GLOBAL RETRIEVALS OF CLOUD CONDENSATION NUCLEI AND AEROSOL ABSORPTION BASED ON EARTHCARE ATLID OBSERVATIONS

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& the SoM CL²EAR group

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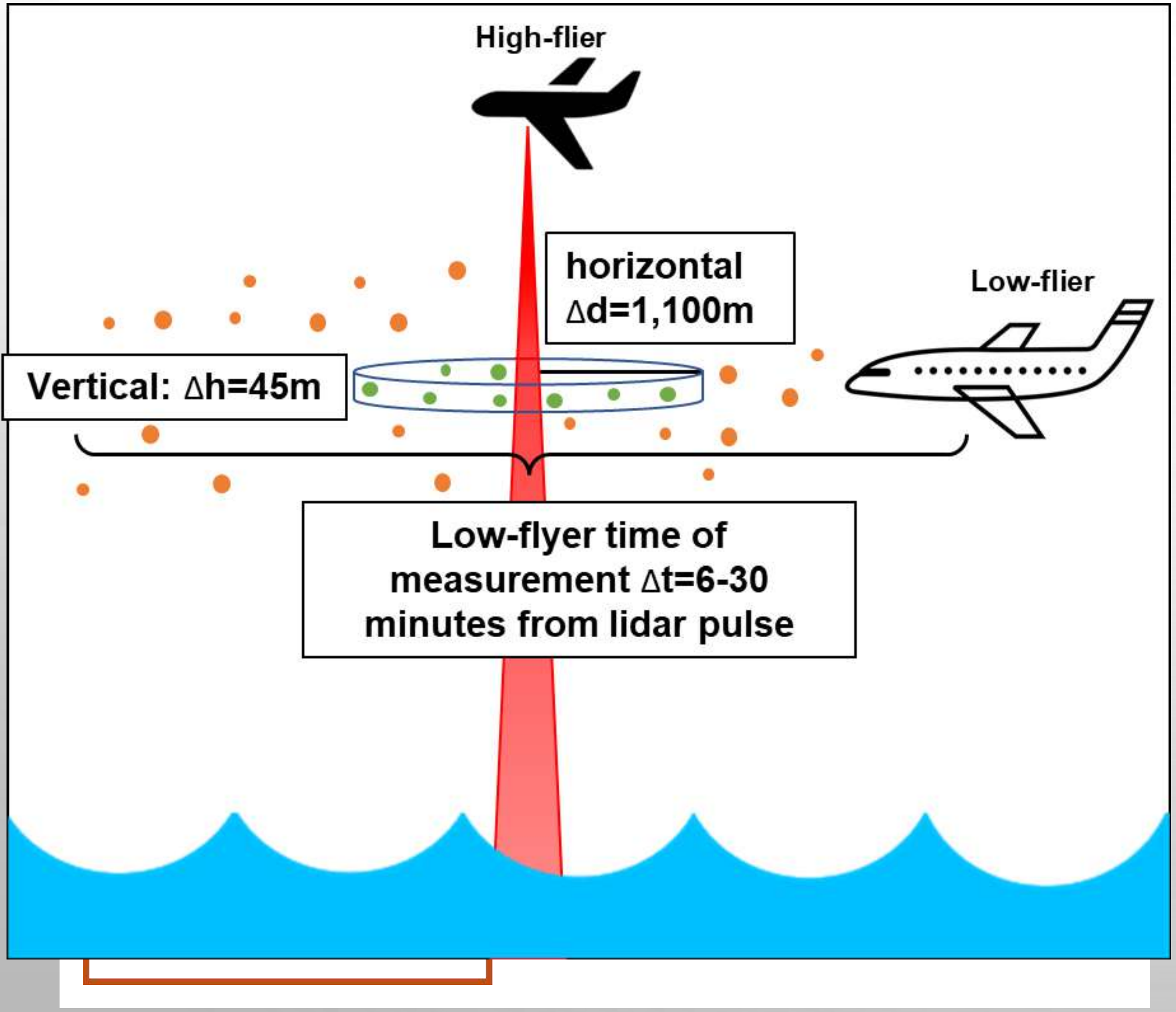
EarthCARE Workshop, Oxford, UK – June 9, 2026

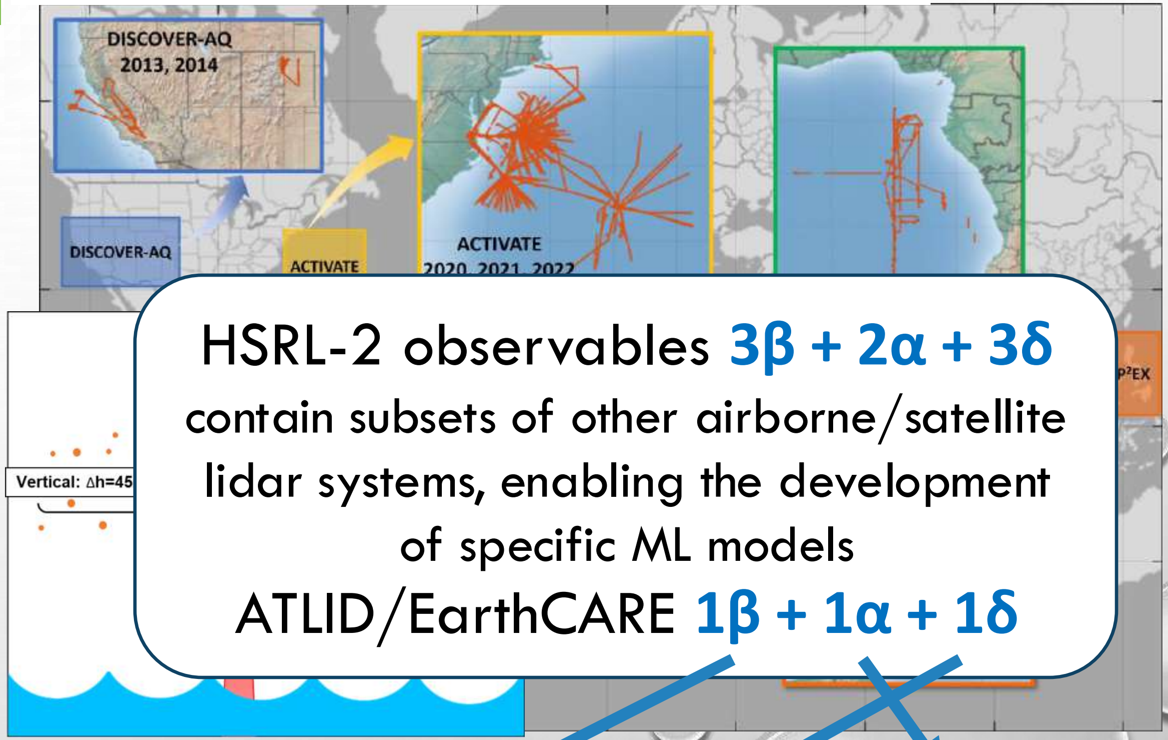
CLouds · CLimatE · Aerosols · Radiation

The Machine Learning augmentation… to physics-based aerosol retrievals

Machine Learning models to estimate CCN and ABS from multispectral lidar and reanalysis data as predictors



Redemann and Gao, Nature Communications, 2024

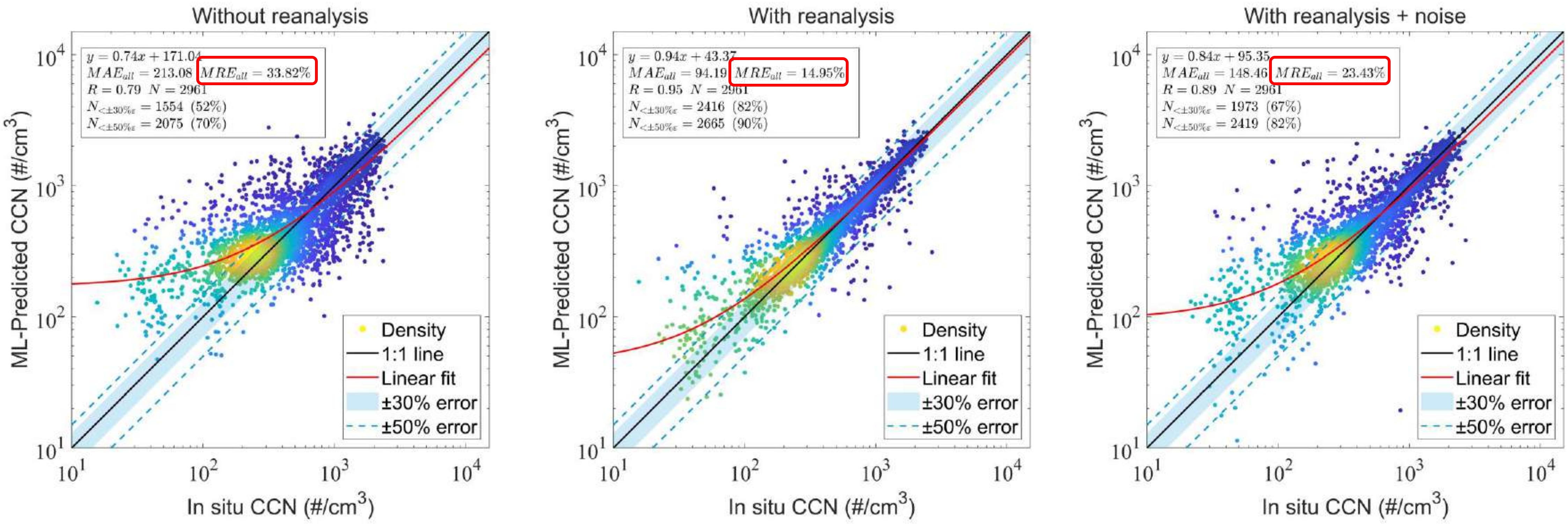


HSRL-2 observables **3β + 2α + 3δ** contain subsets of other airborne/satellite lidar systems, enabling the development of specific ML models

ATLID/EarthCARE **1β + 1α + 1δ**

Lidar observables	BSC_{355}, BSC_{532}, BSC_{1064}, EXT_{355}, EXT_{532}, $DEPO_{355}$, $DEPO_{532}$, $DEPO_{1064}$
Reanalysis	Relative humidity (RH), Temperature (T)
In situ	CCN concentration at 0.4% SS (~9,900) Absorption, ABS @ 532nm (~2,700)

Simulation of ML retrievals: CCN for EarthCARE/ATLID observables (1β + 1α + 1δ)



Adding reanalysis RH, T

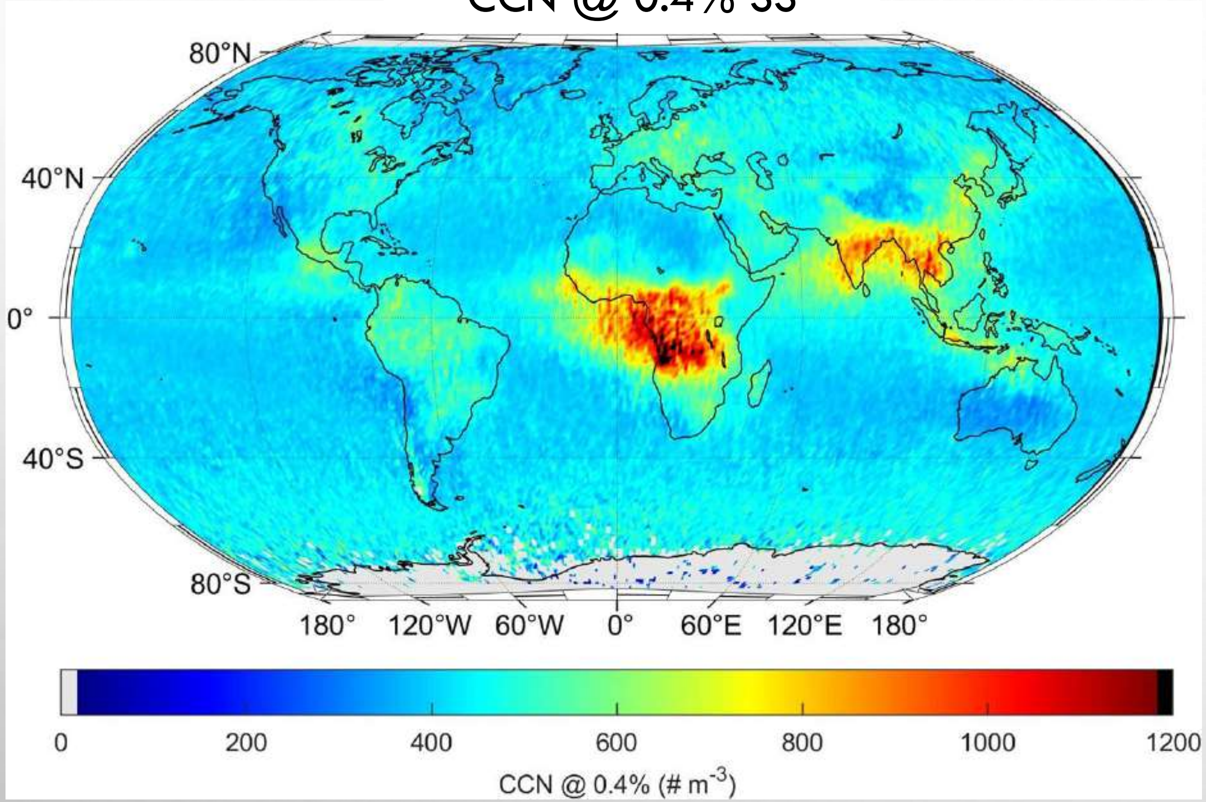
Adding simulated noise

Redemann and Gao, Nature Comm., 2024

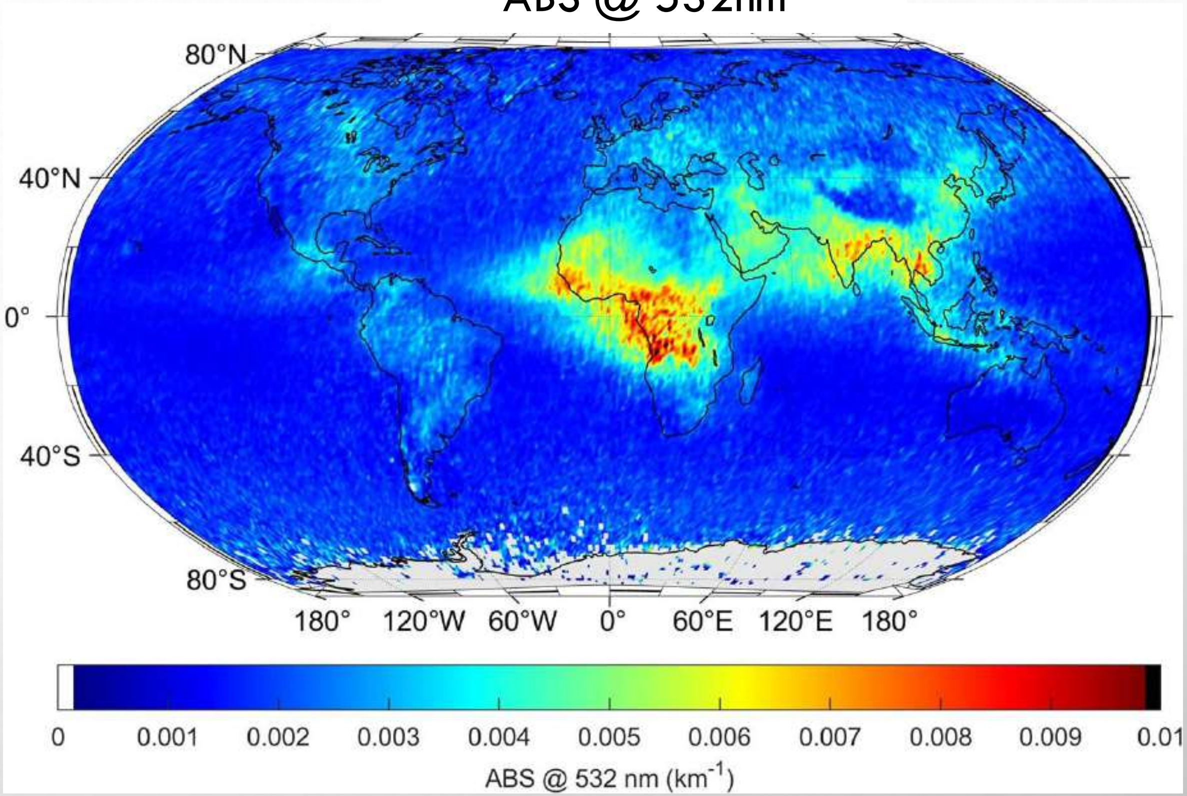
Global maps of CCN and ABS using ML models applied to ATLID

September 2024 – August 2025

CCN @ 0.4% SS



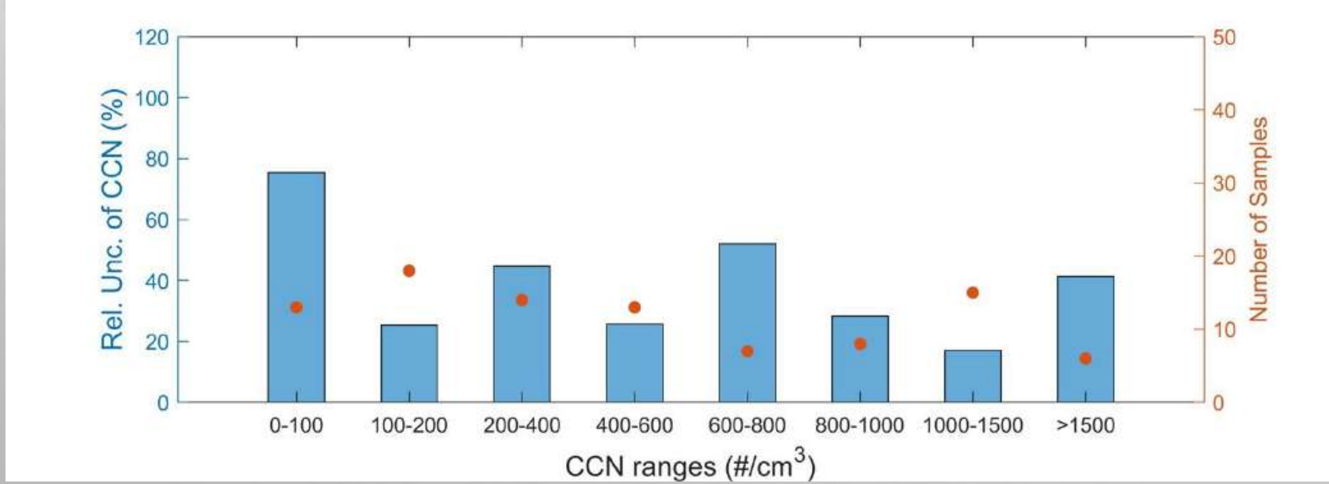
ABS @ 532nm

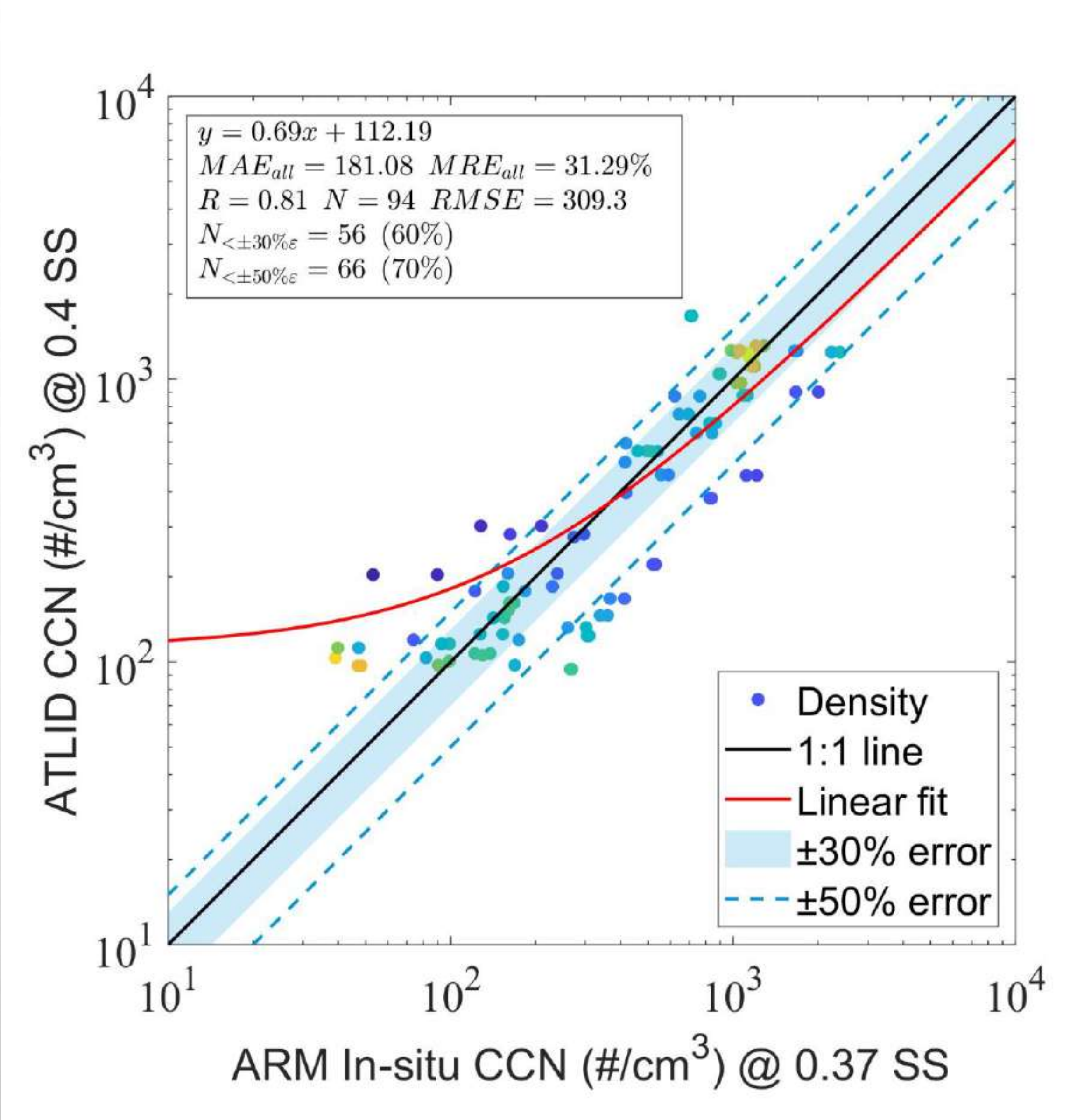


- Data: low-res. ATLID Version BA
- Additional data quality control:
  - Exclude grids (500m vertical) with less than 100 samples
- Spatial averaging:
  - Horizontal: 1 degree, Vertical: 0-10 km

