Vertical microphysical profiles and closure calculations

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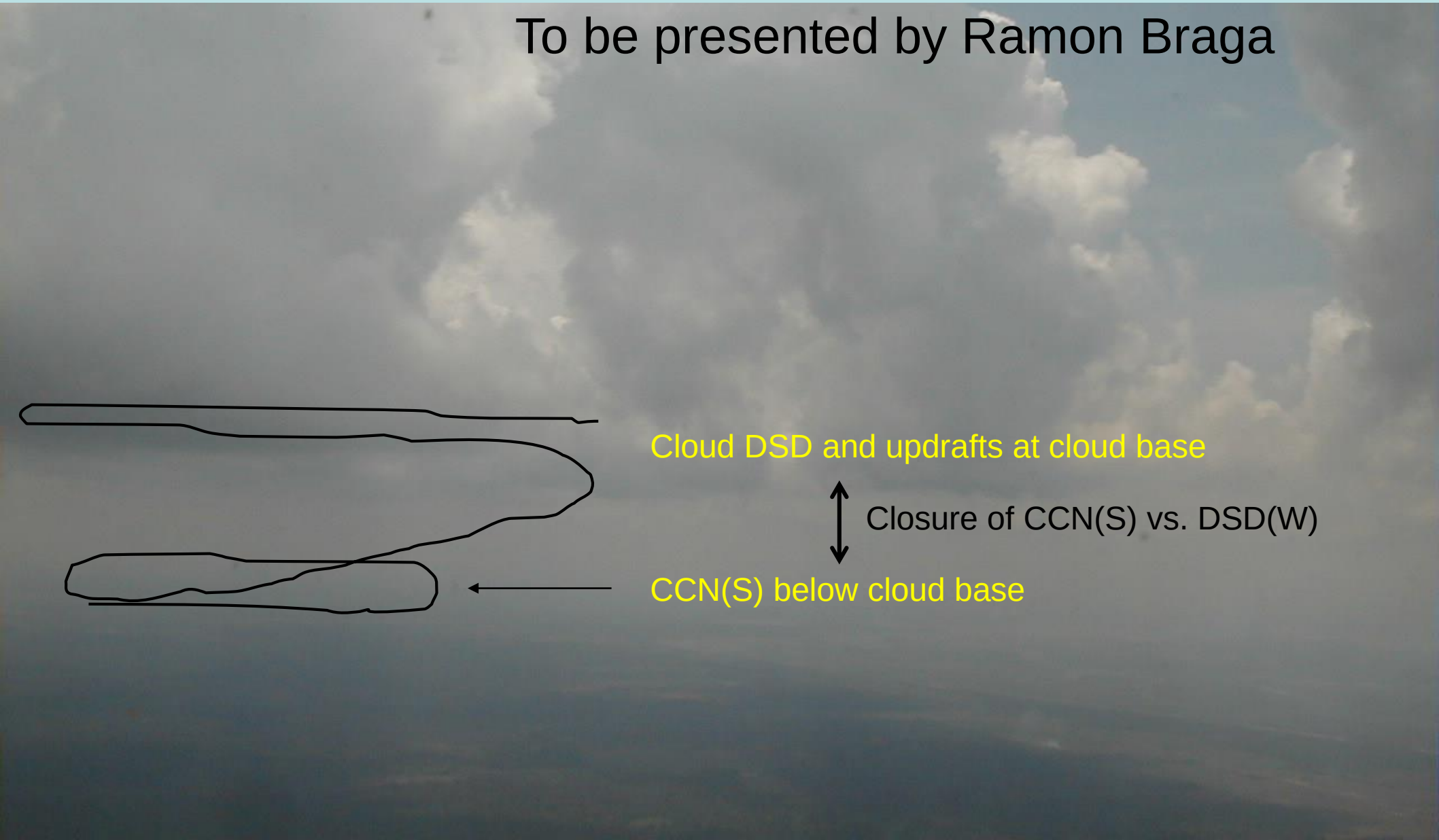
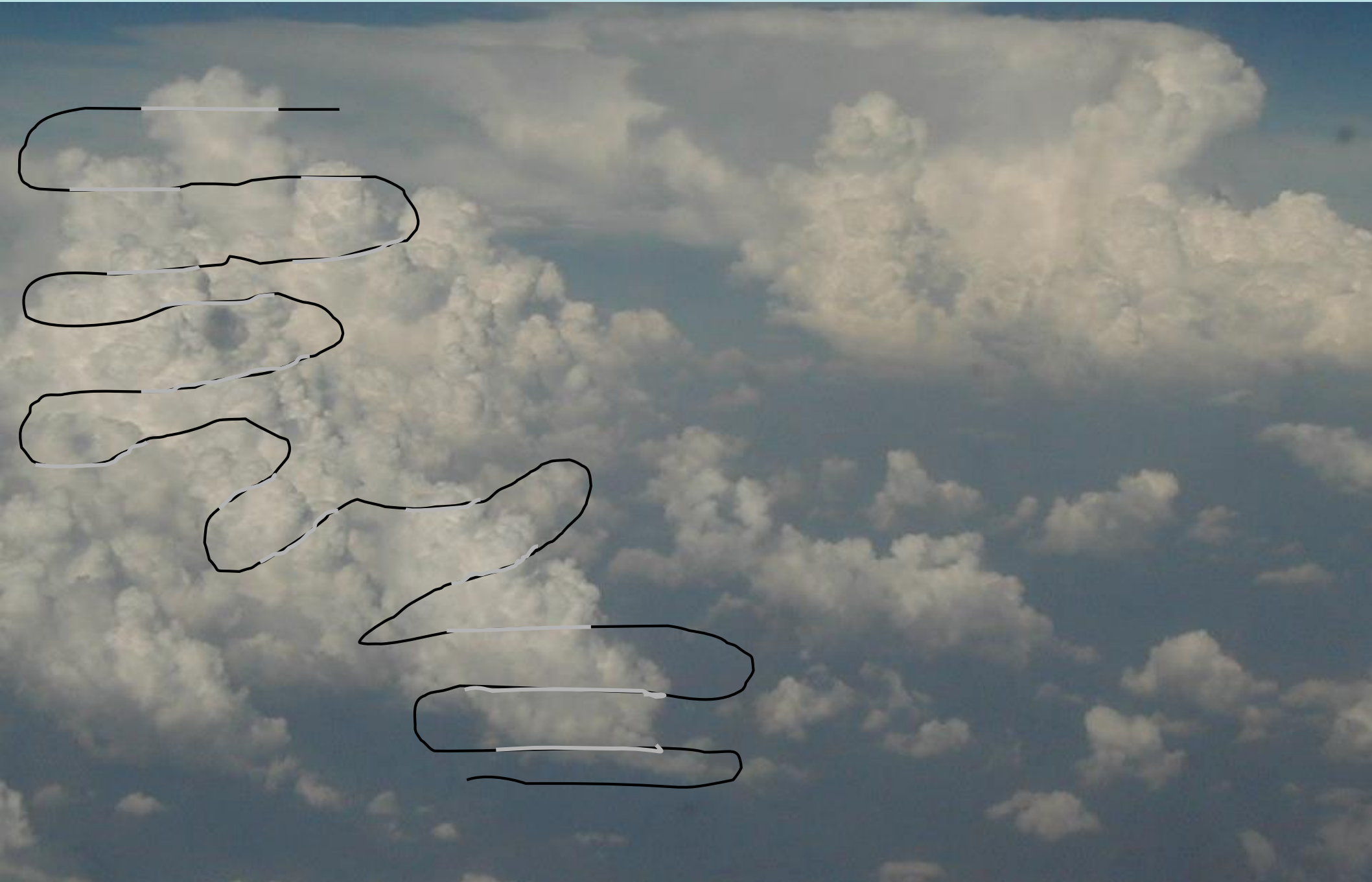
Closure between aerosols and cloud base drop size distribution (DSD): This can be done by combining measured CCN supersaturation (S) activation spectrum below cloud base, with the measured cloud drop number concentrations (Nd) and updrafts measured (Wb) at the non-precipitating base of the same cloud cluster.



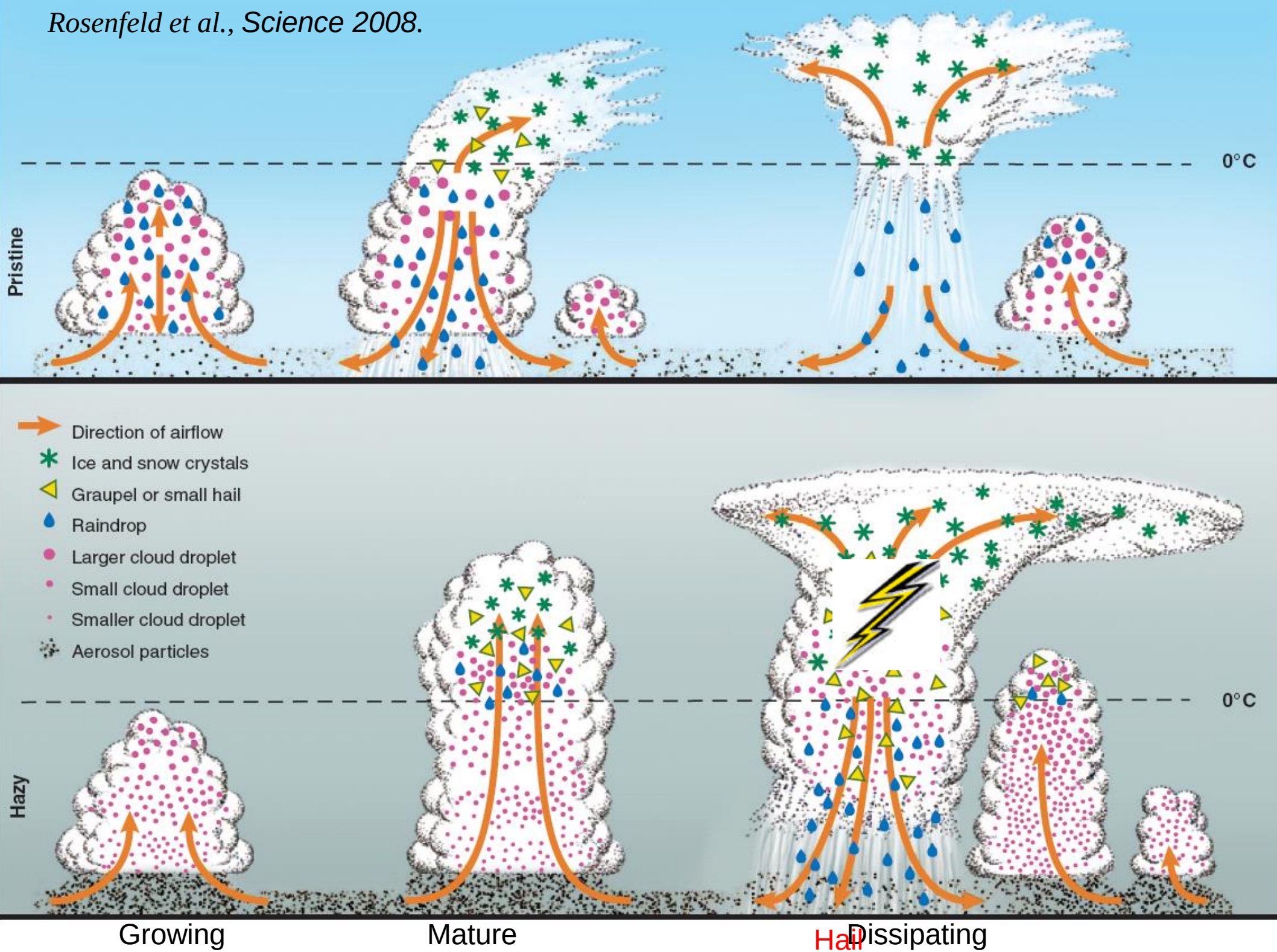
2. **Vertical evolution of cloud and hydrometeor DSD**, thermodynamics and updrafts.

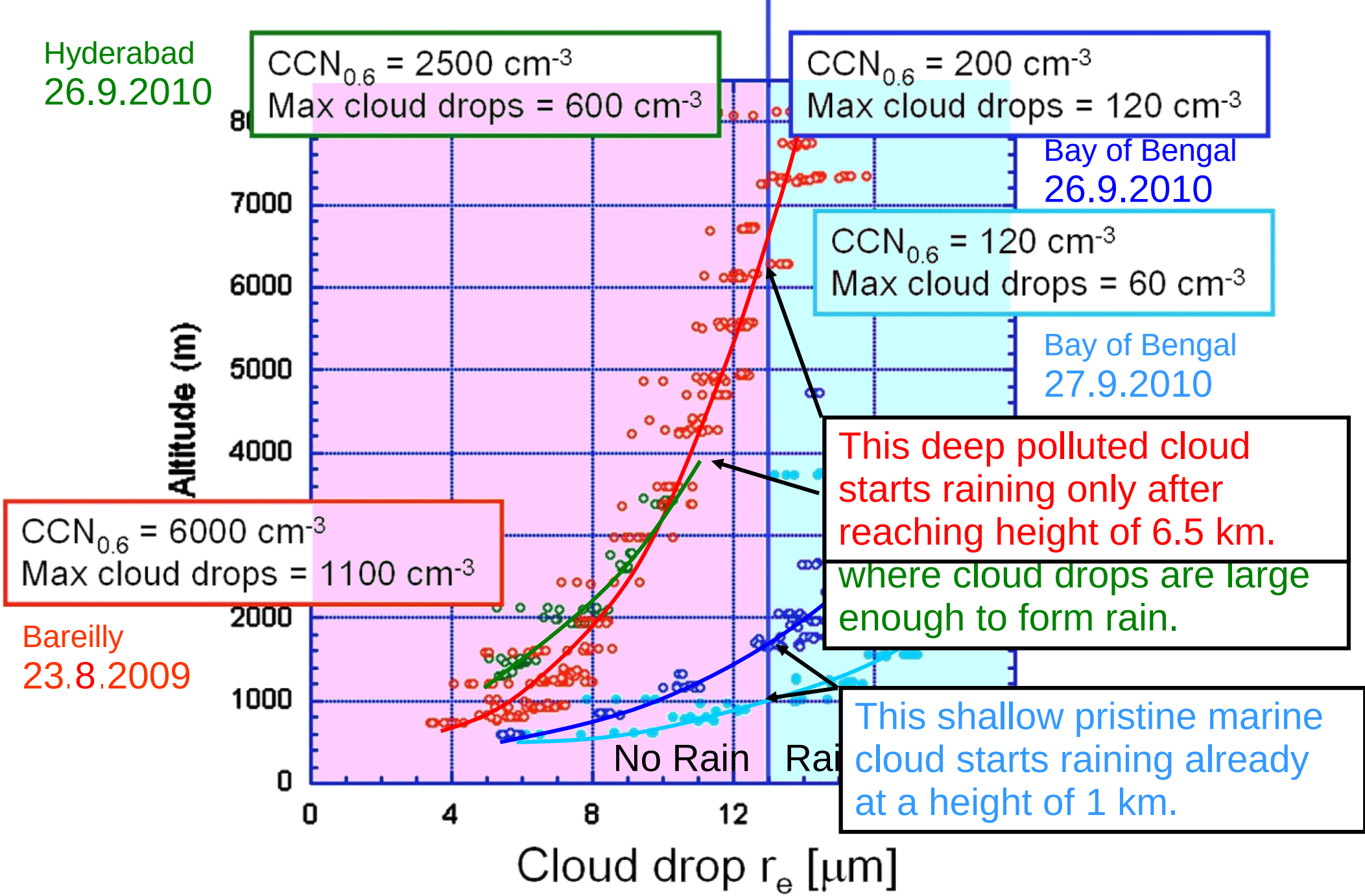
Flying through the developing cloud tops prevents contamination by precipitation falling from above.



First time measurements of cloud aerosol interactions in mixed phase and ice convective clouds in the Amazon.

Rosenfeld et al., Science 2008.





The relation between r_e and depth cloud depth above its base (D) is uniquely related to CCN.

Rosenfeld and Woodley, CAIPEEX-2 Final report to IITM.

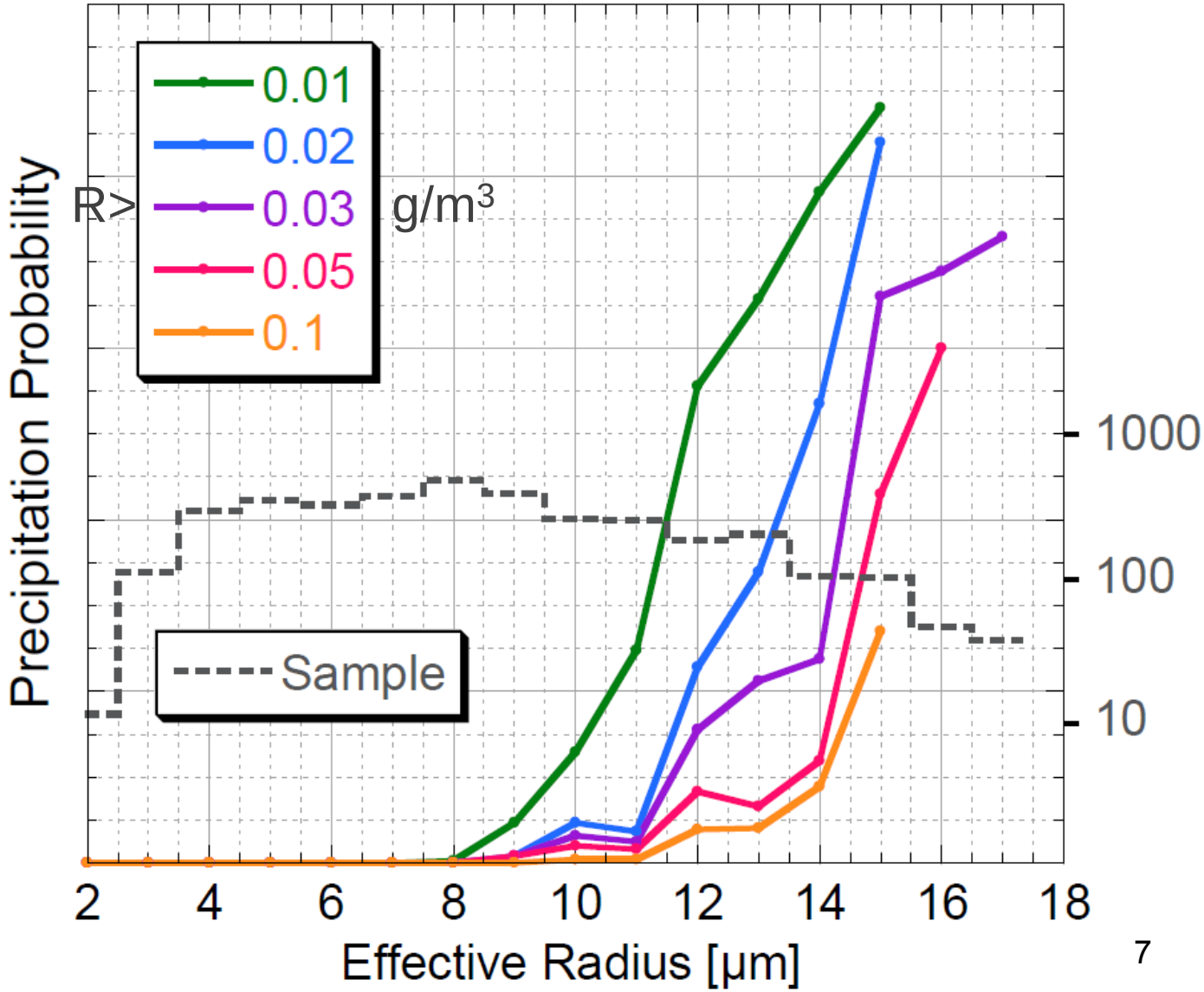
How sensitive is the threshold value?

Rain initiates at 10-12 μm, but accelerates strongly above 14 μm.

$$r_{e_c} \approx 14 \mu m$$

R is rain water content in drops with diameters of 0.1-0.25 mm, as measured by the Cloud Imaging Probe (CIP).

R> 0.01 – 0.1 g/m^3 raises the precipitation flag.



Freud and Rosenfeld, JGR 2012.

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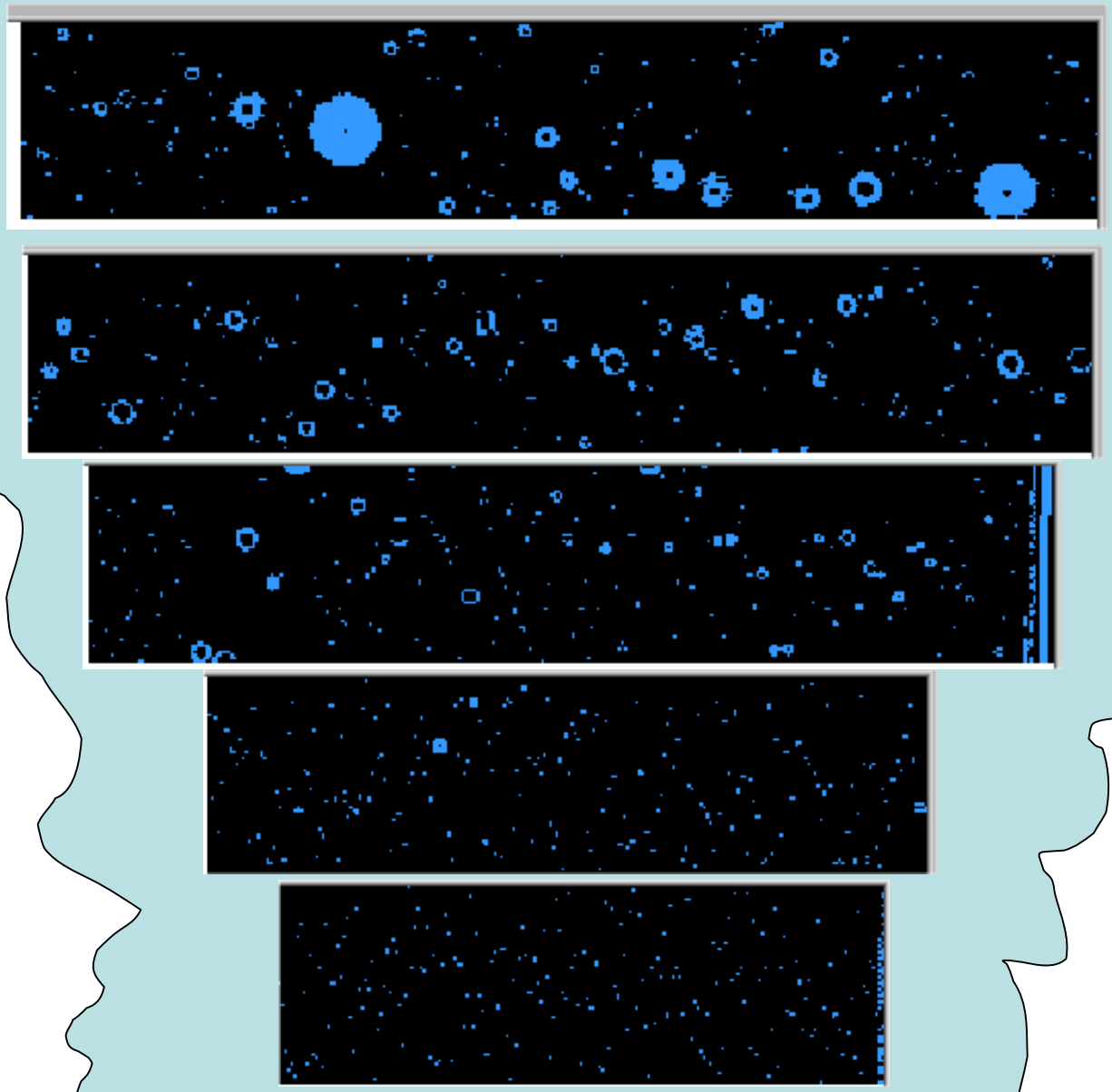
Height, m	Temp, °C
7,073 m,	-12.2 °C
6,793 m,	-11.8 °C
6,124 m,	-8.7 °C
5,816 m,	-6.8 °C
4,406 m,	+1.3 °C



Aircraft measured images of vertical development of cloud and rain drops in the cloud

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Why do we need the vertical profiles of cloud drop size distributions?

Aerosol composition + size distribution → CCN(S)
CCN(S) + Updrafts → Cloud base drop concentrations (Nd_b)
$Nd_b \approx$ adiabatic drop concentrations (Nd_a)

$Re_a \approx Re$, due to nearly inhomogeneous cloud mixing.

$LWC_a \alpha Re_a^3 Nd_a$
$LWC_a \alpha$ Cloud depth above its base (D)

} D for a given $Re_a \alpha Nd_a$
D for a given Re α Nd_b

Coalescence rate α Re^5 → Rain initiates at Re ≈ 13-14 μm

D for Re= 14 μm α Nd_b

The critical D for rain initiation (Dc) is D where Re reaches 14 μm

→ Dc α Nd_b

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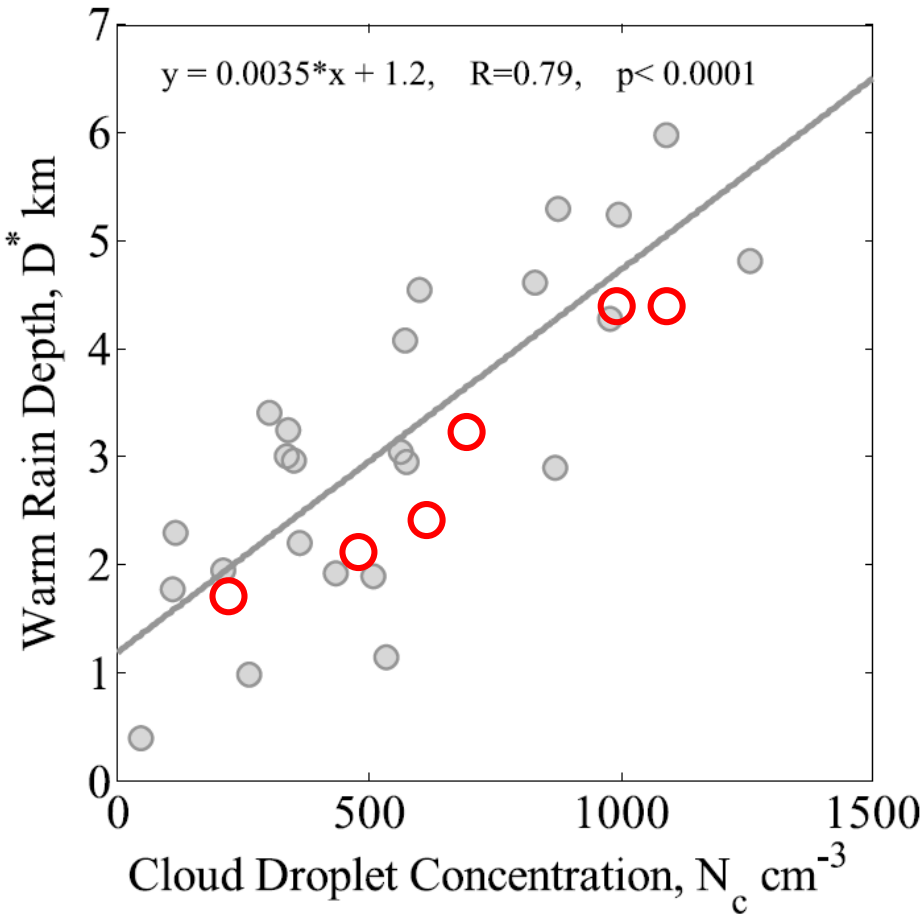
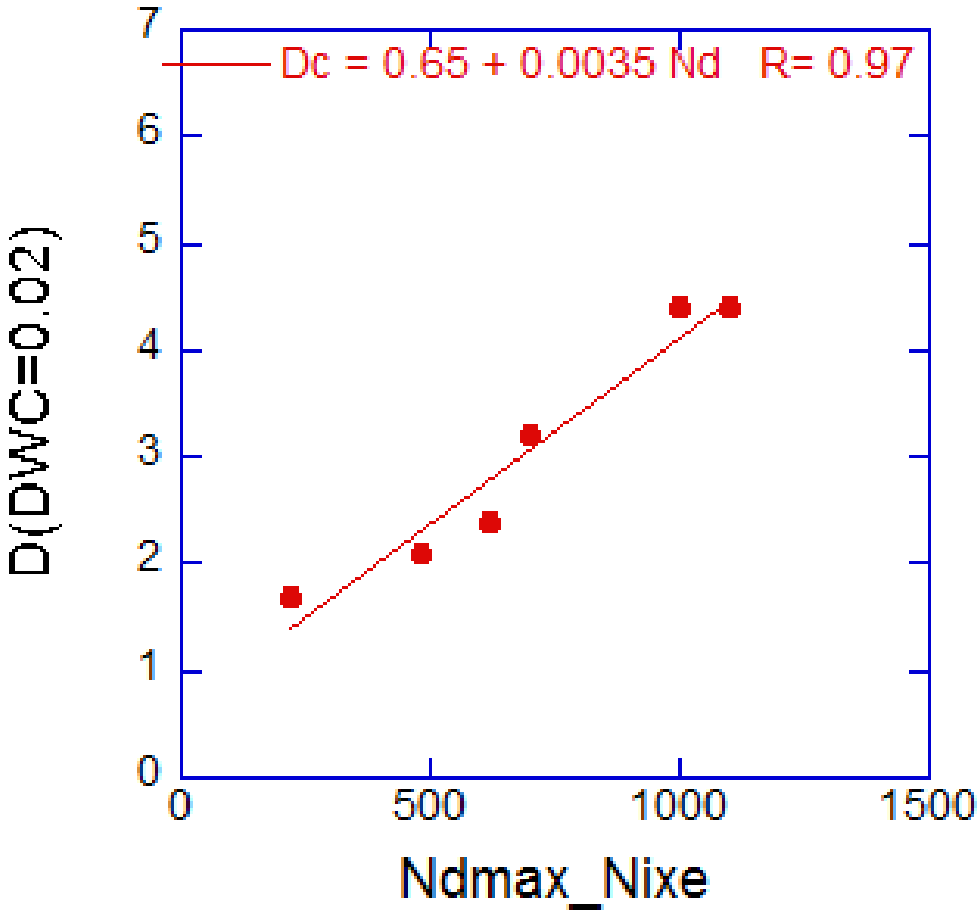
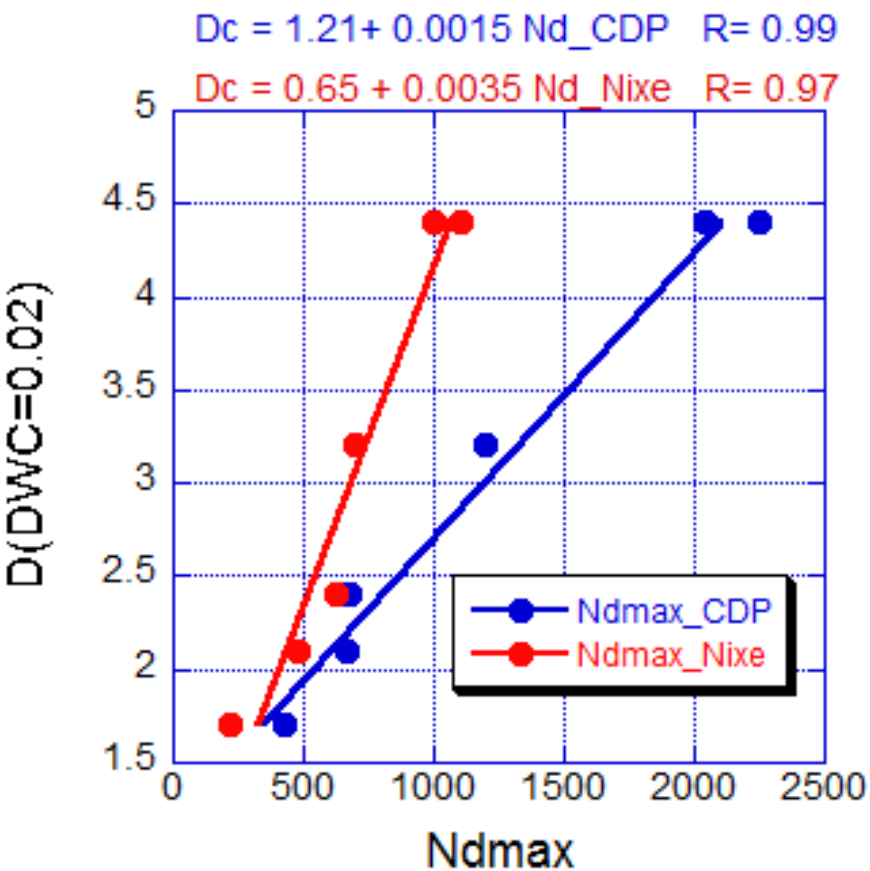
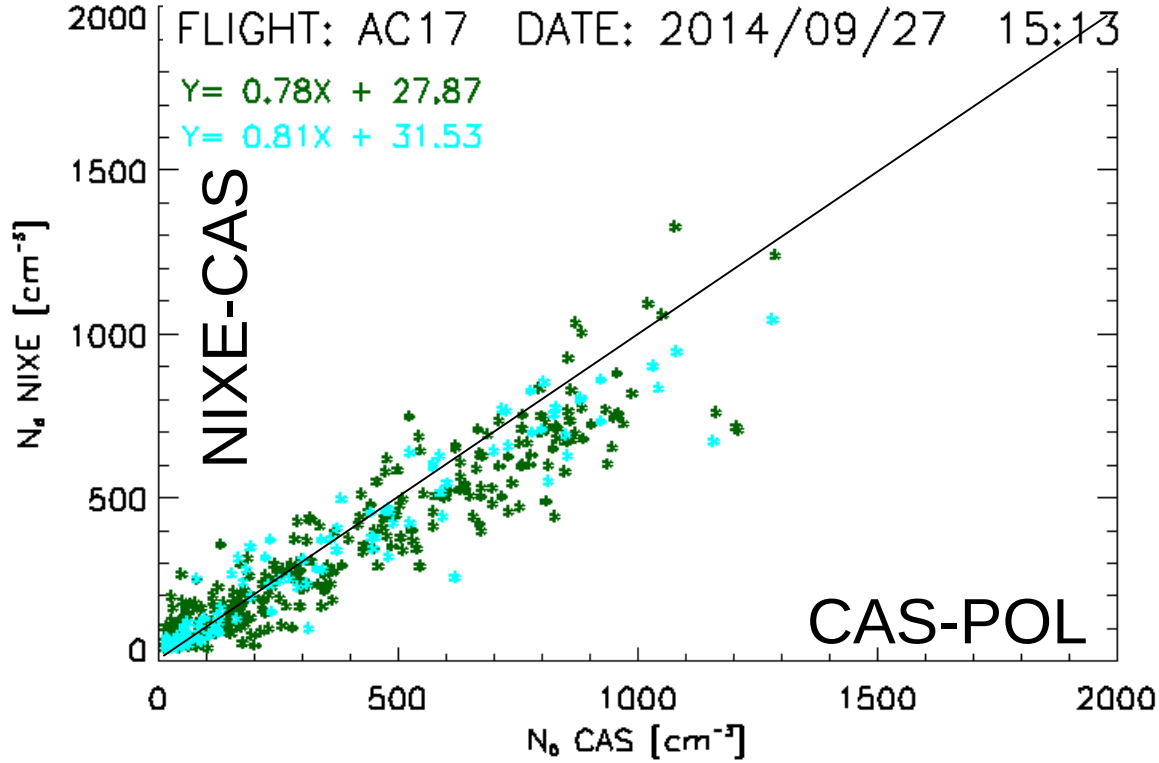
CAIPEEX flights, India 2009+2010
Konwar et al., JGR 2012

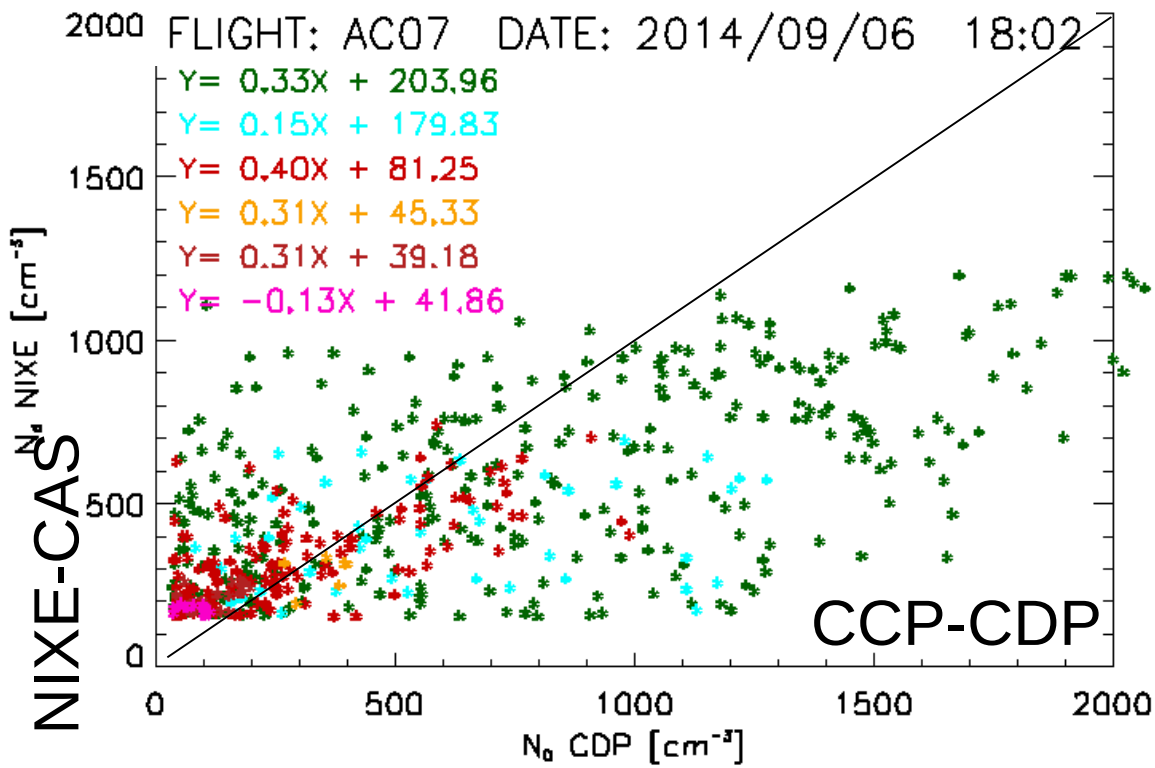


ACRIDICON, Amazon 9/2014

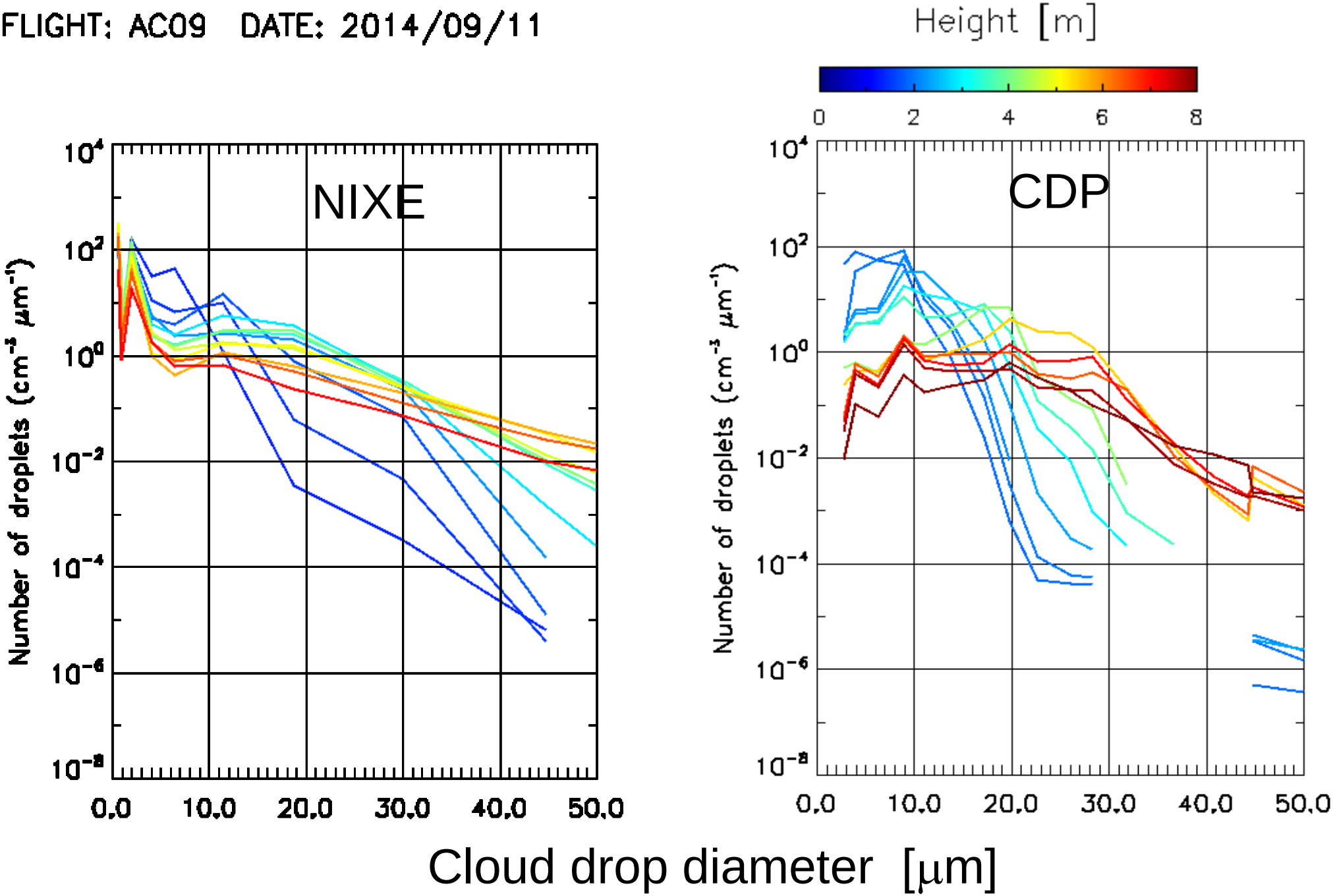



Dc = 1.21+ 0.0015 Nd_CDP R= 0.99
Dc = 0.65 + 0.0035 Nd_Nixe R= 0.97
D(DWC=0.02)
Ndmax
Ndmax_CDP
Ndmax_Nixe

