Ice-Over-Water Cloud Properties in an Artificial Neural Network Approach

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CERES Science Team Meeting
October 17-19, 2023,
NASA Goddard Institute for Space Studies
2880 Broadway New York, NY

Motivation

- CERES has always had the goal of multilayer (ML) retrievals to improve quantification of the relationships between clouds and radiation within the atmosphere

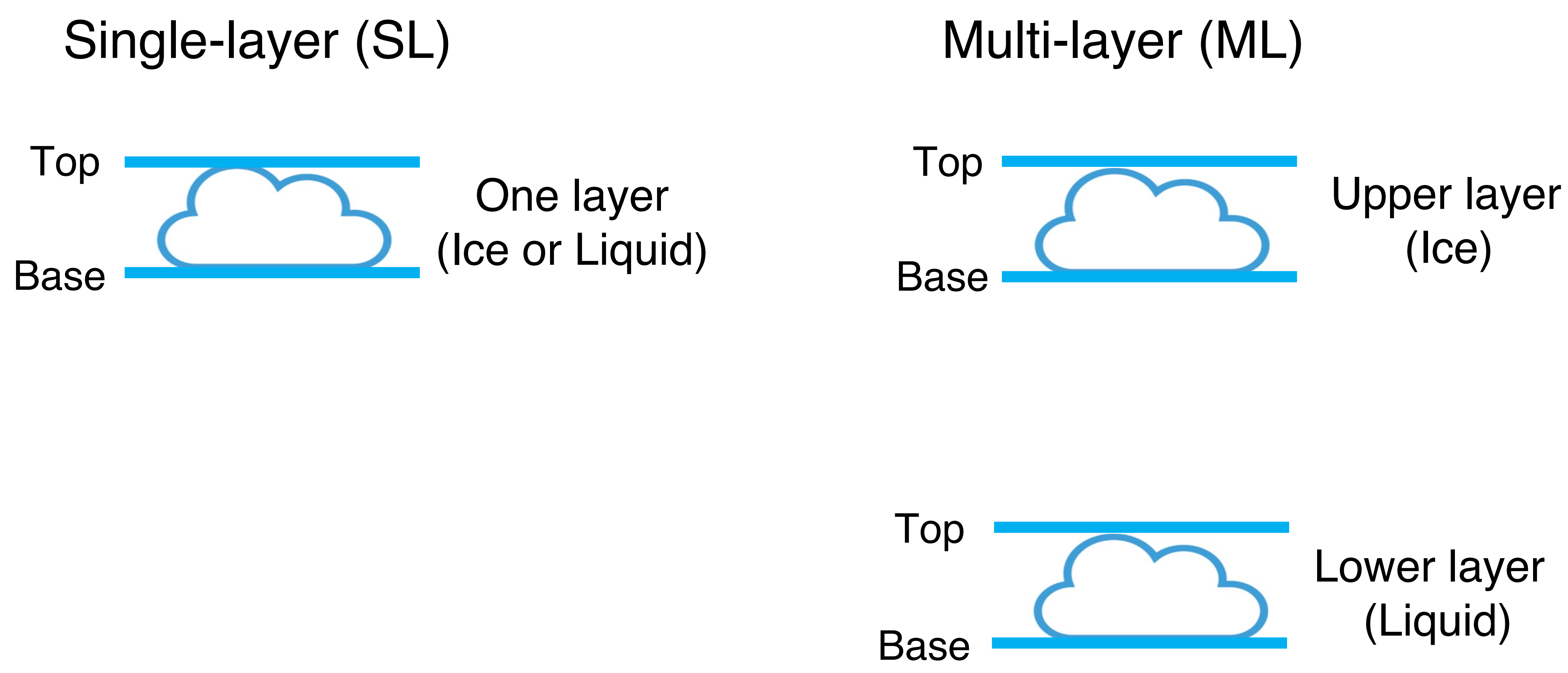
- CERES Ed4 MODIS used Modified CO2 Absorption Technique (MCAT) to detect ML clouds (ice over water, primarily) and retrieve the properties
  - MCAT detection yields **negative** net gain in accuracy (NGA = true ML - false ML), although some true ML clouds detected
  - Cloud top heights CTH from 2-layer MCAT clouds underestimated by 2.6 km for upper CTH and overestimated low CTH by 1.2 km

    (Viudez-Mora et al., 2015)
  - MCAT deemed unreliable and not used, need a more reliable approach

- International GEWEX Cloud Assessment Program recommends that cloud retrieval algorithms focus on the vertical structure of clouds
  - Most major cloud groups have or are attempting to include ML clouds in their retrievals. *(Stubenrauch et al., 2023 submitted)*
  - Model for CERES is C3M analysis showing improvement when **realistic cloud vertical profiles** are used to adjust SARB input

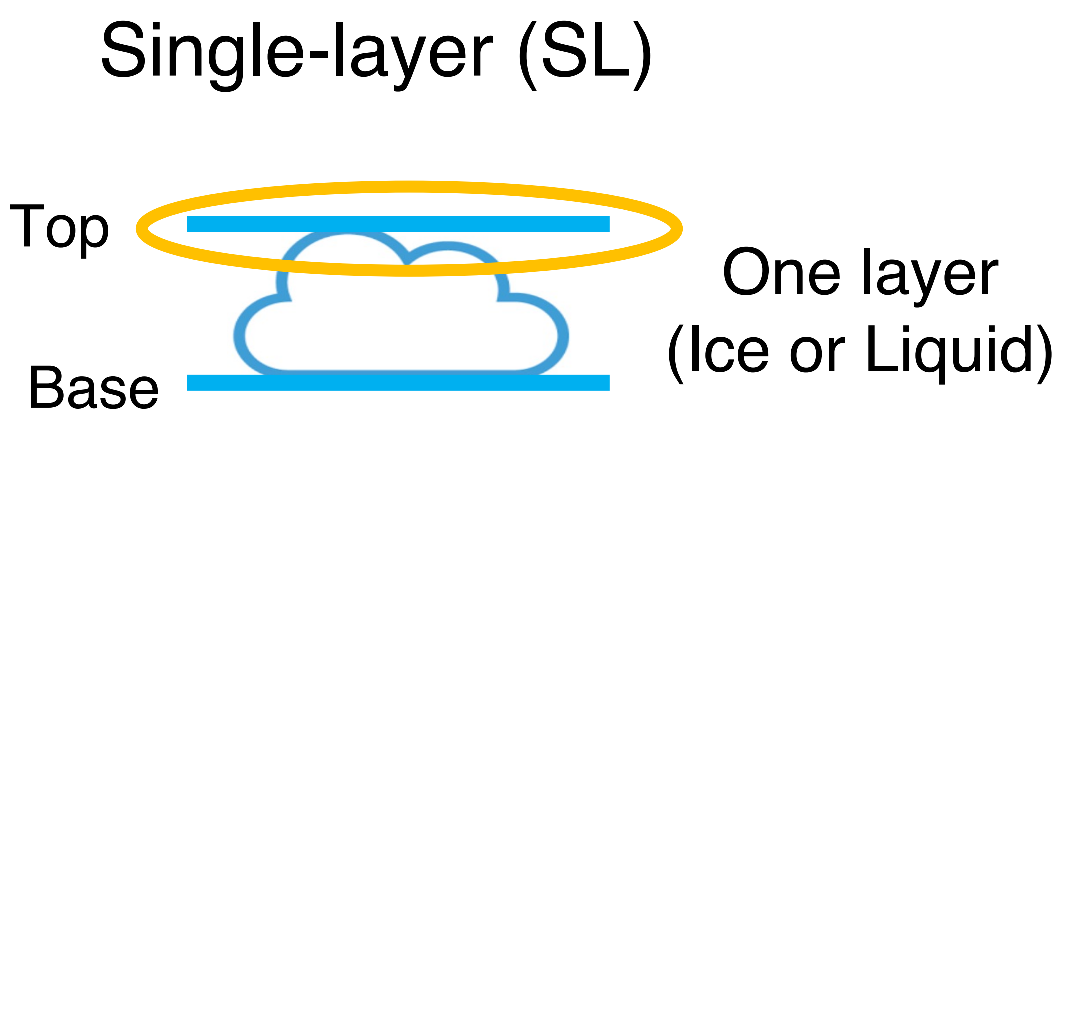
    (Ham et al., JCAM, 2023)

Cloud-top/base Heights from Aqua MODIS Using a Neural Network Approach



- **ML defined as ice-over-water cloud system, where ice-cloud base is separated from water cloud top by 1 km or more**
  - *Same as ML detection method*
- **SL and ML trained separately with CALIPSO-CloudSat data (C3M)**
  - ***Preliminary results*****:** daytime, snow-ice free surfaces
  - Input includes Lat, Lon, SZA, CODv, elev, BT37, BT85, BT11, BT12, 3 BTDs, T(z), RH(z). (with and without BT67)
  - Uses one year, 2008, of data sampled to accommodate computer memory
    - *SL uses all low and midlevel pixels, and every third high pixel, then sample at 1/8 -> 2.55 M pixels*
    - *ML uses the same, but no secondary sampling -> 2.56 M pixels*
    - *Presented results use all matched pixels (~36 M pixels), no diminished high cloud sampling*

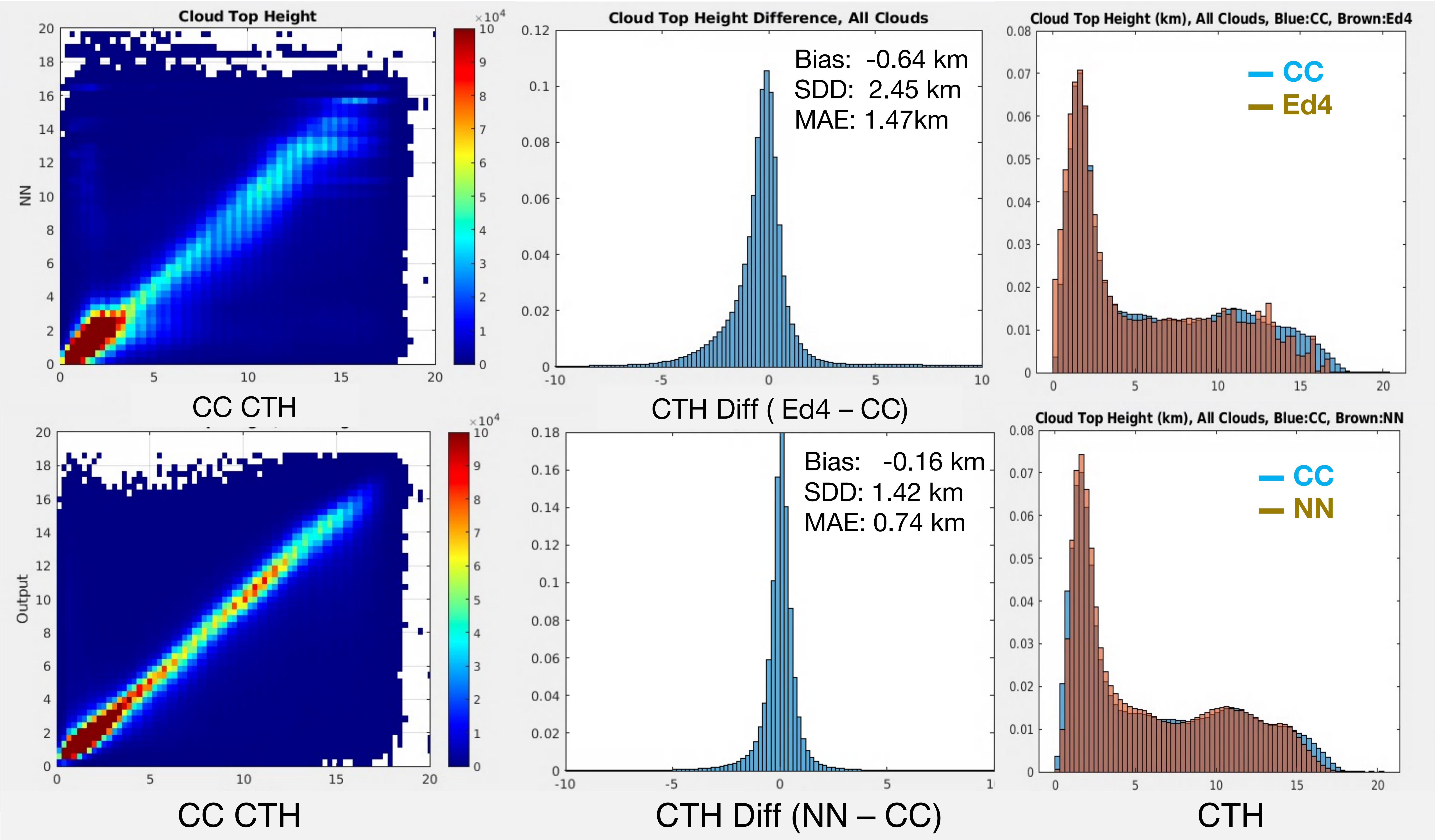
Cloud Top Heights (CTH)



