TCu Ice

Background and HIWC-2022 Observations

Questions

- How and where does the ice form?
  - Primary ice
  - Secondary ice production (SIP)
- How does it impact precipitation formation?
- Impact on small cloud droplet concentration
  - Water vapor competition
  - Collection and riming

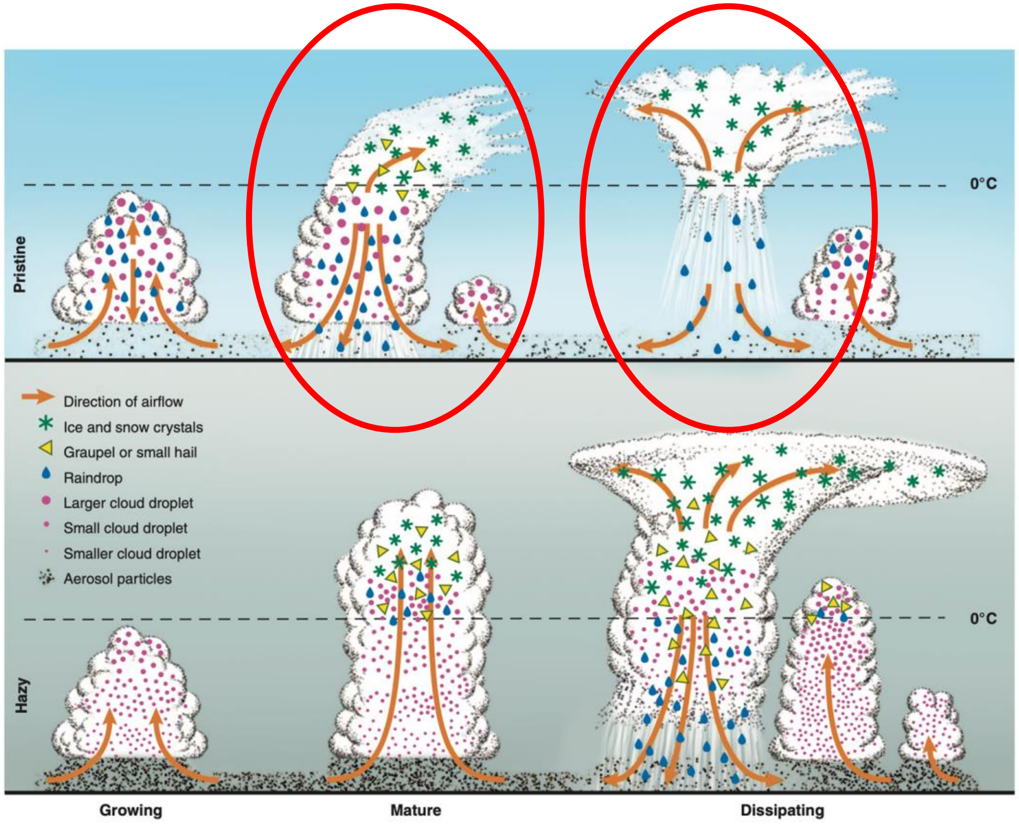


Fig. 2. Evolution of deep convective clouds developing in the pristine (top) and polluted (bottom) atmosphere. Cloud droplets coalesce into raindrops that rain out from the pristine clouds. The smaller drops in the polluted air do not precipitate before reaching the supercooled levels, where they freeze onto ice precipitation that falls and melts at lower levels. The additional release of latent heat of freezing aloft and reabsorbed heat at lower levels by the melting ice implies greater upward heat transport for the same amount of surface precipitation in the more polluted atmosphere. This means consumption of more instability for the same amount of rainfall. The inevitable result is invigoration of the convective clouds and additional rainfall, despite the slower conversion of cloud droplets to raindrops (*43*).

Rosenfeld, et al. 2008

Outline

- Previous field campaigns
  - KWAJEX
  - SEAC4RS
  - ICE-T

- Lab studies on secondary ice relevant to TCu

- HIWC-2022 observations

Previous field campaigns:

TRMM - KWAJEX (1999)

- UND Citation measured deep convection at various levels, up to -36°C
- Clean aerosol conditions
- Liquid water started to decrease at -5°C
- Rapid glaciation, liquid mostly depleted by -17°C
- Found that updraft speed does not have much of an effect on droplet concentrations

Previous field campaigns:

TRMM - KWAJEX (1999)

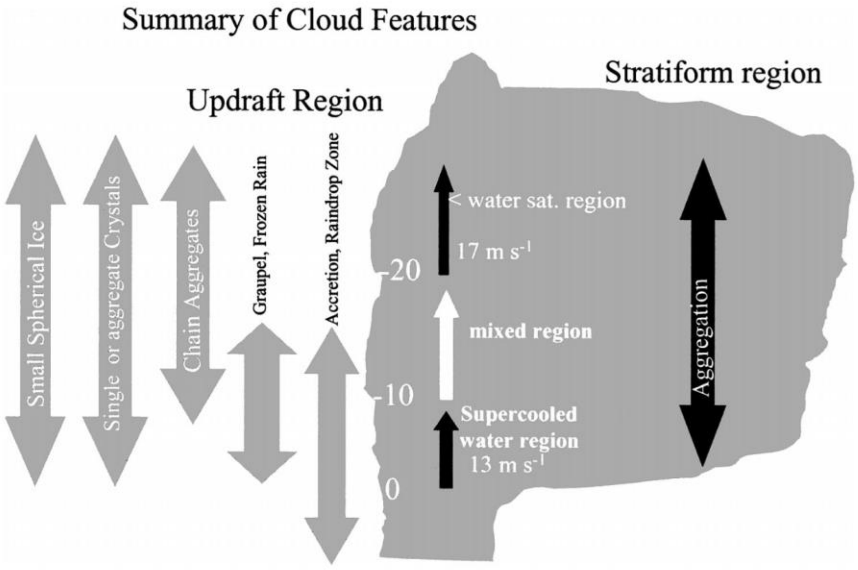


FIG. 14. Diagram of particle types and characteristics of convective cloud features in LBA and KWAJEX.

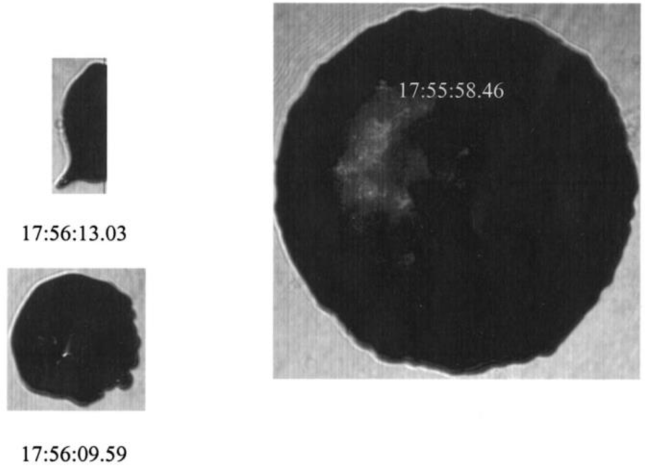


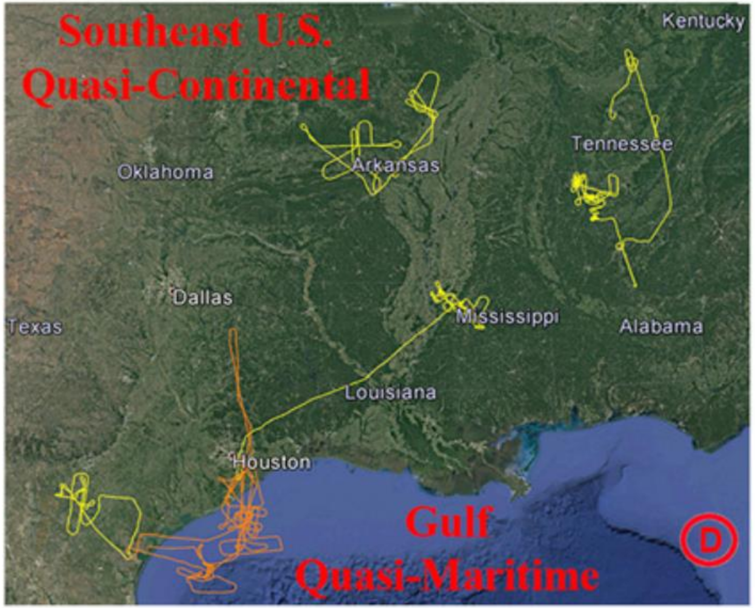
FIG. 11. (a) Examples of CPI images found during the pass depicted in Fig. 7b, and (b) examples from 13 Feb 1999 just before the pass in Fig. 7, at a temperature of −10°C.

Stith et al. 2004

Previous field campaigns:

SEAC4RS - Texas and Gulf of Mexico (2013)

- DC-8 and SPEC Learjet
- Measurements in coastal ‘quasi-continental’ fresh updraft clouds and marine TCu over the Gulf



Lawson, et al. 2017

Previous field campaigns:

SEAC4RS

- Lawson et al. (2017) found that large drops tend to freeze before small (<100 micron) drops
- Separated ice/liquid in mixed-phase clouds
- Marine convection on average had lower droplet and ice concentrations, although different temperature ranges make comparison difficult