Validation of ATLID-CCN retrievals against ARM in situ data

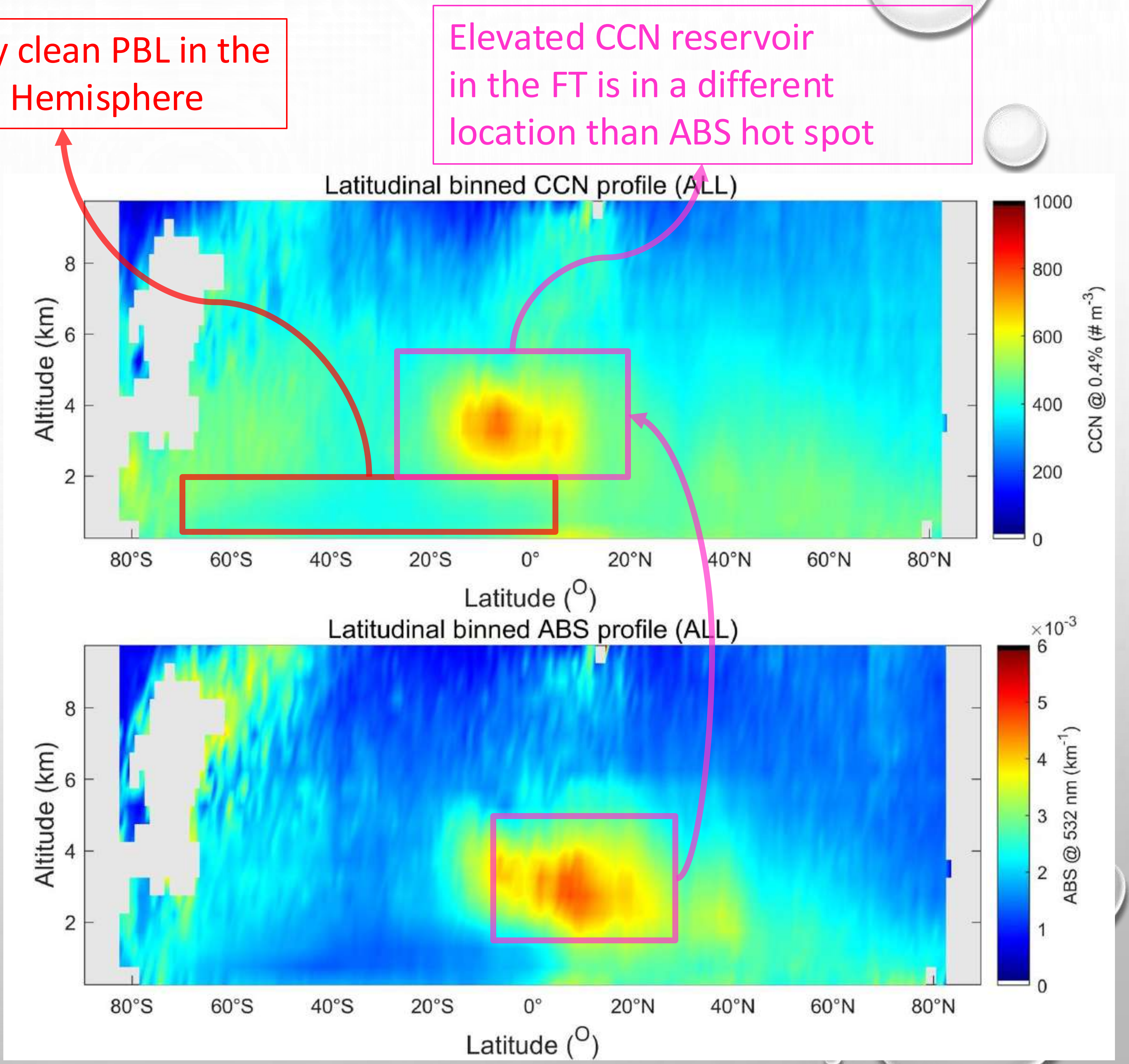
- In-situ surface data from ARM SGP, BNF, CRG & ENA:
  - Hourly averaged CCN
- ATLID retrievals:
  - ATLID BA version profiles below 500m
- Collocation criteria:
  - Temporal < 30 mins
  - Spatial < 50 km





Global vertical distributions of CCN and ABS from ATLID

- Data: low-res. ATLID BA data
- Time range: first 12 months
  - ➢ Sep.1, 2024 – Aug. 31, 2025
- Spatial averaging:
  - ➢ Horizontal: 1 degree
  - ➢ Vertical: 500 m from 0-10 km
- Retrieval criteria:
  - ➢ Positive ATLID EBD value
  - ➢ Quality assurance flagged as good
  - ➢ Target classification identified as aerosol
  - ➢ Uncertainty thresholds:
    - EXT & BSC <100% & DEPOL < 50%
- Additional data quality control:
  - ➢ Exclude grids with number of samples less than 100

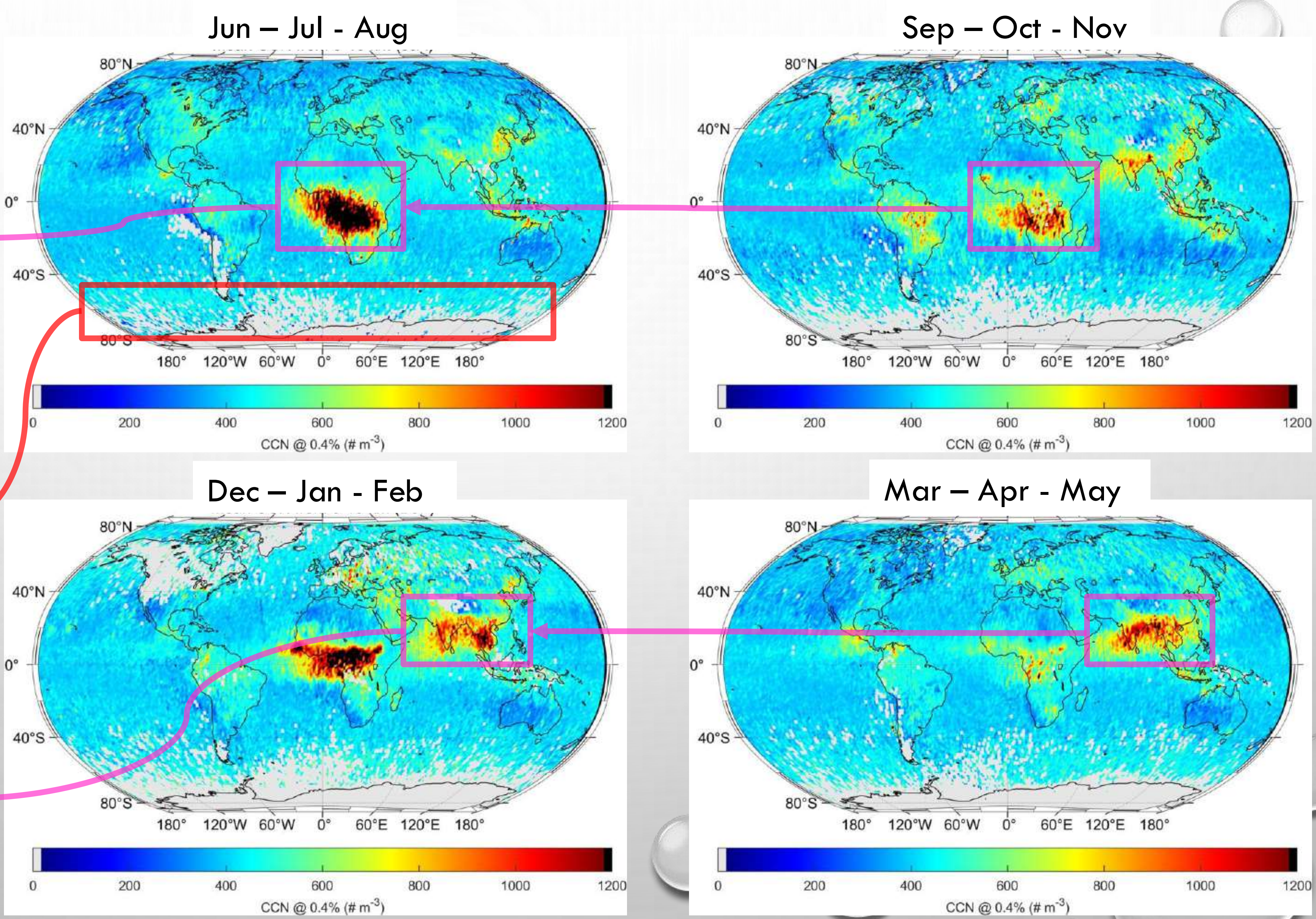


Global Seasonal Distributions of CCN

African sources dominate in NH summer and fall

Pristine, cloudy, bright surface conditions in Southern Oceans produce few retrievals

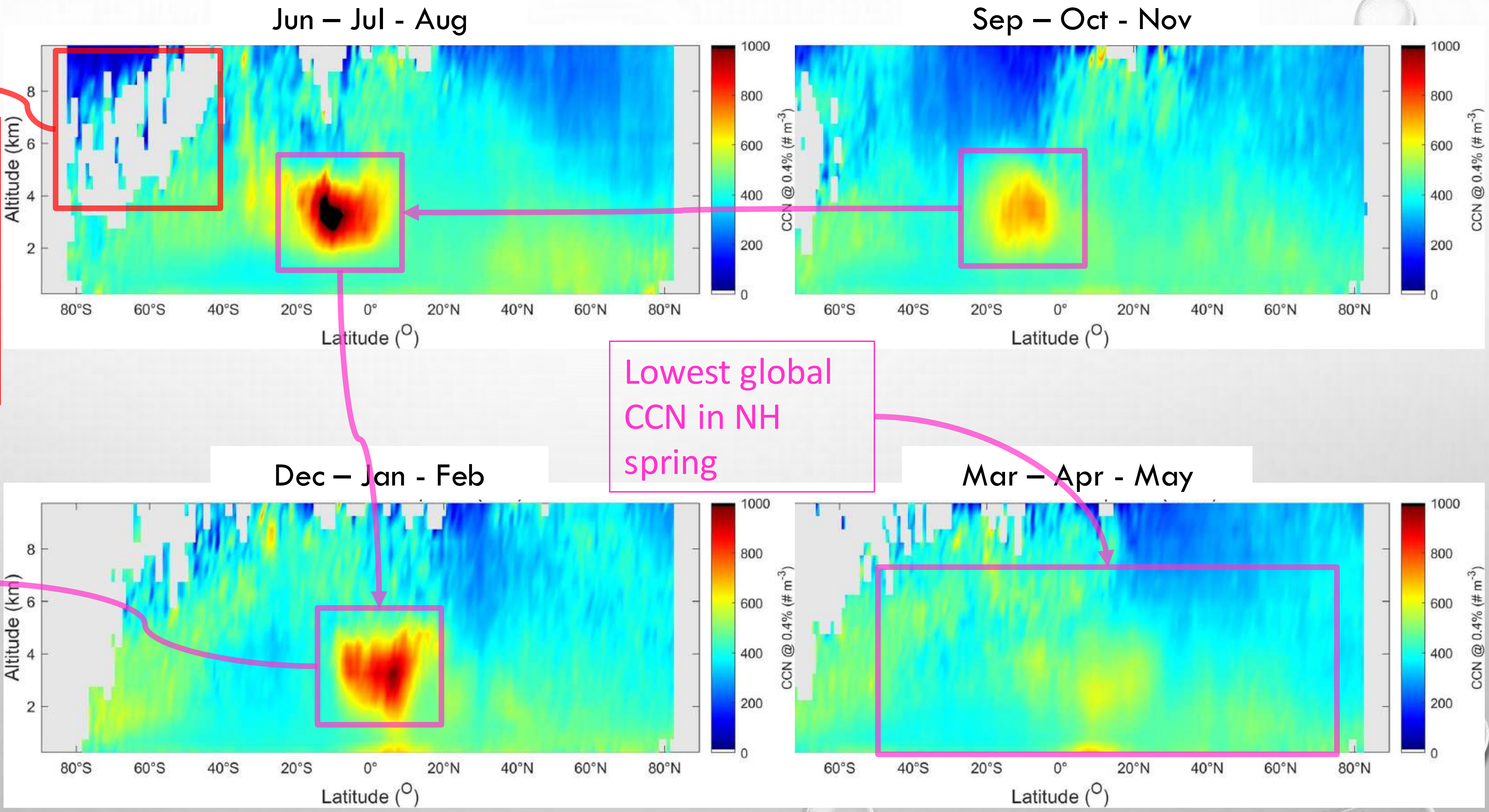
Asian and SE Asian sources contribute most stongly in NH winter and spring



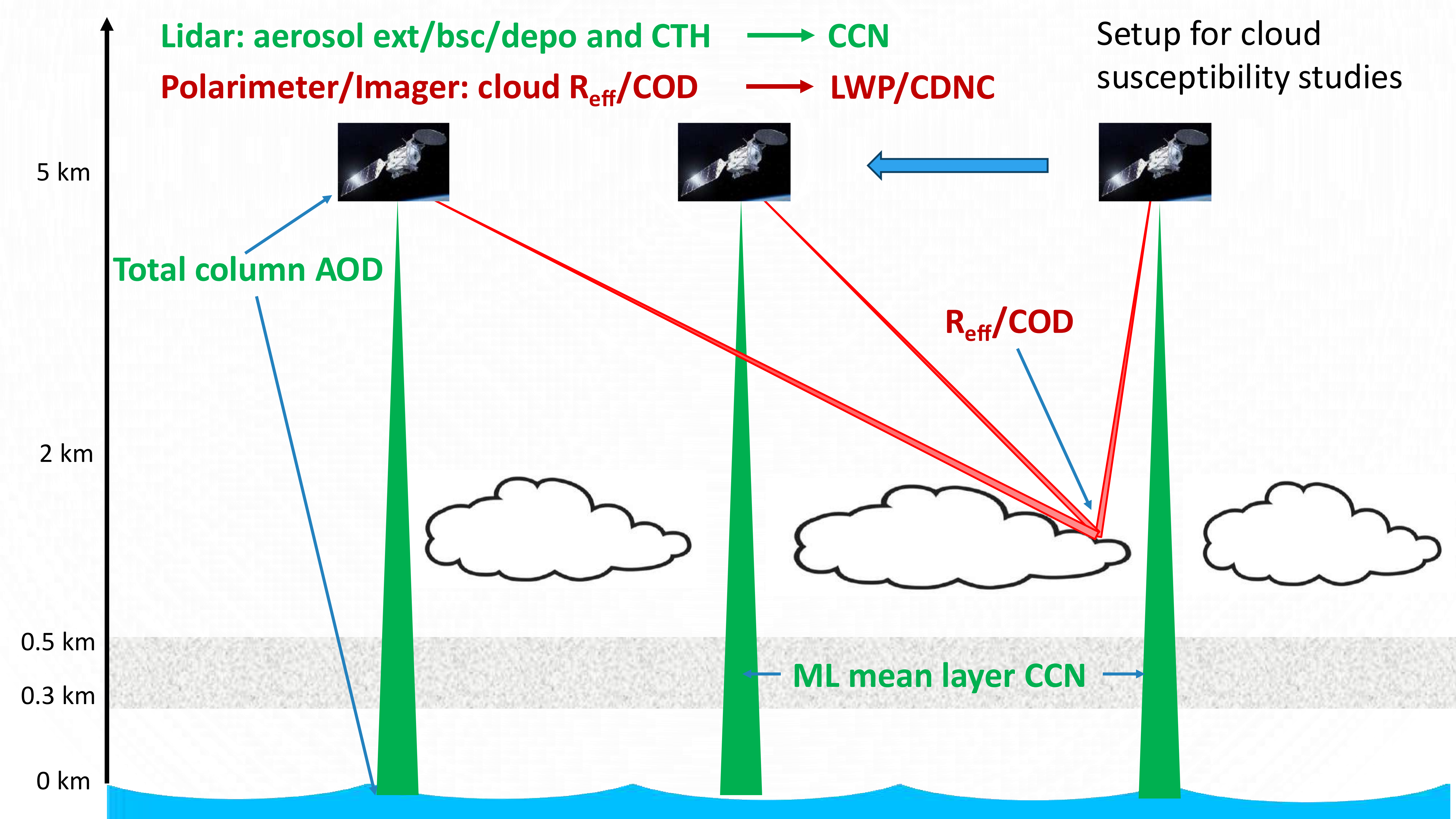
Global Seasonal Vertical Distributions of CCN

Pristine, cloudy, bright surface conditions in Southern Oceans produce few retrievals

