Automated retrieval of cloud and aerosol properties from the ARM Raman lidar

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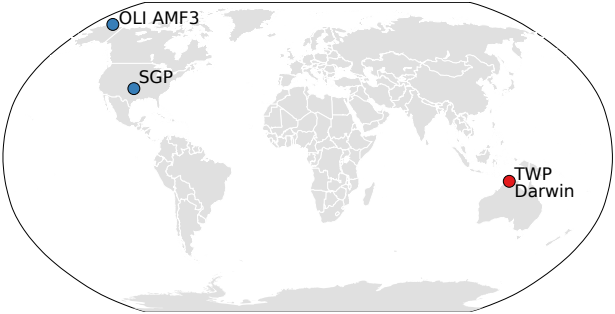

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- Nitrogen channels
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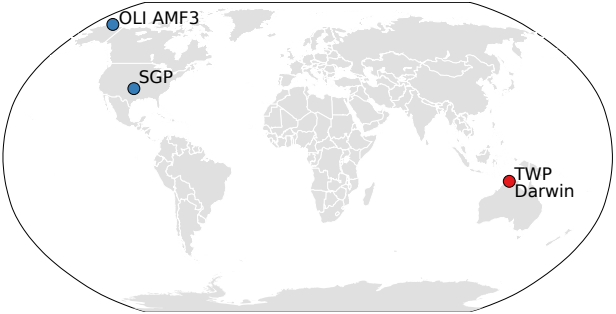

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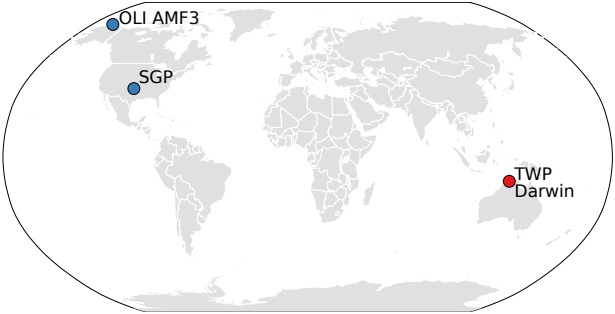

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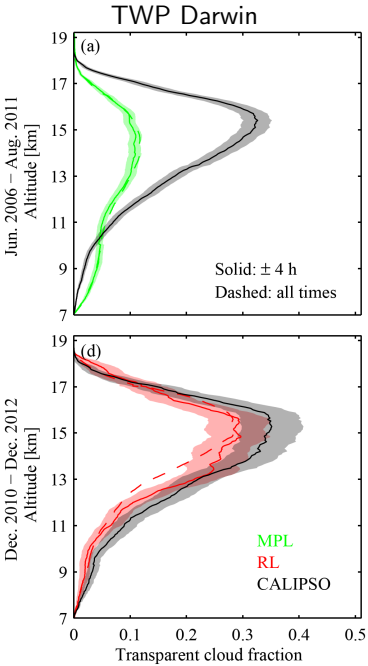

(Thorsen et al., 2013b)

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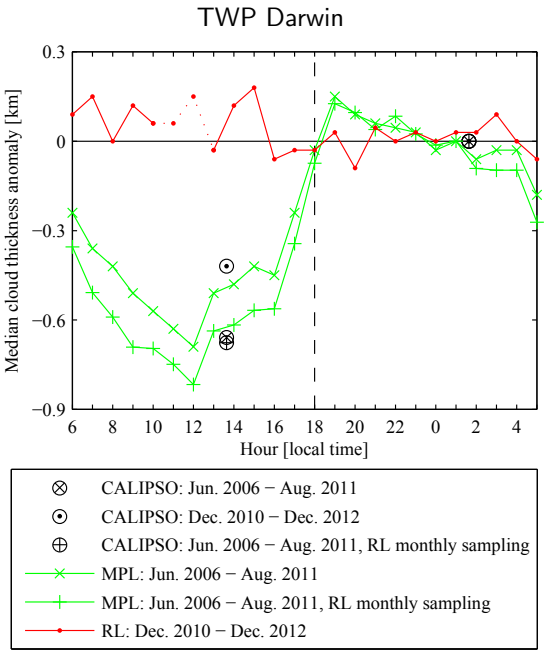
  - Detection is unbiased by the solar background



(Thorsen et al., 2013b)

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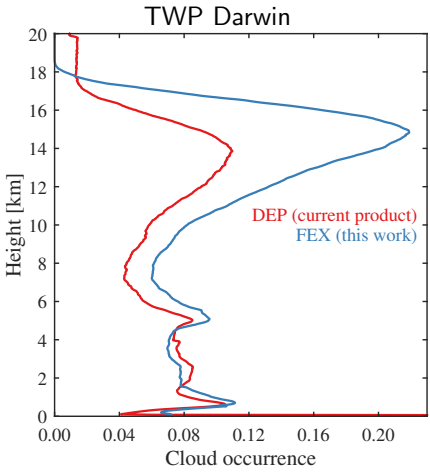

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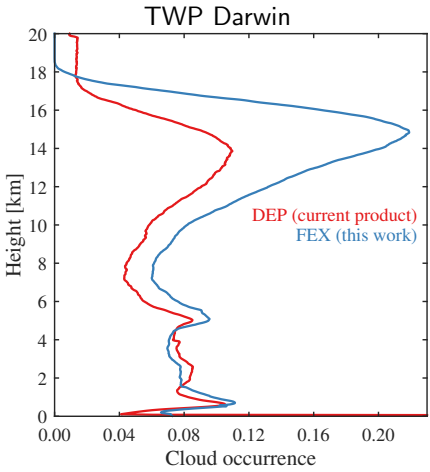

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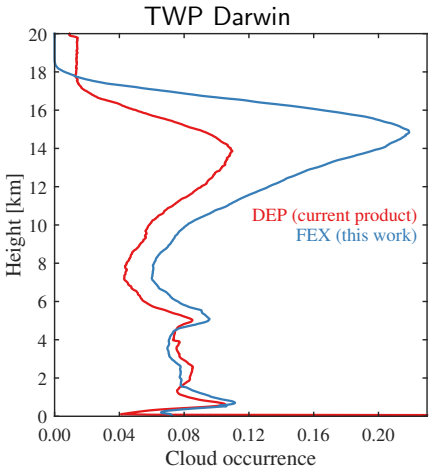
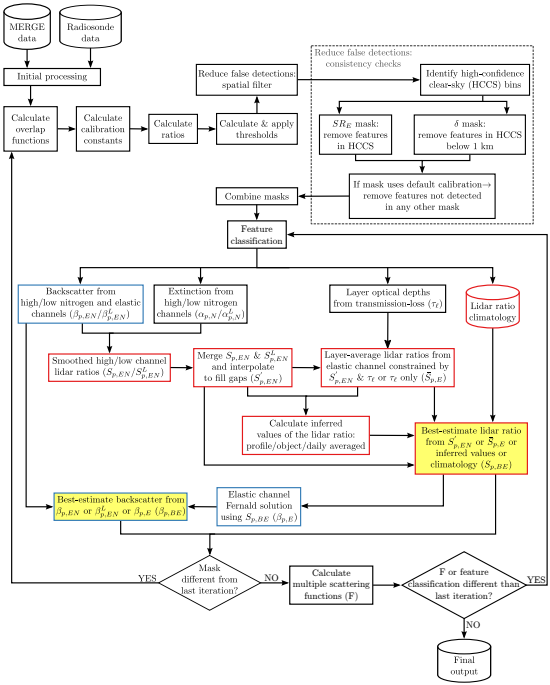


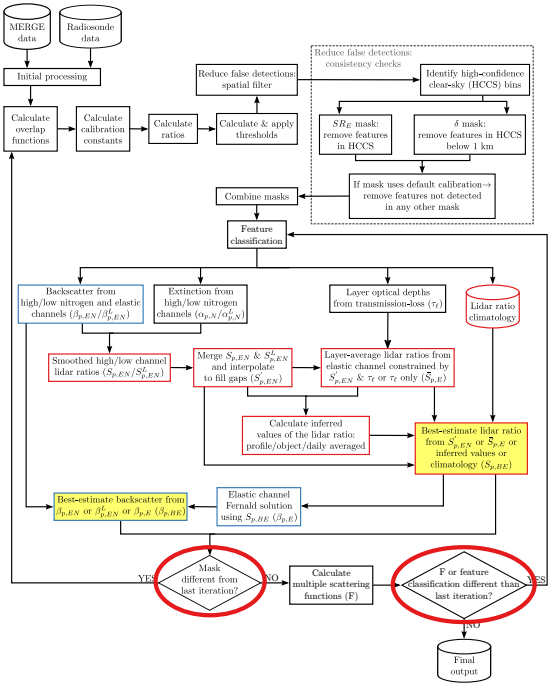
Objective: A new automated algorithm for Feature detection (cloud+aerosol) and EXtinction retrieval (FEX).

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

FEX


MERGE data
Radiosonde data
Initial processing
Calculate overlap functions
Calculate calibration constants
Calculate ratios
Calculate & apply thresholds
Reduce false detections: spatial filter
Reduce false detections: consistency checks
Identify high-confidence clear-sky (HCCS) bins
SR_E mask: remove features in HCCS
δ mask: remove features in HCCS below 1 km
If mask uses default calibration→ remove features not detected in any other mask
Combine masks
Feature classification
Backscatter from high/low nitrogen and elastic channels ($\beta_{p,EN}/\beta^{\ell}_{p,EN}$)
Extinction from high/low nitrogen channels ($\alpha_{p,N}/\alpha^{\ell}_{p,N}$)
Layer optical depths from transmission-loss (τ_l)
Lidar ratio climatology
Smoothed high/low channel lidar ratios ($S_{p,EN}/S^{\ell}_{p,EN}$)
Merge $S_{p,EN}$ & $S^{\ell}_{p,EN}$ and interpolate to fill gaps ($\bar{S}_{p,EN}$)
Layer-average lidar ratios from elastic channel constrained by $\bar{S}^{\ell}_{p,EN}$ & τ_l or τ_l only ($\bar{S}_{p,E}$)
Calculate inferred values of the lidar ratio: profile/object/daily averaged
Best-estimate lidar ratio from $\bar{S}^{\ell}_{p,EN}$ or $\bar{S}_{p,E}$ or inferred values or climatology ($\bar{S}_{p,BE}$)
Best-estimate backscatter from $\beta_{p,EN}$ or $\beta^{\ell}_{p,EN}$ or $\beta_{p,E}$ ($\beta_{p,BE}$)
Elastic channel Fernald solution using $\bar{S}_{p,BE}$ ($\beta_{p,E}$)
Mask different from last iteration?
YES
NO
Calculate multiple scattering functions (F)
F or feature classification different than last iteration?
YES
NO
Final output

FEX



- Iterative

  (everything depends on everything else)

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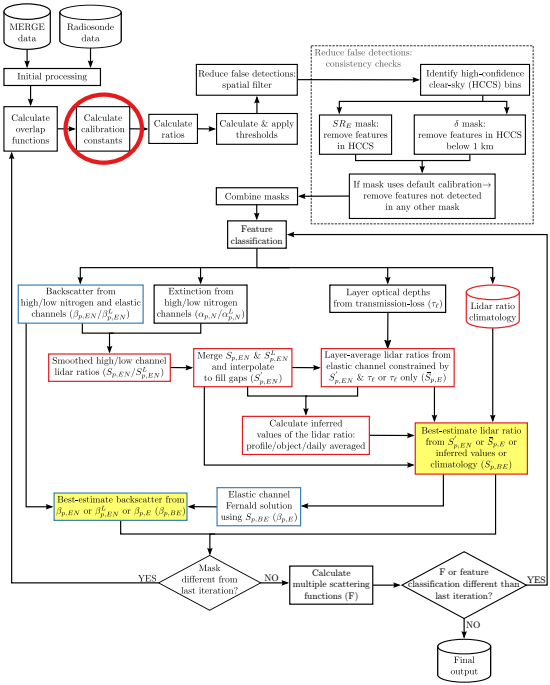