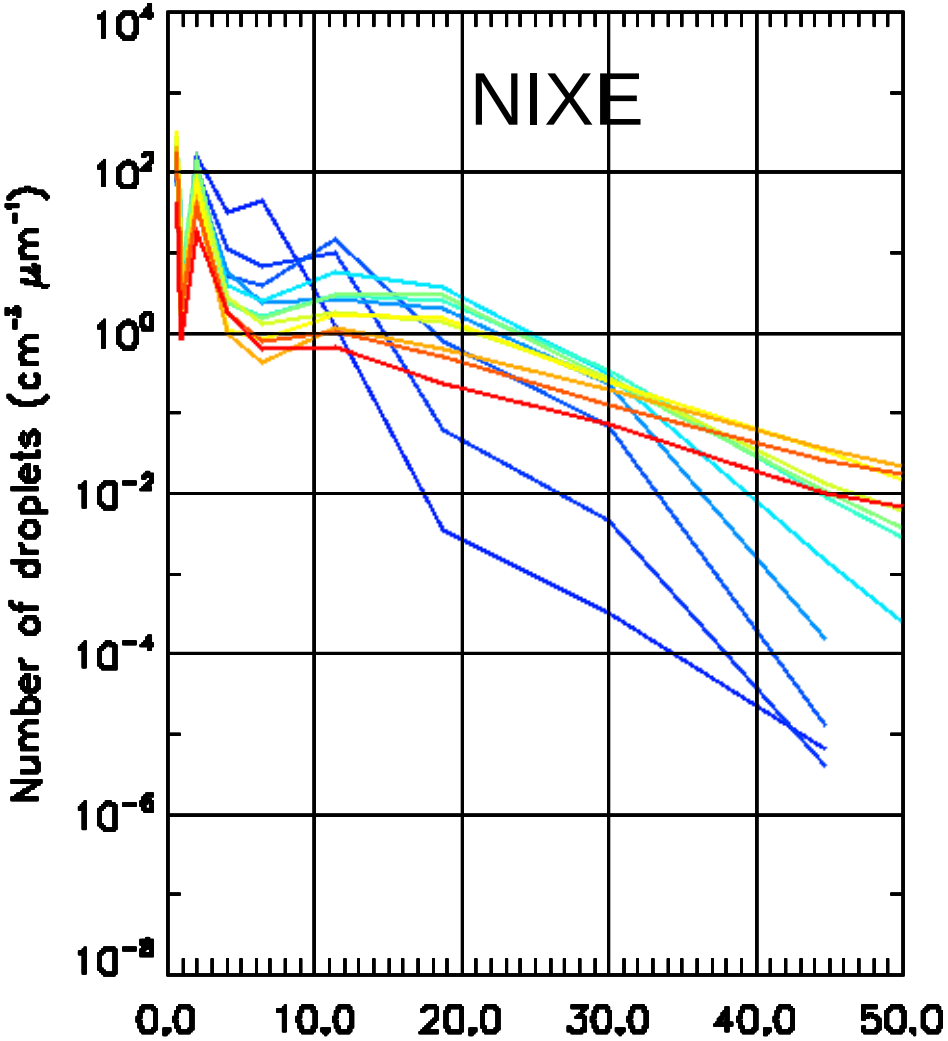

FLIGHT: AC17 DATE: 2014/09/27 15:13
Y= 0.78X + 27.87
Y= 0.81X + 31.53
NIXE-CAS
CAS-POL
N_d NIXE [cm⁻³]
N_0 CAS [cm⁻³]

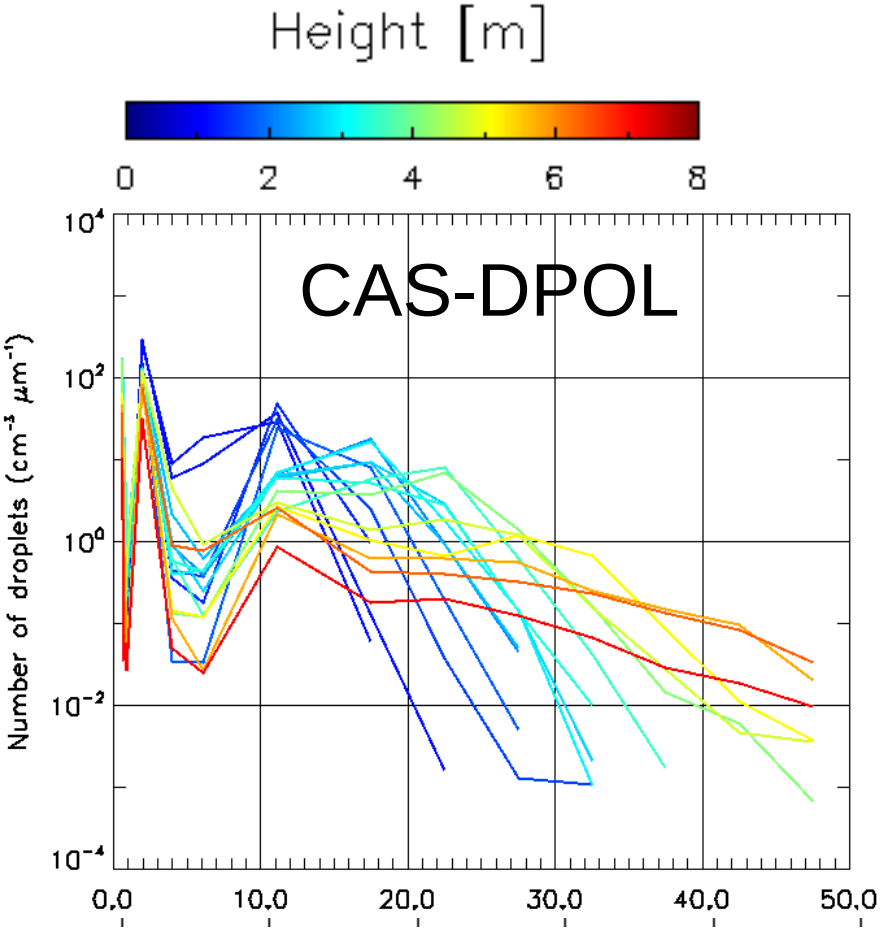

FLIGHT: AC07 DATE: 2014/09/06 18:02
Y= 0.33X + 203.96
Y= 0.15X + 179.83
Y= 0.40X + 81.25
Y= 0.31X + 45.33
Y= 0.31X + 39.18
Y= -0.13X + 41.86
NIXE-CAS
CCP-CDP
N_d NIXE [cm⁻³]
N_0 CDP [cm⁻³]

FLIGHT: AC09 DATE: 2014/09/11

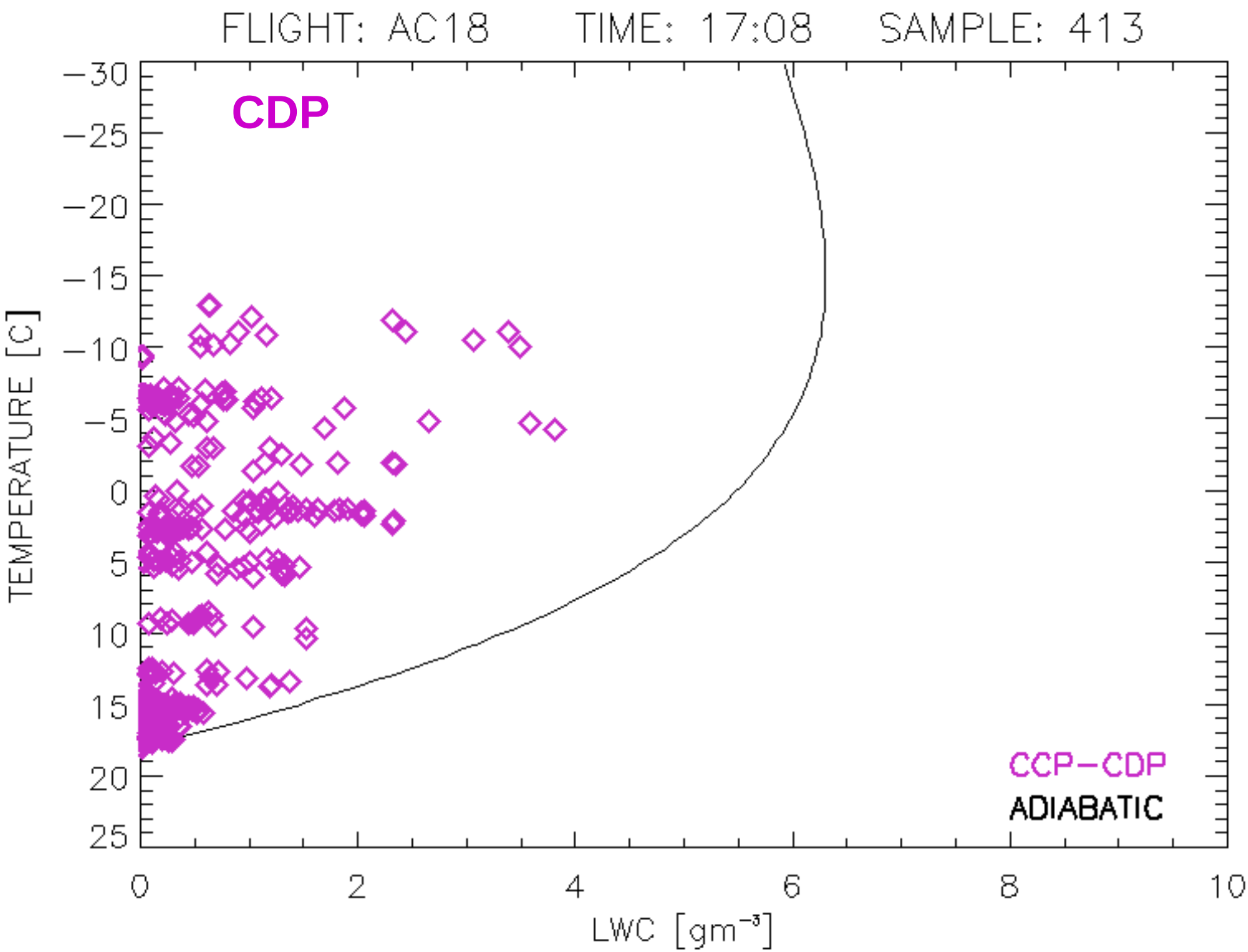


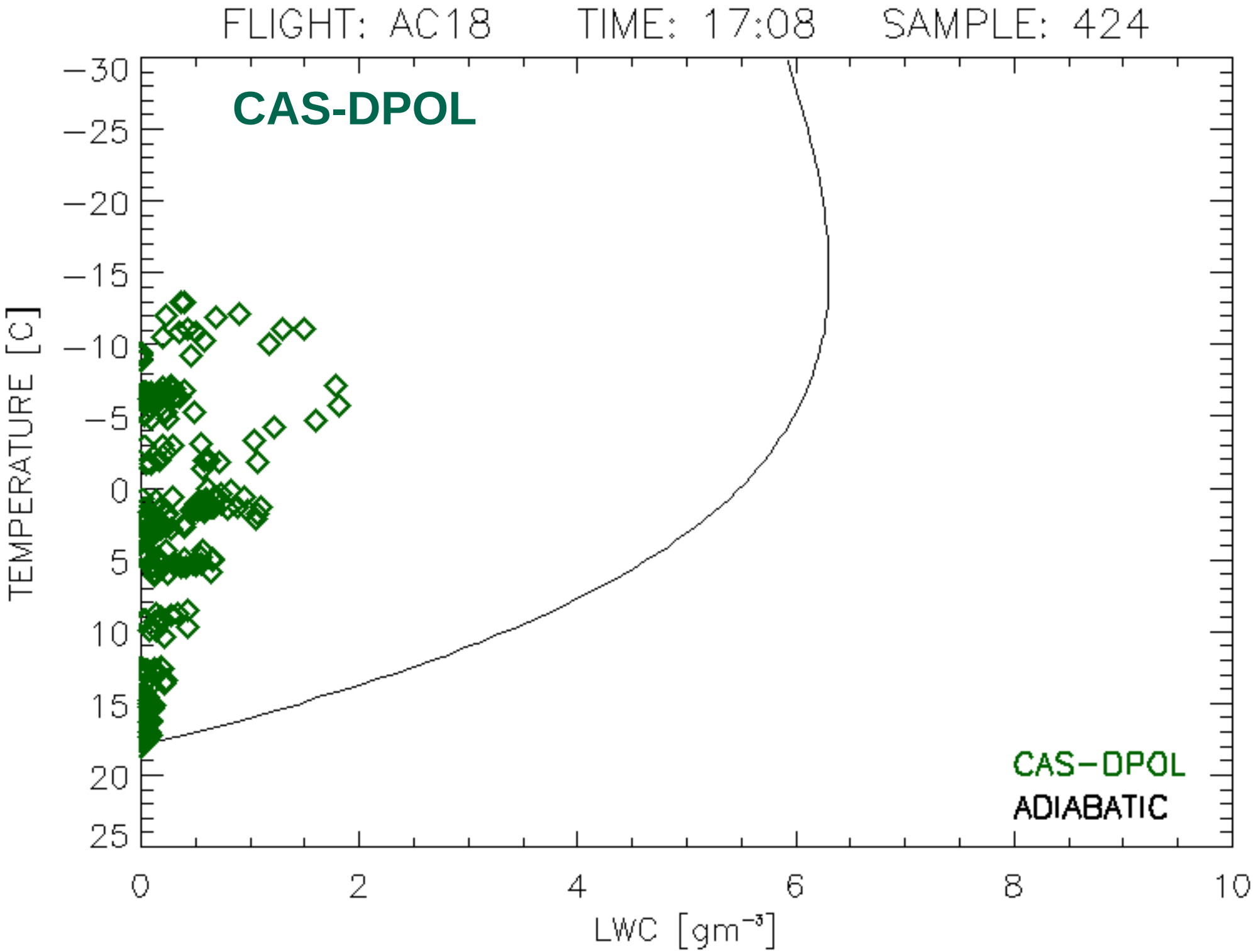
FLIGHT: AC09 DATE: 2014/09/11

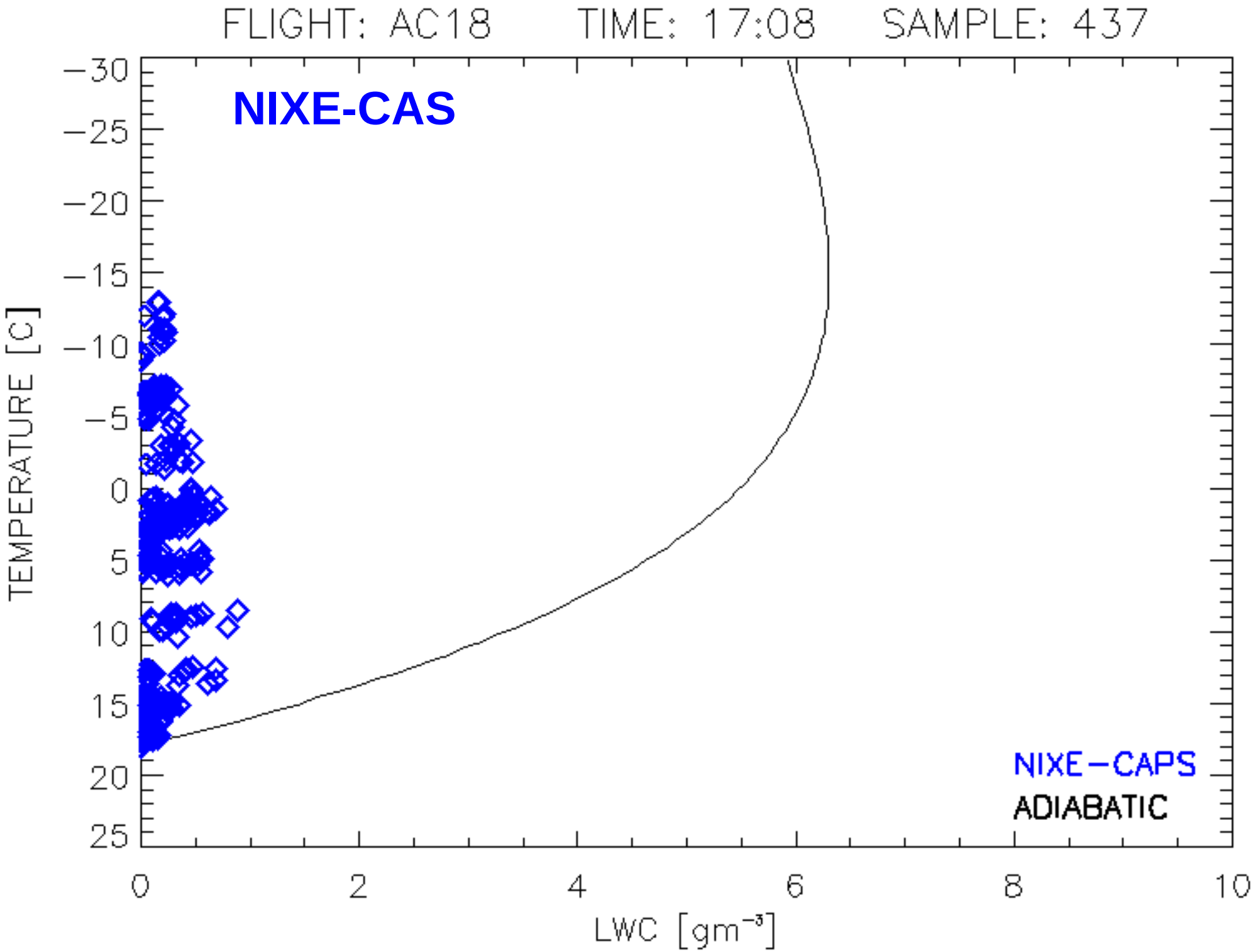


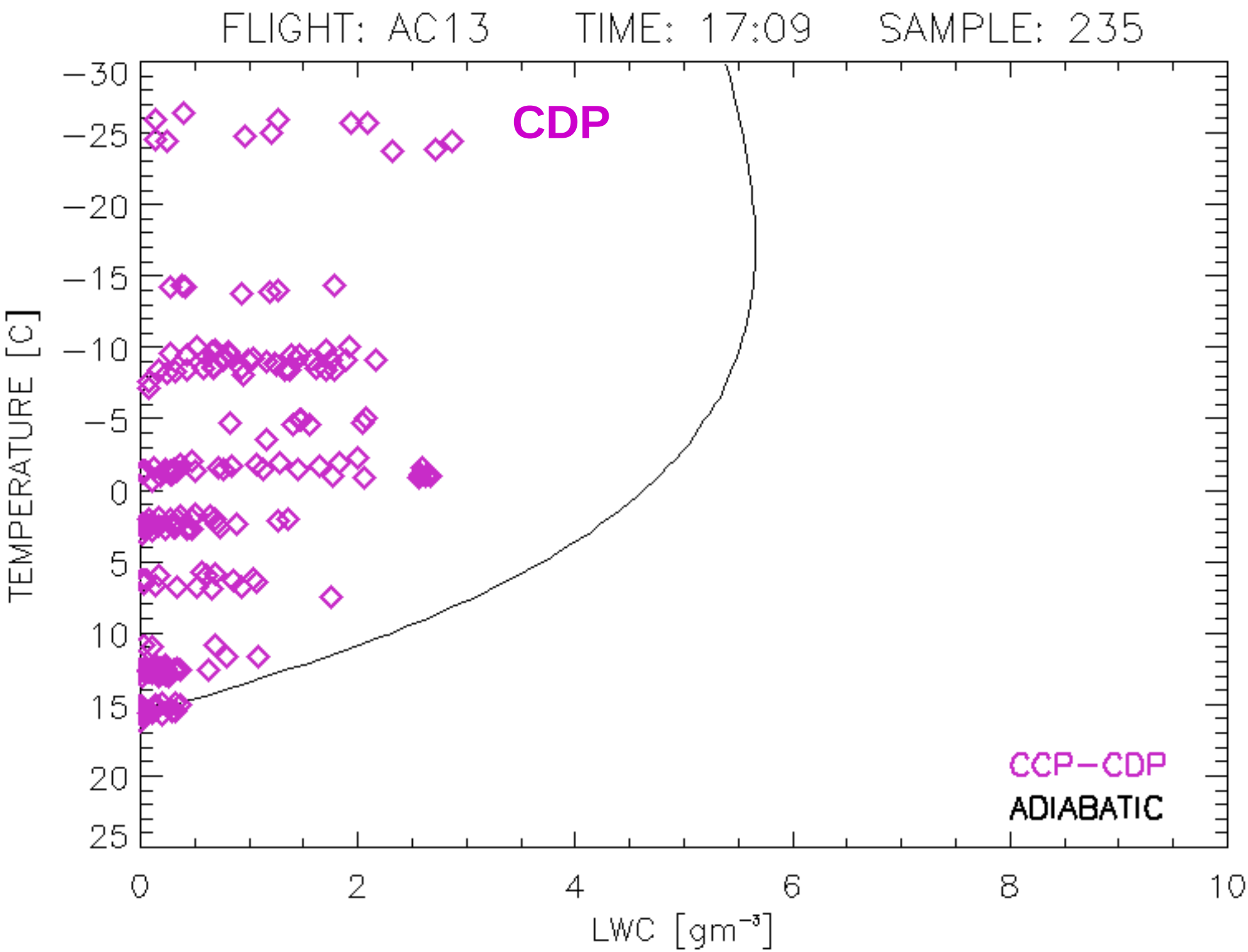


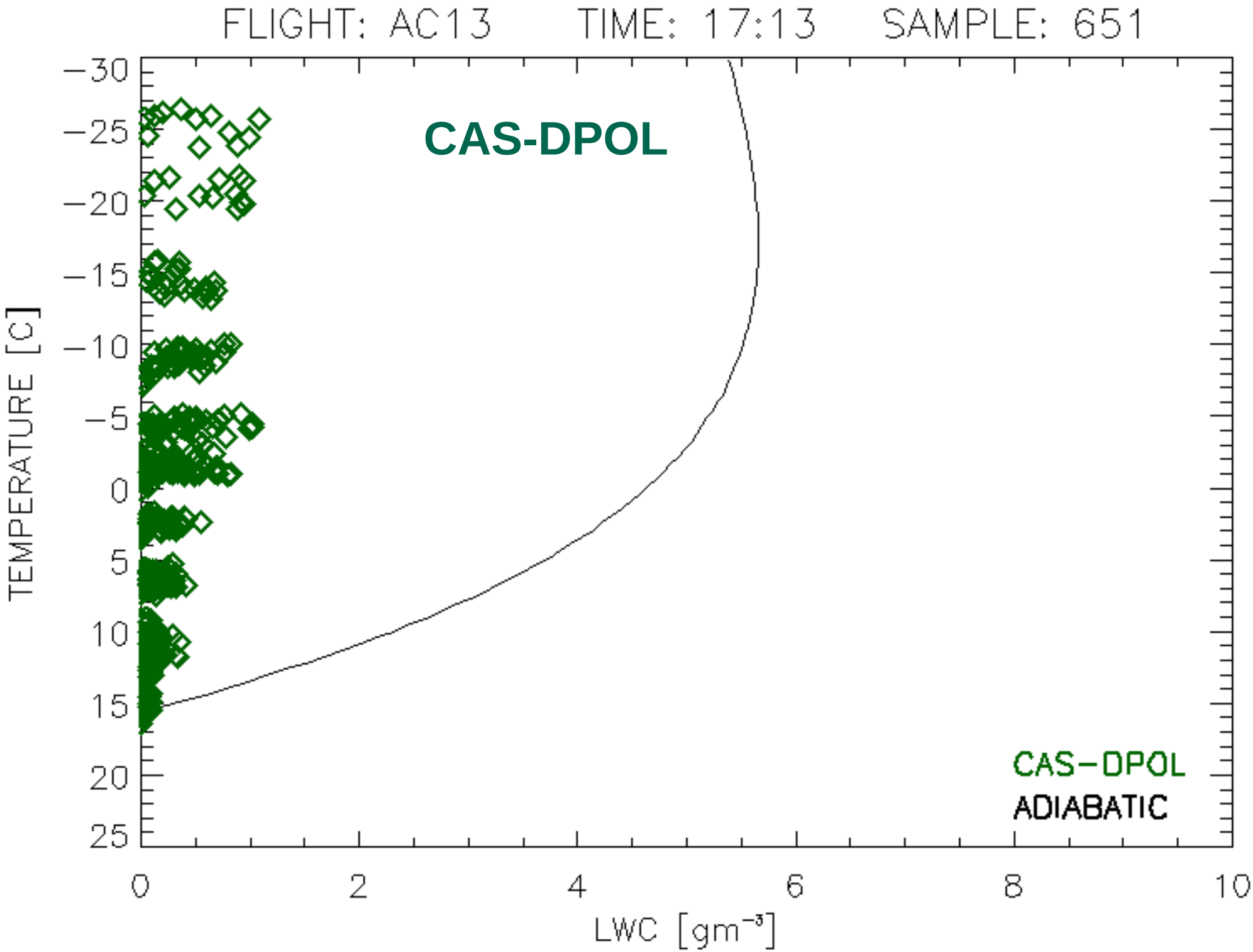
Cloud drop diameter [μm]

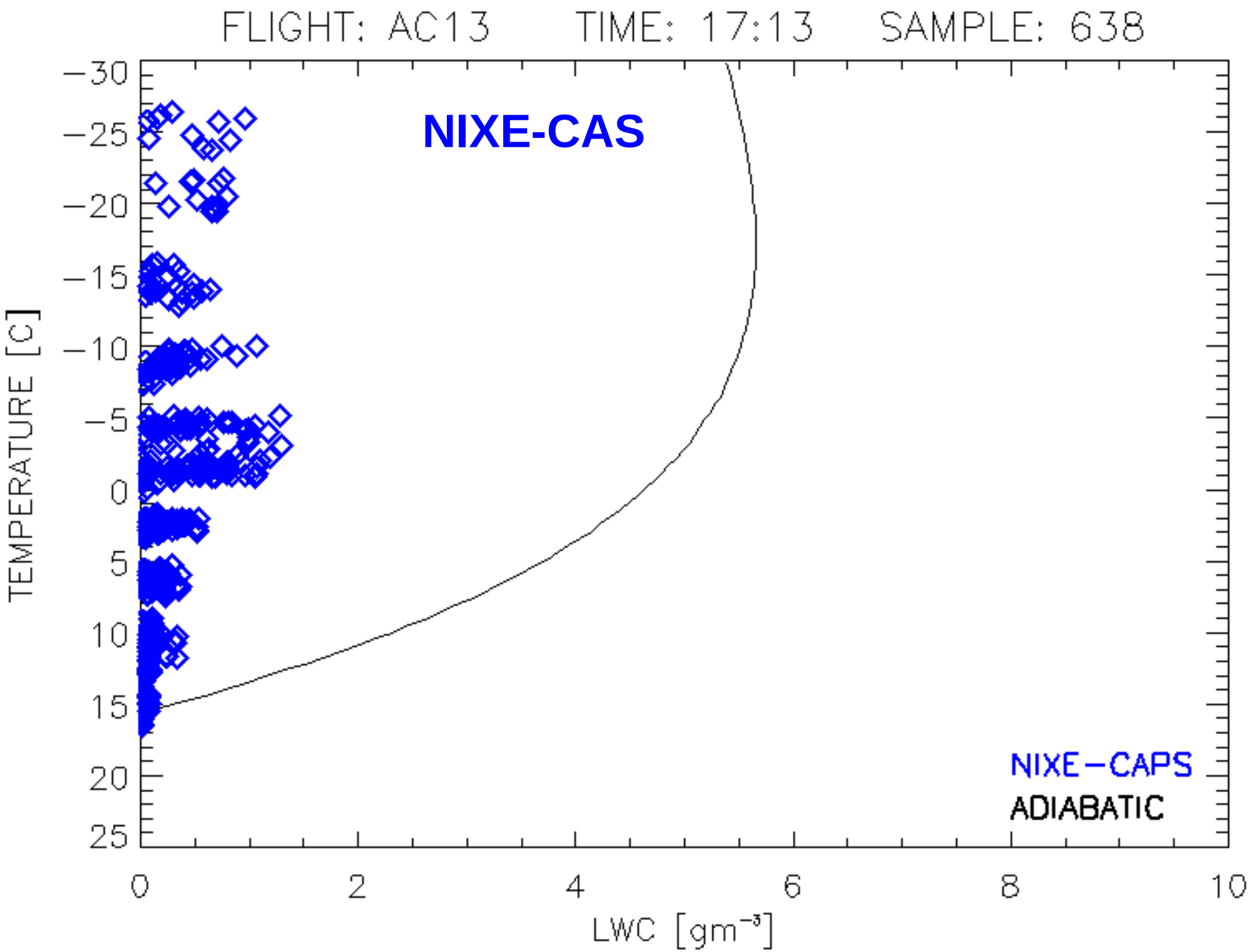

FLIGHT: AC18 TIME: 17:08 SAMPLE: 413
CDP
TEMPERATURE [C]
LWC [gm⁻³]
CCP−CDP
ADIABATIC
−30
−25
−20
−15
−10
−5
0
5
10
15
20
25
0
2
4
6
8
10


FLIGHT: AC18 TIME: 17:08 SAMPLE: 424
CAS-DPOL
TEMPERATURE [C]
−30
−25
−20
−15
−10
−5
0
5
10
15
20
25
0
2
4
6
8
10
LWC [gm⁻³]
CAS−DPOL
ADIABATIC


FLIGHT: AC18 TIME: 17:08 SAMPLE: 437
NIXE-CAS
TEMPERATURE [C]
−30
−25
−20
−15
−10
−5
0
5
10
15
20
25
0
2
4
6
8
10
LWC [gm⁻³]
NIXE−CAPS
ADIABATIC


FLIGHT: AC13 TIME: 17:09 SAMPLE: 235
CDP
CCP−CDP
ADIABATIC
TEMPERATURE [C]
LWC [gm⁻³]
−30
−25
−20
−15
−10
−5
0
5
10
15
20
25
0
2
4
6
8
10

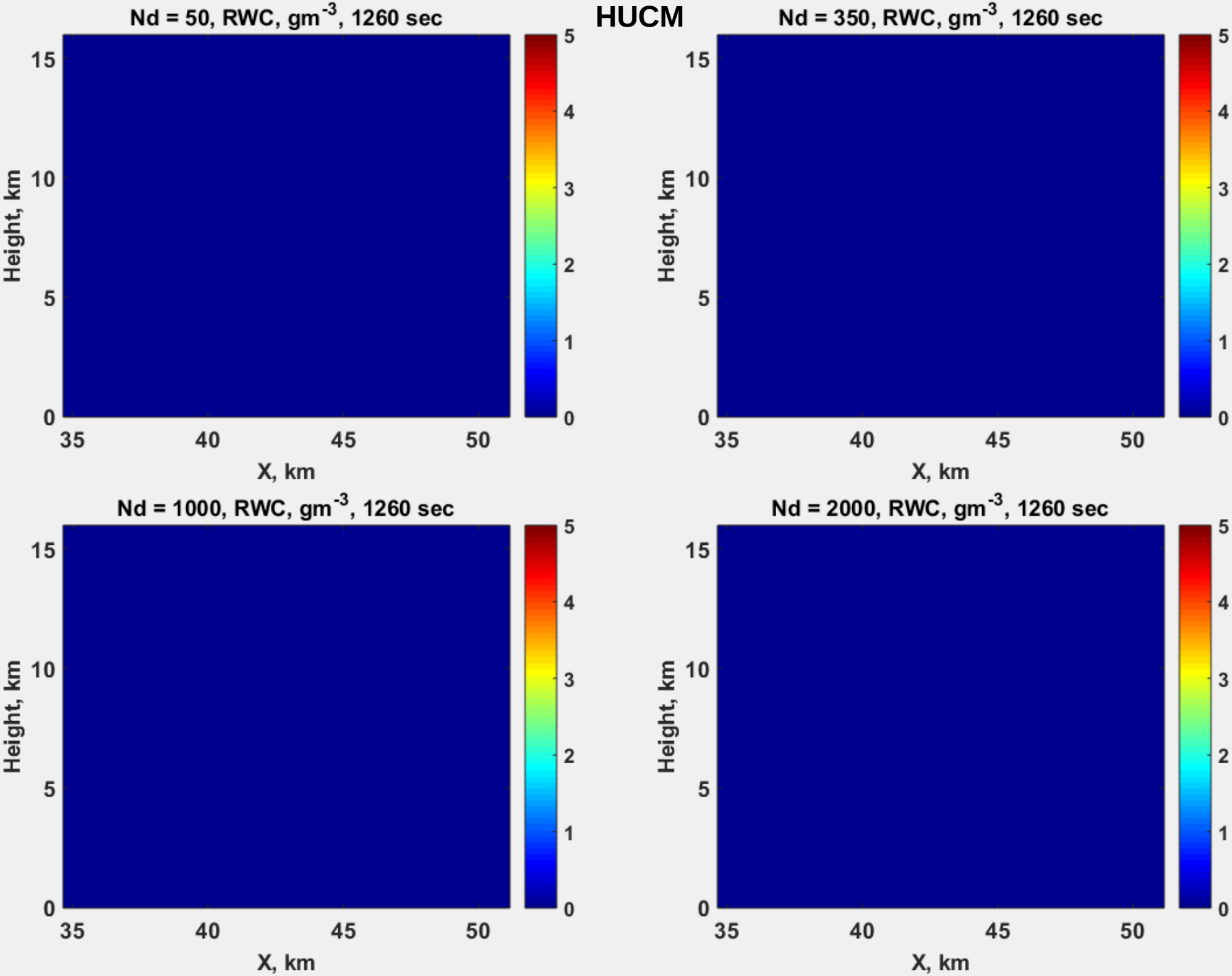

FLIGHT: AC13 TIME: 17:13 SAMPLE: 651
CAS-DPOL
TEMPERATURE [C]
−30
−25
−20
−15
−10
−5
0
5
10
15
20
25
0
2
4
6
8
10
LWC [gm⁻³]
CAS−DPOL
ADIABATIC

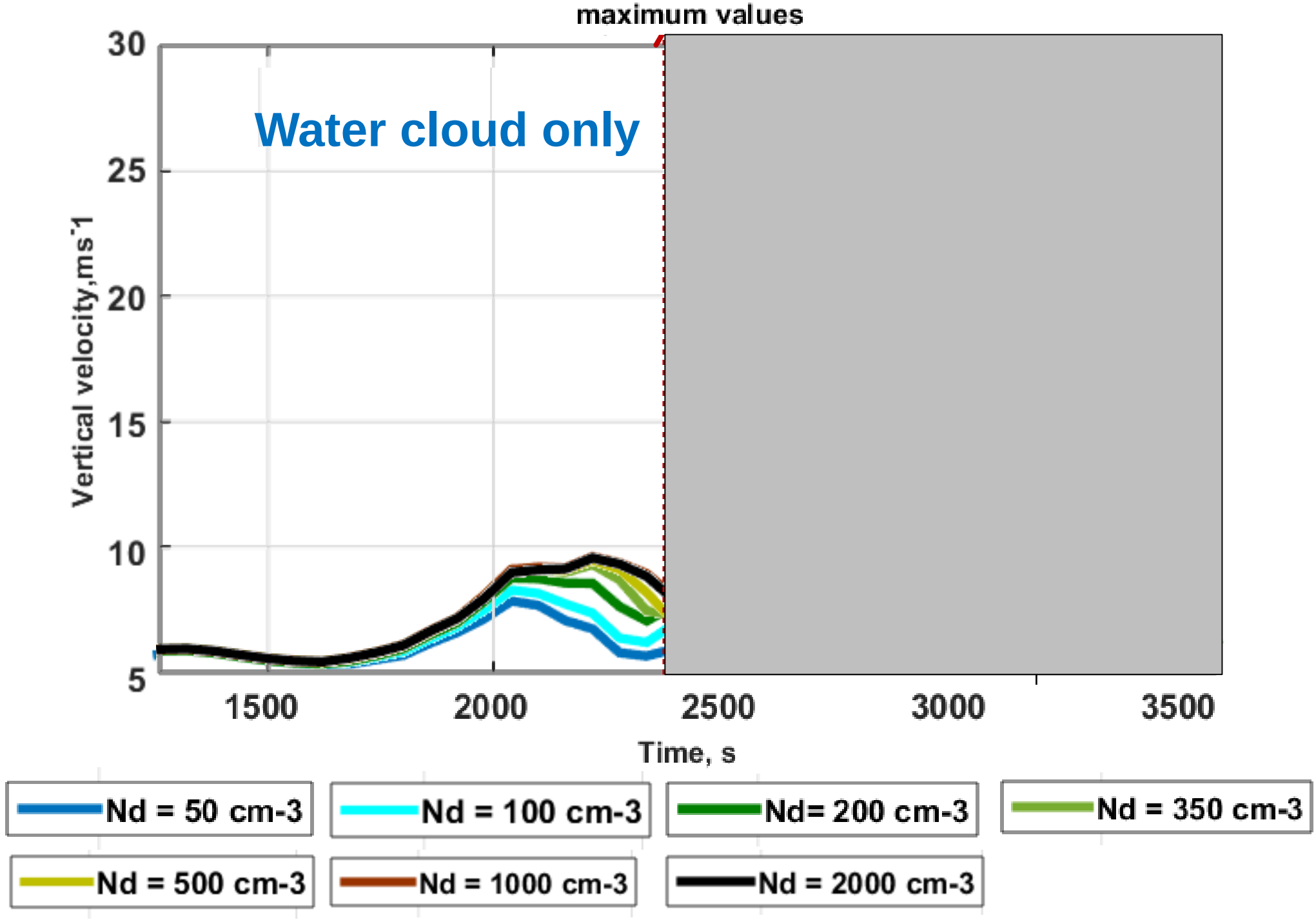

FLIGHT: AC13 TIME: 17:13 SAMPLE: 638
NIXE-CAS
NIXE−CAPS
ADIABATIC
TEMPERATURE [C]
LWC [gm⁻³]
−30
−25
−20
−15
−10
−5
0
5
10
15
20
25
0
2
4
6
8
10

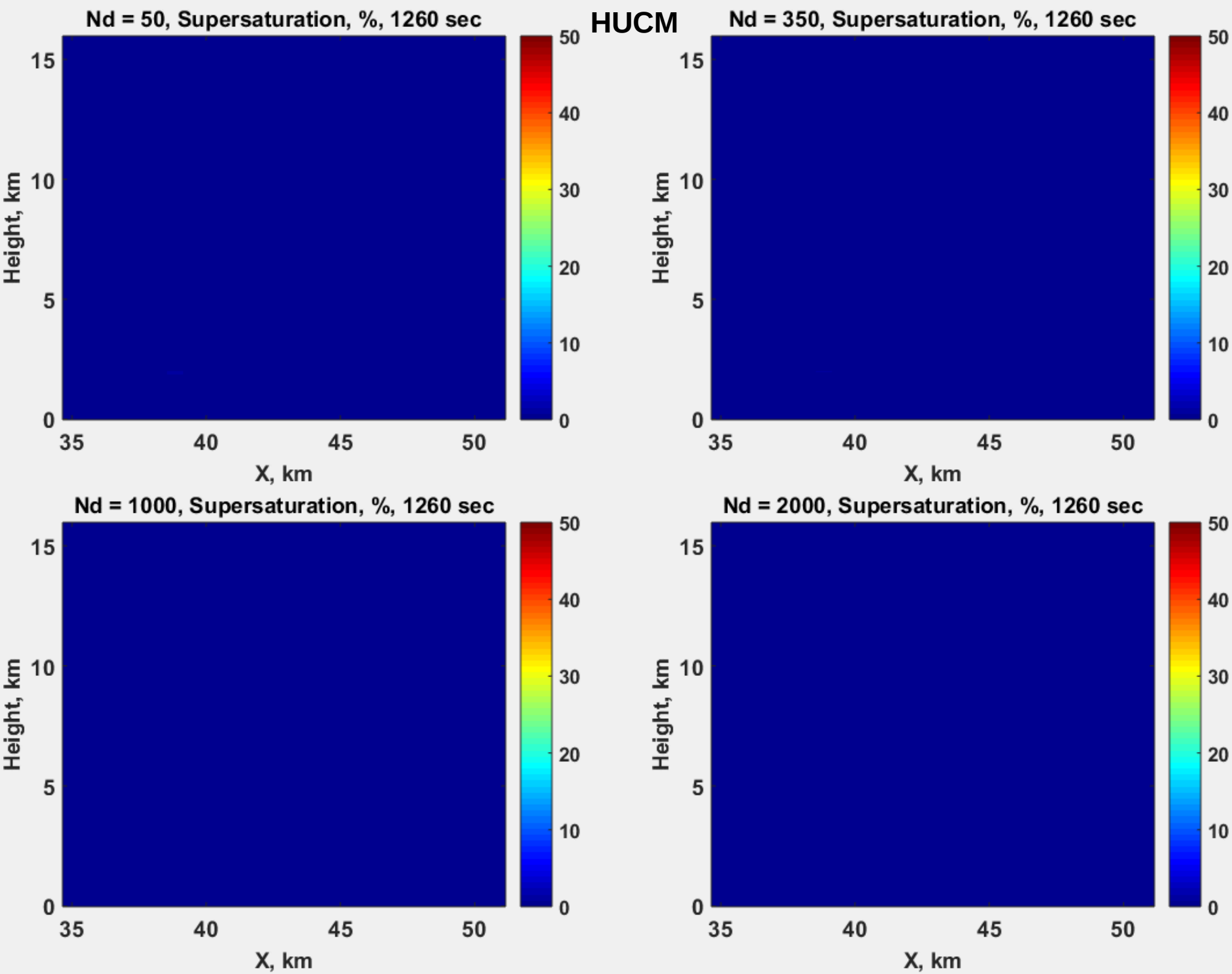
Which cloud probe to believe?