Hot spots/ reservoirs of CCN in the lower FT in all seasons



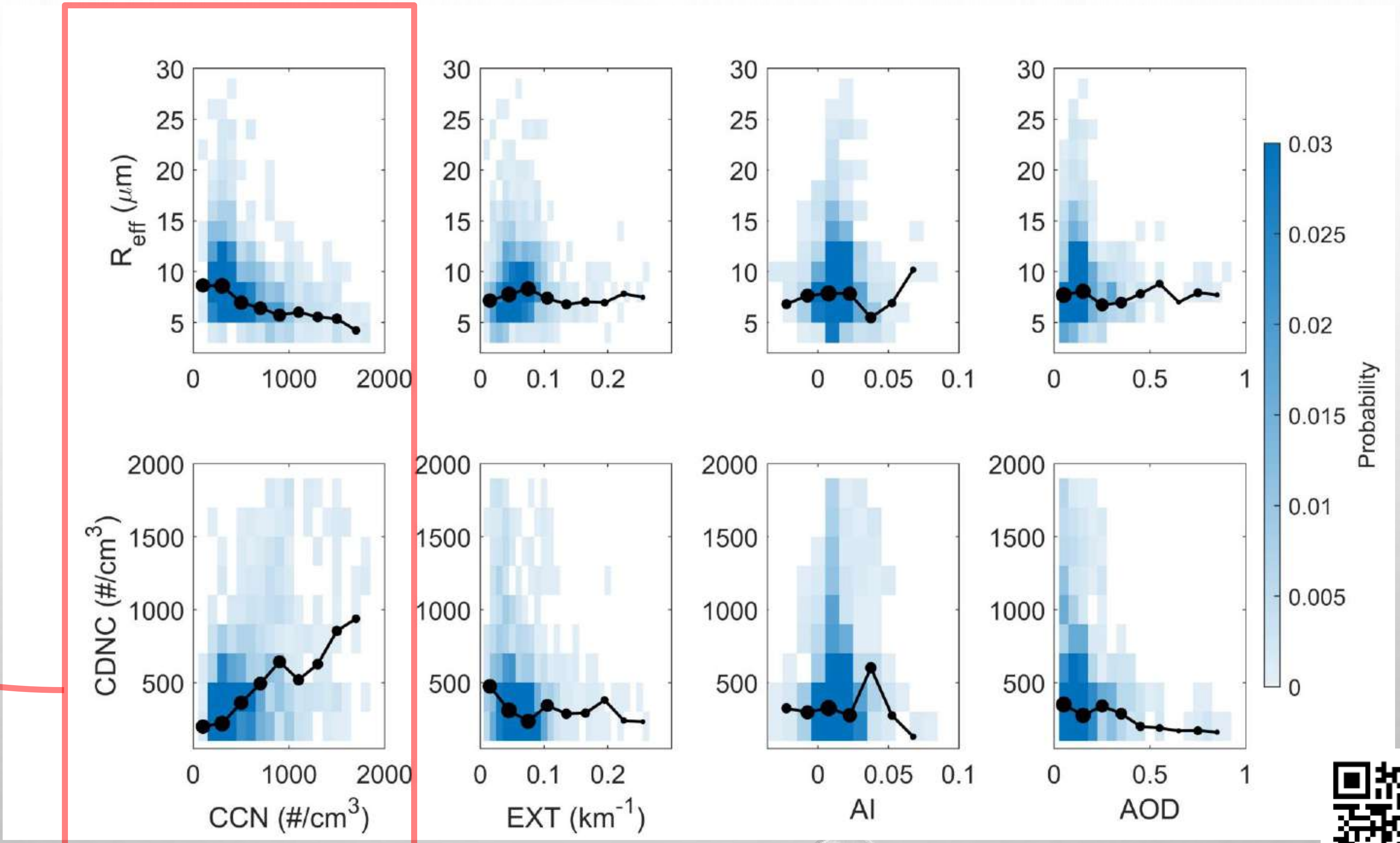
Lowest global CCN in NH spring



Lidar: aerosol ext/bsc/depo and CTH
CCN
Polarimeter/Imager: cloud R_{eff}/COD
LWP/CDNC
Setup for cloud susceptibility studies
5 km
Total column AOD
R_{eff}/COD
2 km
0.5 km
0.3 km
ML mean layer CCN
0 km

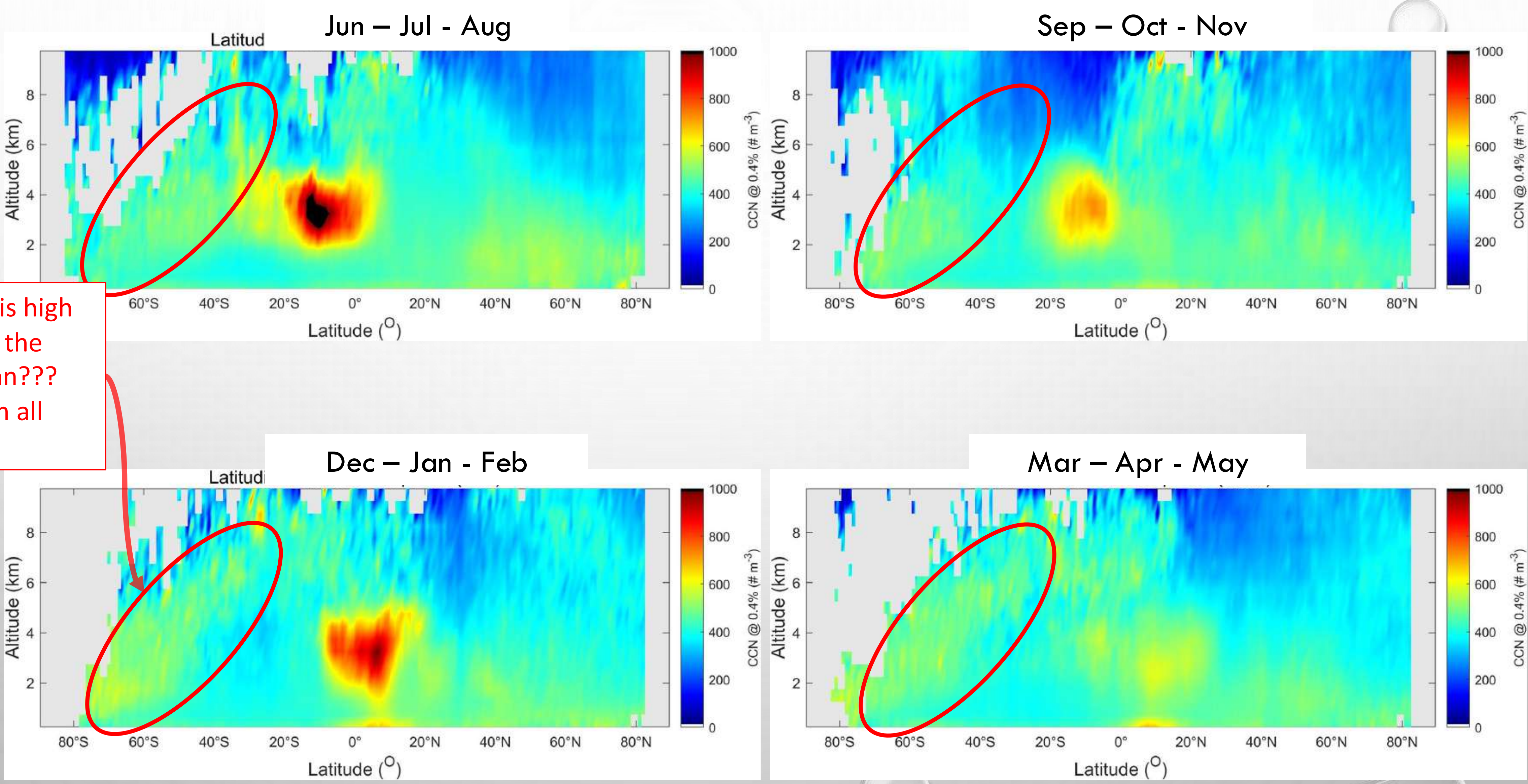
Important application of ML-CCN: cloud susceptibility

ML-CCN provides physically more plausible constraints on ACI in ACTIVATE than aerosol optical properties.



Gao et al., GRL, 53, e2026GL122006. https://doi.org/10.1029/2026GL122006

Global Seasonal Vertical Distributions of CCN



What about this high CCN feature in the Southern Ocean???

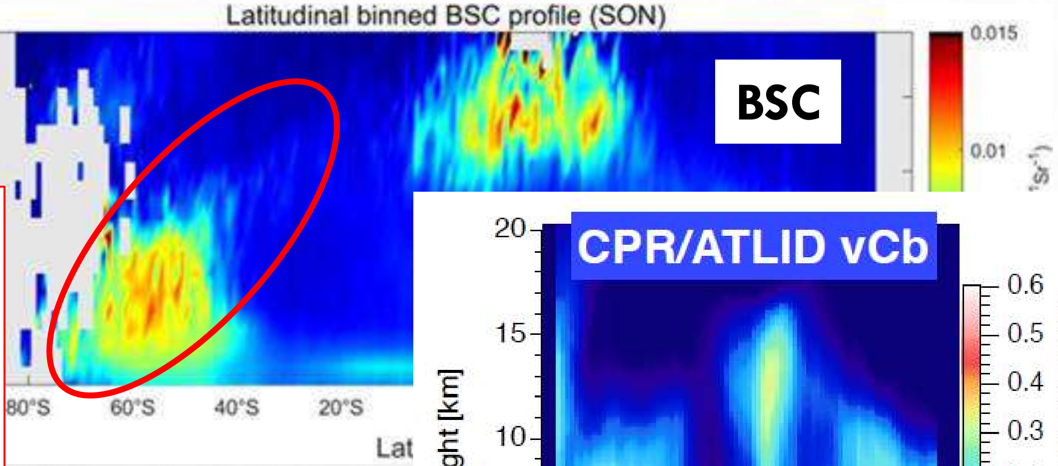
1) It exists in all seasons

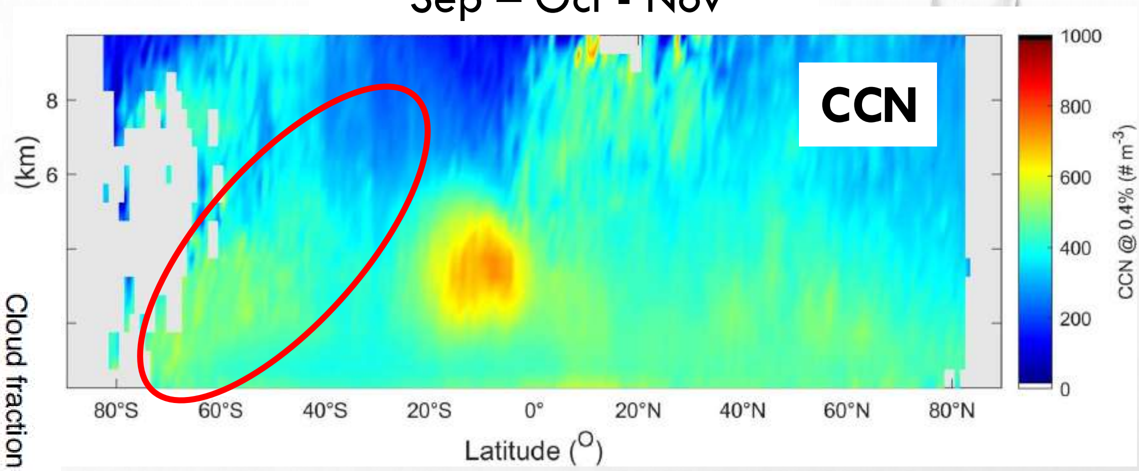
Global Seasonal Vertical Distributions of BSC/EXT/DEPOL & CCN

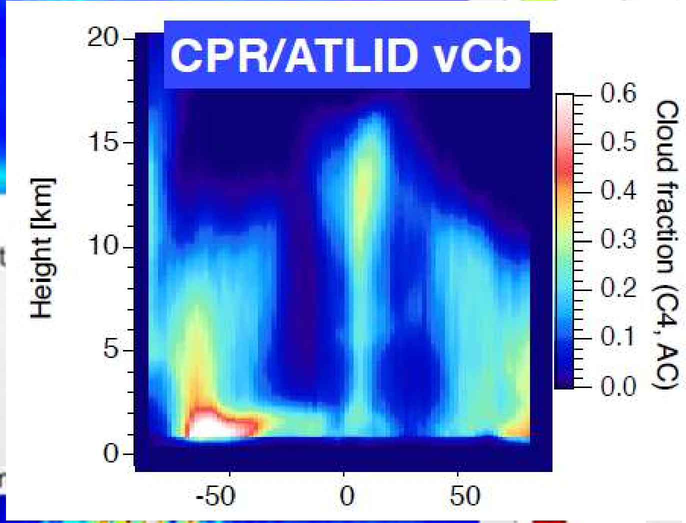
Sep – Oct - Nov

What about this high CCN feature in the Southern Ocean???

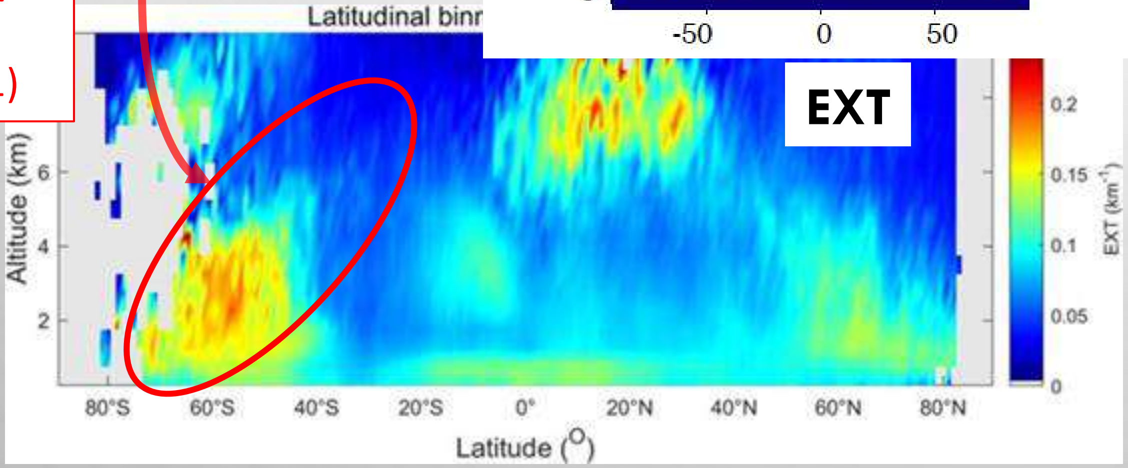
1) It exists in all seasons
2) It is related to high BSC and EXT, but only moderate DEPOL (~0.1)

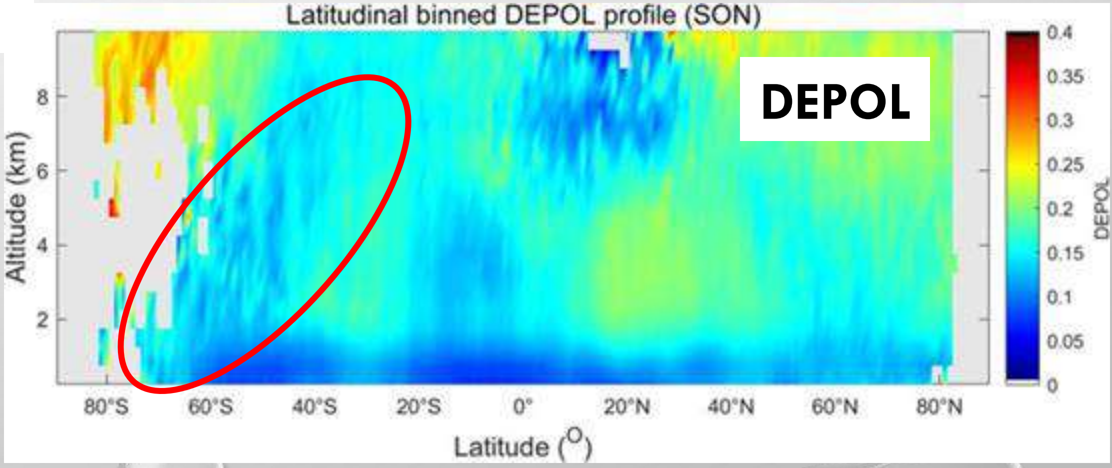






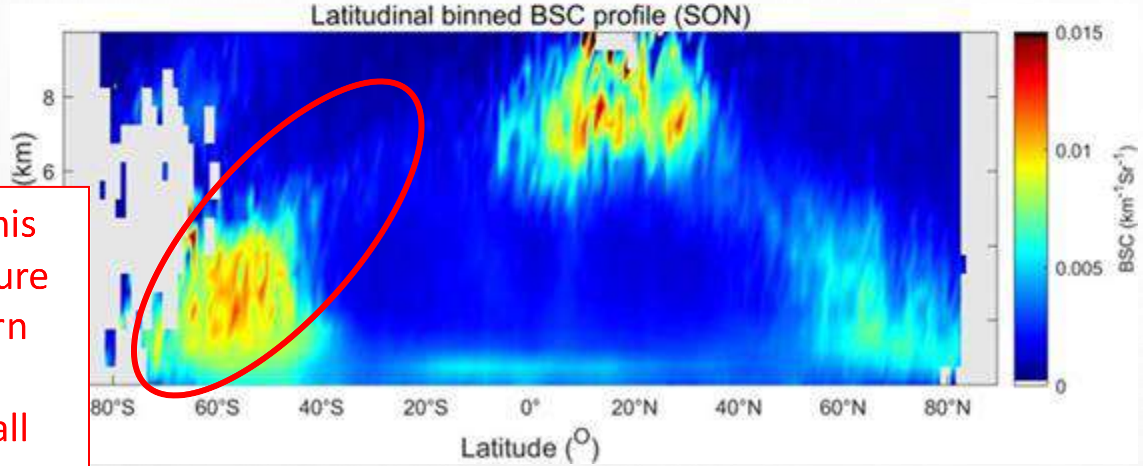
Cloud Fraction, courtesy of Okamoto-san

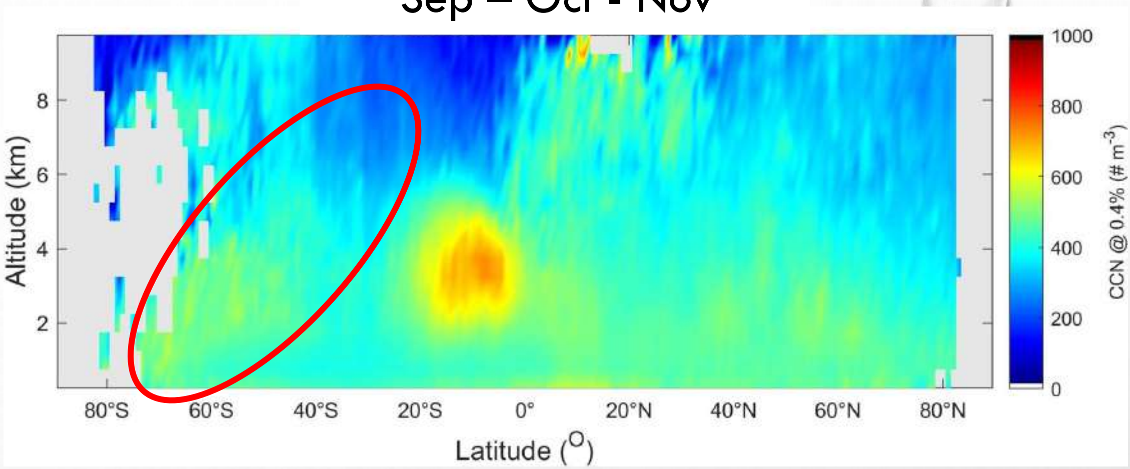




Global Seasonal Vertical Distributions of BSC/EXT/DEPOL & CCN

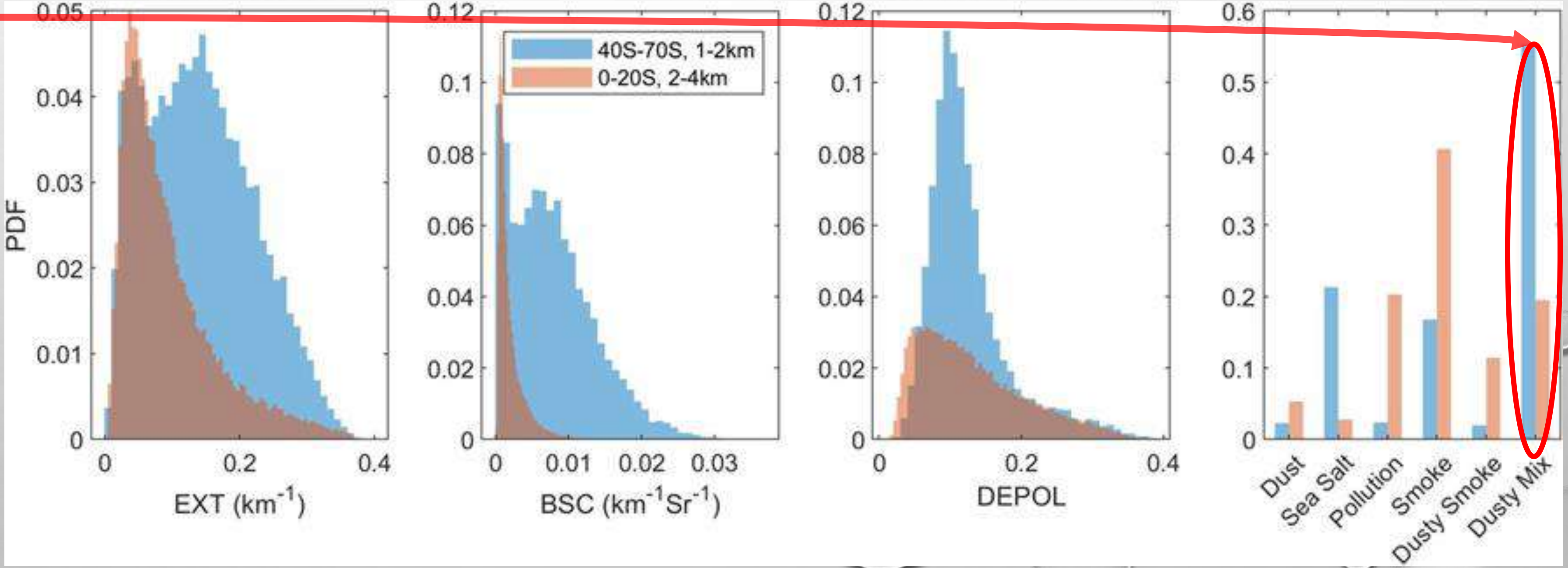
Sep – Oct - Nov





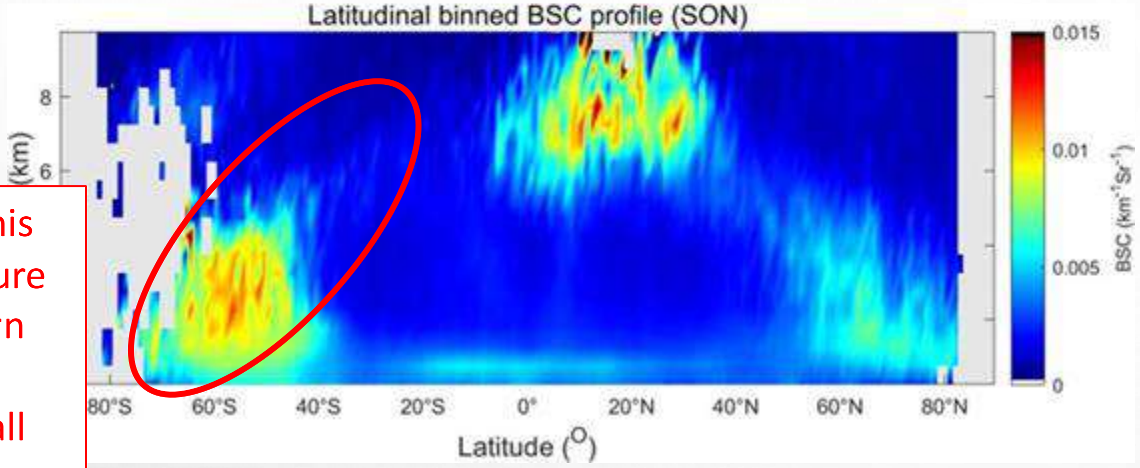
What about this high CCN feature in the Southern Ocean???