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- Improved calibration

  (done at highest resolution possible)

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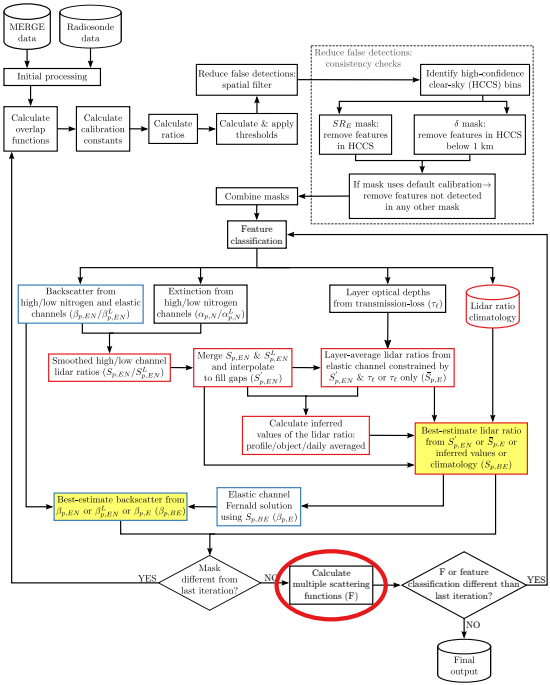

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  (for clouds: up to 30% bias in extinction)

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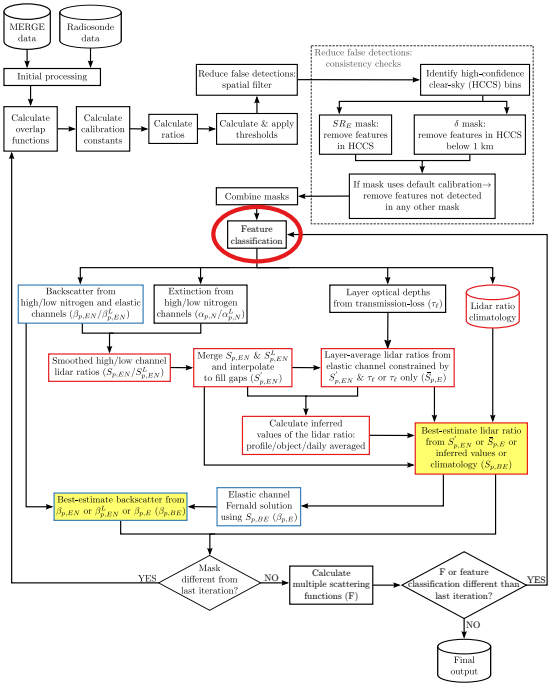

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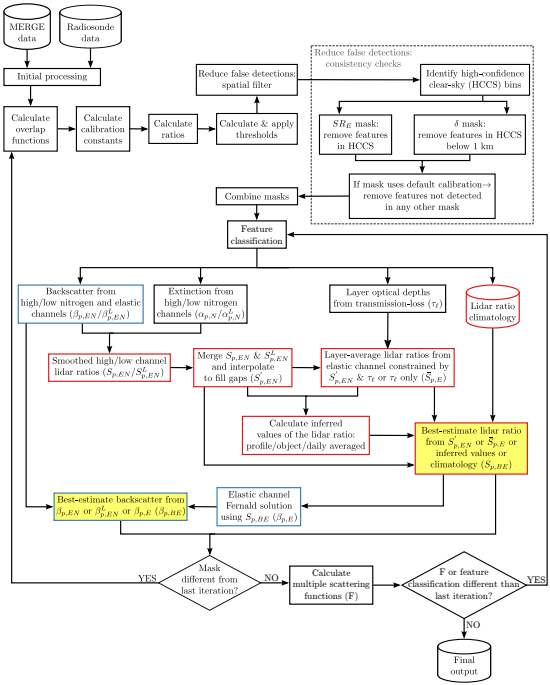

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- Main components:
  1. Feature detection
  2. Extinction retrieval

Feature detection

Examine multiple quantities for features:

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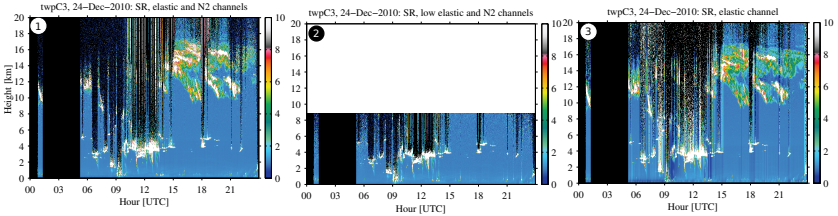
- 3 ways (❶,❷,❸) to calculate the scattering ratio $= \frac{\text{total (particulates+molecules) scattering}}{\text{molecular scatter}}$
  - scattering ratio $> 1 \rightarrow$ feature



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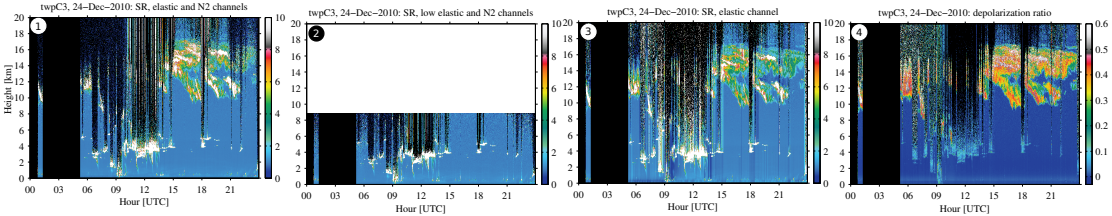

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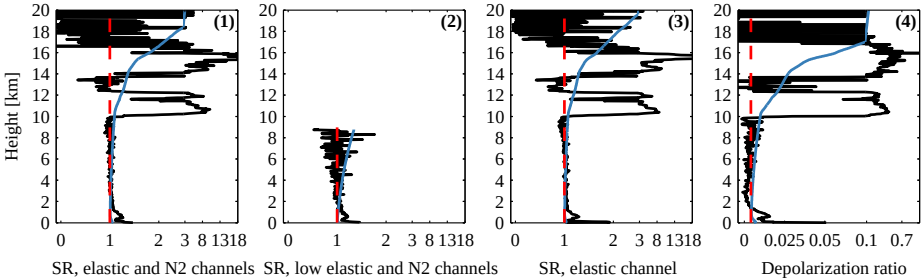
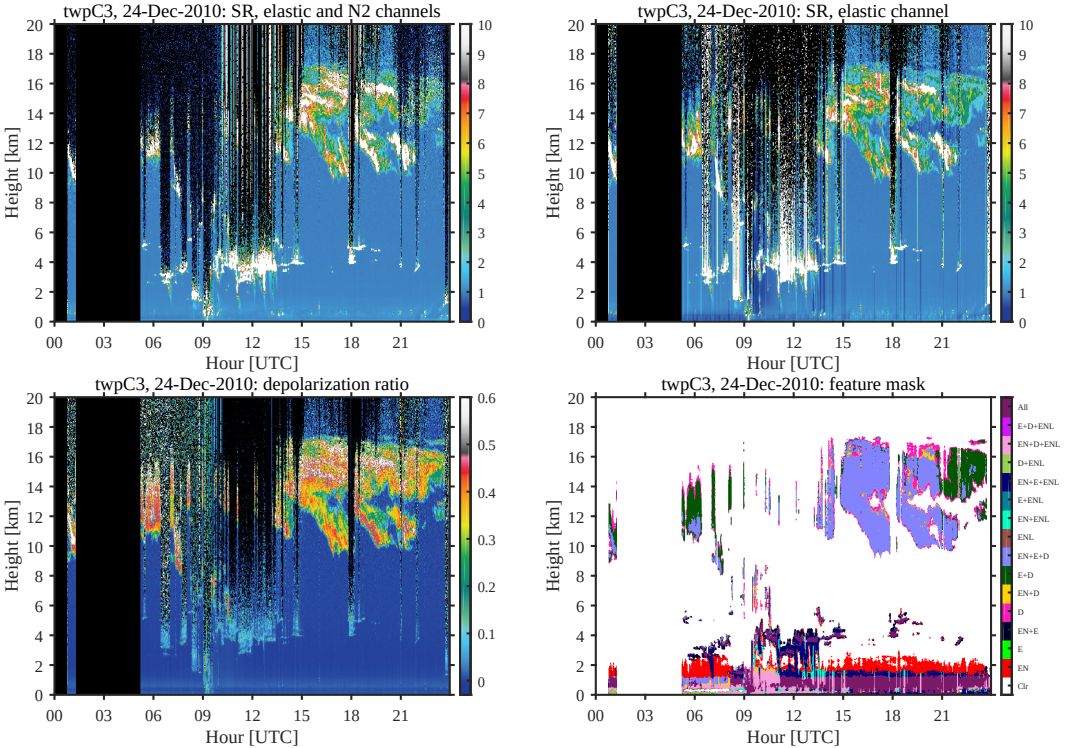
- Volume depolarization ratio (❹)
- Calculate range-dependent and context sensitive thresholds for each ratio $\rightarrow$ combine into a single mask





- All 4 ratios together > any single ratio (in a mean sense too)

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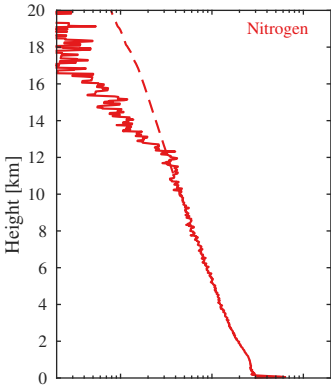

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   - Layer-averaged lidar ratio from an analytical solution for backscatter
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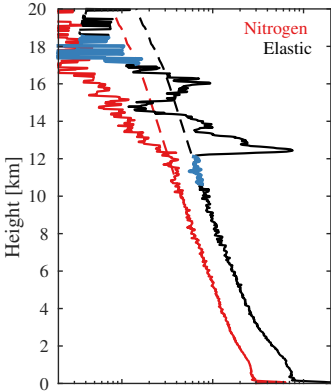

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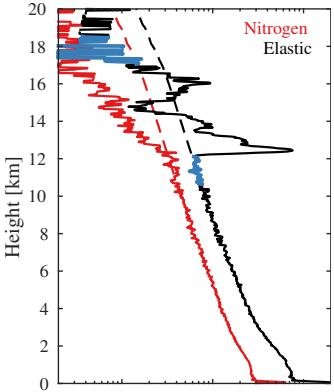
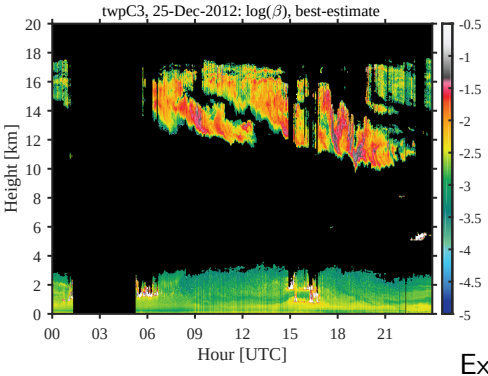
❸ Elastic channel

