Automatic Lidar and Ceilometer Framework (ALCF)

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University of Canterbury, 19 July 2019

Introduction

Introduction

- topic: active remote sensing of clouds and aerosol
- ground-based or spaceborne instruments
- lidar, radar, ...
- focus of this talk: lidars
- problem: unlike spaceborne lidars, ground-based lidars do not have well-developed processing and model evaluation tools
- **ALCF** – Automatic Lidar and Ceilometer Framework – open source tool for processing of lidar data and lidar simulation

alcf-lidar.github.io

GitHub

ALCF beta

Automatic Lidar and Ceilometer Framework

About Installation Tutorial Documentation Support

ALCF is an open source command line tool for processing of automatic lidar and ceilometer (ALC) data and intercomparison with atmospheric models such as general circulation models (GCMs), numerical weather prediction (NWP) models and reanalyses utilising a lidar simulator of the COSP instrument simulator framework. ALCs are vertically pointing atmospheric lidars, measuring cloud and aerosol backscatter. The primary focus of ALCF are atmospheric studies of cloud using ALC observations and model cloud validation.

Features

Multiple instruments and models

ALCF can process data from multiple ceilometers and lidars: Vaisala CL31, CL51, Lufft CHM 15k, Sigma Space MiniMPL. Multiple models and reanalyses are supported by the lidar simulator: MERRA-2, AMPS, NZCSM.

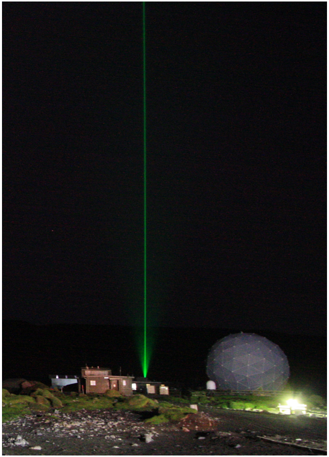
ALCs

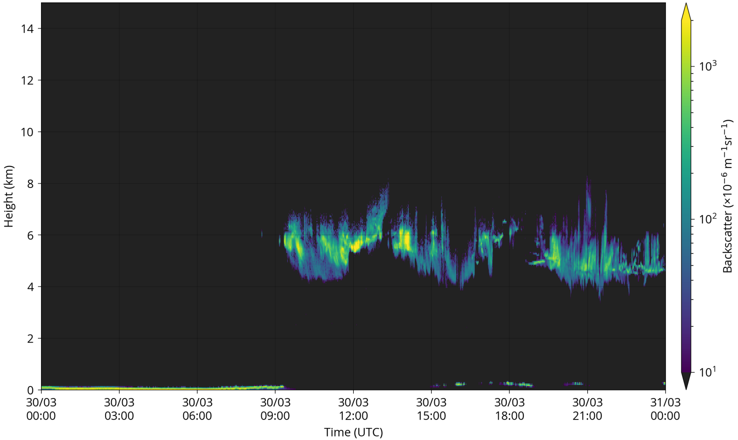
- *automatic lidars* and *ceilometers*
- measurement of cloud and aerosol with laser ranging
- vertical or off-zenith
- range: 7–15 km (typically)
- types:
  - **lidars** – high power/resolution, visible or near-infrared, custom or off-the-shelf, optionally polarisation, multiple wavelengths, inelastic scattering
  - **ceilometers** – low power lidars, often near-infrared, off-the-shelf, single wavelength, no polarisation, no inelastic scattering
- ceilometers commonly used at airports for cloud base height determination and recently volcanic ash detection, weather & climate research
- lidars used for weather & climate research, aerosol detection
- space equivalents: Space Shuttle/LITE, ICESat/GLAS, CALIPSO/CALIOP, ISS/CATS, EarthCARE/ATLID (future)
- ALCF supported ALCs: Vaisala CL31, CL51, Lufft CHM 15k, Sigma Space MiniMPL