Single-Layer Cloud-Top Heights (CTH, SL), Daytime, Snow/Ice Free Surface, 2008

Ed4 CTH

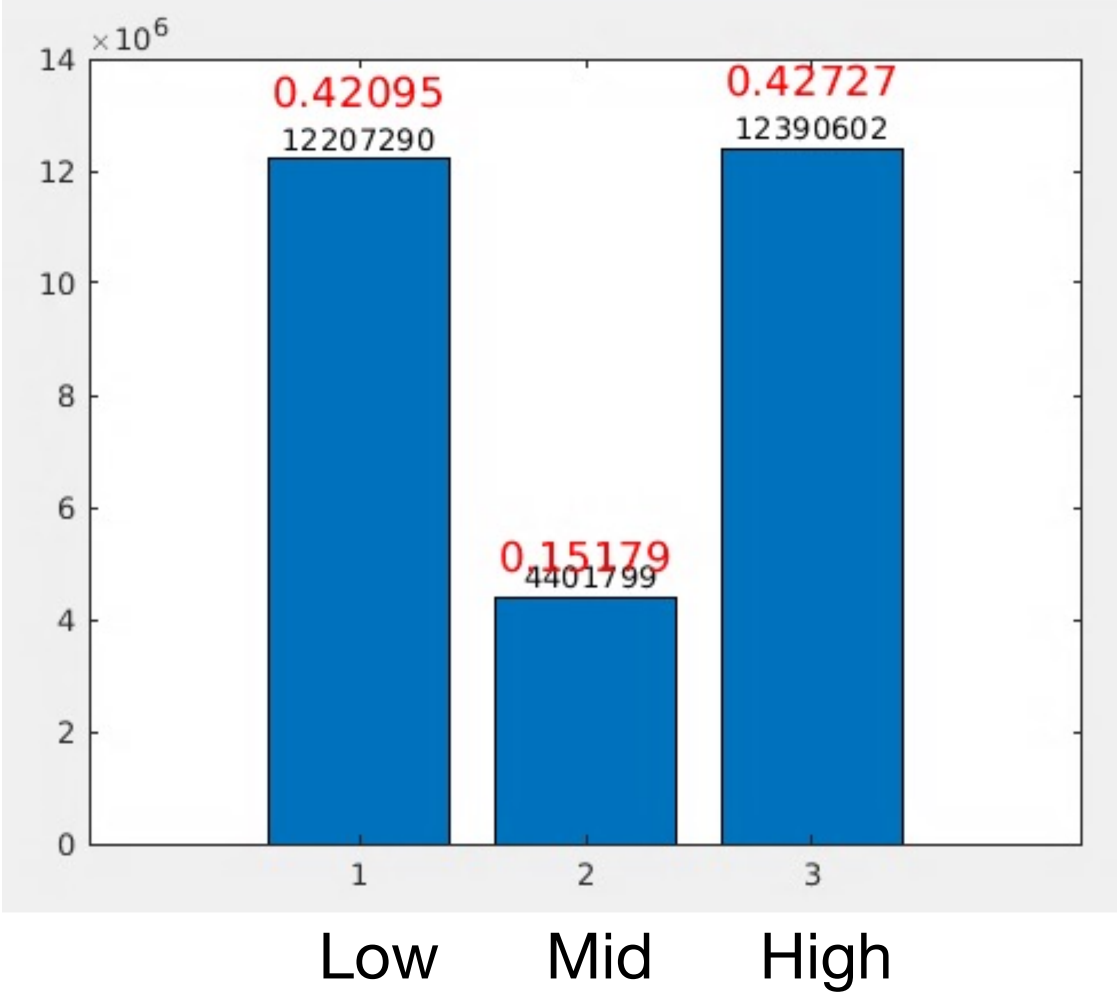
NN CTH



All quantities in km

- **Bias** = mean difference, Aqua - CC
- **SDD** = std dev of differences
- **MAE** = mean absolute error

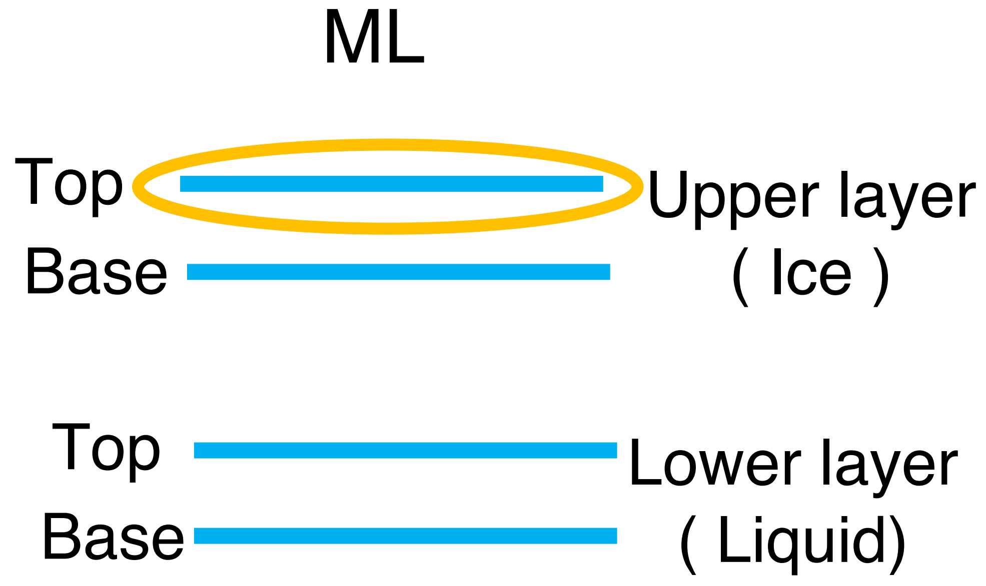
Sample Distribution, ~ 29 million

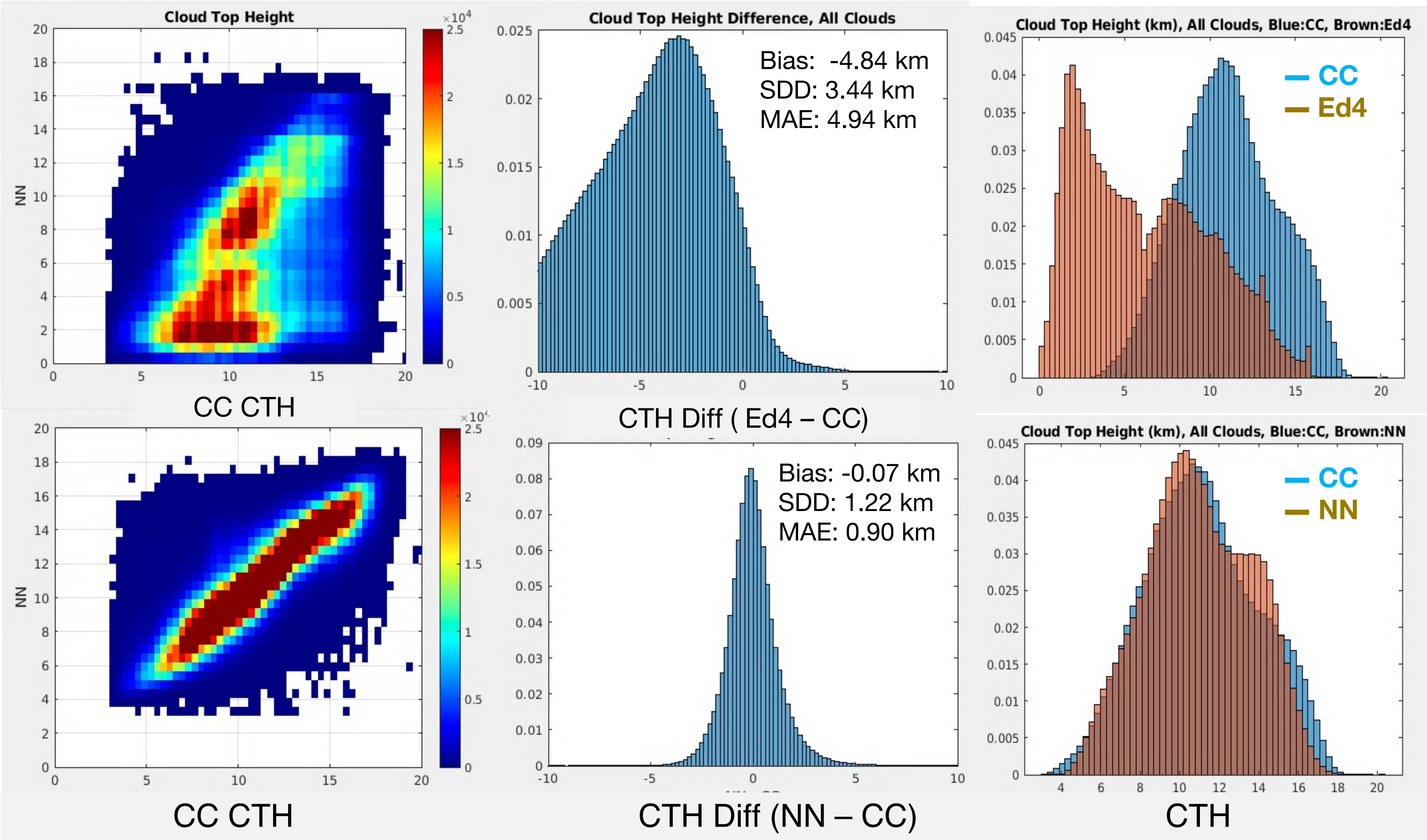


Low: 0 < CTH <= 3 km
Mid: 3 < CTH <= 6 km
High: CTH > 6 km

- NN almost removes overall bias
- NN nearly halves the standard deviation of the differences
- NN halves the mean absolute error

Multi-Layer Upper Cloud Top Heights (CTH, ML), Daytime, Snow/Ice Free, 2008

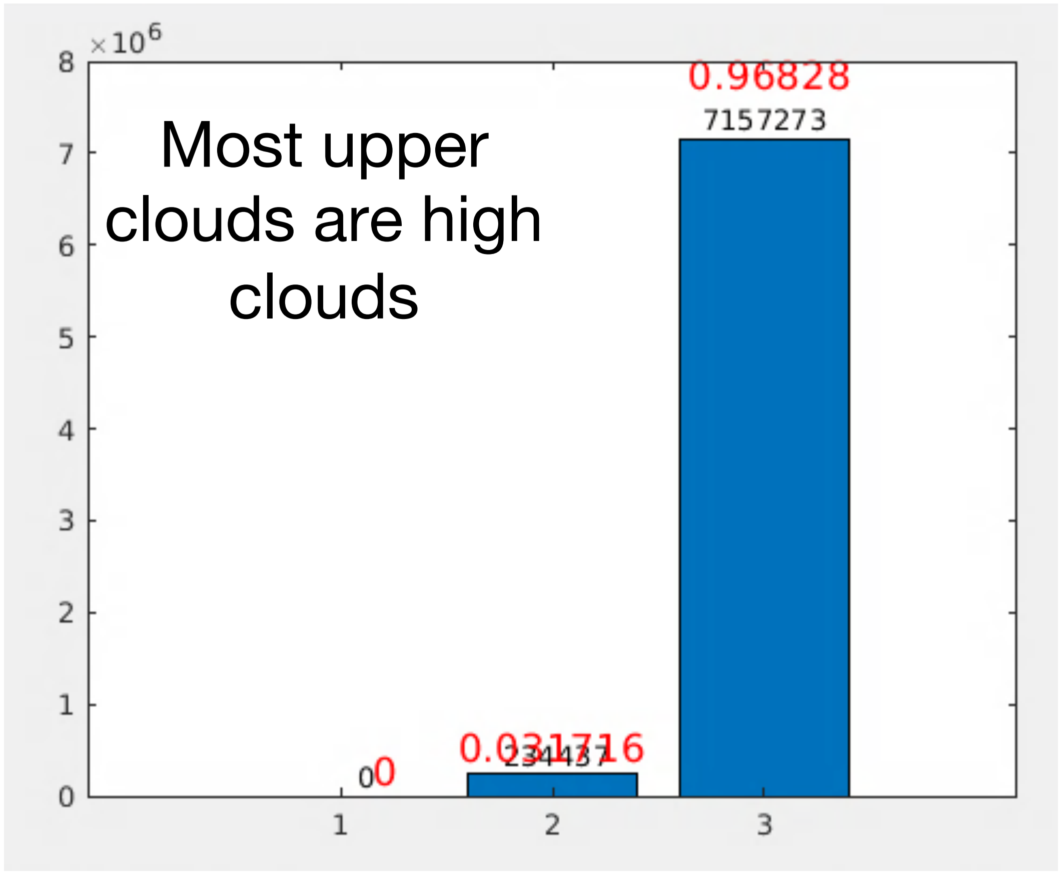




All quantities in km

- **Bias** = mean difference, CC- Aqua
- **SDD** = std dev of differences
- **MAE** = mean absolute error