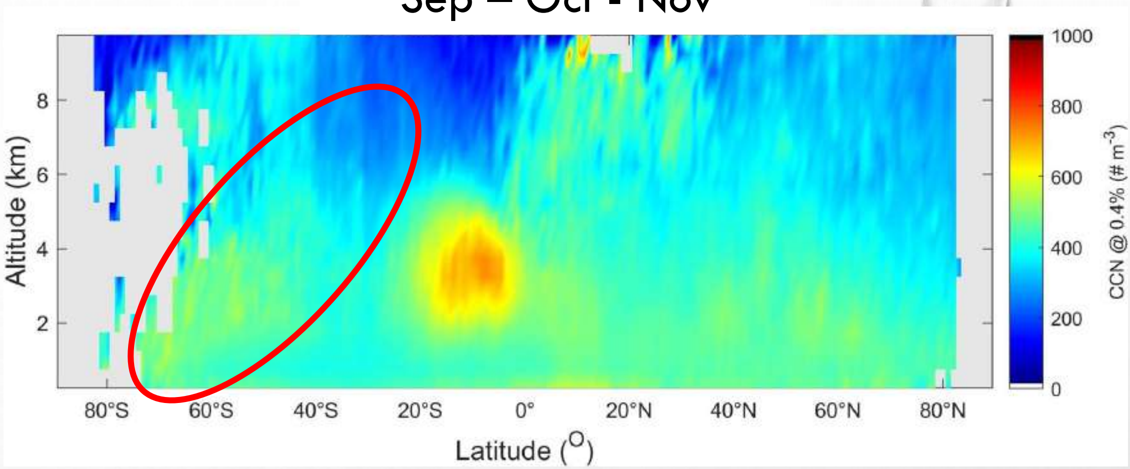
1) It exists in all seasons
2) It is related to high BSC and EXT, but only moderate DEPOL (~0.1)
3) It is classified as mostly Dusty Mix



Global Seasonal Vertical Distributions of BSC/EXT/DEPOL & CCN

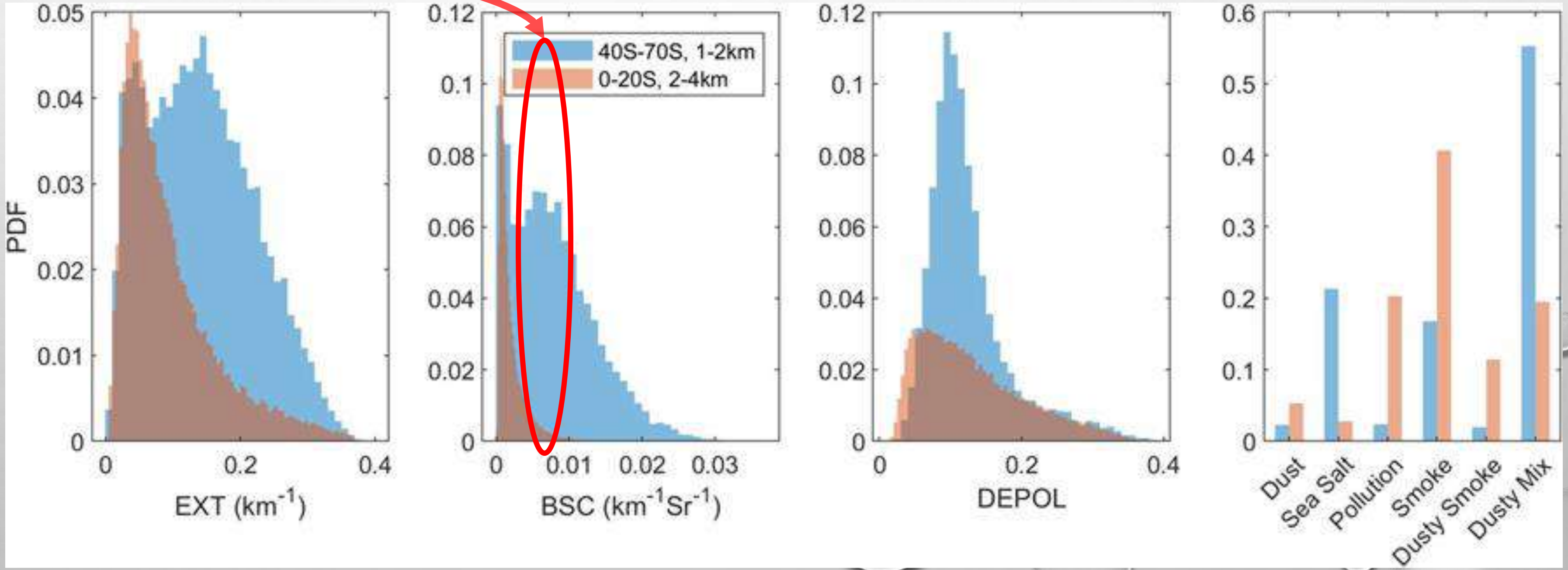
Sep – Oct - Nov





What about this high CCN feature in the Southern Ocean???

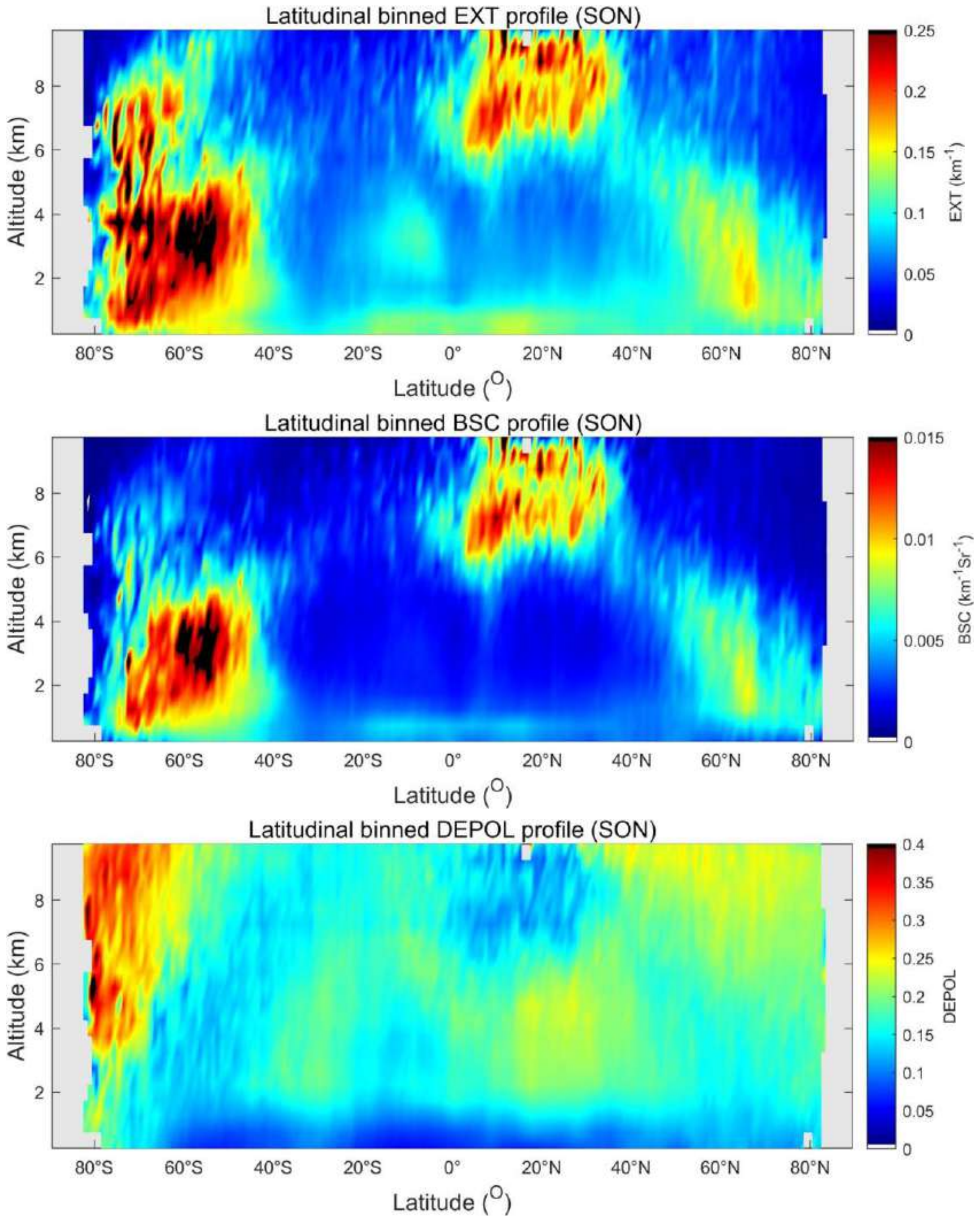
1) It exists in all seasons
2) It is related to high BSC and EXT, but only moderate DEPOL (~0.1)
3) It is classified as mostly Dusty Mix
4) The pdf of BSC shows second mode which is not likely aerosol



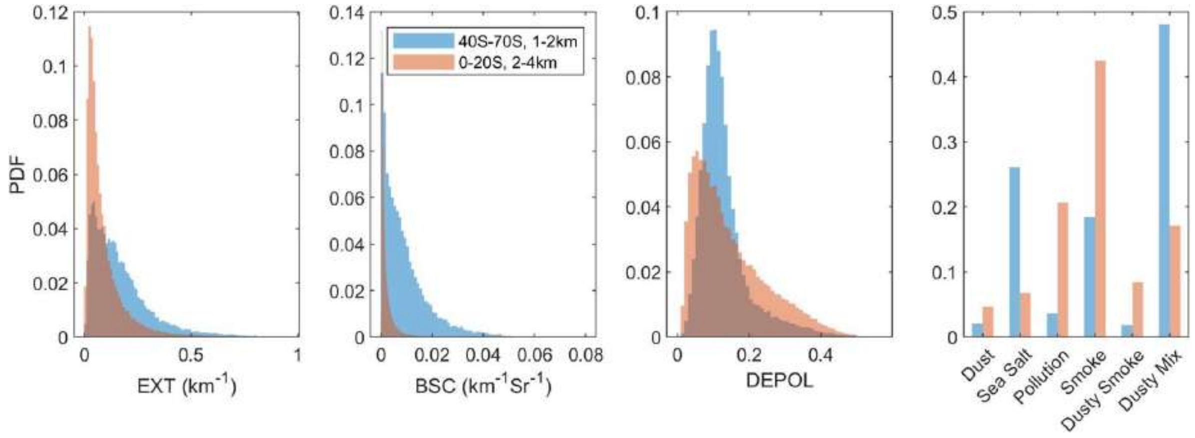
Conclusions

1. The complete first year of ATLID observations have been used to predict global, vertically-resolved CCN @ 0.4% SS and ABS at 532 nm
2. Validation against in situ measurements indicates mean relative errors in CCN of less than 30% for CCN>100/cm^3
3. Global CCN data can be made available upon request - great potential to constrain ESMs
4. Possible target misclassifications and sampling issues: Elevated CCN in the Southern Oceans is primarily due to consistent occurrence of “dusty mix” aerosol type, which is likely due to cloud contamination
5. **We need a science & cal/val campaign in the Southern Ocean**

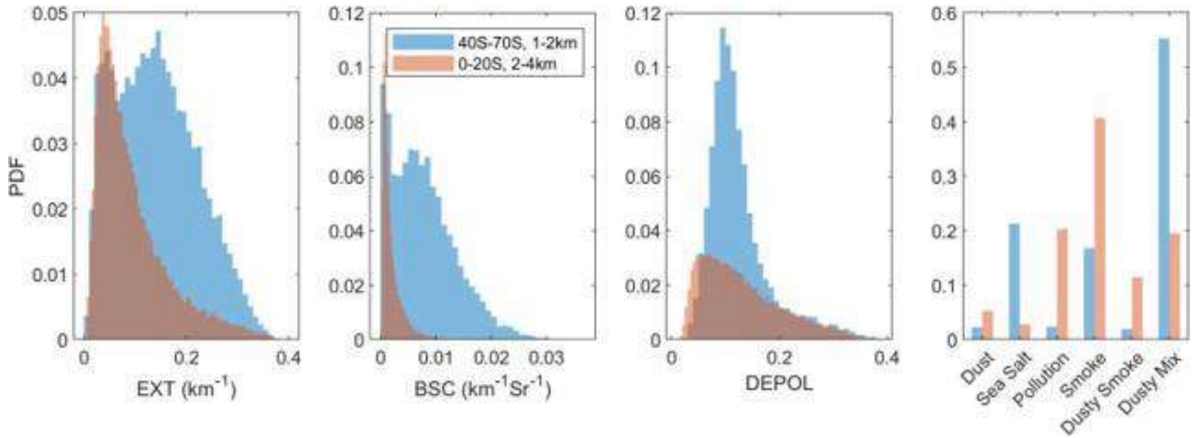
Profiles for the season SON (No retrieval/uncertainty screening).



Before screening:
40S-70S: 57 0-20S: 212



After screening:
40S-70S: 51 0-20S: 134



Algorithm flowchart

ATLID | WALES | BOTH

ATLID
EBD-L2A
E&B&D
@355nm

ATLID
TC

WALES
E&B&D
@532nm &
B@1064

Cloud screening
(BSR>10 @ 0-8km
BSR>4 @ >8km)

QA Good (0)

QA Good (0)

Select aerosol pixels
(EXT<1km^{-1} &
BSC<0.05km^{-1}Sr^{-1} &
DEPOL<0.6)

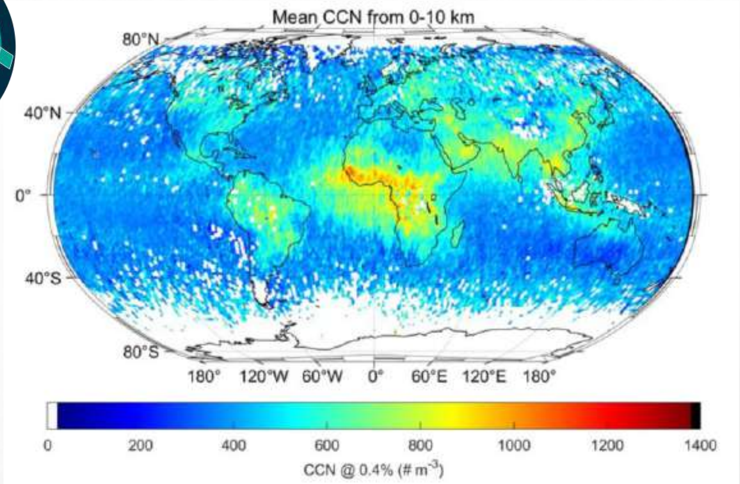
ML-'ATLID' CCN & ABS models

CCN profiles @ 0.4% SS & ABS

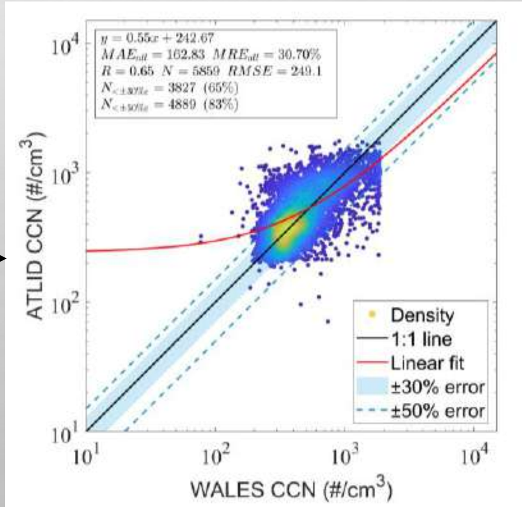
ML-'WALES' CCN & ABS model

Spatiotemporal averaging
(T10s & V150m)