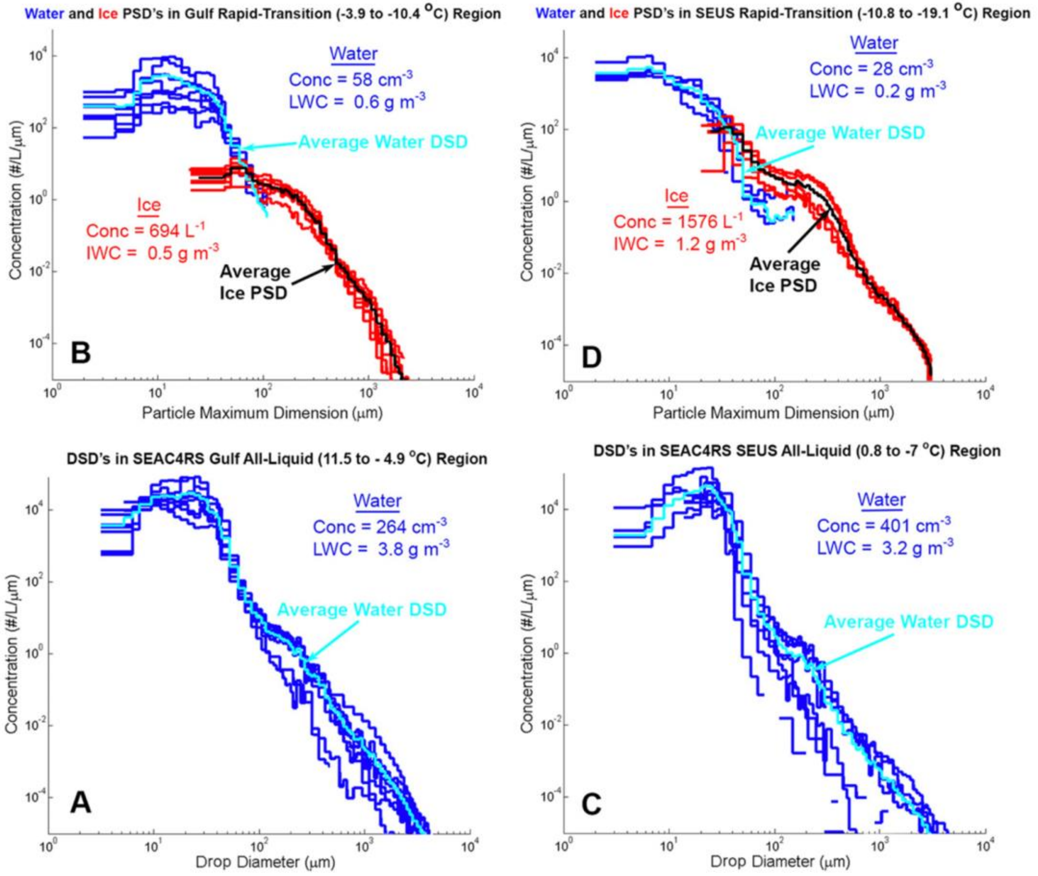


FIG. 7. Particle size distributions in the (a) all-liquid region and (b) rapid transition region of Gulf clouds and the (c) all-liquid region and (d) rapid transition region of SEUS clouds.

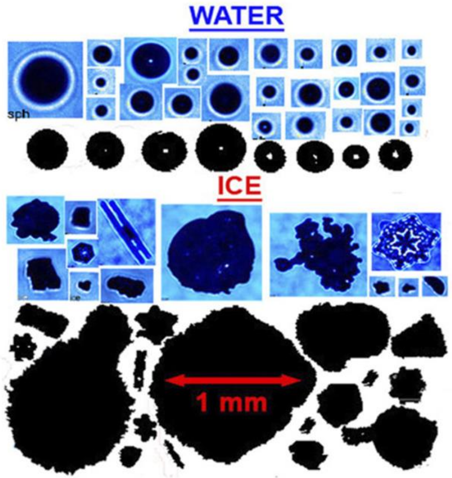
Previous field campaigns:

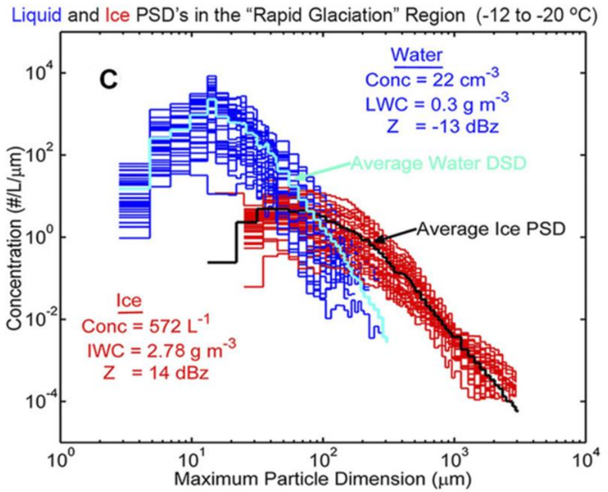
ICE-T, U.S. Virgin Islands 2013

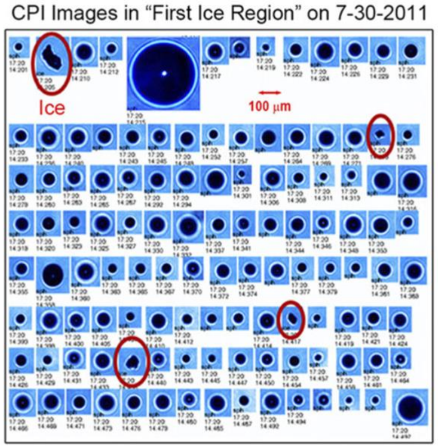
- NCAR C-130 and SPEC Learjet measured many TCu at various levels
- Learjet penetrated cloud tops regularly, similar to the HIWC-2002 flights
- Ubiquitous evidence for SIP due to droplet breakup
- Primary nucleation speculated to be from biogenic IN (Lawson et al. 2017) or mineral dust (Heymsfield and Willis 2014)

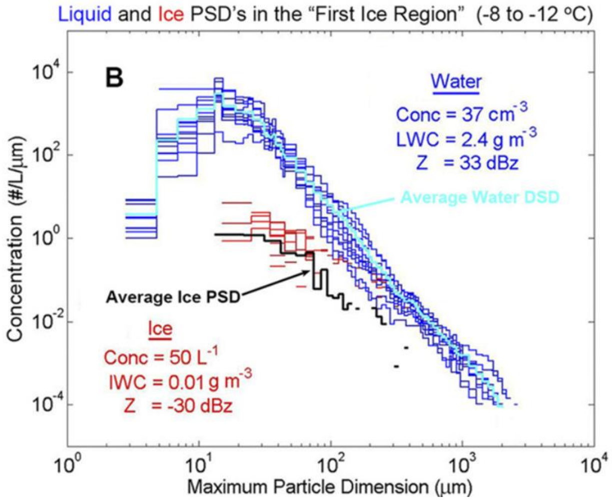
ICE-T

Similar cloud particles to what we observed in HIWC-2022, including high-resolution imagery