Lufft CHM 15k

Lidar operation

- pulsed lidar – short laser pulses are sent out to the atmosphere, backscatter is measurement by the receiver
- raw output: received signal strength as a function of range
- signal can be converted to (volume) backscatter coefficient (m^{-1}sr^{-1}) (requires calibration)
- instruments often uncalibrated, report backscatter in arbitrary units (a.u.) proportional to the backscatter coefficient
- range averaging about 30–50 m (typical)
- temporal averaging 2–30 s (typical)
- result: 2-dimensional “curtain” plot (time $\times$ range)




14
12
10
8
6
4
2
0
Height (km)
30/03 00:00
30/03 03:00
30/03 06:00
30/03 09:00
30/03 12:00
30/03 15:00
30/03 18:00
30/03 21:00
31/03 00:00
Time (UTC)
10^3
10^2
10^1
Backscatter ($\times10^{-6}$ m^{-1}sr^{-1})

Lidar equation

- special case of the radiative transfer equation (RTE) / Beer–Lambert law:

$$P(r) = C\frac{1}{r^2}\beta(r)\exp\left(-2\int_0^r \alpha(r')\mathrm{d}r'\right)$$

- $r = c\Delta t$
- c – speed of light
- Δt – time delta
- P – signal strength (received power)
- C – calibration constant
- r – range (m)
- β – (volume) backscatter coefficient
- α – (volume) extinction coefficient

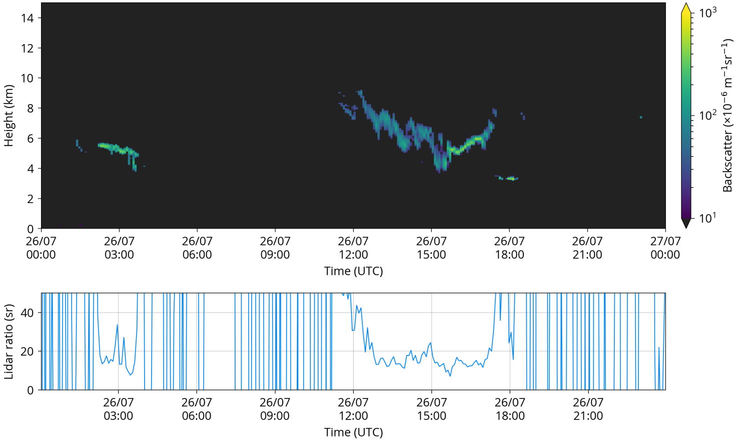
Lidar data processing

Lidar data processing

- processing of backscatter to get derived products
- products: cloud layers, PBL height, aerosol layers, cloud/aerosol types
- inversion (Fernald, Klett): aerosol concentration, AOD, ...
- products are firmware dependent and closed (black boxes) – hard/impossible to compare between instruments and models
- ALCF: **calibration**, **noise removal**, **cloud detection**
- aim: make it easy to make similar products to what is common in satellite Earth observation

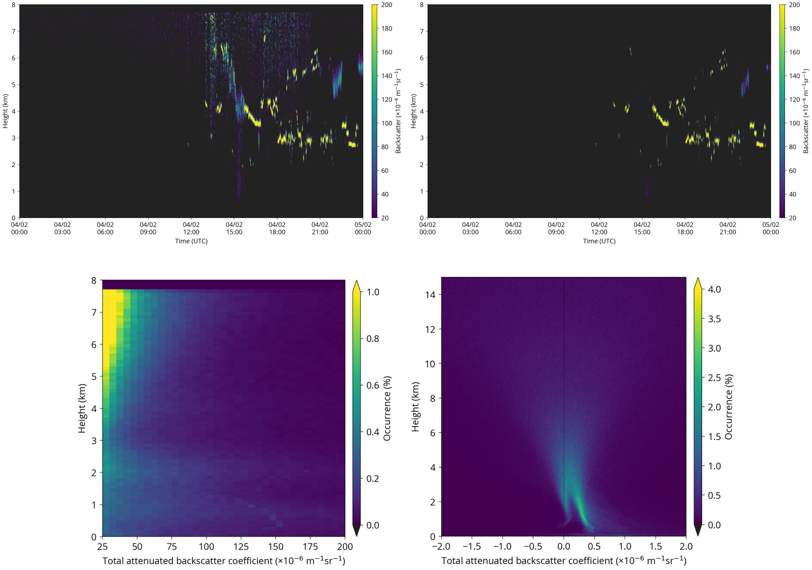
Calibration

- two common methods:
  1. fully attenuating stratocumulus clouds tend to result in a particular lidar ratio when backscatter is integrated vertically
  2. molecular backscatter can be compared with expected profile in aerosol-free atmosphere
- [1] appears to be easier/more common, especially with ceilometers
- [2] ceilometers need long integration time to detect molecular backscatter, aerosol optical depth potentially unknown (unless measured by a sun photometer)
- [1] lidar ratio tends to be about 10–20 sr
- ALCF implements [1] by plotting column lidar ratio along backscatter