Spatiotemporal averaging



Objective of this talk

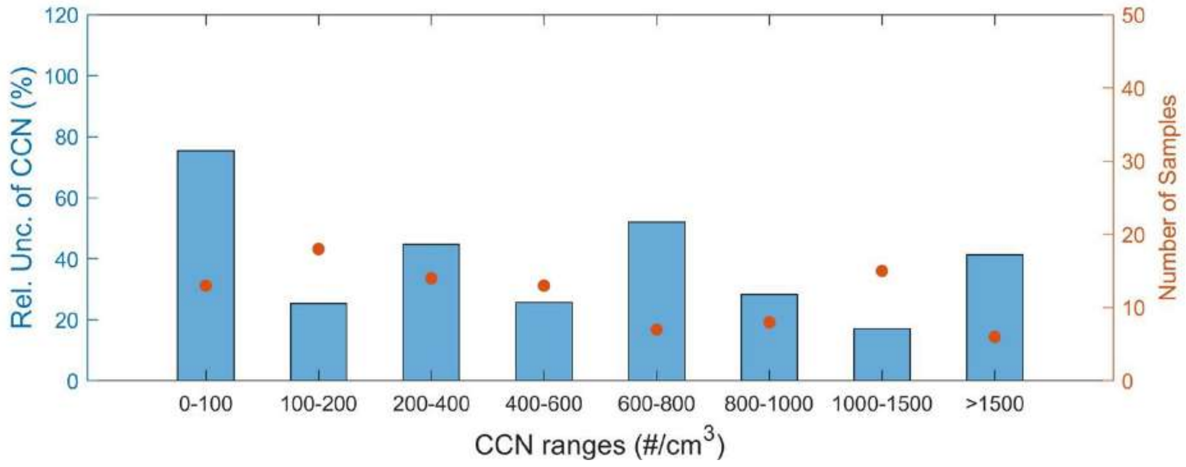


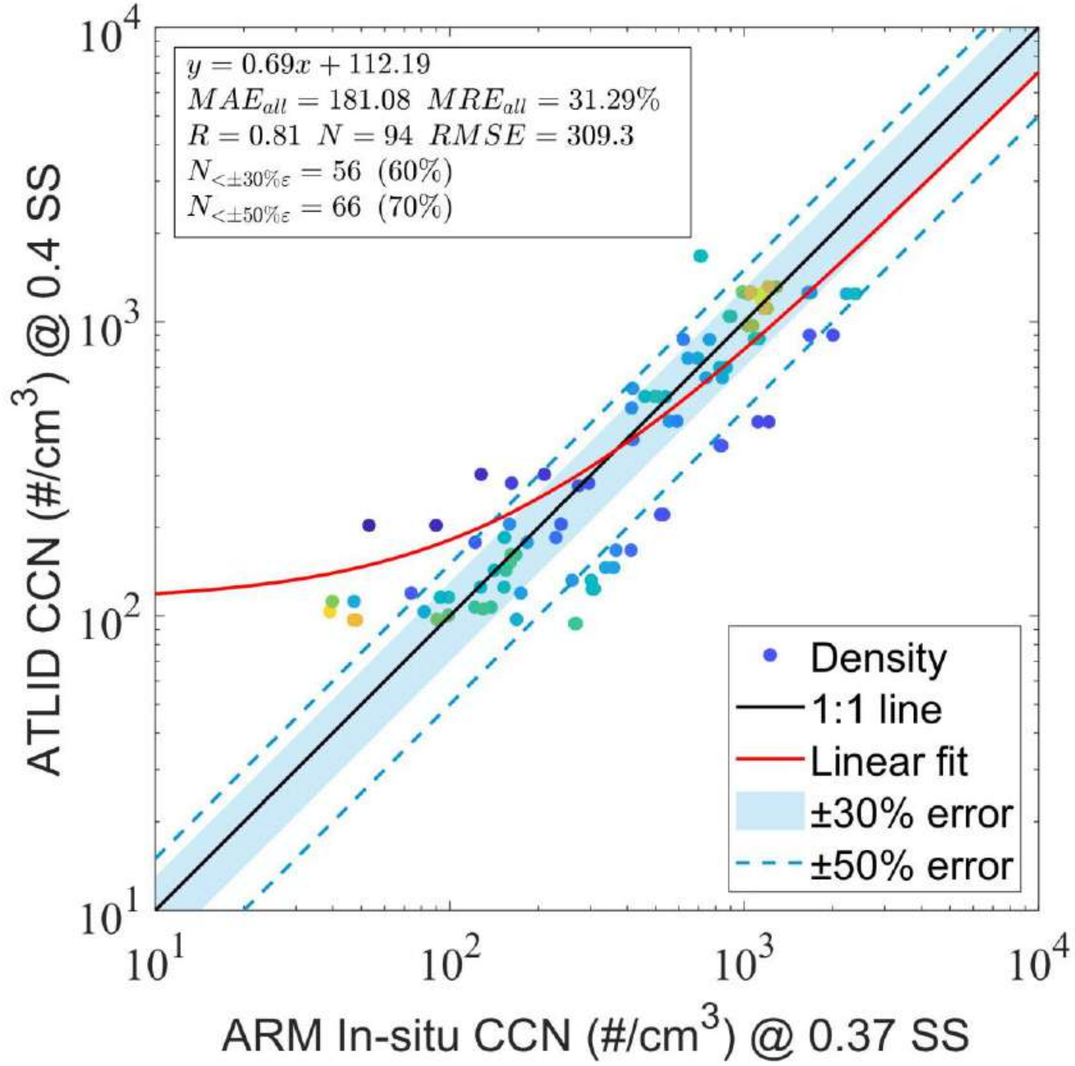
Objective 1 of this talk

ORCESTRA

Validation of ATLID-CCN retrievals against near surface in situ data from ARM

- In-situ surface data from ARM SGP, BNF, CRG & ENA:
  - ➢ Hourly averaged CCN
- ATLID retrievals:
  - ➢ ATLID BA version profiles below 500m
- Collocation criteria:
  - ➢ Temporal < 30 mins
  - ➢ Spatial < 50 km





Flowchart of the WALES CCN retrieval

WALES
E&B&D @532nm & B@1064

↓

Quality status
Good data (Flag=0)

↓

Spatiotemporal averaging
10S & 150m

↓

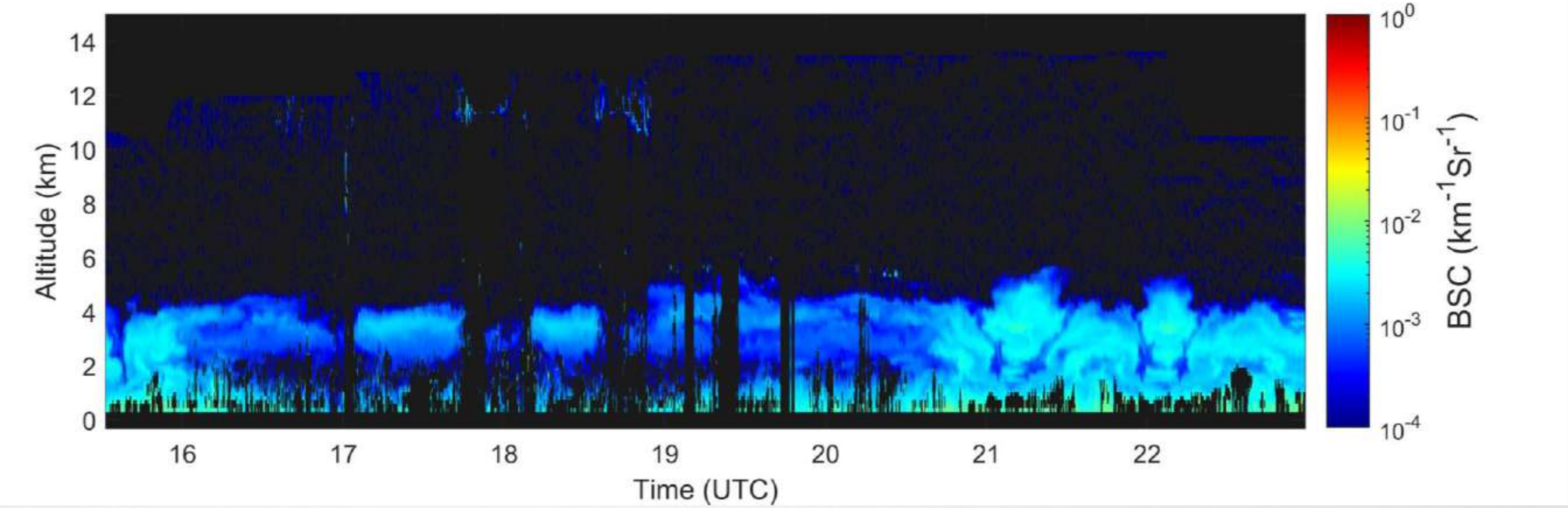
Retain only 'aerosol' pixels (arbitrary)
EXT<1km & BSC<0.05km^{-1}Sr^{-1} & DEPOL<0.6

↓

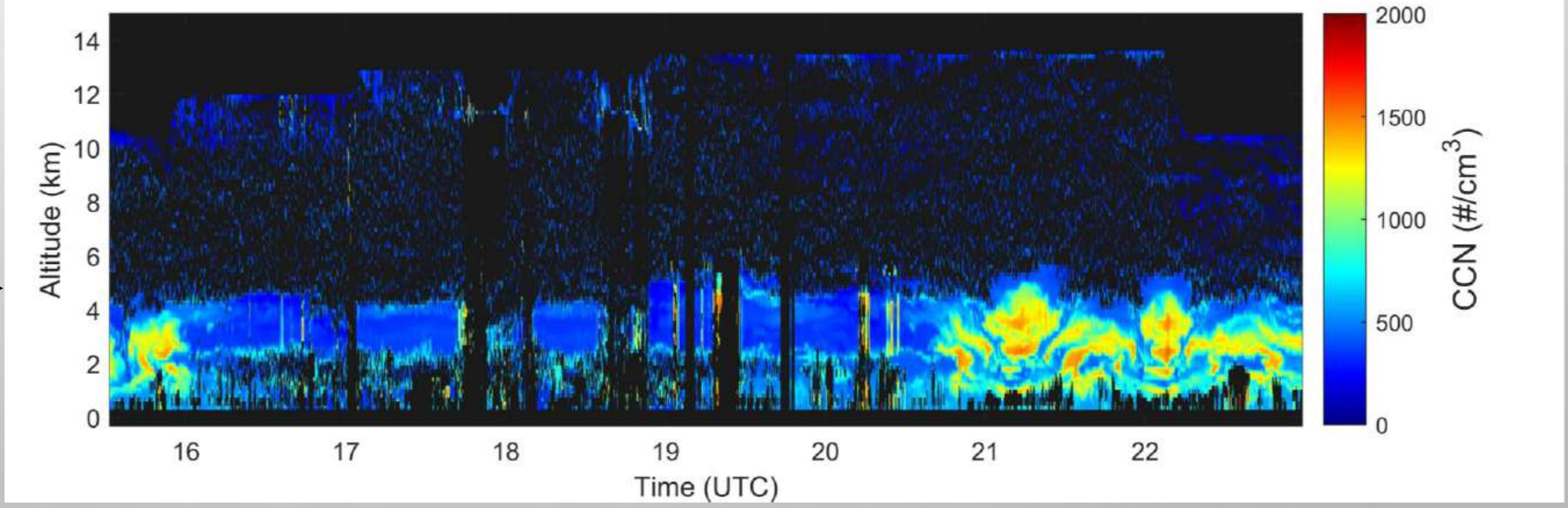
ML-CCN algorithm

PERCUSION
ORCESTRA

WALES 'aerosol' BSC on 20240813

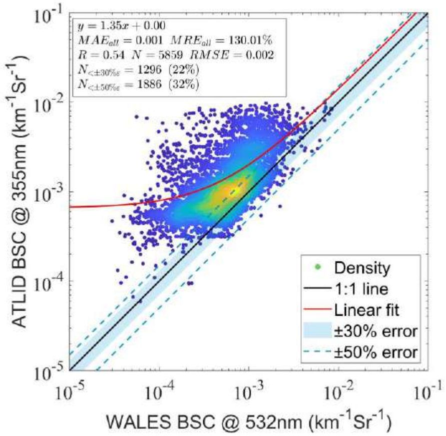


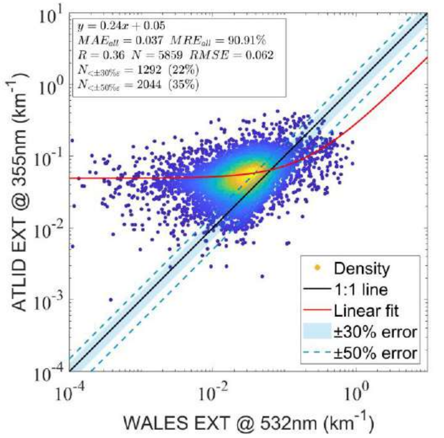
WALES retrieved CCN on 20240813

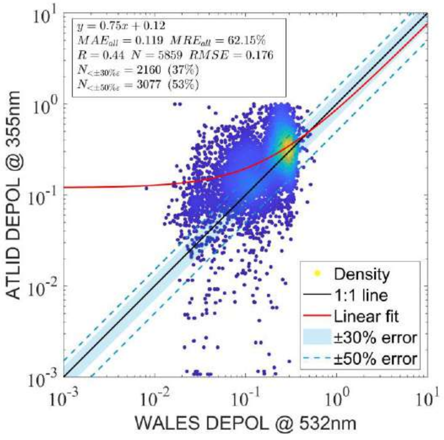


Comparison of lidar observables between WALES and ATLID

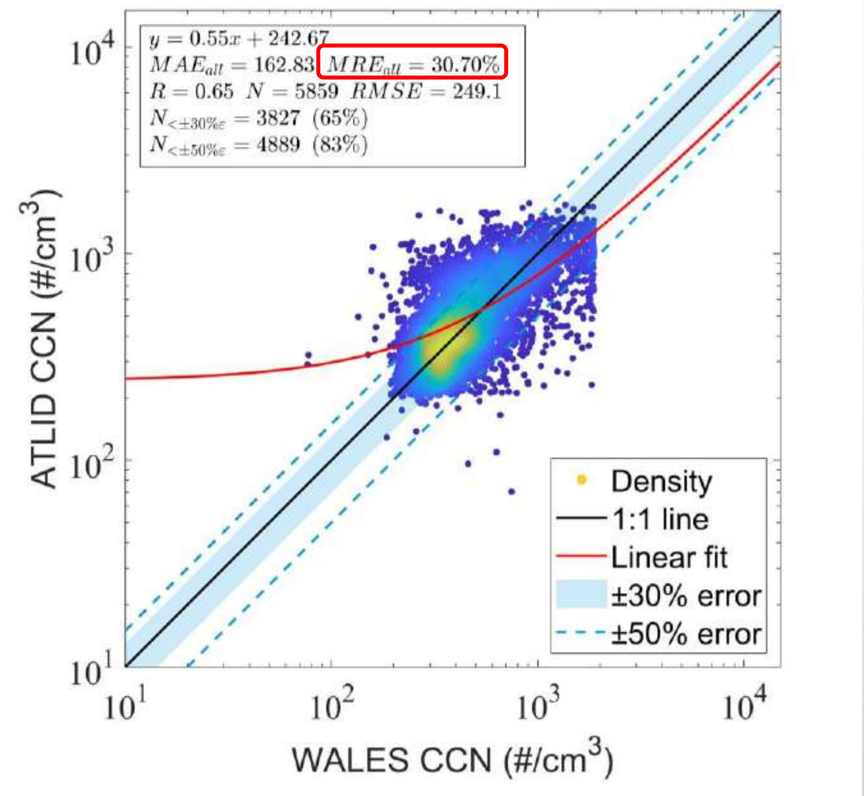
Input observables for ML model



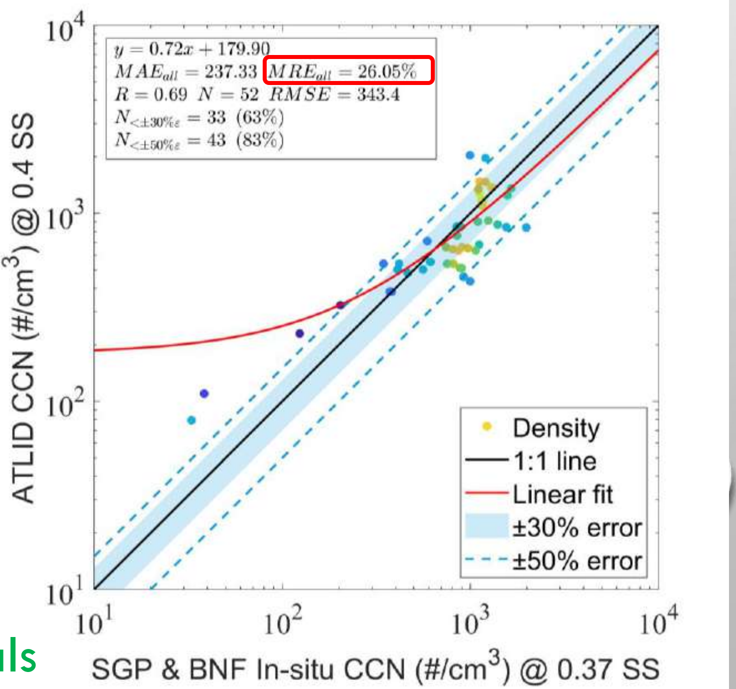




ML-based CCN retrievals



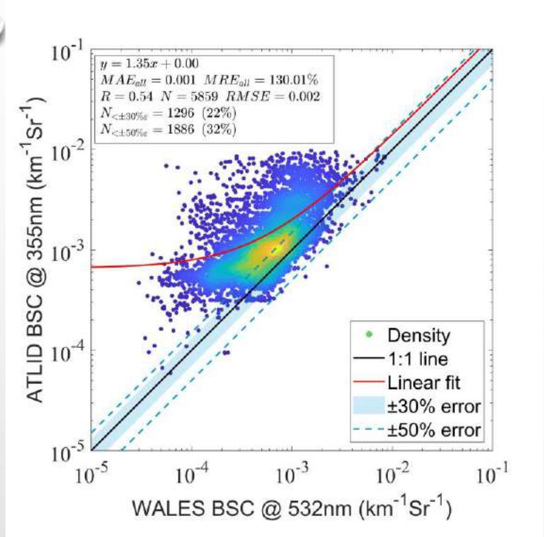
- WALES: 10s & 150m vertical
- ATLID: BA version L2A-EBD profile, ~1km horiz. & 100m vert.
- Exclude EXT>1km^{-1}, BSC>0.05km^{-1}Sr^{-1}, DEPOL>0.6
- Collocation between ATLID and WALES
  - < 15 mins
  - Horizontal distance < 2 km
  - Vert distance < 100 m

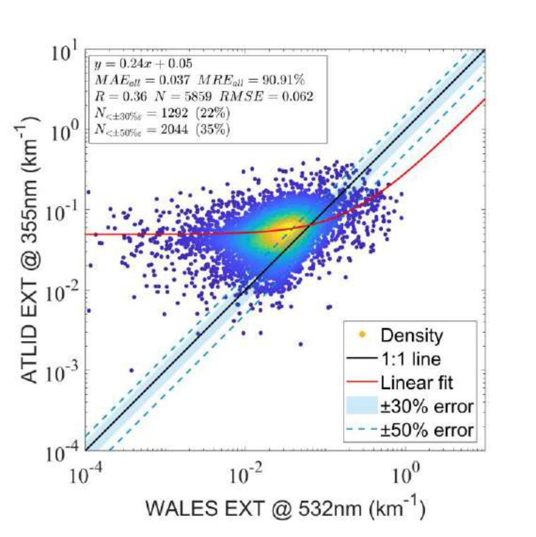


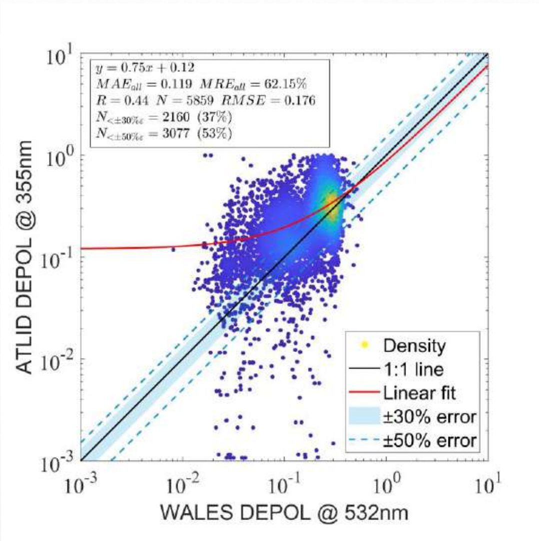
Validation of ATLID ML-based CCN retrievals

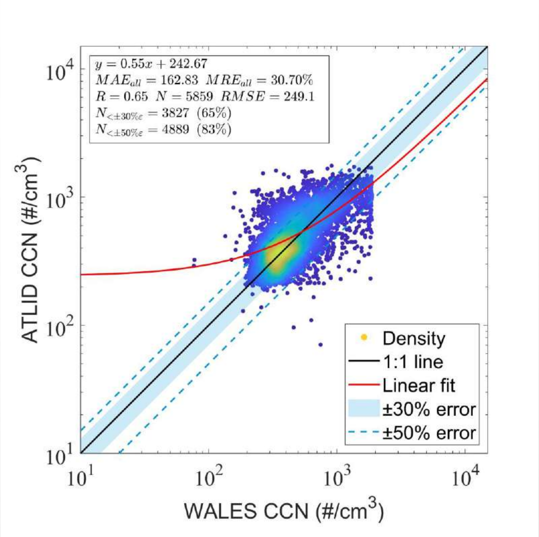
Data screening based on ATLID uncertainties in BCS, EXT, and DEPOL

No filtering



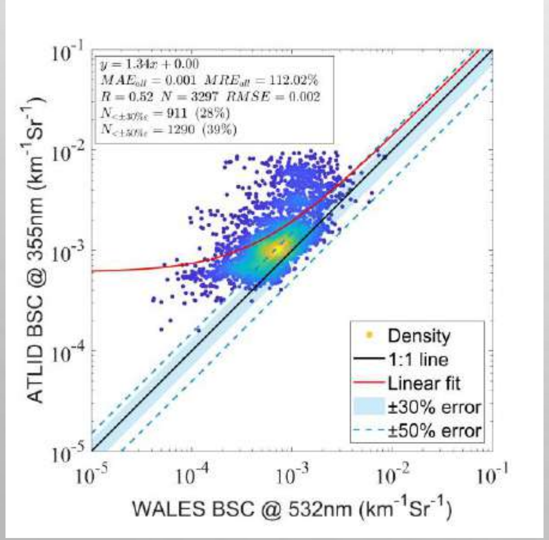


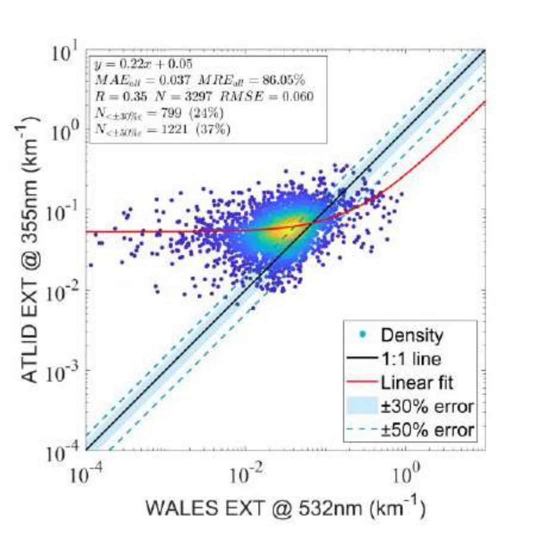


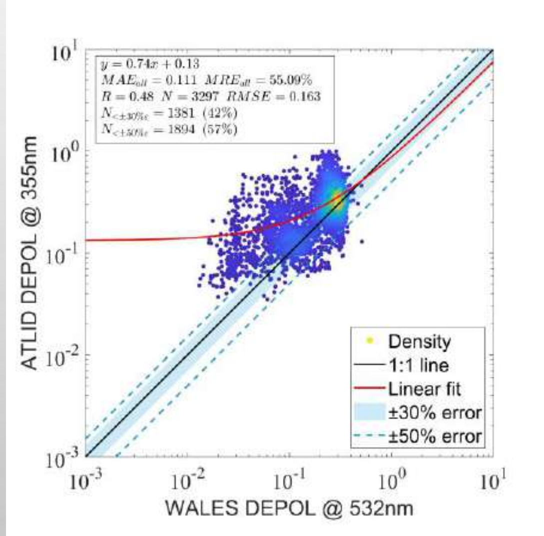


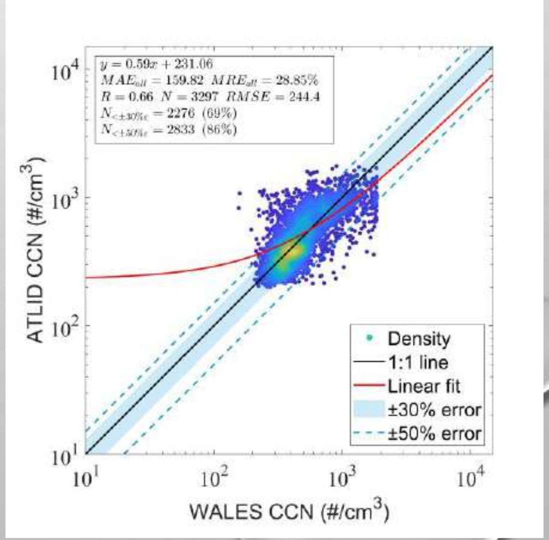
Excluding samples with higher ATLID uncertainty improves the consistency between ATLID and WALES.