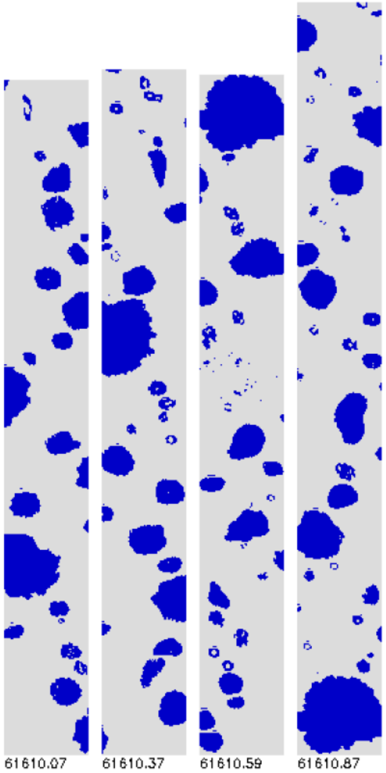


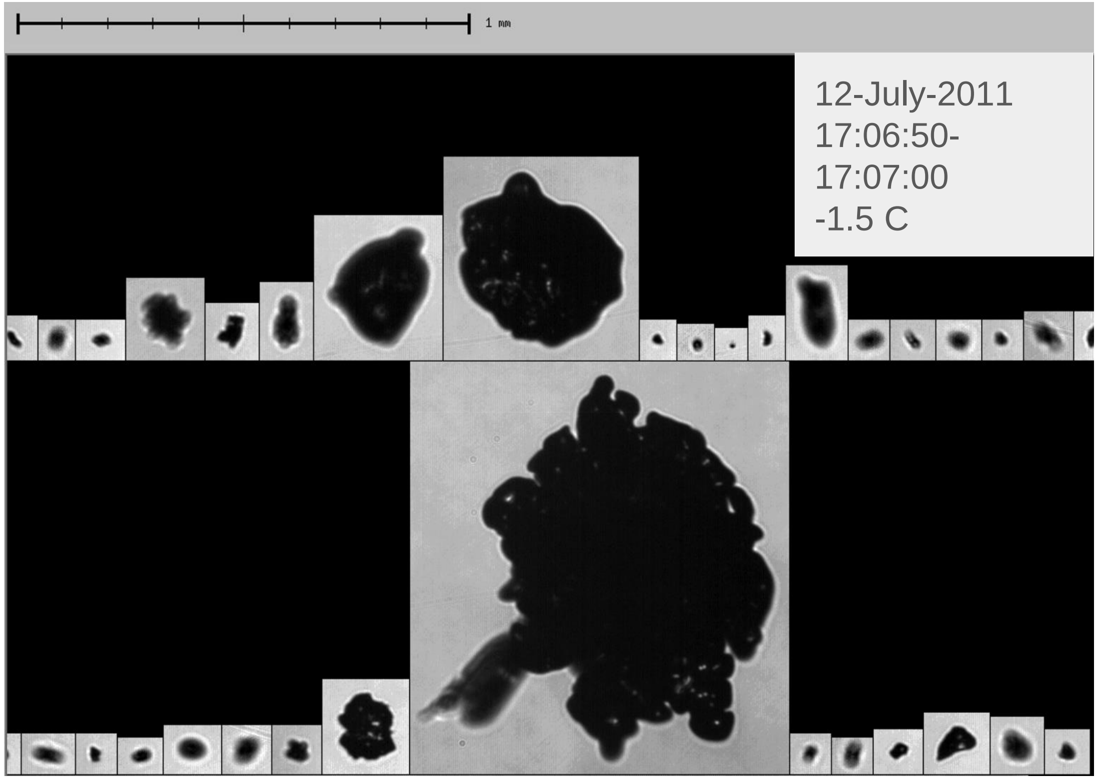


Lawson, et al. 2017

ICE-T

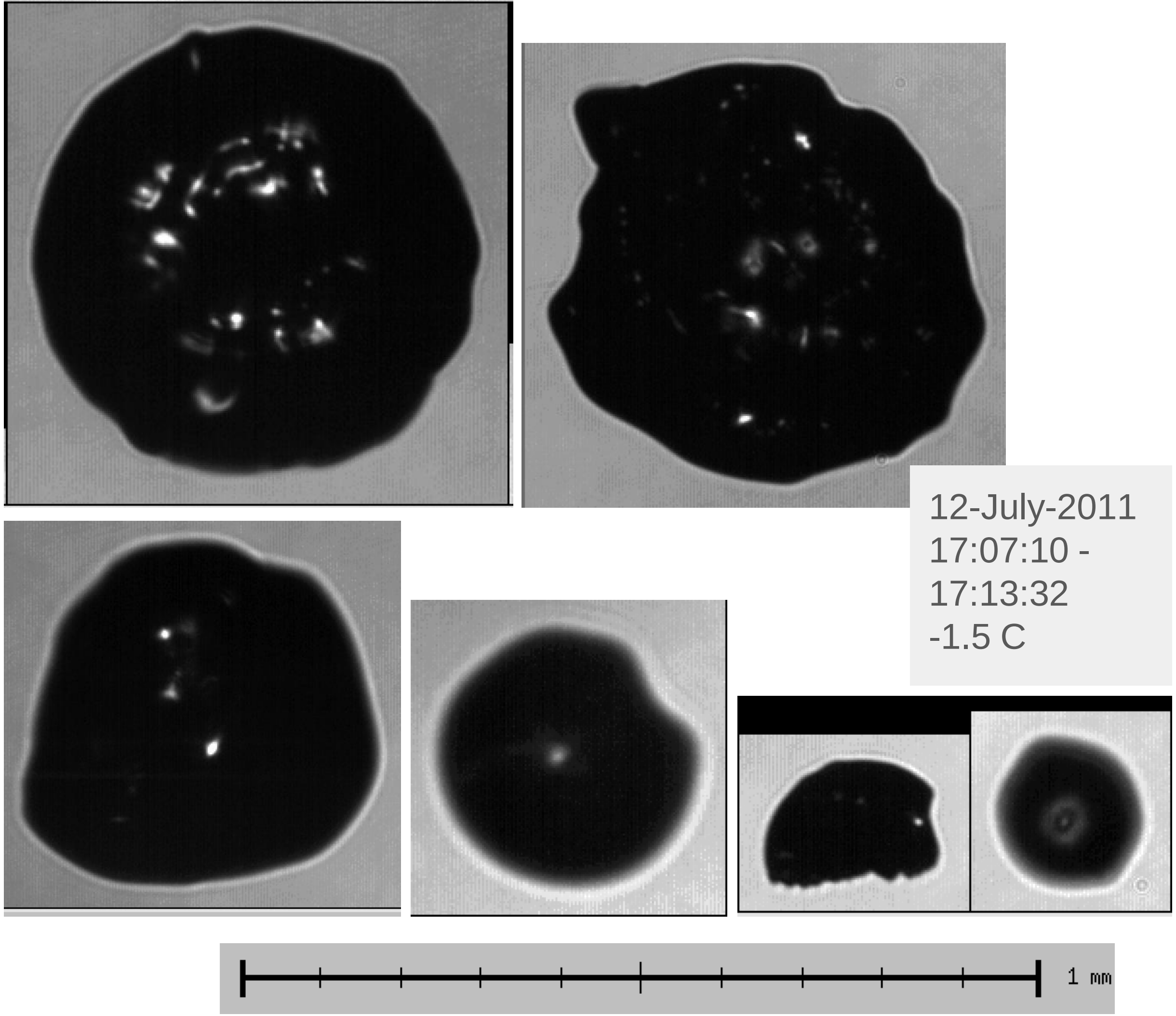
C-130 CPI: more detailed view of graupel than what we have in HIWC-2022 (Fast 2D-C and CPI)





ICE-T

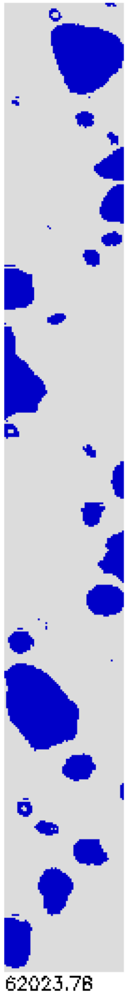
C-130 CPI: Frozen droplets, also observed in HIWC-2022

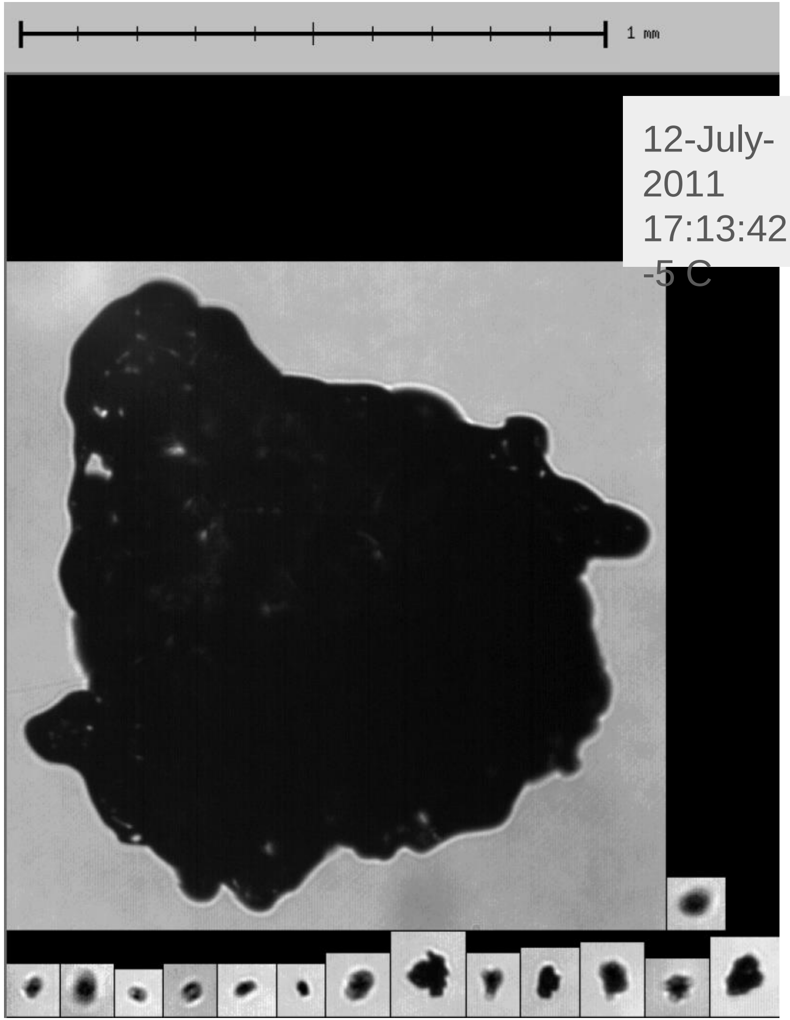


ICE-T

Similar cloud particles to what we observed in HIWC-2022

C-130 Fast 2D-C and CPI

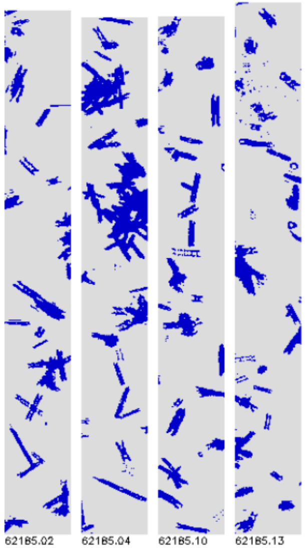


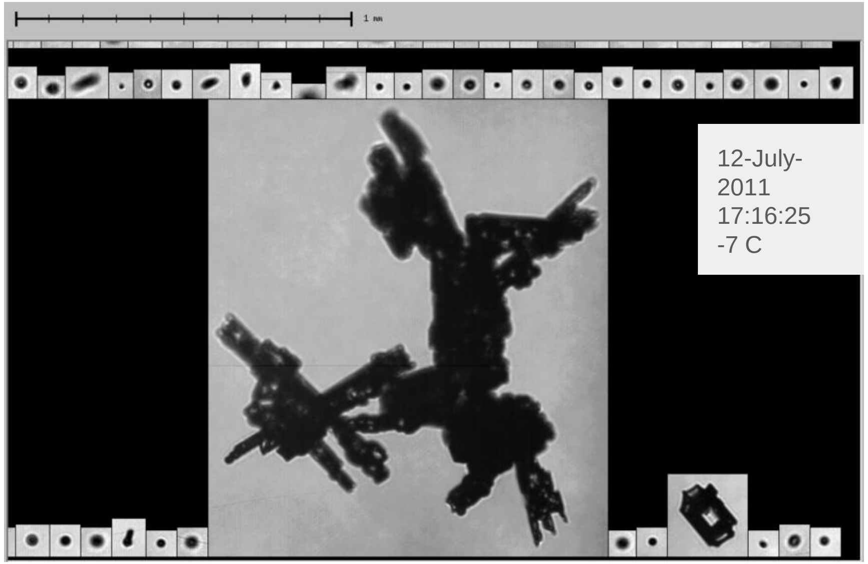


12-July-2011
17:13:42
-5 C

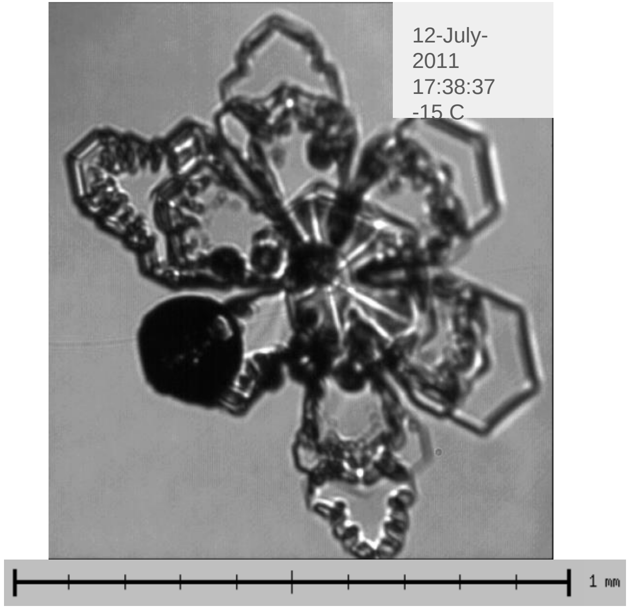
ICE-T

Needles (not regularly seen in HIWC-2022)





Contact nucleation and possible droplet breakup



Lab Studies

Secondary Ice Production (SIP)
(mainly drop freezing)

Laboratory Studies:

1: Knight & Knight 1973

- Broken drops found preserved as hailstone embryos
- 3-4 mm in diameter

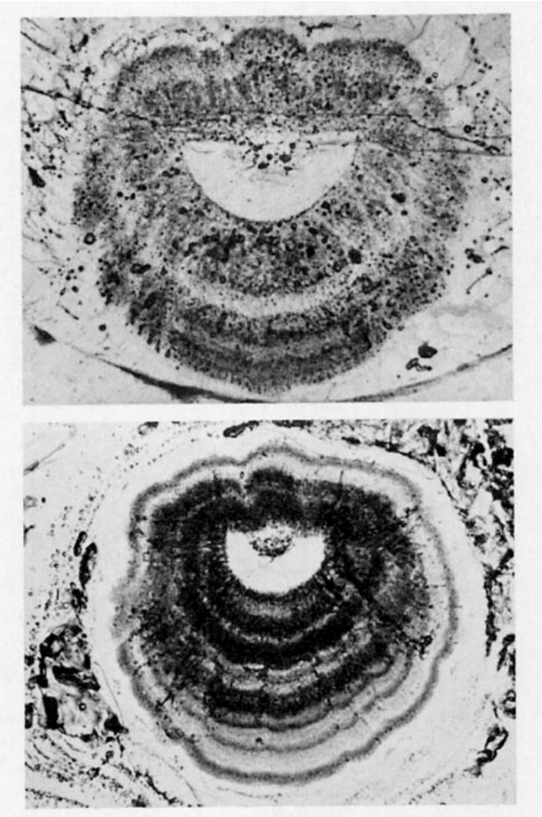


FIG. 1. Embryo portions of two stones with broken-drop centers. Top: collected North of Stoneham, Colo., on 15 July 1971, length of the flat side of the hemisphere 2.9 mm; bottom: collected at Sickles, Okla., 18 June 1973, length of the flat side of the hemisphere 4.1 mm. In both of these cases, further accretion appears to be dry growth, and is clearly much faster on the rounded side of the hemisphere than on the flat side, indicating that these hemispheres tend to fall with the rounded side down. This is most commonly the case.