Sample Distribution ~ 7.4 million

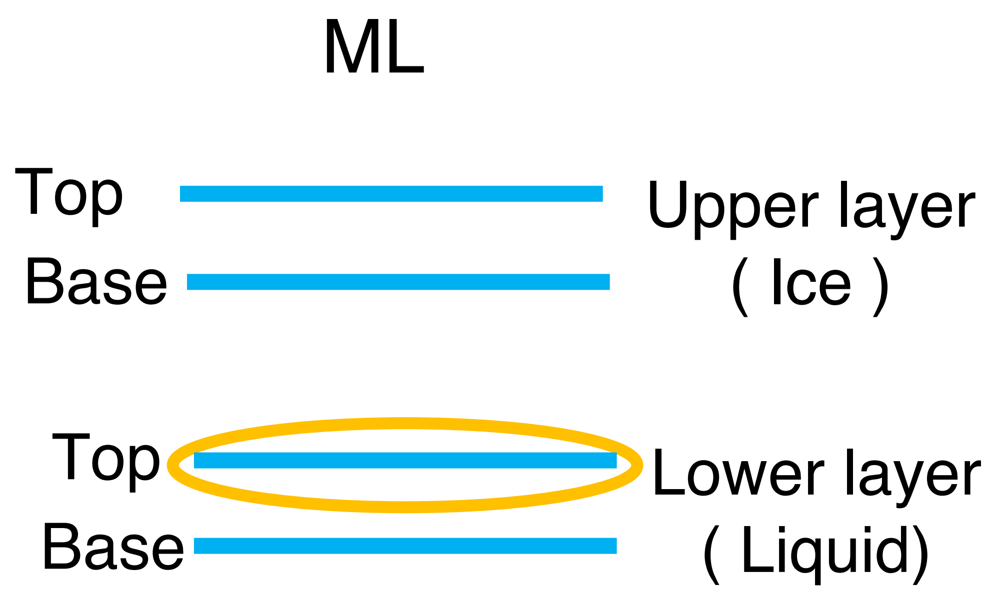


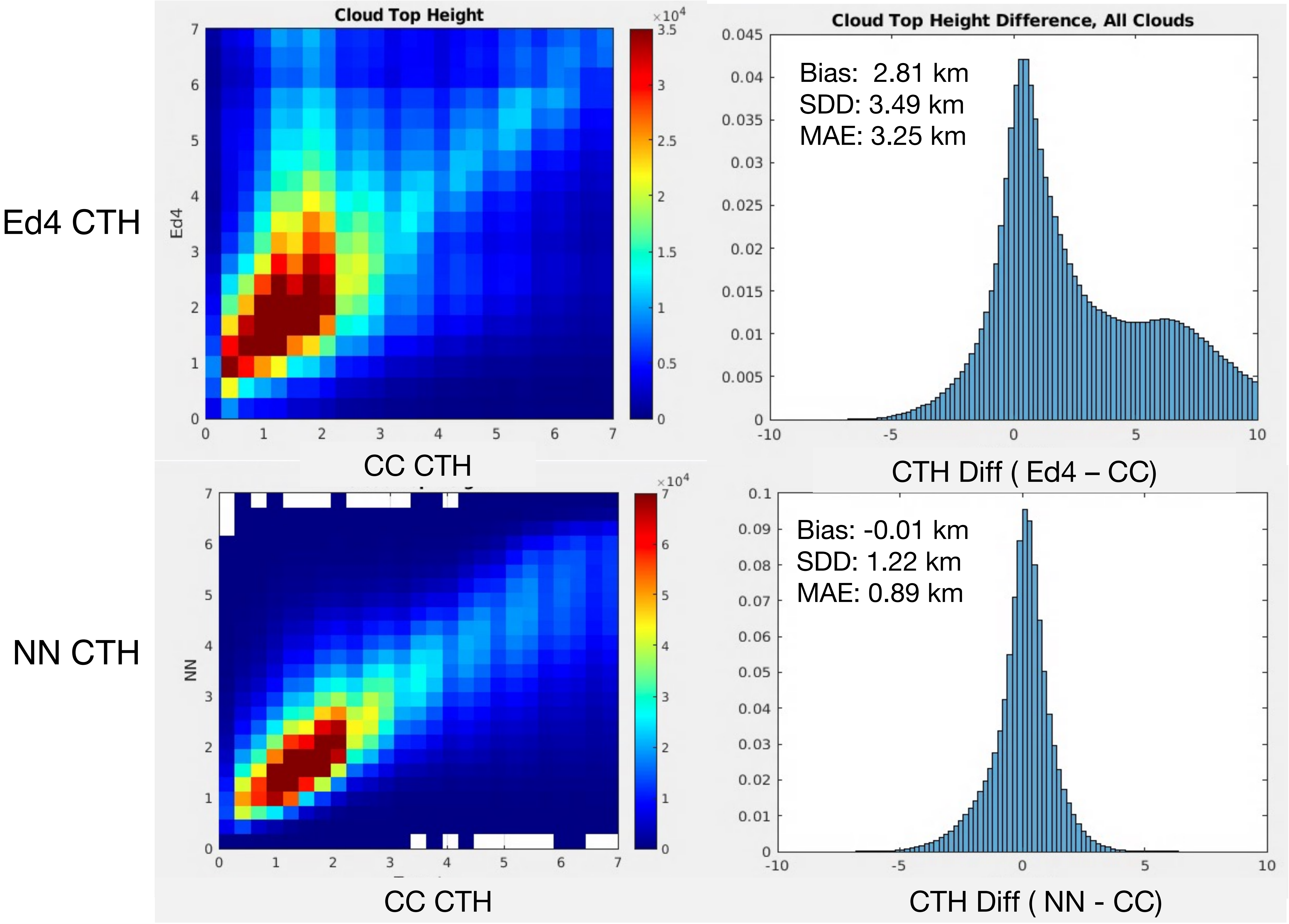
Low Mid High

Low: 0 < CTH <= 3 km
Mid: 3 < CTH <= 6 km
High: CTH > 6 km

- NN removes overall bias
- NN SDD ~ 1/3 of Ed4 SDD
- NN MAE < 1 km, ~1/5 of Ed4 MAE

Multi-Layer **Lower** Cloud Top Heights, Daytime, Snow/Ice Free, 2008



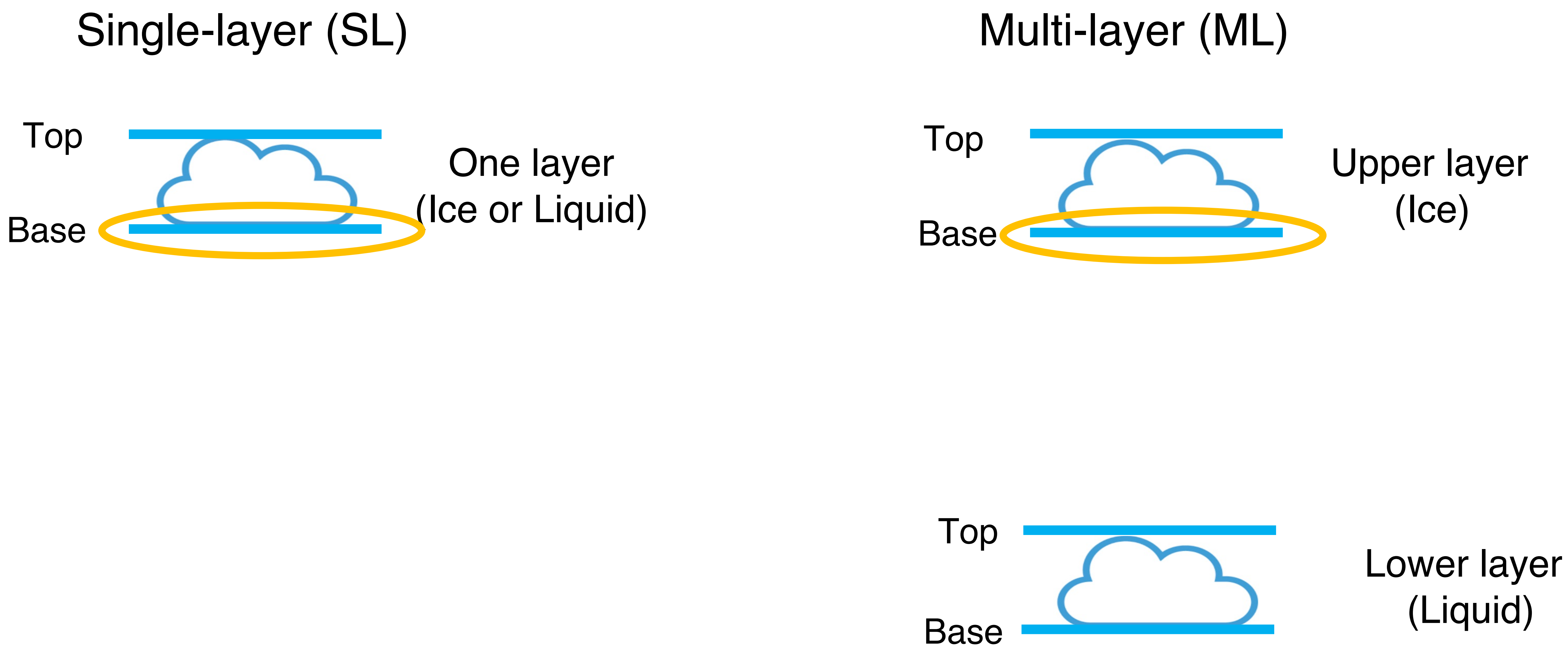


- Almost no bias for NN
- NN SDD is as good as SL SDD and upper ML SDD
- NN MAE < 1 km, ~1/4 of Ed4 MAE

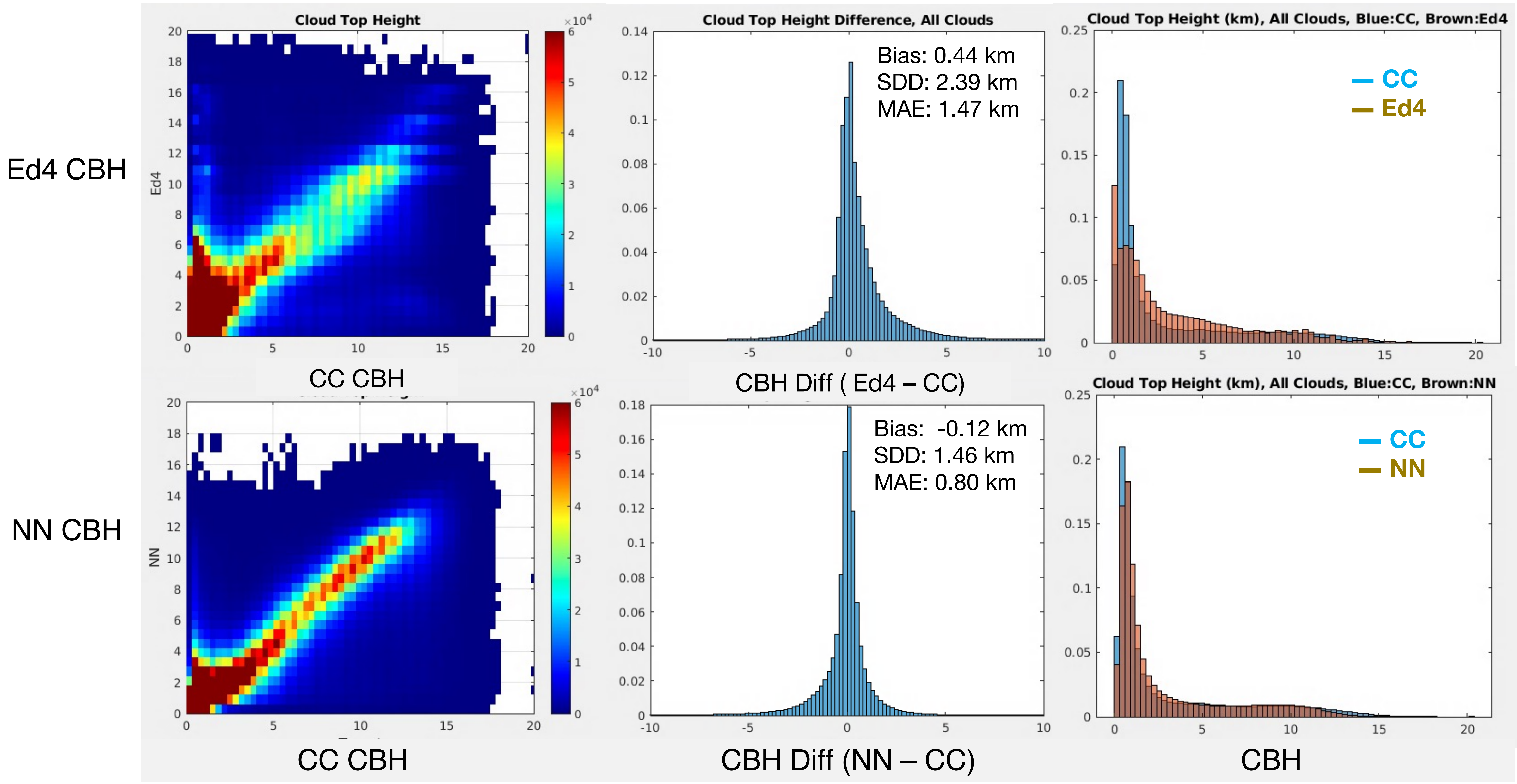
	ΔZ		SDD		MAE	
	Ed4	NN	Ed4	NN	Ed4	NN
Multilayer Lower Cloud						
All	2.81	**-0.01**	3.49	**1.22**	3.25	**0.89**
Mid	2.27	**-0.61**	3.46	**1.07**	3.09	**0.94**
Low	3.25	**0.54**	3.46	**0.84**	3.39	**0.73**

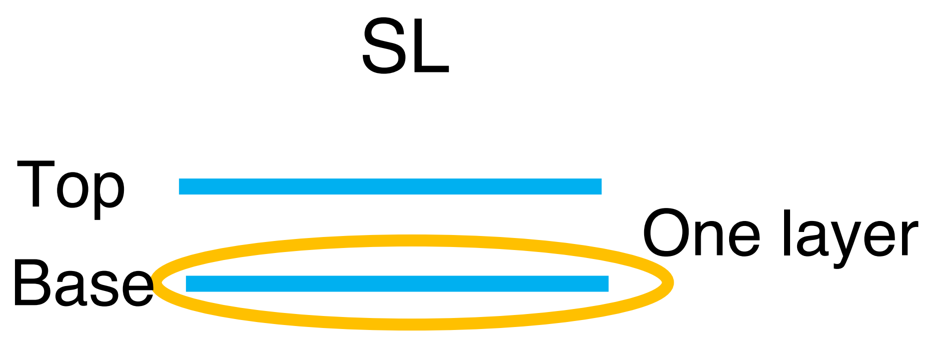
- Mean difference worse than SL Mid and Low
- SDD smaller than SL Mid and Low
- MAE greater than SL mid and low

Cloud Base Heights (CBH)



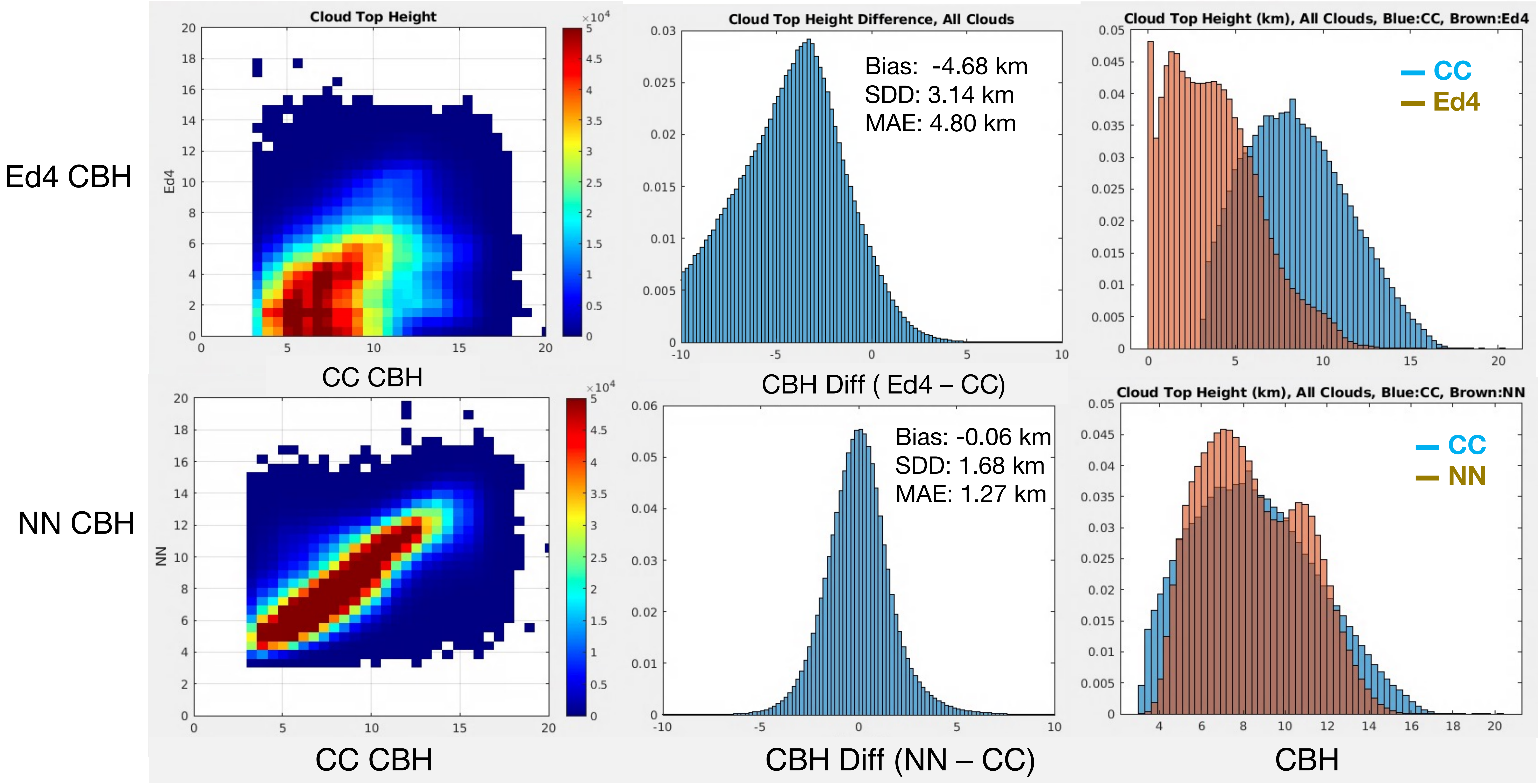
Single-Layer Cloud-Base Heights (CBH), Daytime, Snow/Ice Free, 2008