50%









CCN and ABS retrievals from EarthCARE-ATLID observations

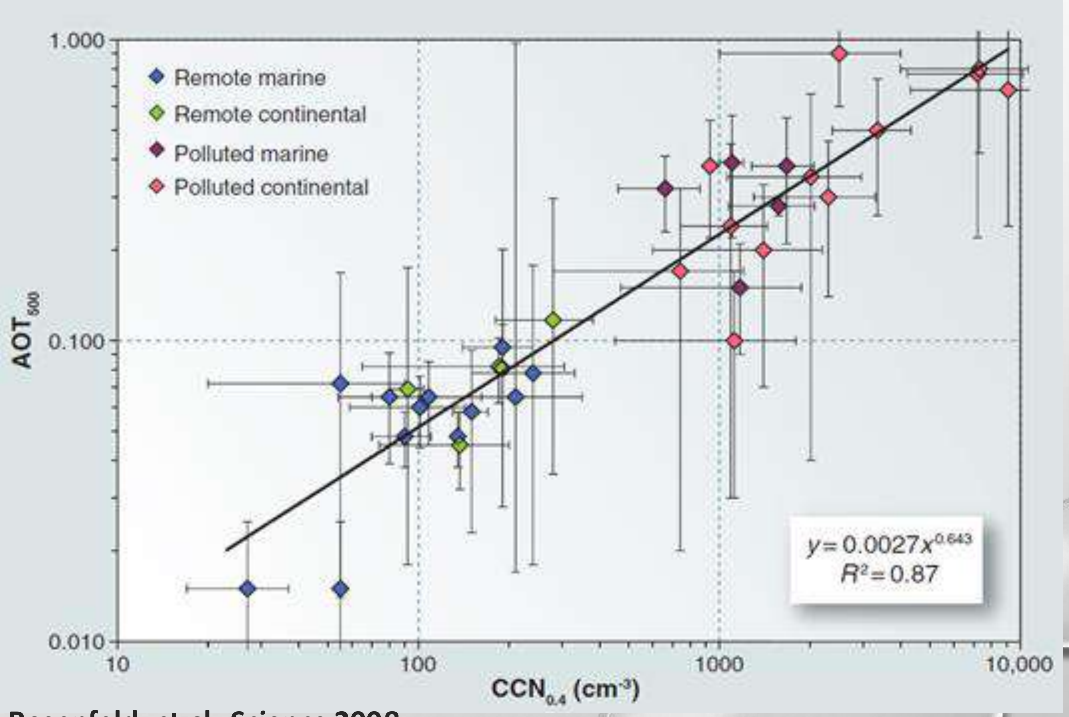
Objectives

Overarching:

- Global, vertically resolved CCN and ABS from EarthCARE-ATLID using a novel Machine Learning (ML) algorithm (Redemann and Gao, 2024)

Detailed Objectives for today:

1. Comparison of ATLID observations and ML-retrieved CCN and ABS to airborne lidar (WALES) in ORCESTRA campaign
2. Preliminary global distribution of ATLID-based CCN and ABS based on 6 months of ATLID data (Aug. 2024 – Jan. 2025)



Rosenfeld, et al. *Science* 2008

REVIEW ARTICLE
10.1002/2013RG000441

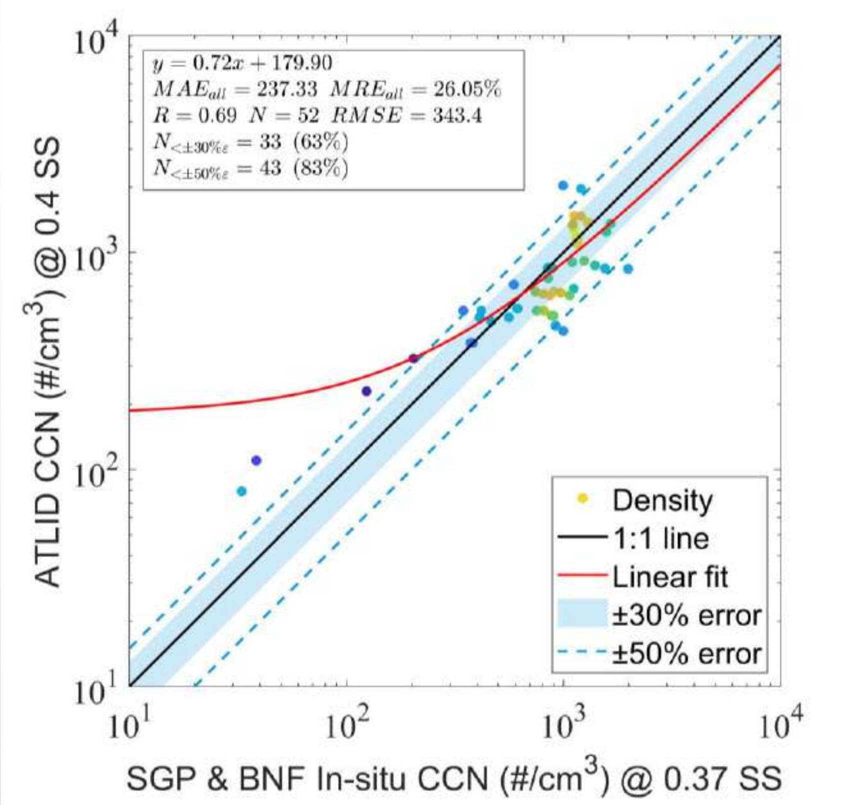
Key Points:
- Quantifying aerosol-cloud-climate interactions is a major challenge
- The science of existing and emerging new observational methods is reviewed
- A roadmap for in situ and remote sensing energy closure experiments is provided

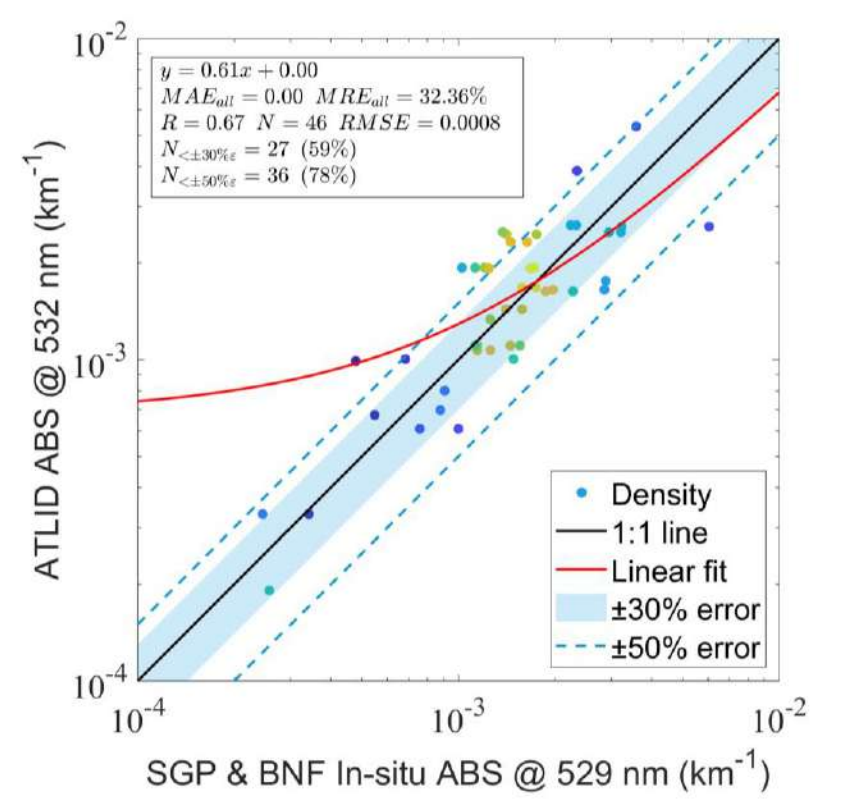
Global observations of aerosol-cloud-precipitation-climate interactions

Daniel Rosenfeld[1], Meinrat O. Andreae[2], Ari Asmi[3], Mian Chin[4], Gerrit de Leeuw[3,5], David P. Donovan[6], Ralph Kahn[4], Stefan Kinne[7], Niku Kivekäs[5,8], Markku Kulmala[3], William Lau[4], K. Sebastian Schmidt[9], Tanja Suni[3], Thomas Wagner[10], Martin Wild[11], and Johannes Quaas[12]

[1]Institute of Earth Sciences, The Hebrew University of Jerusalem, Israel, [2]Biogeochemistry Department, Max Planck Institute for Chemistry, Mainz, Germany, [3]Department of Physics, University of Helsinki, Helsinki, Finland, [4]Earth Science Division, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, [5]Atmospheric Composition Research Unit, Finnish

Validation of ATLID CCN and ABS ML-retrievals against in situ data





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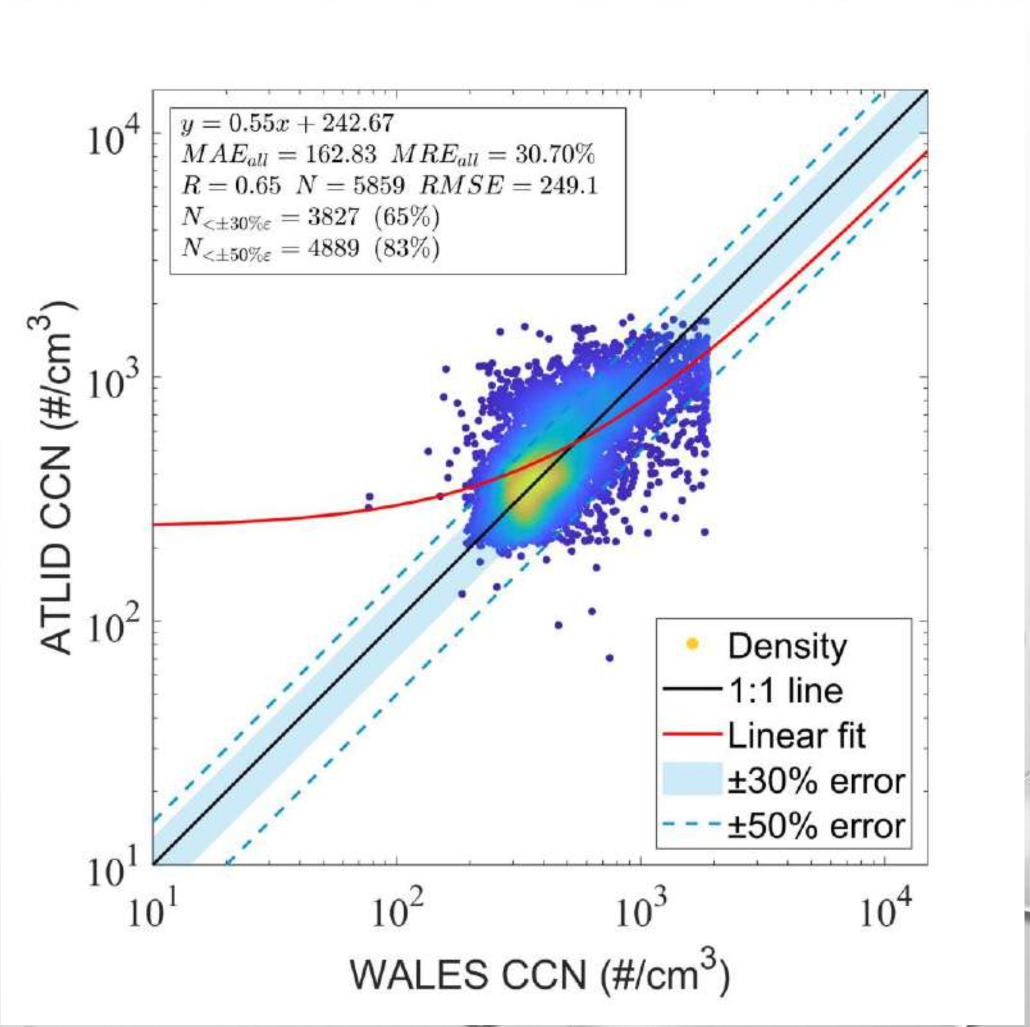
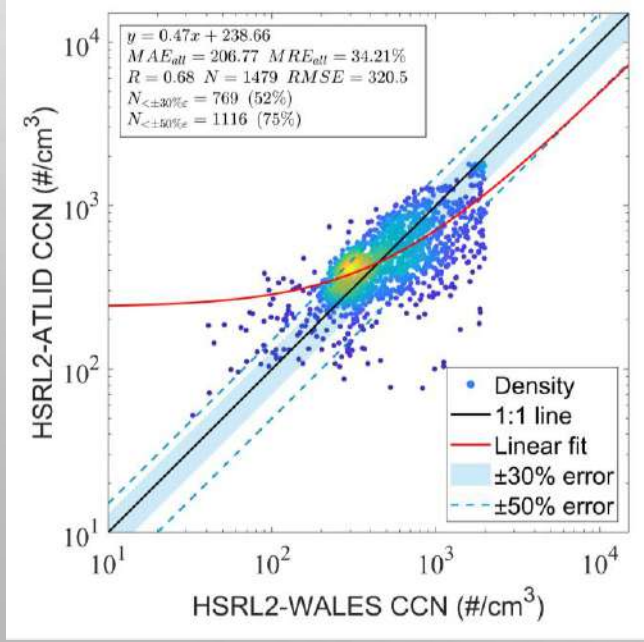
  - Horizontal distance < 2 km
  - Vertical distance < 100 m

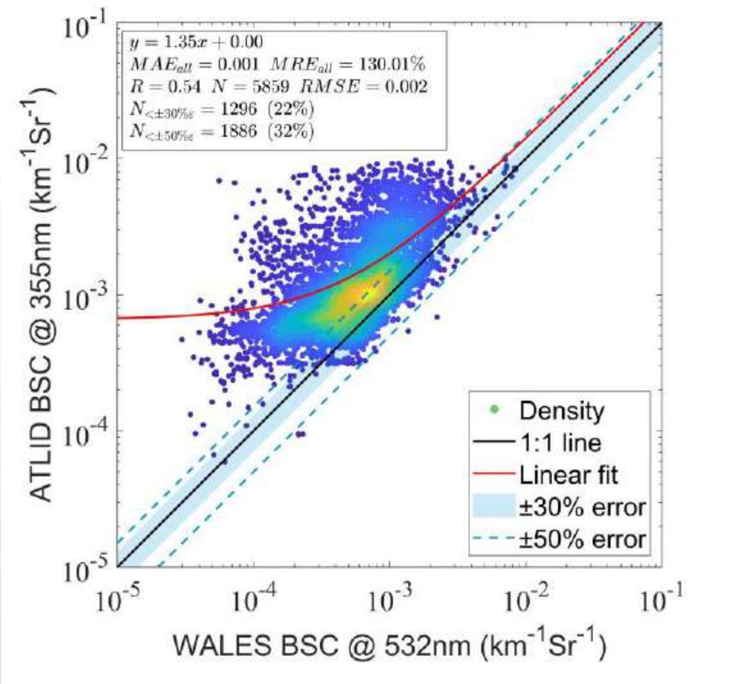


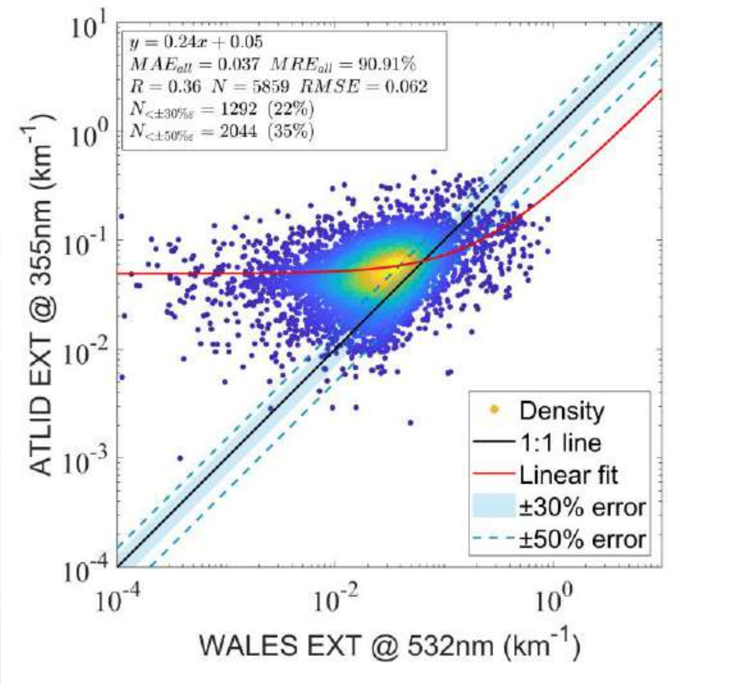
CCN retrievals using WALES and ATLID observations