Laboratory Studies:

2: Hallett & Mossop 1974

- Found secondary ice was produced in a cloud chamber when a spinning rod started to rime at various temperatures
- SIP was mostly active in the -3°C to -8°C range
- Speculated that somehow related to columnar crystal growth at -5°C, but no firm physical mechanism

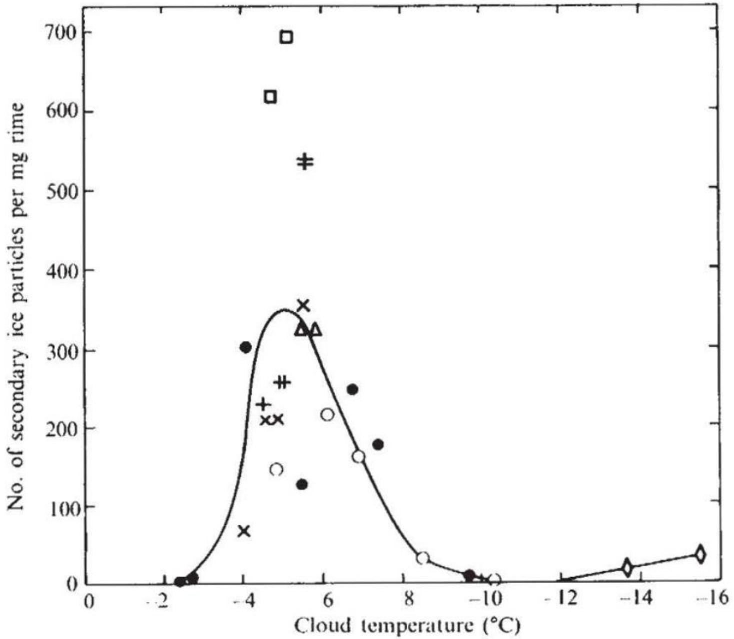
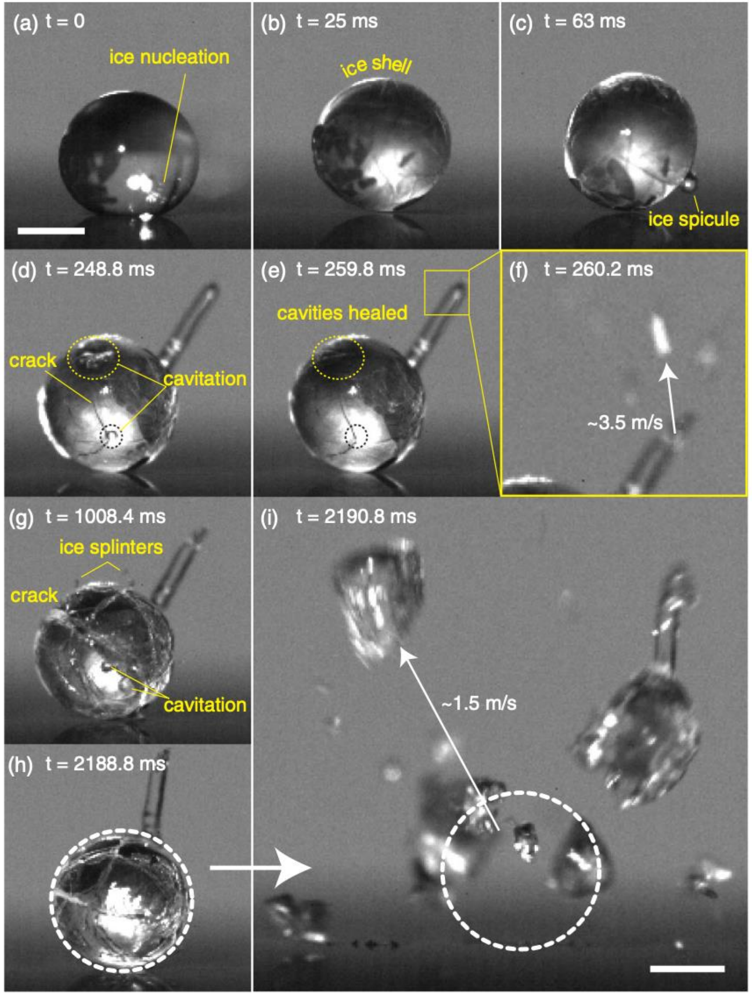


FIG. 2 Production of secondary ice particles by riming as a function of temperature at a target velocity of 2.7 m s^{-1}. Different symbols indicate different days. The curve was drawn by averaging the points over narrow temperature intervals.

Laboratory Studies:

3: Wildeman et al. 2017

- Froze supercooled drops in the laboratory and characterized the forces required for spontaneous breakup
- Showed mathematically how large (~mm) drops more likely to explode, while impossible to happen with small (<50 microns) droplets



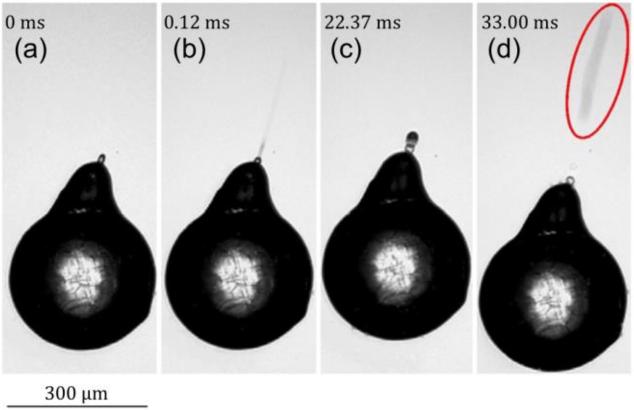
Laboratory Studies:

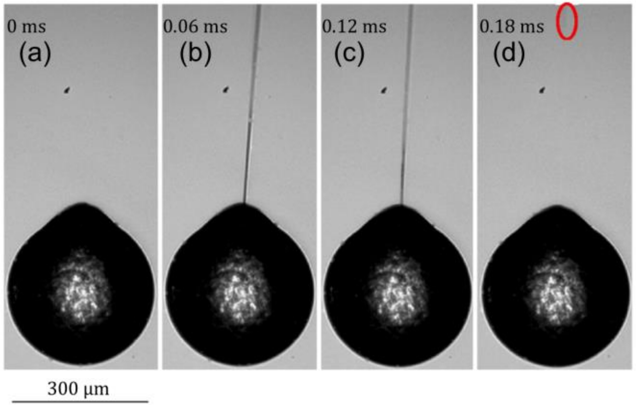
4: Lauber et al. 2018

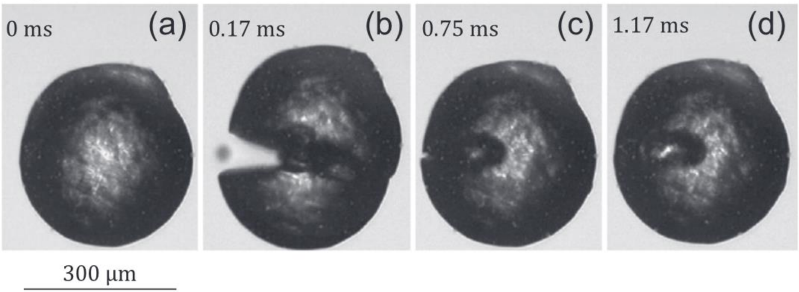
- High speed video of water ejection and SIP from levitated freezing drops
- Observed a number of possible SIP mechanisms
  - Bubble breakup
  - Jets
  - Explosion
  - Explosion + recombination
- Large droplets (~300 um) generally required for SIP
- Small droplets (~85 um) far less productive