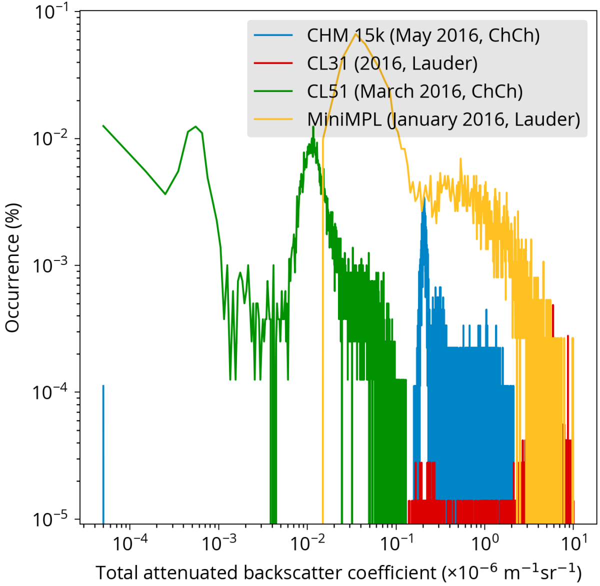

Height (km)
14
12
10
8
6
4
2
0
26/07
00:00
26/07
03:00
26/07
06:00
26/07
09:00
26/07
12:00
26/07
15:00
26/07
18:00
26/07
21:00
27/07
00:00
Time (UTC)
10^3
10^2
10^1
Backscatter ($\times 10^{-6}$ m^{-1}sr^{-1})
Lidar ratio (sr)
40
20
0
26/07
03:00
26/07
06:00
26/07
09:00
26/07
12:00
26/07
15:00
26/07
18:00
26/07
21:00
Time (UTC)

Noise

- noise sources:
  1. sunlight
  2. electronic noise
  3. multiple scattering
- some types are constant over the entire range [1, 2]
- we estimate noise distribution at the highest range (approximately normal), calculate mean and standard deviation, subtract mean scaled by r^2 at all levels, note the standard deviation



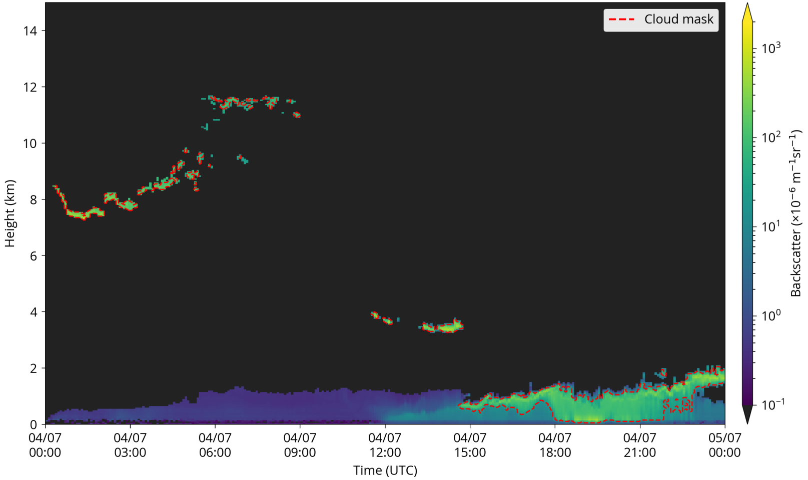
Height (km)
Time (UTC)
Backscatter (×10⁻⁶ m⁻¹sr⁻¹)
04/02 00:00
04/02 03:00
04/02 06:00
04/02 09:00
04/02 12:00
04/02 15:00
04/02 18:00
04/02 21:00
05/02 00:00
Height (km)
Occurrence (%)
Total attenuated backscatter coefficient (×10⁻⁶ m⁻¹sr⁻¹)
Height (km)
Occurrence (%)
Total attenuated backscatter coefficient (×10⁻⁶ m⁻¹sr⁻¹)



