The capabilities of lidar datasets for radiative heating rate and flux calculations

Tyler Thorsen; Qiang Fu
University of Washington

David Turner
NOAA/National Severe Storms Laboratory

Rob Newsom; Jennifer Comstock
Pacific Northwest National Laboratory

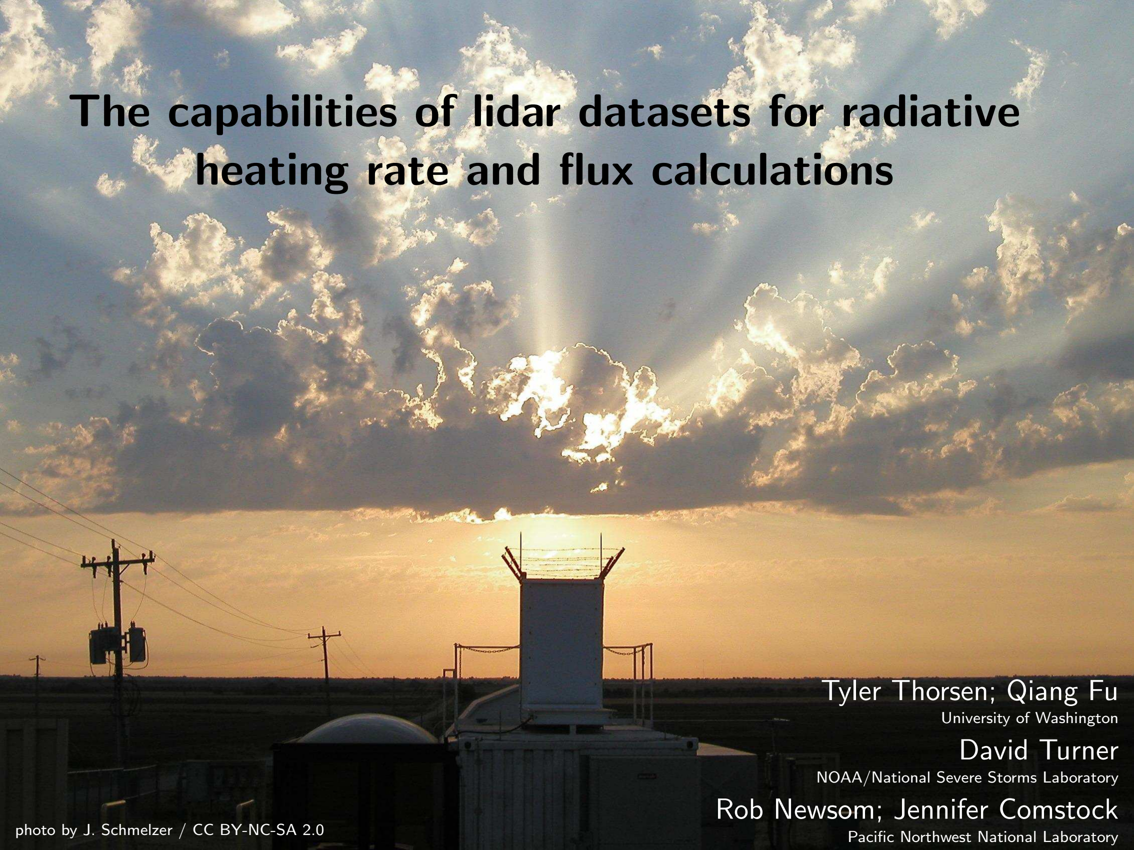


photo by J. Schmelzer / CC BY-NC-SA 2.0

Lidars and radiative fluxes

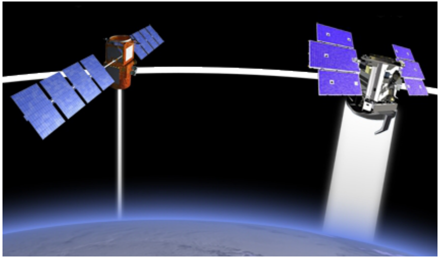
Vertical profiles of visible-wavelength extinction coefficients

Lidars and radiative fluxes

Vertical profiles of visible-wavelength extinction coefficients

- Synergy with cloud radar
  - Complementary sensitivities to cloud
    (radar: poorer sensitivity; lidar: attenuation)
  - For ice, radar+lidar $\rightarrow$ particle size
    (e.g. Wang and Sassen 2002; Delanoe and Hogan 2008)
- Aerosol properties

A-train:



CALIPSO CloudSat

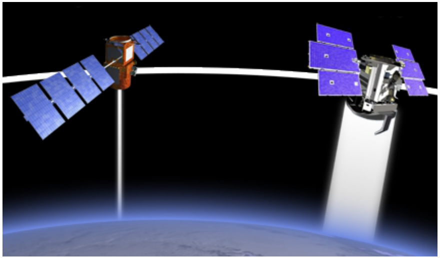
ARM:

MPL
(micropulse lidar)

MMCR
(millimeter cloud radar)

- Both sets are large quantities of data, commonly used (separately)

A-train:



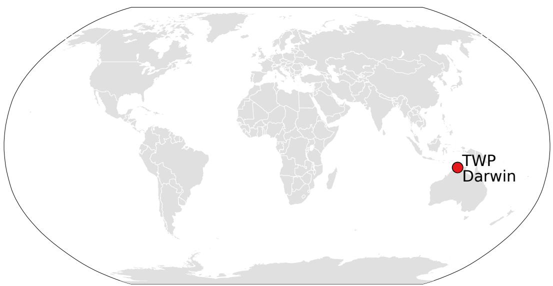
CALIPSO CloudSat

ARM:

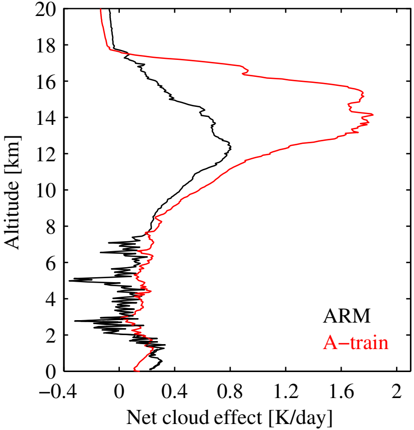
MPL (micropulse lidar)

MMCR (millimeter cloud radar)

- Both sets are large quantities of data, commonly used (separately)
- Compute cloud radiative effect using ARM and A-train radar+lidar observations over Darwin, Australia

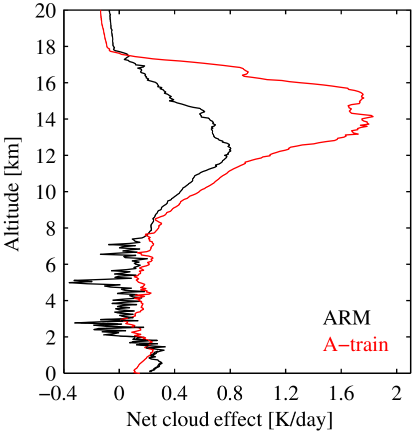


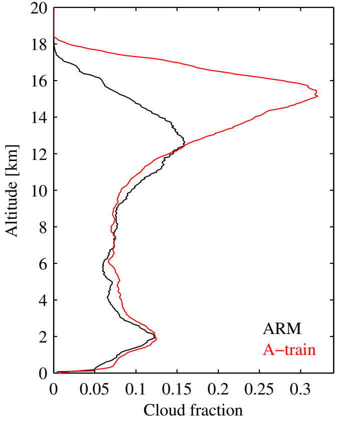
Cloud radiative effect (Thorsen et al. 2013a)



- Up to 1.4 K/day difference

Cloud radiative effect (Thorsen et al. 2013a)





- Up to 1.4 K/day difference

- Mostly due to differences in lidar occurrence profiles: MPL detects much less cirrus than CALIPSO
  - Combination of complete attenuation and a poorer sensitivity

The elastic lidar equation

We are using extinction from these lidars BUT

- Single-channel elastic backscatter lidars don't actually measure extinction

$$S_{\lambda_0}(z) \propto \beta_{p,\lambda_0}(z) \times \exp\left[- \int_0^z \alpha_{p,\lambda_0}(z^{'}) dz^{'}\right]$$

The elastic lidar equation

We are using extinction from these lidars BUT

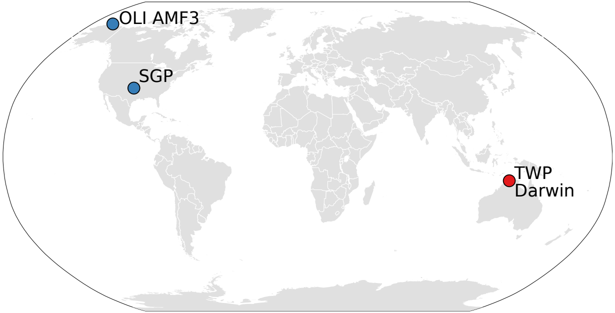
- Single-channel elastic backscatter lidars don't actually measure extinction

$$S_{\lambda_0}(z) \propto \beta_{p,\lambda_0}(z) \times \exp\left[-\int_0^z \alpha_{p,\lambda_0}(z')dz'\right]$$

  - Assume "lidar-ratio" profile: $S_p(z) = \alpha_p(z)/\beta_p(z)$
  - The lidar ratio is not constant $\rightarrow$ large errors in extinction

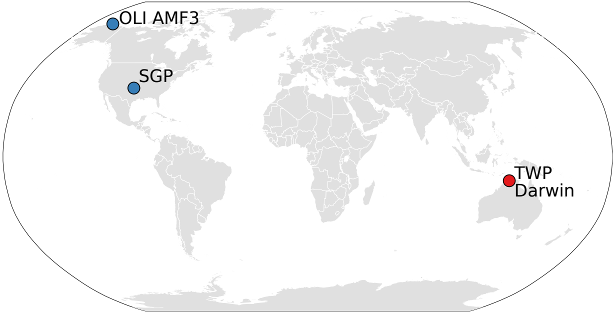
The ARM Raman lidar (RL)