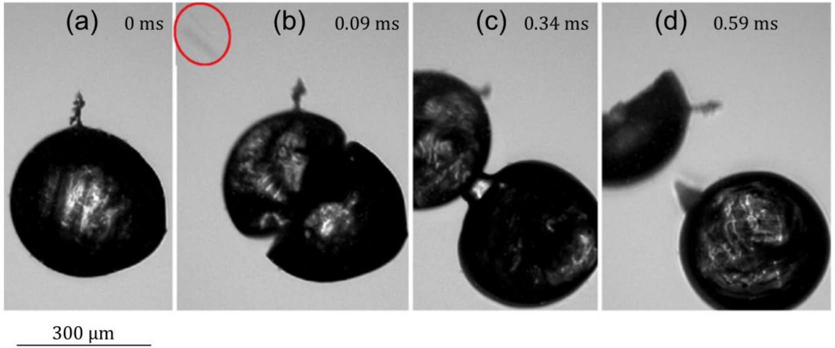
4: Lauber et al. 2018

4 SIP mechanisms









4: Lauber et al. 2018

Higher cracking and breakup frequency with contaminated water

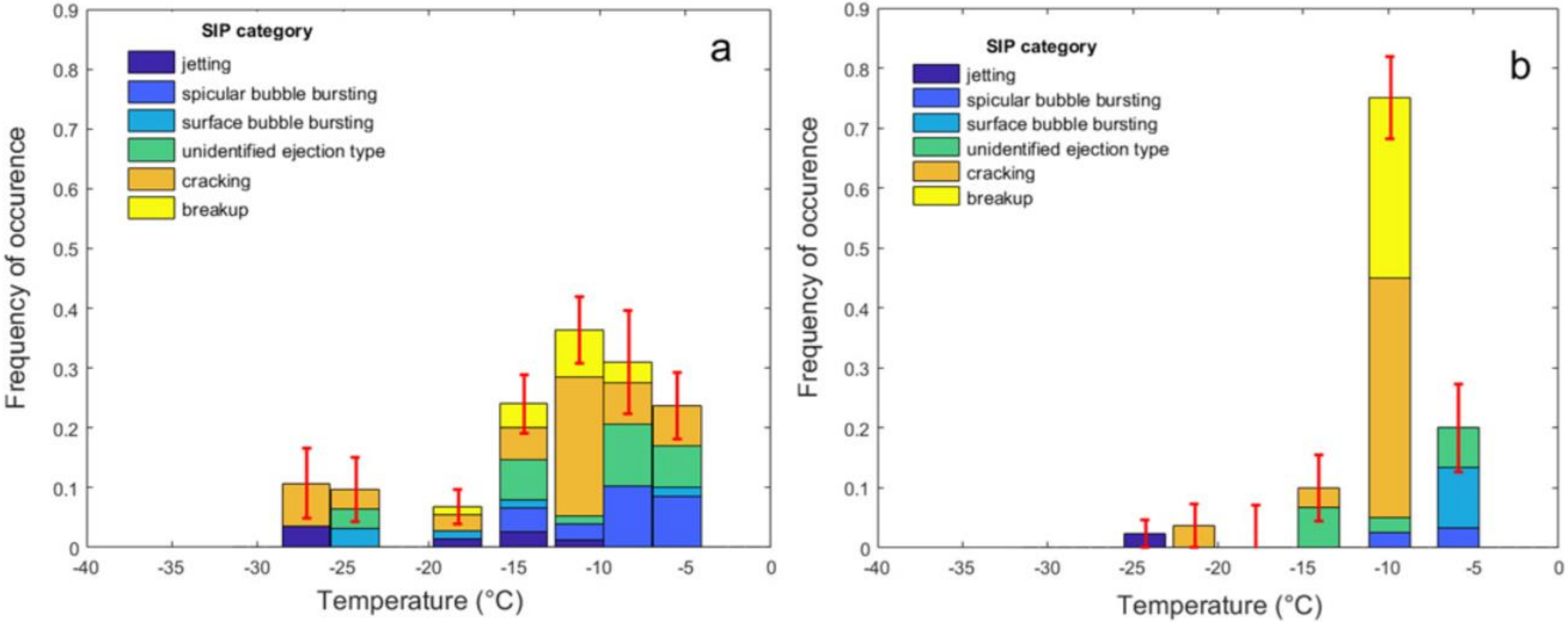


FIG. 8. Mechanism-resolved SIP frequency of occurrence for large droplets as a function of temperature: (a) pure water droplets and (b) droplets containing PSL particles.

4: Lauber et al. 2018

Larger drops break up more frequently and produce more secondary fragments

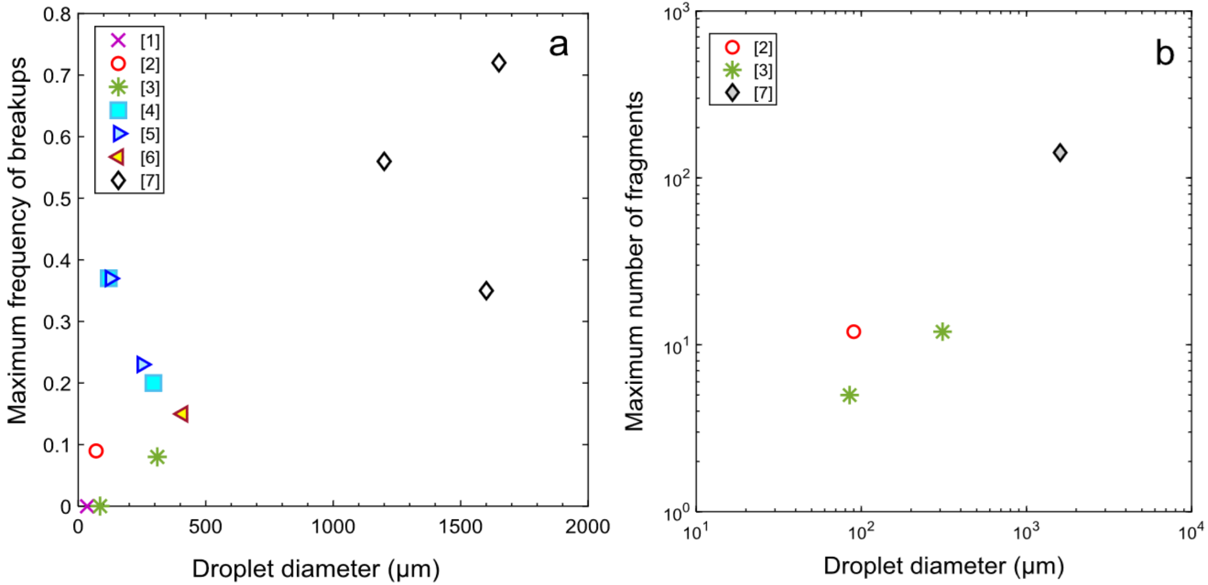


FIG. 9. Previous results of the laboratory studies of SIP. (a) The maximum frequency of breakups and (b) the maximum number of ejected splinters (if provided) over the droplet size for freely levitated pure water droplets. The reference numbers are as follows: 1–Hobbs and Alkezweeny (1968), 2–Brownscombe and Thorndike (1968), –our own results reported herein, 4–Takahashi (1975), 5–Takahashi and Yamashita (1970), 6–Pruppacher and Schlamp (1975), and 7–Kolomeychuk et al. (1975).

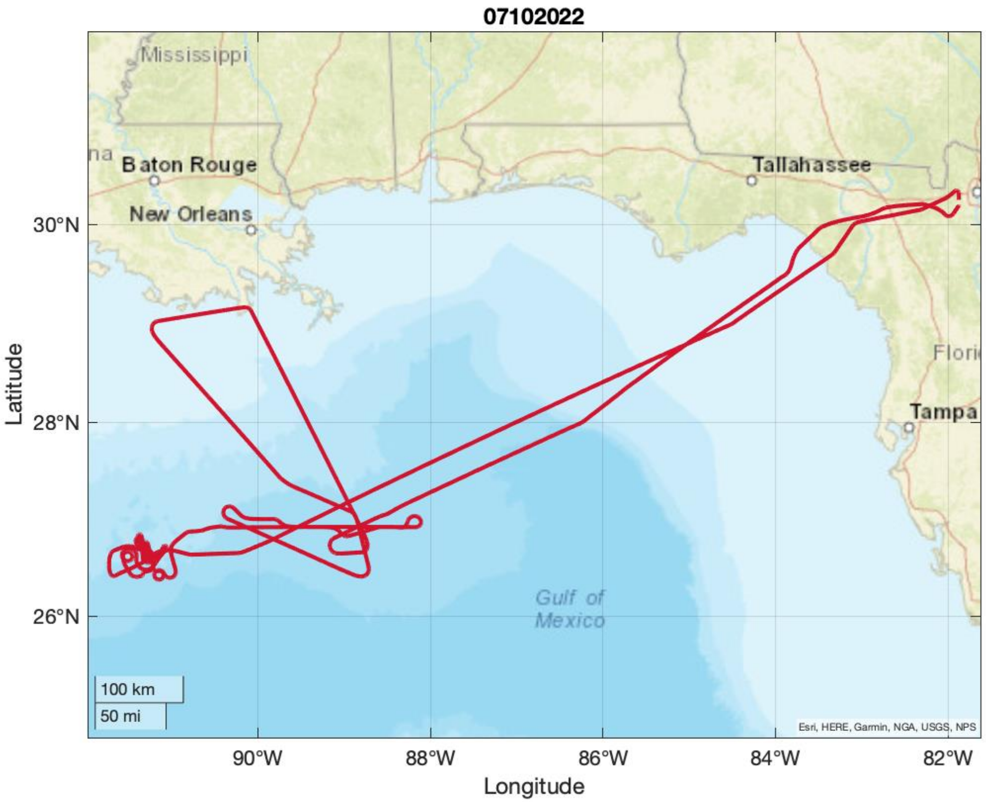
Modeling Studies

- Lawson et al. 2015 used 1D cloud model to show that droplet breakup could reproduce observed ice concentrations
- Many others with broader SIP mechanisms (e.g. mechanical breakup, sublimation) not just in small cumulus
  - Yano and Phillips 2011
  - Gupta et al. 2023
  - Connolly et al. 2007
  - …

HIWC-2022 Observations

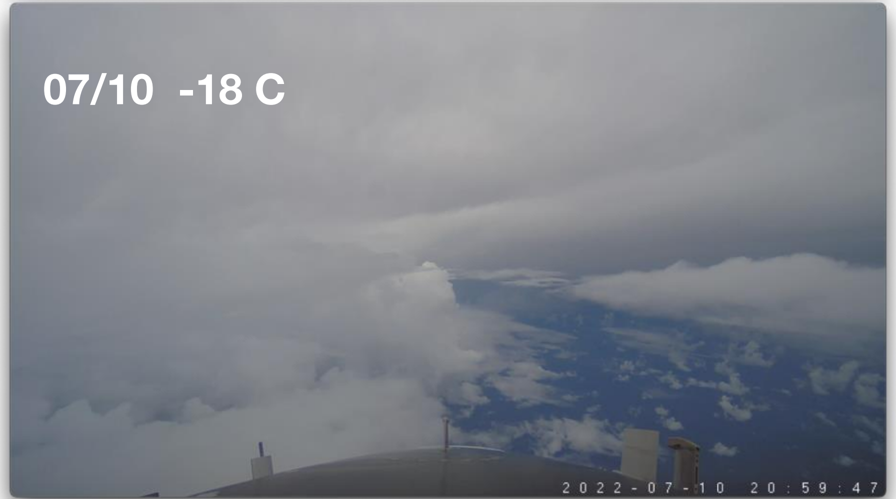
July 10, 2022

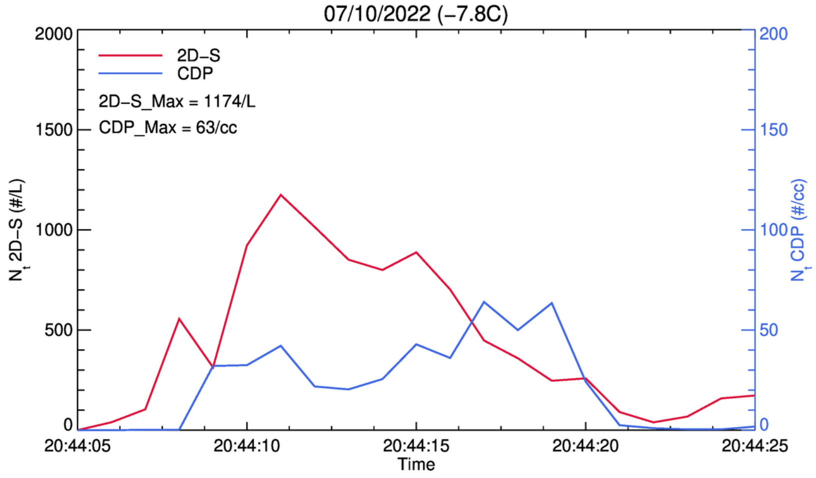
- Several cloud penetrations at -18 C and -8 C
- Cirrus deck overhead
- Complicated cloud field, clouds not clearly isolated