CHM 15k (May 2016, ChCh)
CL31 (2016, Lauder)
CL51 (March 2016, ChCh)
MiniMPL (January 2016, Lauder)
Occurrence (%)
Total attenuated backscatter coefficient (×10^{-6} m^{-1}sr^{-1})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

Cloud detection

- various algorithms exist, but we need something simple for comparison with models
- models don't simulate vertical gradients very well
- can we just use a backscatter threshold?
  - cloud backscatter tends to vary on log scale – not very sensitive
  - optimal choice seems to be 10^{-6} sr^{-1}m^{-1} (after calibration)
  - temporal and vertical subsampling to increase signal-to-noise ratio (default: 5 min by 50 m)
  - we know the noise standard deviation – if backscatter is at least 3 standard deviations greater than the threshold – it is cloud
- result: cloud mask, cloud base height
- advantages/disadvantages:
  - works well for simulated backscatter (explained later)
  - works for any range
  - possibly cannot detect faint clouds
  - occasionally misidentifies boundary layer aerosol as cloud if the threshold is too low
  - cannot distinguish cloud from precipitation or aerosol

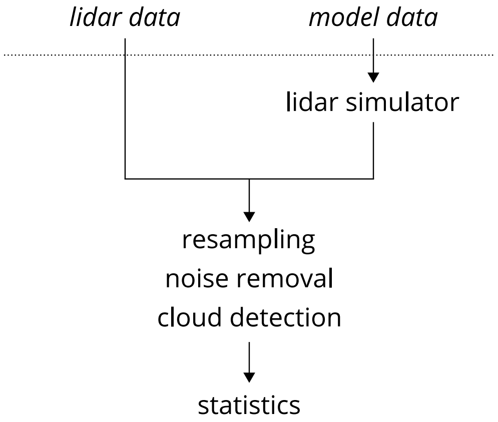


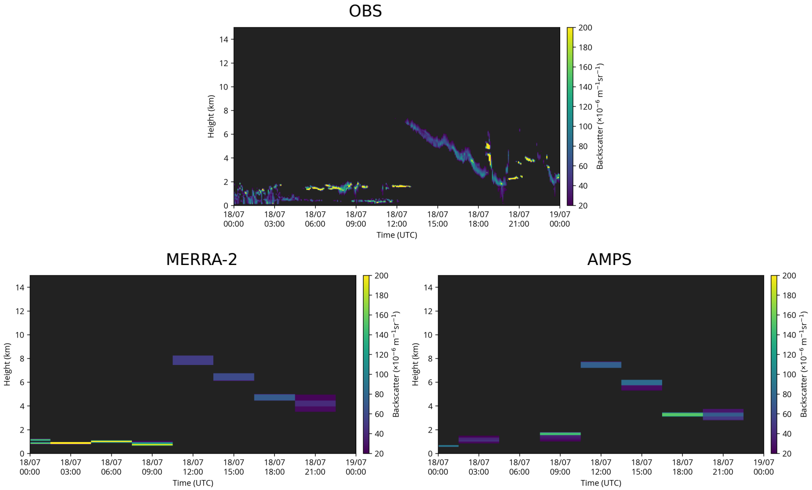
Cloud mask
Height (km)
Time (UTC)
Backscatter (×10^{-6} m^{-1}sr^{-1})
14
12
10
8
6
4
2
0
04/07 00:00
04/07 03:00
04/07 06:00
04/07 09:00
04/07 12:00
04/07 15:00
04/07 18:00
04/07 21:00
05/07 00:00
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}