- Measures an elastic signal and a Raman-scattered nitrogen signal



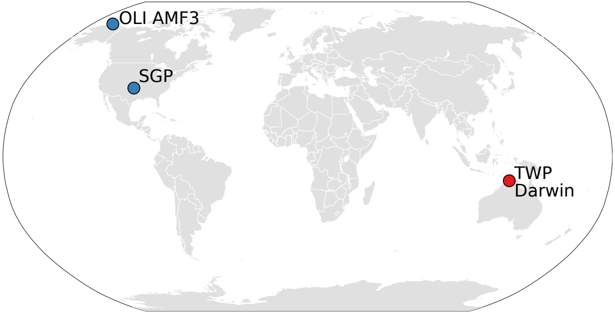
The ARM Raman lidar (RL)

- Measures an elastic signal and a Raman-scattered nitrogen signal
- Nitrogen signal is independent of particulate backscatter
  $S_{\lambda_{N_2}}(z) \propto \exp\left[-\int_0^z \alpha_{p,\lambda_0}(z')dz'\right]$



The ARM Raman lidar (RL)

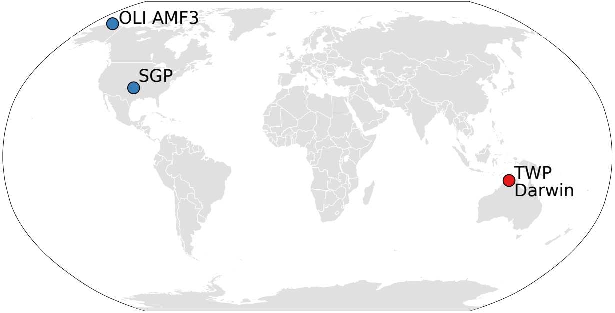
- Measures an elastic signal and a Raman-scattered nitrogen signal
- Nitrogen signal is independent of particulate backscatter
  $S_{\lambda_{N_2}}(z) \propto \exp\left[-\int_0^z \alpha_{p,\lambda_0}(z')dz'\right]$
- Can directly-measure cloud/aerosol extinction and backscatter



The ARM Raman lidar (RL)

- Measures an elastic signal and a Raman-scattered nitrogen signal
- Nitrogen signal is independent of particulate backscatter
  $S_{\lambda_{N_2}}(z) \propto \exp\left[-\int_0^z \alpha_{p,\lambda_0}(z')dz'\right]$
- Can directly-measure cloud/aerosol extinction and backscatter
- More sensitive than the ARM MPL; cirrus occurrence agrees well with CALIPSO; cloud/aerosol detection is unbiased by the solar background

(Thorsen et al. 2013b)

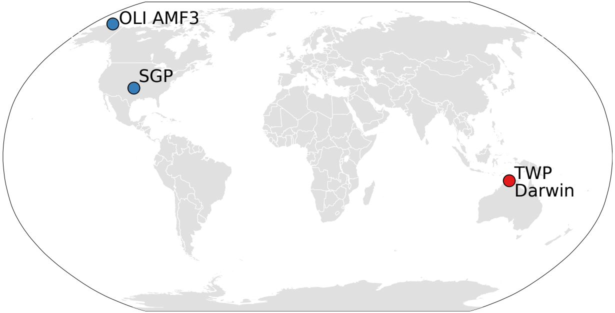


The ARM Raman lidar (RL)

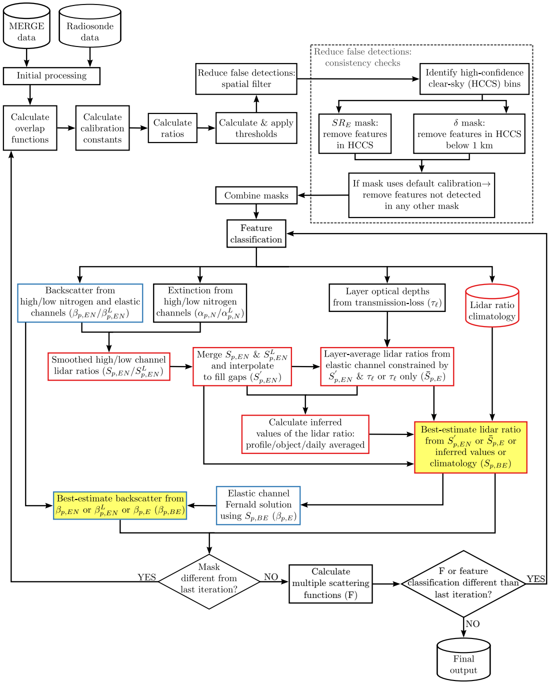
- Measures an elastic signal and a Raman-scattered nitrogen signal
- Nitrogen signal is independent of particulate backscatter
  $S_{\lambda_{N_2}}(z) \propto \exp\left[-\int_0^z \alpha_{p,\lambda_0}(z')dz'\right]$
- Can directly-measure cloud/aerosol extinction and backscatter
- More sensitive than the ARM MPL; cirrus occurrence agrees well with CALIPSO; cloud/aerosol detection is unbiased by the solar background

  (Thorsen et al. 2013b)
- Bonus: water vapor and temperature

  (Turner et al., 2002; Newsom et al., 2010)