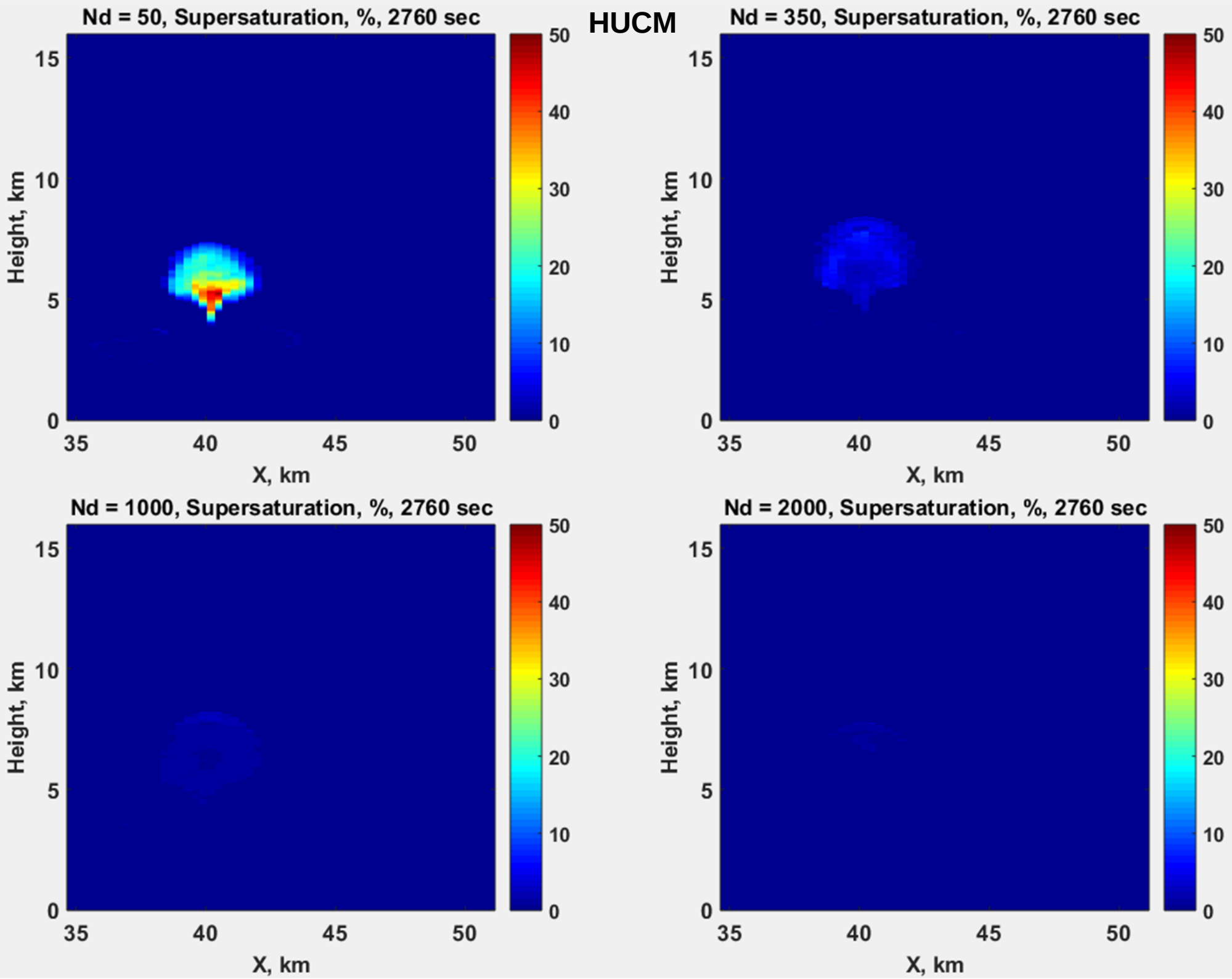
- CDP appears to have double Nd and LWC with respect to both CAS probes.
- CAS DSD is distorted badly at sizes < 10 μm, and has a poor size resolution above 10 μm.
- While CAS LWC looks unrealistically low, CDP Nd looks unrealistically high.

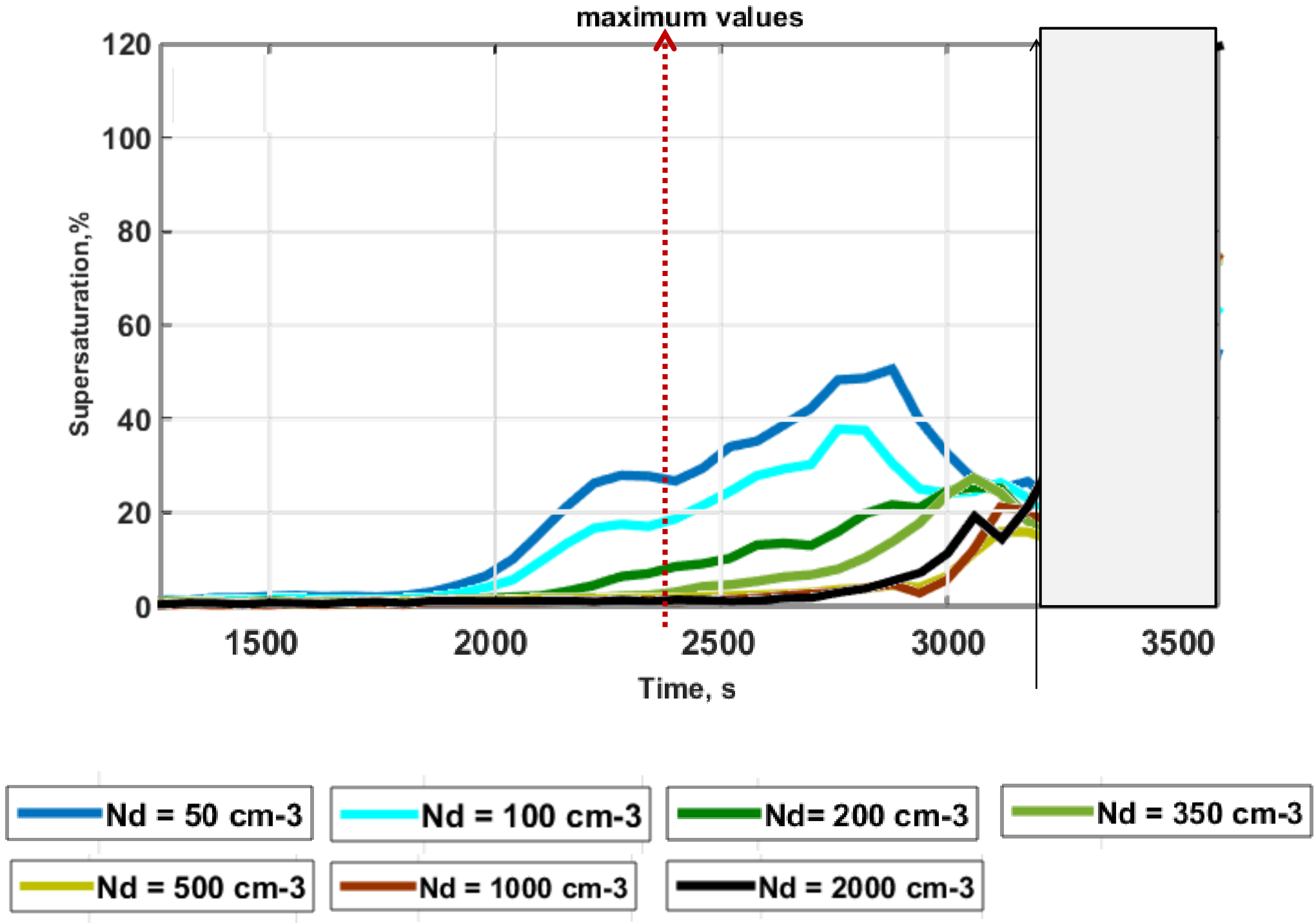
Conclusion: additional calibration and QC required

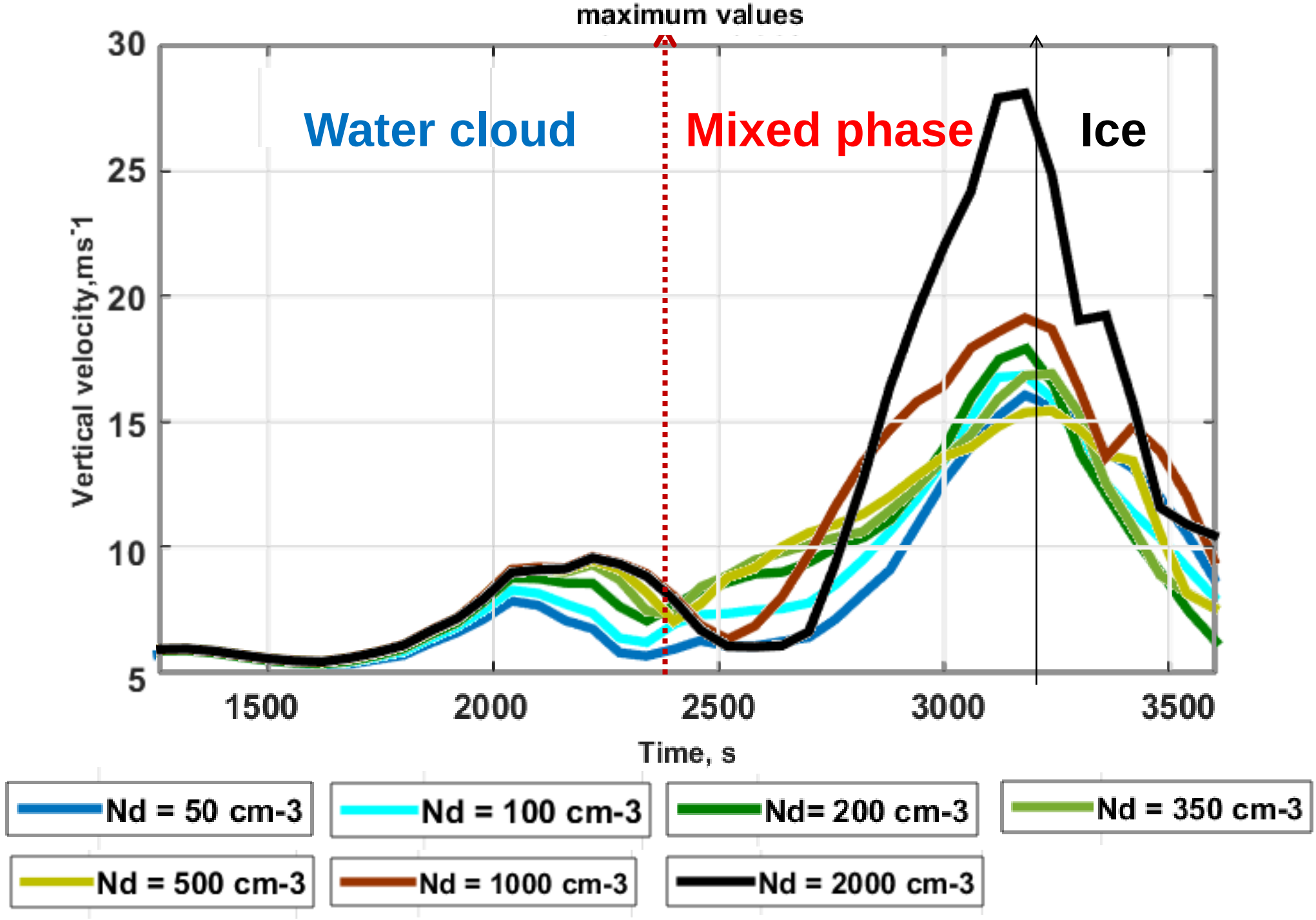

HUCM
Nd = 50, RWC, gm-3, 1260 sec
Nd = 350, RWC, gm-3, 1260 sec
Nd = 1000, RWC, gm-3, 1260 sec
Nd = 2000, RWC, gm-3, 1260 sec
Height, km
X, km
0
5
10
15
35
40
45
50
0
1
2
3
4
5

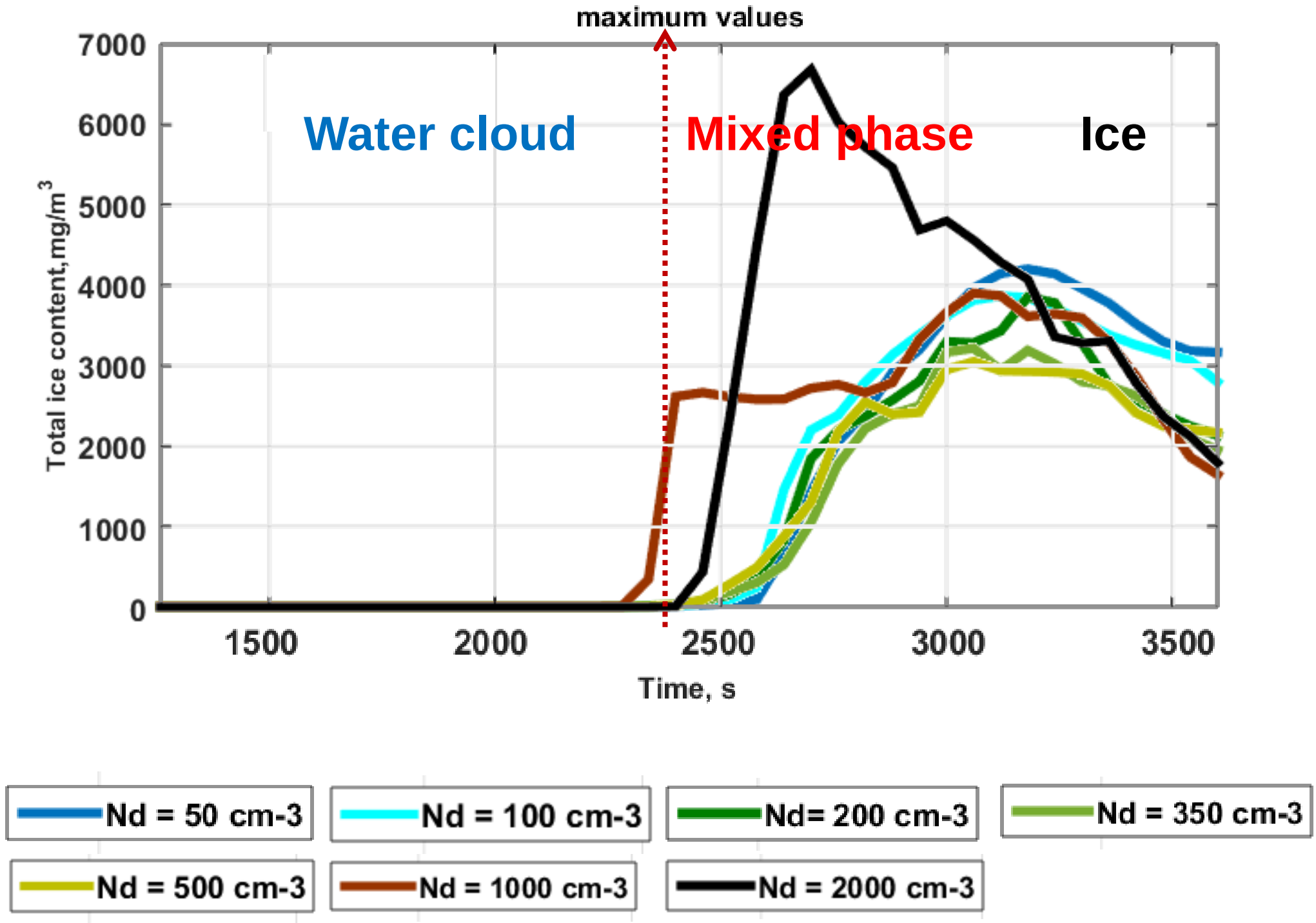

maximum values
Water cloud only
Vertical velocity,ms^-1
30
25
20
15
10
5
1500
2000
2500
3000
3500
Time, s
Nd = 50 cm-3
Nd = 100 cm-3
Nd= 200 cm-3
Nd = 350 cm-3
Nd = 500 cm-3
Nd = 1000 cm-3
Nd = 2000 cm-3

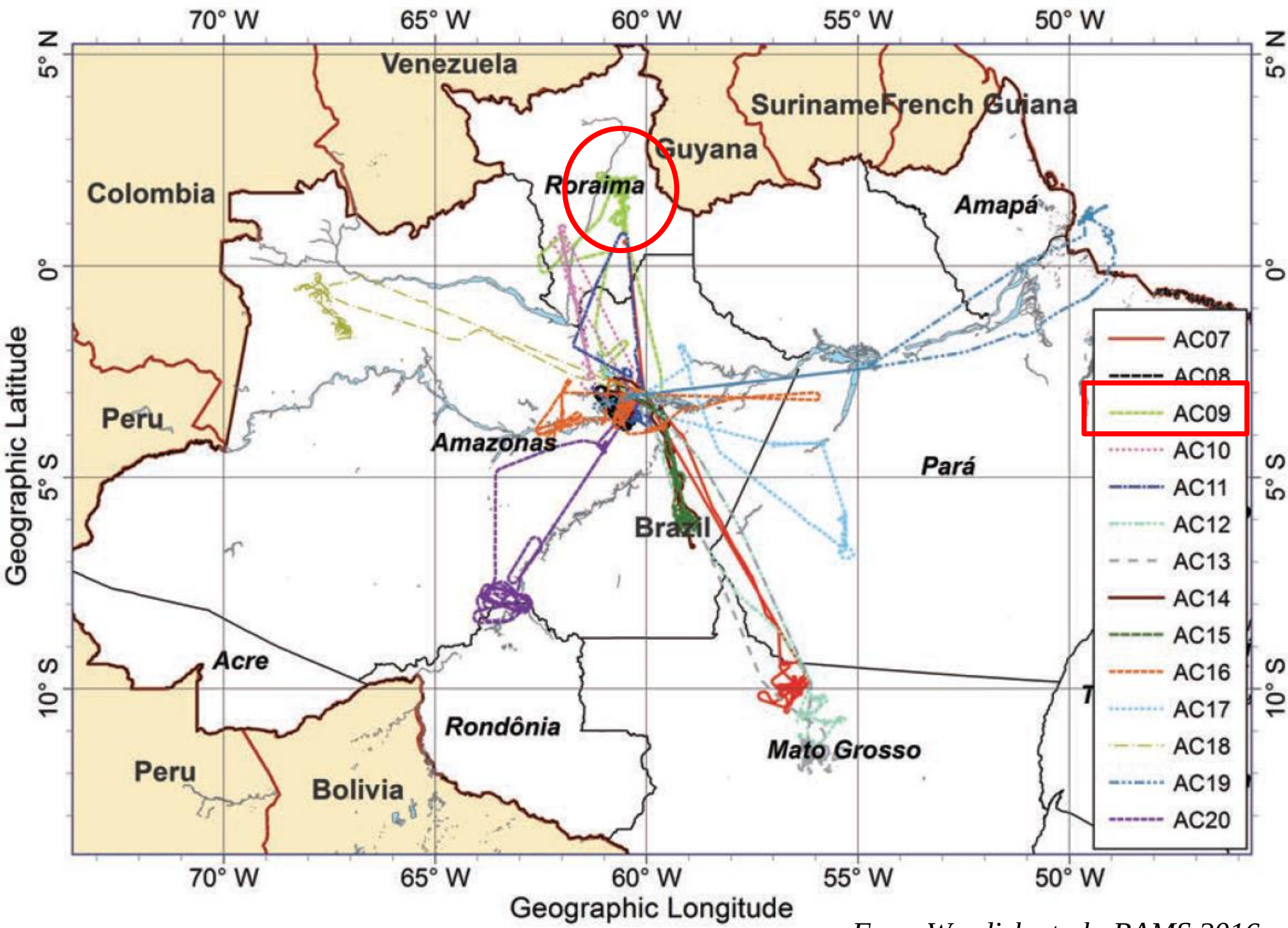

HUCM
Nd = 50, Supersaturation, %, 1260 sec
Nd = 350, Supersaturation, %, 1260 sec
Nd = 1000, Supersaturation, %, 1260 sec
Nd = 2000, Supersaturation, %, 1260 sec
Height, km
X, km
0
5
10
15
35
40
45
50
0
10
20
30
40
50


HUCM
Nd = 50, Supersaturation, %, 2760 sec
Nd = 350, Supersaturation, %, 2760 sec
Nd = 1000, Supersaturation, %, 2760 sec
Nd = 2000, Supersaturation, %, 2760 sec
Height, km
X, km
0
5
10
15
35
40
45
50
0
10
20
30
40
50


maximum values
120
100
80
60
40
20
0
Supersaturation,%
1500
2000
2500
3000
3500
Time, s
Nd = 50 cm-3
Nd = 100 cm-3
Nd= 200 cm-3
Nd = 350 cm-3
Nd = 500 cm-3
Nd = 1000 cm-3
Nd = 2000 cm-3

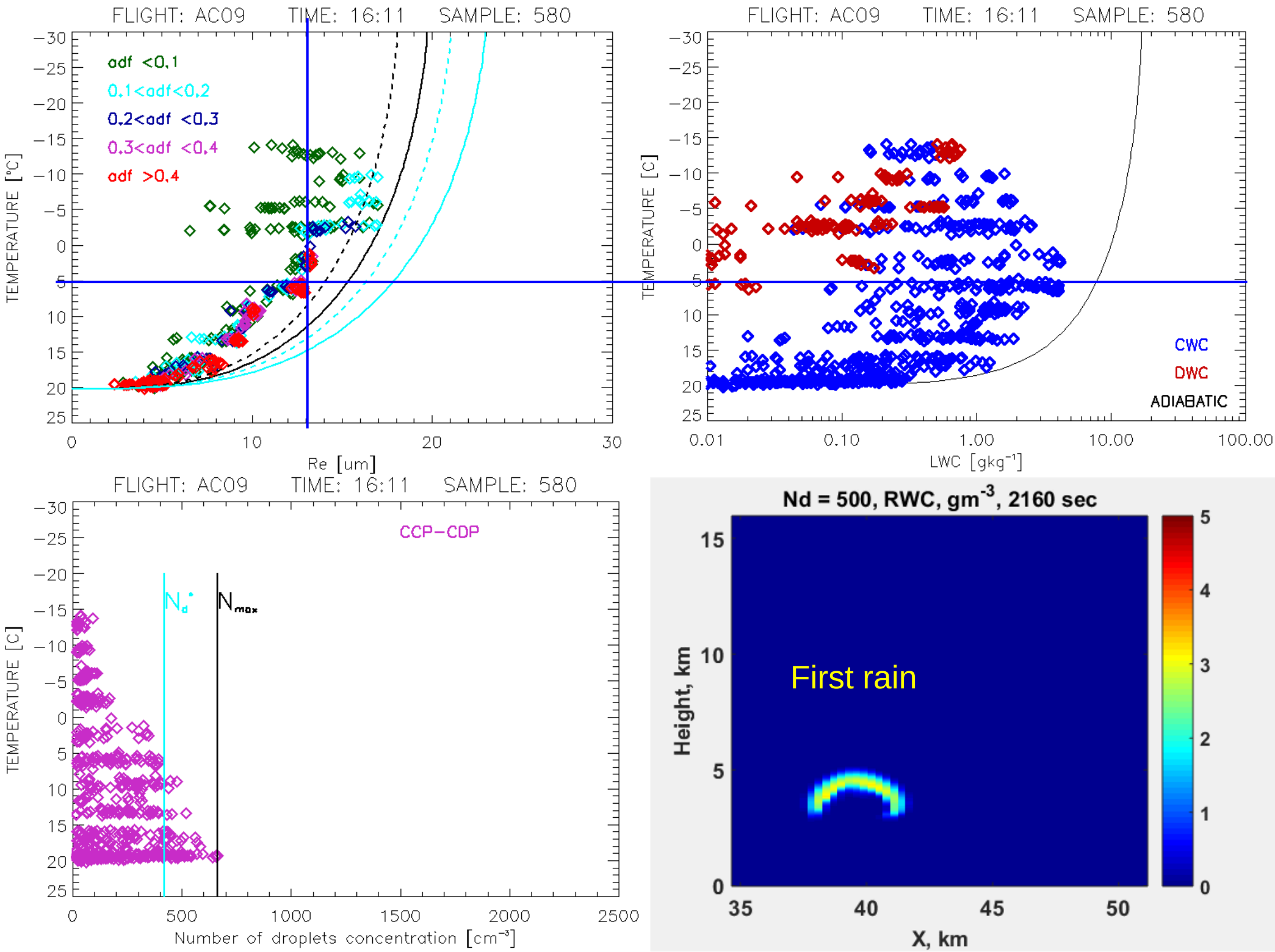

maximum values
Water cloud
Mixed phase
Ice
Vertical velocity,ms^-1
30
25
20
15
10
5
1500
2000
2500
3000
3500
Time, s
Nd = 50 cm-3
Nd = 100 cm-3
Nd= 200 cm-3
Nd = 350 cm-3
Nd = 500 cm-3
Nd = 1000 cm-3
Nd = 2000 cm-3

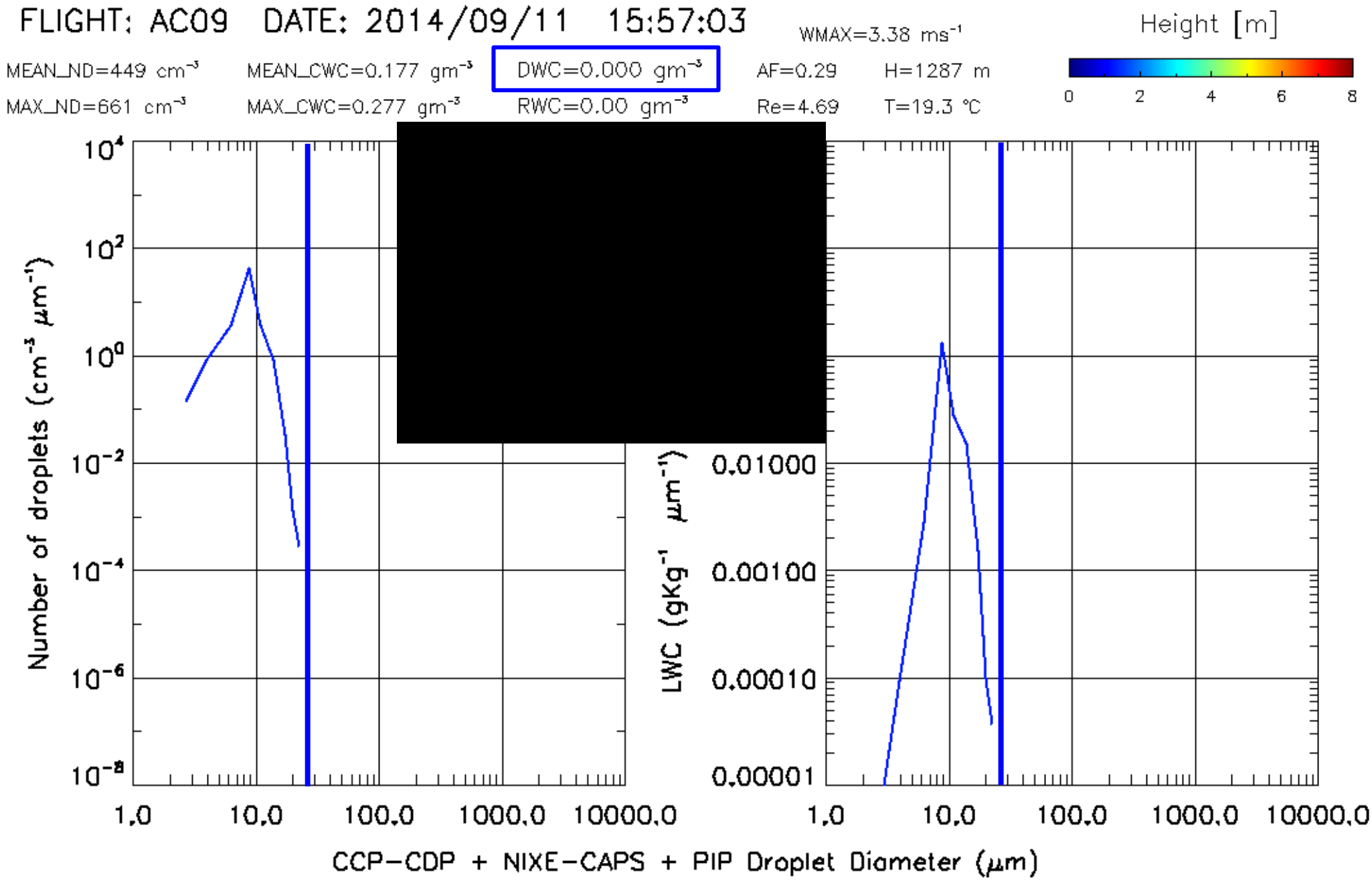

maximum values
Water cloud
Mixed phase
Ice
Total ice content,mg/m3
7000
6000
5000
4000
3000
2000
1000
0
1500
2000
2500
3000
3500
Time, s
Nd = 50 cm-3
Nd = 100 cm-3
Nd= 200 cm-3
Nd = 350 cm-3
Nd = 500 cm-3
Nd = 1000 cm-3
Nd = 2000 cm-3

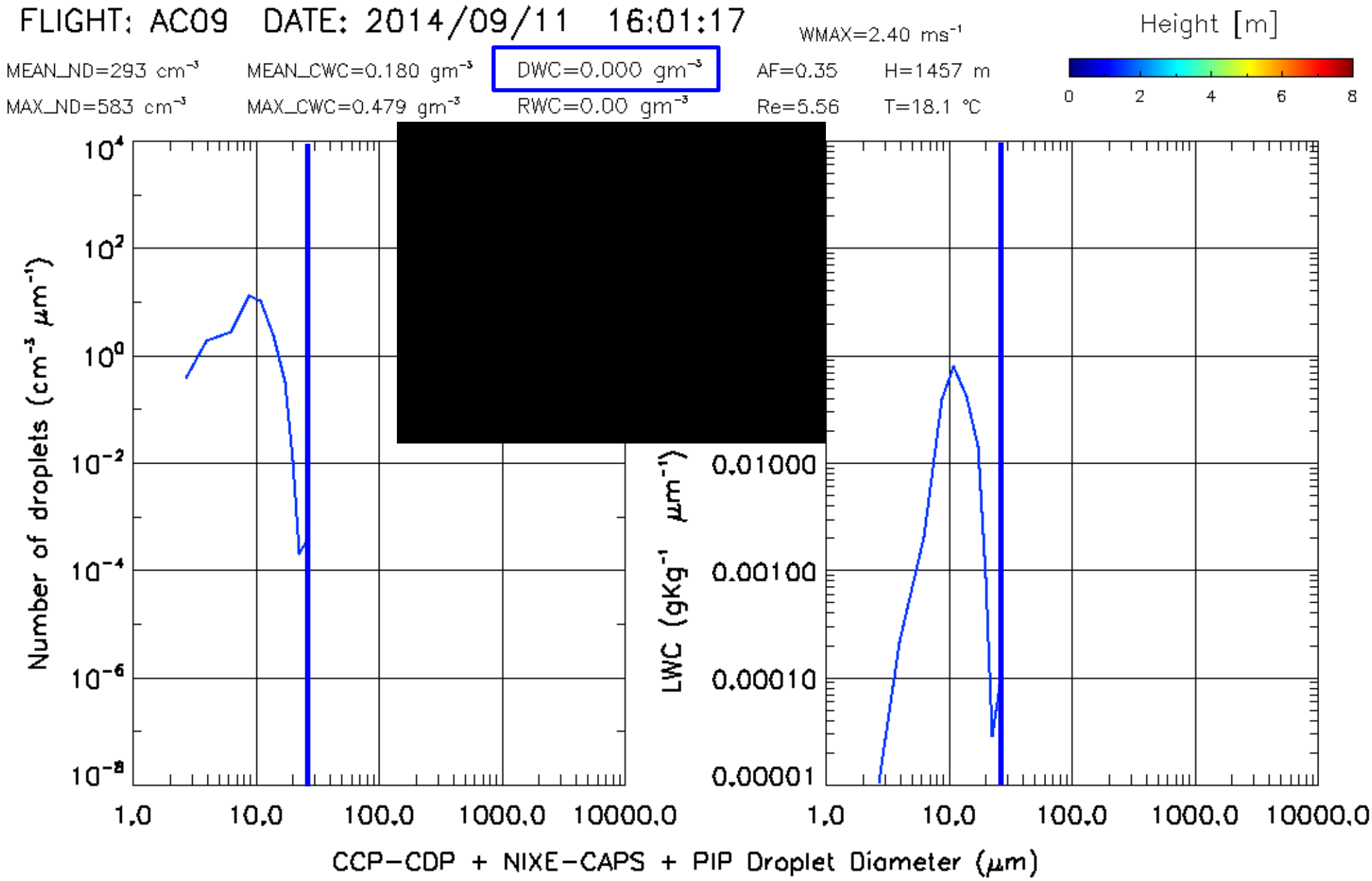


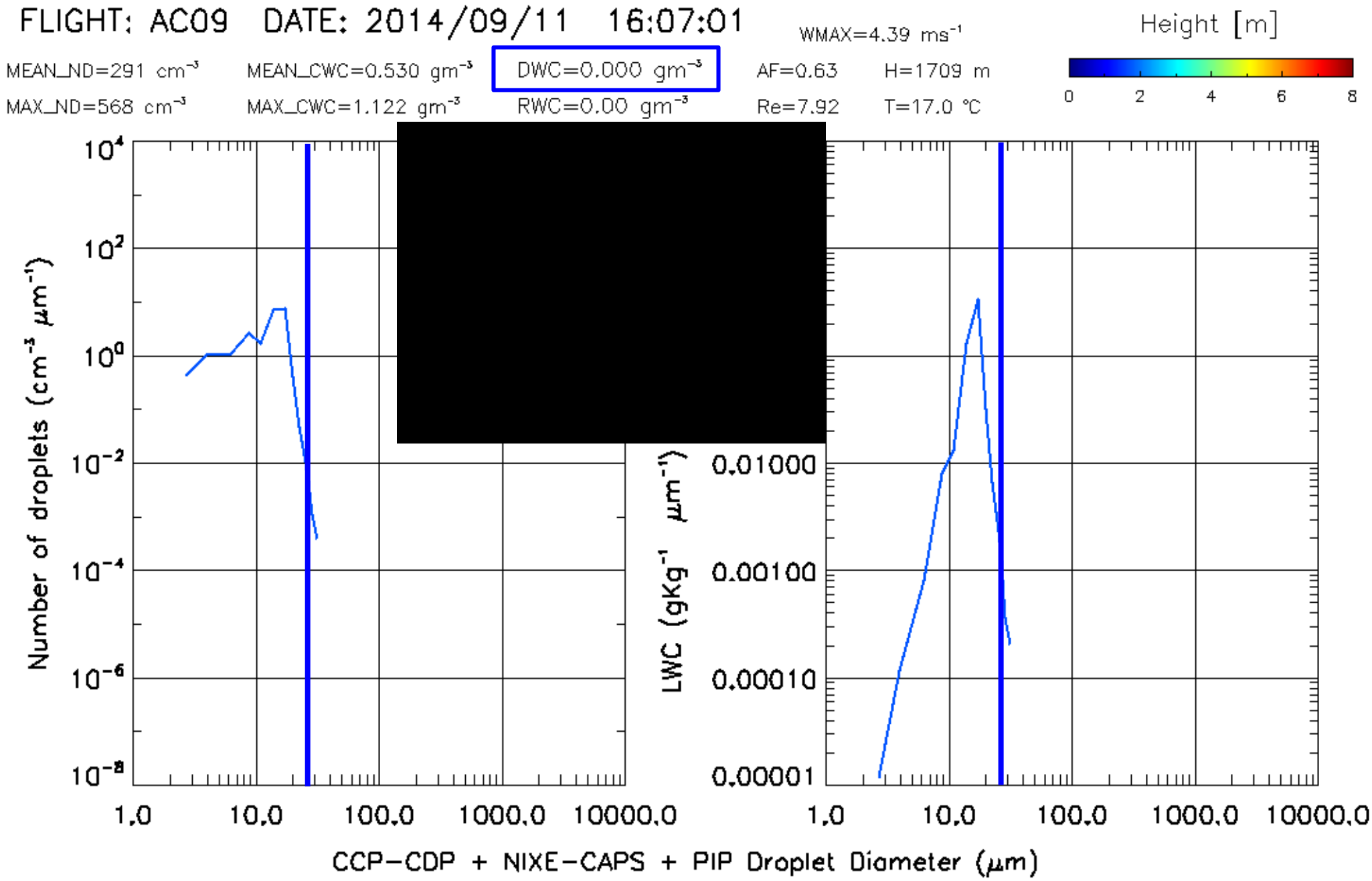
From Wendish et al., BAMS 2016

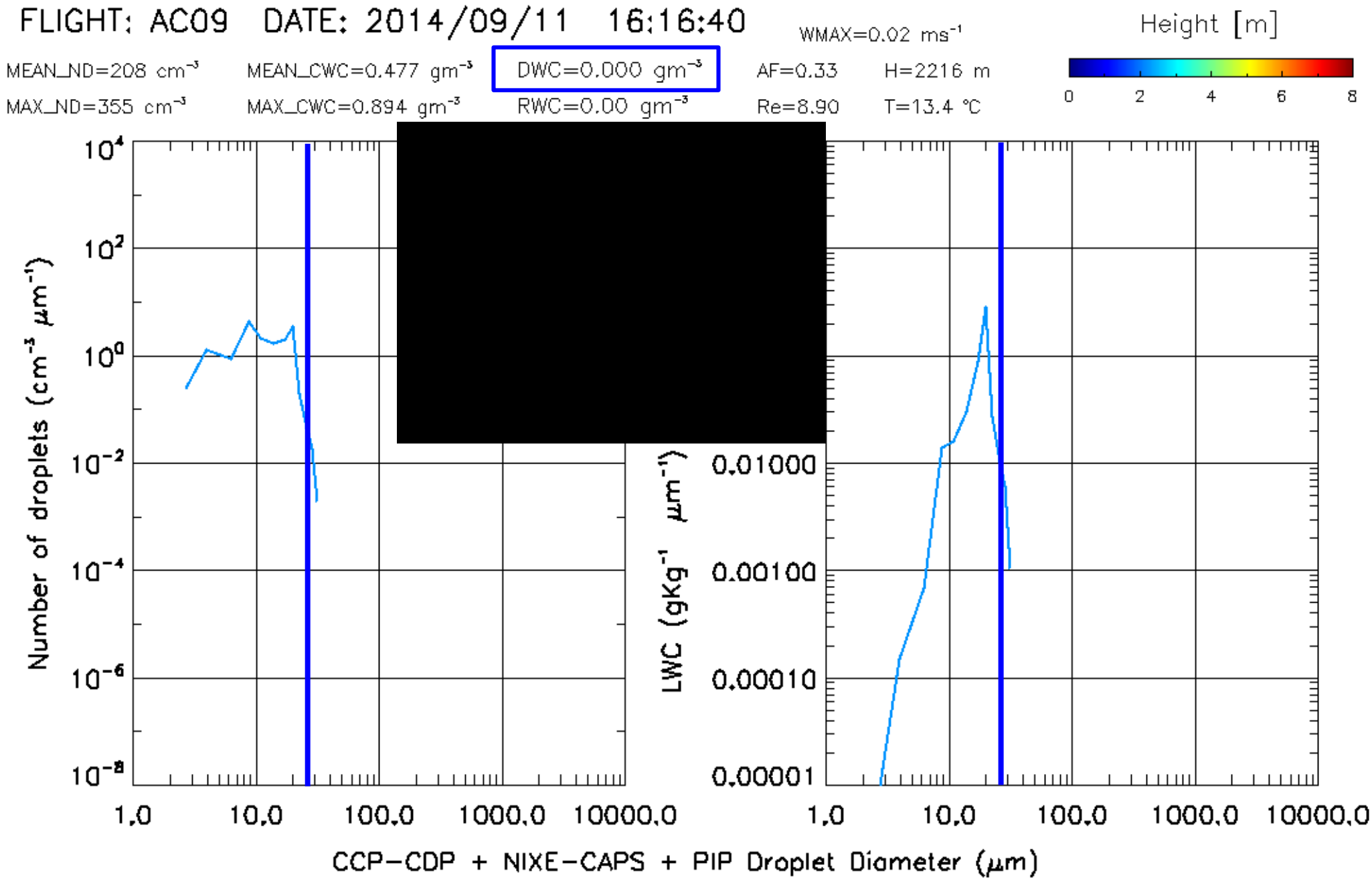
FIG. 6. Flight tracks for all scientific missions (AC07 to AC20).