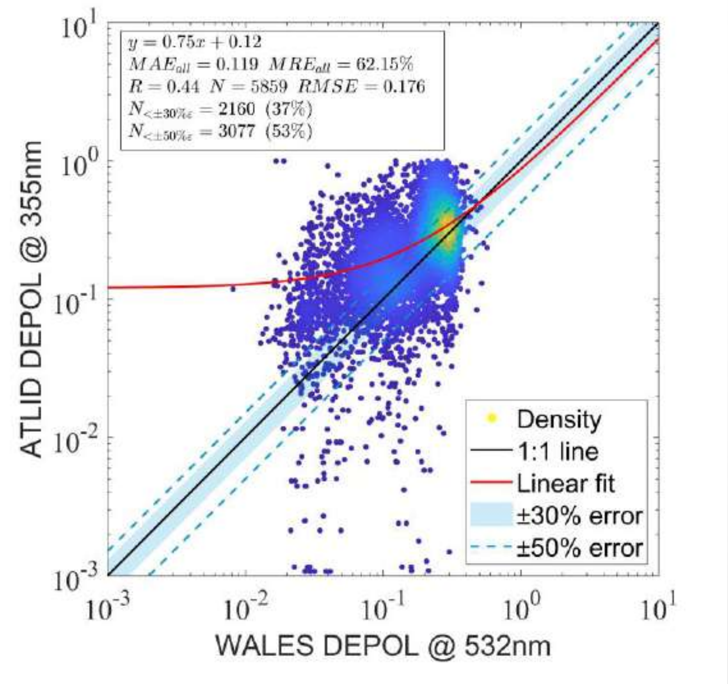


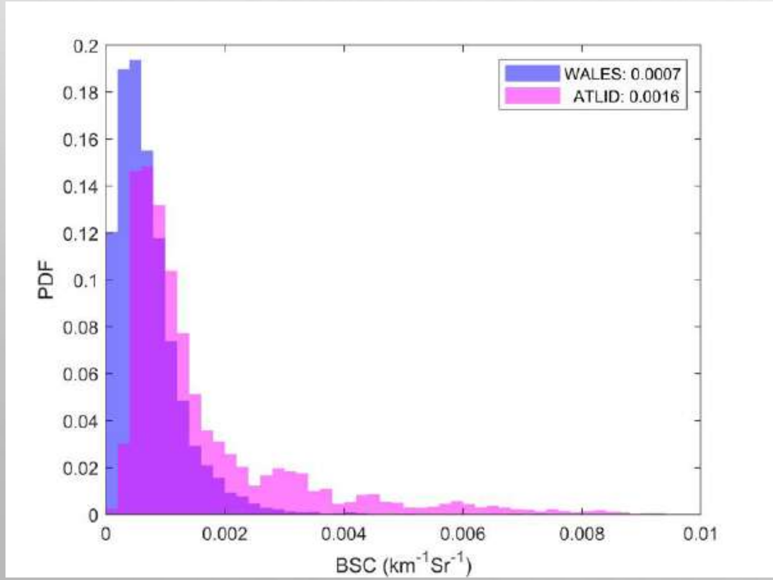
CCN retrievals from HSRL-2 data using WALES and ATLID observables (not observations)

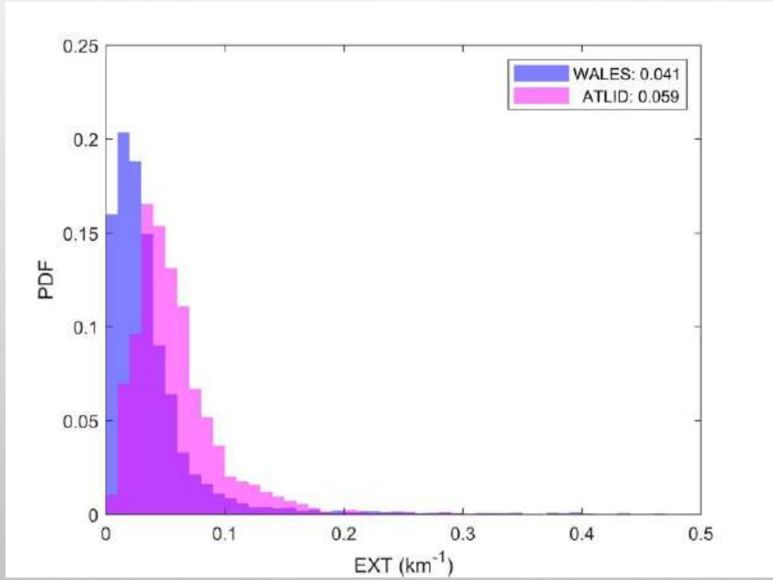
Comparison of lidar GVs between WALES and ATLID

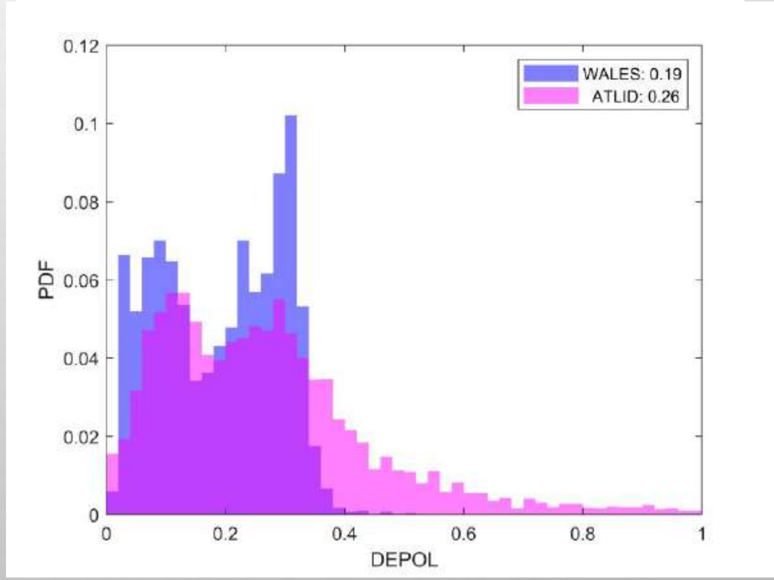








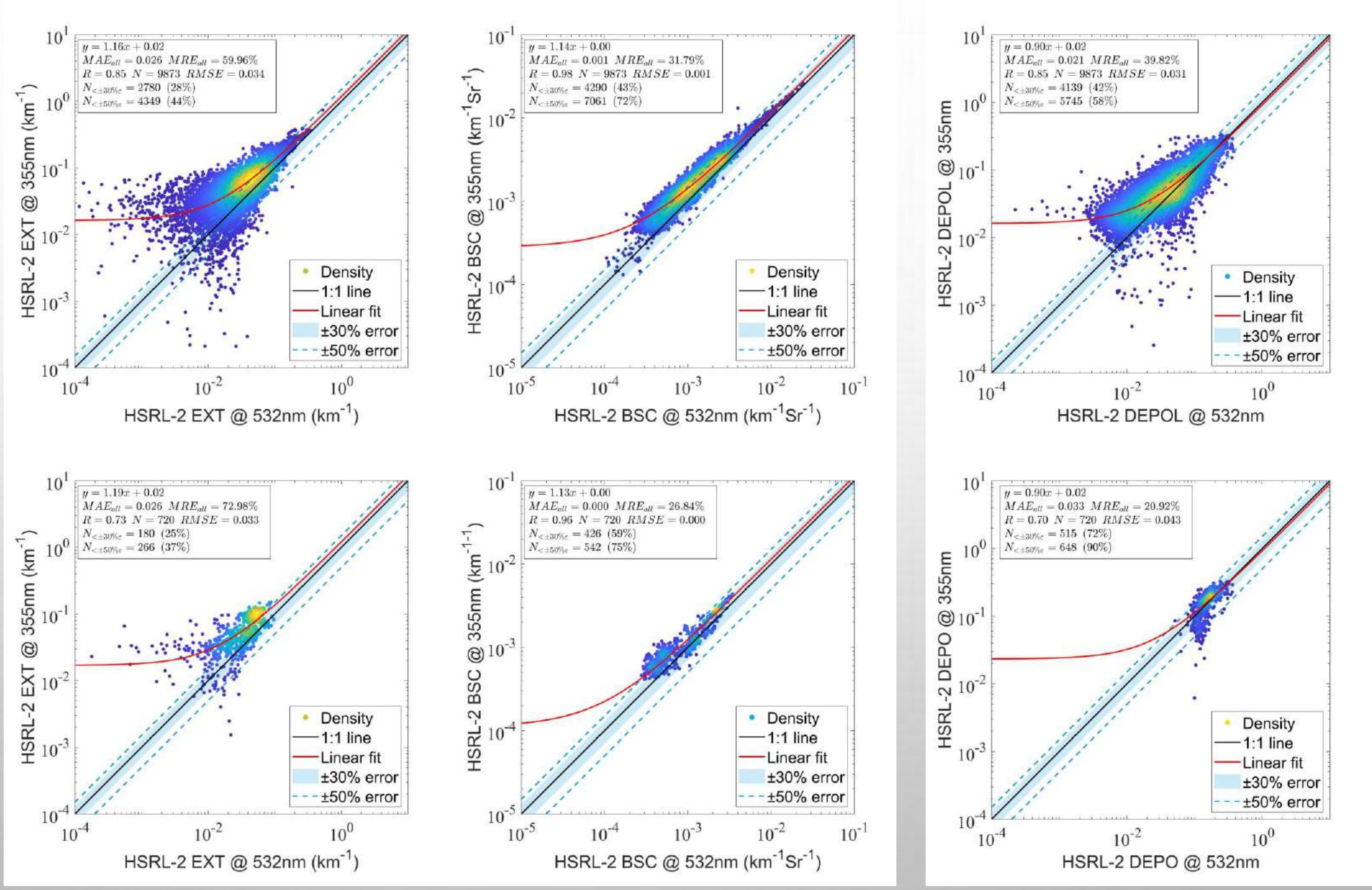




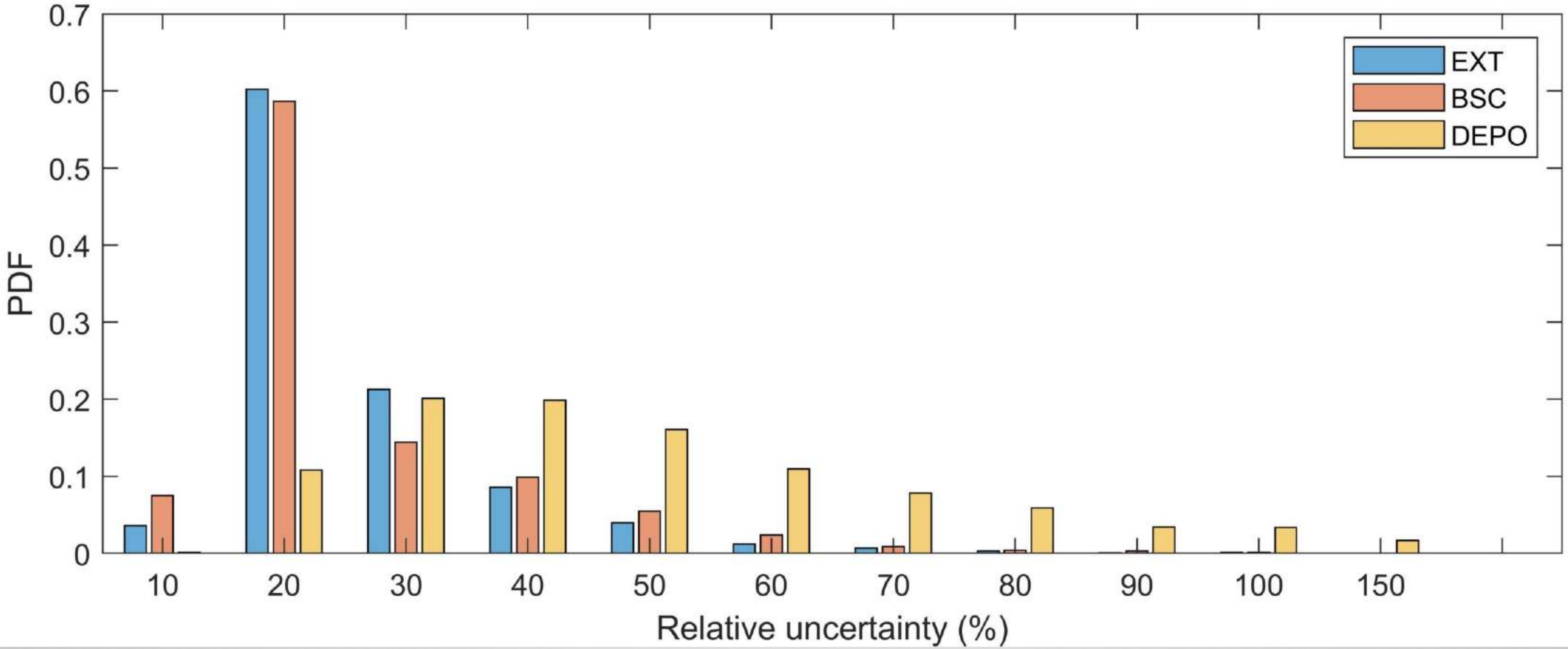
Comparison of NASA HSRL-2 lidar spectral observables

All aerosol types

Dusty Mix
(Similar environment to ORCSTRA)

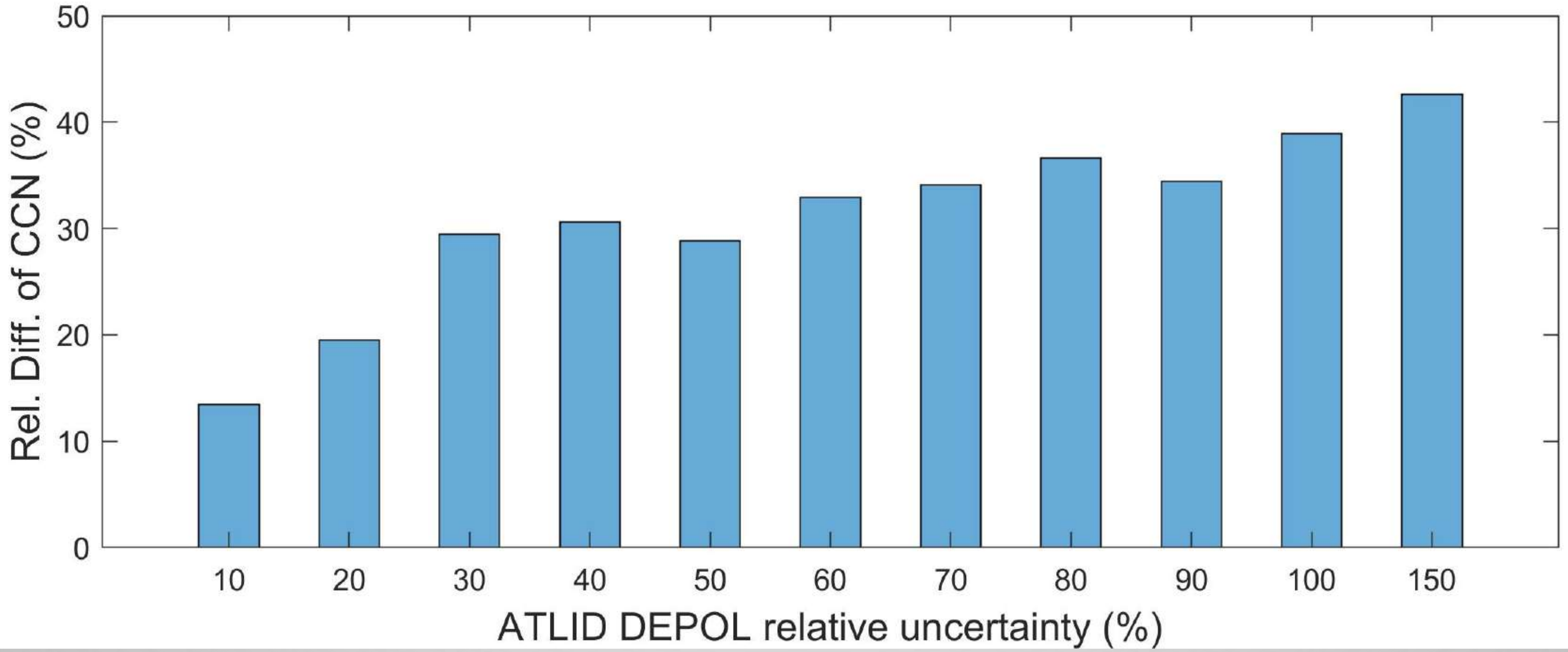


Distributions of ATLID observables uncertainty (BA)



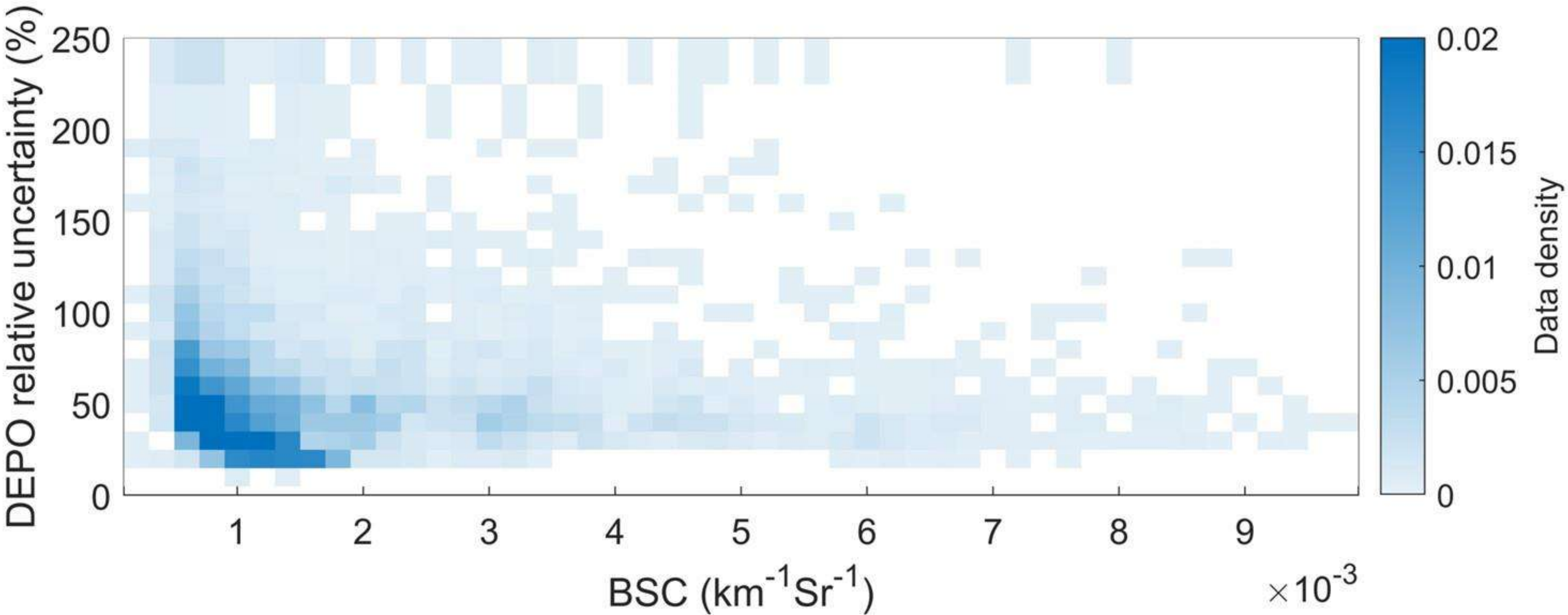
- Relative uncertainty = ATLID reported GV uncertainty / reported GV values X 100%
- DEPOL is associated with larger relative uncertainty than EXT and BSC.

Relative difference of CCN between ATLID and WALES as a function of DEPOL uncertainty



The relative differences in CCN increase with increasing uncertainties in ATLID depol.

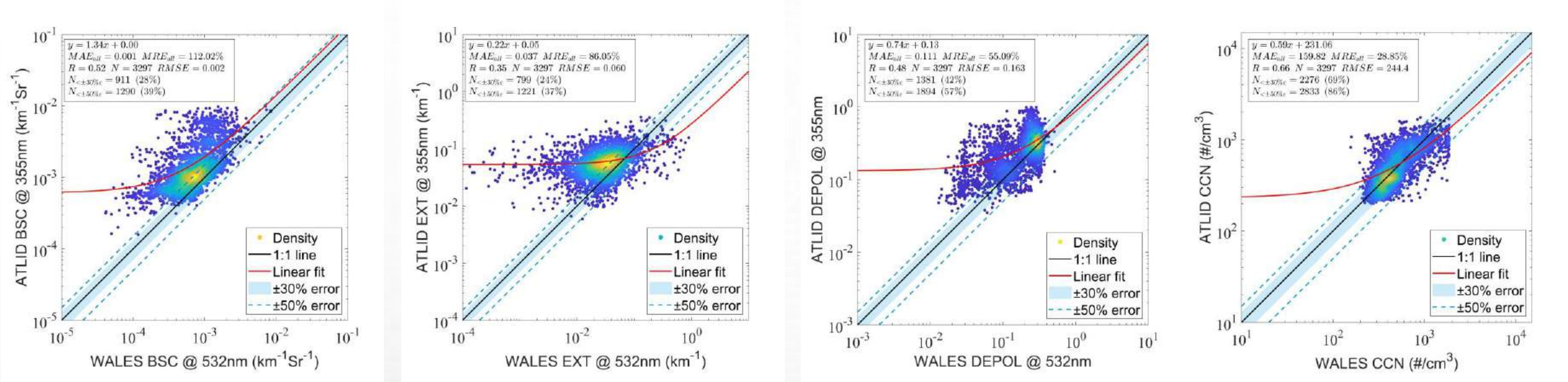
Distributions of ATLID DEPOL uncertainty as a function of BSC value



- Higher DEPOL uncertainty is likely associated with lower BSC (lower SNR).
- Removing high-uncertainty DEPOL samples is likely to eliminate observations in clean regions.