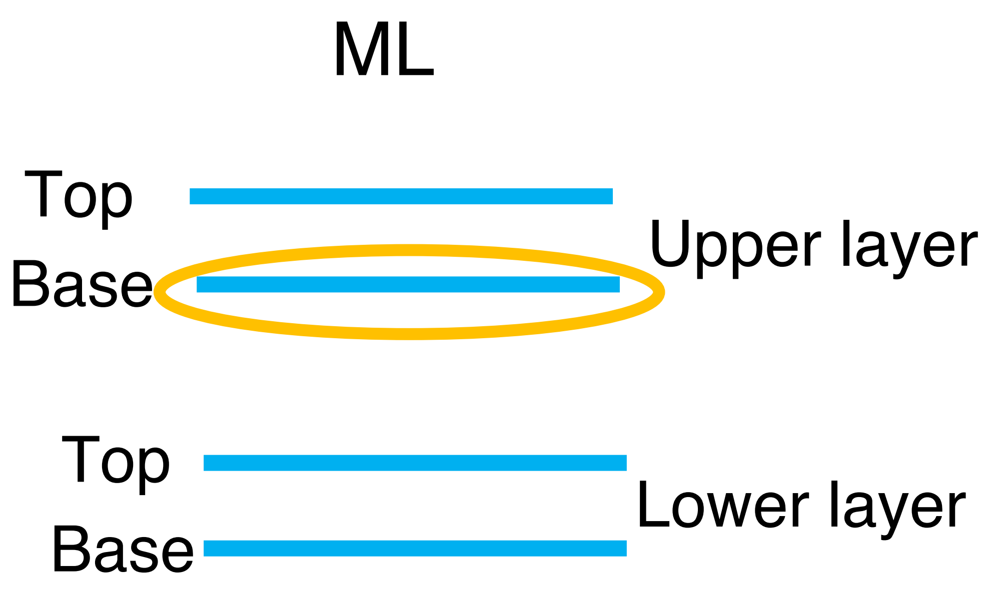




- Results very similar to SL CTH

Multi-Layer Upper Cloud-Base Heights (CBH), Daytime, Snow/Ice Free, 2008





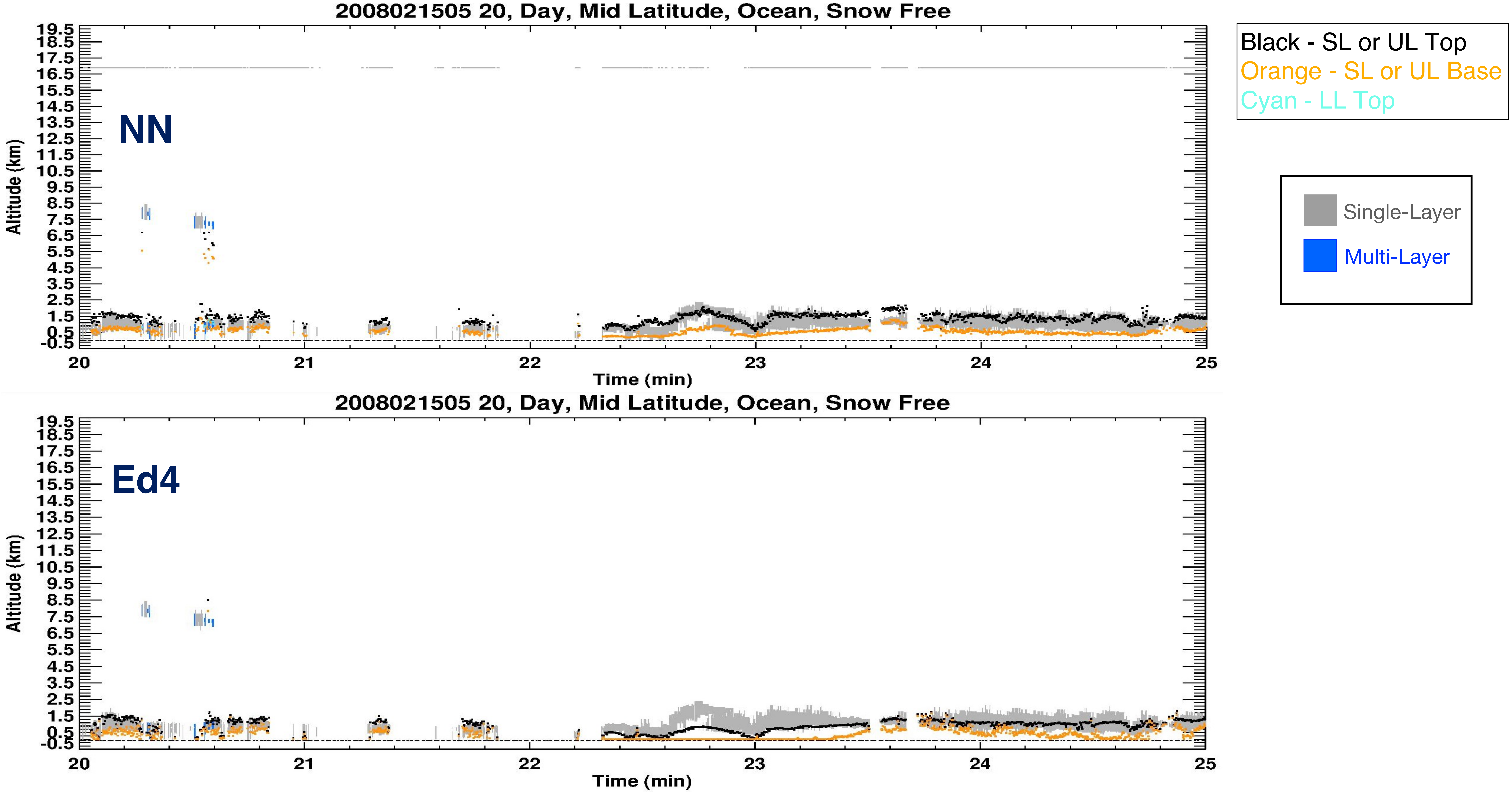
- Bias similar to ML CTH
- SDD & MAE worse slightly compared to ML CTH

Examples of Cloud Height Distributions, Curtain Pictures

Example of Cloud Height Distribution

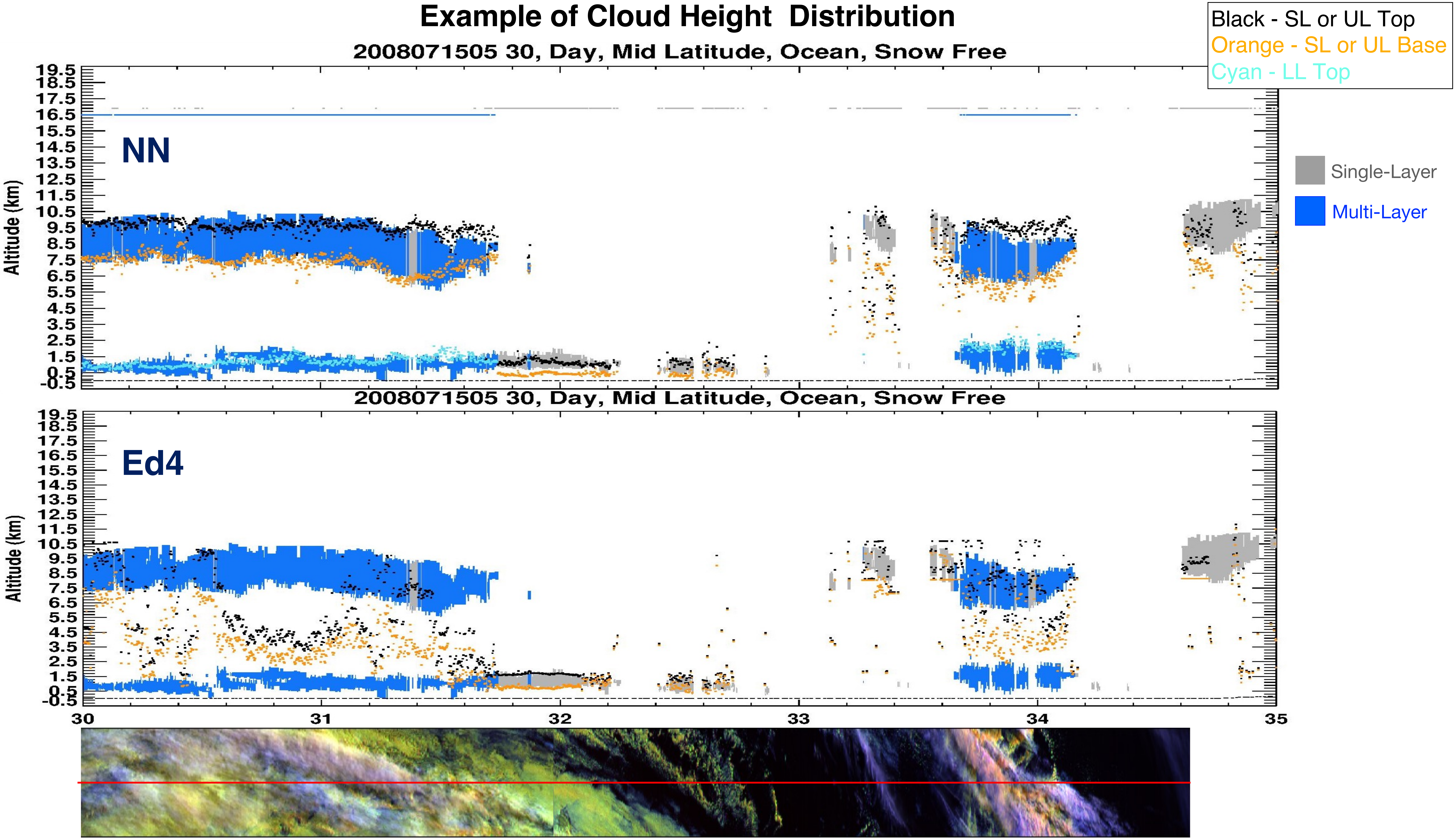
- The heights produced by the new methods, NN, provide a better characterization of cloud vertical structure than Ed4

Example of Cloud Height Distribution



- The heights produced by the new methods, NN, provide a better characterization of cloud vertical structure than Ed4

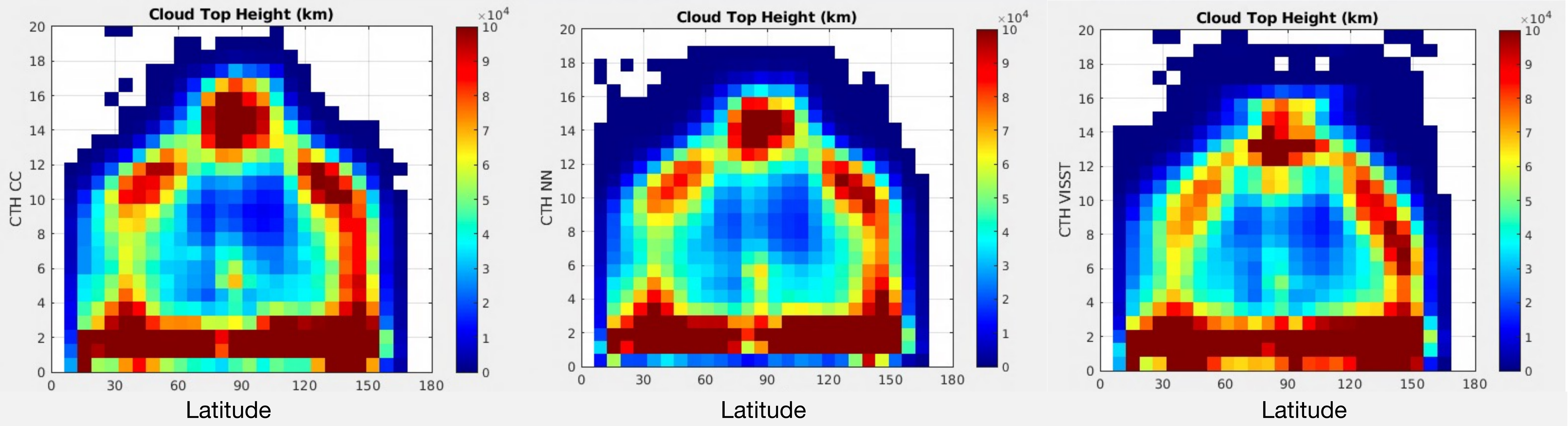
Example of Cloud Height Distribution



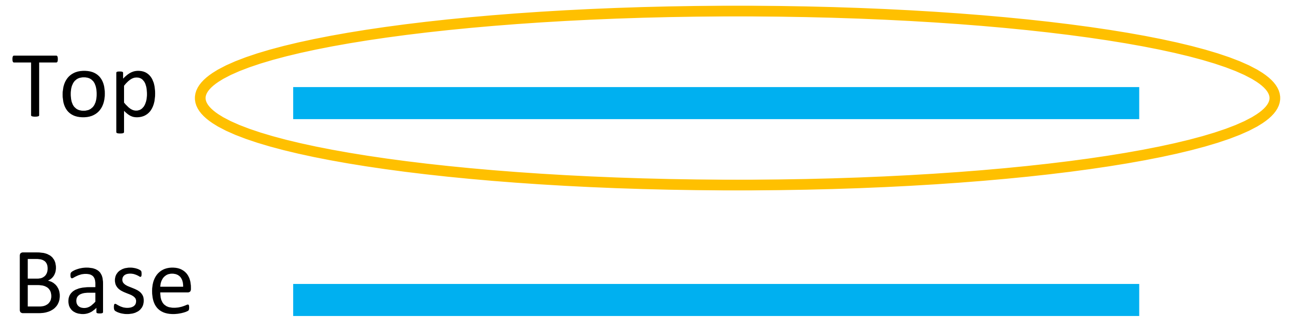
Zonal Distribution of CTH / CBH

Zonal Distribution of Single-Layer Cloud Top Heights over Snow Free Surfaces, Daytime, 2008