Lidar simulator

Lidar simulator

- comparison between models and lidar observations for model evaluation
- here we focus on clouds – occurrence and opacity (albedo)
- models: cloud liquid/ice mass concentration
- lidars: backscatter coefficient
- direct comparison: convert backscatter to cloud liquid/ice mass concentration (hard, requires inversion)
- indirect comparison: convert cloud liquid/ice to backscatter (requires radiative transfer calculations)
- COSP/ACTSIM – satellite simulator package and lidar simulator, has been used with CALIPSO, and recently with ground-based lidars
- ground-based vs. spaceborne lidar differences:
    - viewing geometry (easy)
    - wavelength – Rayleigh (easy) and Mie scattering (hard)


lidar data
model data
lidar simulator
resampling
noise removal
cloud detection
statistics


OBS
MERRA-2
AMPS
Height (km)
Time (UTC)
Backscatter (×10⁻⁶ m⁻¹sr⁻¹)
18/07 00:00
18/07 03:00
18/07 06:00
18/07 09:00
18/07 12:00
18/07 15:00
18/07 18:00
18/07 21:00
19/07 00:00

Mie scattering

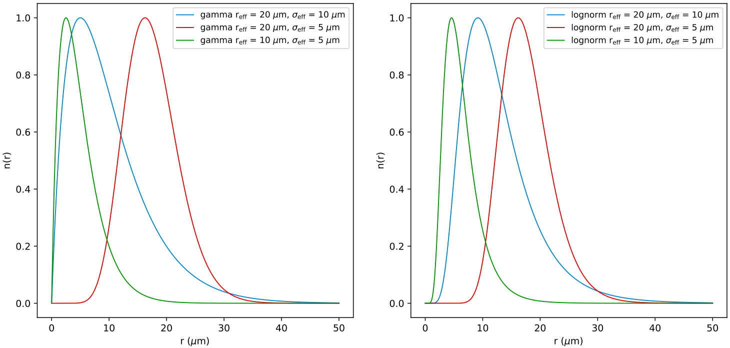
- scattering by spherical dielectric particles
- needs to be re-calculated for each laser wavelength
- extinction/scattering efficiency and scattering phase function
- scattering phase function highly-dependent on size parameter $x = 2\pi r/\lambda$
- cloud liquid/ice crystal theoretical distribution assumption:
  - Gamma
  - log-normal
- distribution parametrised by effective radius and effective standard deviation
- we integrate extinction efficiency, scattering phase function at 180 degrees over the size distribution to get the lidar ratio
- result: lookup table of lidar ratio as a function of the effective radius
- not all models provide effective radius – default 30 μm if not available
- (almost?) no models provide effective standard deviation – default 1/4 of effective radius

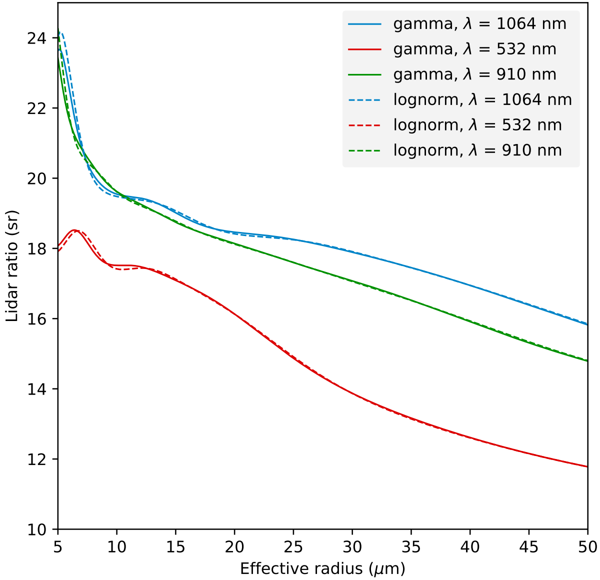
$$r_{\text{eff}} = \frac{\int_0^\infty r^3 n(r) \mathrm{d}r}{\int_0^\infty r^2 n(r) \mathrm{d}r}, \quad \sigma_{\text{eff}}^2 = \frac{\int_0^\infty (r - r_{\text{eff}})^2 r^2 n(r) \mathrm{d}r}{\int_0^\infty r^2 n(r) \mathrm{d}r}, \tag{1}$$

$$n(r) \propto \frac{1}{r} \exp\left(-\frac{(\log r - \mu)^2}{2\sigma^2}\right) \tag{2}$$

$$n(r) \propto r^{(1-3\nu_{\text{eff}})/\nu_{\text{eff}}} \exp\left(-\frac{r}{r_{\text{eff}}\nu_{\text{eff}}}\right) \tag{3}$$

$$k = \beta/\alpha_e = \frac{\int_0^\infty Q_s r^2 P_\pi(\pi)/(4\pi) n(r) \mathrm{d}r}{\int_0^\infty Q_e r^2 n(r) \mathrm{d}r} \tag{4}$$