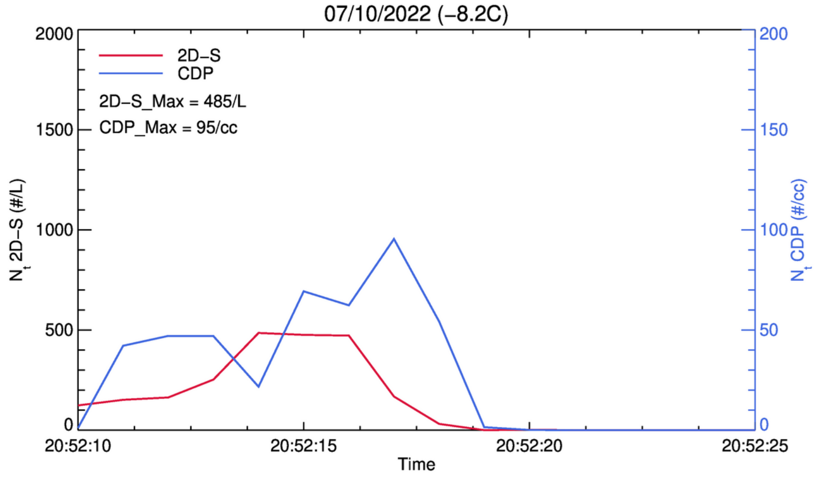


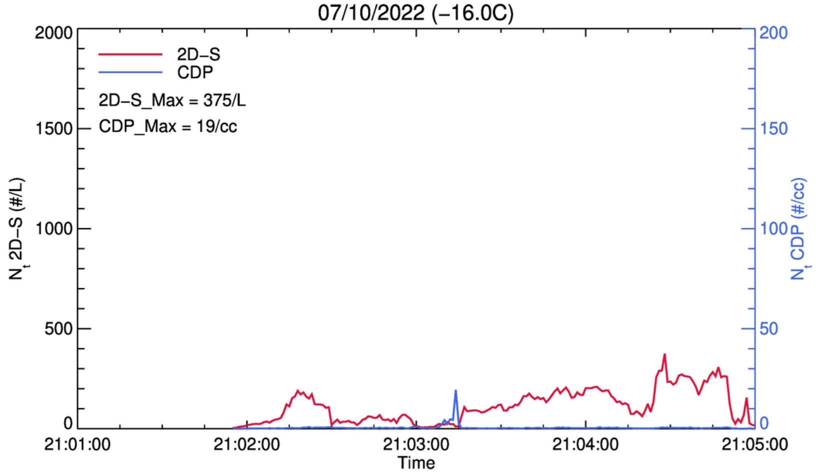

07/10 -8 C
2022-07-10 20:42:48


07/10 -8 C
2022-07-10 20:50:24


07/10 -18 C
2022-07-10 20:59:47

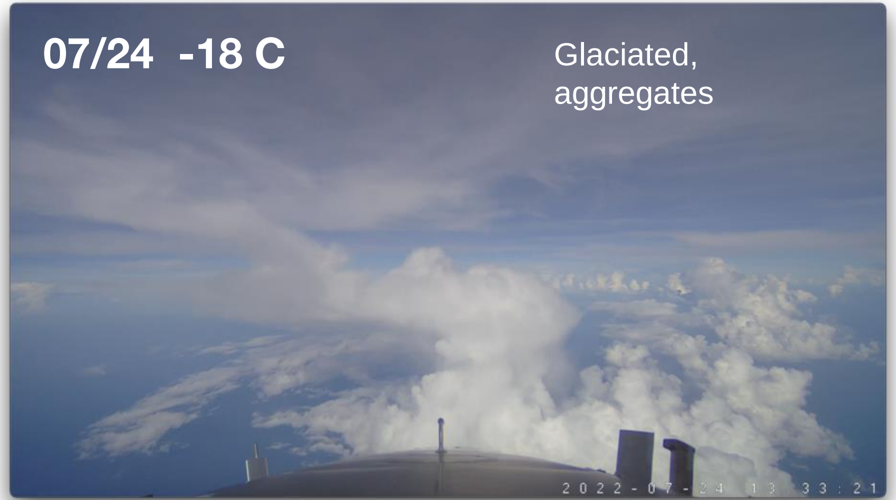

07/10/2022 (−7.8C)
2D−S
CDP
2D−S_Max = 1174/L
CDP_Max = 63/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
2000
1500
1000
500
0
200
150
100
50
0
20:44:05
20:44:10
20:44:15
20:44:20
20:44:25
Time


07/10/2022 (−8.2C)
2D−S
CDP
2D−S_Max = 485/L
CDP_Max = 95/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
2000
1500
1000
500
0
200
150
100
50
0
20:52:10
20:52:15
20:52:20
20:52:25
Time


07/10/2022 (−16.0C)
2D−S
CDP
2D−S_Max = 375/L
CDP_Max = 19/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
2000
1500
1000
500
0
200
150
100
50
0
21:01:00
21:02:00
21:03:00
21:04:00
21:05:00
Time

July 24, 2022

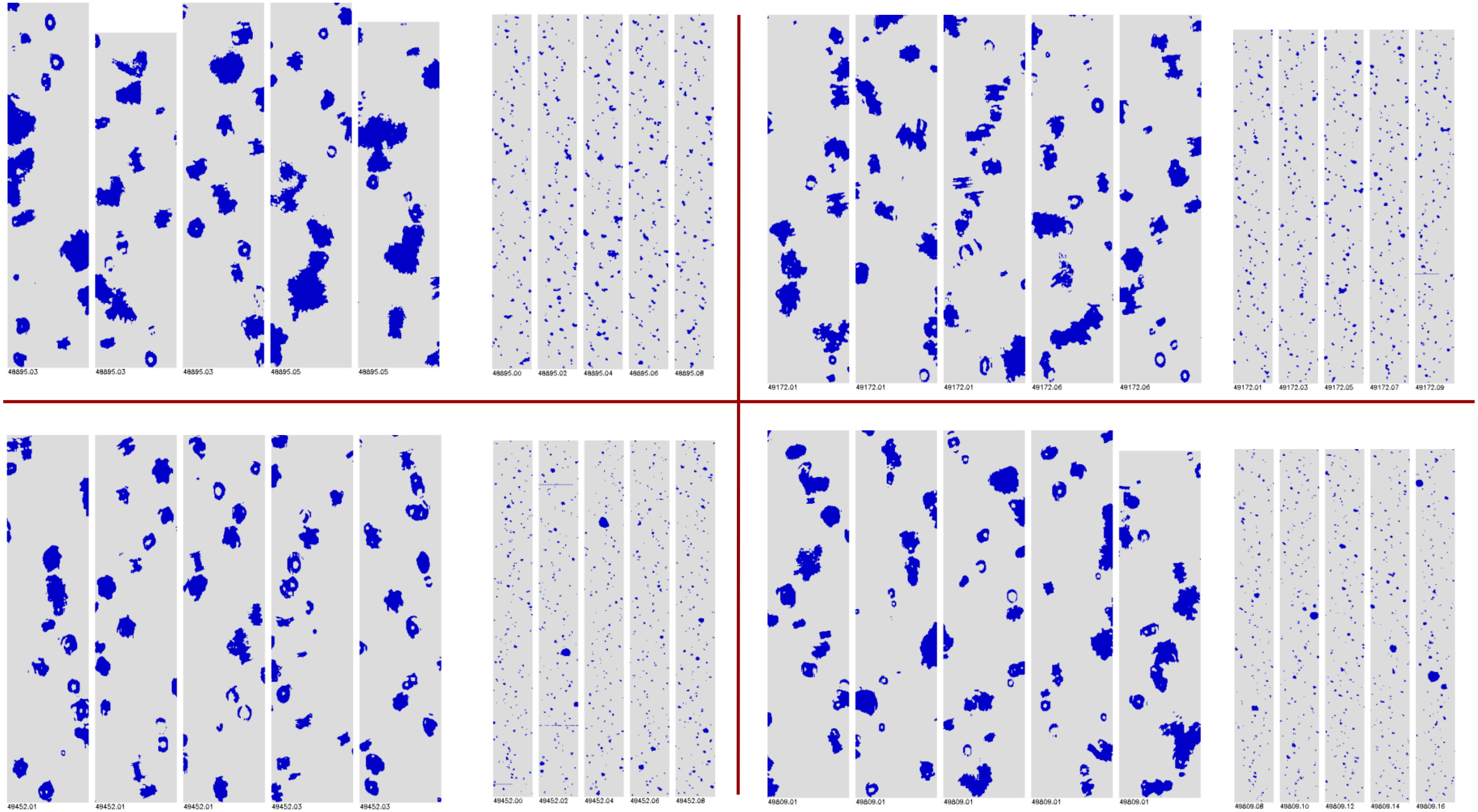
- **-18 C**: 4 cloud penetrations
  - Light cirrus overhead
  - All cloud passes were fully glaciated
  - No graupel
  - No liquid water
  - Low CDP concentrations
- **-9 C**: 6 cloud penetrations
  - Moderate CDP concentrations measured in two clouds
- PIP Intermittent