CTH, CC　　　　CTH, NN　　　　CTH, Ed4

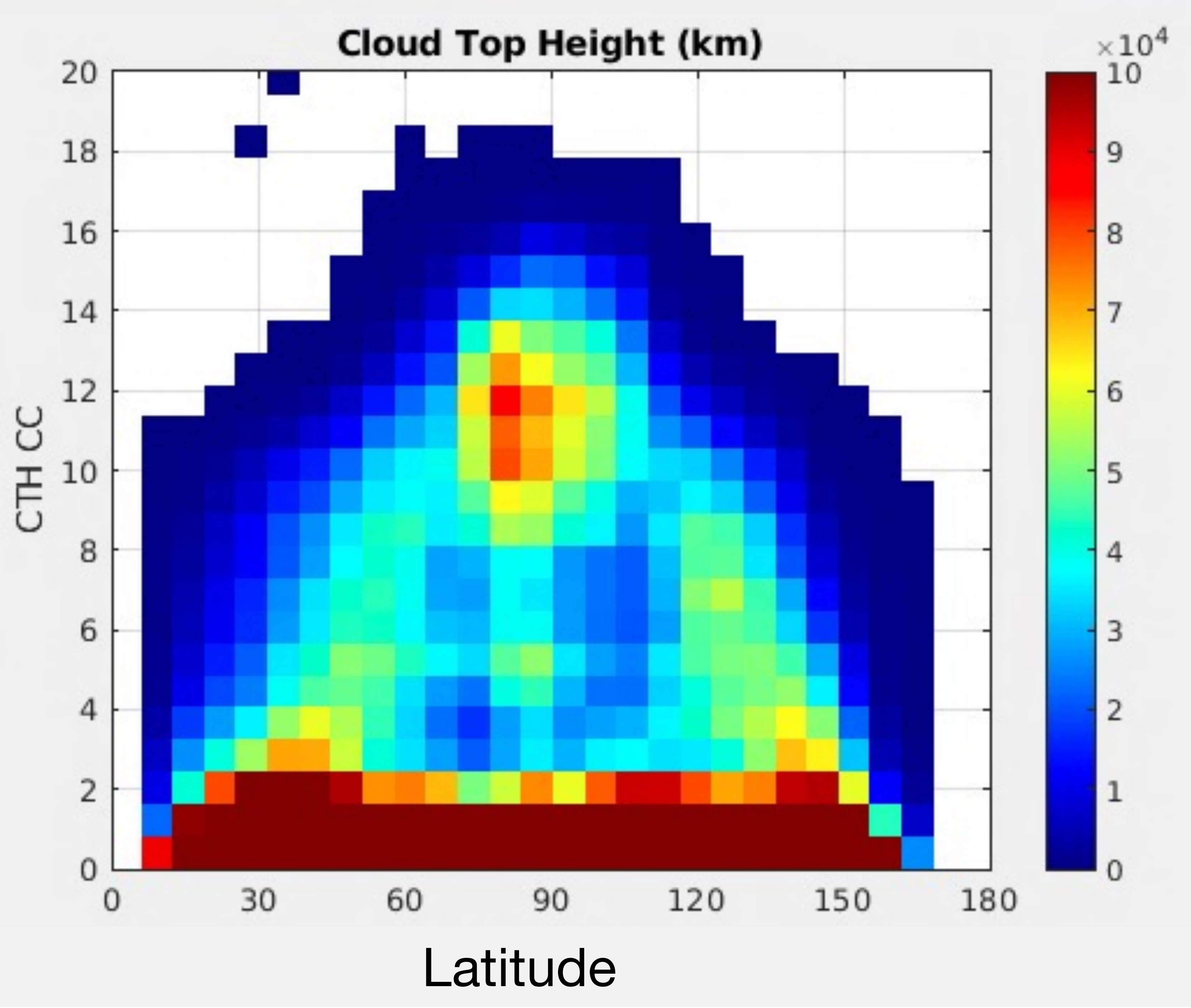


SL

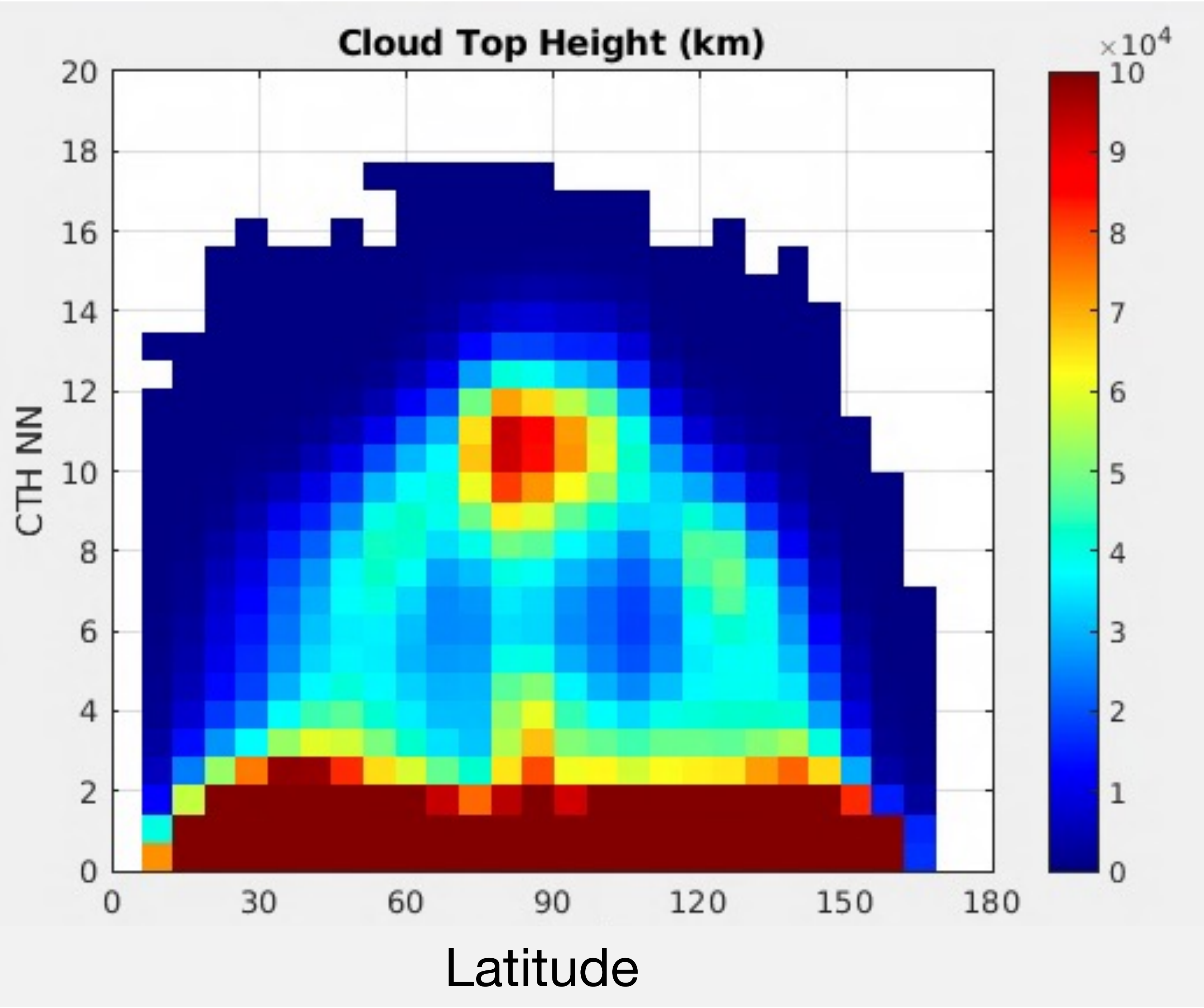


Zonal Distribution of Single-Layer Cloud Base Heights over Snow Free Surfaces, Daytime, 2008