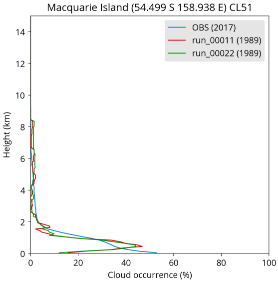

gamma r_{eff} = 20 μm, σ_{eff} = 10 μm
gamma r_{eff} = 20 μm, σ_{eff} = 5 μm
gamma r_{eff} = 10 μm, σ_{eff} = 5 μm
n(r)
r (μm)
lognorm r_{eff} = 20 μm, σ_{eff} = 10 μm
lognorm r_{eff} = 20 μm, σ_{eff} = 5 μm
lognorm r_{eff} = 10 μm, σ_{eff} = 5 μm
n(r)
r (μm)

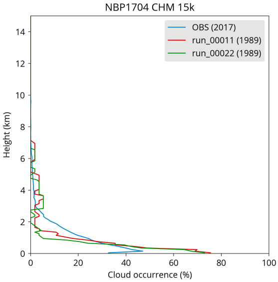


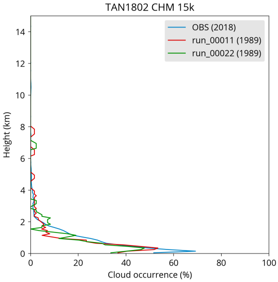
gamma, λ = 1064 nm
gamma, λ = 532 nm
gamma, λ = 910 nm
lognorm, λ = 1064 nm
lognorm, λ = 532 nm
lognorm, λ = 910 nm
Lidar ratio (sr)
Effective radius (μm)
10
12
14
16
18
20
22
24
5
10
15
20
25
30
35
40
45
50