07/24 -18 C
Glaciated, aggregates
2022-07-24 13:33:21


Glaciated, aggregates
2022-07-24 13:37:49


Glaciated, small ice crystals, small graupel on PIP
2022-07-24 13:42:23


Glaciated, small ice and aggregates, graupel on PIP
2022-07-24 13:48:13


48895.03
48895.03
48895.03
48895.05
48895.05
48895.00
48895.02
48895.04
48895.06
48895.08
49172.01
49172.01
49172.01
49172.06
49172.06
49172.01
49172.03
49172.05
49172.07
49172.09
49452.01
49452.01
49452.01
49452.03
49452.03
49452.00
49452.02
49452.04
49452.06
49452.08
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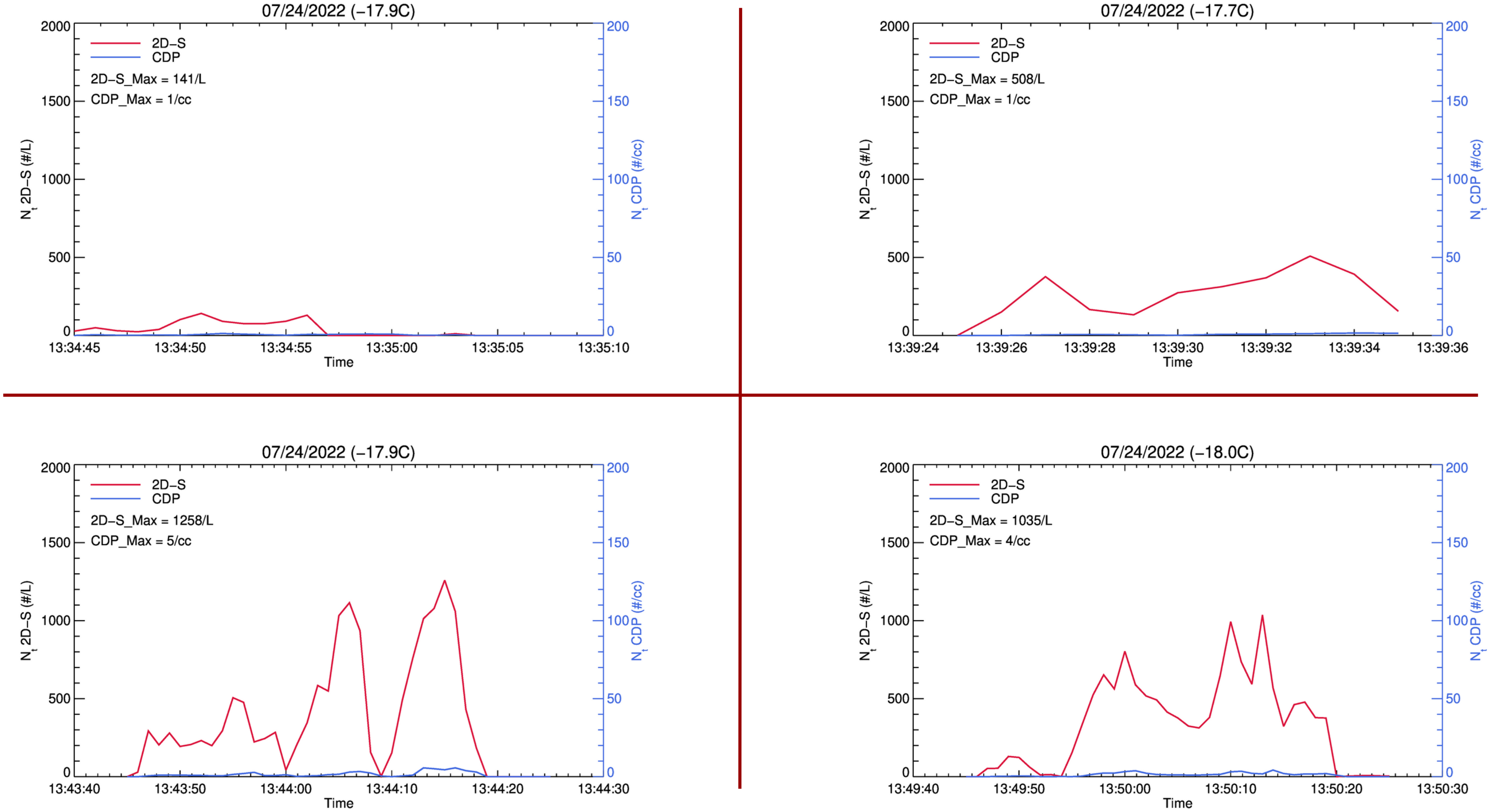
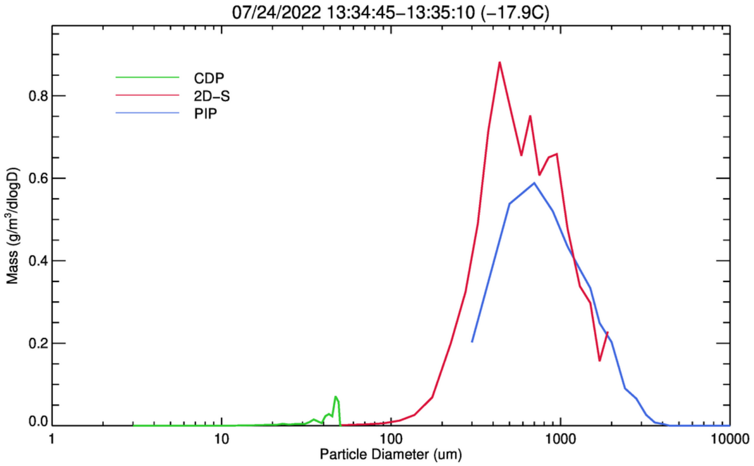
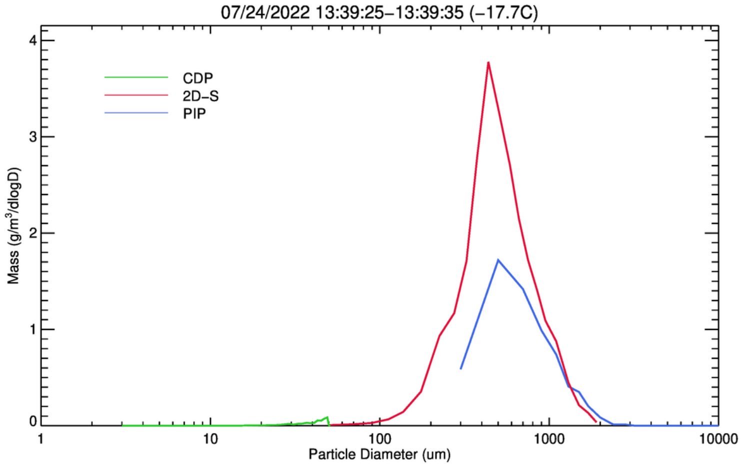
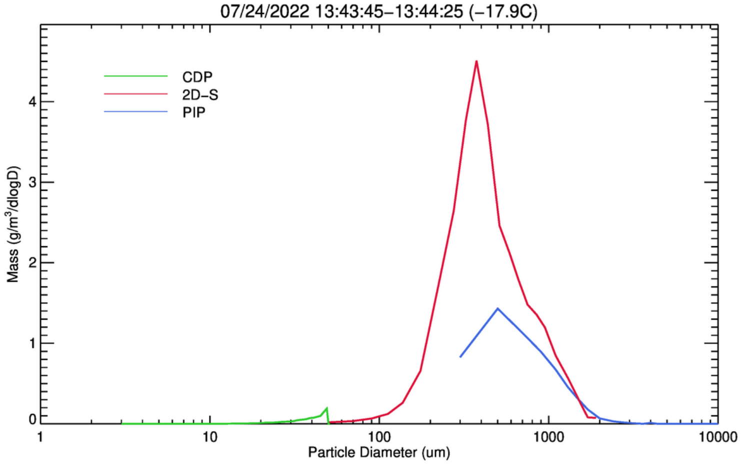
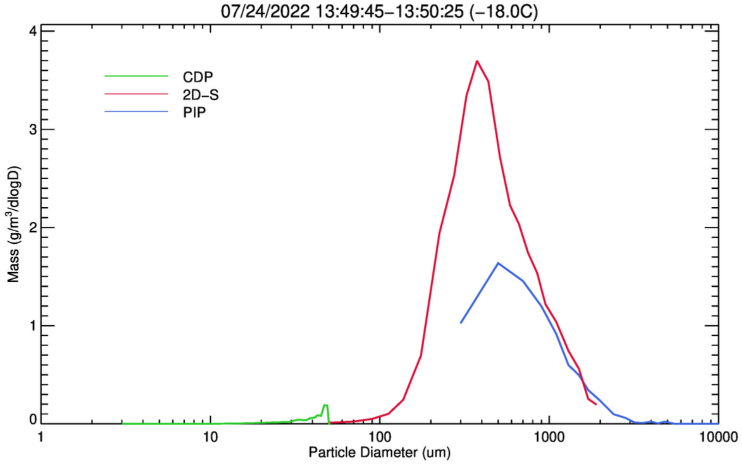
49809.14
49809.16