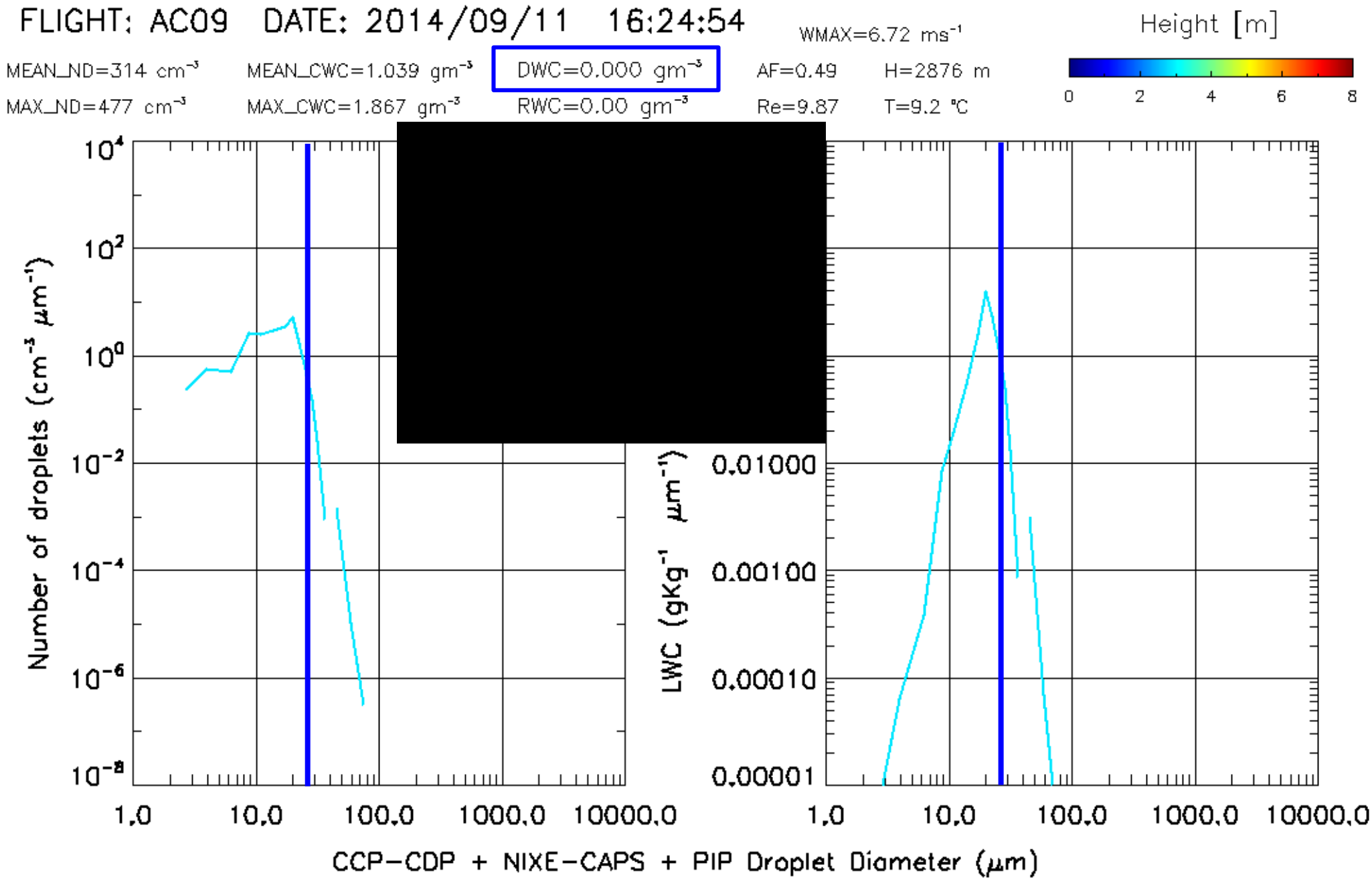

FLIGHT: AC09 TIME: 16:11 SAMPLE: 580
adf <0.1
0.1<adf<0.2
0.2<adf <0.3
0.3<adf <0.4
adf >0.4
TEMPERATURE [°C]
Re [um]
FLIGHT: AC09 TIME: 16:11 SAMPLE: 580
CWC
DWC
ADIABATIC
TEMPERATURE [C]
LWC [gkg⁻¹]
FLIGHT: AC09 TIME: 16:11 SAMPLE: 580
CCP−CDP
N_d^*
N_{max}
TEMPERATURE [C]
Number of droplets concentration [cm⁻³]
Nd = 500, RWC, gm^{-3}, 2160 sec
First rain
Height, km
X, km

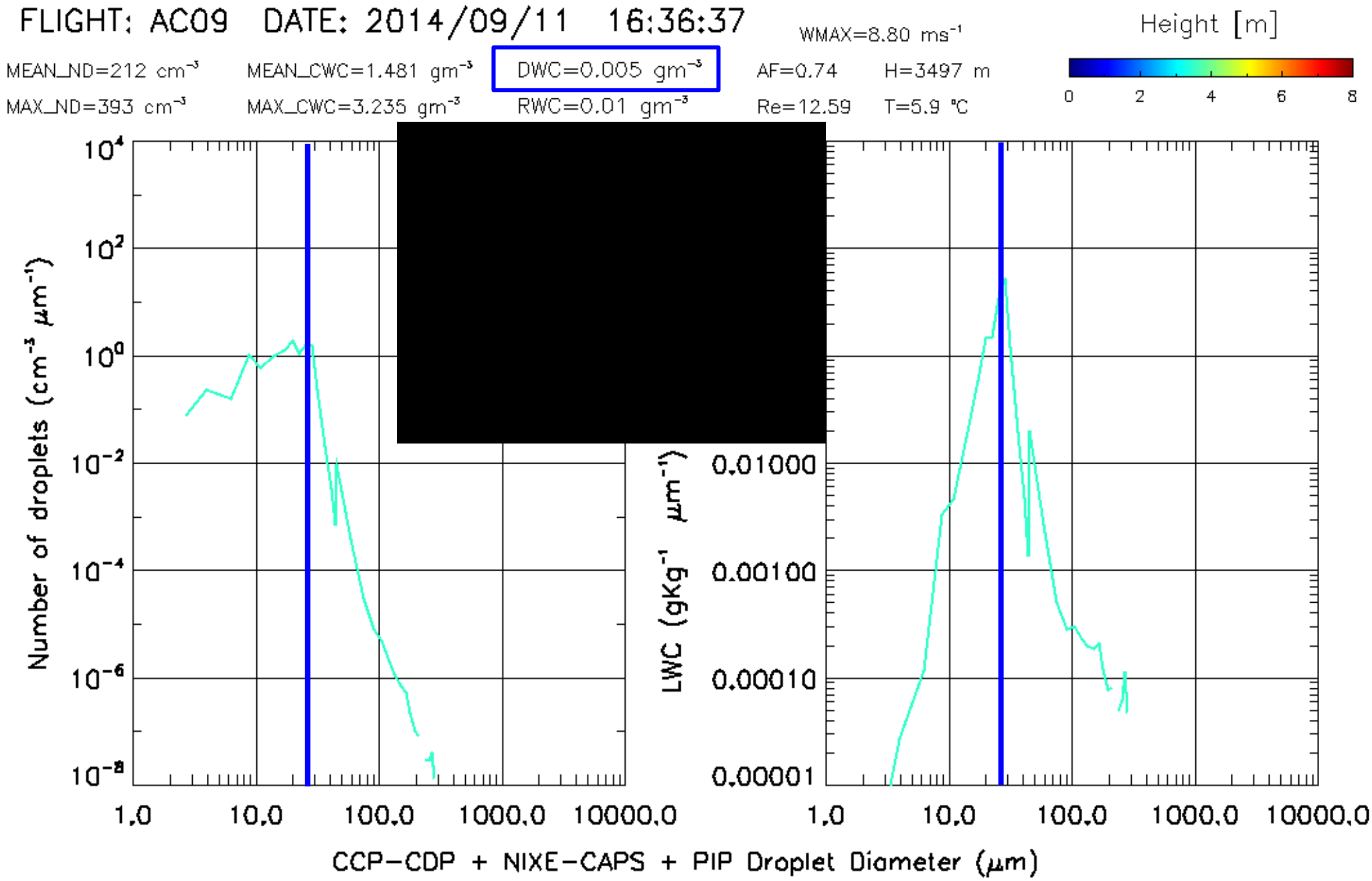

FLIGHT: AC09 DATE: 2014/09/11 15:57:03
WMAX=3.38 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=449 cm⁻³
MEAN_CWC=0.177 gm⁻³
DWC=0.000 gm⁻³
AF=0.29
H=1287 m
MAX_ND=661 cm⁻³
MAX_CWC=0.277 gm⁻³
RWC=0.00 gm⁻³
Re=4.69
T=19.3 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

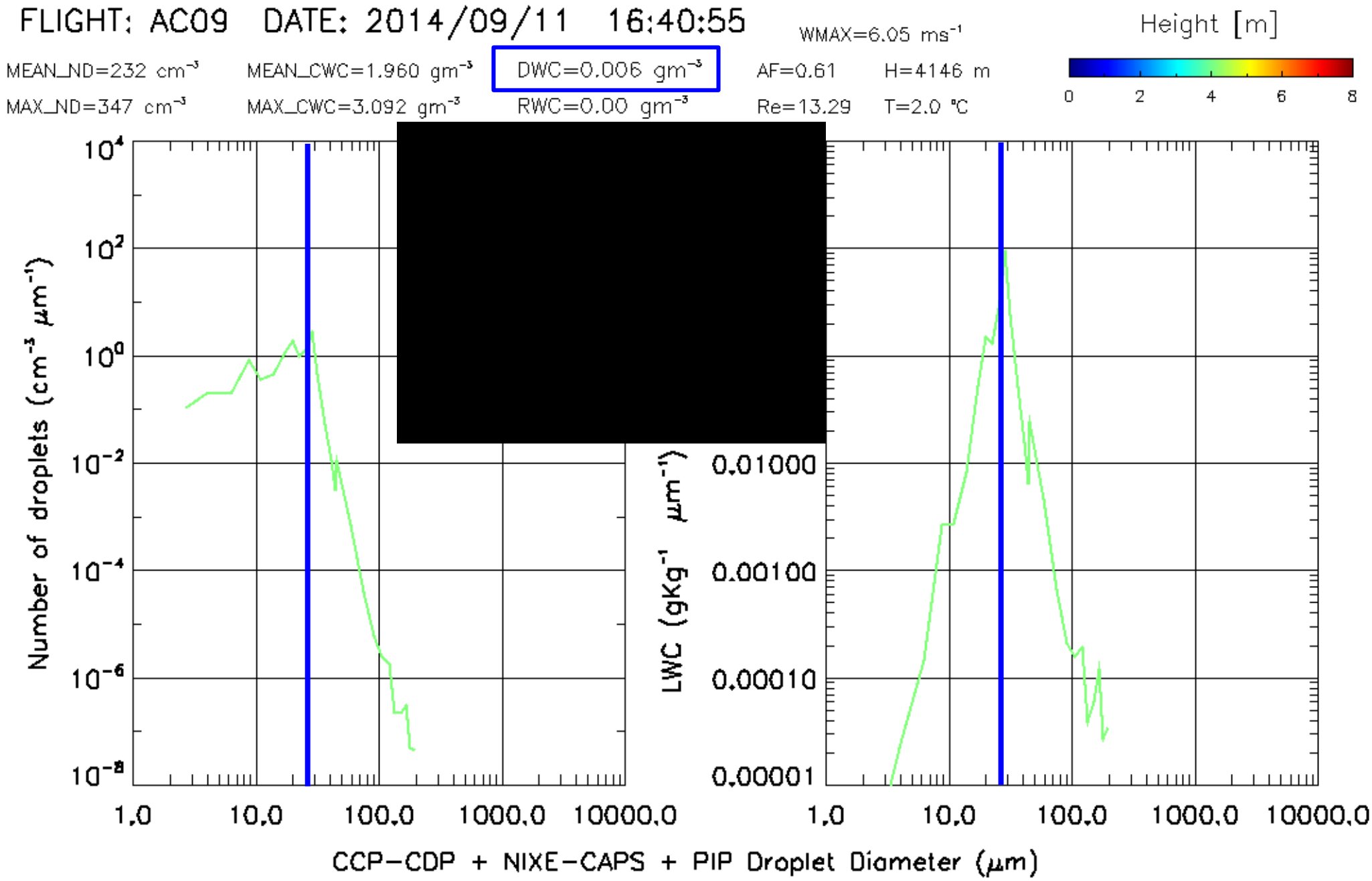

FLIGHT: AC09 DATE: 2014/09/11 16:01:17
WMAX=2.40 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=293 cm⁻³
MEAN_CWC=0.180 gm⁻³
DWC=0.000 gm⁻³
AF=0.35
H=1457 m
MAX_ND=583 cm⁻³
MAX_CWC=0.479 gm⁻³
RWC=0.00 gm⁻³
Re=5.56
T=18.1 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP-CDP + NIXE-CAPS + PIP Droplet Diameter (μm)

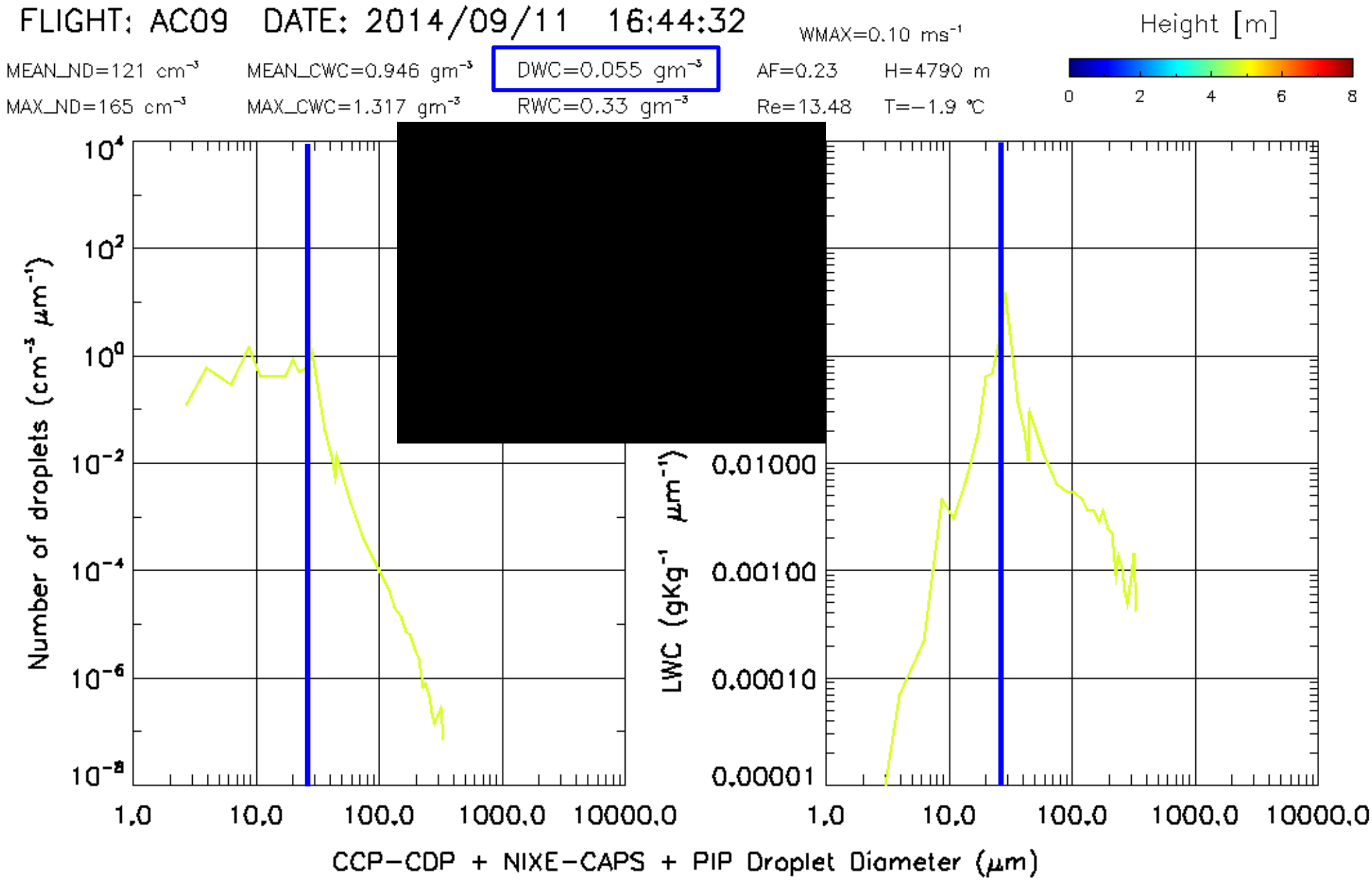

FLIGHT: AC09 DATE: 2014/09/11 16:07:01
WMAX=4.39 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=291 cm⁻³
MEAN_CWC=0.530 gm⁻³
DWC=0.000 gm⁻³
AF=0.63
H=1709 m
MAX_ND=568 cm⁻³
MAX_CWC=1.122 gm⁻³
RWC=0.00 gm⁻³
Re=7.92
T=17.0 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
0.01000
0.00100
0.00010
0.00001
1.0 10.0 100.0 1000.0 10000.0
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

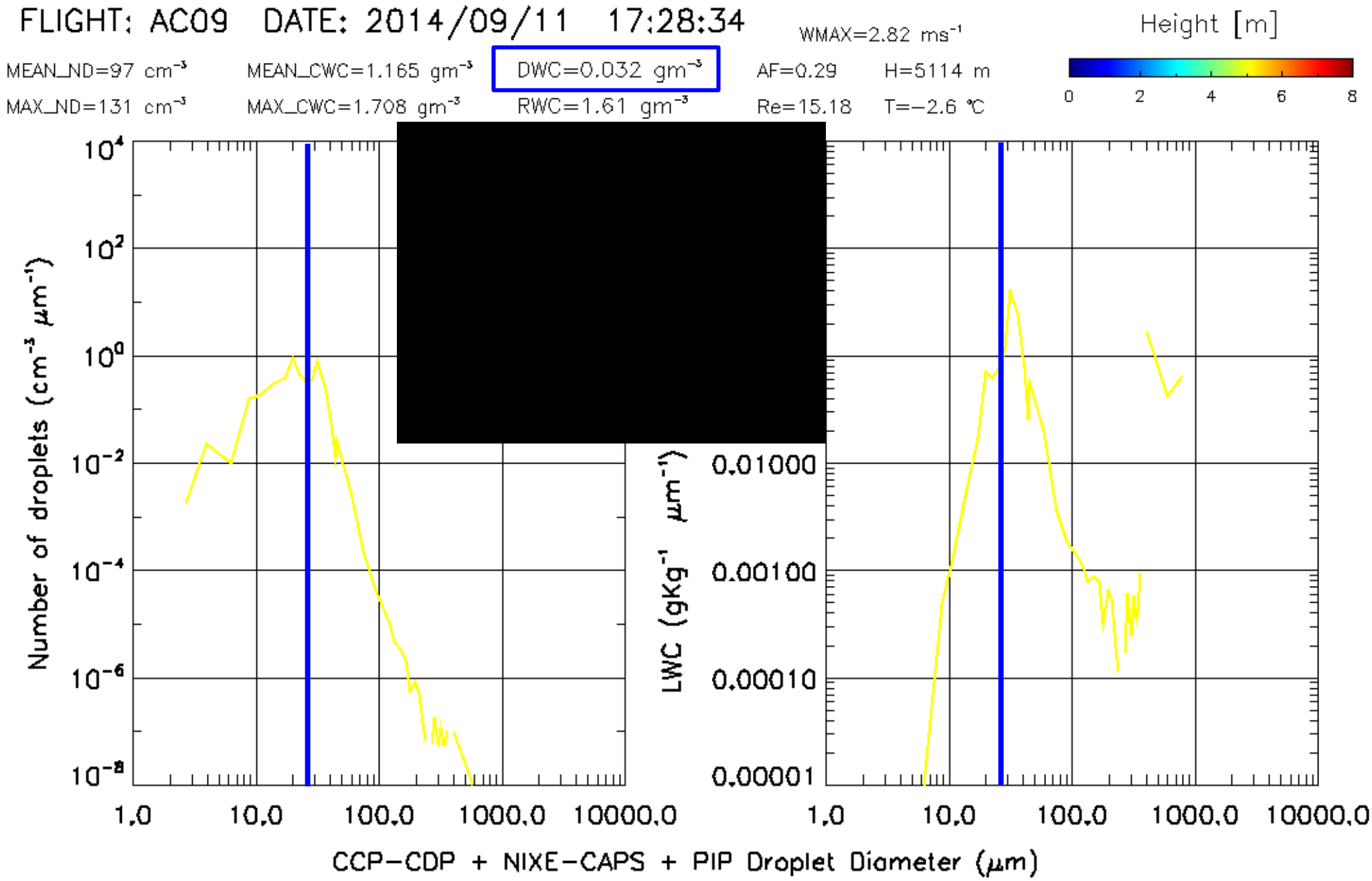

FLIGHT: AC09 DATE: 2014/09/11 16:16:40
WMAX=0.02 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=208 cm⁻³
MEAN_CWC=0.477 gm⁻³
DWC=0.000 gm⁻³
AF=0.33
H=2216 m
MAX_ND=355 cm⁻³
MAX_CWC=0.894 gm⁻³
RWC=0.00 gm⁻³
Re=8.90
T=13.4 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP-CDP + NIXE-CAPS + PIP Droplet Diameter (μm)

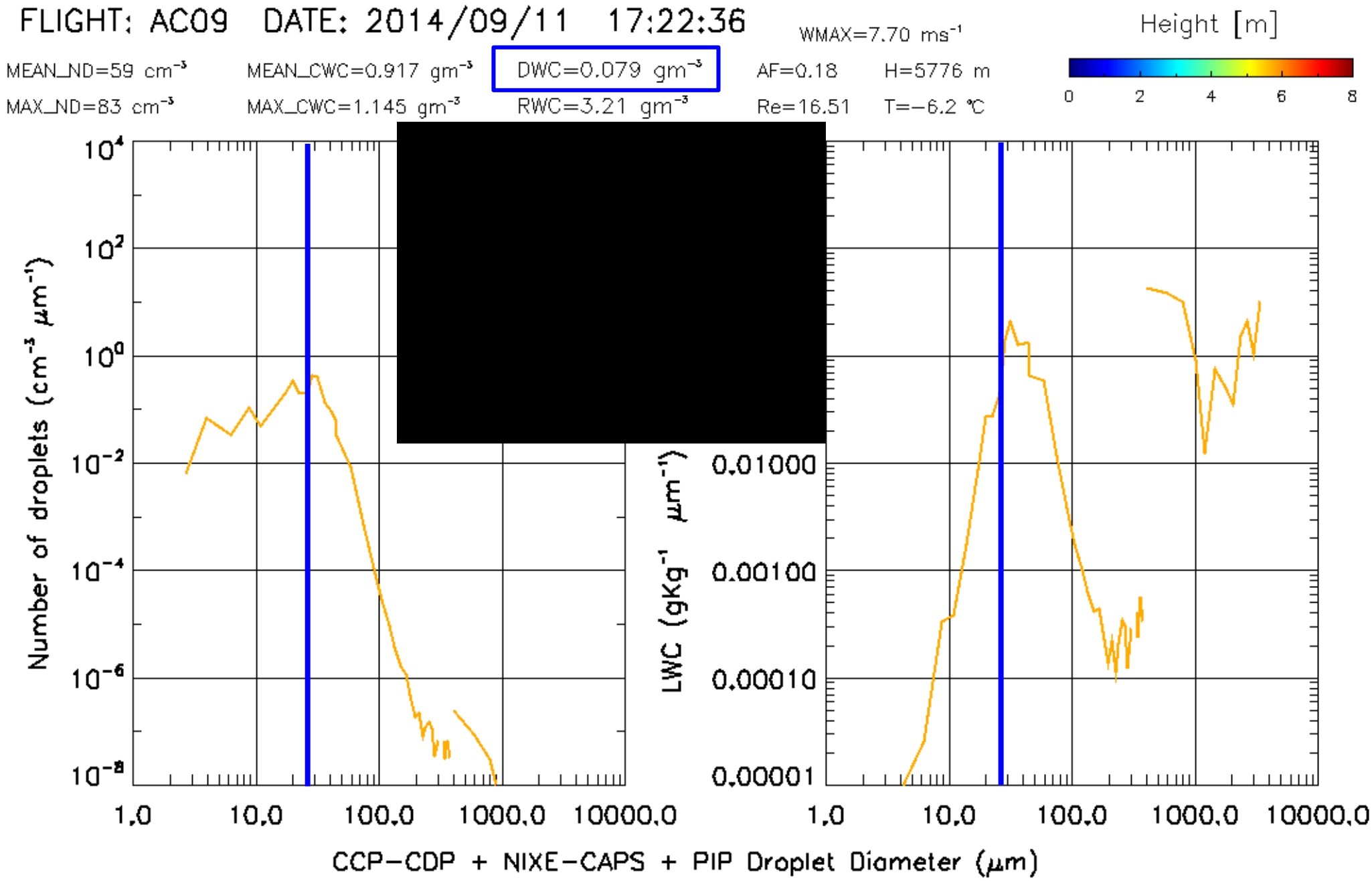

FLIGHT: AC09 DATE: 2014/09/11 16:24:54
WMAX=6.72 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=314 cm⁻³
MEAN_CWC=1.039 gm⁻³
DWC=0.000 gm⁻³
AF=0.49
H=2876 m
MAX_ND=477 cm⁻³
MAX_CWC=1.867 gm⁻³
RWC=0.00 gm⁻³
Re=9.87
T=9.2 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP-CDP + NIXE-CAPS + PIP Droplet Diameter (μm)

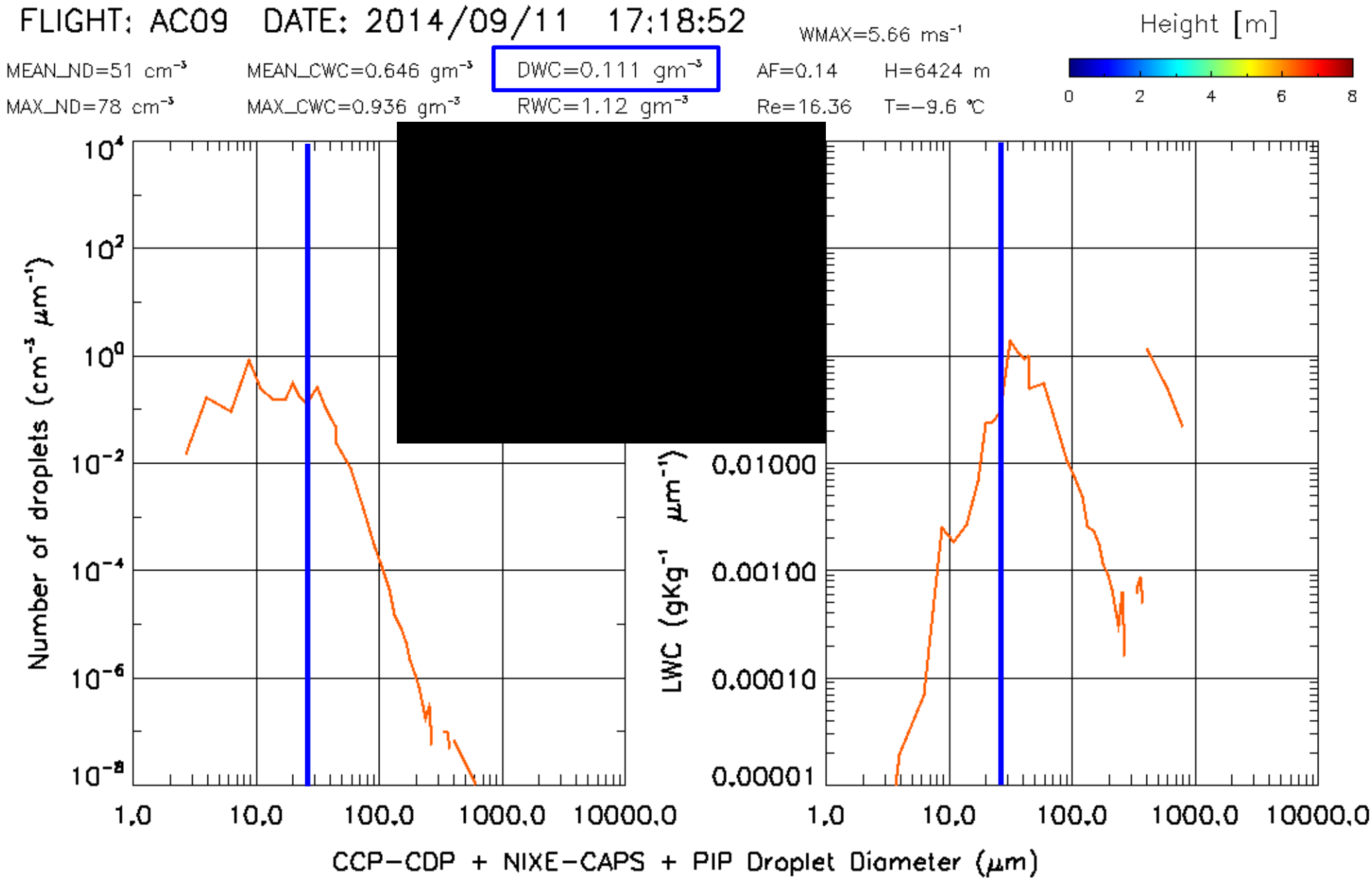

FLIGHT: AC09 DATE: 2014/09/11 16:36:37
WMAX=8.80 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=212 cm⁻³
MEAN_CWC=1.481 gm⁻³
DWC=0.005 gm⁻³
AF=0.74
H=3497 m
MAX_ND=393 cm⁻³
MAX_CWC=3.235 gm⁻³
RWC=0.01 gm⁻³
Re=12.59
T=5.9 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

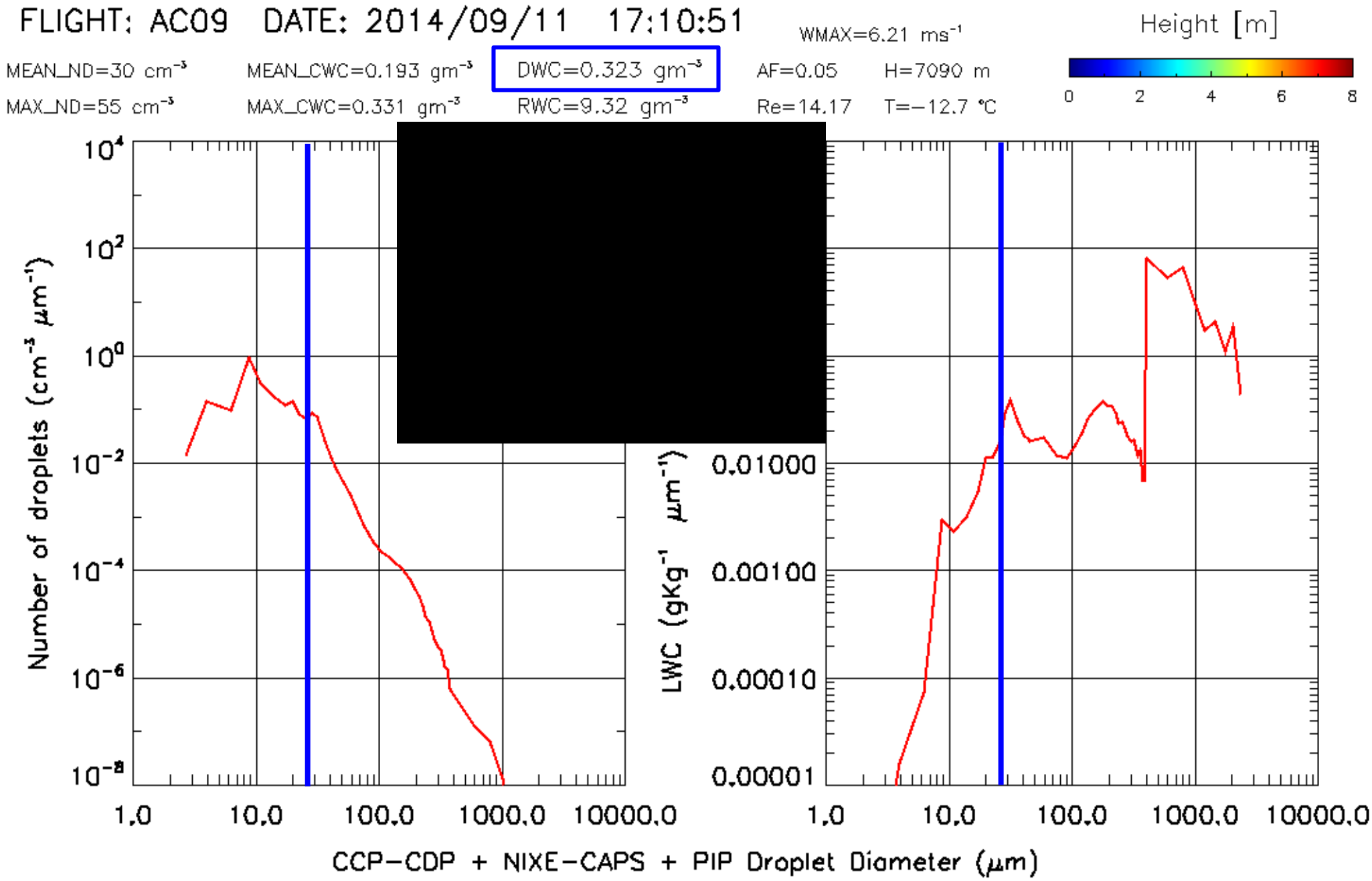

FLIGHT: AC09 DATE: 2014/09/11 16:40:55
WMAX=6.05 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=232 cm⁻³
MEAN_CWC=1.960 gm⁻³
DWC=0.006 gm⁻³
AF=0.61
H=4146 m
MAX_ND=347 cm⁻³
MAX_CWC=3.092 gm⁻³
RWC=0.00 gm⁻³
Re=13.29
T=2.0 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

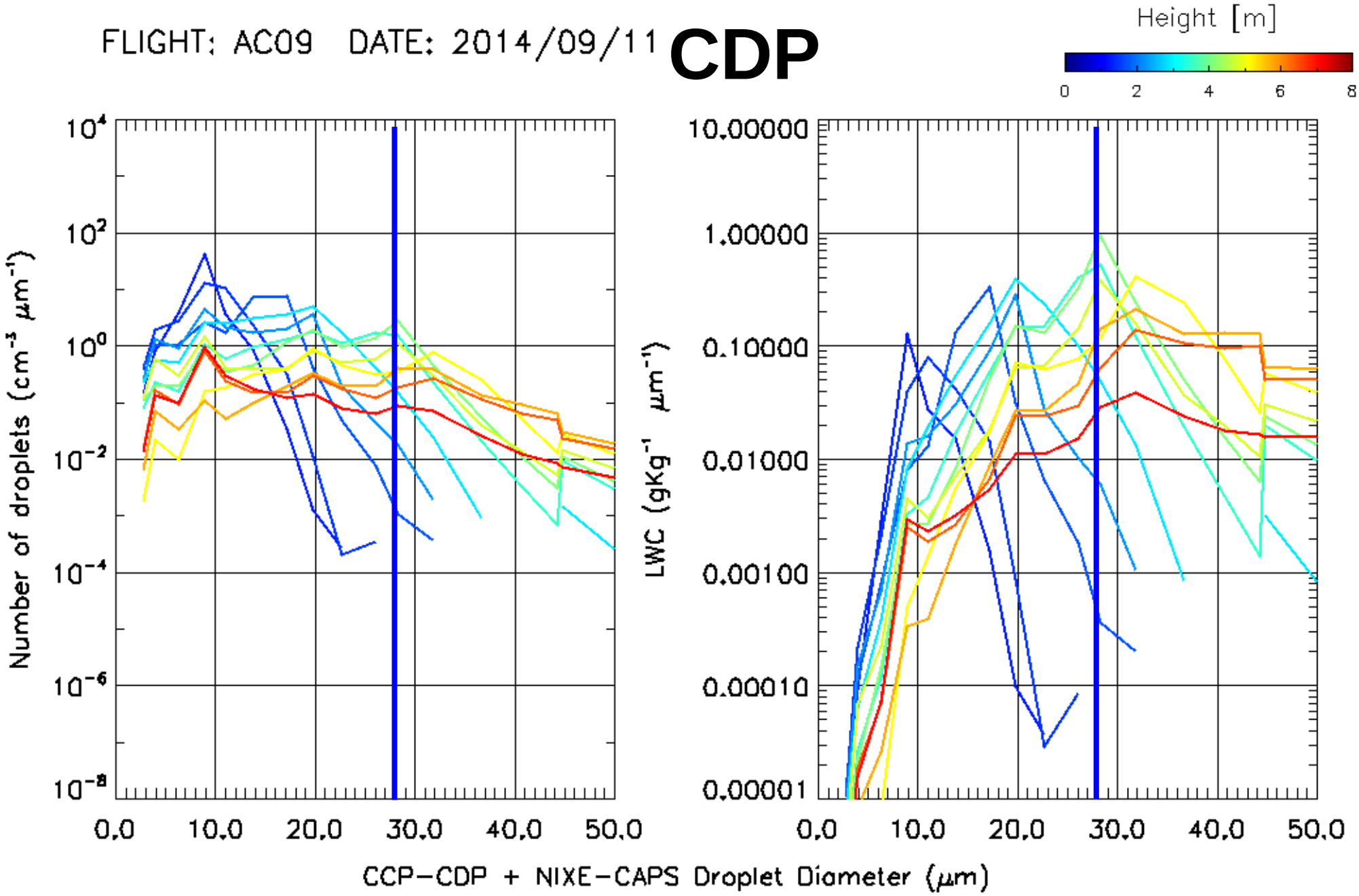

FLIGHT: AC09 DATE: 2014/09/11 16:44:32
WMAX=0.10 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=121 cm⁻³
MEAN_CWC=0.946 gm⁻³
DWC=0.055 gm⁻³
AF=0.23
H=4790 m
MAX_ND=165 cm⁻³
MAX_CWC=1.317 gm⁻³
RWC=0.33 gm⁻³
Re=13.48
T=−1.9 ℃
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
1.0 10.0 100.0 1000.0 10000.0
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