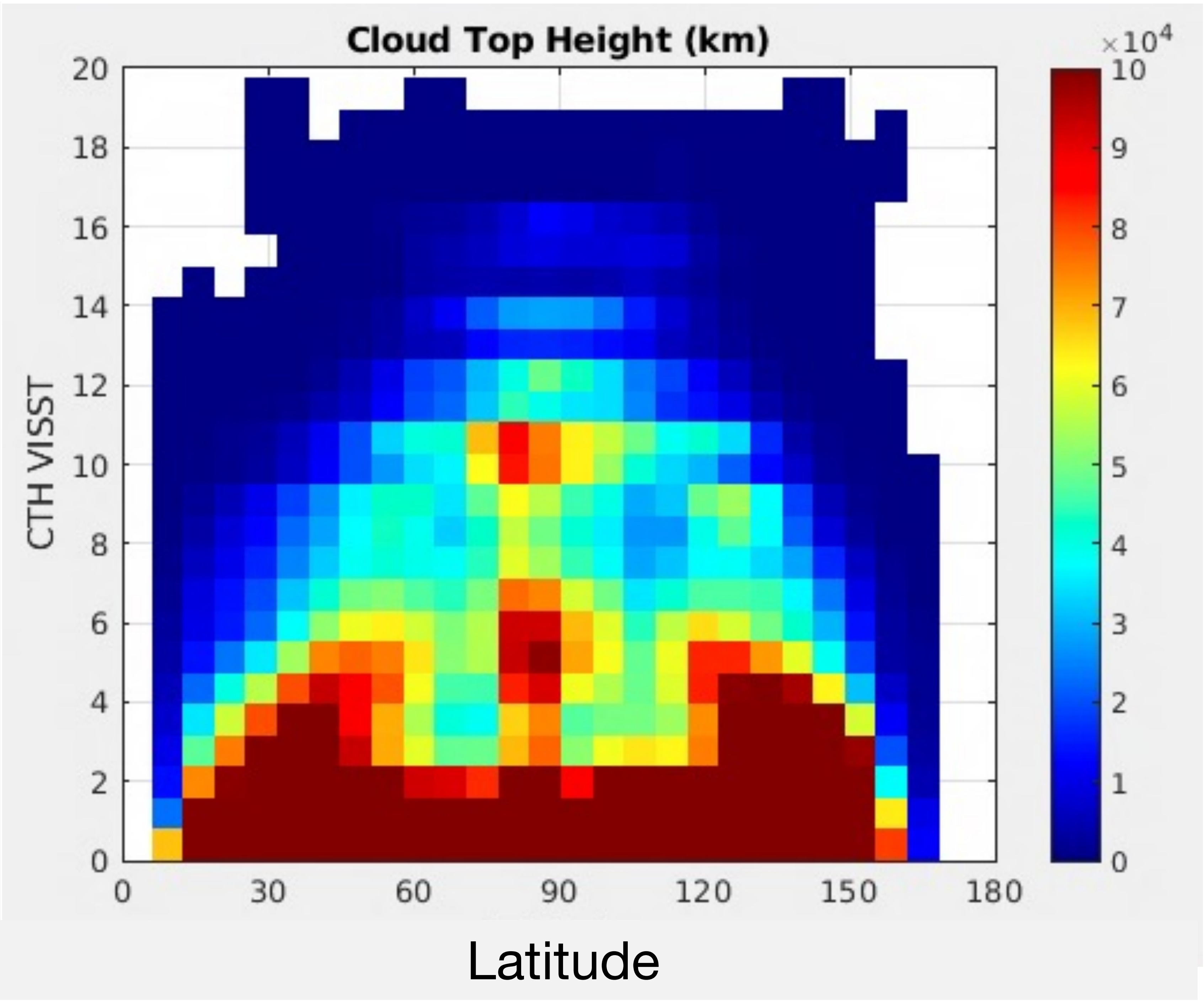
CBH, CC



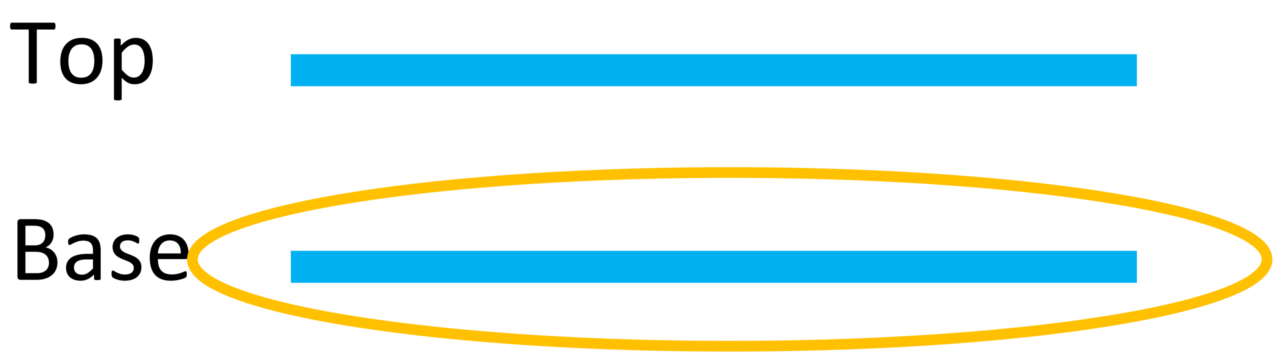
CBH, NN



CBH, Ed4



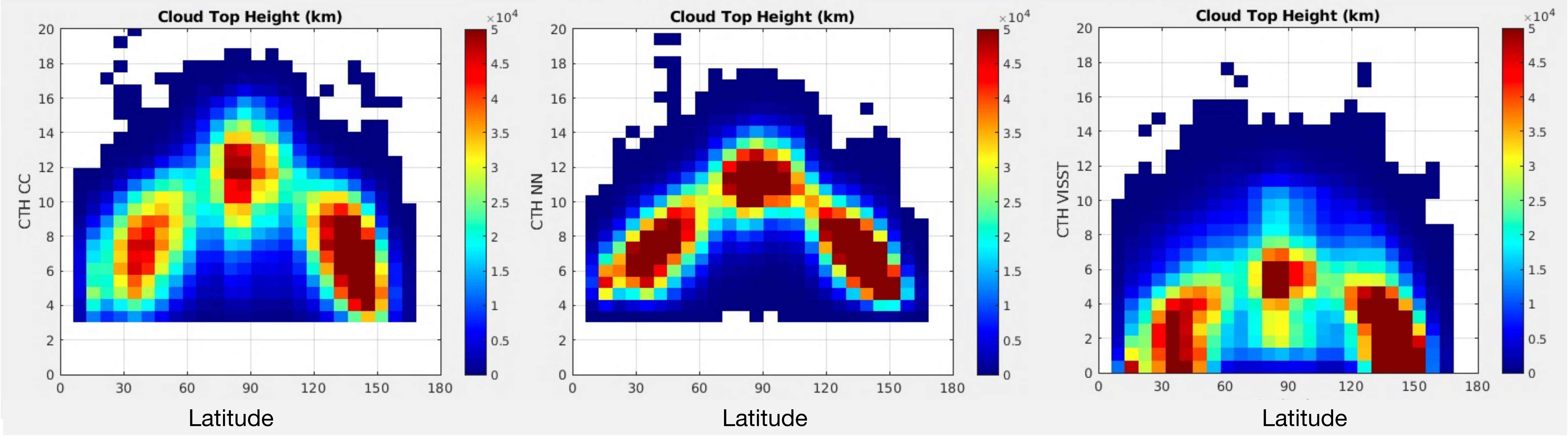
SL

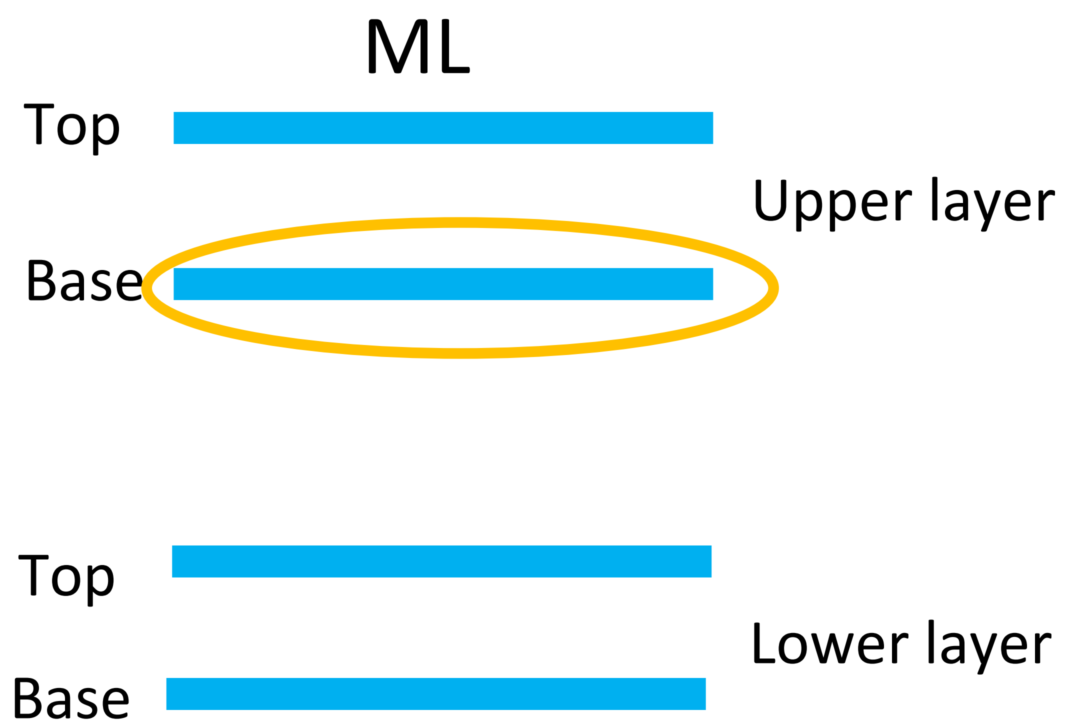


Zonal Distribution of both Upper & Lower Layer Cloud Top Heights over Snow Free Surfaces, Daytime, 2008

Zonal Distribution of Upper-Layer Cloud Base Heights over Snow Free Surfaces, Daytime, 2008

CBH, CC | CBH, NN | CBH, Ed4



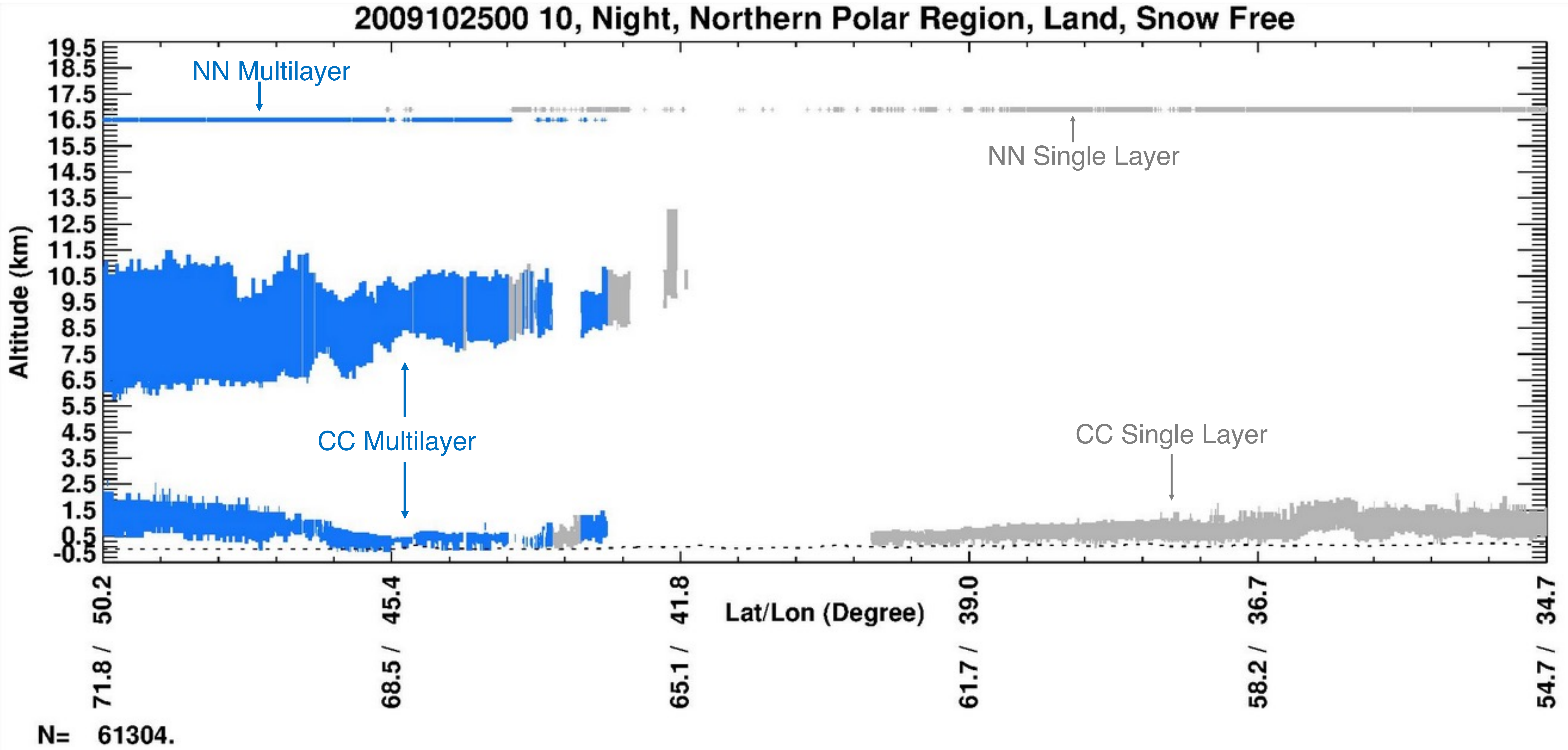


Multilayer Detection → Precursor of SL / ML NN Cloud Height Retrieval

- **Multilayer Artificial Neural Network (MLANN) trained using Aqua MODIS and CALIPSO-CloudSat data from 2008 C3M**
  - Breaks scenes into eight categories: snow/ice-free, snow/ice-covered, day, night, VISST liquid, VISST ice clouds
  - Trained with 2008 data, validated with 2009 data; very robust
    - *Correctly identifies ML and SL scenes together, 86 - 89% of the time*
    - *Detects more than half of ML clouds with ice separated > 1 km from the lower water cloud*
      - Tends to miss ML more when upper cloud CODu < 0.3, or CODu > 5
    - *As accurate or more accurate than any currently available method*
      - Minimizes false detections, giving positive gains in accuracy
    - *Full swath coverage enabled by application of VZA-dependent correction factors*
  - Can be enhanced by further logic using CTHs from NN and VISST
  - Applicable now to VIIRS with fusion data
    - *Accuracy diminishes some without 6.7 and 13.3 μm channels, would need retraining*

Sun-Mack et al., 2023: Identification of ice-over-water multilayer clouds using an artificial network with multispectral satellite data, submitted to Atmos. Meas. Tech.

Example of NN Multilayer Detection



Fractional Net Gain in Accuracy (NGA) in Cloud Layering Identification

NGA = trueML fraction - falseML fraction, in % of total cloud cover

- trueML fraction = ML pixels from NN that match ice-over-water ML pixels from CloudSat-CALIPSO data
- falseML fraction = ML pixels from NN that match SL pixels from CloudSat-CALIPSO data
- ML = ice-over-water cloud system with separation distance, SD = ice base CTH - water top CTH
- **bold** denotes higher value in one-to-one comparisons, *parentheses* indicate MLtrue

Time, Ed4 phase	†Ed4	†MLANN SD > 1 km
Day, ice	-6.2 (10.5)	**6.2 (12.1)**
Day, water	1.6 (5.3)	**8.2 (12.6)**
Night, ice	0.2 (11.7)	**10.2 (17.1)**
Night, water	-0.6 (2.8)	**5.2 (8.1)**

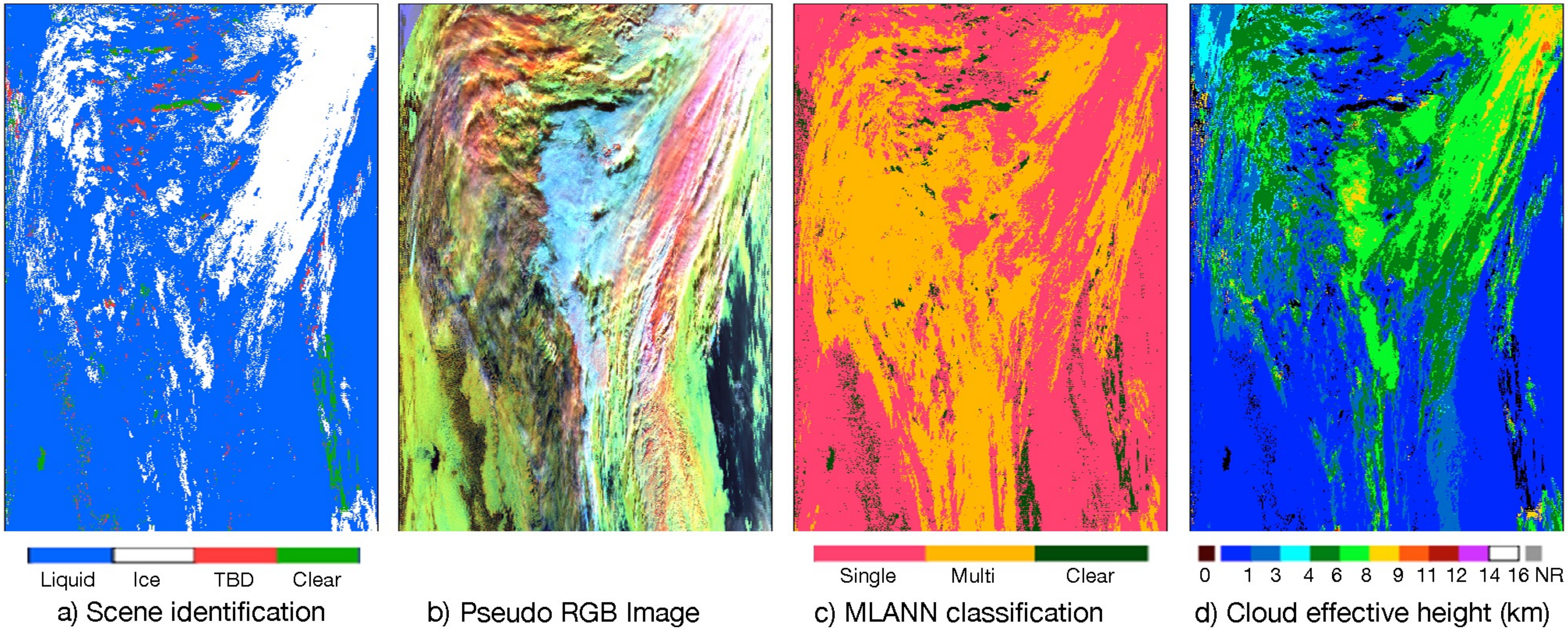
†April 2009, Aqua MODIS, CALIPSO Horizontal averaging $\leq$ 5 km

*July 2009, Aqua MODIS, CALIPSO Horizontal averaging $\leq$ 80 km

- MLANN trained using SD > 1 km produces a net gain in information allowing the confident deconstruction of the MODIS radiances into 2 separate cloud layers for more ML clouds than either Ed4 CO2-based ML detection or MLANN trained with SD > 3 km
- MLANN trained using SD is as accurate or more accurate than other currently available methods.
- Positive NGA indicates a reduction in uncertainty

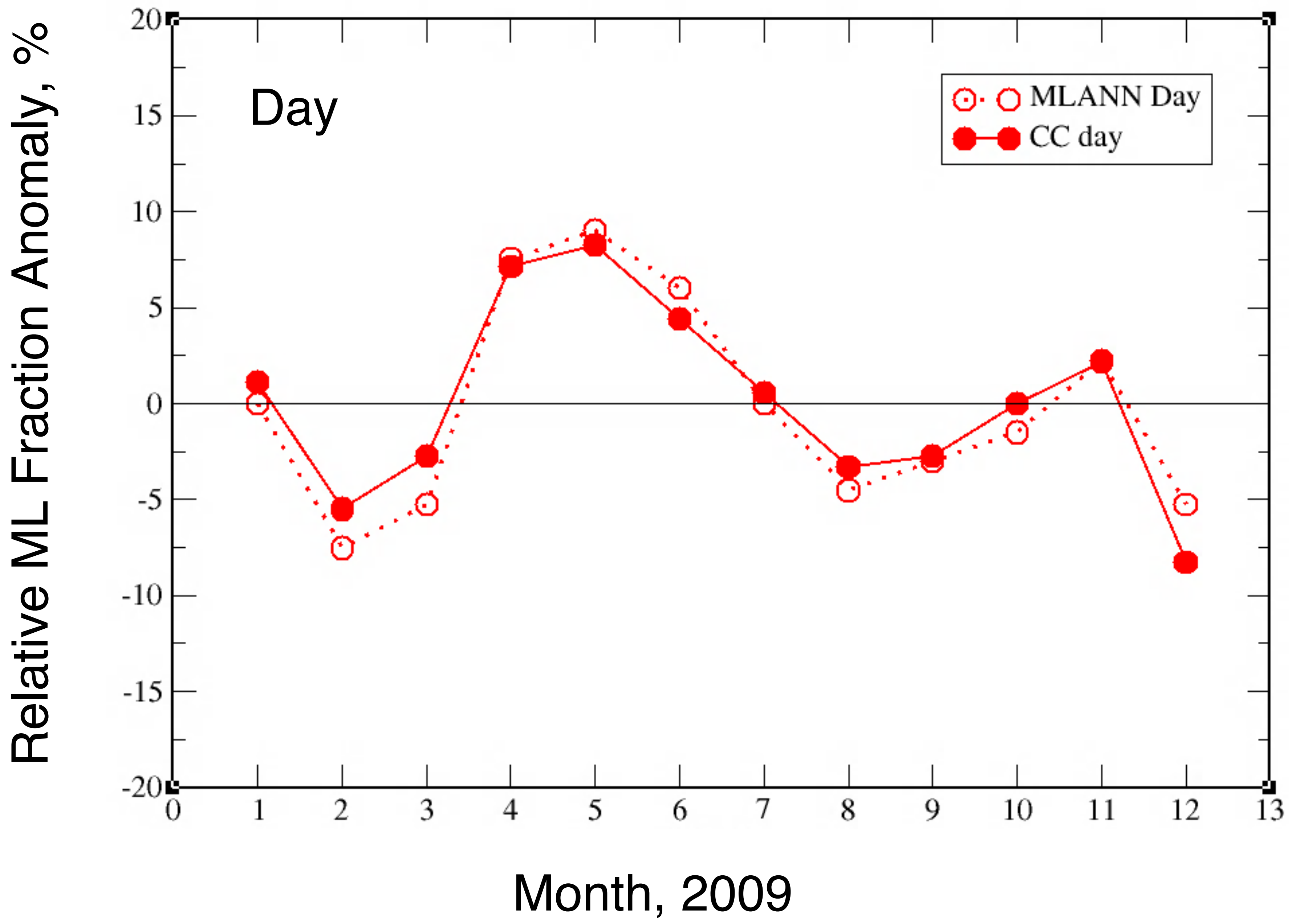
Example Swath Application, Aqua MODIS data, 16 April 2009, ~3:50 UTC