- Assume lidar-ratio profile; analytical solution for backscatter
- Constraints from ❶ and ❷
- **Large biases possible, but small random error**

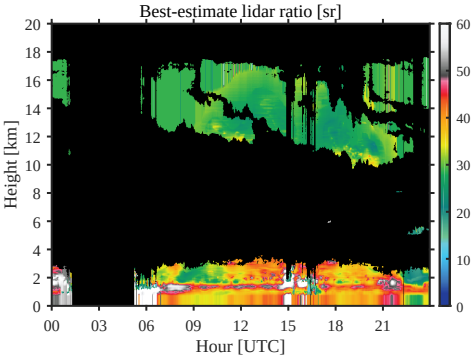


Combine the 3 methods to create a extinction best-estimate for all features

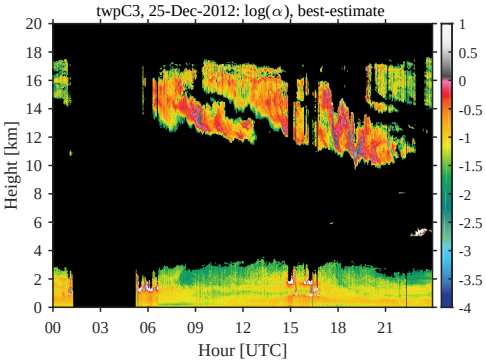
Particulate backscatter



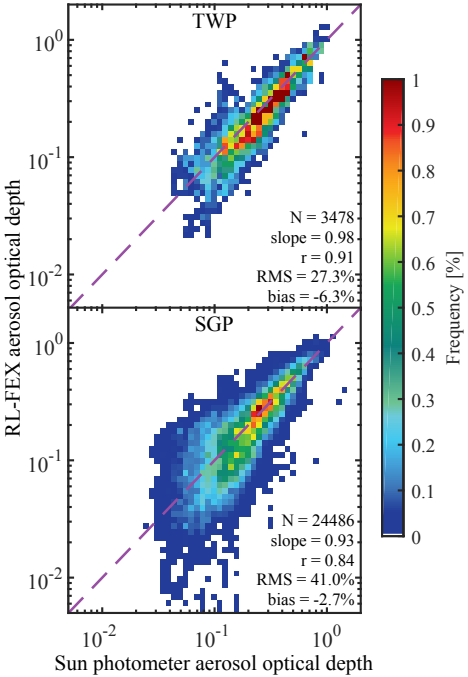
Lidar ratio



Extinction



Aerosol optical depth: comparison to AERONET



- 4/5 years of TWP/SGP data
- Bias error less than ∼6%

Summary

- New automated algorithm for the ARM RL developed
  - Multiple quantities used to identify features
    - All quantities together better than any one
    - Depolarization makes identifying cirrus easier
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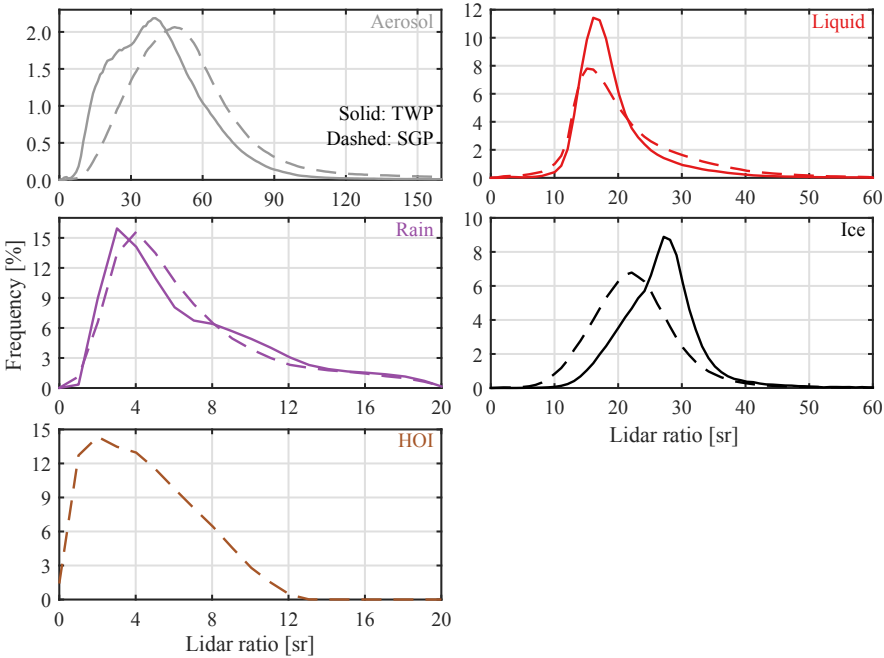
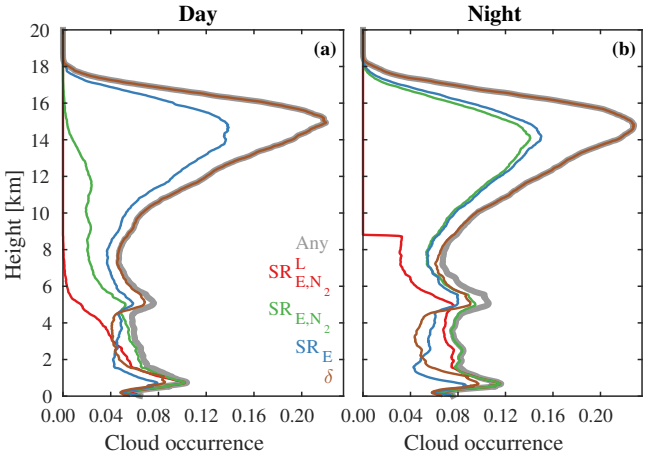
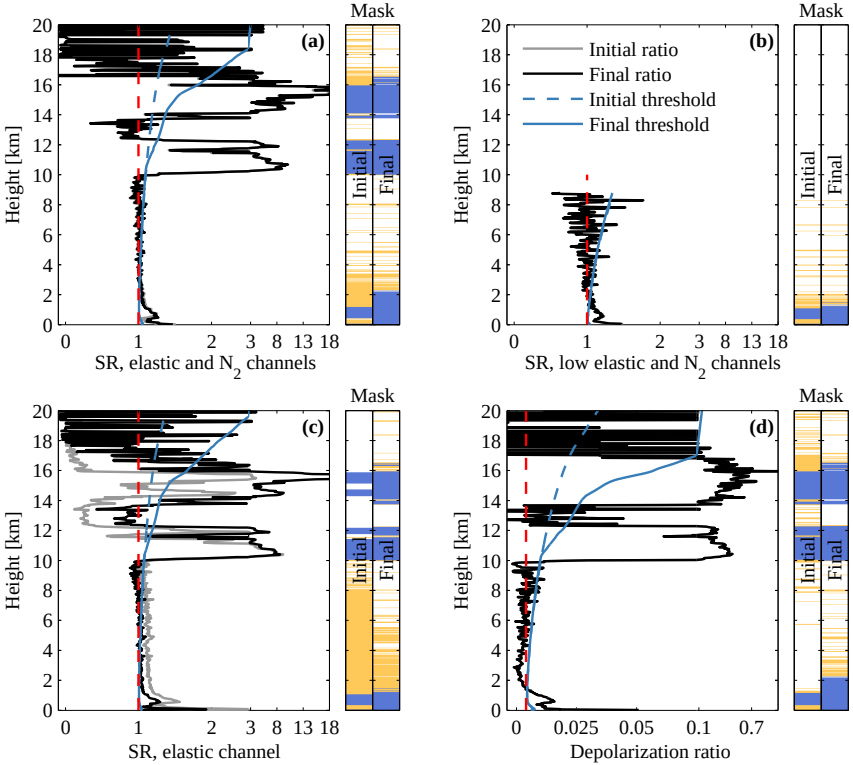
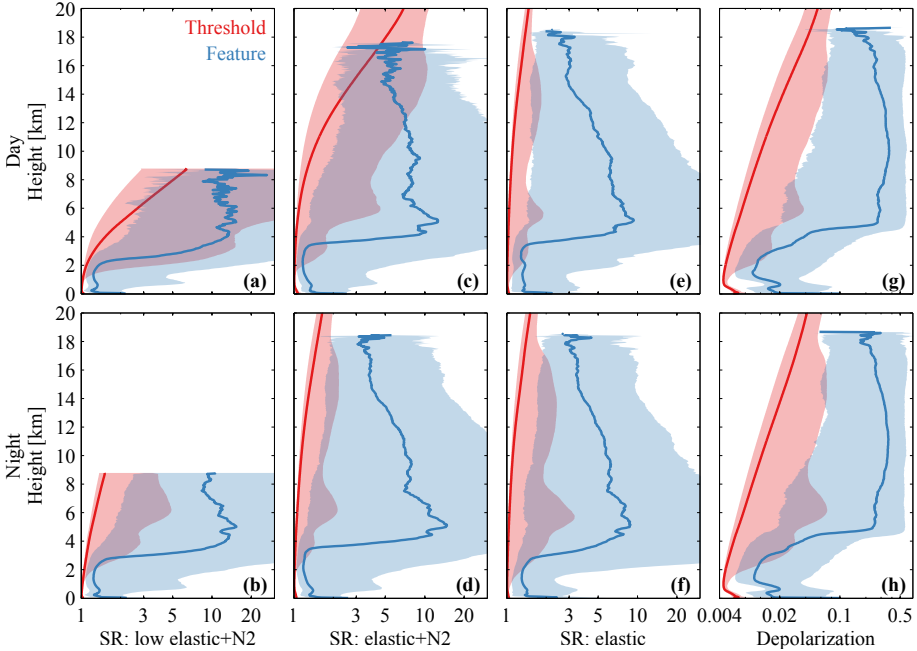
- Directly-retrieved extinction
- Lidar ratio $\sim$ microphysical properties of the particle
  - Critical input for an elastic lidar (e.g. CALIPSO, MPL)
- Unprecedented look at ice extinction/lidar ratio (vertical, seasonal, diurnal, regional dependence?)

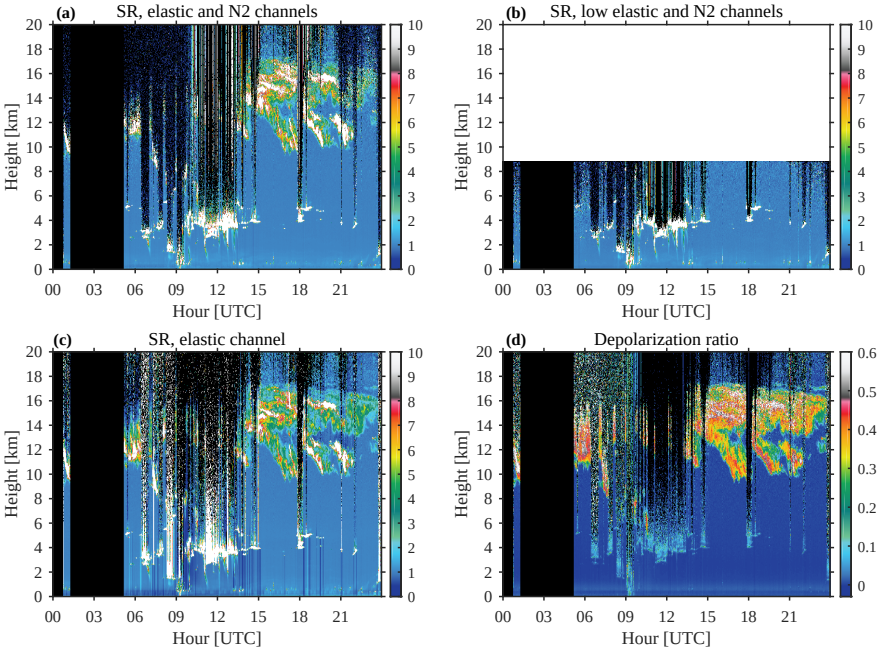
Aerosol and **cloud** microphysical/process-level insight from combining observations made by the RL: **extinction**, **backscatter**, **depolarization**, temperature, water vapor, relative humidity all in the same volume.