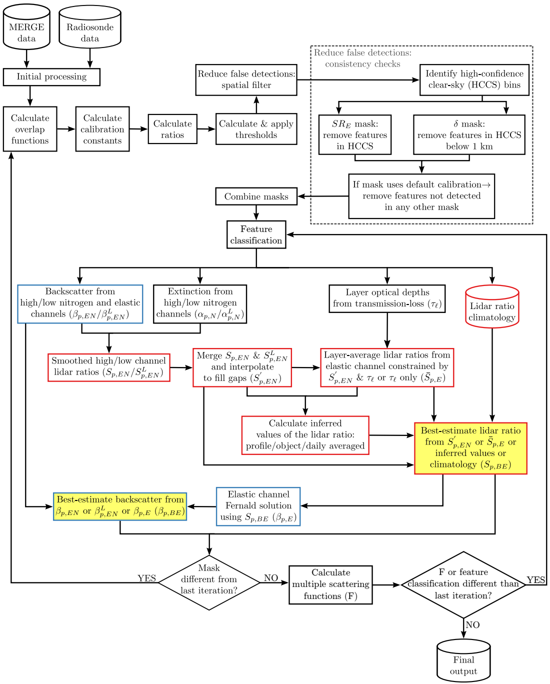
RL-FEX (**F**eature detection and **EX**tinction retrieval)



- New automated retrieval algorithm for the ARM RL
- Comprehensively addresses the lidar retrieval problem

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

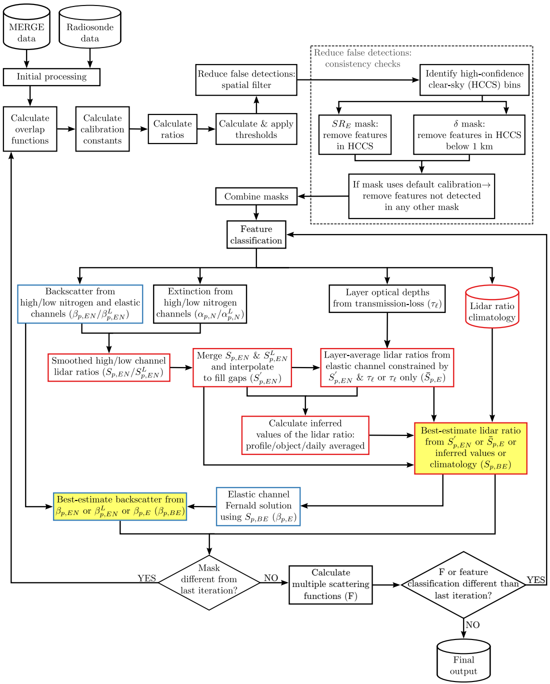
RL-FEX (**F**eature detection and **EX**tinction retrieval)



- New automated retrieval algorithm for the ARM RL
- Comprehensively addresses the lidar retrieval problem
- RL-FEX makes possible statistical comparisons of CALIPSO cloud/aerosol properties to an advanced lidar
    - All previous work has focused on comparisons using case studies or small sample sizes

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

RL-FEX (**F**eature detection and **EX**tinction retrieval)



- New automated retrieval algorithm for the ARM RL
- Comprehensively addresses the lidar retrieval problem
- RL-FEX makes possible statistical comparisons of CALIPSO cloud/aerosol properties to an advanced lidar
    - All previous work has focused on comparisons using case studies or small sample sizes
- We now have a true climatology of cloud/aerosol extinction

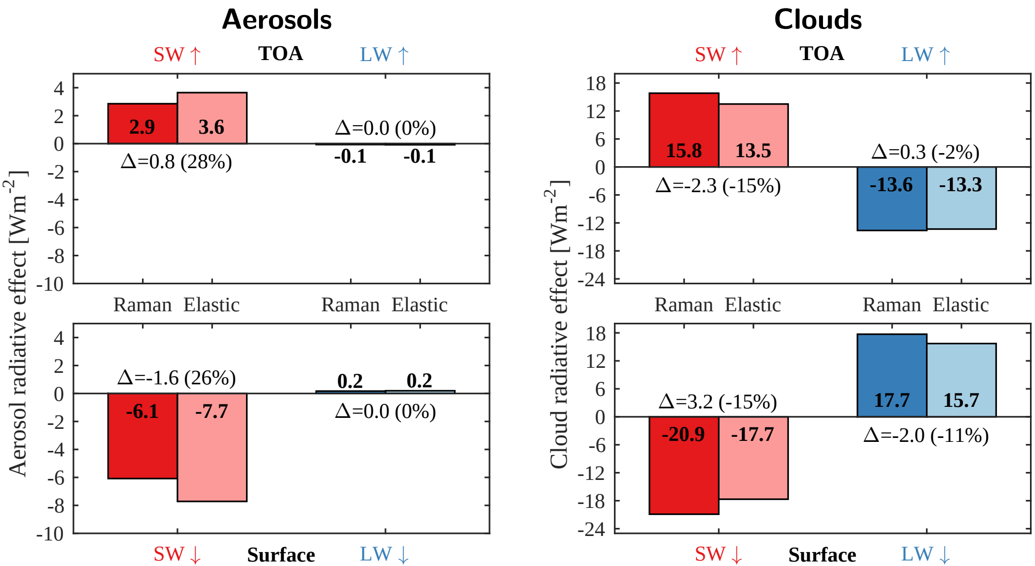
(Thorsen et al. 2015; Thorsen and Fu 2015)

How does using extinction from an elastic lidar (e.g. CALIPSO/MPL) affect your radiative flux calculation?