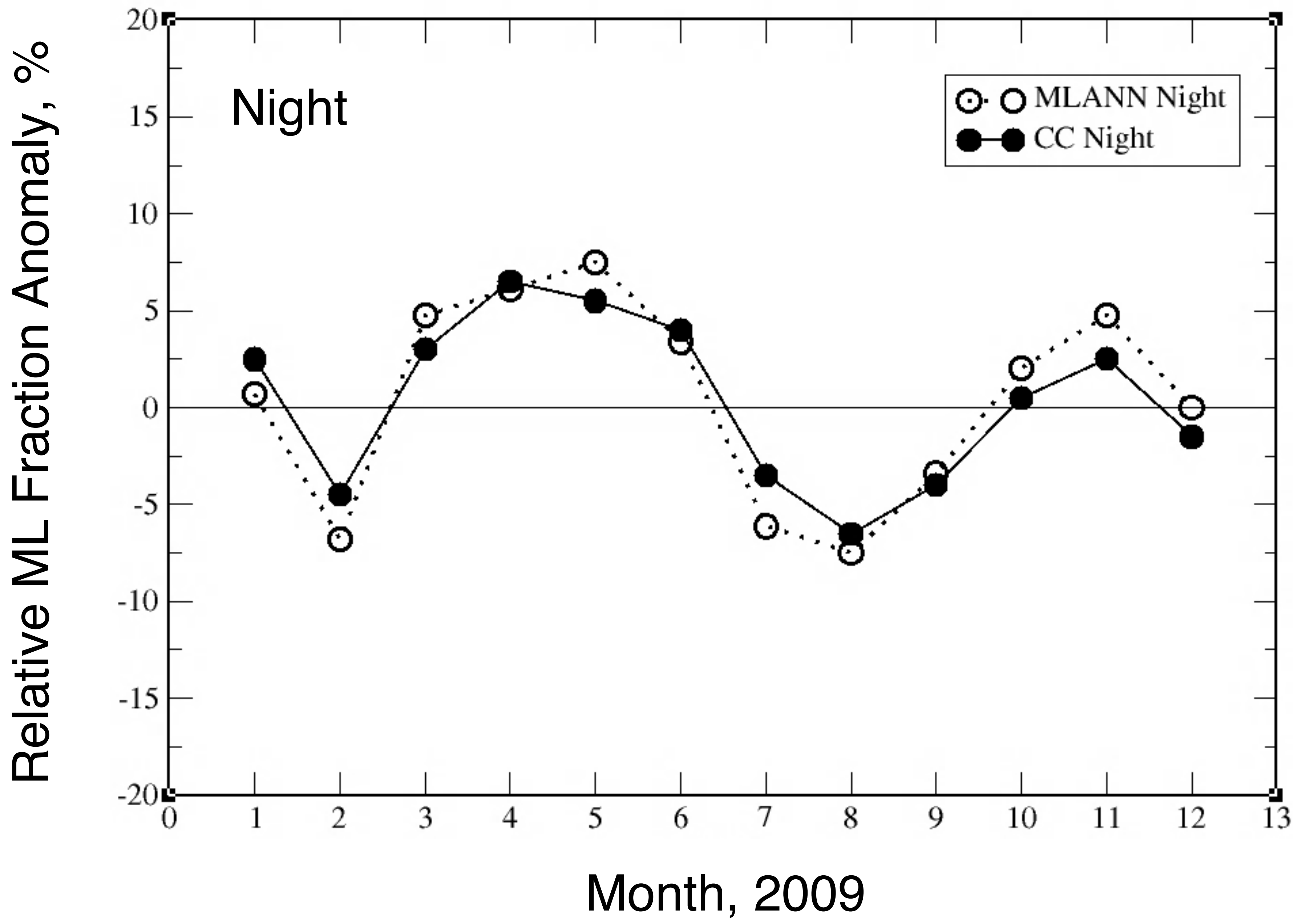
62°S (top) and 52°S (bottom) around 165°E



- Thin cirrus revealed as ice in some cases, blurry part of the RGB image, greater CTH in upper left and center
- MLANN catches much of the ML out to the edge and leaves many of the optically thick high clouds as SL

ML Seasonal Anomalies, 2009 over snow / ice free surfaces





- MLANN swath captures seasonal variability to within 1-2% of CC both day and night

Summary of NN CTH/CBH Retrievals

- **CTH & CBH for CERES can be determined more accurately for CERES using a neural network method**
  - Uncertainties reduced by more than 20%, if trained for SL and ML separately
  - Dramatic reductions in accuracy relative to Ed4 VISST approach
  - Accuracies represent the state of the art
  - Uses only IR channels: it is applicable to all other satellites, theoretically
    - Need test with VIIRS, GOES, etc.
  - $\Delta Zup = 0 \pm 1.26$ km compared to MCAT $\Delta Zup = -2.6 \pm 1.9$ km
  - $\Delta Zlow = 0 \pm 1.20$ km vs MCAT $\Delta Zlow = -1.2 \pm 2.0$ km
  - Clear improvement over Ed4

- **Only daytime snow-free data used**
  - Future analyses will use nighttime and snow/ice-covered surfaces
    - Early results see only slight decrease in accuracy

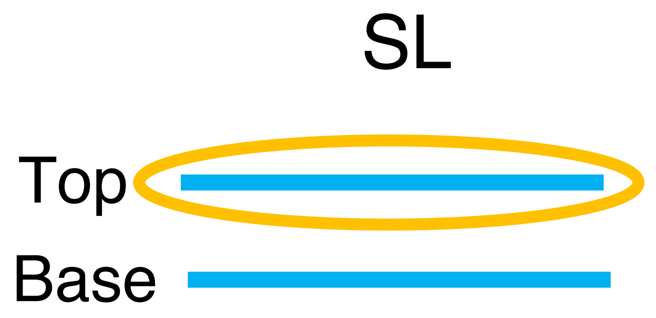
- **Need to test with full dataset and with MLANN results to determine the true expected errors**
  - Need validation using a different year of data and Terra
  - Look at full swath dependencies (VZA radiance corrections?)

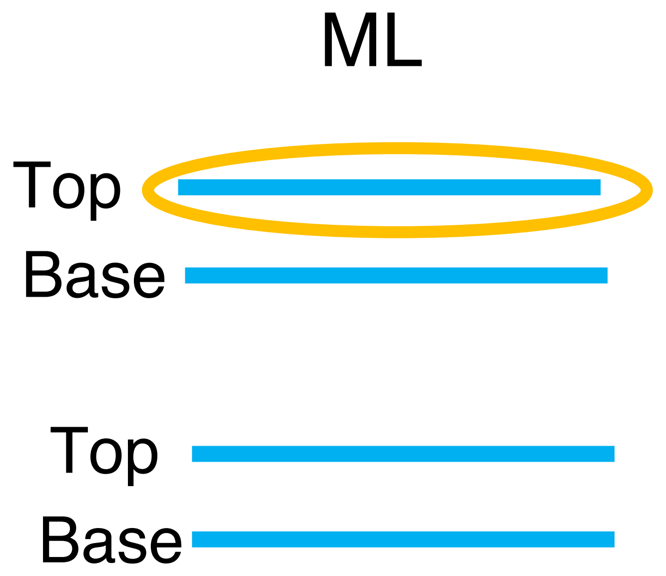
- **6.7-µm channel used, will need fusion data for VIIRS, or remove the parameters and retrain**
  - Initial analyses indicate only small loss in accuracy with no 6.7-µm channel

- **Operational use will require constraining the results, e.g.,**
  - No base heights below the surface or above max expected tropopause
  - Base height of upper cloud below top of lower cloud, etc.

BackUps

Summary of Daytime Cloud Top Height Analysis, Snow/Ice Free, 2008





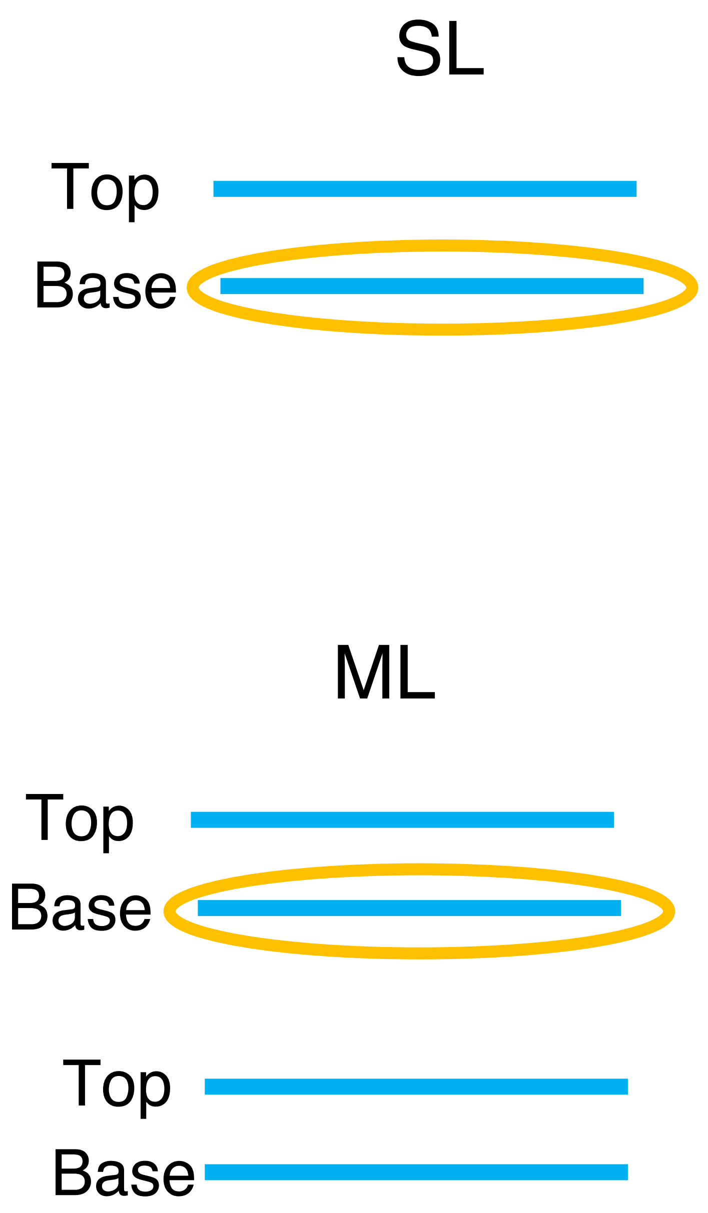
	ΔZ		SDD		MAE	
	Ed4	**NN**	**Ed4**	**NN**	**Ed4**	**NN**
Single Layer						
All	-0.64	**-0.16**	2.45	**1.42**	1.47	**0.74**
High	-1.55	**-0.57**	2.70	**1.79**	2.10	**1.08**
Mid	-0.69	**-0.12**	1.99	**1.02**	1.51	**0.65**
Low	0.27	**0.23**	1.96	**0.93**	0.83	**0.44**
Multilayer Upper Cloud						
All	-4.83	**-0.07**	3.44	**1.22**	4.94	**0.90**
High	-4.91	**-0.11**	3.45	**1.19**	5.01	**0.89**
Mid	-2.48	**1.10**	1.82	**1.39**	2.80	**1.22**

All quantities in km
- **ΔZ** = mean difference, CC- Aqua
- **SDD** = std dev of differences
- **MAE** = mean absolute error

Low: 0 < CTH <= 3 km
Mid: 3 < CTH <= 6 km
High: CTH > 6 km

- **SL top heights improvement over Ed4**
  - Bias: all down to zero; high dropped **63**%; mid down by **83**%; low down by **15%**
  - SDD: all down by 47%; high down 34%; mid down by 51%; low down by 52%
  - MAE: all down by 50%; high down by 49%; mid down by 57%; low dropped by 48%
- **ML top heights also a great improvement, decrease in every category**
  - Bias: all to zero; high down 98%; mid down by 56%
  - SDD: all by 63%; high by 65%; mid by 24%
  - MAE: all by 80%; high down by 81%; mid down by 66%

Summary of Daytime Cloud-Base Height Analysis, Snow / Ice Free, 2008



	ΔZ		SDD		MAE	
	Ed4	NN	Ed4	NN	Ed4	NN
Single Layer						
All	0.44	**-0.12**	2.39	**1.47**	1.47	**0.80**
High	-1.41	**-1.21**	3.00	**2.28**	2.32	**1.71**
Mid	0.40*	**-0.55**	2.18	**1.49**	1.60	**1.24**
Low	0.96	**0.24**	1.93	**0.90**	1.22	**0.48**
Multilayer Upper Clouds						
All	-4.68	**-0.06**	3.14	**1.68**	4.80	**1.27**
High	-5.40	**-0.43**	3.06	**1.55**	5.46	**1.24**
Mid	-2.16	**1.25**	1.89	**1.45**	2.47	**1.41**