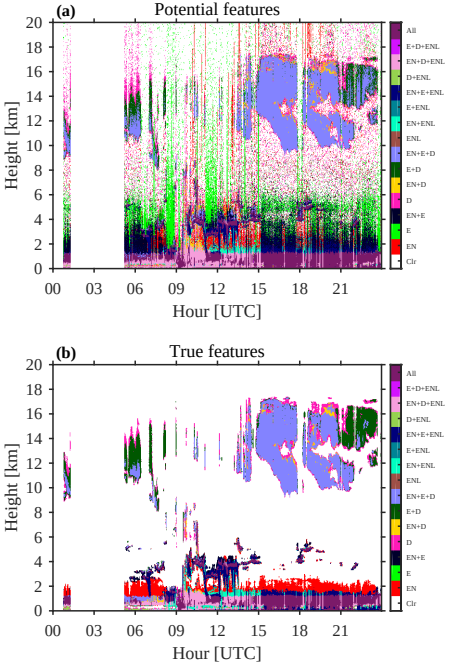

Aerosol
Solid: TWP
Dashed: SGP
Liquid
Rain
Ice
HOI
Frequency [%]
Lidar ratio [sr]
Lidar ratio [sr]

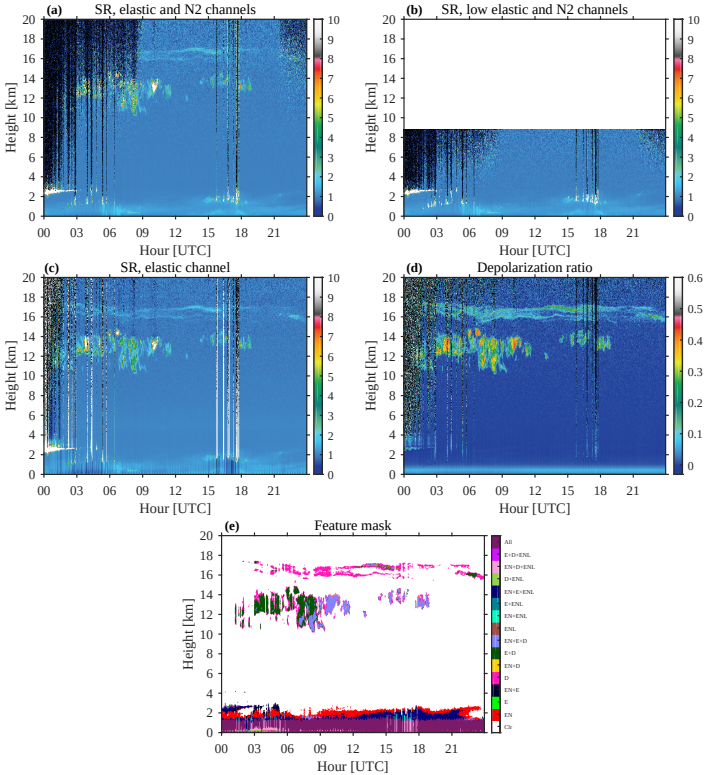

Day
Night
(a)
(b)
Height [km]
Cloud occurrence
Cloud occurrence
Any
SR L E,N2
SR E,N2
SR E
δ
0
2
4
6
8
10
12
14
16
18
20
0.00
0.04
0.08
0.12
0.16
0.20

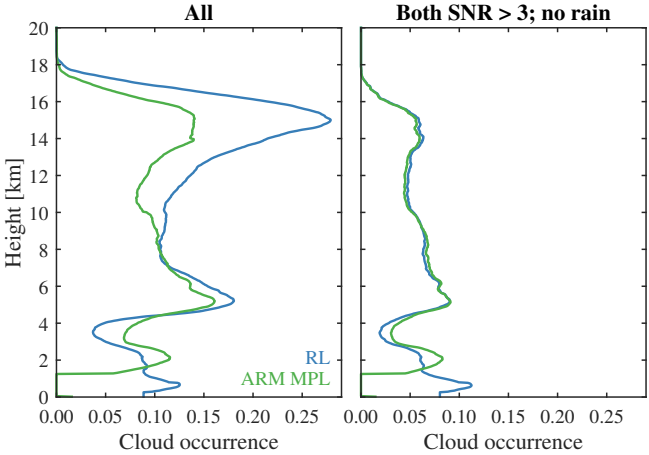

(a)
(b)
(c)
(d)
Mask
Initial
Final
Height [km]
SR, elastic and N2 channels
SR, low elastic and N2 channels
SR, elastic channel
Depolarization ratio
Initial ratio
Final ratio
Initial threshold
Final threshold

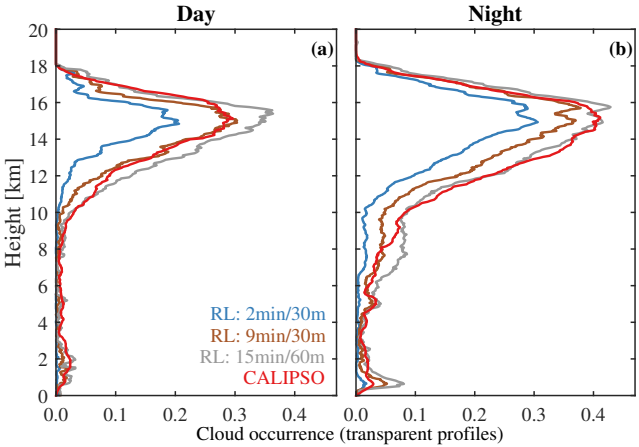

Threshold
Feature
Day
Night
Height [km]
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
SR: low elastic+N2
SR: elastic+N2
SR: elastic
Depolarization

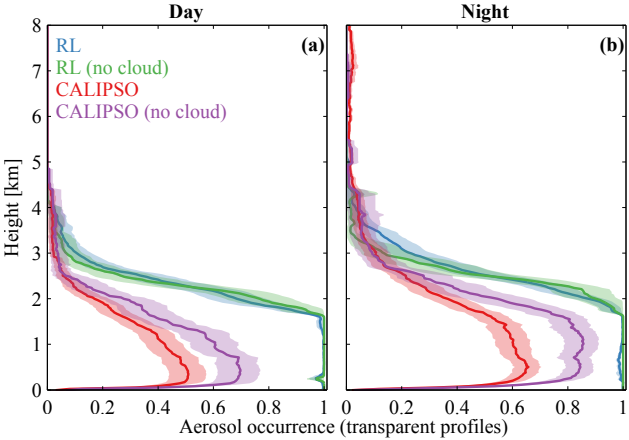

(a)
SR, elastic and N2 channels
(b)
SR, low elastic and N2 channels
(c)
SR, elastic channel
(d)
Depolarization ratio
Height [km]
Hour [UTC]
00 03 06 09 12 15 18 21
0 2 4 6 8 10 12 14 16 18 20
0 1 2 3 4 5 6 7 8 9 10
0 0.1 0.2 0.3 0.4 0.5 0.6

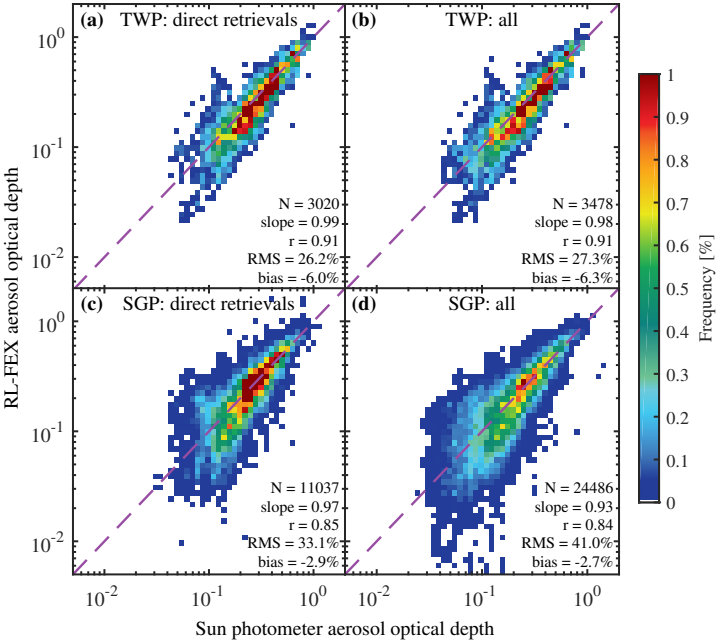

(a)
Potential features
Height [km]
Hour [UTC]
00 03 06 09 12 15 18 21
0 2 4 6 8 10 12 14 16 18 20
All
E+D+ENL
EN+D+ENL
D+ENL
EN+E+ENL
E+ENL
EN+ENL
ENL
EN+E+D
E+D
EN+D
D
EN+E
E
EN
Clr
(b)
True features
Height [km]
Hour [UTC]
00 03 06 09 12 15 18 21
0 2 4 6 8 10 12 14 16 18 20
All
E+D+ENL
EN+D+ENL
D+ENL
EN+E+ENL
E+ENL
EN+ENL
ENL
EN+E+D
E+D
EN+D
D
EN+E
E
EN
Clr

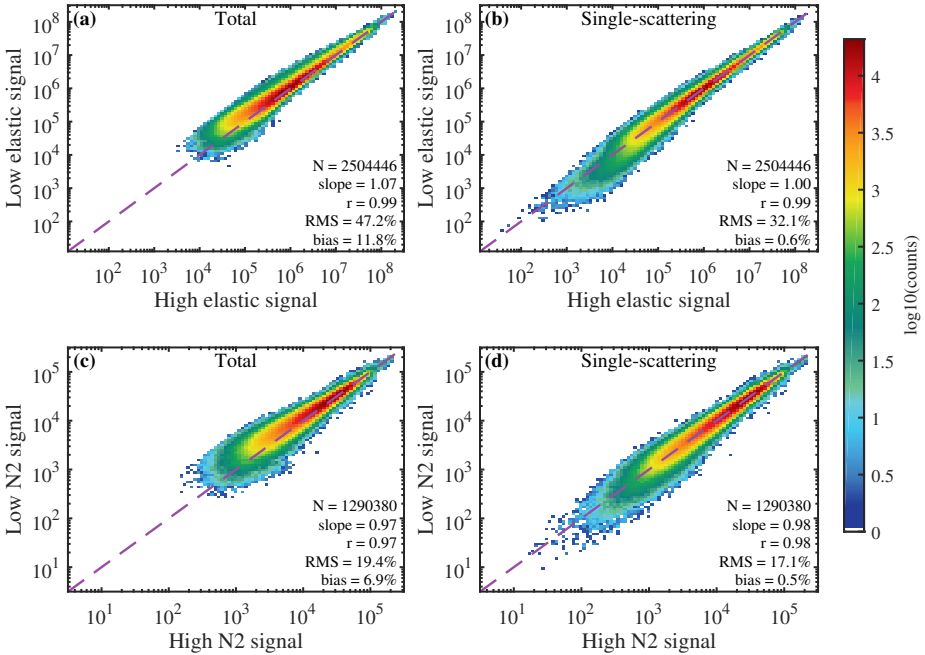

(a) SR, elastic and N2 channels
(b) SR, low elastic and N2 channels
(c) SR, elastic channel
(d) Depolarization ratio
(e) Feature mask
Height [km]
Hour [UTC]
00 03 06 09 12 15 18 21
All
E+D+ENL
EN+D+ENL
D+ENL
EN+E+ENL
E+ENL
EN+ENL
ENL
EN+E+D
E+D
EN+D
D
EN+E
E
EN
Cir