How does using extinction from an elastic lidar (e.g. CALIPSO/MPL) affect your radiative flux calculation?

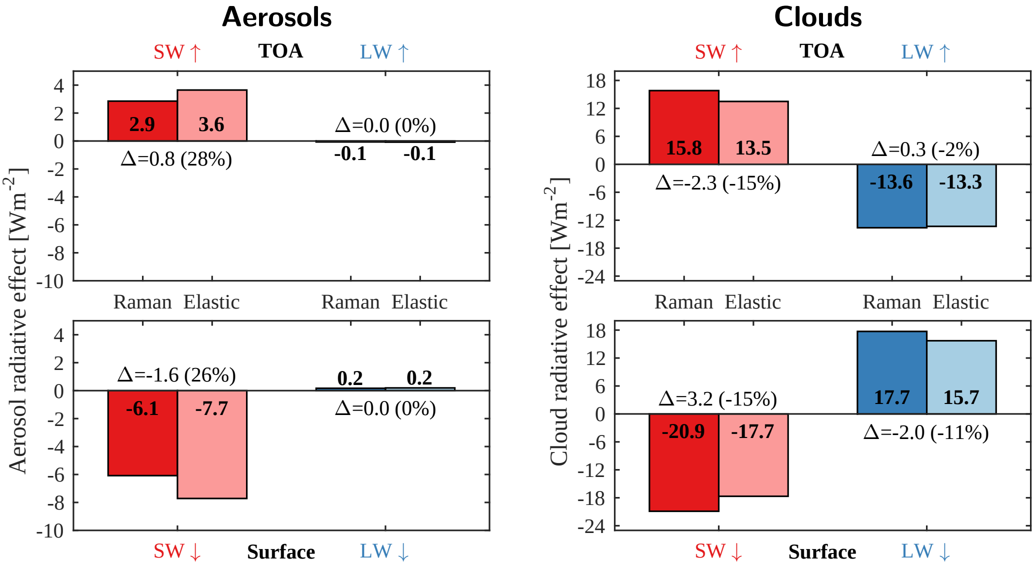
1. Calculate flux using RL-FEX best-estimate extinction
2. Calculate flux using elastic channel-only retrieved extinction (i.e. assumed lidar ratios)
   - TOA & surface aerosol/cloud radiative effect (i.e. subtract clear-sky flux)
   - Multiyear mean values

SGP site (Oklahoma): Raman vs. elastic extinction



- Aerosols: 25–30% difference
- Clouds: $\leq$ 15% difference, some cancellation in the net

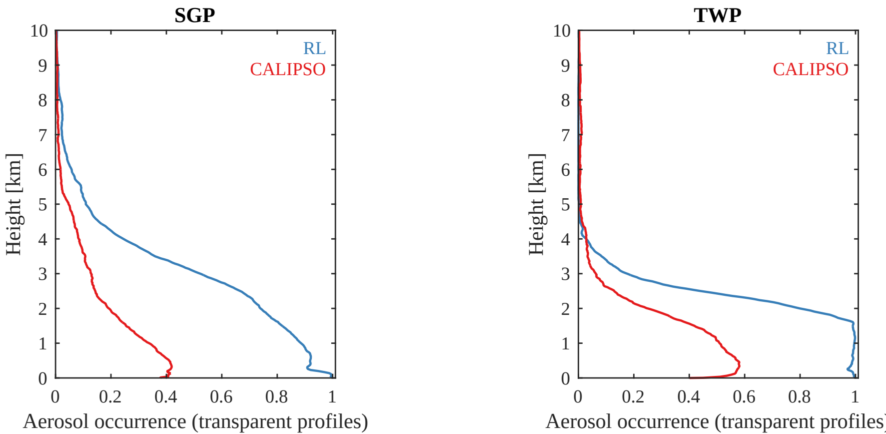
SGP site (Oklahoma): Raman vs. elastic extinction



- Aerosols: 25–30% difference
- Clouds: $\leq$ 15% difference, some cancellation in the net
- This is a "lidar-biased" view (only ~3-4 optical depths worth of particulates)

CALIPSO and Raman lidar aerosol occurrence

CALIPSO and Raman lidar aerosol occurrence



- Transparent profiles only (laser has fully penetrated the atmosphere)
- CALIPSO detects much less aerosol than the RL