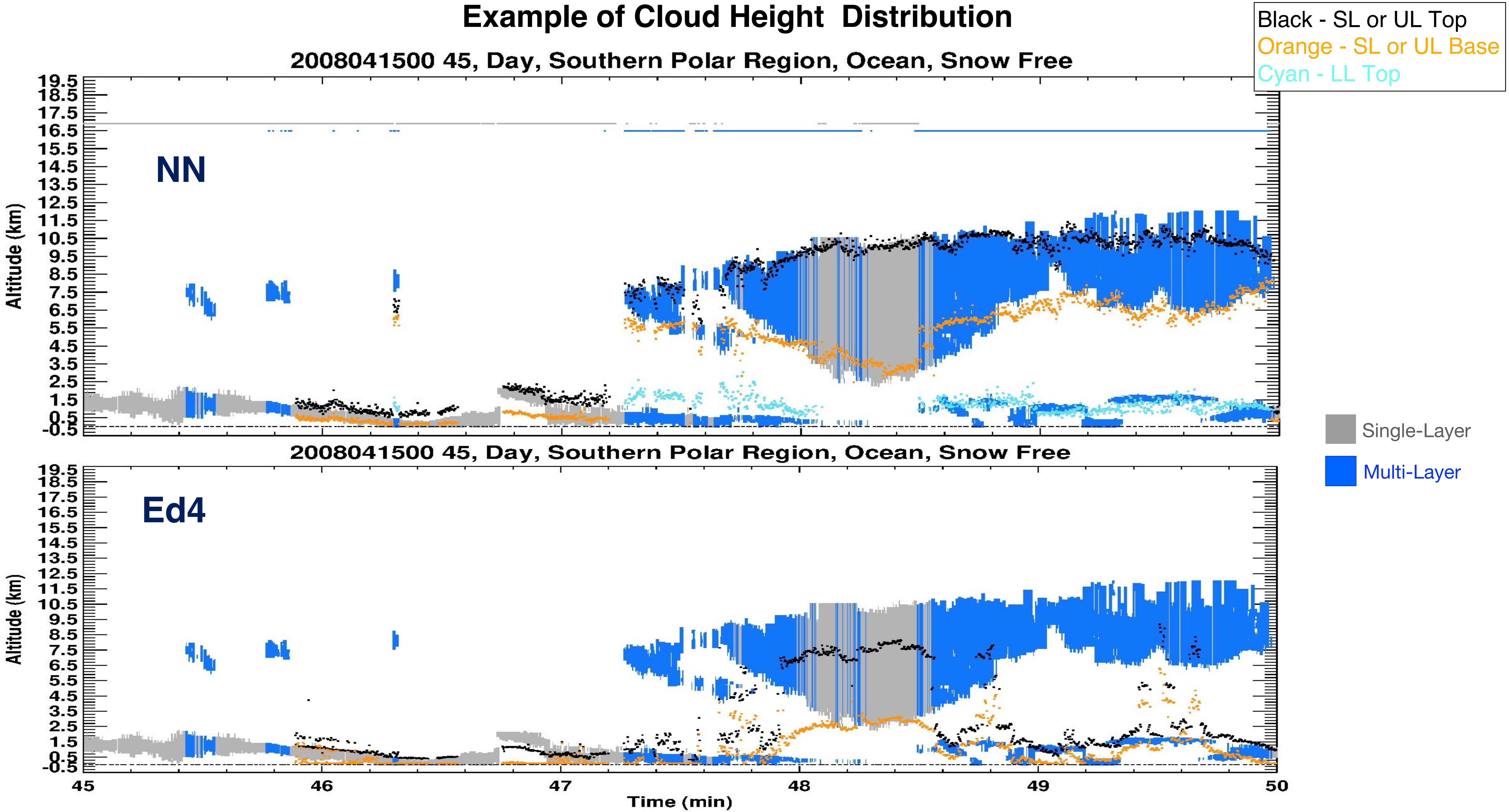
* only Ed4 value better than NN value

All quantities in km
- **ΔZ** = mean difference, CC- Aqua
- **SDD** = std dev of differences
- **MAE** = mean absolute error

Low: 0 < CTH <= 3 km
Mid: 3 < CTH <= 6 km
High: CTH > 6 km

- **SL base heights improvement over Ed4**
  - Bias: all down to zero; high dropped 15%; mid increased by 100%; low down by 75%
  - SDD: all down by 45%; high down 24%; mid down by 40%; low down by 55%
  - MAE: all down by 50%; high down by 25%; mid down by 27%; low dropped by 60%
- **ML base heights also a great improvement, decrease in every category**
  - Bias: all to zero; high 92%; mid down by 42%
  - SDD: all by 46%; high by 50%; mid by 25%
  - MAE: all by 73%; high down by 77%; mid down by 43%

Example of Cloud Height Distribution



• The heights produced by the new methods, NN, provide a better characterization of cloud vertical structure than Ed4

Consistency Between MODIS and VIIRS

Summary of Daytime Cloud Top Height Analysis

All quantities in km (w/o 6.7-µm input parameters)

	ΔZ		SDD		MAE	
	Ed4	**NN**	**Ed4**	**NN**	**Ed4**	**NN**
Single Layer						
All	-0.29	**0.00** (0.00)	2.25	**1.20** (1.24)	1.23	**0.61** (0.63)
High	-1.56	**-0.57** (-0.62)	2.70	**1.79** (1.85)	2.10	**1.08** (1.15)
Mid	-0.69	**-0.12** (-0.08)	1.99	**1.01** (1.06)	1.51	**0.65** (0.68)
Low	0.27	**0.23** (0.23)	1.96	**0.92** (0.93)	0.84	**0.44** (0.44)
Multilayer Upper Cloud						
All	-4.69	**0.00** (0.00)	3.41	**1.26** (1.29)	4.82	**0.92** (0.95)
High	-4.91	**-0.11** (-0.12)	3.45	**1.19** (1.21)	5.01	**0.89** (0.91)
Mid	-2.48	**1.10** (1.20)	1.82	**1.39** (1.42)	2.80	**1.22** (1.32)

Cloud Base Height statistics are similar to CTH, not show.

All quantities in km

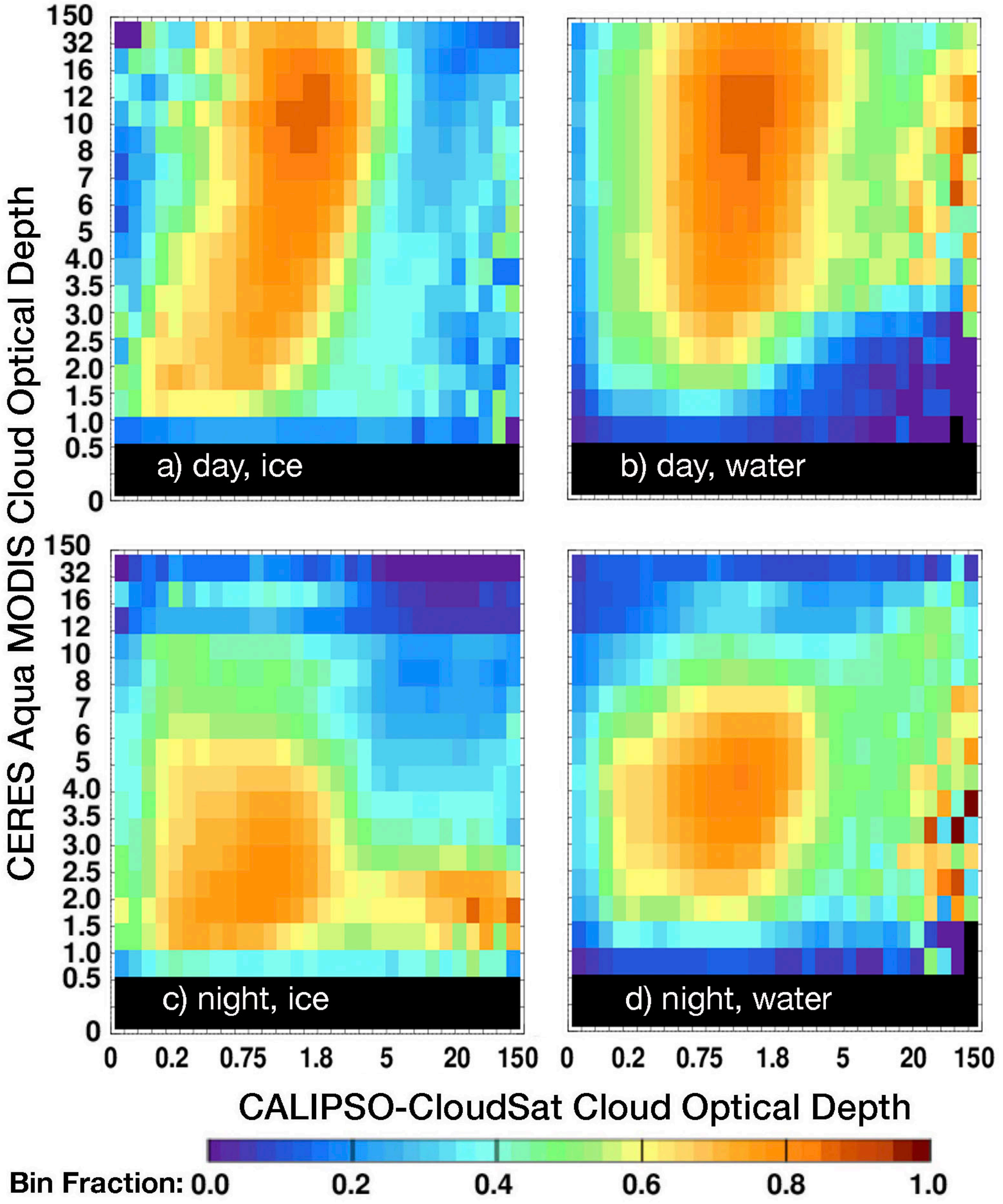
- **DZ** = mean difference, CC- Aqua
- **SDD** = std dev of differences
- **MAE** = mean absolute error

Without 6.7-µm Input

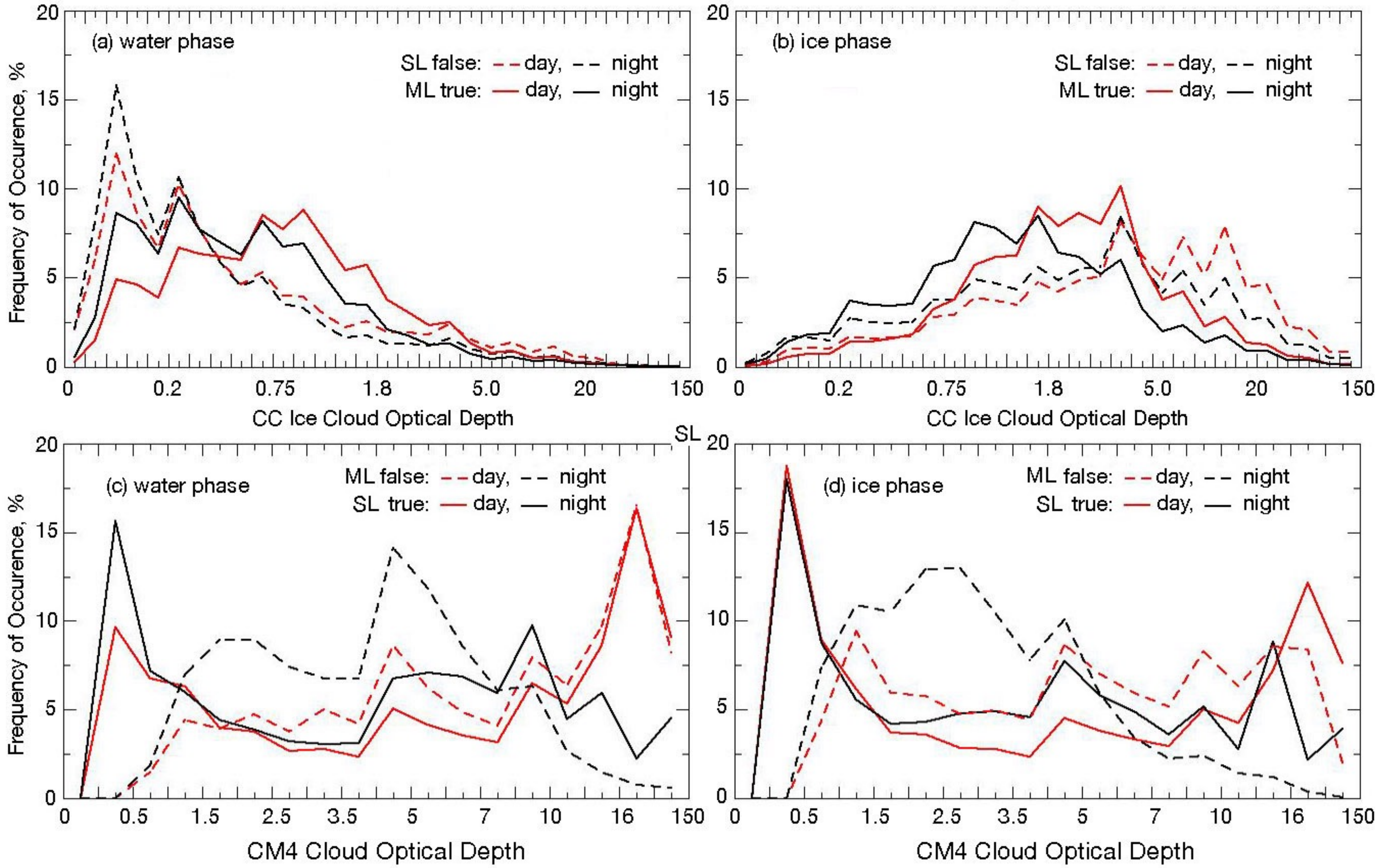
- Overall
  - No effect on bias
  - 3-4% increase in SDD
  - SL: no effect on MAE; ML: 2% rise
- High
  - 9% rise in bias
  - 1 - 3% rise in SDD
  - 2 - 3% rise in MAE
- Mid
  - SL: 33% drop in bias, ML: 9% rise
  - 0 - 3% rise in SDD
  - 1 - 2% increase in MAE
- Low
  - No impact

Sensitivity of MLANN Detection to Cloud Optical Depths, Snow-Free Surfaces, 2009

3-D Distributions of Recall, fraction of ML Clouds Detected as Functions of COD_{CM4} & COD_{CCice}



2-D Distributions of Layer Classification Functions of COD_{CM4} (bottom) or COD_{CCice} (top)



- 50% of missed ML for COD_{cc} < 0.4 for water phase; COD_{cc} > 2-3 for ice phase
- 50% false ML for COD_{cm} < 3.5 at night, < 7 during day for water phase
- 50% false ML for COD_{cm} < 2.5 at night,< 5 during day for ice phase

- Daytime: RC greatest for COD_{CCice} = 1.7, COD_{CM4} = 11, RC < 50% for COD_{CCice} < 0.3
  RC < 50% when $COD_{CCice} \approx COD_{CM4}$ or when COD_{CCice} > 4-5
  Few ML detected when COD_{CM4} < 1.5

- Nighttime: RC greatest for COD_{CCice} = 0.9, COD_{CM4} = 2 for ice
  RC greatest for COD_{CCice} = 0.9, COD_{CM4} = 4 for water
  RC < 50% when COD_{CCice} < 0.1, >5.0