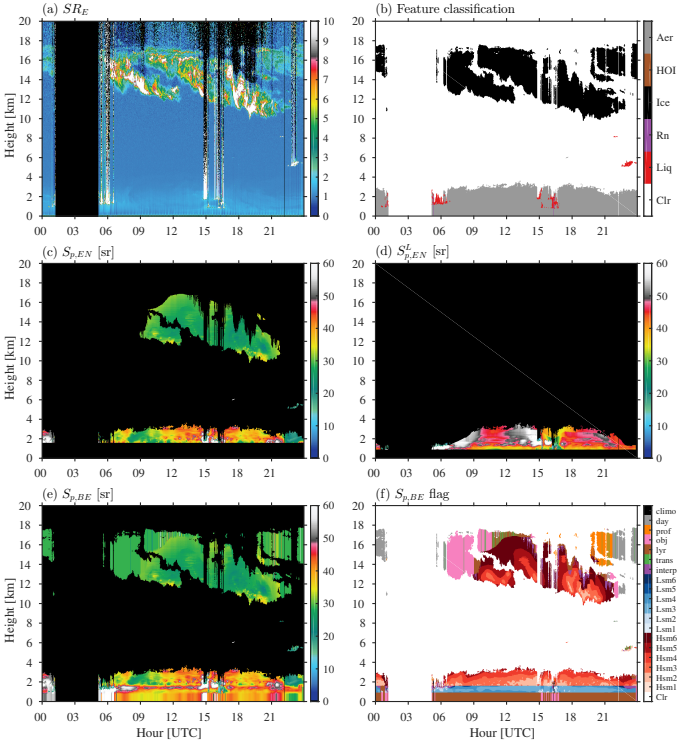

All
Both SNR > 3; no rain
Height [km]
0
2
4
6
8
10
12
14
16
18
20
0.00
0.05
0.10
0.15
0.20
0.25
Cloud occurrence
RL
ARM MPL

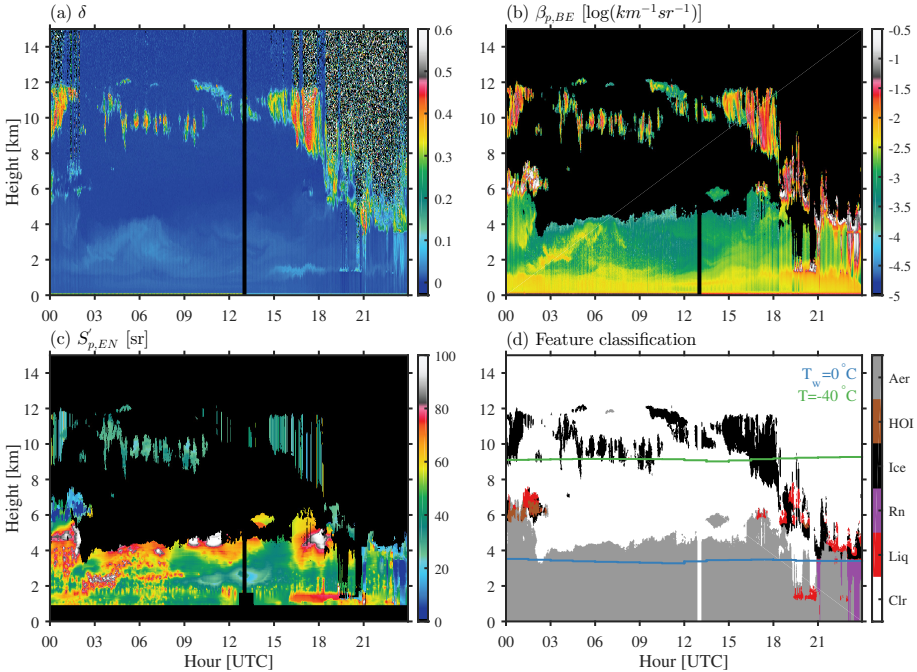

Day
Night
(a)
(b)
Height [km]
20
18
16
14
12
10
8
6
4
2
0
0.0
0.1
0.2
0.3
0.4
RL: 2min/30m
RL: 9min/30m
RL: 15min/60m
CALIPSO
Cloud occurrence (transparent profiles)

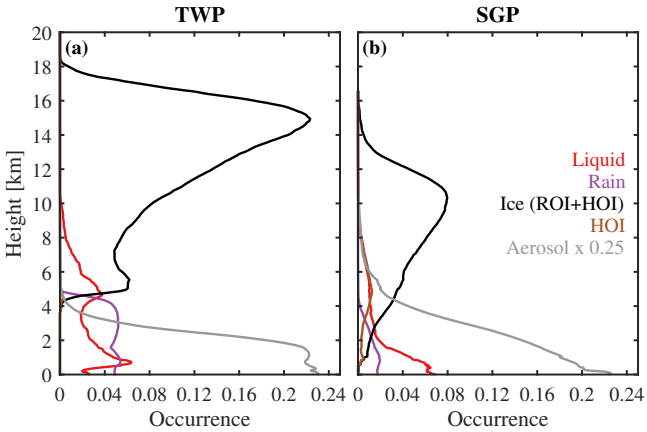

Day
Night
(a)
(b)
RL
RL (no cloud)
CALIPSO
CALIPSO (no cloud)
Height [km]
0
1
2
3
4
5
6
7
8
0
0.2
0.4
0.6
0.8
1
Aerosol occurrence (transparent profiles)

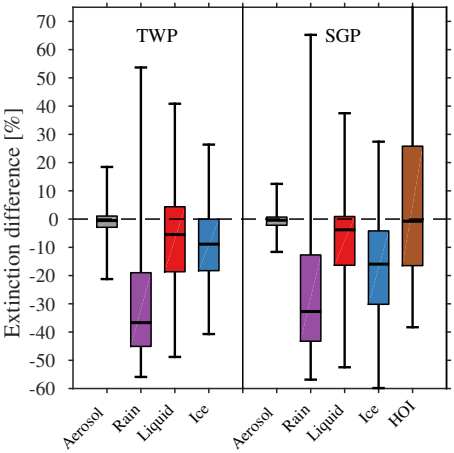

(a) TWP: direct retrievals
N = 3020
slope = 0.99
r = 0.91
RMS = 26.2%
bias = -6.0%
(b) TWP: all
N = 3478
slope = 0.98
r = 0.91
RMS = 27.3%
bias = -6.3%
(c) SGP: direct retrievals
N = 11037
slope = 0.97
r = 0.85
RMS = 33.1%
bias = -2.9%
(d) SGP: all
N = 24486
slope = 0.93
r = 0.84
RMS = 41.0%
bias = -2.7%
RL-FEX aerosol optical depth
Sun photometer aerosol optical depth
Frequency [%]

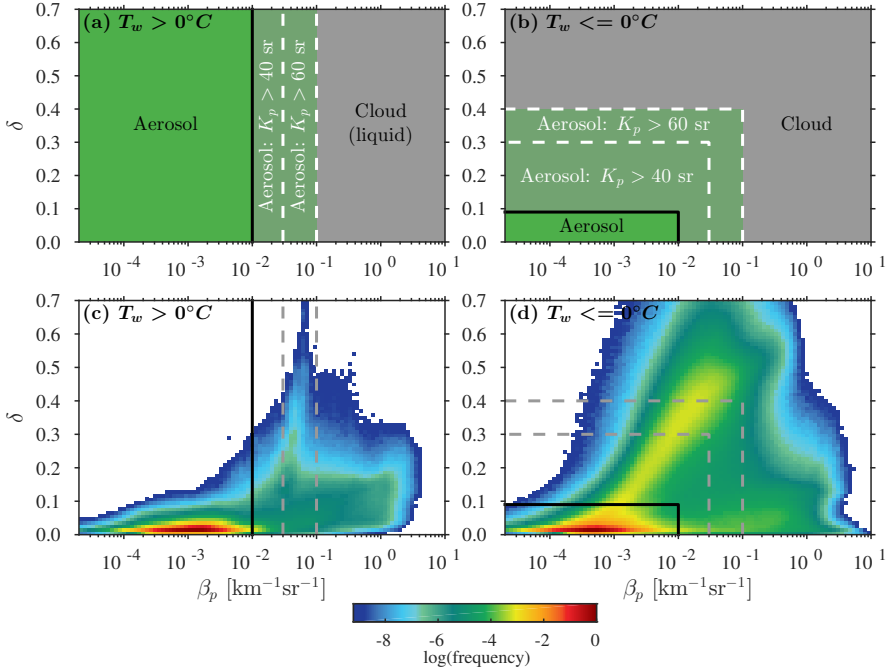

(a)
Total
N = 2504446
slope = 1.07
r = 0.99
RMS = 47.2%
bias = 11.8%
Low elastic signal
High elastic signal
(b)
Single-scattering
N = 2504446
slope = 1.00
r = 0.99
RMS = 32.1%
bias = 0.6%
Low elastic signal
High elastic signal
(c)
Total
N = 1290380
slope = 0.97
r = 0.97
RMS = 19.4%
bias = 6.9%
Low N2 signal
High N2 signal
(d)
Single-scattering
N = 1290380
slope = 0.98
r = 0.98
RMS = 17.1%
bias = 0.5%
Low N2 signal
High N2 signal
log10(counts)

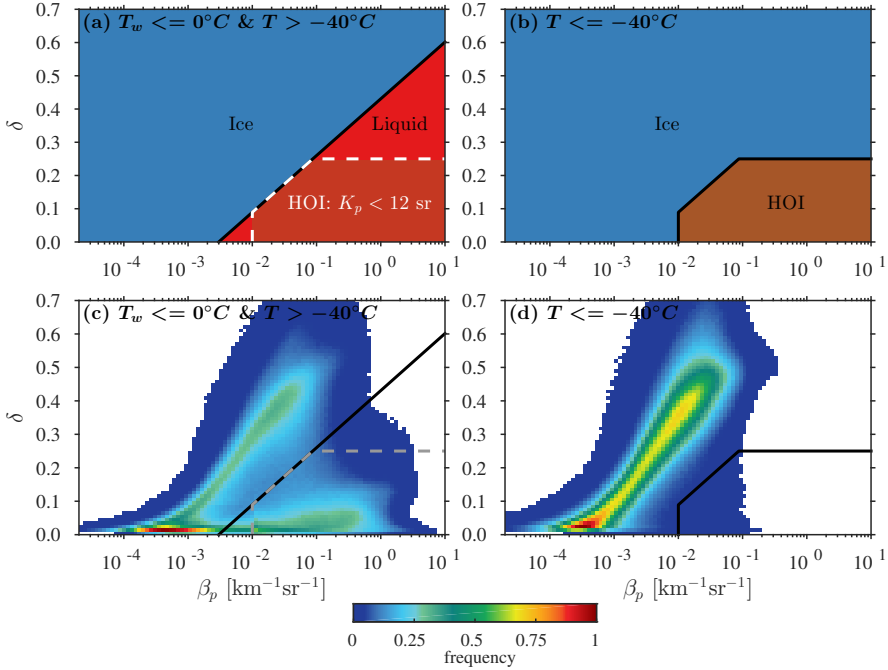

(a) SR_E
(b) Feature classification
(c) $S_{p,EN}$ [sr]
(d) $S^L_{p,EN}$ [sr]
(e) $S_{p,BE}$ [sr]
(f) $S_{p,BE}$ flag
Height [km]
Hour [UTC]
Aer
HOI
Ice
Rn
Liq
Clr
climo
day
prof
obj
lyr
trans
interp
Lsm6
Lsm5
Lsm4
Lsm3
Lsm2
Lsm1
Hsm6
Hsm5
Hsm4
Hsm3
Hsm2
Hsm1
Clr

