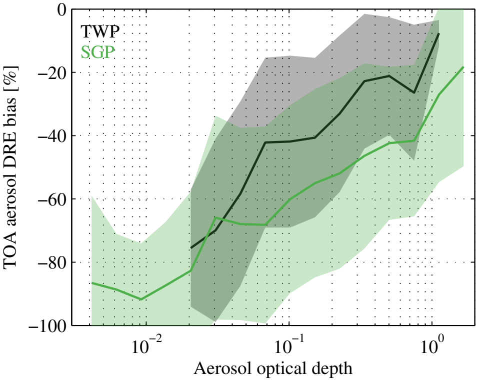
Global implications

- Aerosol that goes undetected is consistent with random noise considerations
  - CALIPSO's SNR is too low to detect all aerosol during both day and night.

- Even for large aerosol optical depths, the bias remains significant
- The global mean ocean AOD as measured by CALIPSO is 0.09

  (Winker et al., 2013)
- AOD=0.09 → -35% to -50% aerosol DRE bias at the two ARM sites

	Clear-sky ocean
Passive sensor-based (Yu et al. *ACP* 2006)	$-5.0\ Wm^{-2}$
CALIPSO-based (Oikawa et al. *JGR* 2013)	$-3.21\ Wm^{-2}$ (-36%)
CALIPSO-based (Matus et al. *JCLIM* 2015)	$-2.6\ Wm^{-2}$ (-48%)



Conclusions

- The results presented here strongly suggest that newer estimates of the global aerosol DRE that rely solely on CALIPSO aerosol observations (Oikawa et al. *JGR* 2013); Matus et al. *JCLIM* 2015) are biased weak (i.e. too small in magnitude).
- This study demonstrates that our knowledge of the global aerosol DRE remains incomplete.
- While CALIPSO allows for more consistent global estimates of the aerosol DRE in all scene types, its detection sensitivity is likely not sufficient for detecting all radiatively-significant aerosol.
- Passive sensors outperform CALIPSO in observing thin AOD since CALIPSO is sensitive to the backscatter in a relatively small volume while passive sensors measure the vertically-integrated scattering.
- However, the limitation of accurate passive retrievals to cloud-free ocean as well as potential biases from cloud contamination makes fully and accurately assessing global aerosol DRE difficult.

We don't know the global aerosol DRE

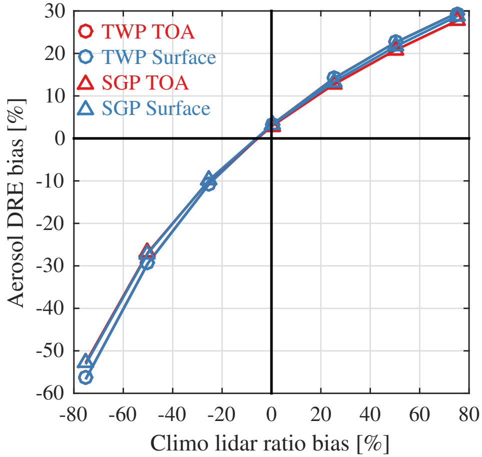
CALIPSO-inferred aerosol direct radiative effects: Bias estimates using ground-based Raman lidars; TJ Thorsen, Q Fu; Journal of Geophysical Research, 2015.

Effect of assumed lidar ratios

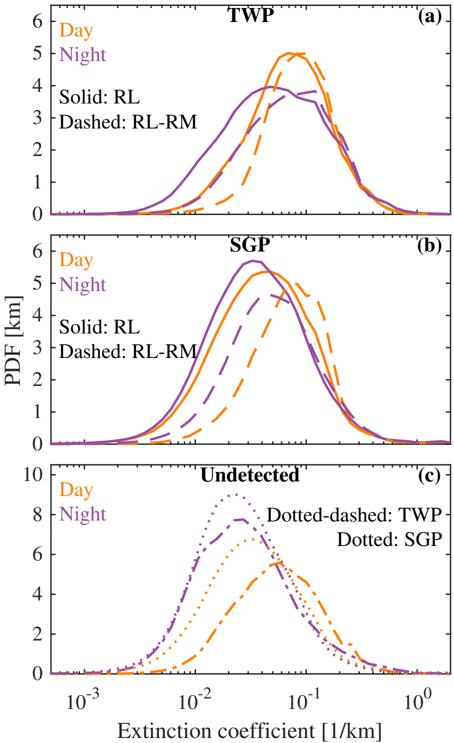
- CALIPSO's processing:
  Detect → cloud/aerosol → 6 aerosol subtypes → lidar ratio → extinction → flux