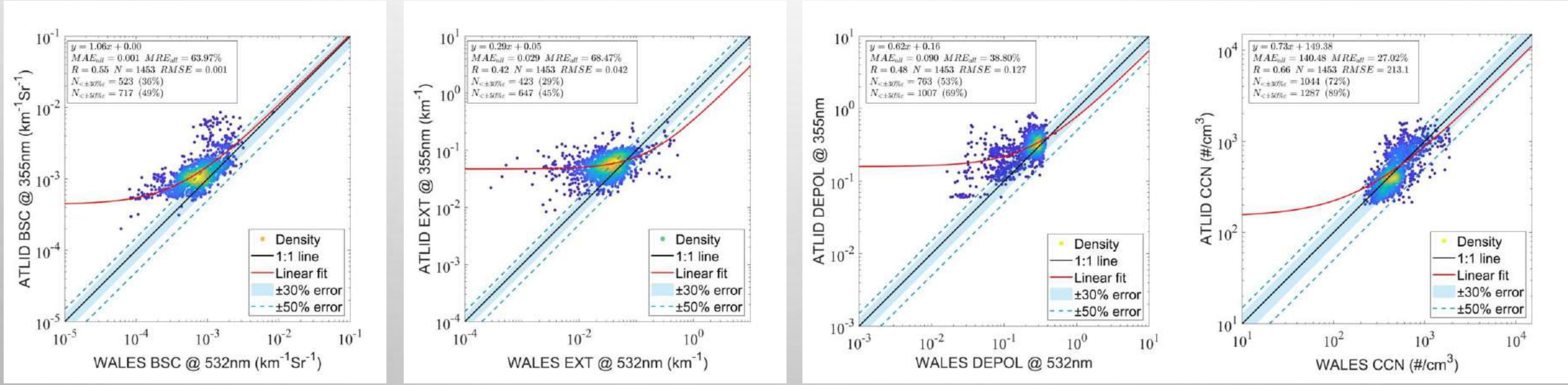
Excluding higher uncertainty samples for all three lidar GVs

50%



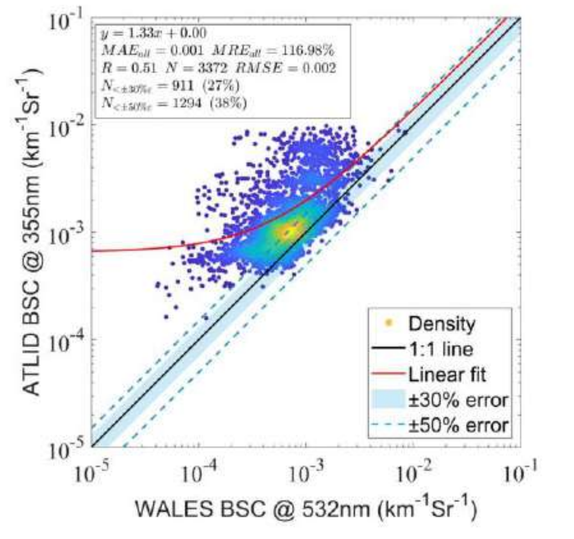
Excluding samples with higher ATLID uncertainty improves the consistency between ATLID and WALES.

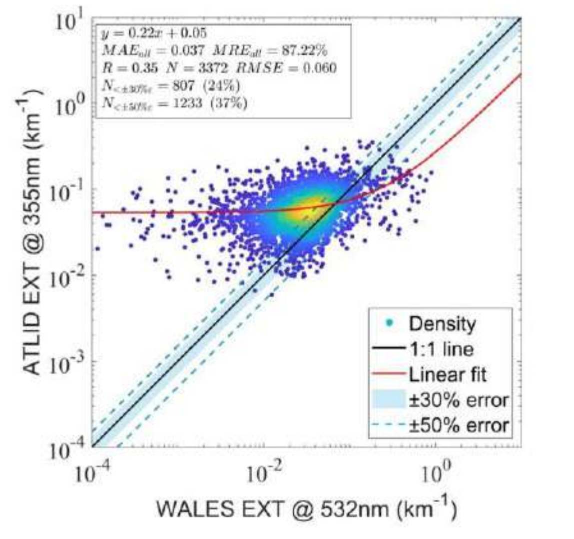
30%

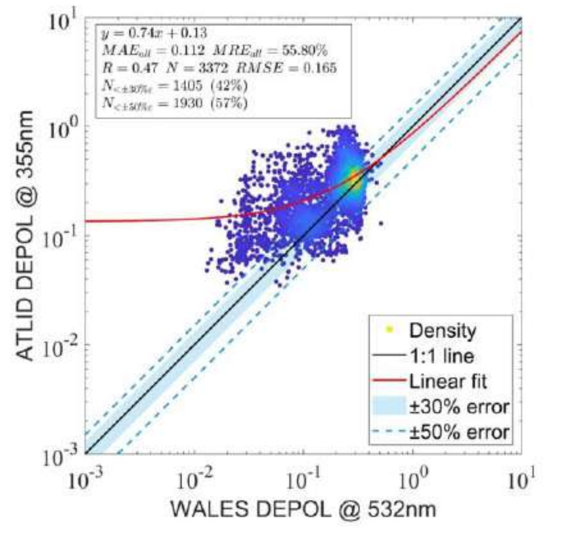


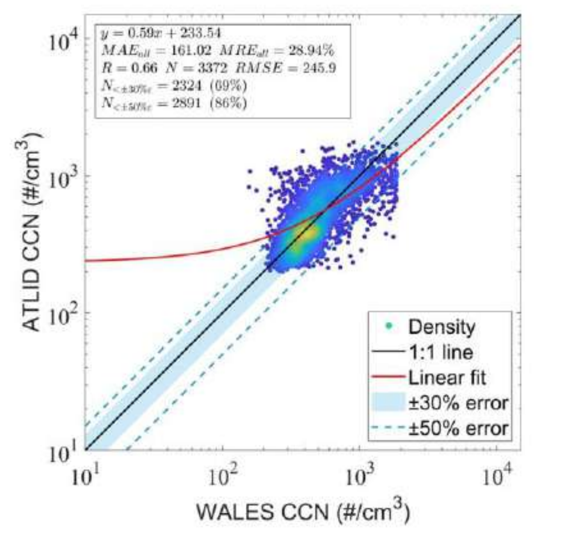
Excluding higher uncertainty samples for ATLID DEPOL 355 nm

50%

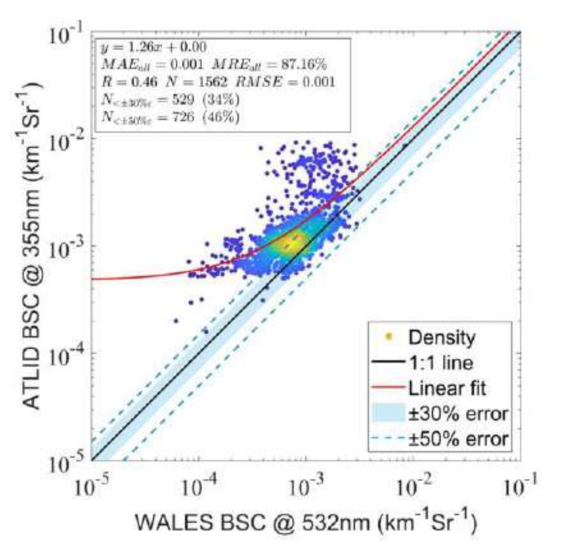


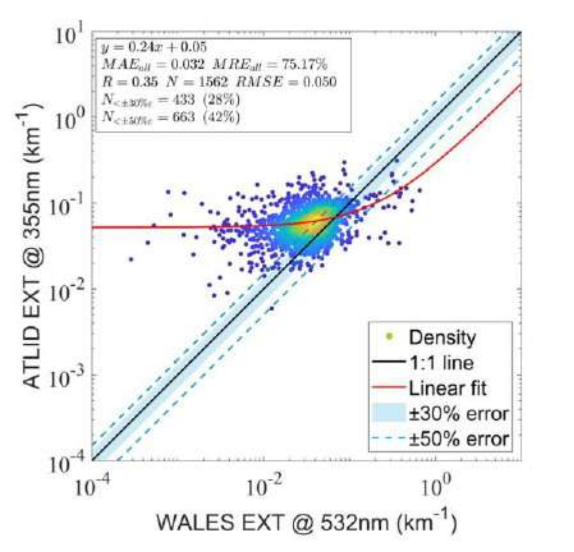


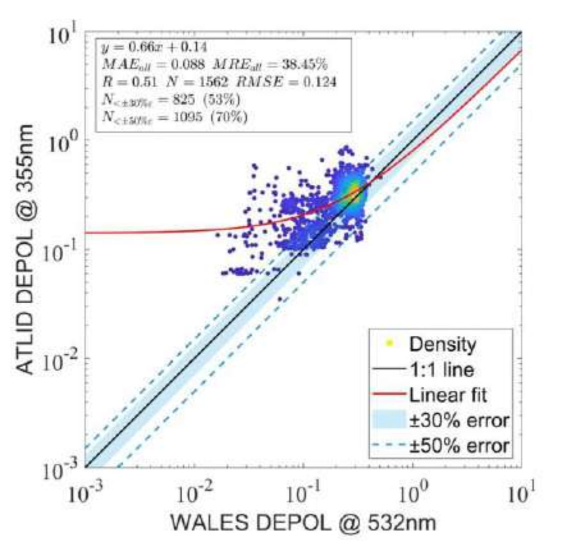


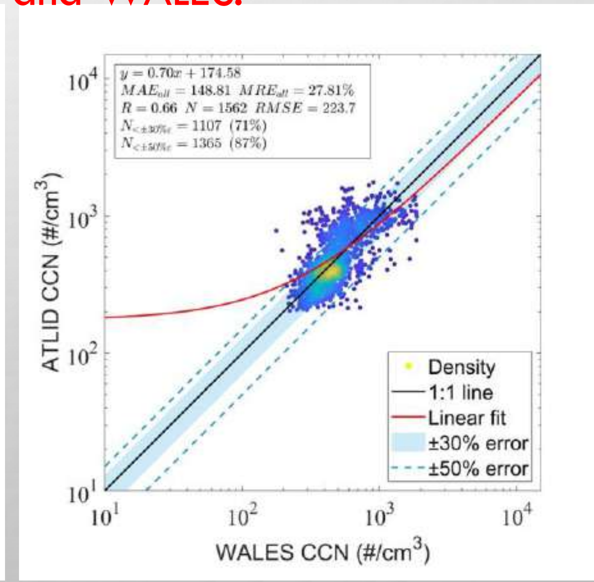


Excluding samples with higher ATLID DEPOL uncertainty improves the consistency between ATLID and WALES.





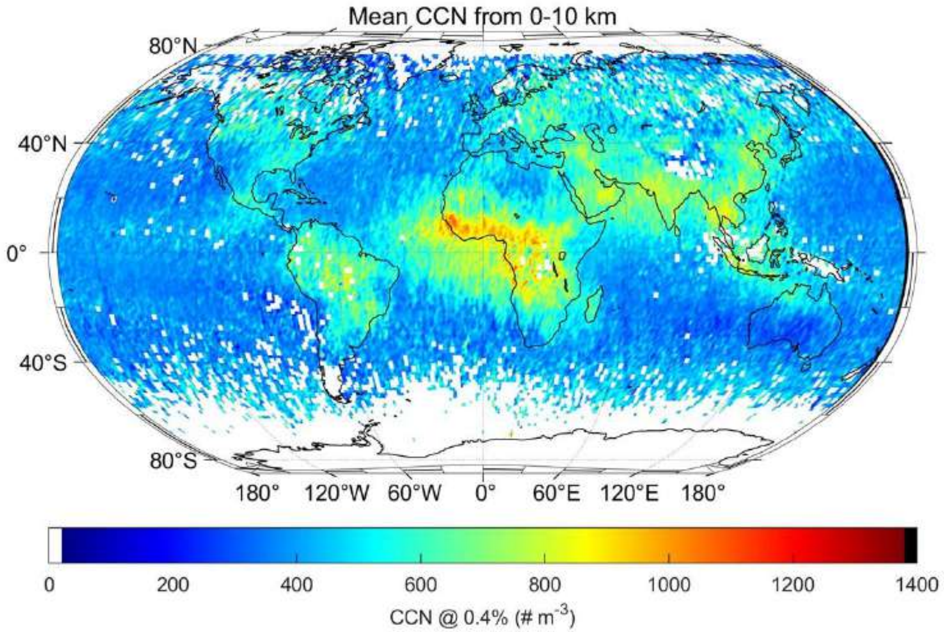


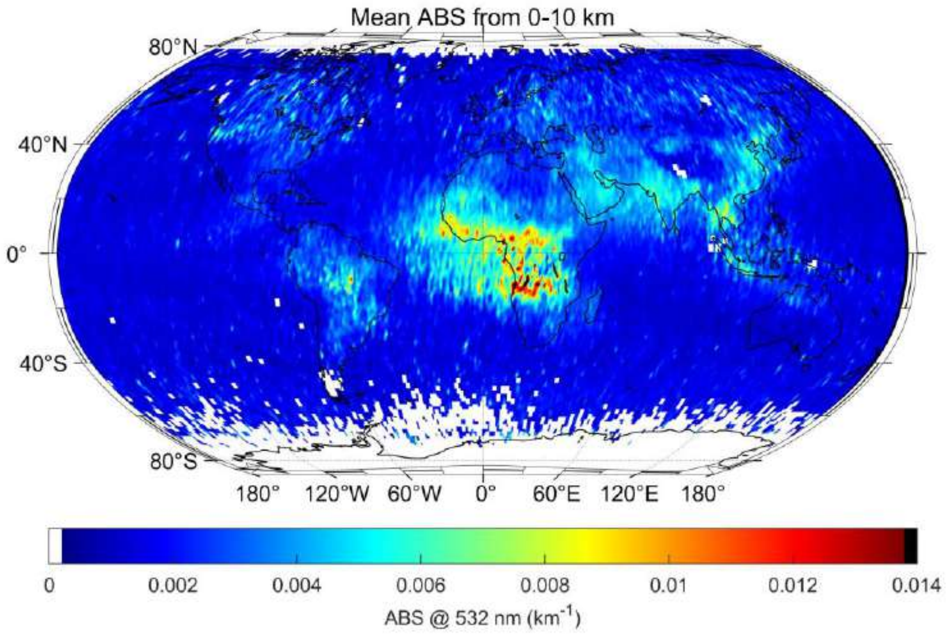


30%

Global maps of CCN and ABS from ATLID

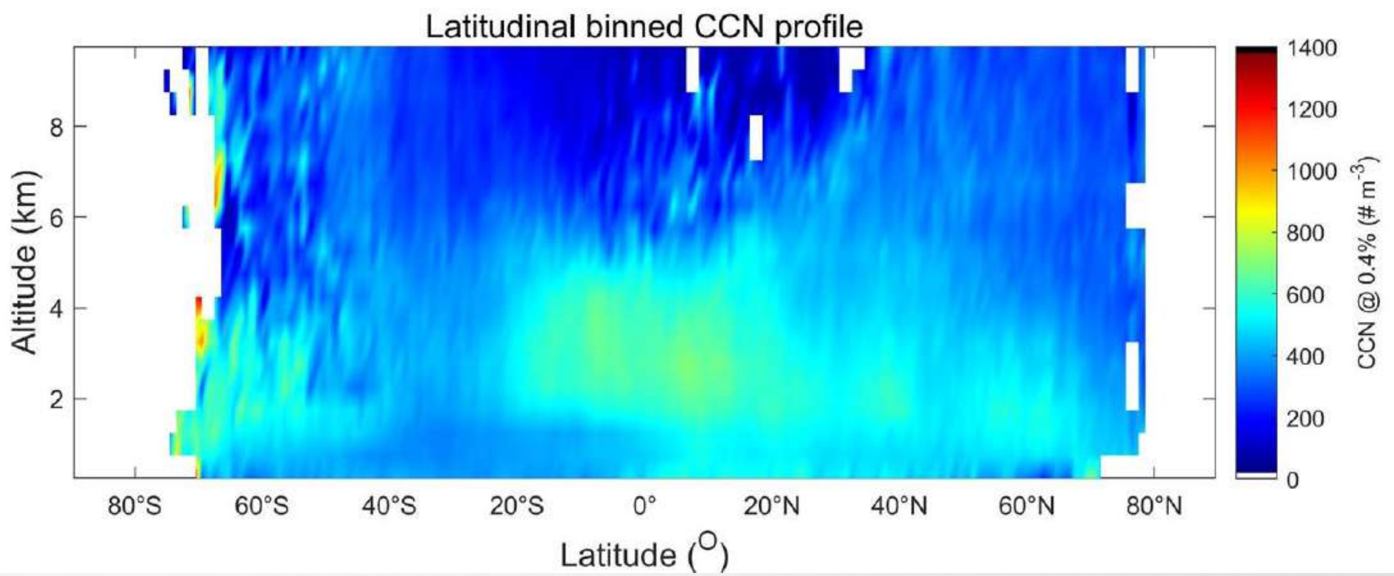
- Data: low-res. ATLID BA data
- Time range: first 6 months
  - Aug 01, 2024 – Jan 30, 2025
- Spatial averaging:
  - Horizontal: 1 degree
  - Vertical: 0-10 km
- Additional data quality control:
  - Exclude grids (500m vertical) with number of samples less than 200

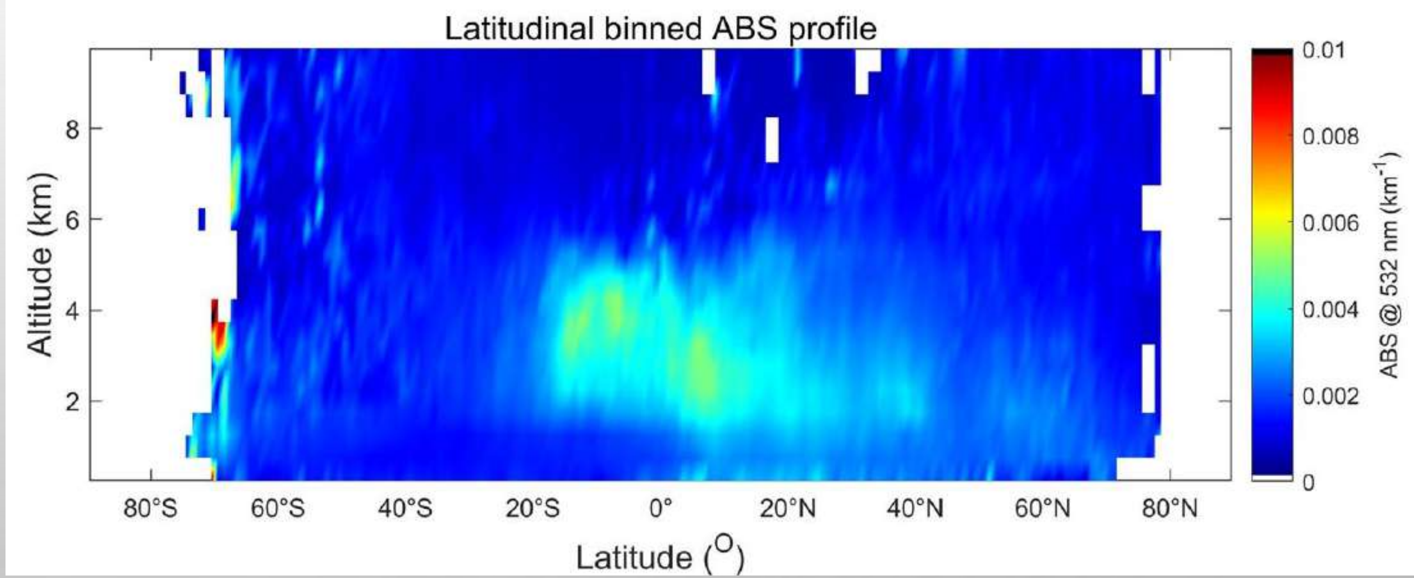




Global vertical distributions of CCN and ABS from ATLID

- Data: low-res. ATLID BA data
- Time range: first 6 months
  - Aug 01, 2024 – Jan 30, 2025
- Spatial averaging:
  - Horizontal: 1 degree
  - Vertical: 500 m from 0-10 km
- Additional data quality control:
  - Exclude grids with number of samples less than 200





Number of valid samples:

Valid data criteria:

- EBD are simultaneously available & >0
- EBD and TC data pass QA filtering (QA = 0)
- EBD relative errors < 100%
- TC classification indicates aerosol
- EBD values meet the retrieval criteria