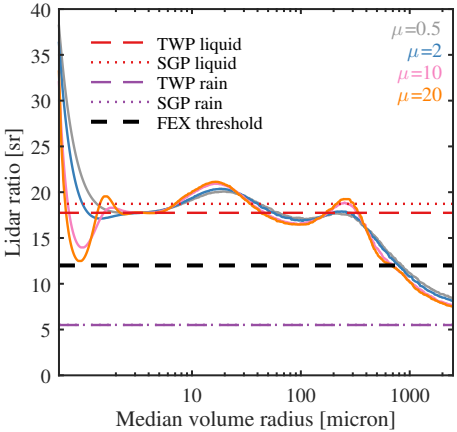

(a) δ
(b) $\beta_{p,BE}$ [log($km^{-1}sr^{-1}$)]
(c) $S'_{p,EN}$ [sr]
(d) Feature classification
Height [km]
Hour [UTC]
T_w=0 °C
T=-40 °C
Aer
HOI
Ice
Rn
Liq
Clr

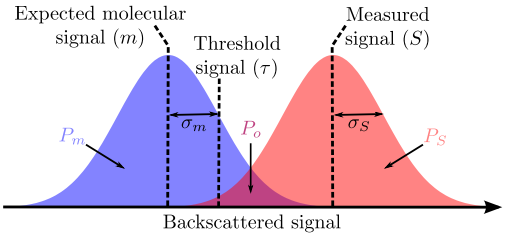

TWP
SGP
(a)
(b)
Height [km]
Occurrence
Occurrence
Liquid
Rain
Ice (ROI+HOI)
HOI
Aerosol x 0.25

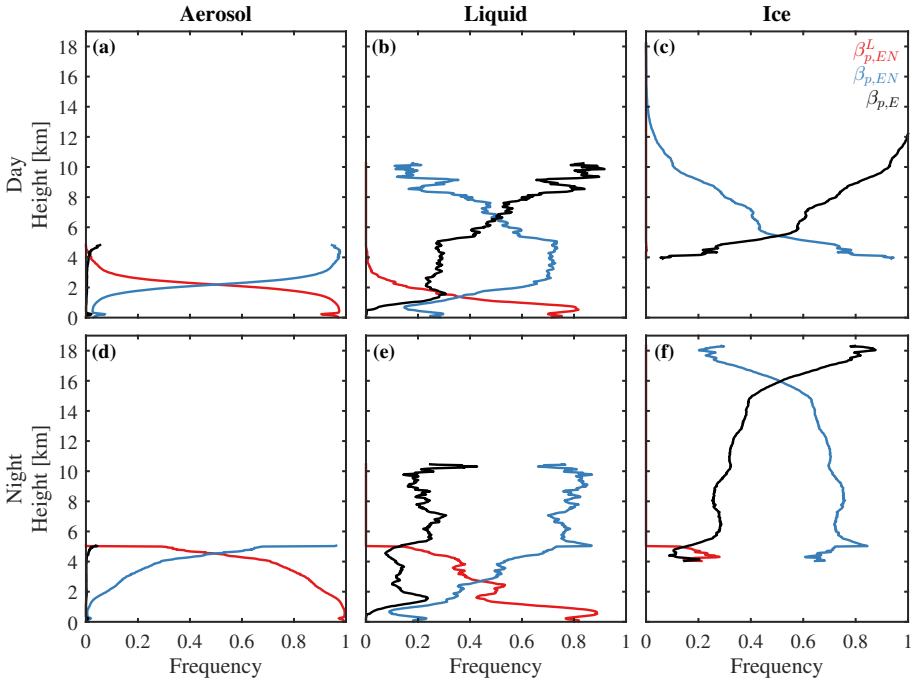

TWP
SGP
Extinction difference [%]
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Aerosol
Rain
Liquid
Ice
Aerosol
Rain
Liquid
Ice
HOI

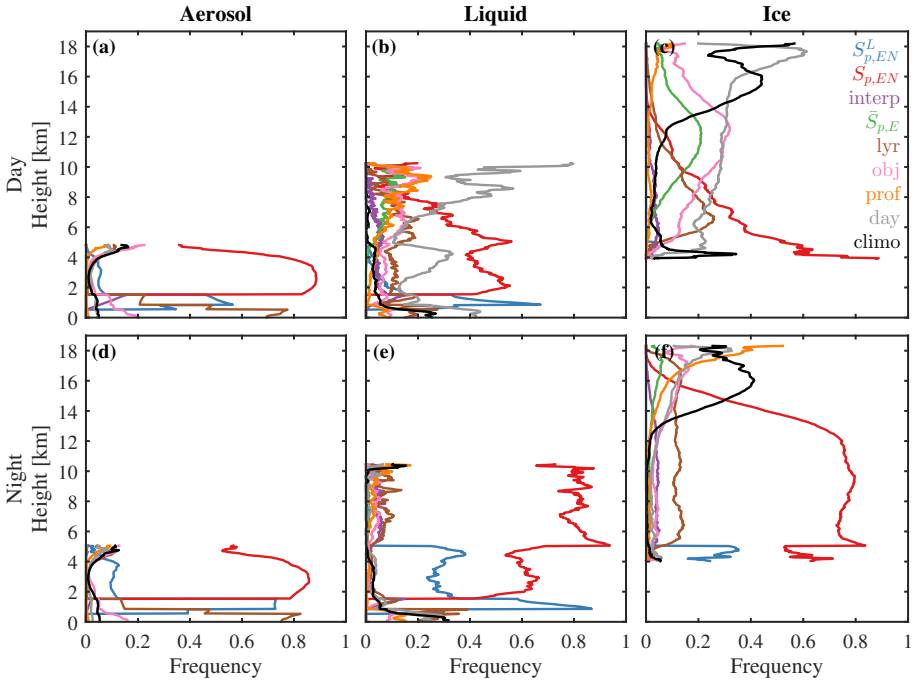

(a) $T_w > 0°C$
Aerosol
Aerosol: $K_p > 40$ sr
Aerosol: $K_p > 60$ sr
Cloud (liquid)
(b) $T_w <= 0°C$
Aerosol: $K_p > 60$ sr
Aerosol: $K_p > 40$ sr
Aerosol
Cloud
(c) $T_w > 0°C$
(d) $T_w <= 0°C$
δ
β_p [km^{-1}sr^{-1}]
log(frequency)

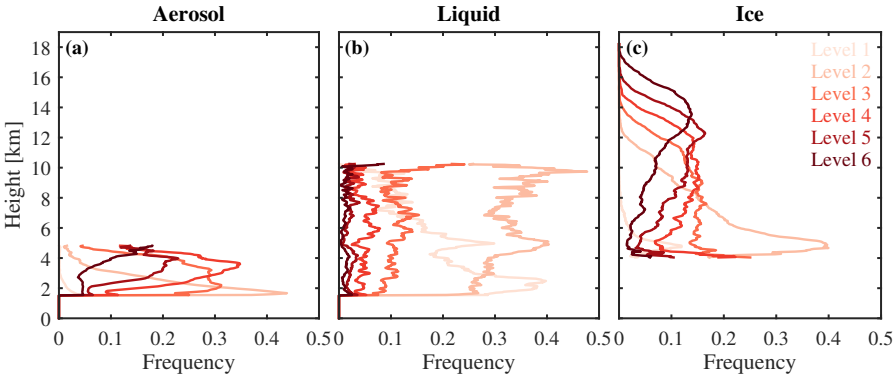

(a) $T_w <= 0°C$ & $T > -40°C$
Ice
Liquid
HOI: $K_p < 12$ sr
(b) $T <= -40°C$
Ice
HOI
(c) $T_w <= 0°C$ & $T > -40°C$
(d) $T <= -40°C$
δ
β_p [km^{-1}sr^{-1}]
frequency
0
0.25
0.5
0.75
1


TWP liquid
SGP liquid
TWP rain
SGP rain
FEX threshold
μ=0.5
μ=2
μ=10
μ=20
Lidar ratio [sr]
Median volume radius [micron]
0
5
10
15
20
25
30
35
40
10
100
1000


Expected molecular signal (m)
Threshold signal (τ)
Measured signal (S)
P_m
σ_m
P_o
σ_S
P_S
Backscattered signal


Aerosol
Liquid
Ice
(a)
(b)
(c)
(d)
(e)
(f)
$\beta^L_{p,EN}$
$\beta_{p,EN}$
$\beta_{p,E}$
Day
Night
Height [km]
Frequency
0
2
4
6
8
10
12
14
16
18
0.2
0.4
0.6
0.8
1


Aerosol
Liquid
Ice
(a)
(b)
(c)
(d)
(e)
(f)
Day
Night
Height [km]
Frequency
$S^L_{p,EN}$
$S_{p,EN}$
interp
$\bar{S}_{p,E}$
lyr
obj
prof
day
climo


Aerosol
Liquid
Ice
(a)
(b)
(c)
Height [km]
Frequency
Level 1
Level 2
Level 3
Level 4
Level 5
Level 6

Lidar ratio: Raman method

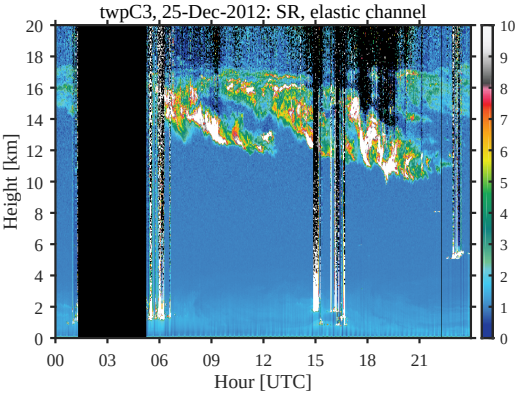
- Obtain a smoothed lidar ratio ($= \frac{\text{extinction}}{\text{backscatter}}$)
  (easier; quasi-high resolution extinction)

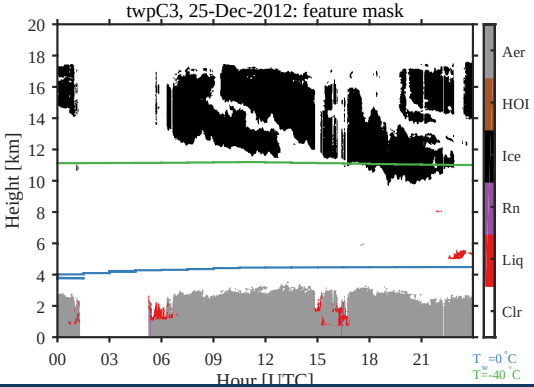
Lidar ratio: Raman method

- Obtain a smoothed lidar ratio ($= \frac{\text{extinction}}{\text{backscatter}}$)
  (easier; quasi-high resolution extinction)
- Lower height bins ignored (overlap)