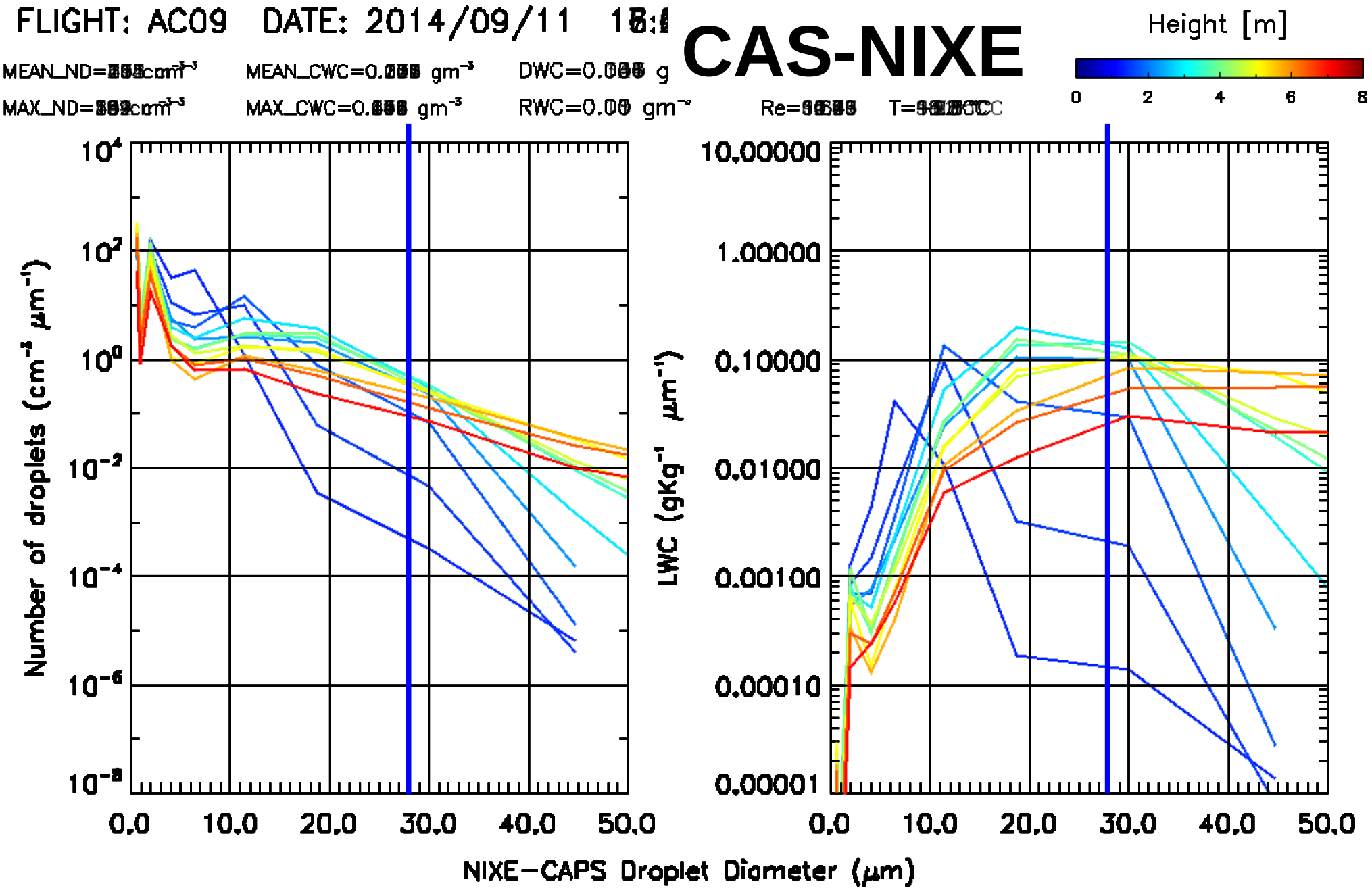

FLIGHT: AC09 DATE: 2014/09/11 17:28:34
WMAX=2.82 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=97 cm⁻³
MEAN_CWC=1.165 gm⁻³
DWC=0.032 gm⁻³
AF=0.29
H=5114 m
MAX_ND=131 cm⁻³
MAX_CWC=1.708 gm⁻³
RWC=1.61 gm⁻³
Re=15.18
T=−2.6 ℃
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
0.01000
0.00100
0.00010
0.00001
1.0 10.0 100.0 1000.0 10000.0
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

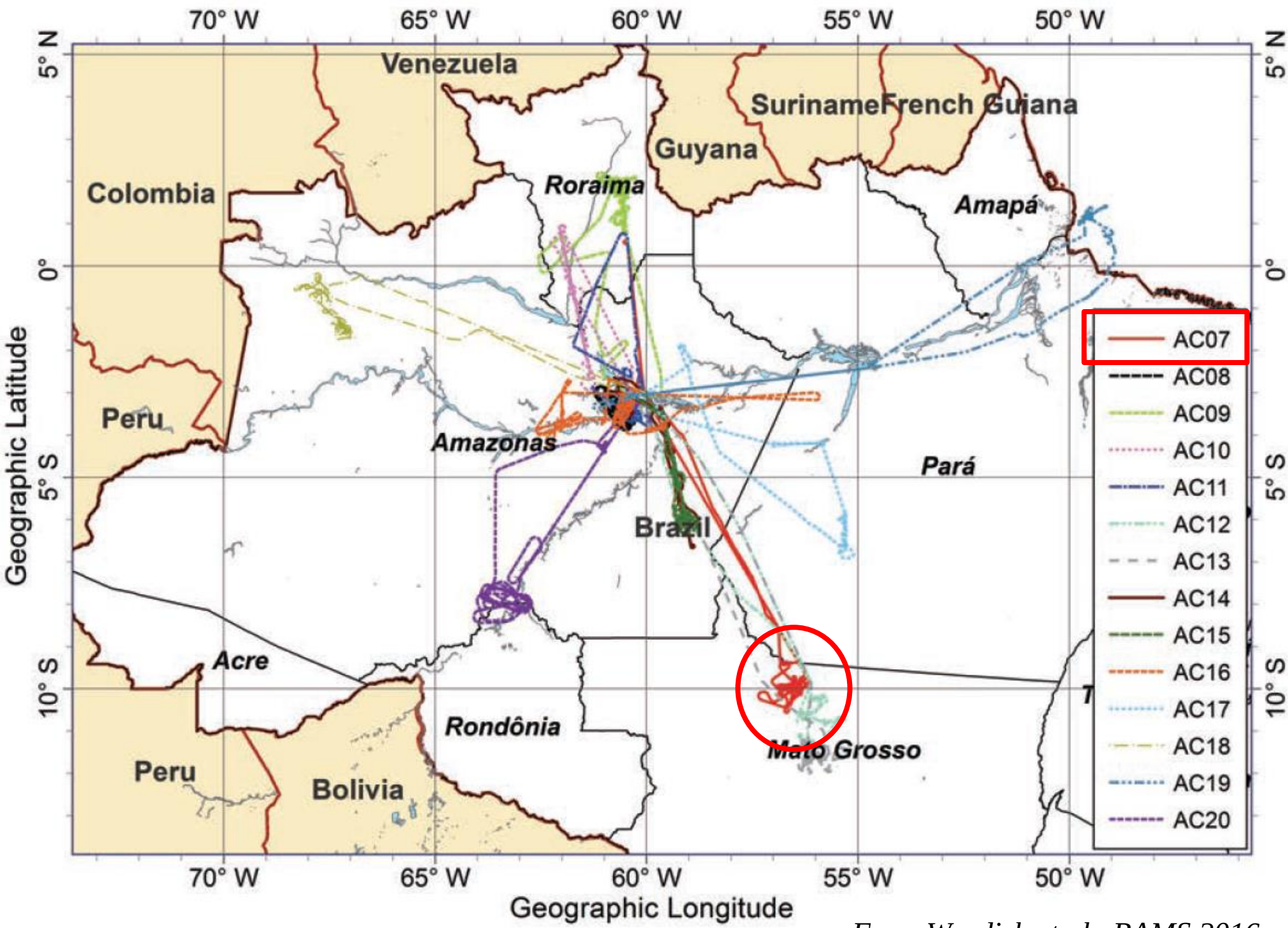

FLIGHT: AC09 DATE: 2014/09/11 17:22:36
WMAX=7.70 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=59 cm⁻³
MEAN_CWC=0.917 gm⁻³
DWC=0.079 gm⁻³
AF=0.18
H=5776 m
MAX_ND=83 cm⁻³
MAX_CWC=1.145 gm⁻³
RWC=3.21 gm⁻³
Re=16.51
T=−6.2 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
0.01000
0.00100
0.00010
0.00001
1.0 10.0 100.0 1000.0 10000.0
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)


FLIGHT: AC09 DATE: 2014/09/11 17:18:52
WMAX=5.66 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=51 cm⁻³
MEAN_CWC=0.646 gm⁻³
DWC=0.111 gm⁻³
AF=0.14
H=6424 m
MAX_ND=78 cm⁻³
MAX_CWC=0.936 gm⁻³
RWC=1.12 gm⁻³
Re=16.36
T=−9.6 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)


FLIGHT: AC09 DATE: 2014/09/11 17:10:51
WMAX=6.21 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=30 cm⁻³
MEAN_CWC=0.193 gm⁻³
DWC=0.323 gm⁻³
AF=0.05
H=7090 m
MAX_ND=55 cm⁻³
MAX_CWC=0.331 gm⁻³
RWC=9.32 gm⁻³
Re=14.17
T=−12.7 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
0.01000
0.00100
0.00010
0.00001
1.0 10.0 100.0 1000.0 10000.0
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

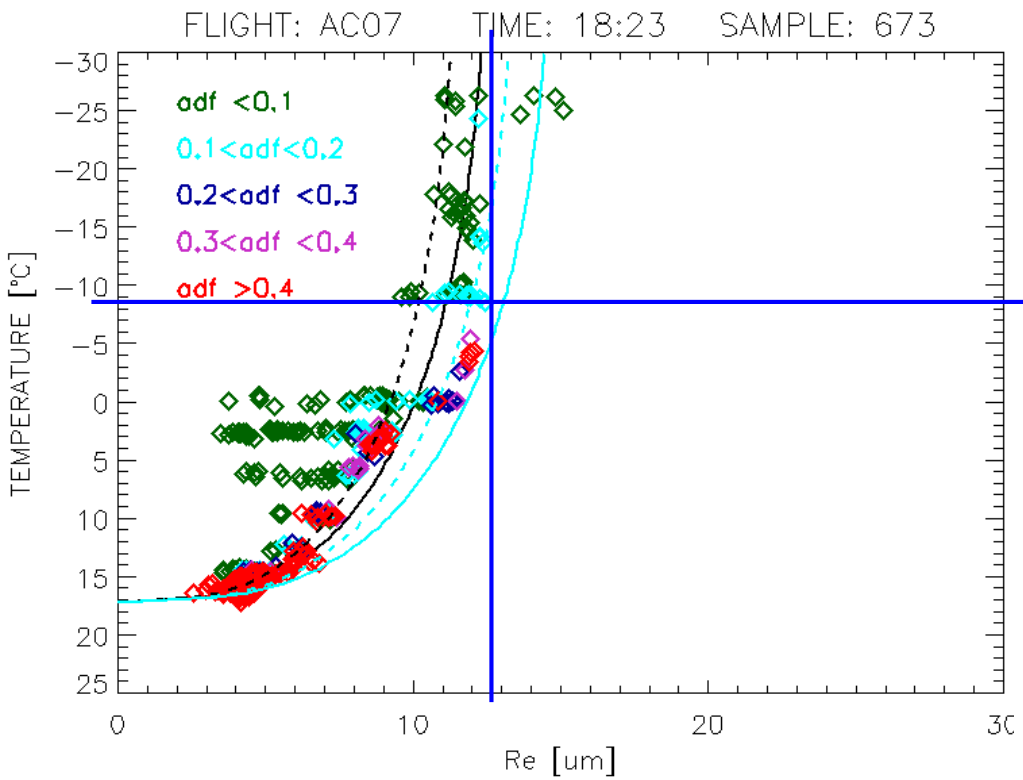

FLIGHT: AC09 DATE: 2014/09/11
CDP
Height [m]
0
2
4
6
8
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS Droplet Diameter (μm)
0.0
10.0
20.0
30.0
40.0
50.0

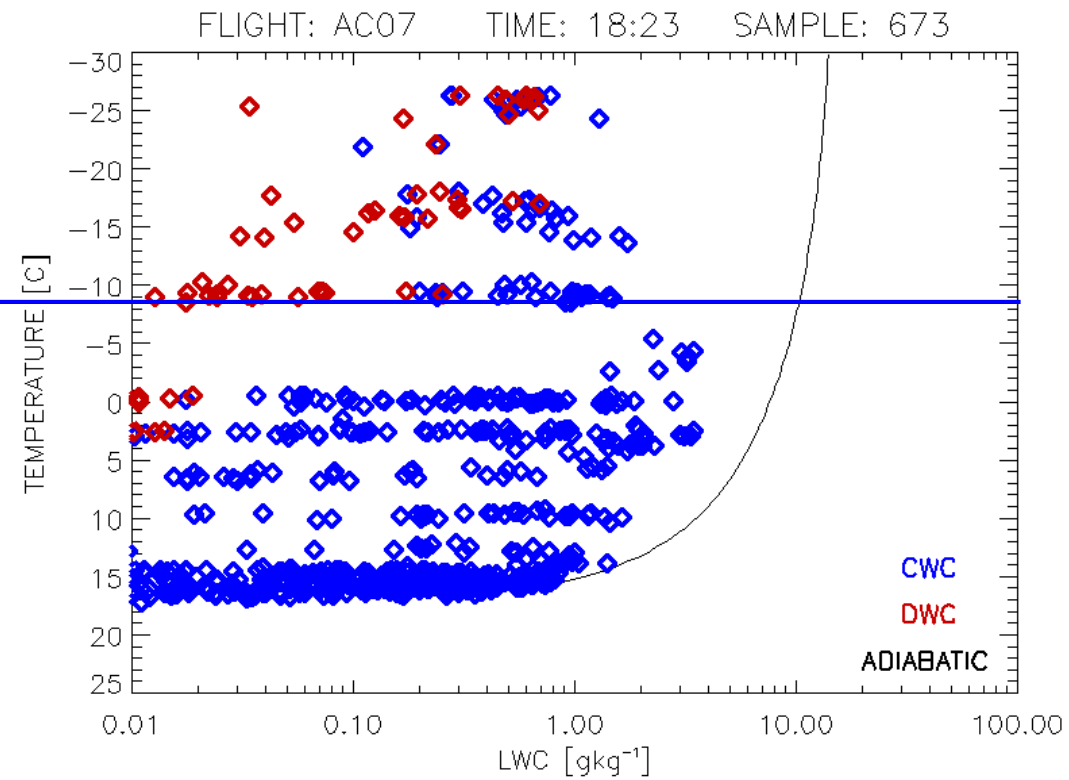

FLIGHT: AC09 DATE: 2014/09/11
CAS-NIXE
Height [m]
0
2
4
6
8
MEAN_ND=
MEAN_CWC=
DWC=
MAX_ND=
MAX_CWC=
RWC=
Re=
T=
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
NIXE-CAPS Droplet Diameter (μm)
0.0
10.0
20.0
30.0
40.0
50.0
10.00000
1.00000
0.10000
0.01000
0.00100
0.00010
0.00001

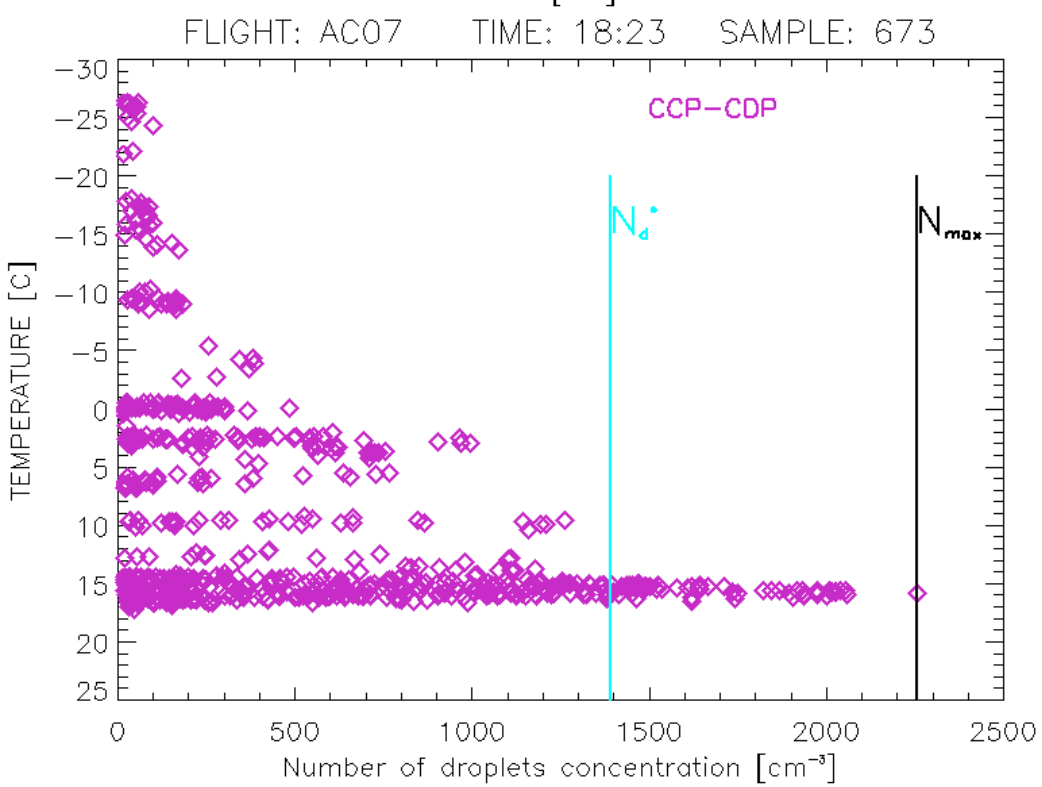


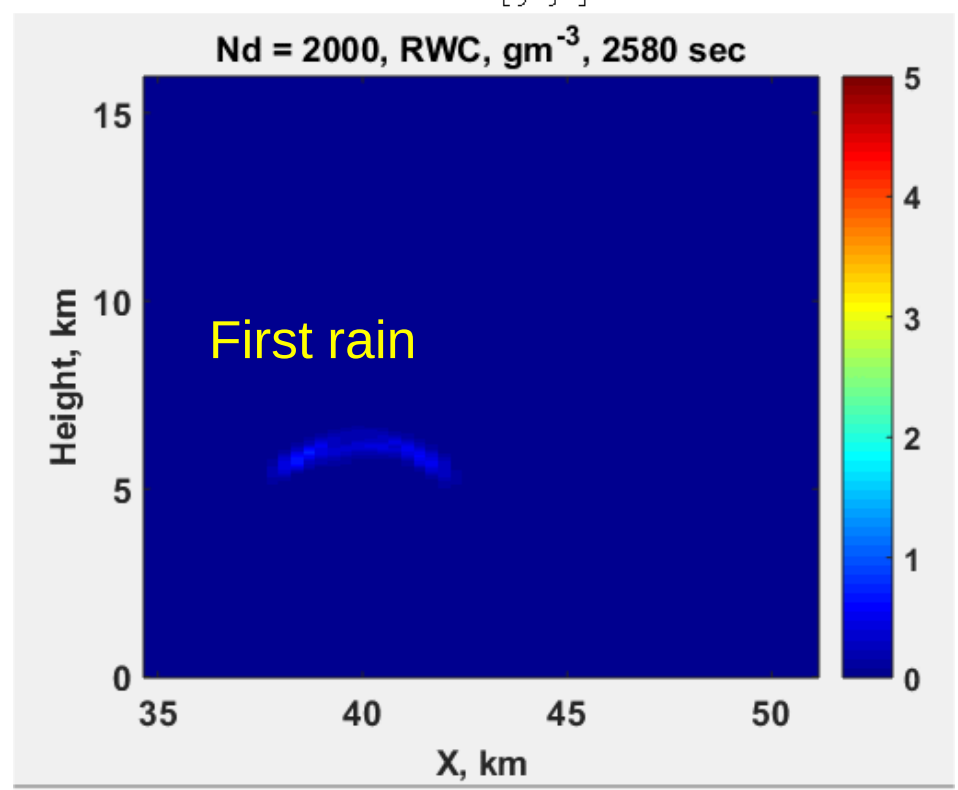
From Wendish et al., BAMS 2016

FIG. 6. Flight tracks for all scientific missions (AC07 to AC20).


FLIGHT: AC07 TIME: 18:23 SAMPLE: 673
adf <0.1
0.1<adf<0.2
0.2<adf <0.3
0.3<adf <0.4
adf >0.4
TEMPERATURE [°C]
Re [um]


FLIGHT: AC07 TIME: 18:23 SAMPLE: 673
TEMPERATURE [C]
LWC [gkg⁻¹]
CWC
DWC
ADIABATIC


FLIGHT: AC07 TIME: 18:23 SAMPLE: 673
CCP−CDP
Nd*
Nmax
TEMPERATURE [C]
Number of droplets concentration [cm⁻³]


Nd = 2000, RWC, gm-3, 2580 sec
First rain
Height, km
X, km

FLIGHT: AC07 DATE: 2014/09/06 18:14:11

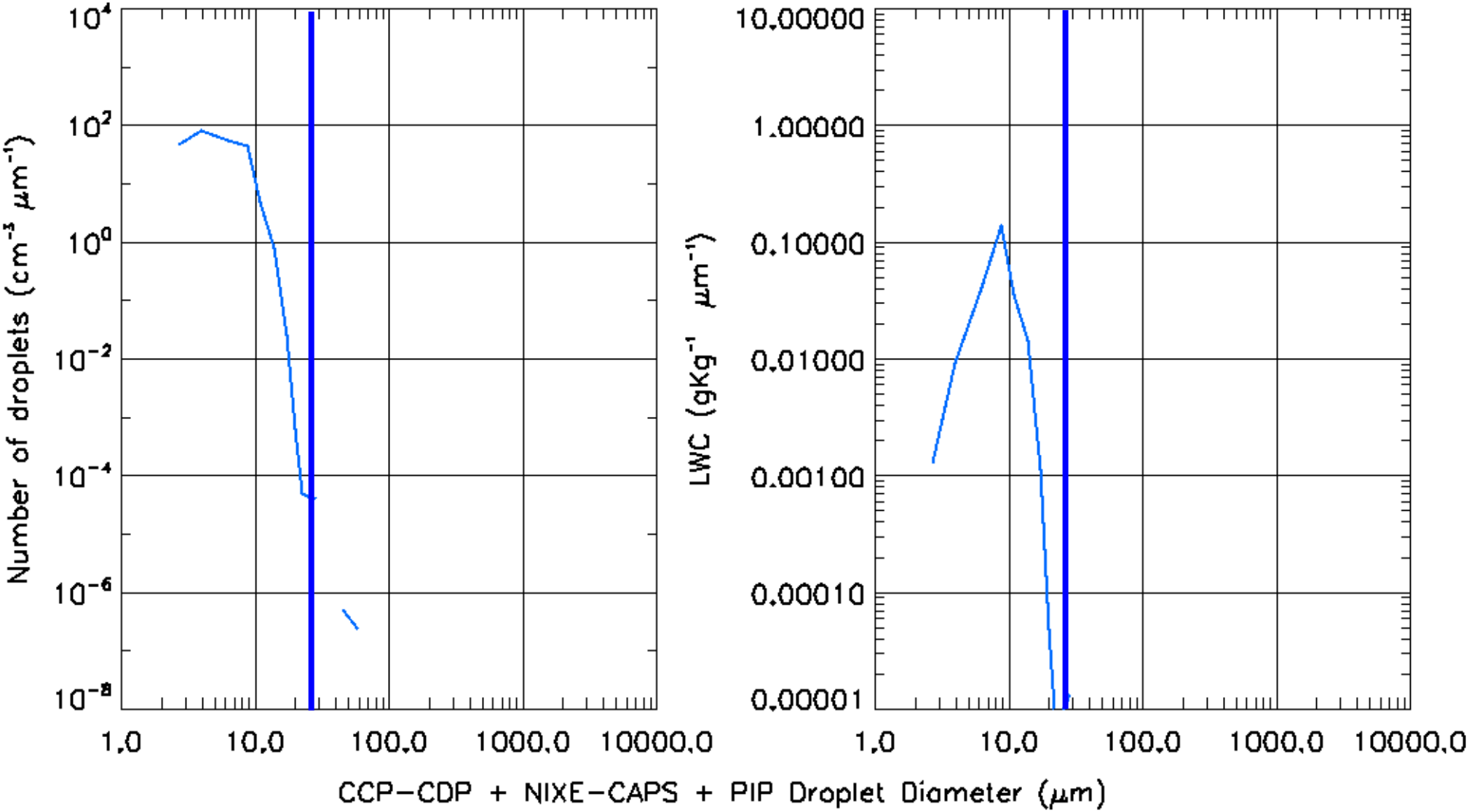
WMAX=6.15 ms^{-1}

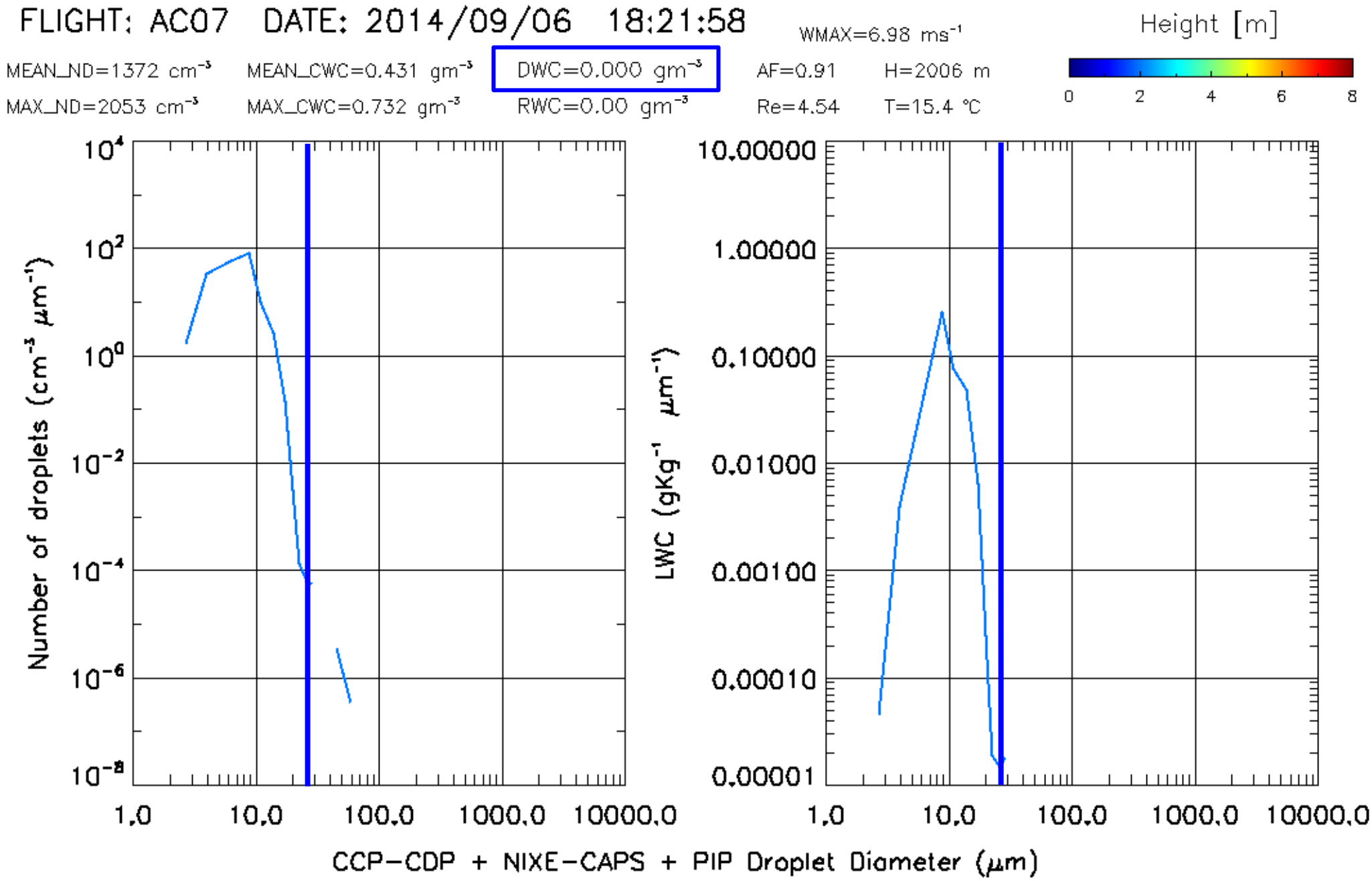
Height [m]

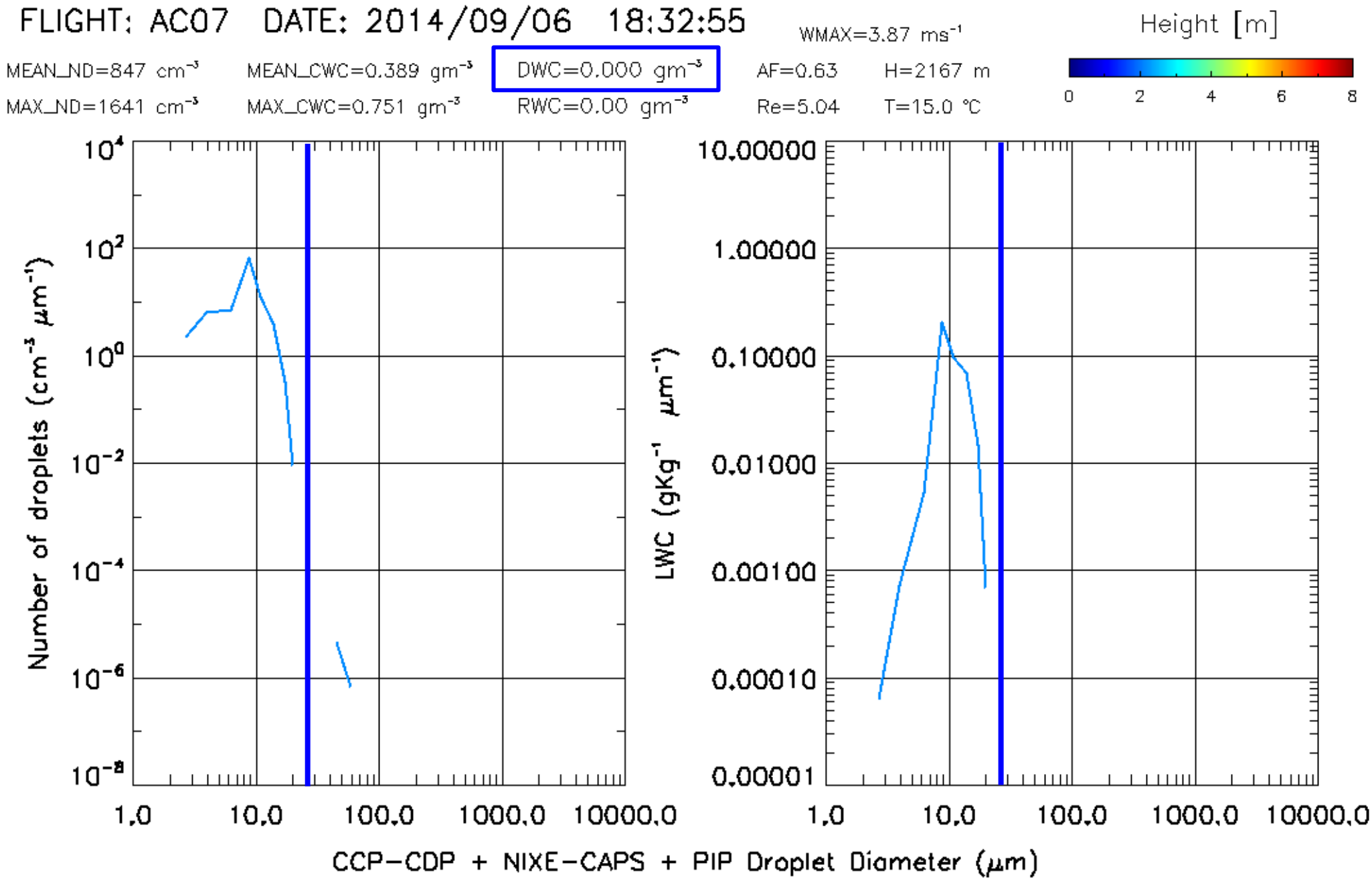
0 2 4 6 8

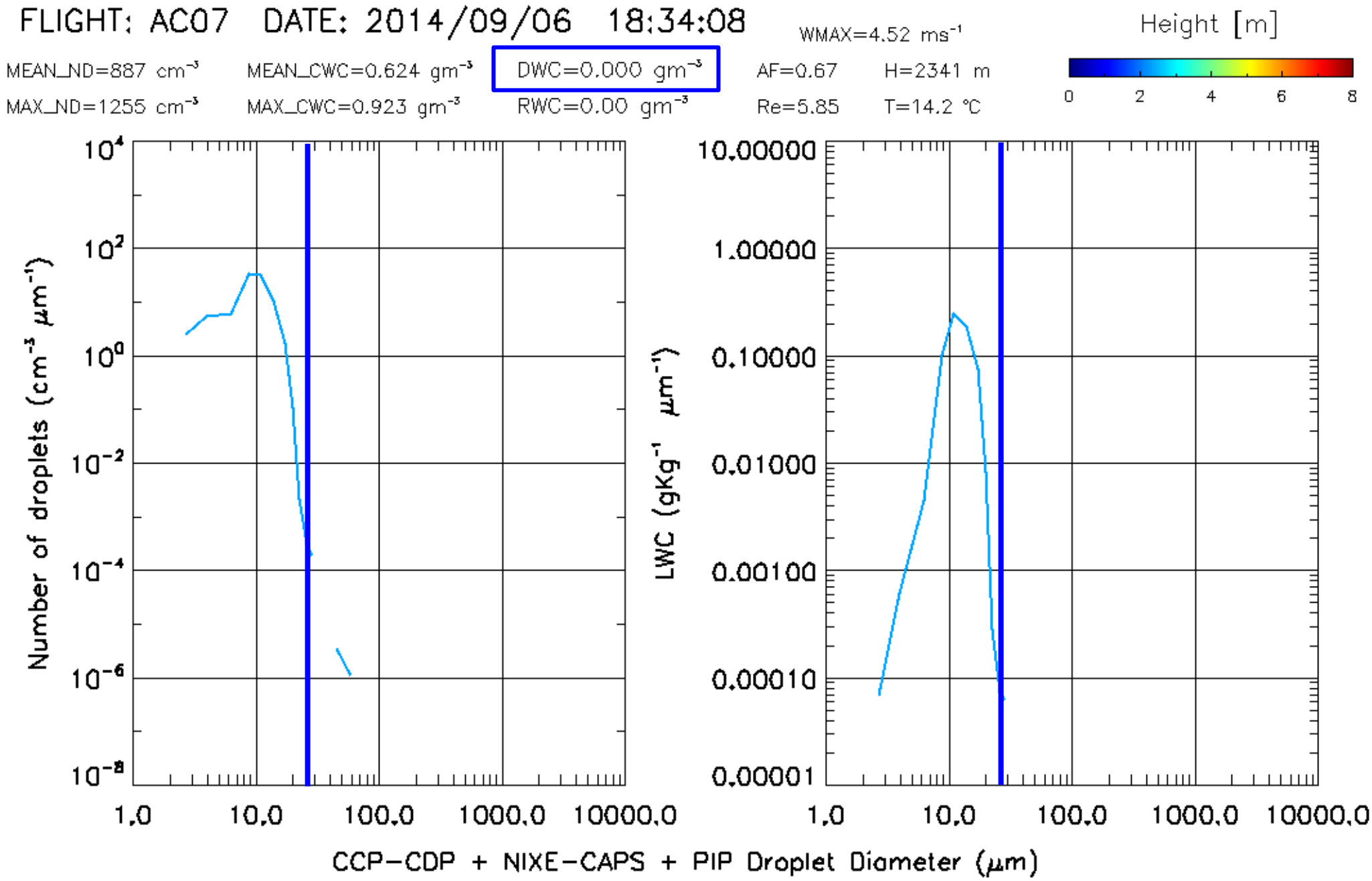
MEAN_ND=1239 cm^{-3} MEAN_CWC=0.242 gm^{-3} DWC=0.000 gm^{-3} AF=0.72 H=1908 m

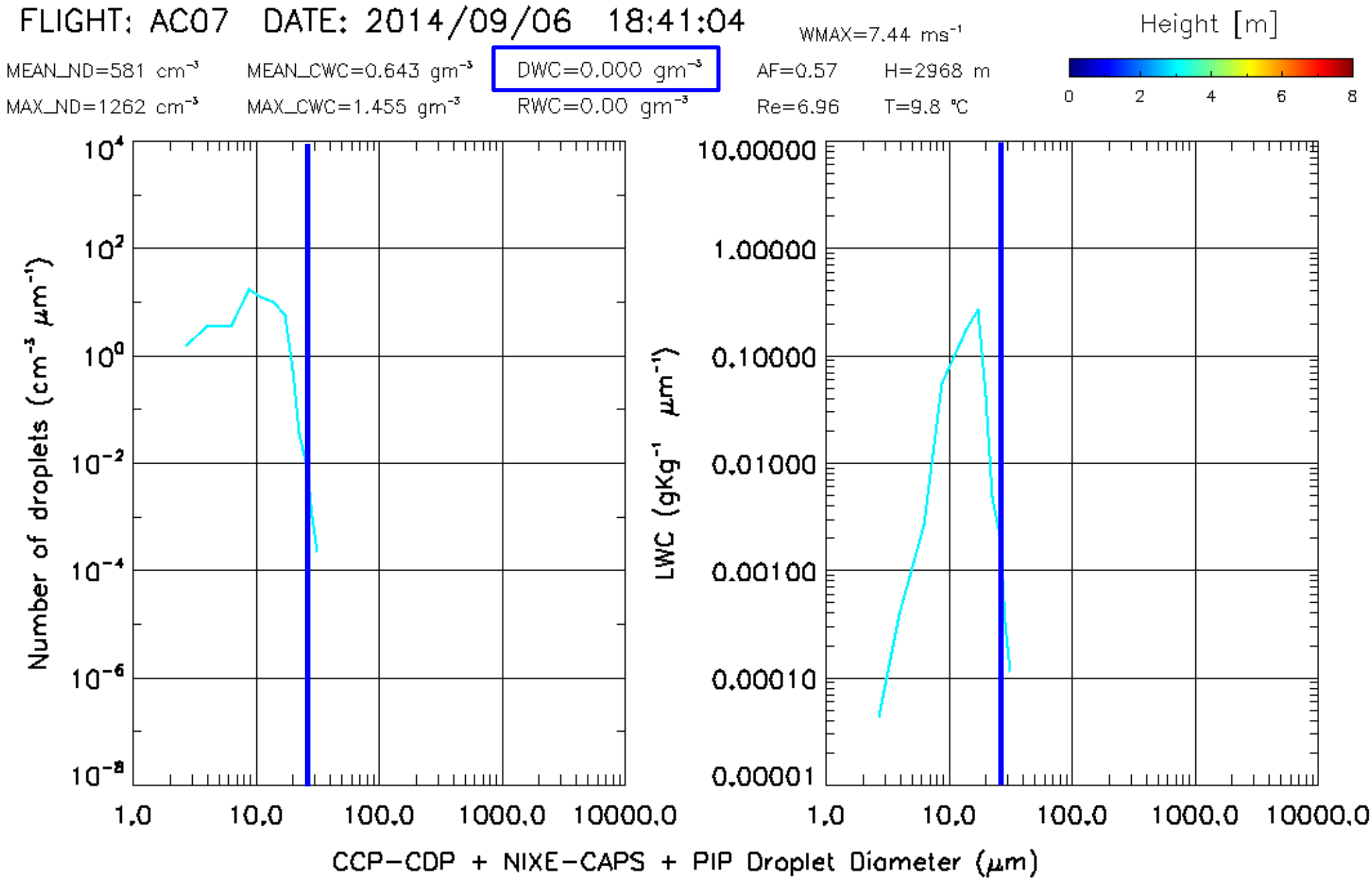
MAX_ND=2254 cm^{-3} MAX_CWC=0.422 gm^{-3} RWC=0.00 gm^{-3} Re=4.09 T=15.8 °C




FLIGHT: AC07 DATE: 2014/09/06 18:21:58
WMAX=6.98 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=1372 cm⁻³
MEAN_CWC=0.431 gm⁻³
DWC=0.000 gm⁻³
AF=0.91
H=2006 m
MAX_ND=2053 cm⁻³
MAX_CWC=0.732 gm⁻³
RWC=0.00 gm⁻³
Re=4.54
T=15.4 °C
Number of droplets (cm⁻³ µm⁻¹)
LWC (gKg⁻¹ µm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (µm)


FLIGHT: AC07 DATE: 2014/09/06 18:32:55
WMAX=3.87 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=847 cm⁻³
MEAN_CWC=0.389 gm⁻³
DWC=0.000 gm⁻³
AF=0.63
H=2167 m
MAX_ND=1641 cm⁻³
MAX_CWC=0.751 gm⁻³
RWC=0.00 gm⁻³
Re=5.04
T=15.0 °C
Number of droplets (cm⁻³ µm⁻¹)
LWC (gKg⁻¹ µm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (µm)


FLIGHT: AC07 DATE: 2014/09/06 18:34:08
WMAX=4.52 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=887 cm⁻³
MEAN_CWC=0.624 gm⁻³
DWC=0.000 gm⁻³
AF=0.67
H=2341 m
MAX_ND=1255 cm⁻³
MAX_CWC=0.923 gm⁻³
RWC=0.00 gm⁻³
Re=5.85
T=14.2 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)


FLIGHT: AC07 DATE: 2014/09/06 18:41:04
WMAX=7.44 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=581 cm⁻³
MEAN_CWC=0.643 gm⁻³
DWC=0.000 gm⁻³
AF=0.57
H=2968 m
MAX_ND=1262 cm⁻³
MAX_CWC=1.455 gm⁻³
RWC=0.00 gm⁻³
Re=6.96
T=9.8 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP-CDP + NIXE-CAPS + PIP Droplet Diameter (μm)