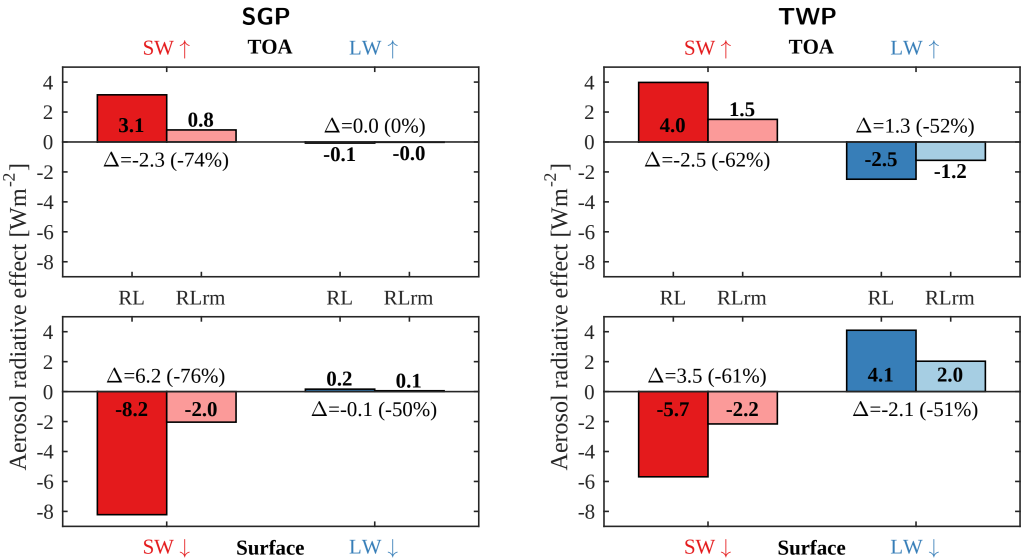
- Is the aerosol missed by CALIPSO radiatively important?

1. Calculation using all aerosol detected by the RL
2. Calculation using RL data, but with aerosol randomly removed (multiple times) to force a CALIPSO-like occurrence profile ("RL degraded to CALIPSO's sensitivity")

- Is the aerosol missed by CALIPSO radiatively important?

❶ Calculation using all aerosol detected by the RL

❷ Calculation using RL data, but with aerosol randomly removed (multiple times) to force a CALIPSO-like occurrence profile ("RL degraded to CALIPSO's sensitivity")



- Significant biases of ∼ 50–75%

Global estimates of shortwave direct aerosol effects at TOA

Global estimates of shortwave direct aerosol effects at TOA

- Passive sensors: -5 Wm^{-2} (mostly limited to clear-sky ocean)

  (Yu et al. 2006 and references therein)

Global estimates of shortwave direct aerosol effects at TOA

- Passive sensors: -5 Wm^{-2} (mostly limited to clear-sky ocean)

  (Yu et al. 2006 and references therein)

- Active sensors: -0.6 to -1.9 Wm^{-2} (using CALIPSO: all-sky, land+ocean, vertically-resolved)

  (Oikawa et al. 2013; Matus et al. 2015)

Global estimates of shortwave direct aerosol effects at TOA

- Passive sensors: -5 Wm^{-2} (mostly limited to clear-sky ocean)

  (Yu et al. 2006 and references therein)

- Active sensors: -0.6 to -1.9 Wm^{-2} (using CALIPSO: all-sky, land+ocean, vertically-resolved)

  (Oikawa et al. 2013; Matus et al. 2015)

Are these estimates smaller due to CALIPSO's poor sensitivity?

(causes a $\sim$70% reduction at the two ARM sites)

Summary

- CALIPSO+CloudSat better suited for heating rate calculations than MPL+MMCR due to the MPL's lack of sensitivity.
- RL-FEX: new retrieval for the ARM Raman lidar. Provides directly-retrieved cloud/aerosol extinction coefficients.
- Assumptions needed to obtain extinction from elastic lidars results in $\sim$25% biases in the inferred aerosol radiative effects and $\leq$15% in the cloud radiative effects.
- A significant amount of aerosol goes undetected by CALIPSO
  - This lack of aerosol reduces the inferred aerosol radiative effects significantly ($\sim$50–75%)

Global estimates of shortwave direct aerosol effects at TOA

- Passive sensors: -5 Wm^{-2} (mostly limited to clear-sky ocean)

  (Yu et al. 2006 and references therein)

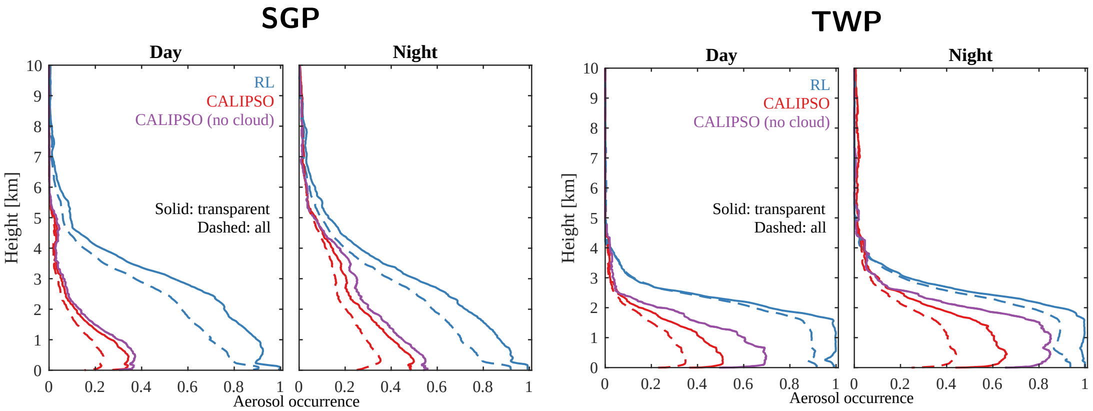
- Active sensors: -0.6 to -1.9 Wm^{-2} (using CALIPSO: all-sky, land+ocean, vertically-resolved)