- The wavelength difference between CALIPSO (532 nm) and RL (355 nm) precludes a direct assessment of CALIPSO's lidar ratios. Instead the aerosol DRE is computed with
  ❶ Directly retrieved RL extinction
  ❷ Lidar ratio fixed (climatology±bias)

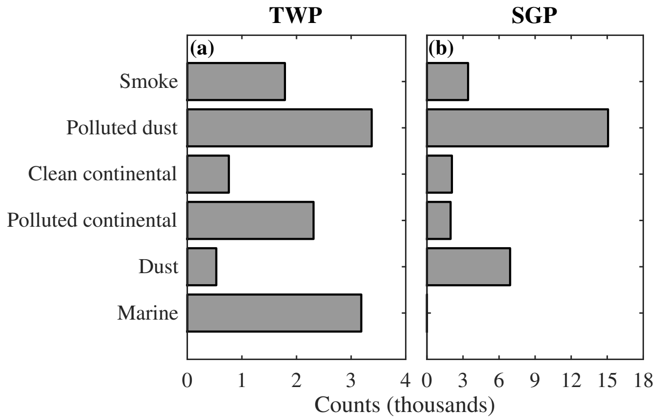
- If the selection of lidar ratio by CALIPSO can reproduce the climatological value at a particular location, then the aerosol DRE can be accurately calculated.

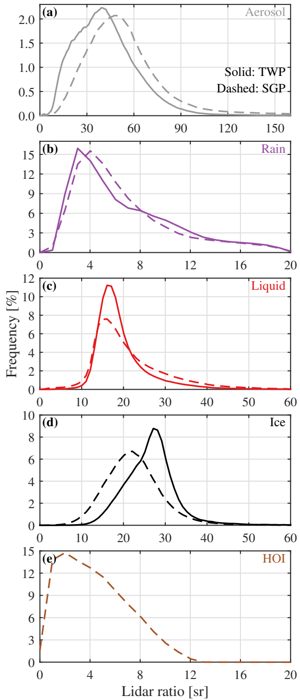


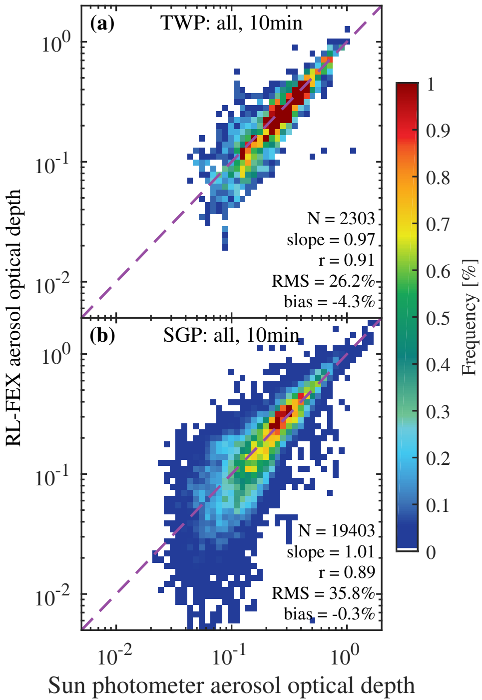
- Rogers et al. *AMT* (2014) found approximately a +20% bias in CALIPSO's lidar ratio which would correspond to about +10% bias in the aerosol DRE.


TWP
(a)
Day
Night
Solid: RL
Dashed: RL-RM
SGP
(b)
Day
Night
Solid: RL
Dashed: RL-RM
Undetected
(c)
Day
Night
Dotted-dashed: TWP
Dotted: SGP
PDF [km]
Extinction coefficient [1/km]

CALIPSO aerosol layer classifications




(a)
Aerosol
Solid: TWP
Dashed: SGP
0.0
0.5
1.0
1.5
2.0
0
30
60
90
120
150
(b)
Rain
0
3
6
9
12
15
0
4
8
12
16
20
(c)
Liquid
Frequency [%]
0
2
4
6
8
10
12
0
10
20
30
40
50
60
(d)
Ice
0
2
4
6
8
10
0
10
20
30
40
50
60
(e)
HOI
0
3
6
9
12
15
0
4
8
12
16
20
Lidar ratio [sr]


(a) TWP: all, 10min
N = 2303
slope = 0.97
r = 0.91
RMS = 26.2%
bias = -4.3%
(b) SGP: all, 10min
N = 19403
slope = 1.01
r = 0.89
RMS = 35.8%
bias = -0.3%
RL-FEX aerosol optical depth
Sun photometer aerosol optical depth
Frequency [%]
10^0
10^-1
10^-2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1