FLIGHT: AC07 DATE: 2014/09/06 18:48:49

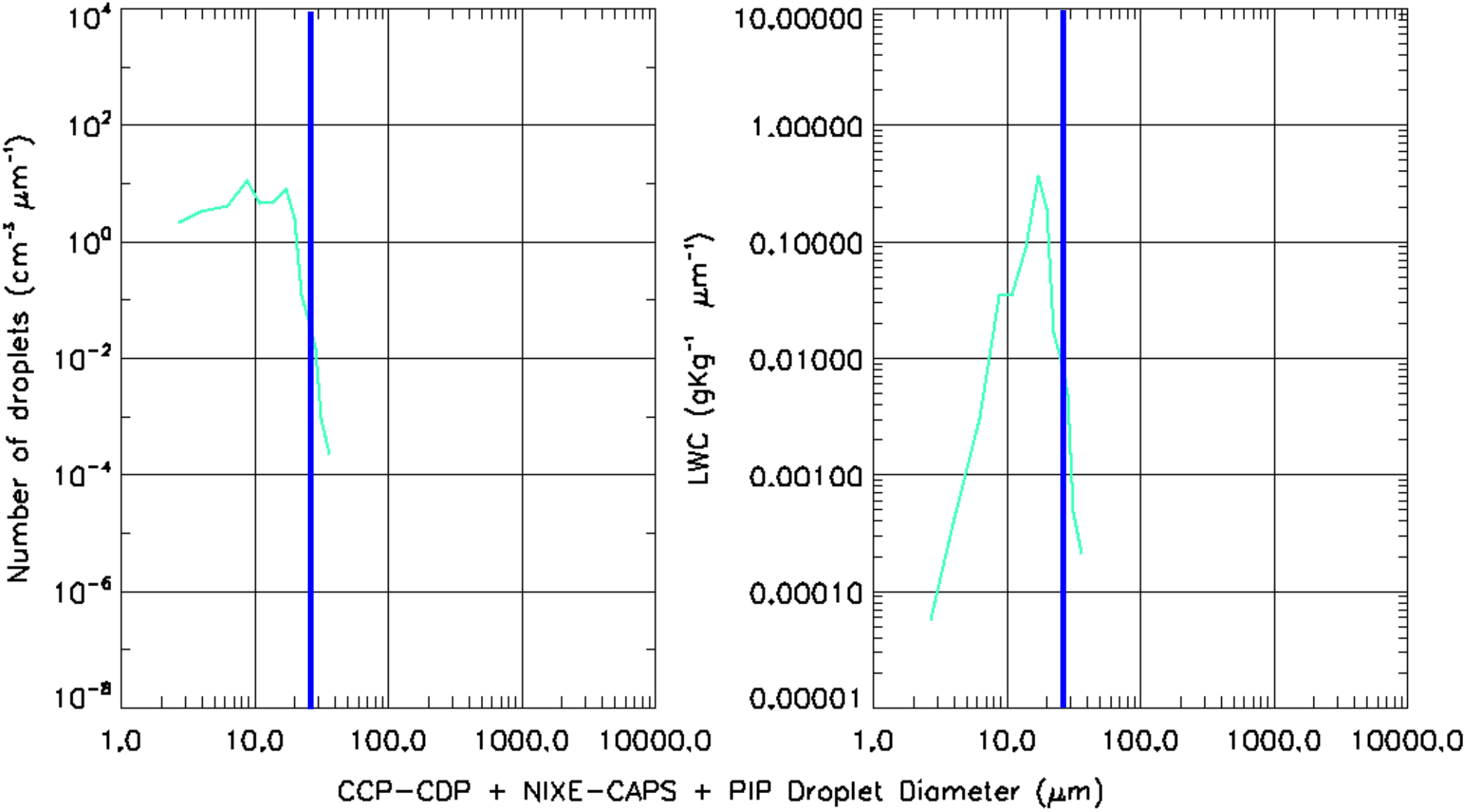
WMAX=0.87 ms^{-1}

Height [m]

0 2 4 6 8

MEAN_ND=453 cm^{-3} MEAN_CWC=0.752 gm^{-3} DWC=0.000 gm^{-3} AF=0.37 H=3612 m

MAX_ND=764 cm^{-3} MAX_CWC=1.178 gm^{-3} RWC=0.00 gm^{-3} Re=8.06 T=5.7 °C



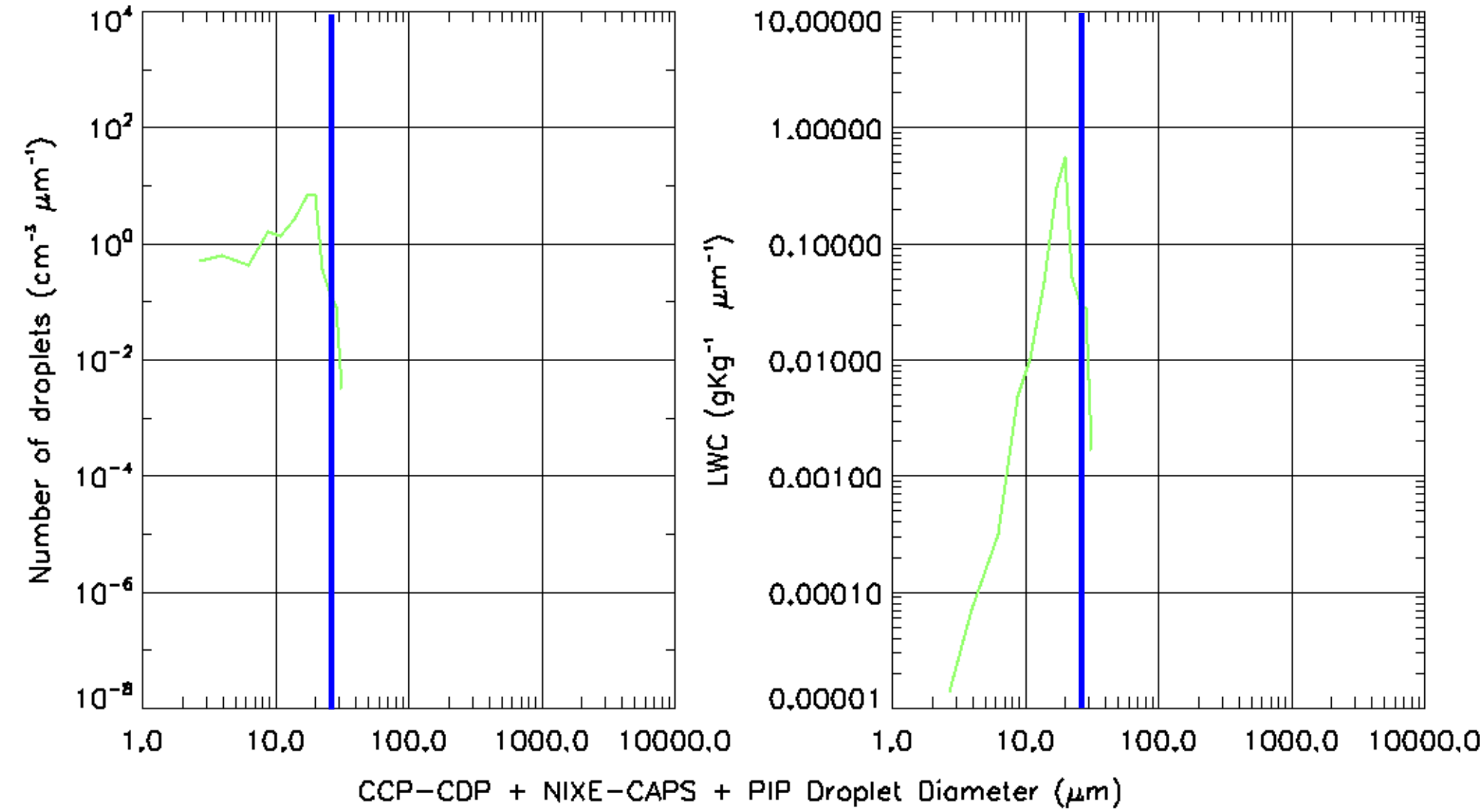
FLIGHT: AC07 DATE: 2014/09/06 18:59:51

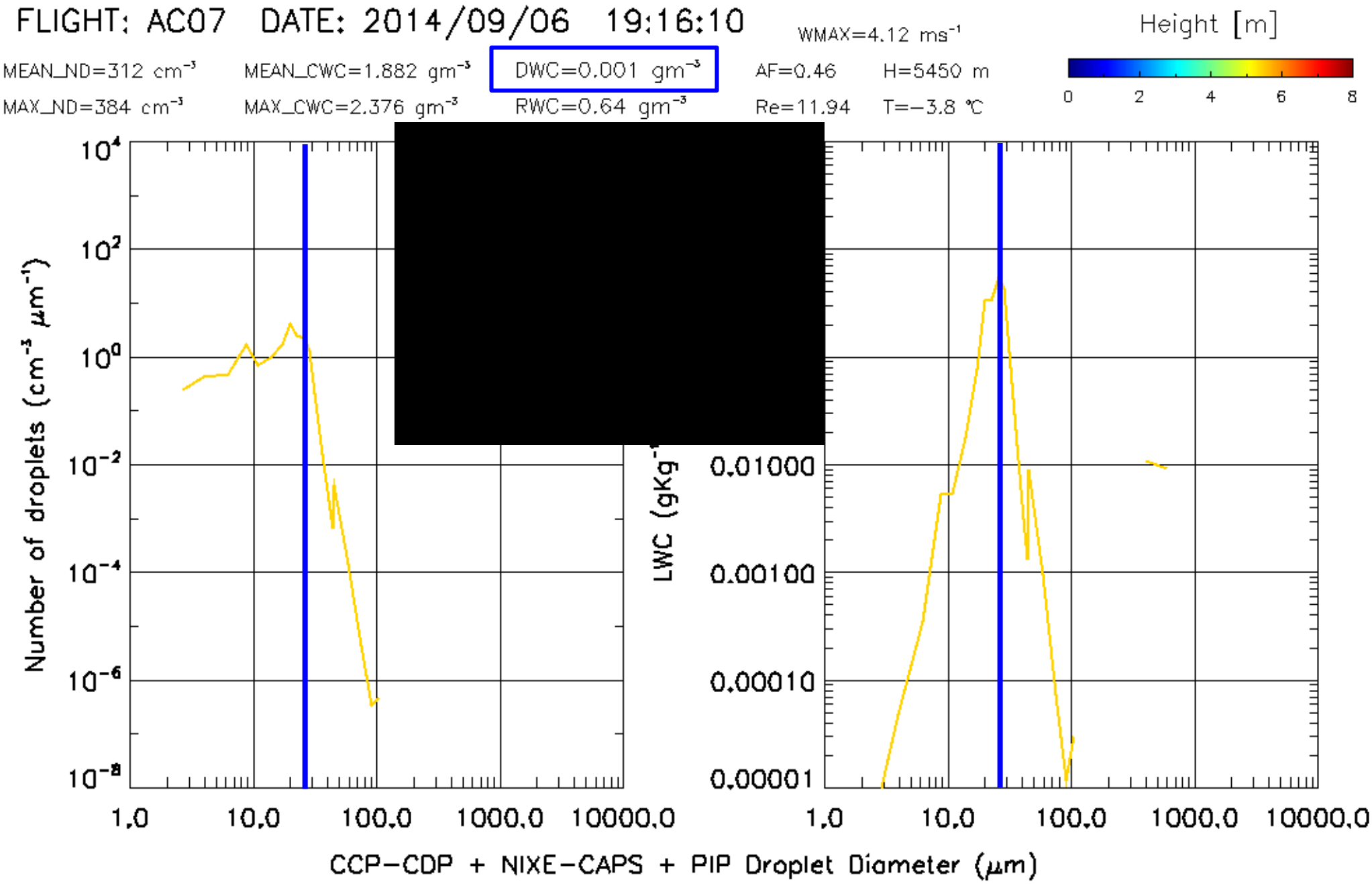
WMAX=0.15 ms^{-1}

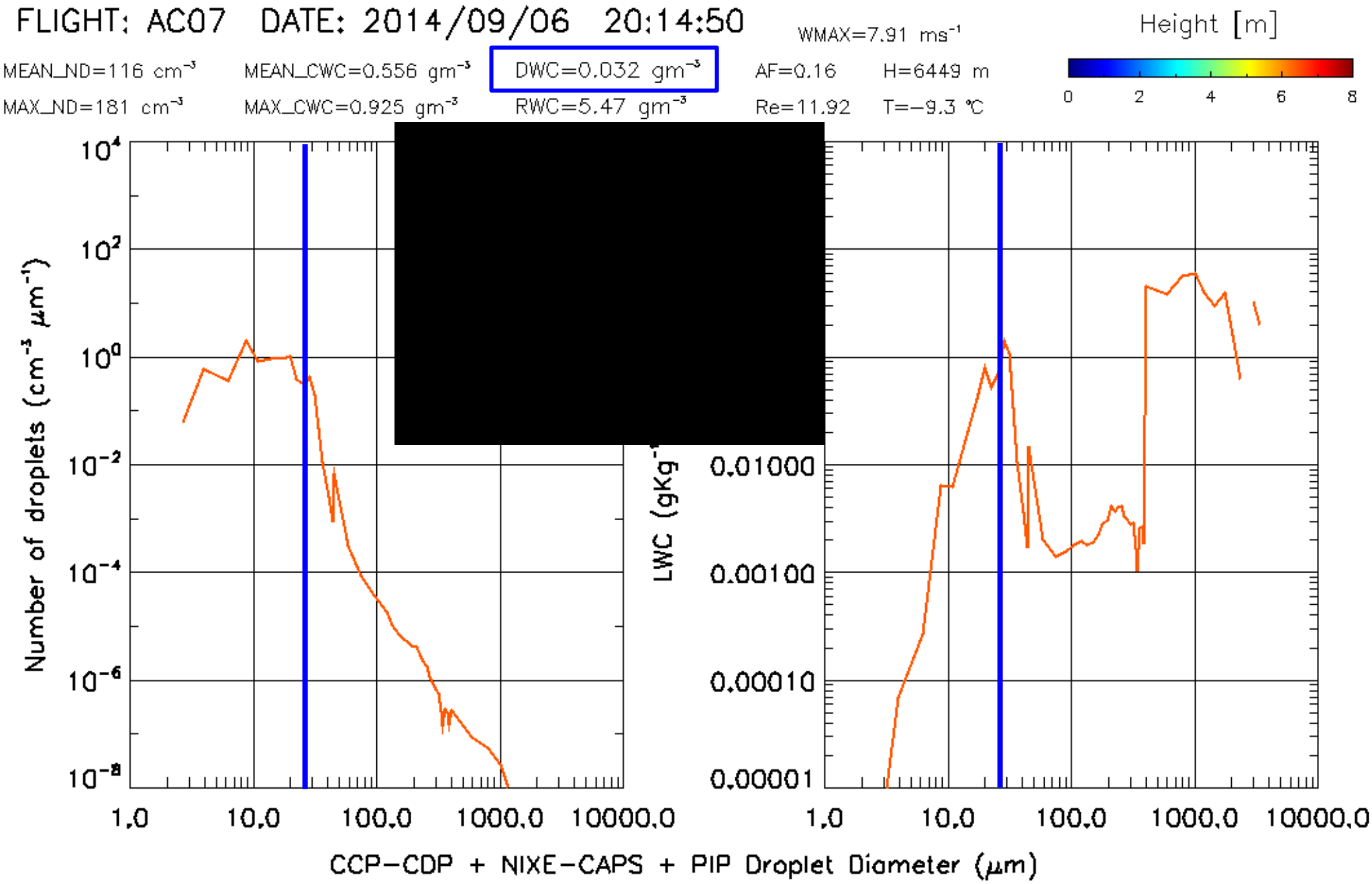
Height [m]

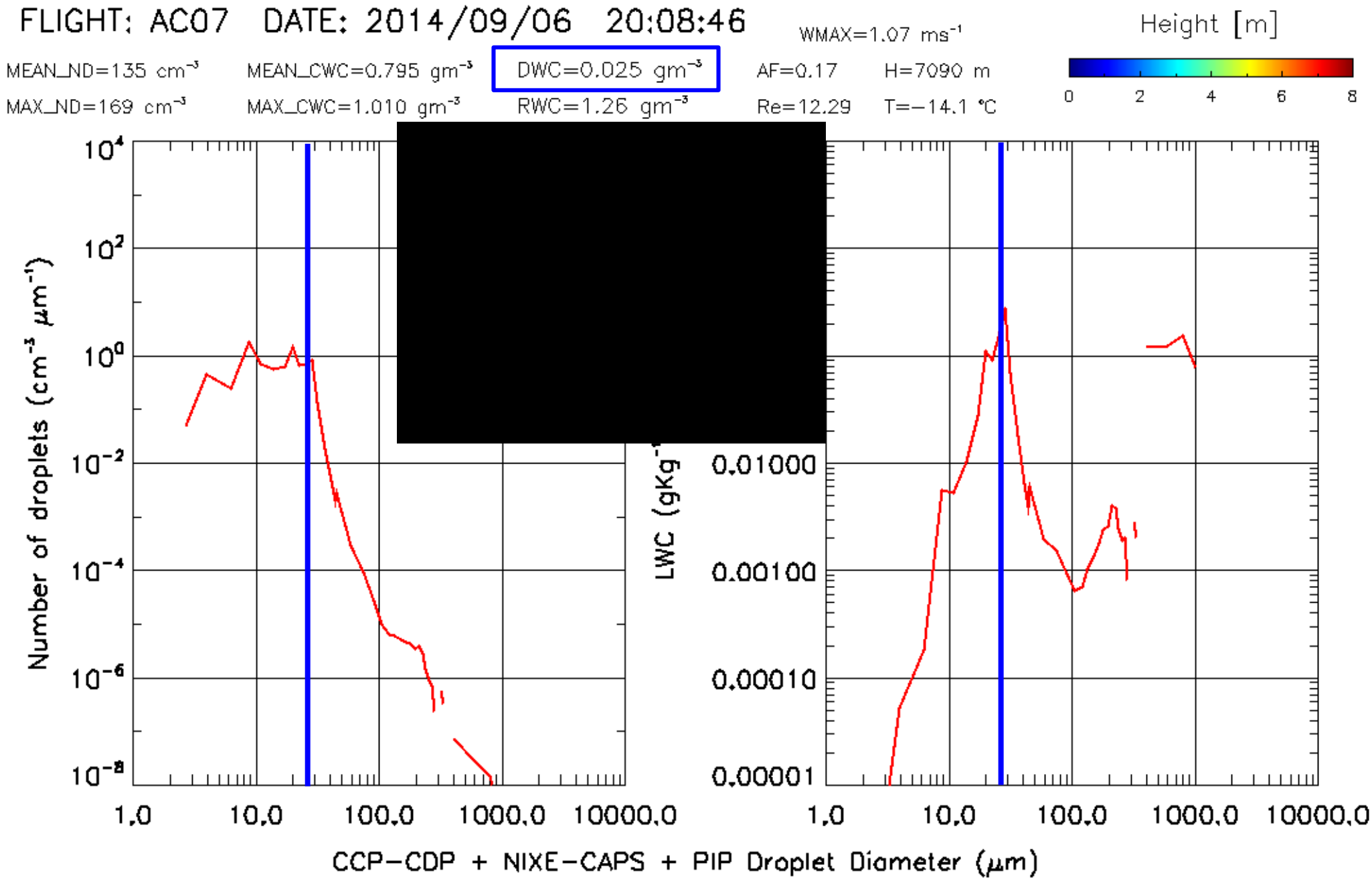
MEAN_ND=340 cm^{-3} MEAN_CWC=1.026 gm^{-3} DWC=0.000 gm^{-3} AF=0.40 H=4255 m

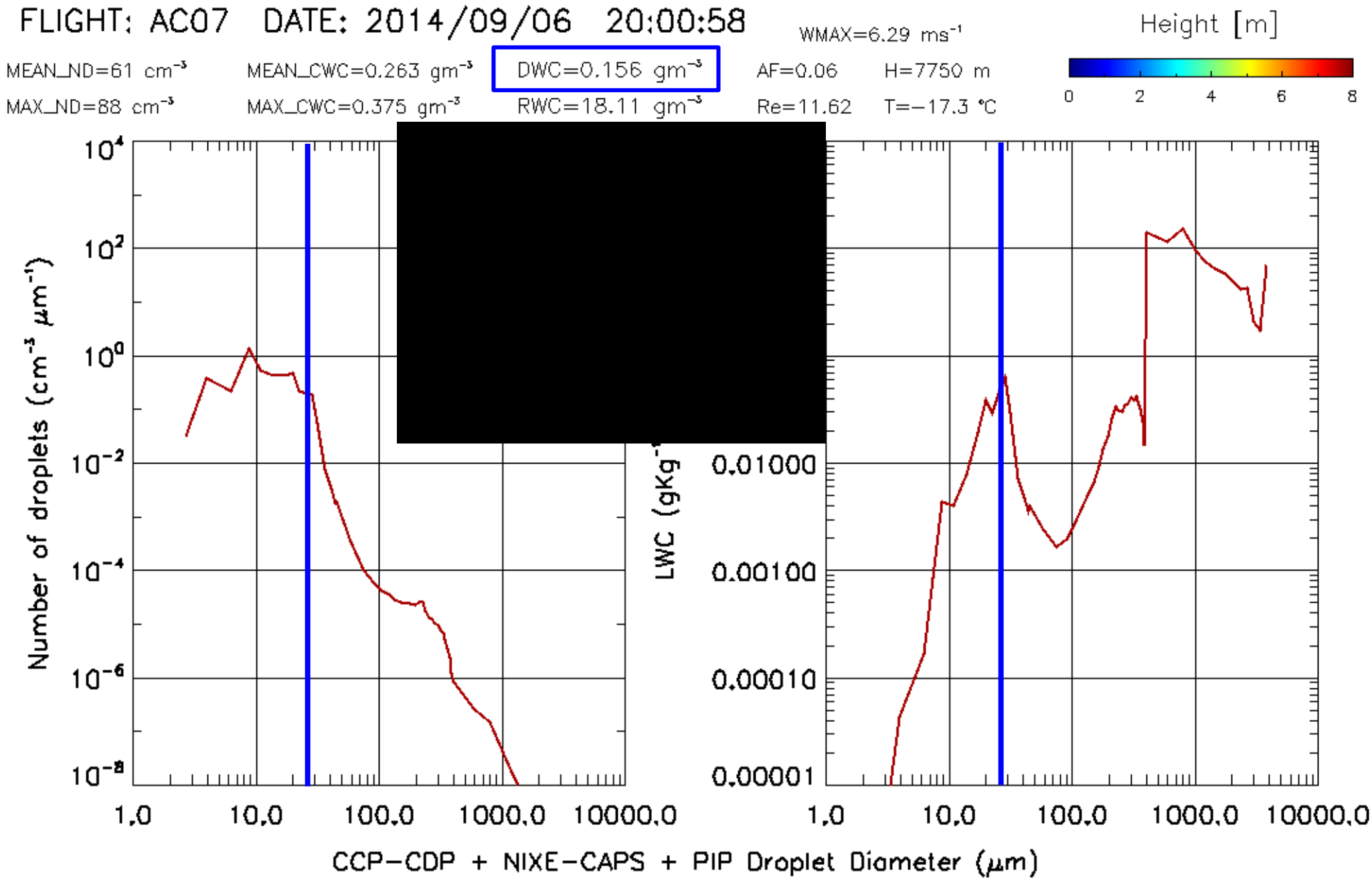
MAX_ND=539 cm^{-3} MAX_CWC=1.602 gm^{-3} RWC=0.08 gm^{-3} Re=9.31 T=2.7 °C

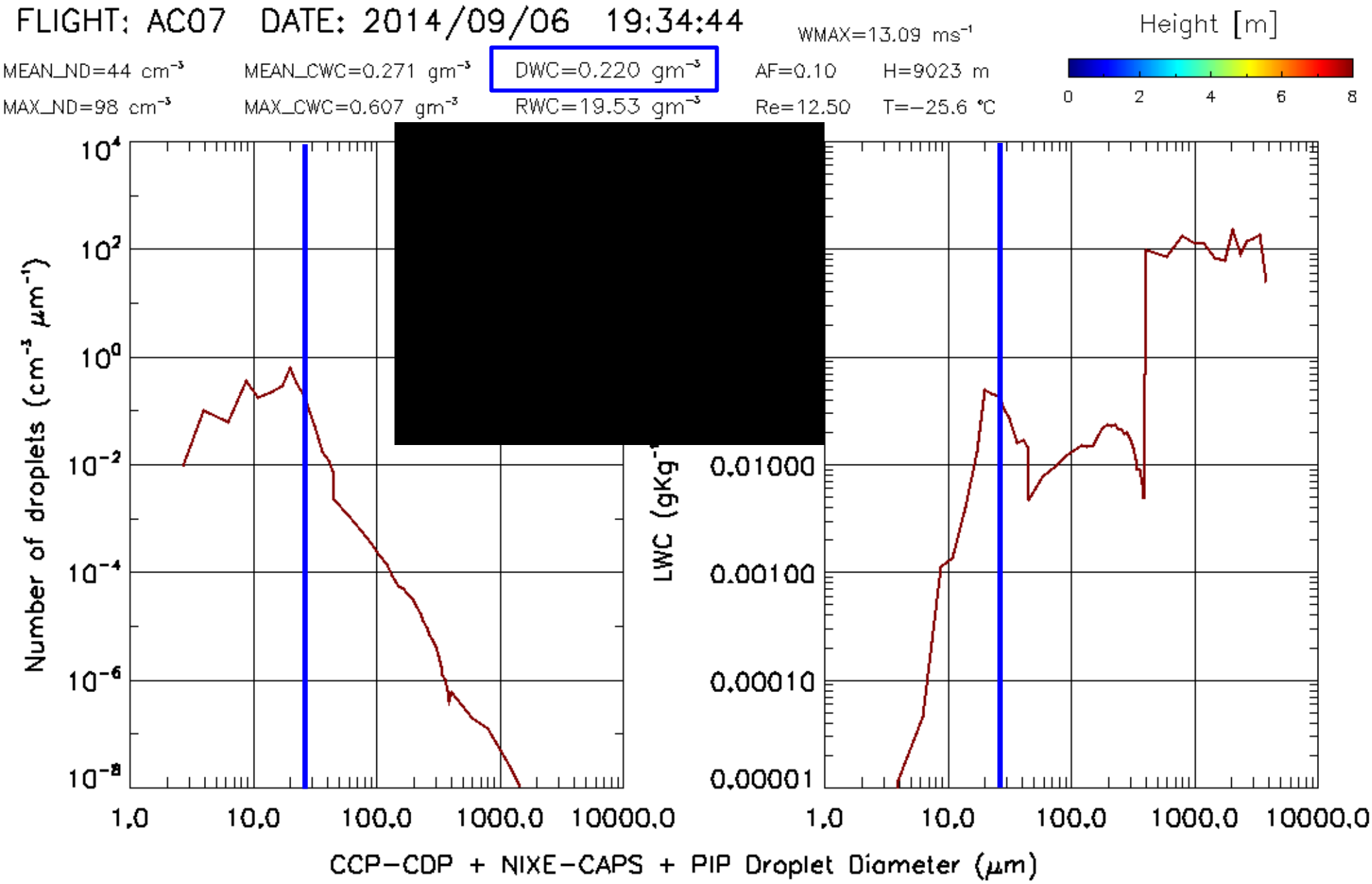


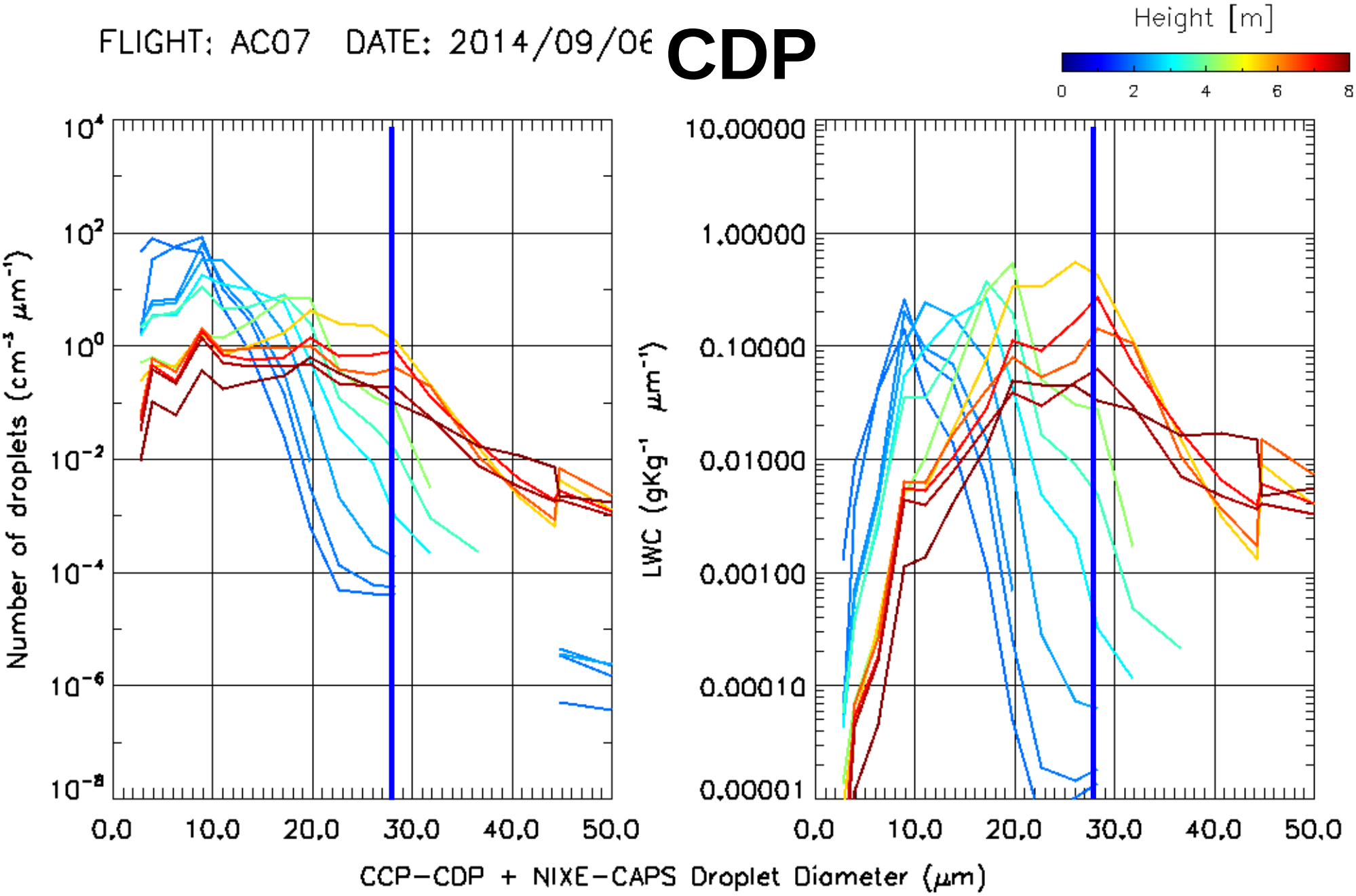

FLIGHT: AC07 DATE: 2014/09/06 19:16:10
WMAX=4.12 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=312 cm⁻³
MEAN_CWC=1.882 gm⁻³
DWC=0.001 gm⁻³
AF=0.46
H=5450 m
MAX_ND=384 cm⁻³
MAX_CWC=2.376 gm⁻³
RWC=0.64 gm⁻³
Re=11.94
T=−3.8 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹)
0.01000
0.00100
0.00010
0.00001
1.0 10.0 100.0 1000.0 10000.0
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

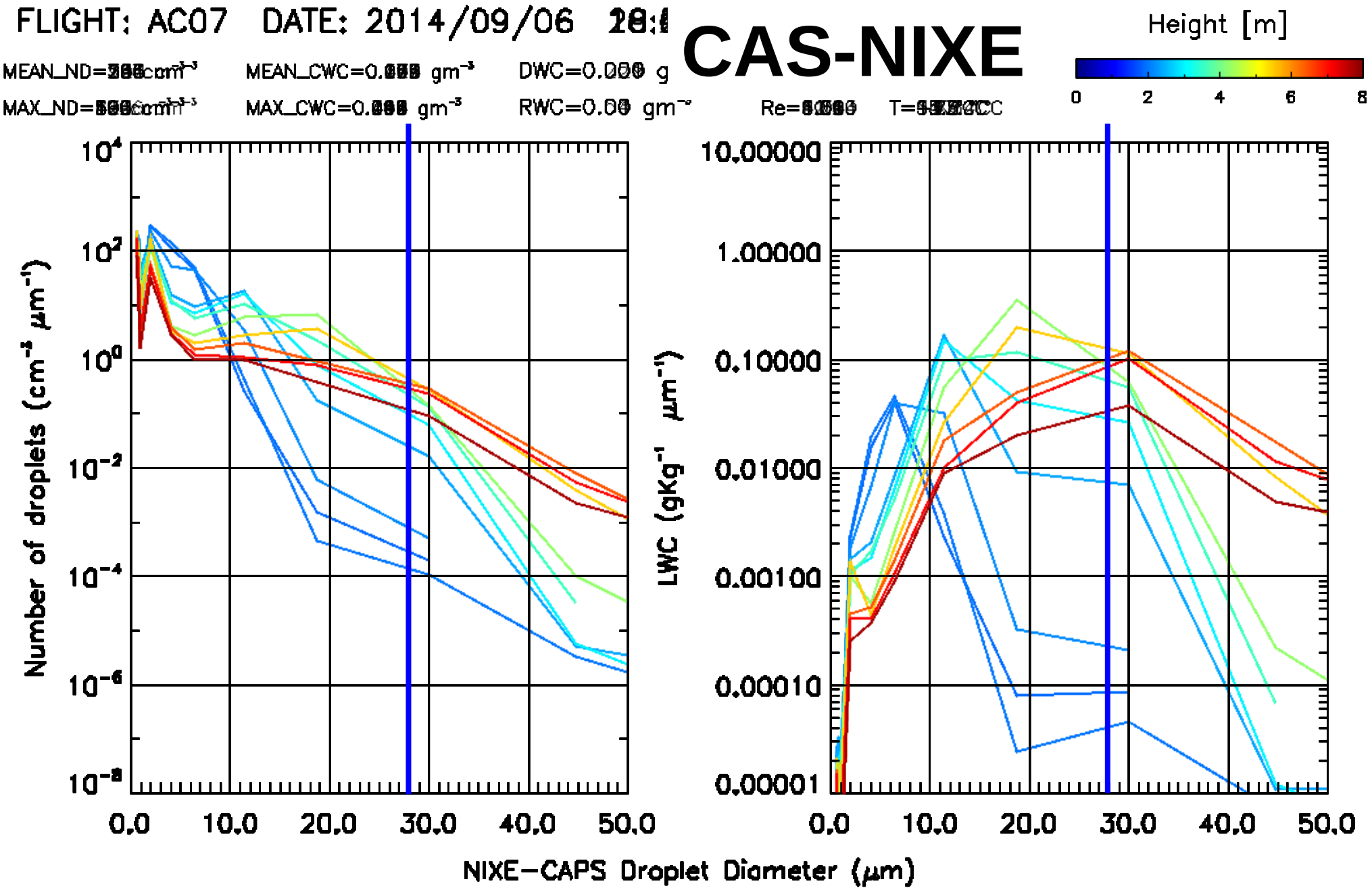

FLIGHT: AC07 DATE: 2014/09/06 20:14:50
WMAX=7.91 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=116 cm⁻³
MEAN_CWC=0.556 gm⁻³
DWC=0.032 gm⁻³
AF=0.16
H=6449 m
MAX_ND=181 cm⁻³
MAX_CWC=0.925 gm⁻³
RWC=5.47 gm⁻³
Re=11.92
T=−9.3 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹)
0.01000
0.00100
0.00010
0.00001
1.0 10.0 100.0 1000.0 10000.0
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

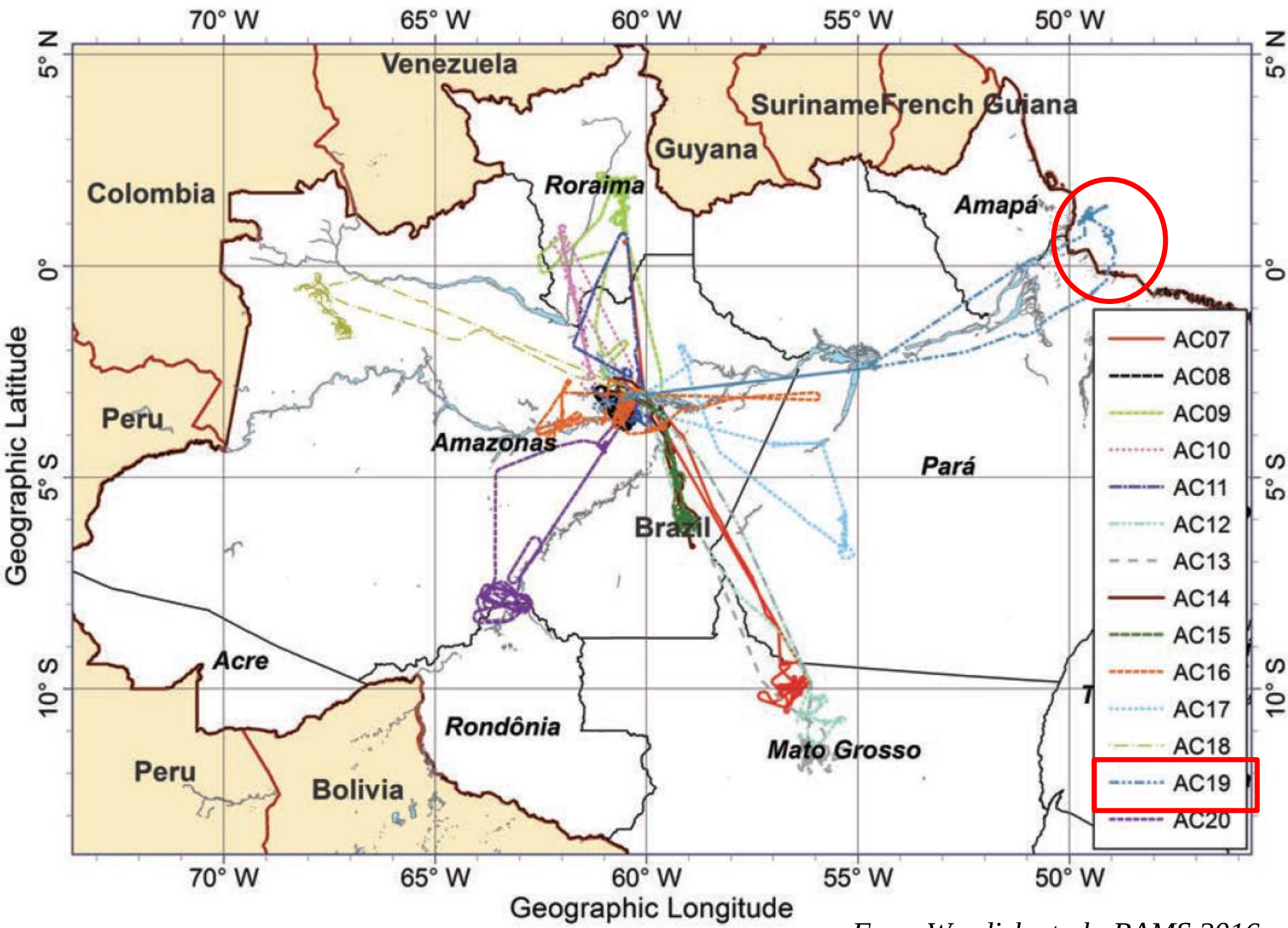

FLIGHT: AC07 DATE: 2014/09/06 20:08:46
WMAX=1.07 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=135 cm⁻³
MEAN_CWC=0.795 gm⁻³
DWC=0.025 gm⁻³
AF=0.17
H=7090 m
MAX_ND=169 cm⁻³
MAX_CWC=1.010 gm⁻³
RWC=1.26 gm⁻³
Re=12.29
T=−14.1 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹)
0.01000
0.00100
0.00010
0.00001
1.0 10.0 100.0 1000.0 10000.0
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)


FLIGHT: AC07 DATE: 2014/09/06 20:00:58
WMAX=6.29 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=61 cm⁻³
MEAN_CWC=0.263 gm⁻³
DWC=0.156 gm⁻³
AF=0.06
H=7750 m
MAX_ND=88 cm⁻³
MAX_CWC=0.375 gm⁻³
RWC=18.11 gm⁻³
Re=11.62
T=−17.3 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹)
0.01000
0.00100
0.00010
0.00001
1.0 10.0 100.0 1000.0 10000.0
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)


FLIGHT: AC07 DATE: 2014/09/06 19:34:44
WMAX=13.09 ms⁻¹
Height [m]
0 2 4 6 8
MEAN_ND=44 cm⁻³
MEAN_CWC=0.271 gm⁻³
DWC=0.220 gm⁻³
AF=0.10
H=9023 m
MAX_ND=98 cm⁻³
MAX_CWC=0.607 gm⁻³
RWC=19.53 gm⁻³
Re=12.50
T=−25.6 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹)
0.01000
0.00100
0.00010
0.00001
1.0 10.0 100.0 1000.0 10000.0
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