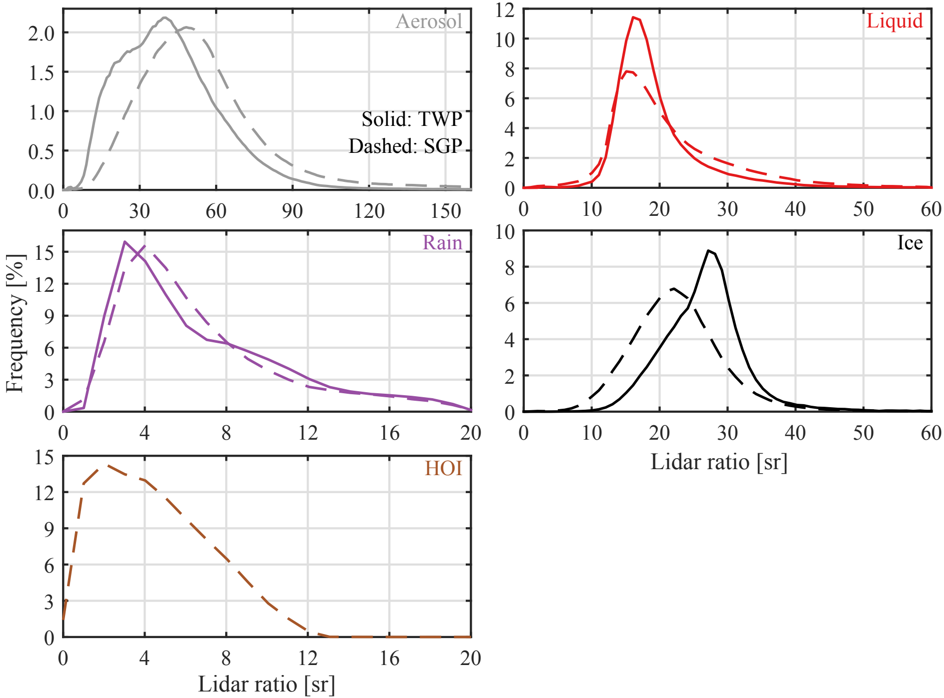
  (Oikawa et al. 2013; Matus et al. 2015)

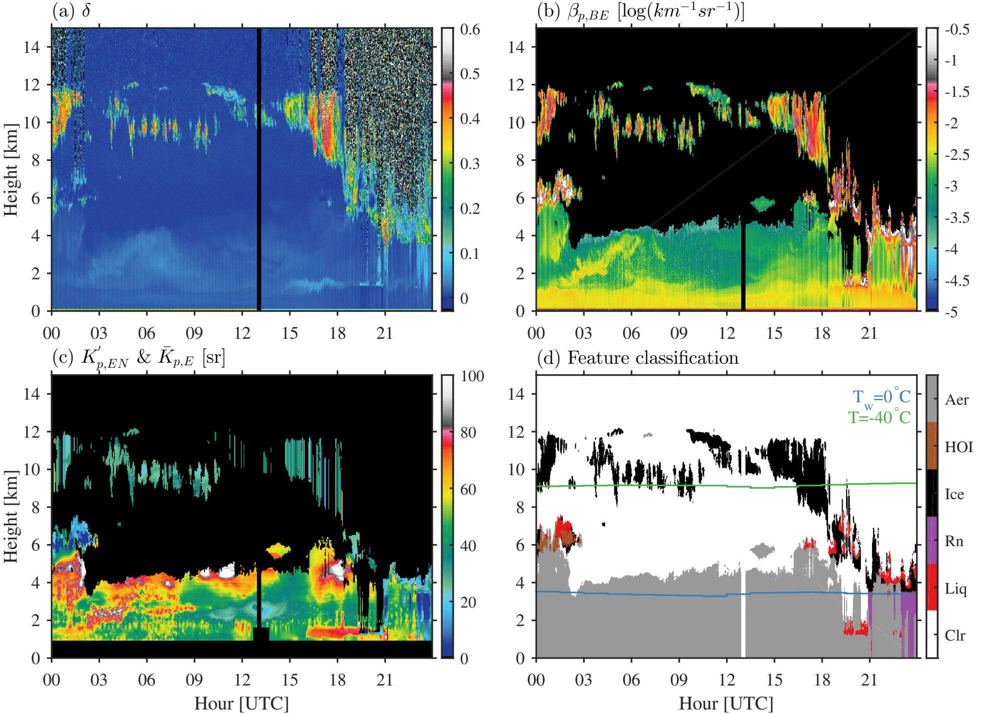
  - Clear-sky ocean: -2.6 to -3.2 Wm^{-2}