Lidar ratio: Raman method

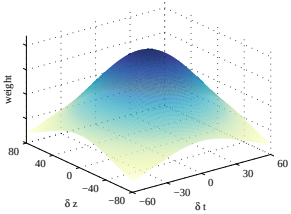
- Obtain a smoothed lidar ratio ($= \frac{\text{extinction}}{\text{backscatter}}$) (easier; quasi-high resolution extinction)
- Lower height bins ignored (overlap)
- Retrieved at multiple effective resolutions
  - Obtain the lidar ratio with a random error $< 30\%$ at the least amount of smoothing possible
  - Higher-resolution feature mask/classification is useful here



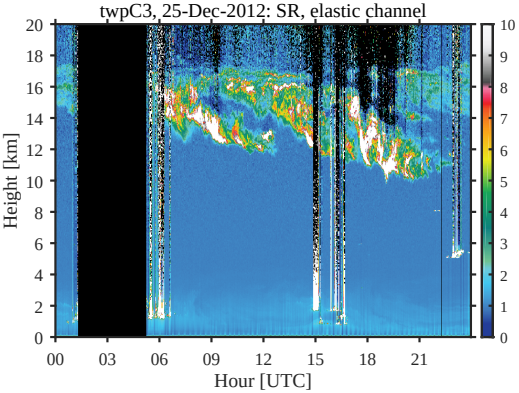


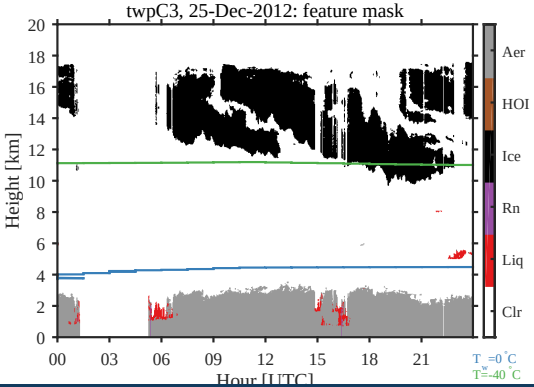
Lidar ratio: Raman method

- Obtain a smoothed lidar ratio ($= \frac{\text{extinction}}{\text{backscatter}}$)
  (easier; quasi-high resolution extinction)
- Lower height bins ignored (overlap)
- Retrieved at multiple effective resolutions
- Smoothing: 2D Gaussian
  (linear = easy to propagate uncertainty)



	Window size	
Level 1	1×1	(0.03 km×2 min)
Level 2	10×5	(0.3 km×10 min)
Level 3	20×15	(0.6 km×30 min)
Level 4	40×30	(1.2 km×60 min)
Level 5	80×60	(2.4 km×120 min)
Level 6	160×120	(4.8 km×240 min)





Lidar ratio: Raman method

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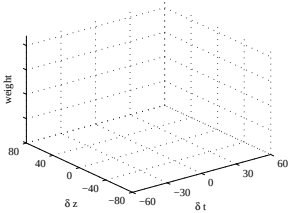

	Window size	
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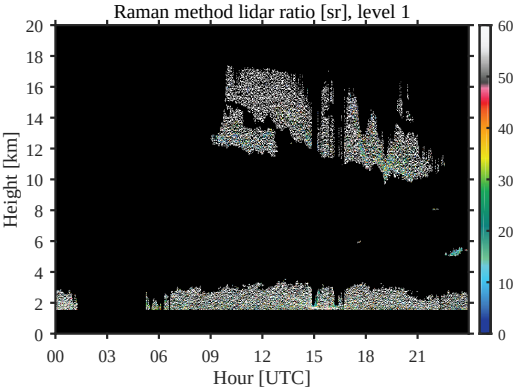

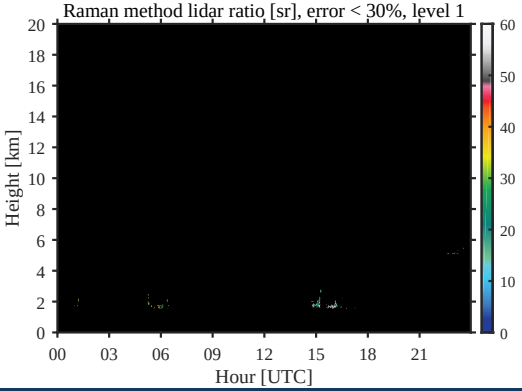

Lidar ratio: Raman method

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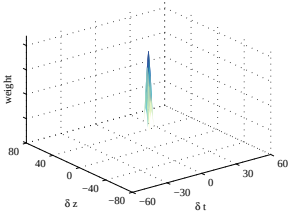

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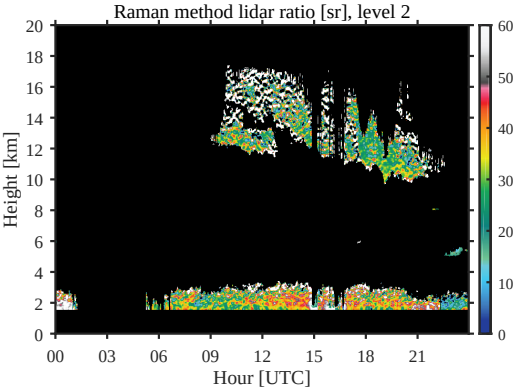

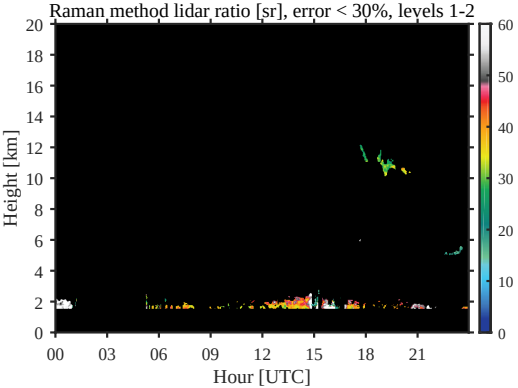

Lidar ratio: Raman method

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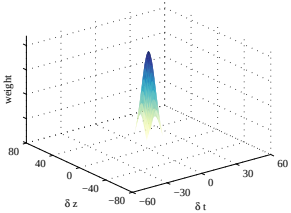

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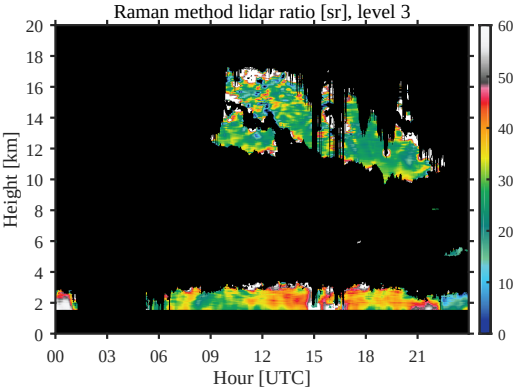

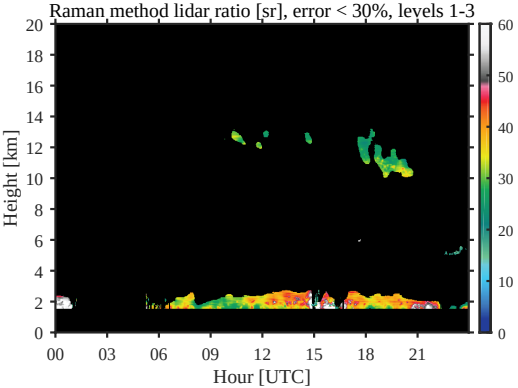

Lidar ratio: Raman method

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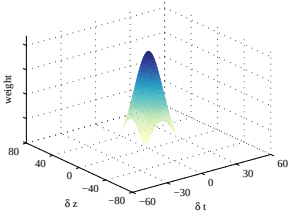
  (linear = easy to propagate uncertainty)



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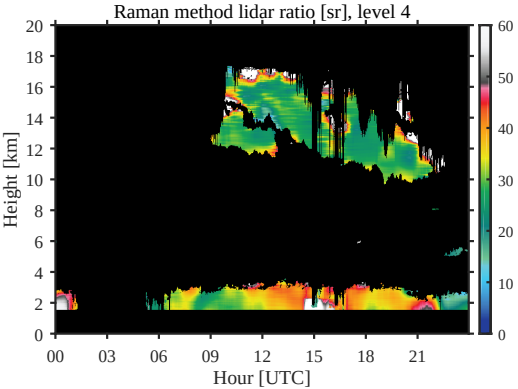

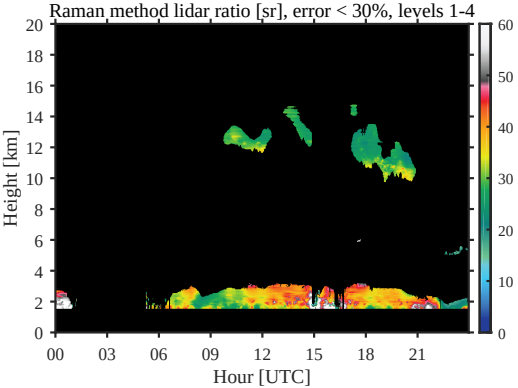

Lidar ratio: Raman method

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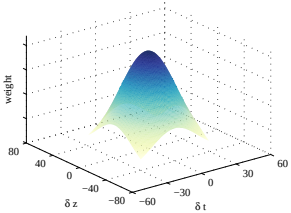
  (easier; quasi-high resolution extinction)
- Lower height bins ignored (overlap)
- Retrieved at multiple effective resolutions
- Smoothing: 2D Gaussian
  (linear = easy to propagate uncertainty)



	Window size	
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Level 2	10×5	(0.3 km×10 min)
Level 3	20×15	(0.6 km×30 min)
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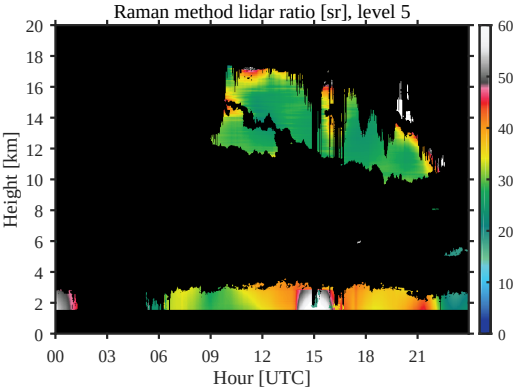
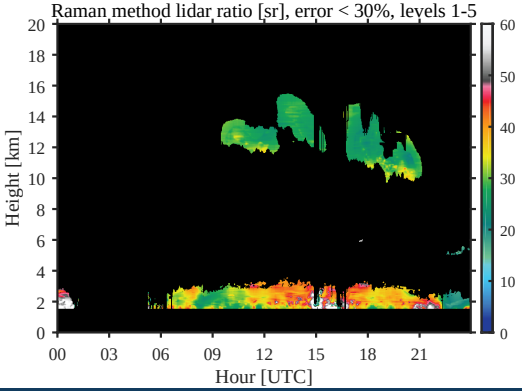
Level 6	160×120	(4.8 km×240 min)





Lidar ratio: Raman method

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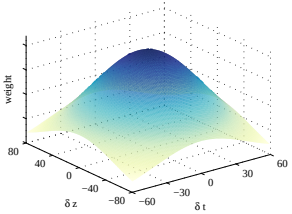
- Retrieved at multiple effective resolutions
- Smoothing: 2D Gaussian
  (linear = easy to propagate uncertainty)