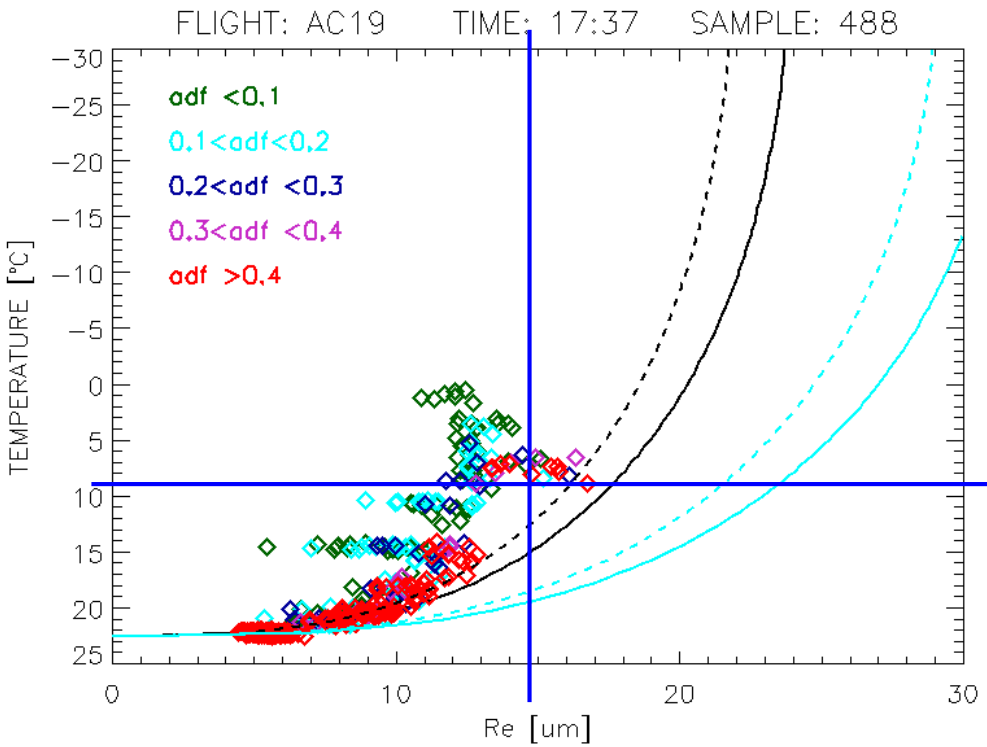

FLIGHT: AC07 DATE: 2014/09/06
CDP
Height [m]
0
2
4
6
8
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS Droplet Diameter (μm)

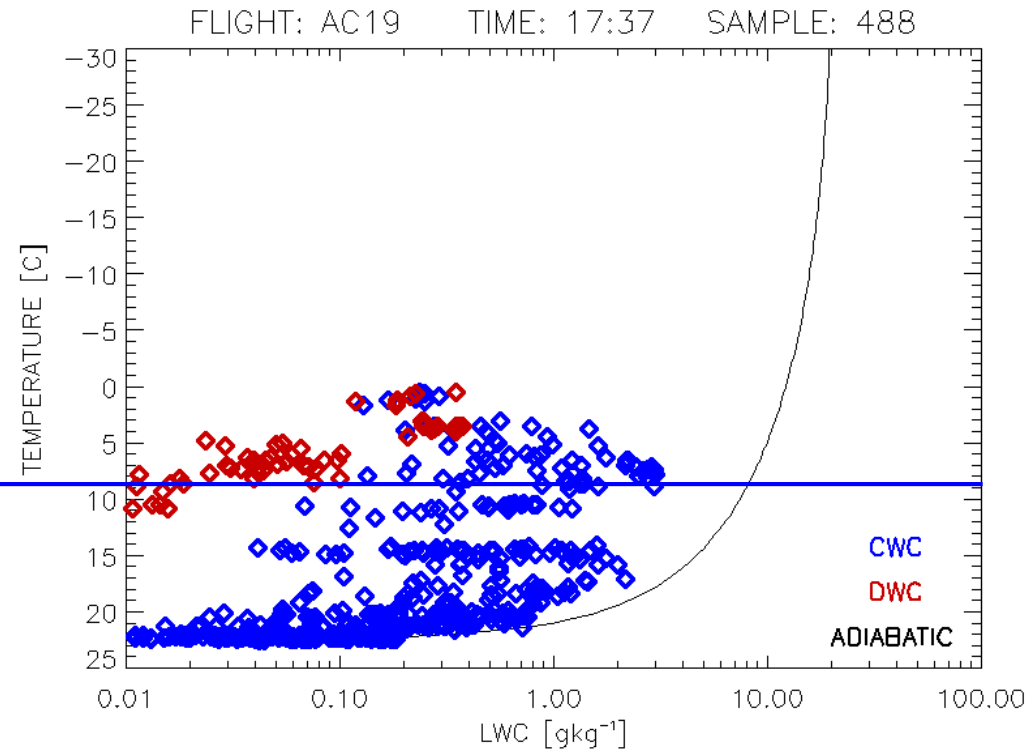

FLIGHT: AC07 DATE: 2014/09/06
CAS-NIXE
Height [m]
0
2
4
6
8
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
NIXE-CAPS Droplet Diameter (μm)
0.0
10.0
20.0
30.0
40.0
50.0
10.00000
1.00000
0.10000
0.01000
0.00100
0.00010
0.00001

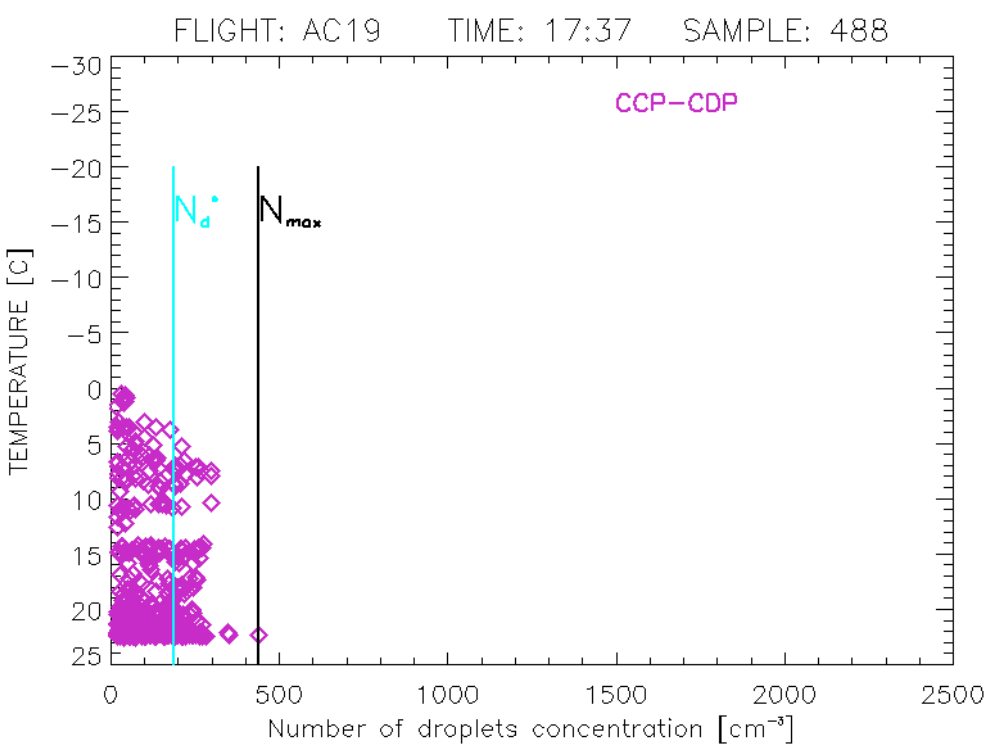


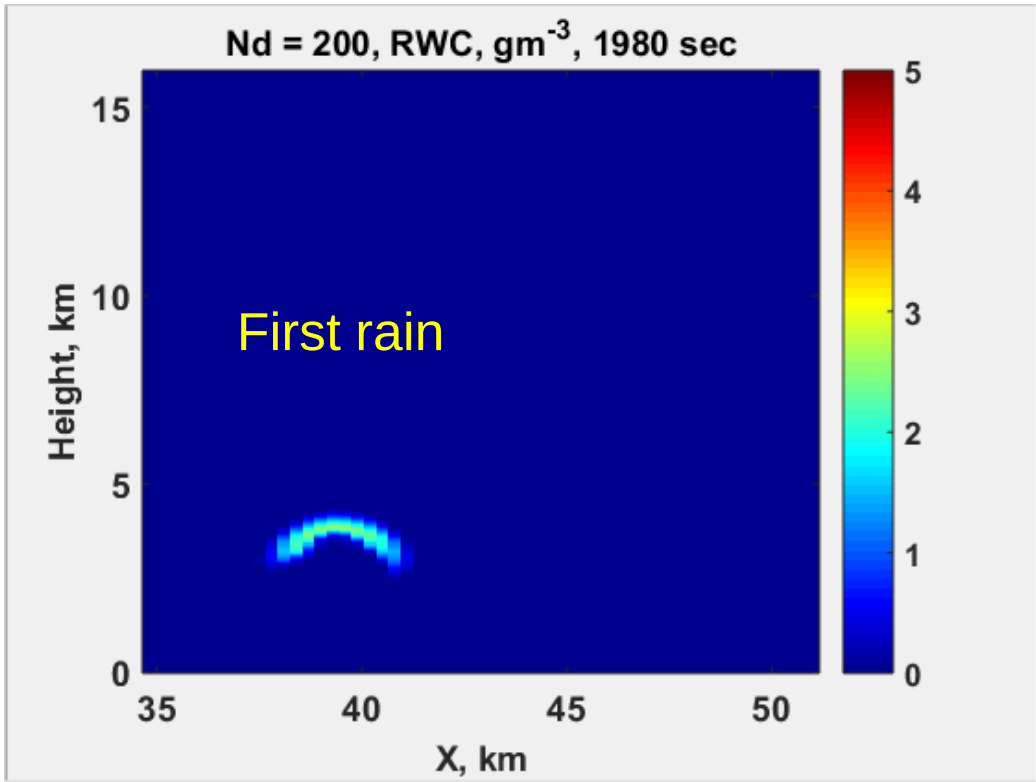
From Wendish et al., BAMS 2016

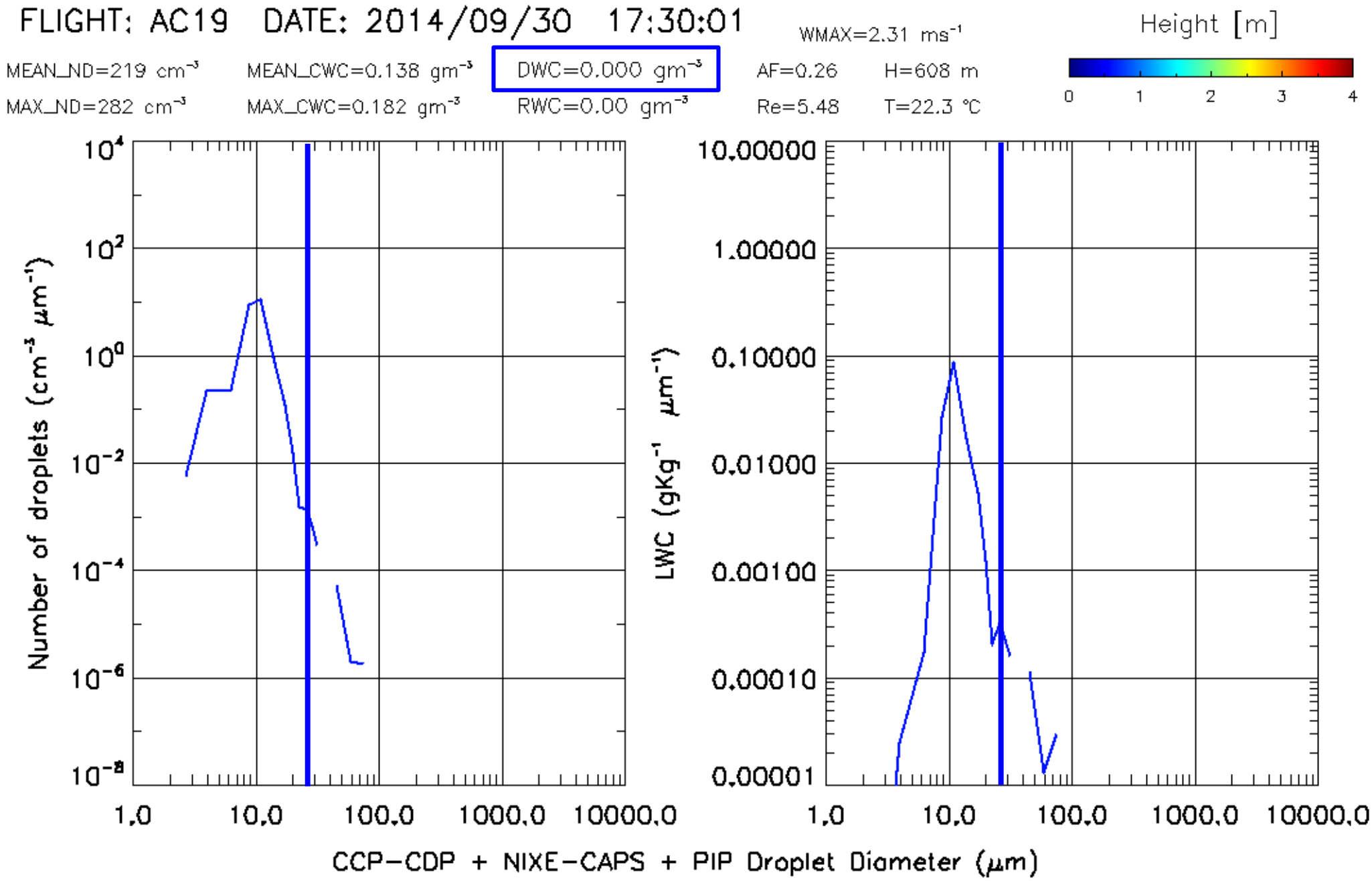
FIG. 6. Flight tracks for all scientific missions (AC07 to AC20).


FLIGHT: AC19 TIME: 17:37 SAMPLE: 488
adf <0.1
0.1<adf<0.2
0.2<adf <0.3
0.3<adf <0.4
adf >0.4
TEMPERATURE [°C]
Re [um]


FLIGHT: AC19 TIME: 17:37 SAMPLE: 488
CWC
DWC
ADIABATIC
TEMPERATURE [C]
LWC [gkg⁻¹]


FLIGHT: AC19 TIME: 17:37 SAMPLE: 488
CCP−CDP
N_d*
N_max
TEMPERATURE [C]
Number of droplets concentration [cm⁻³]


Nd = 200, RWC, gm-3, 1980 sec
First rain
Height, km
X, km


FLIGHT: AC19 DATE: 2014/09/30 17:30:01
WMAX=2.31 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=219 cm⁻³
MEAN_CWC=0.138 gm⁻³
DWC=0.000 gm⁻³
AF=0.26
H=608 m
MAX_ND=282 cm⁻³
MAX_CWC=0.182 gm⁻³
RWC=0.00 gm⁻³
Re=5.48
T=22.3 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

FLIGHT: AC19 DATE: 2014/09/30 17:42:27

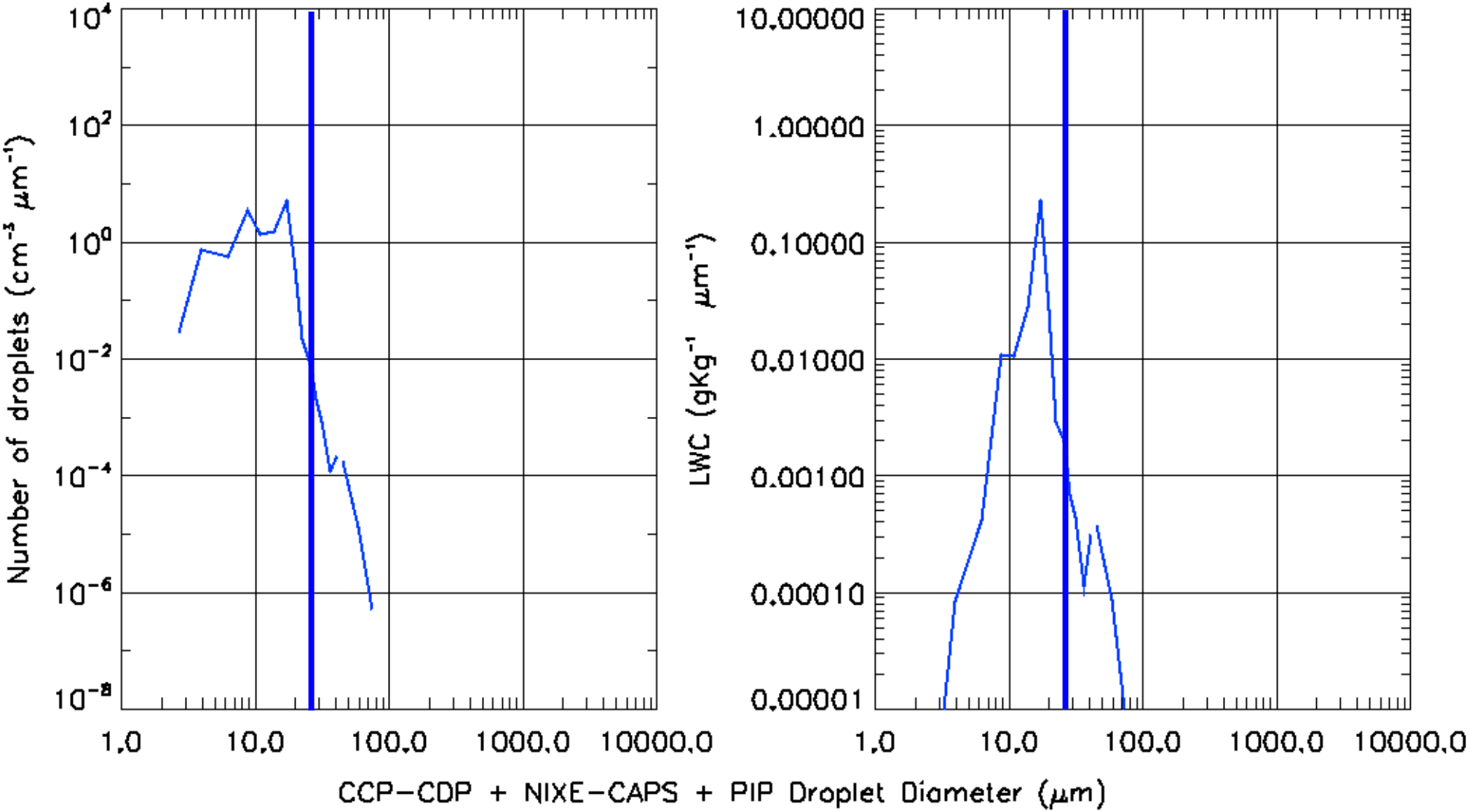
WMAX=2.78 ms^{-1}

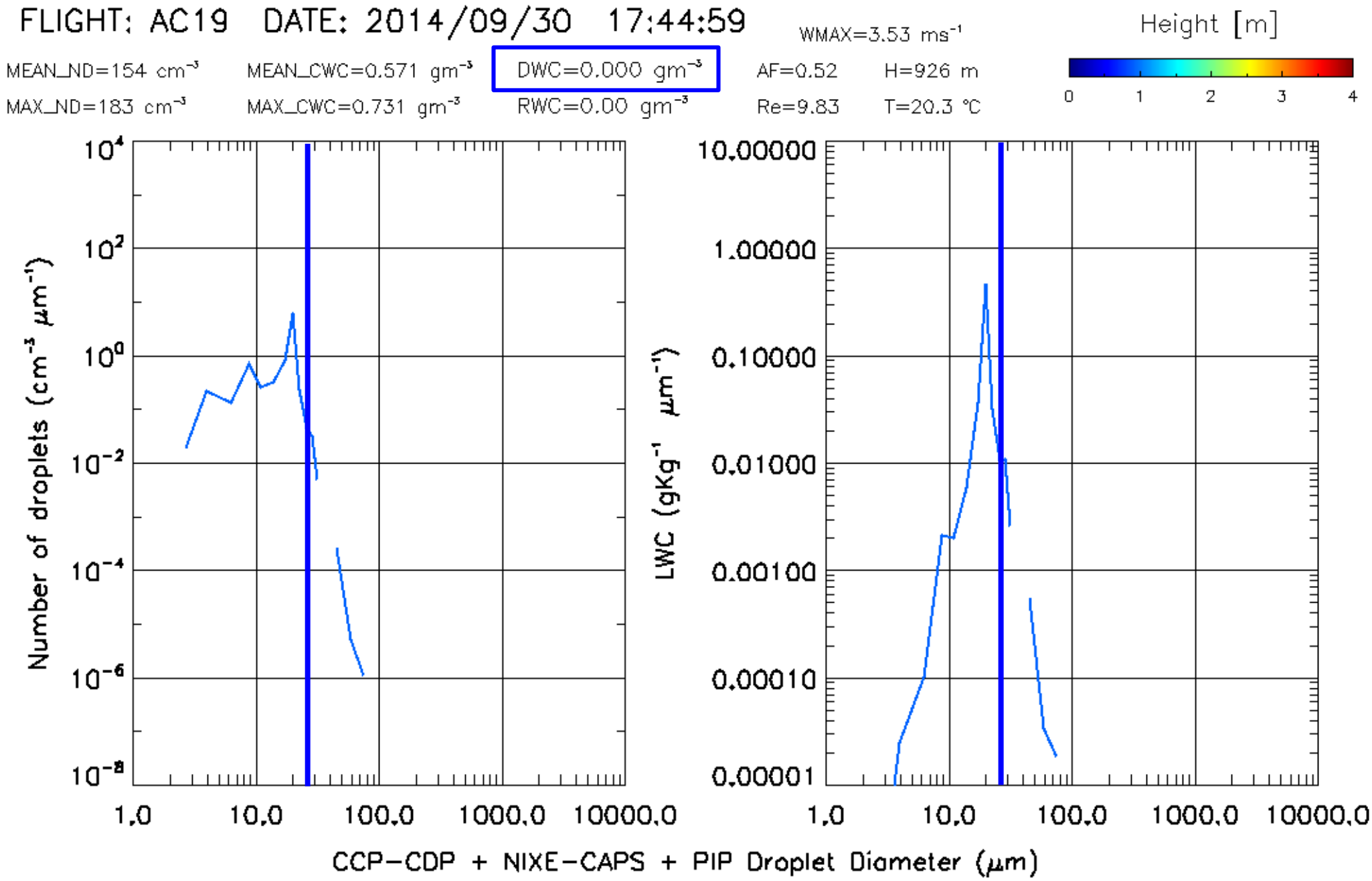
Height [m]

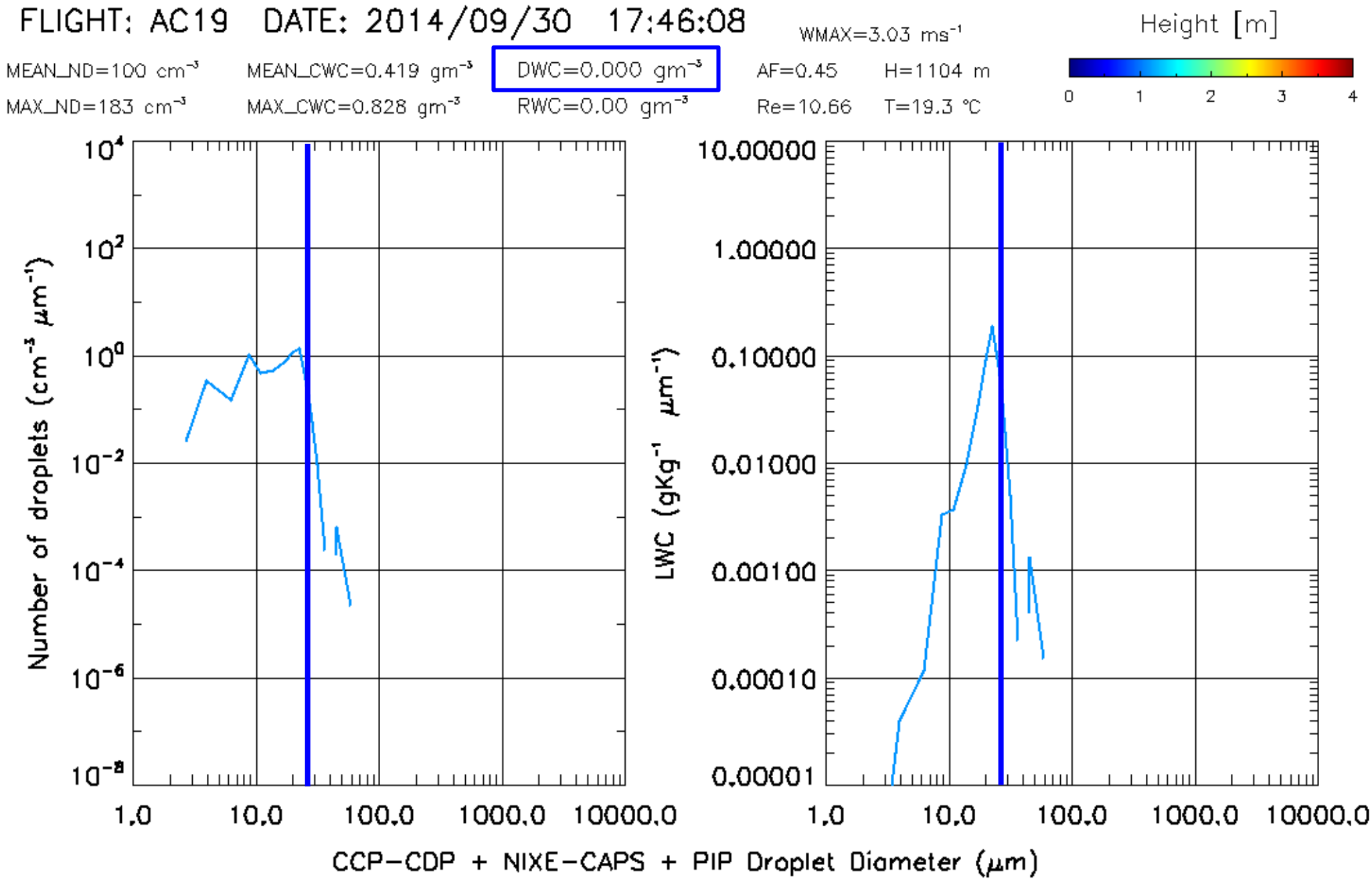
0 1 2 3 4

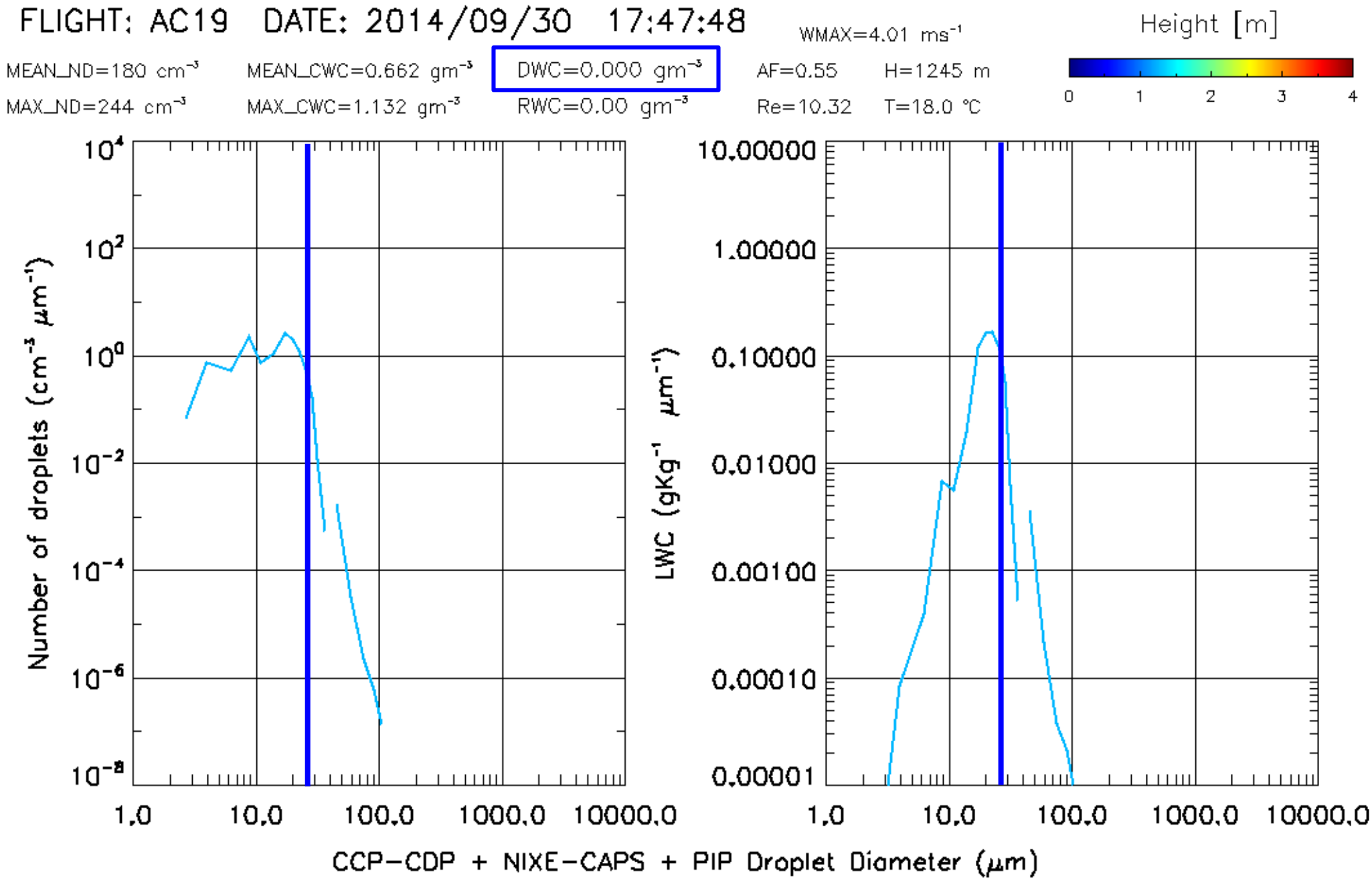
MEAN_ND=168 cm^{-3} MEAN_CWC=0.310 gm^{-3} DWC=0.000 gm^{-3} AF=0.59 H=768 m

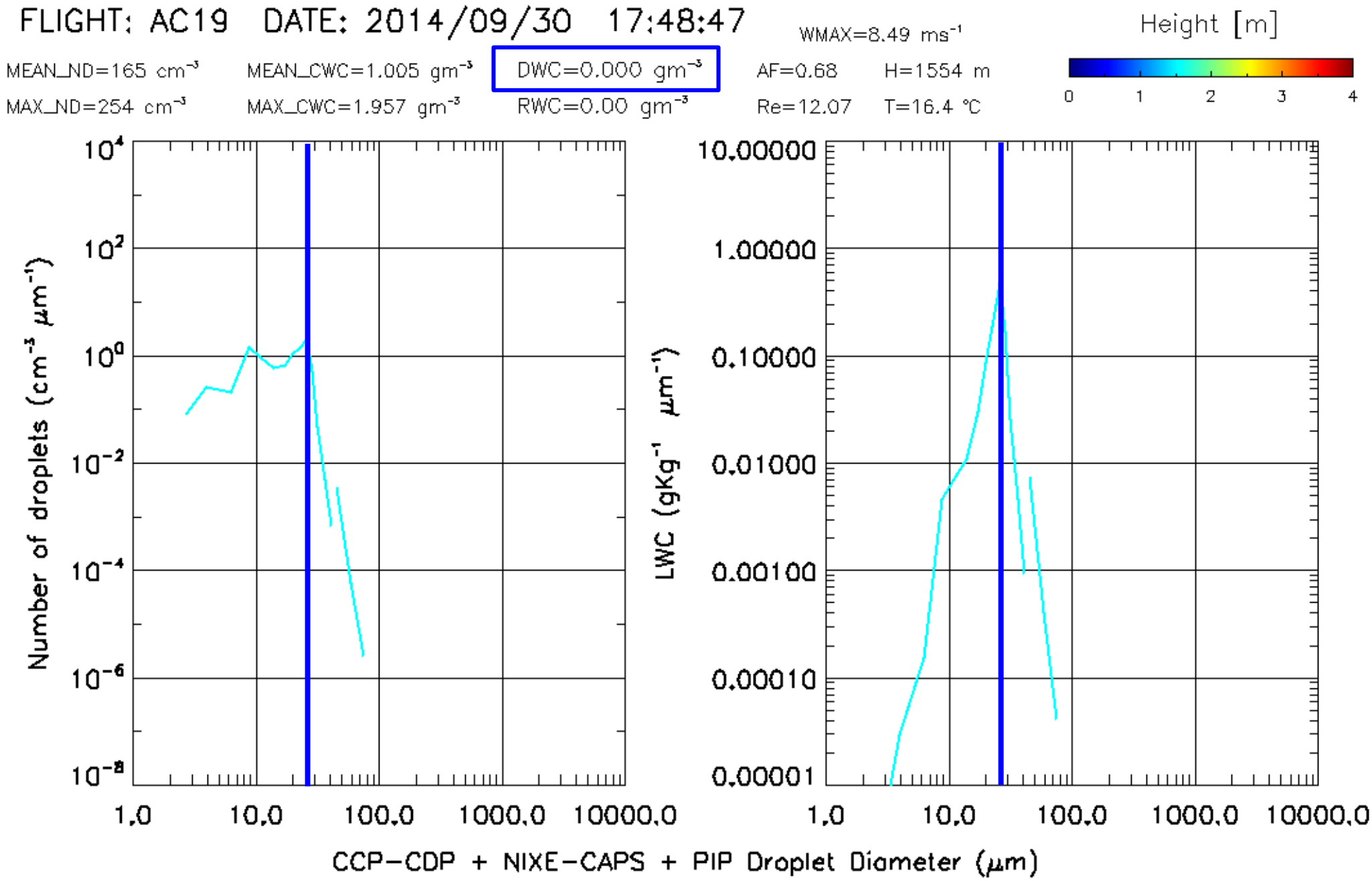
MAX_ND=269 cm^{-3} MAX_CWC=0.697 gm^{-3} RWC=0.00 gm^{-3} Re=8.08 T=21.2 °C

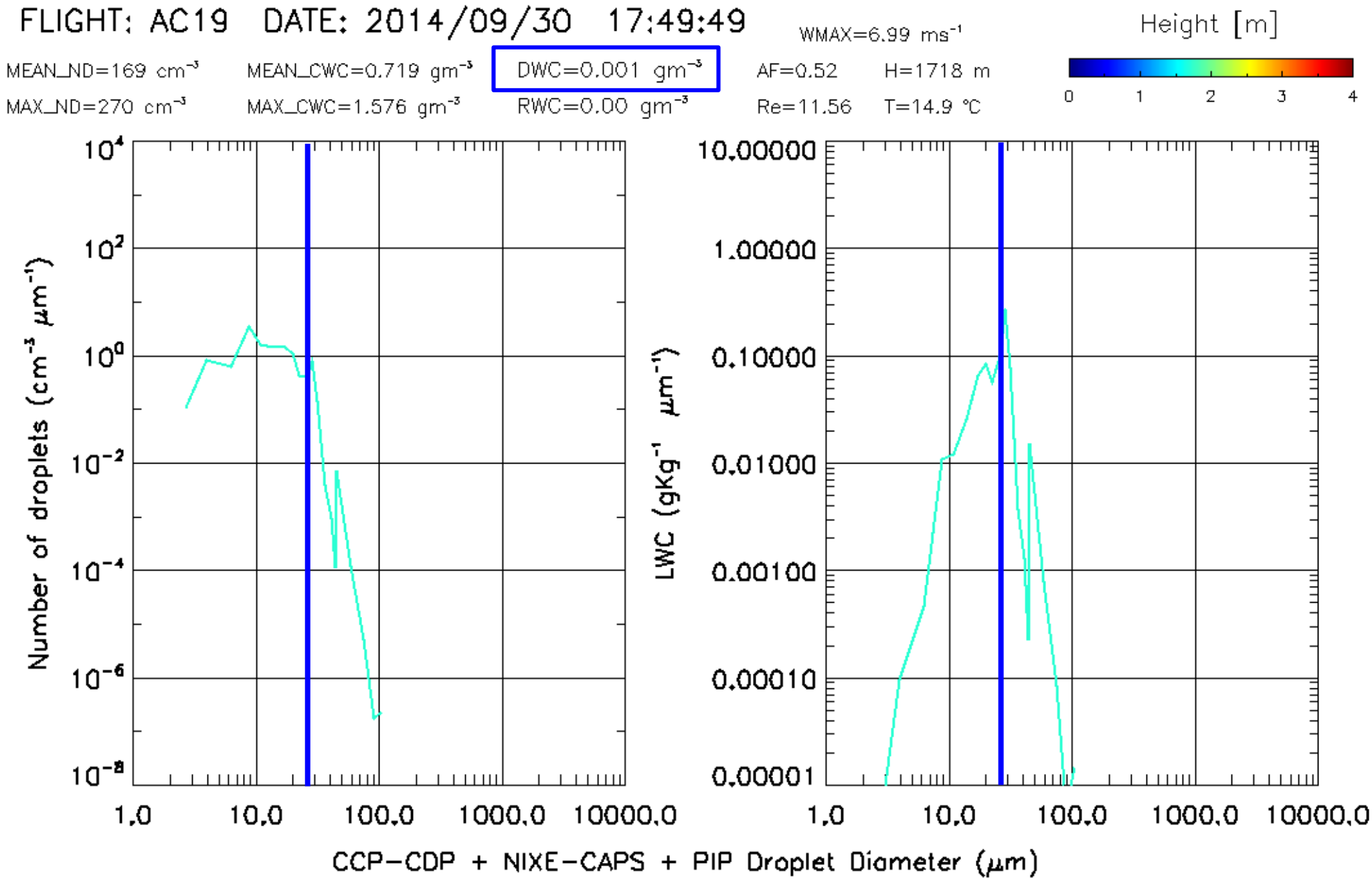


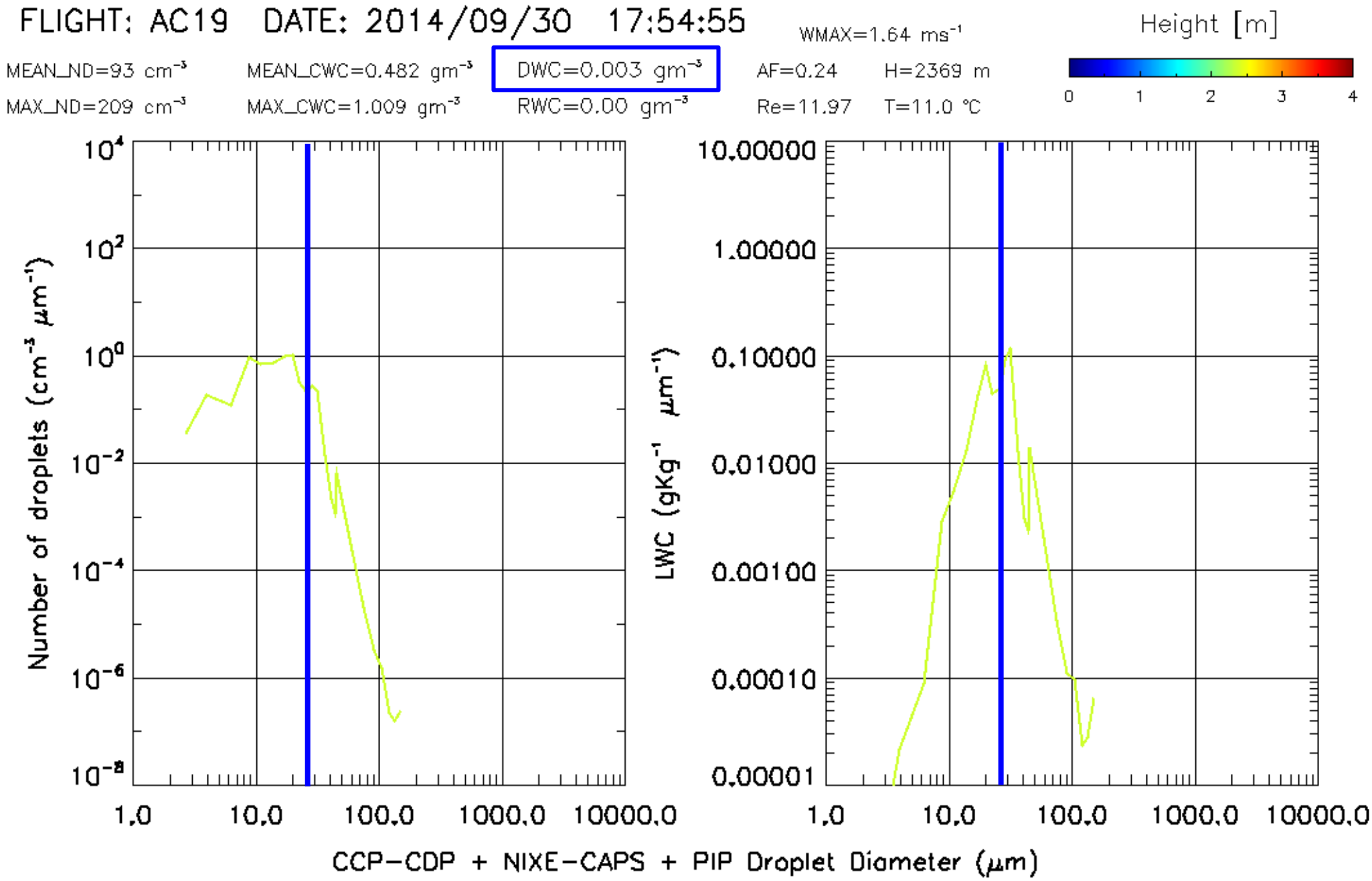

FLIGHT: AC19 DATE: 2014/09/30 17:44:59
WMAX=3.53 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=154 cm⁻³
MEAN_CWC=0.571 gm⁻³
DWC=0.000 gm⁻³
AF=0.52
H=926 m
MAX_ND=183 cm⁻³
MAX_CWC=0.731 gm⁻³
RWC=0.00 gm⁻³
Re=9.83
T=20.3 °C
Number of droplets (cm⁻³ µm⁻¹)
LWC (gKg⁻¹ µm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (µm)