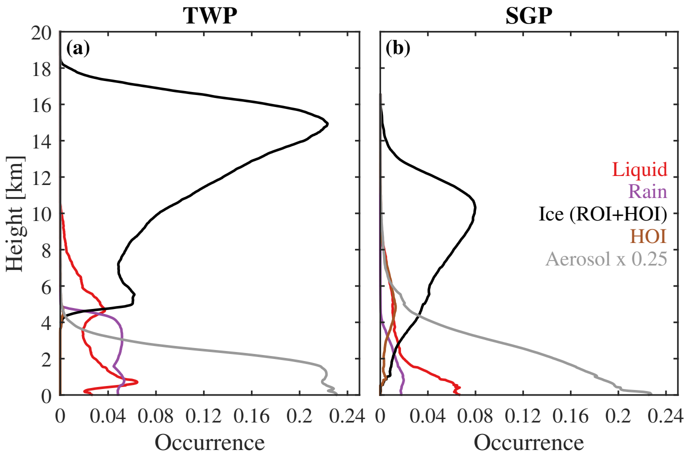
Radiative transfer model details

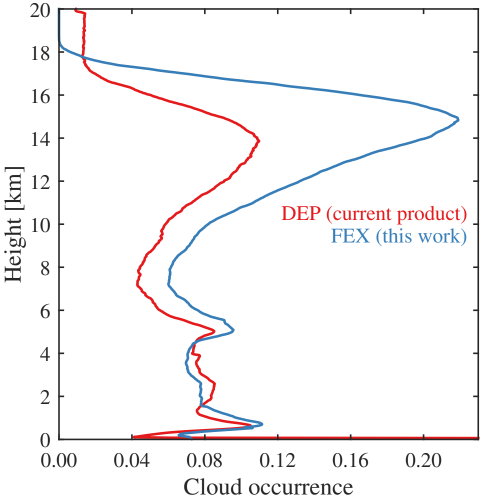
- NASA Fu-Liou, 2 streams
- Pressure / temperature / water vapor from radiosondes; standard profiles (MLS / MLW/ TROP) fill in above
- Ozone: standard profiles
- Surface albedo = 0.2
- Clouds: extinction from RL
  - Liquid: $R_e = 8\mu m$
  - Ice: $D_{ge} = 30\mu m$
- Aerosol
  - RL extinction at 355 nm
  - SGP: d'Almedia continental model
  - TWP: d'Almedia maritime model

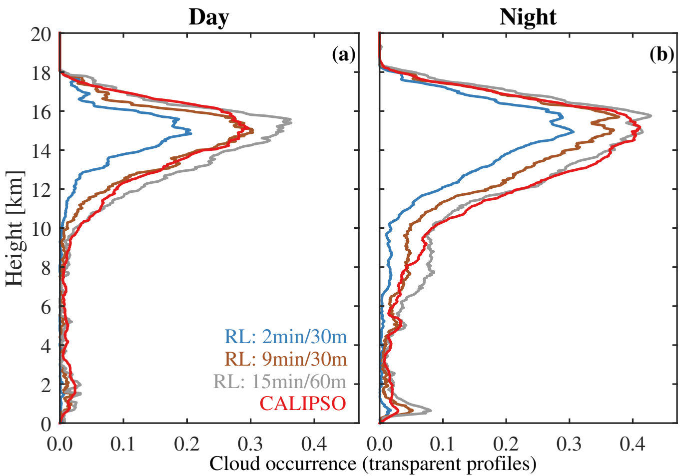

SGP
Day
Night
RL
CALIPSO
CALIPSO (no cloud)
Solid: transparent
Dashed: all
Height [km]
Aerosol occurrence
TWP
Day
Night
RL
CALIPSO
CALIPSO (no cloud)
Solid: transparent
Dashed: all
Height [km]
Aerosol occurrence


Aerosol
Solid: TWP
Dashed: SGP
Liquid
Rain
Ice
HOI
Frequency [%]
Lidar ratio [sr]
Lidar ratio [sr]


(a) δ
(b) $\beta_{p,BE}$ [$\log(km^{-1}sr^{-1})$]
(c) $K'_{p,EN}$ & $\bar{K}_{p,E}$ [sr]
(d) Feature classification
Height [km]
Hour [UTC]
T_w=0°C
T=-40°C
Aer
HOI
Ice
Rn
Liq
Clr


TWP
SGP
(a)
(b)
Height [km]
Occurrence
Occurrence
Liquid
Rain
Ice (ROI+HOI)
HOI
Aerosol x 0.25
0
2
4
6
8
10
12
14
16
18
20
0
0.04
0.08
0.12
0.16
0.2
0.24


20
18
16
14
12
10
8
6
4
2
0
Height [km]
0.00
0.04
0.08
0.12
0.16
0.20
Cloud occurrence
DEP (current product)
FEX (this work)


Day
Night
(a)
(b)
Height [km]
20
18
16
14
12
10
8
6
4
2
0
0.0
0.1
0.2
0.3
0.4
RL: 2min/30m
RL: 9min/30m
RL: 15min/60m
CALIPSO
Cloud occurrence (transparent profiles)