	Window size	
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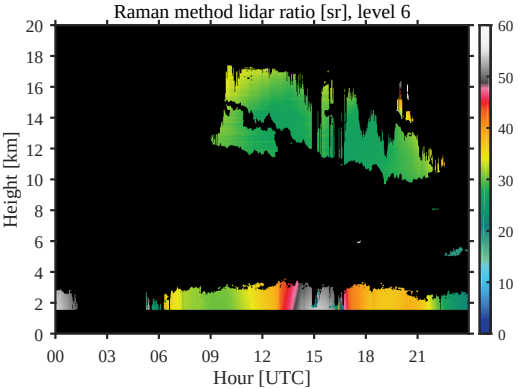
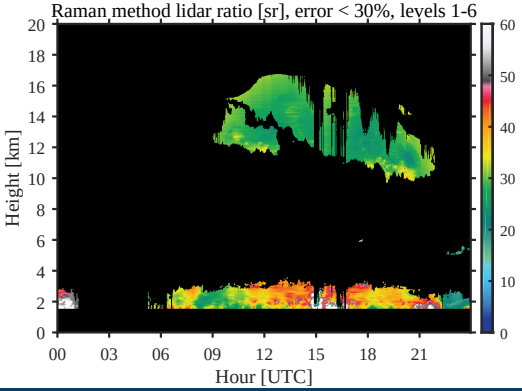
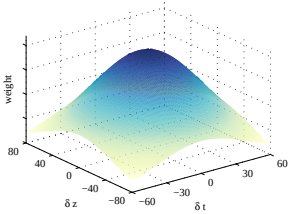
Level 6	160×120	(4.8 km×240 min)



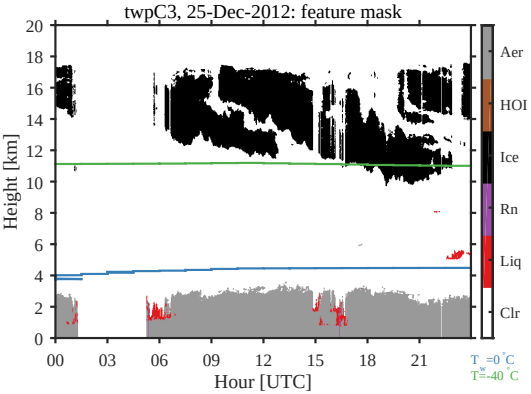


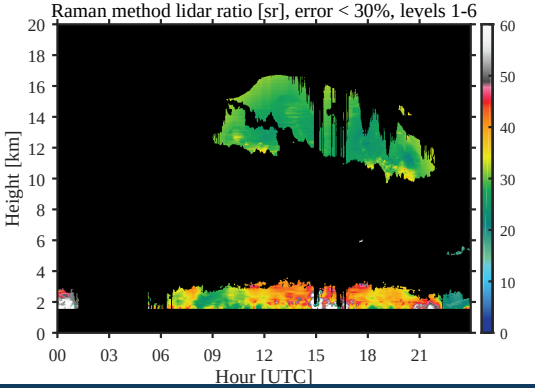
Lidar ratio: Raman method

- Obtain a smoothed lidar ratio ($= \frac{\text{extinction}}{\text{backscatter}}$)
  (easier; quasi-high resolution extinction)
- Lower height bins ignored (overlap)
- Retrieved at multiple effective resolutions
- Smoothing: 2D Gaussian
  (linear = easy to propagate uncertainty)



	Window size	
Level 1	1×1	(0.03 km×2 min)
Level 2	10×5	(0.3 km×10 min)
Level 3	20×15	(0.6 km×30 min)
Level 4	40×30	(1.2 km×60 min)
Level 5	80×60	(2.4 km×120 min)
Level 6	160×120	(4.8 km×240 min)

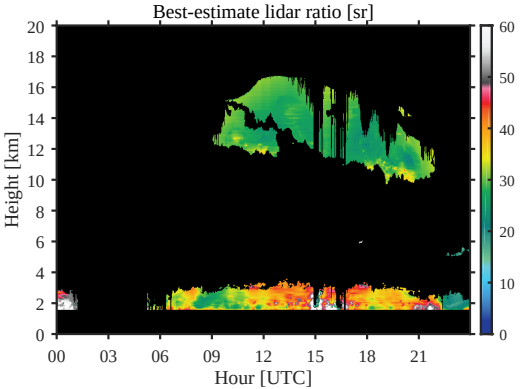


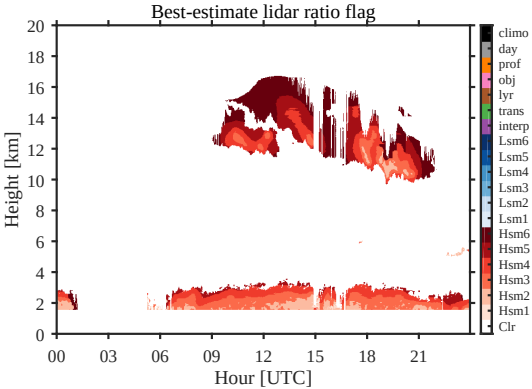


Lidar ratio: Best-estimate

Directly-retrieved:

❶ **High channel Raman method**





Lidar ratio: Best-estimate

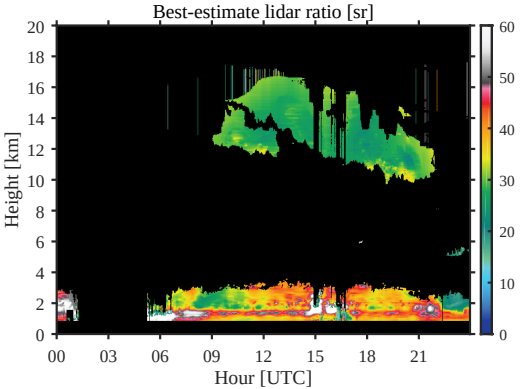
Directly-retrieved:

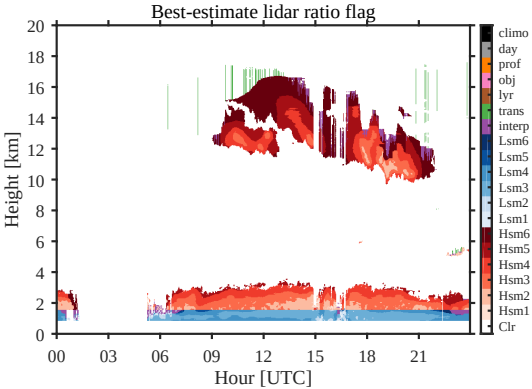
❶ **High channel Raman method**

❷ **Low channel Raman method**

❸ **Interpolation**

❹ **Layer-averaged constrained by transmission-loss and ❶ – ❸**





Lidar ratio: Best-estimate

Directly-retrieved:

❶ **High channel Raman method**

❷ **Low channel Raman method**

❸ **Interpolation**

❹ **Layer-averaged constrained by transmission-loss and ❶ – ❸**

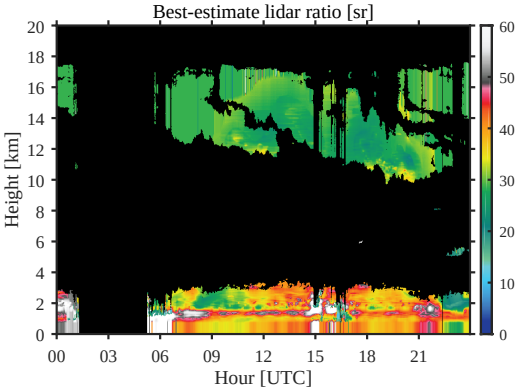
Inferred:

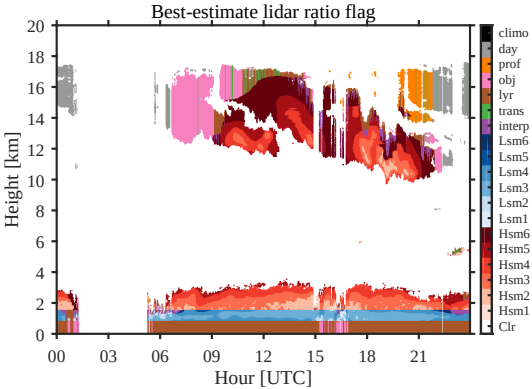
❺ **Layer-averaged: ❶ – ❹**

❻ **Object-averaged: ❶ – ❹**

❼ **Profile-averaged: ❶ – ❹**

❽ **Daily-averaged: ❶ – ❹**





Lidar ratio: Best-estimate

Directly-retrieved:

❶ **High channel Raman method**

❷ **Low channel Raman method**

❸ **Interpolation**

❹ **Layer-averaged constrained by transmission-loss and ❶ – ❸**

Inferred:

❺ **Layer-averaged: ❶ – ❹**

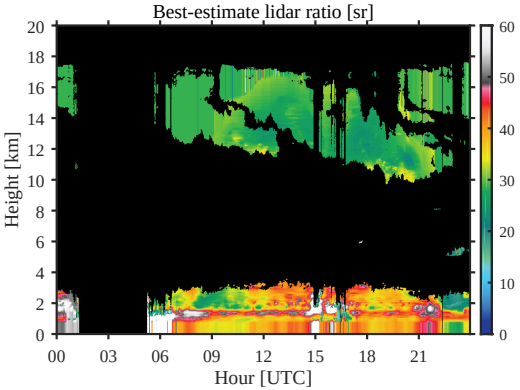
❻ **Object-averaged: ❶ – ❹**

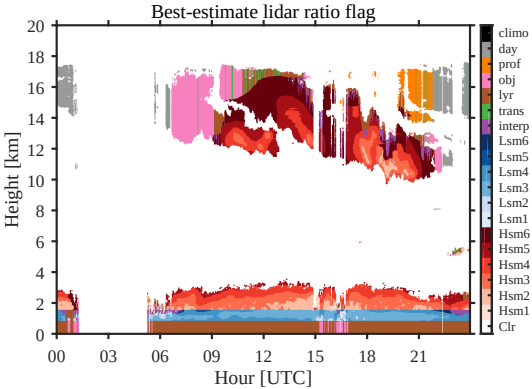
❼ **Profile-averaged: ❶ – ❹**

❽ **Daily-averaged: ❶ – ❹**

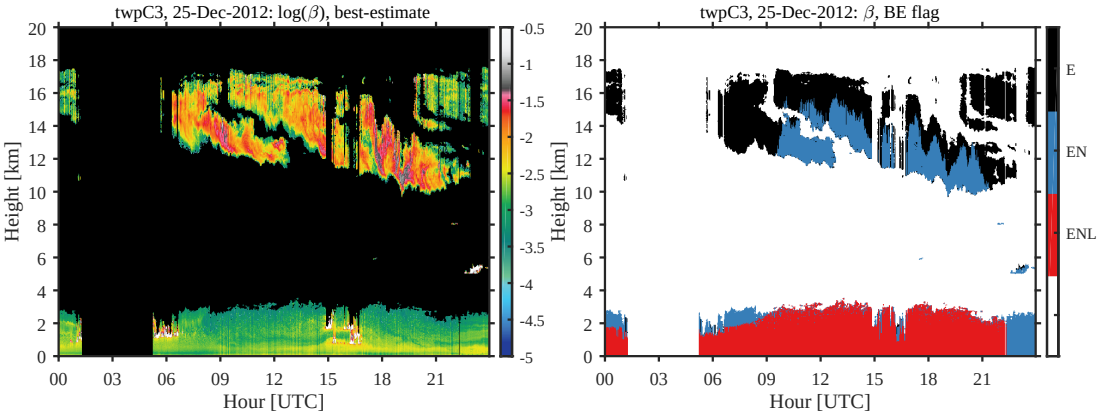
Assumed:

❾ **Climatology from ❶ – ❹**





Particulate backscatter best-estimate



Depending on the nitrogen channels SNRs:

1. Derived from low elastic+nitrogen channels
2. Derived from high elastic+nitrogen channels
3. Derived from high elastic channel: analytical solution using the best-estimate lidar ratio profile