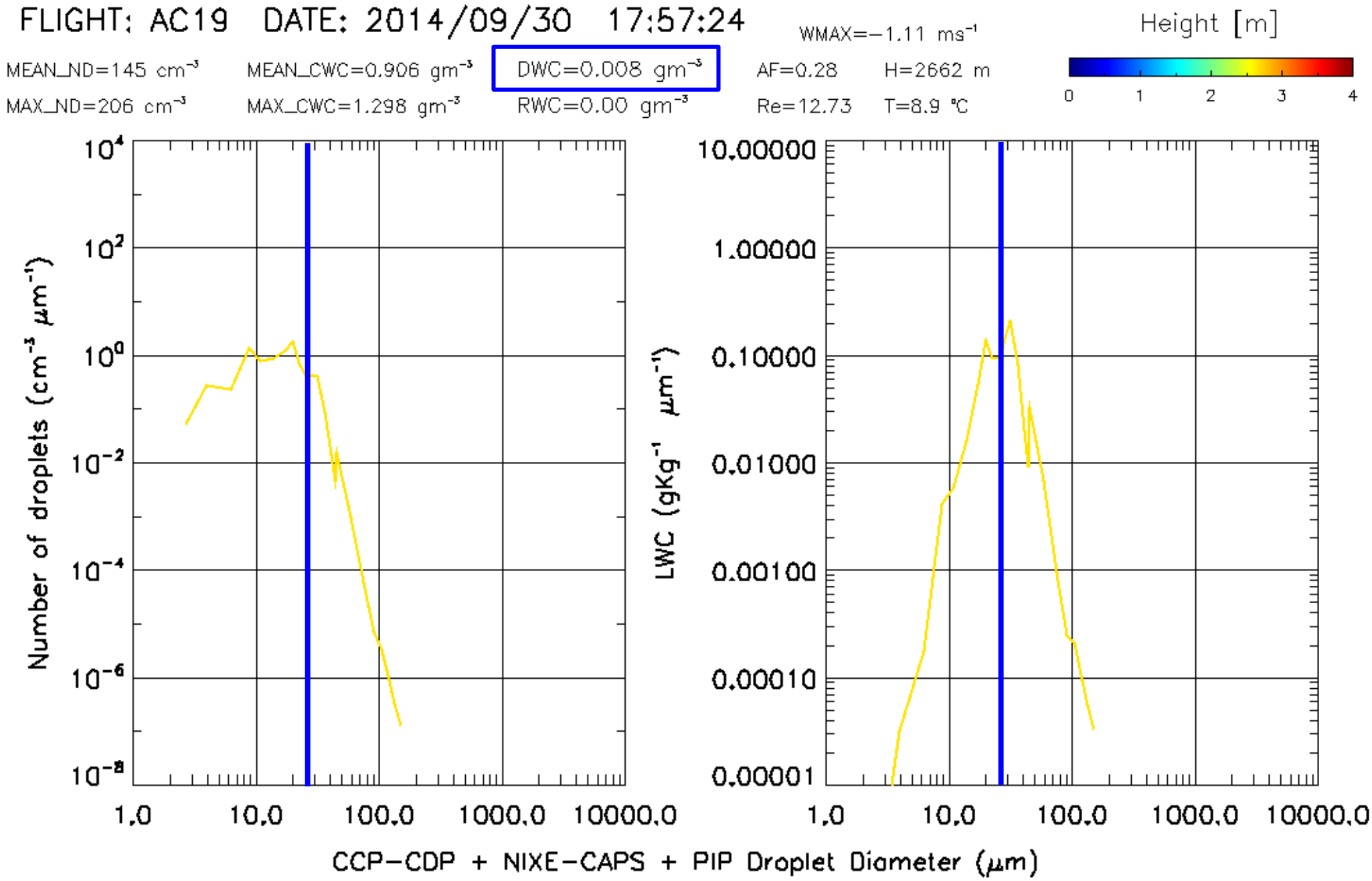

FLIGHT: AC19 DATE: 2014/09/30 17:46:08
WMAX=3.03 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=100 cm⁻³
MEAN_CWC=0.419 gm⁻³
DWC=0.000 gm⁻³
AF=0.45
H=1104 m
MAX_ND=183 cm⁻³
MAX_CWC=0.828 gm⁻³
RWC=0.00 gm⁻³
Re=10.66
T=19.3 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

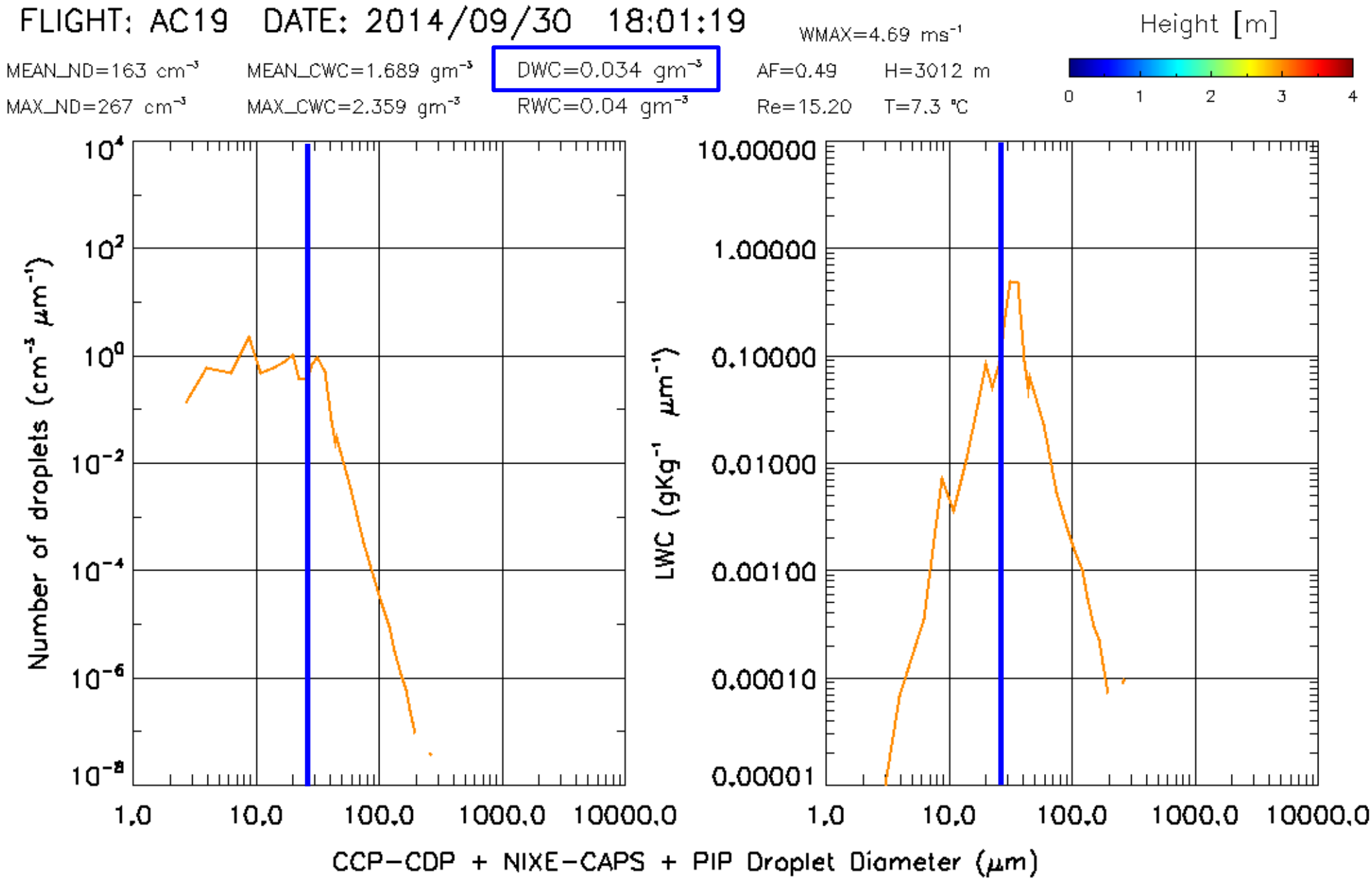

FLIGHT: AC19 DATE: 2014/09/30 17:47:48
WMAX=4.01 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=180 cm⁻³
MEAN_CWC=0.662 gm⁻³
DWC=0.000 gm⁻³
AF=0.55
H=1245 m
MAX_ND=244 cm⁻³
MAX_CWC=1.132 gm⁻³
RWC=0.00 gm⁻³
Re=10.32
T=18.0 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

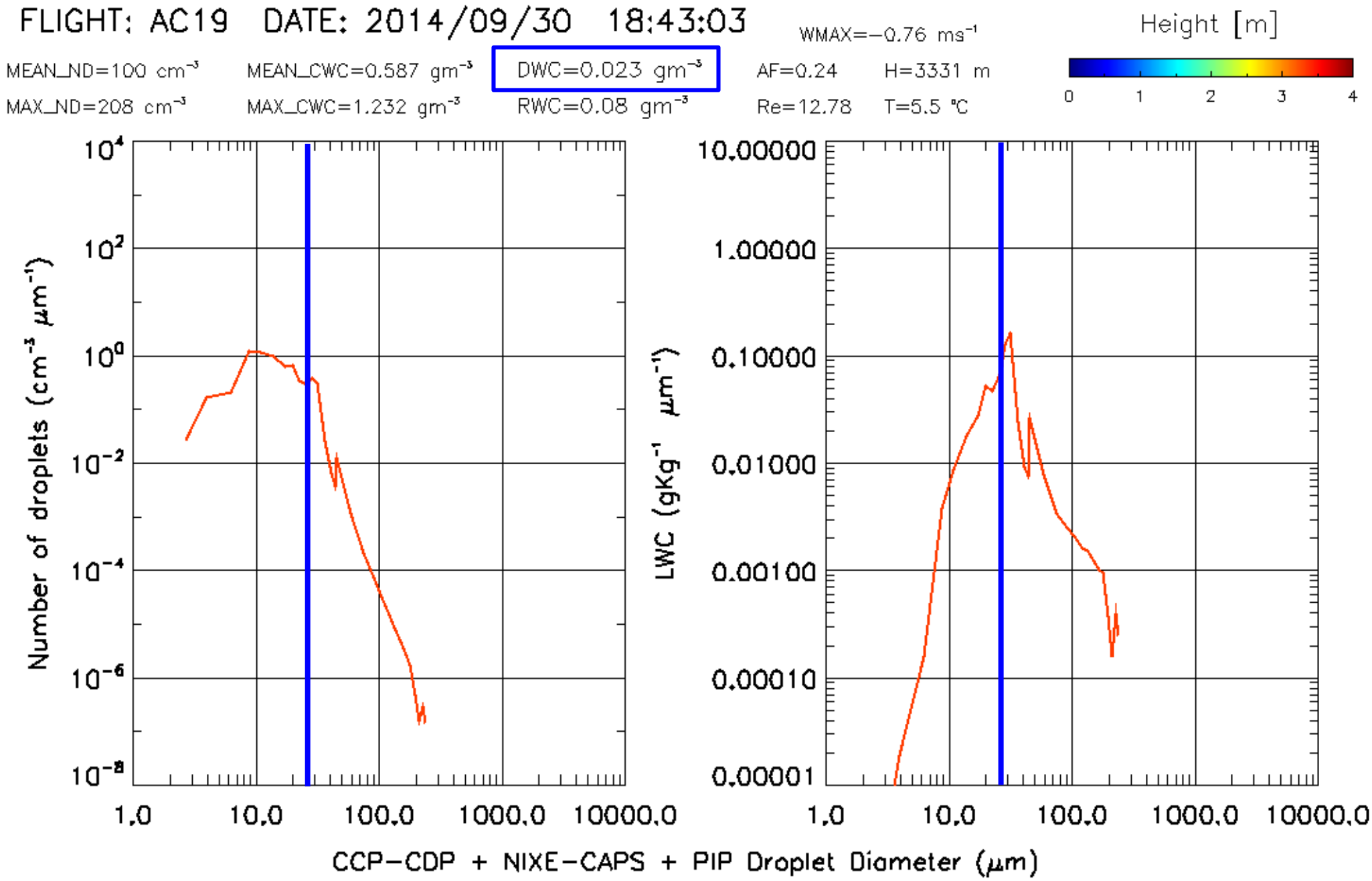

FLIGHT: AC19 DATE: 2014/09/30 17:48:47
WMAX=8.49 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=165 cm⁻³
MEAN_CWC=1.005 gm⁻³
DWC=0.000 gm⁻³
AF=0.68
H=1554 m
MAX_ND=254 cm⁻³
MAX_CWC=1.957 gm⁻³
RWC=0.00 gm⁻³
Re=12.07
T=16.4 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

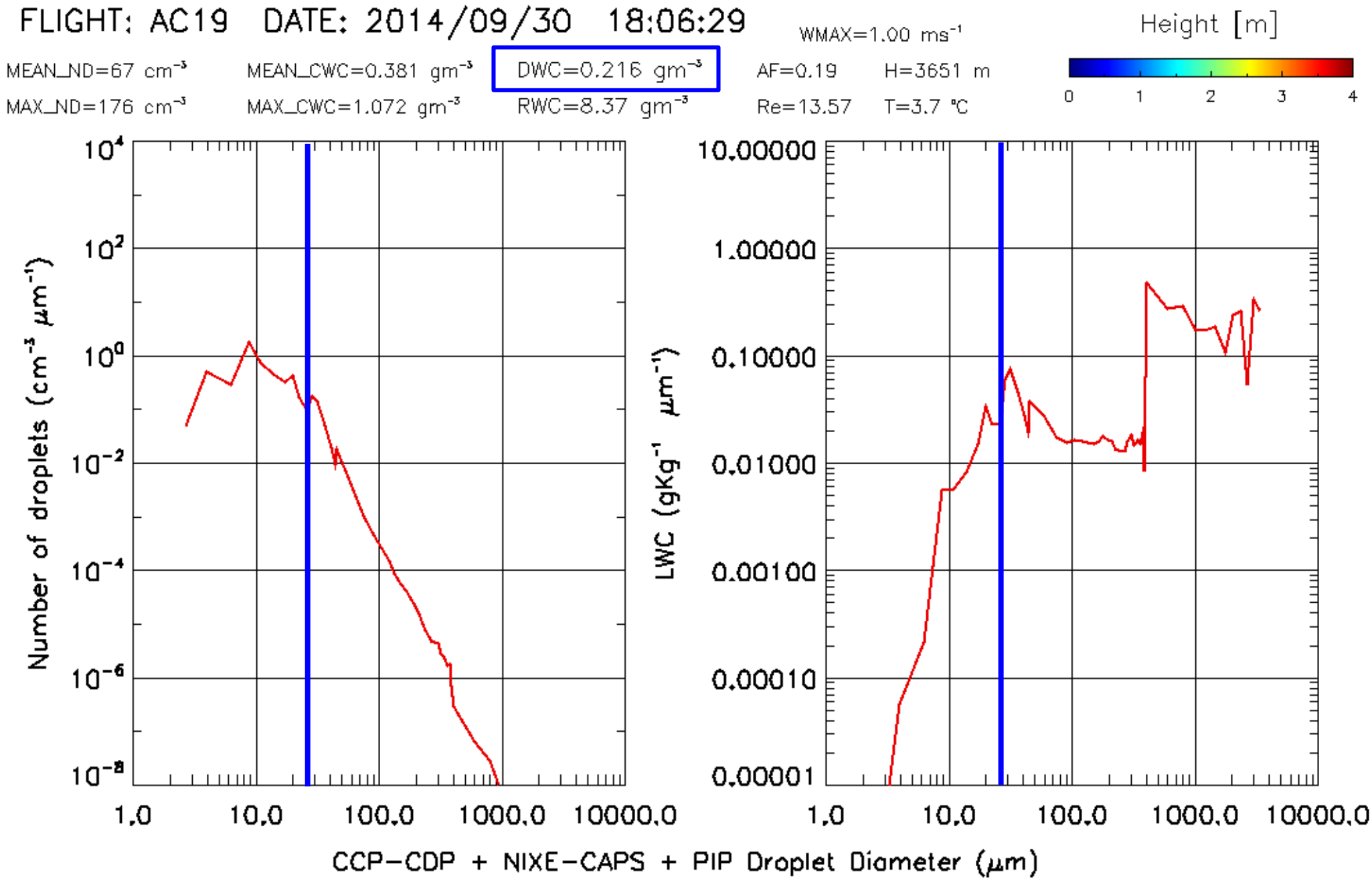

FLIGHT: AC19 DATE: 2014/09/30 17:49:49
WMAX=6.99 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=169 cm⁻³
MEAN_CWC=0.719 gm⁻³
DWC=0.001 gm⁻³
AF=0.52
H=1718 m
MAX_ND=270 cm⁻³
MAX_CWC=1.576 gm⁻³
RWC=0.00 gm⁻³
Re=11.56
T=14.9 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP-CDP + NIXE-CAPS + PIP Droplet Diameter (μm)

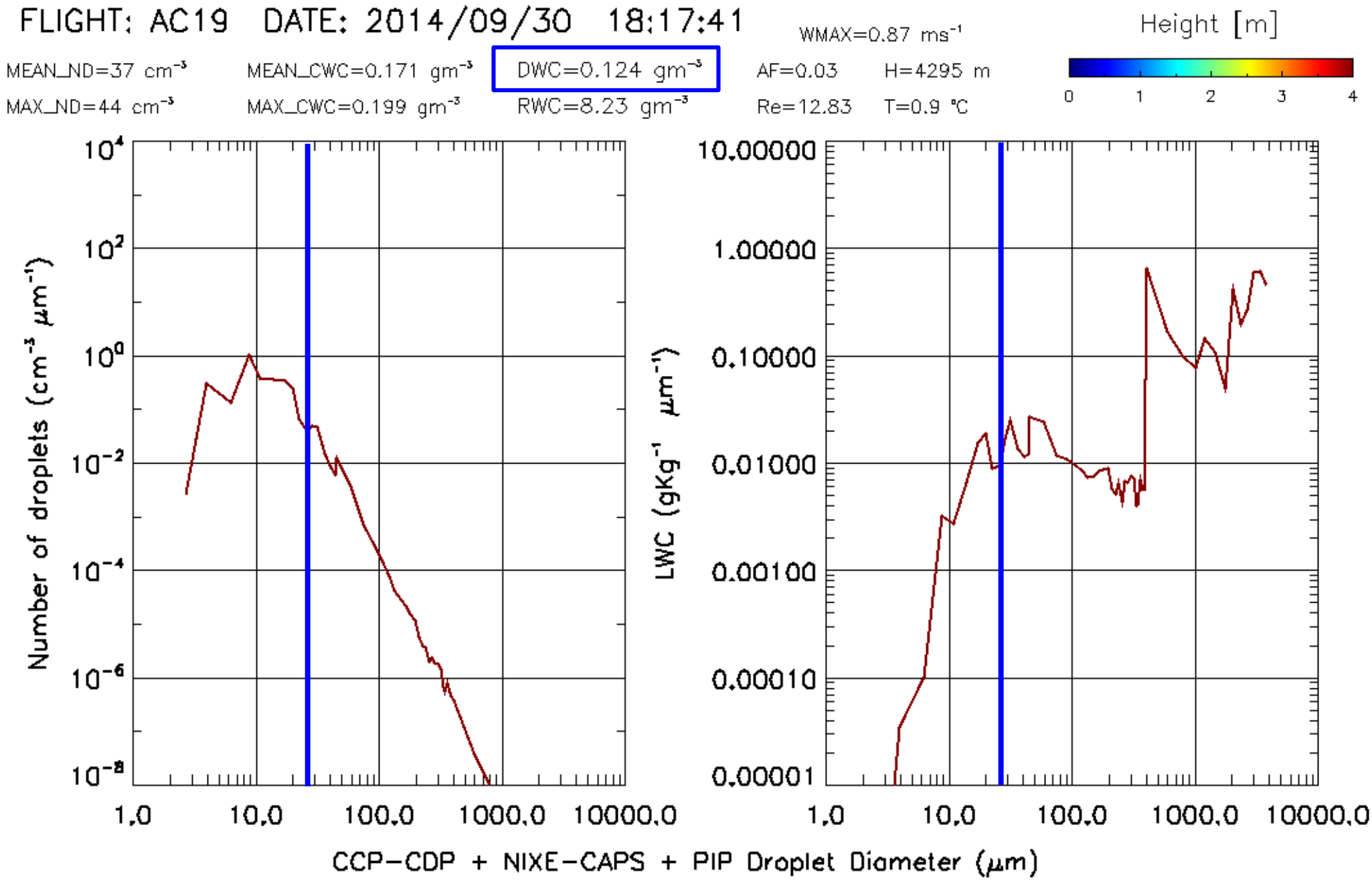

FLIGHT: AC19 DATE: 2014/09/30 17:54:55
WMAX=1.64 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=93 cm⁻³
MEAN_CWC=0.482 gm⁻³
DWC=0.003 gm⁻³
AF=0.24
H=2369 m
MAX_ND=209 cm⁻³
MAX_CWC=1.009 gm⁻³
RWC=0.00 gm⁻³
Re=11.97
T=11.0 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

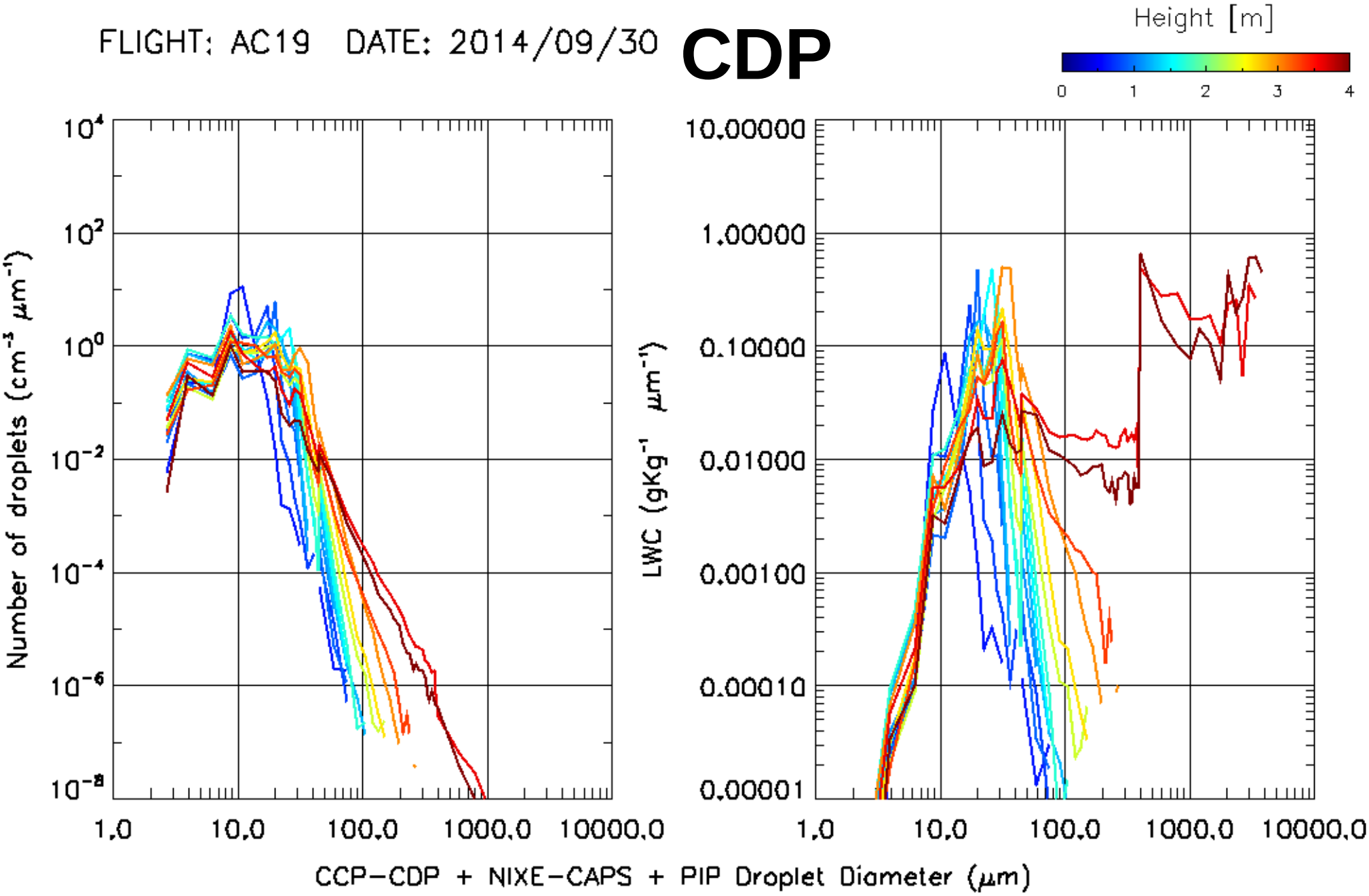

FLIGHT: AC19 DATE: 2014/09/30 17:57:24
WMAX=−1.11 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=145 cm⁻³
MEAN_CWC=0.906 gm⁻³
DWC=0.008 gm⁻³
AF=0.28
H=2662 m
MAX_ND=206 cm⁻³
MAX_CWC=1.298 gm⁻³
RWC=0.00 gm⁻³
Re=12.73
T=8.9 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)

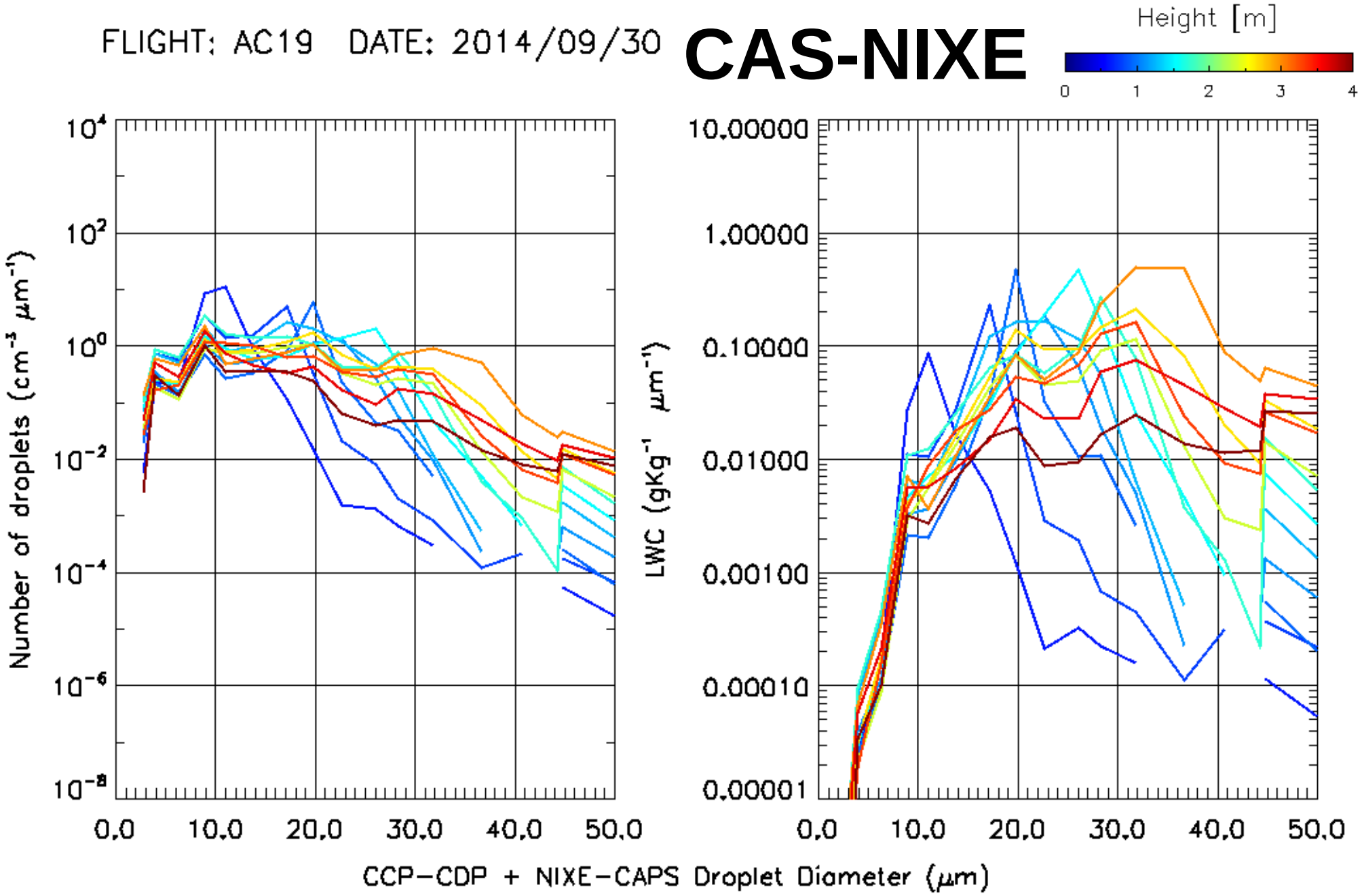

FLIGHT: AC19 DATE: 2014/09/30 18:01:19
WMAX=4.69 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=163 cm⁻³
MEAN_CWC=1.689 gm⁻³
DWC=0.034 gm⁻³
AF=0.49
H=3012 m
MAX_ND=267 cm⁻³
MAX_CWC=2.359 gm⁻³
RWC=0.04 gm⁻³
Re=15.20
T=7.3 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)


FLIGHT: AC19 DATE: 2014/09/30 18:43:03
WMAX=−0.76 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=100 cm⁻³
MEAN_CWC=0.587 gm⁻³
DWC=0.023 gm⁻³
AF=0.24
H=3331 m
MAX_ND=208 cm⁻³
MAX_CWC=1.232 gm⁻³
RWC=0.08 gm⁻³
Re=12.78
T=5.5 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)


FLIGHT: AC19 DATE: 2014/09/30 18:06:29
WMAX=1.00 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=67 cm⁻³
MEAN_CWC=0.381 gm⁻³
DWC=0.216 gm⁻³
AF=0.19
H=3651 m
MAX_ND=176 cm⁻³
MAX_CWC=1.072 gm⁻³
RWC=8.37 gm⁻³
Re=13.57
T=3.7 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)


FLIGHT: AC19 DATE: 2014/09/30 18:17:41
WMAX=0.87 ms⁻¹
Height [m]
0 1 2 3 4
MEAN_ND=37 cm⁻³
MEAN_CWC=0.171 gm⁻³
DWC=0.124 gm⁻³
AF=0.03
H=4295 m
MAX_ND=44 cm⁻³
MAX_CWC=0.199 gm⁻³
RWC=8.23 gm⁻³
Re=12.83
T=0.9 °C
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)


FLIGHT: AC19 DATE: 2014/09/30
CDP
Height [m]
0
1
2
3
4
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS + PIP Droplet Diameter (μm)
1.0
10.0
100.0
1000.0
10000.0
10.00000
1.00000
0.10000
0.01000
0.00100
0.00010
0.00001

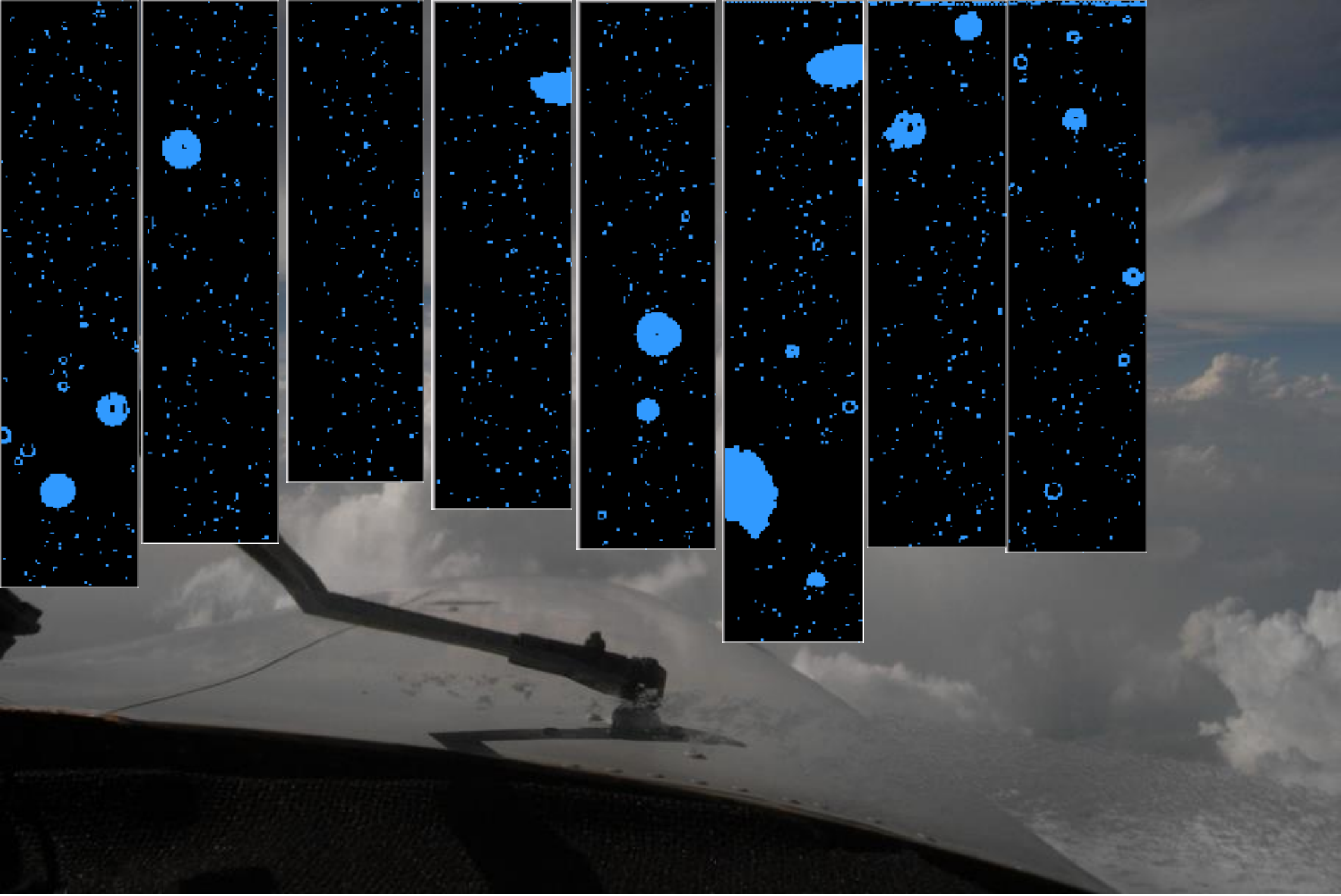

FLIGHT: AC19 DATE: 2014/09/30
CAS-NIXE
Height [m]
0
1
2
3
4
Number of droplets (cm⁻³ μm⁻¹)
LWC (gKg⁻¹ μm⁻¹)
CCP−CDP + NIXE−CAPS Droplet Diameter (μm)
0.0
10.0
20.0
30.0
40.0
50.0

Technical Summary

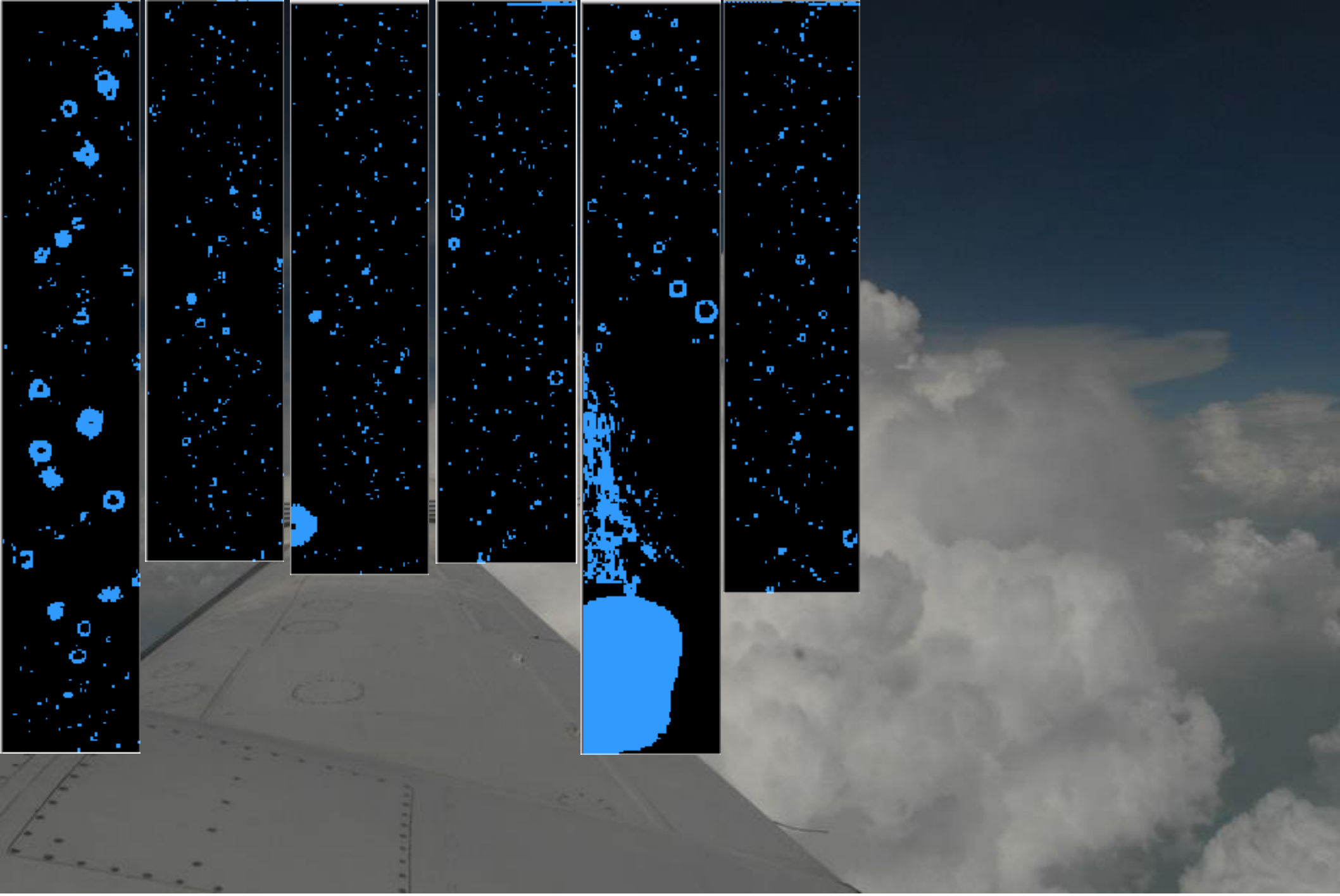
Further scientific advancements require to:

- Calibrate and reconcile the cloud drop probes
- Obtain images of the CIP (PHIPS is not a replacement), as was done in India, Israel, California and most other cloud physics campaigns.
- Classify the hydrometeors to rain and ice.
- Unmask and QC the BAHAMAS updrafts within the clouds.

2009 08 24, 10:14 UT, 6720 m, -8.1ºC. Max HWLWC=1.66 gm-3. N of Bareilly.
The cloud has supercooled rain drops.



2009 08 24, 10:03 UT, 7350 m, -11.8ºC. Max HWLWC=0.87 gm-3. N of Bareilly.
The cloud has small raindrops and larger freezing rain drops.



2009 08 24, 10:00 UT, 7700 m, -14.7ºC. Max HWLWC=1.45 gm-3. N of Bareilly.
The cloud has small rain drops, large freezing rain drops and small graupel.

2009 08 24, 9:57 UT, 8130 m, -17.1ºC. Max HWLWC=0.49 gm-3. N of Bareilly.
The cloud is glaciating, with frozen rain drops, small graupel and ice crystals.

Scientific Summary

- Height for rain initiation (Dc) increases linearly with cloud base drop concentrations (Nd)
- Increasing Dc from 50 to ~500 cm^{-3} incurs warm cloud invigoration due to reducing the large S at low Nd and advanced coalescence.
- Further increase of Nd incurs mixed phase cloud invigoration due to less rainout and thus more latent heat release of freezing.
- Rain initiates at Re > 12 to 13 μm and is fully developed for Re > 14 μm, as in other studies.
- Supercooled cloud water extend to colder temperatures with more Nd and smaller Re.

Thank you for flying with us!

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Scientific Summary

- Height for rain initiation (Dc) increases linearly with cloud base drop concentrations (Nd)
- Increasing Dc from 50 to ~500 cm^{-3} incurs warm cloud invigoration due to reducing the large S at low Nd and advanced coalescence.
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