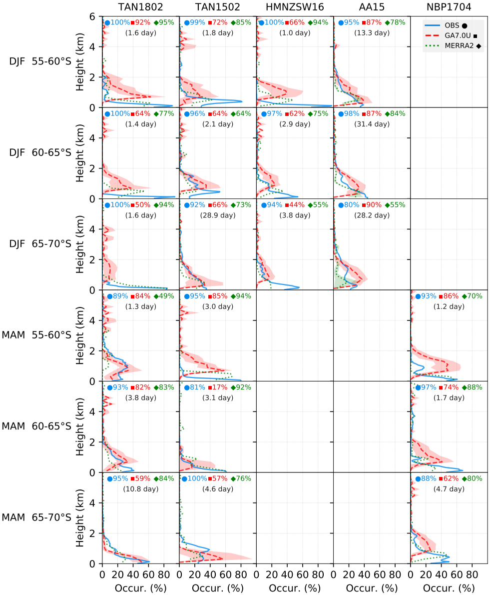
Results

Cloud occurrence







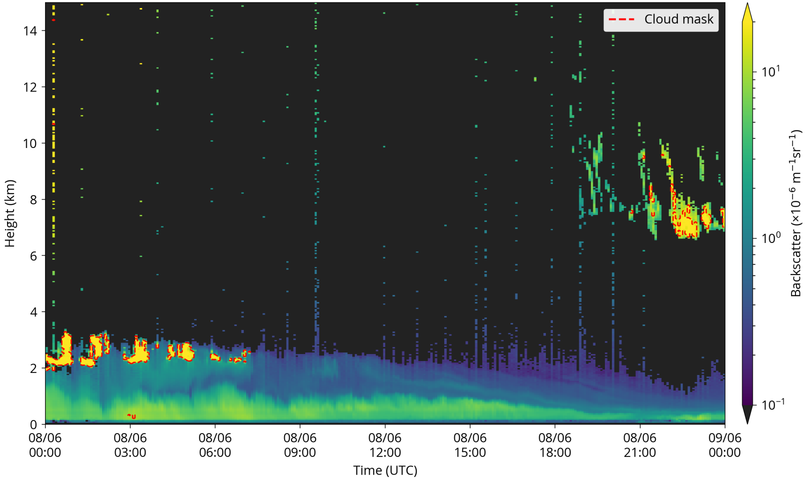


TAN1802
TAN1502
HMNZSW16
AA15
NBP1704
DJF 55-60°S
DJF 60-65°S
DJF 65-70°S
MAM 55-60°S
MAM 60-65°S
MAM 65-70°S
Height (km)
Occur. (%)
OBS ●
GA7.0U ■
MERRA2 ◆
●100% ■92% ◆95% (1.6 day)
●99% ■72% ◆85% (1.8 day)
●100% ■66% ◆94% (1.0 day)
●95% ■87% ◆78% (13.3 day)
●100% ■64% ◆77% (1.4 day)
●96% ■64% ◆64% (2.1 day)
●97% ■62% ◆75% (2.9 day)
●98% ■87% ◆84% (31.4 day)
●100% ■50% ◆94% (1.6 day)
●92% ■66% ◆73% (28.9 day)
●94% ■44% ◆55% (3.8 day)
●80% ■90% ◆55% (28.2 day)
●89% ■84% ◆49% (1.3 day)
●95% ■85% ◆94% (3.0 day)
●93% ■86% ◆70% (1.2 day)
●93% ■82% ◆83% (3.8 day)
●81% ■17% ◆92% (3.1 day)
●97% ■74% ◆88% (1.7 day)
●95% ■59% ◆84% (10.8 day)
●100% ■57% ◆76% (4.6 day)
●88% ■62% ◆80% (4.7 day)

Discussion and conclusion

More?

- many possibilities for improvement:
  - aerosol and precipitation detection
  - boundary layer detection
  - polarization
  - precipitation simulation
  - aerosol simulation
  - lidar inversion
  - cloud type detection
  - support for more instruments and models
  - alternative algorithms: noise removal, calibration, cloud detection
  - water vapour absorption at 910 nm (Vaisala CL31, CL51)



Cloud mask
Height (km)
0
2
4
6
8
10
12
14
08/06 00:00
08/06 03:00
08/06 06:00
08/06 09:00
08/06 12:00
08/06 15:00
08/06 18:00
08/06 21:00
09/06 00:00
Time (UTC)
10^{1}
10^{0}
10^{-1}
Backscatter ($\times 10^{-6}$ m^{-1}sr^{-1})

Conclusion

- ALCF – available already in beta version
- Geoscientific Model Development (GMD) paper in preparation
- we now have a tool which processes lidar data from multiple instruments in a comparable way and includes a lidar simulator supporting multiple models
- enables: lidar data processing, plotting and model evaluation
- output in standard formats (NetCDF) and plotting
- free to use and modify – not yet another vanity paper (rare in the world of ALCs)

Ground-based lidar simulator framework for comparing models and observations

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Abstract. Remote sensing of the atmosphere by spaceborne and ground-based instruments such as lidars and weather radars provides unparalleled amount of information about the atmospheric state, especially cloud and aerosol distribution. It is desirable to use these measurements for climate model and numerical weather prediction model validation, but measured quantities such as backscatter cannot be readily compared to model output. Remote sensing instrument simulators are a commonly used tool for model validation, which by converting model fields to intrument quantities (pseudo-observations) enable direct comparison. This approach has been used exensively with spaceborne instruments in the 5th Climate Model Intercomparison Project utilising the CFMIP Observation Simulator Package (COSP), but so far it lacked support for ground-based lidars. In this study we present a newly developed simulator of a ground-based lidar based on the spaceborne lidar simulator ACTSIM already present in COSP. We describe modifications which were necessary as well as processing of lidar observations required before they can be compared with the simulator output. We also perform validation of the new simulator by applying it to a cloud-resolving model. Three lidar instrumets are discussed: Lufft CHM 15k, Vaisala CL51 and SigmaSpace MiniMPL.

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