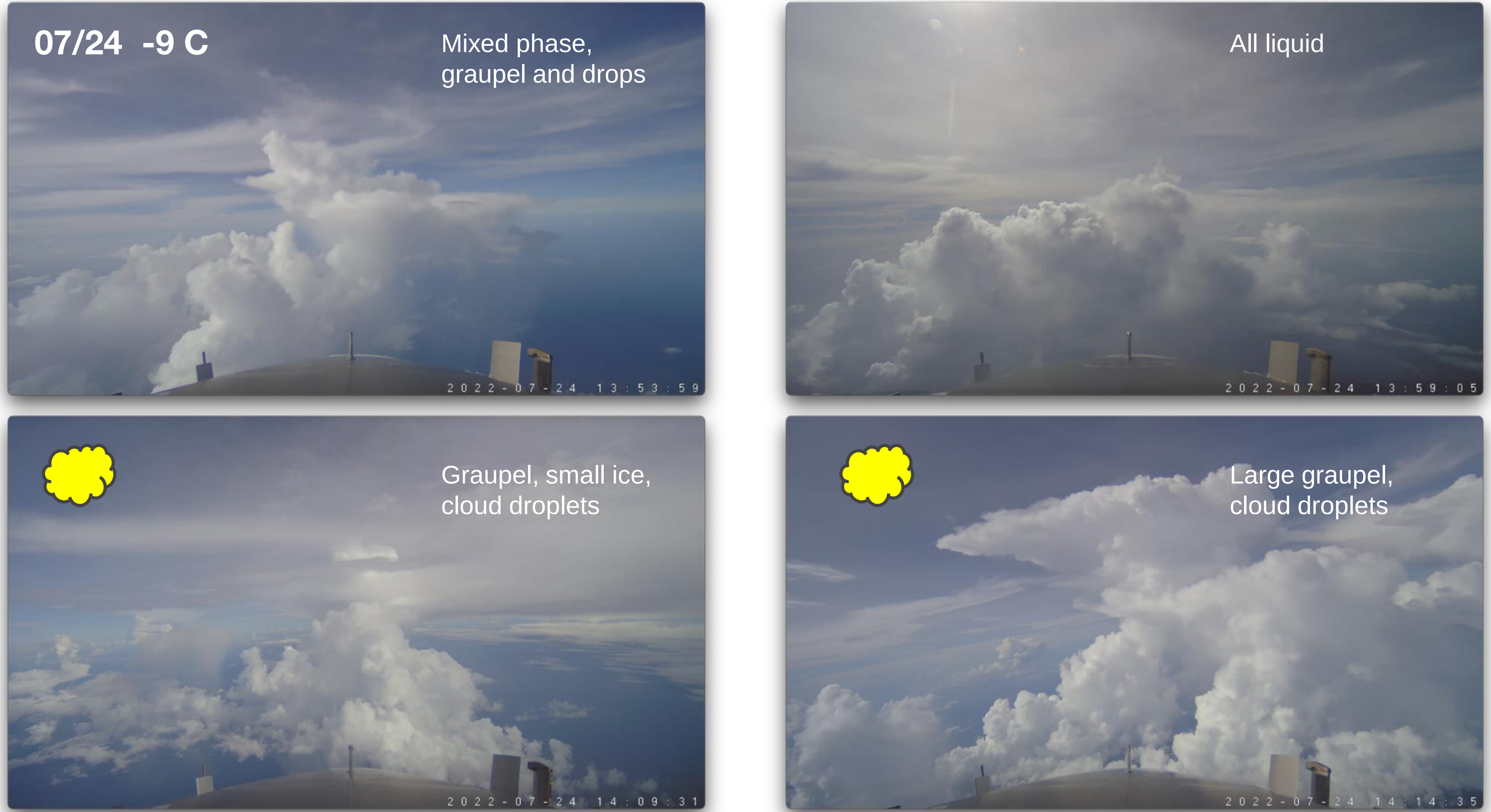

07/24/2022 (−17.9C)
2D−S
CDP
2D−S_Max = 141/L
CDP_Max = 1/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
13:34:45
13:34:50
13:34:55
13:35:00
13:35:05
13:35:10
07/24/2022 (−17.7C)
2D−S
CDP
2D−S_Max = 508/L
CDP_Max = 1/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
13:39:24
13:39:26
13:39:28
13:39:30
13:39:32
13:39:34
13:39:36
07/24/2022 (−17.9C)
2D−S
CDP
2D−S_Max = 1258/L
CDP_Max = 5/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
13:43:40
13:43:50
13:44:00
13:44:10
13:44:20
13:44:30
07/24/2022 (−18.0C)
2D−S
CDP
2D−S_Max = 1035/L
CDP_Max = 4/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
13:49:40
13:49:50
13:50:00
13:50:10
13:50:20
13:50:30
0
500
1000
1500
2000
0
50
100
150
200

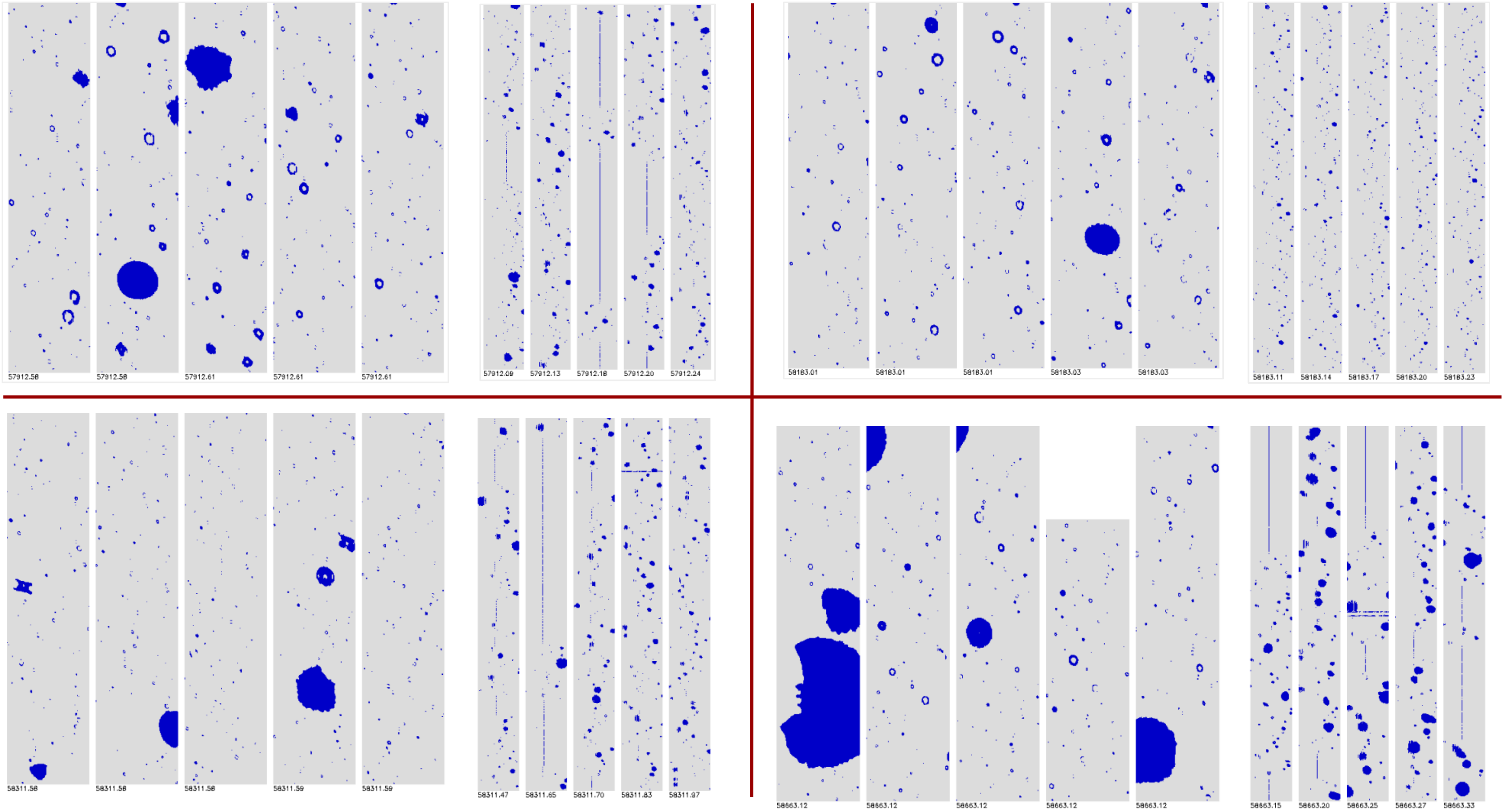

07/24/2022 13:34:45–13:35:10 (–17.9C)
CDP
2D–S
PIP
Mass (g/m^3/dlogD)
Particle Diameter (um)
0.0
0.2
0.4
0.6
0.8
1
10
100
1000
10000

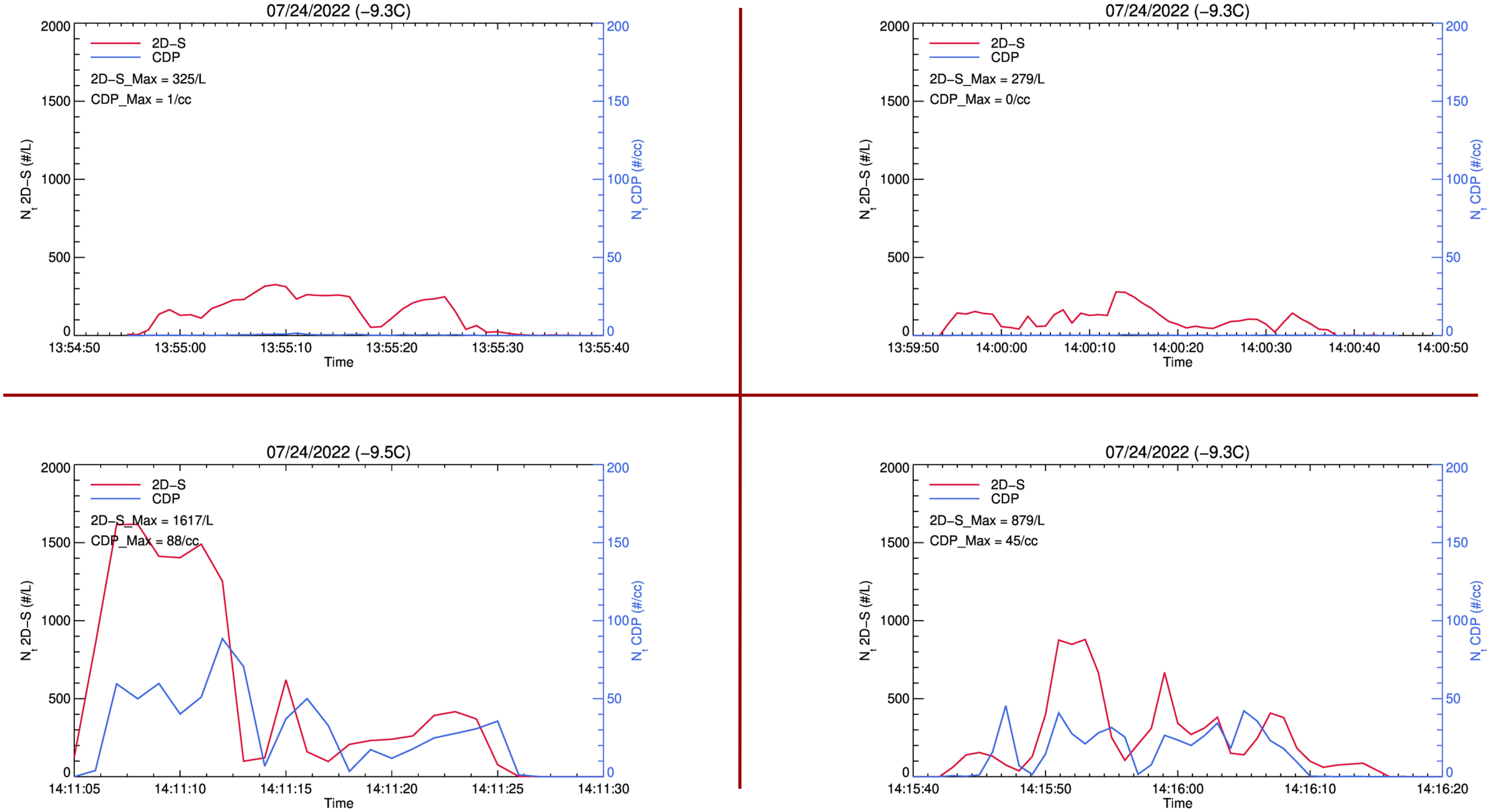

07/24/2022 13:39:25–13:39:35 (–17.7C)
CDP
2D–S
PIP
Mass (g/m^3/dlogD)
Particle Diameter (um)
0
1
2
3
4
1
10
100
1000
10000


07/24/2022 13:43:45–13:44:25 (–17.9C)
CDP
2D–S
PIP
Mass (g/m^3/dlogD)
Particle Diameter (um)
0
1
2
3
4
1
10
100
1000
10000

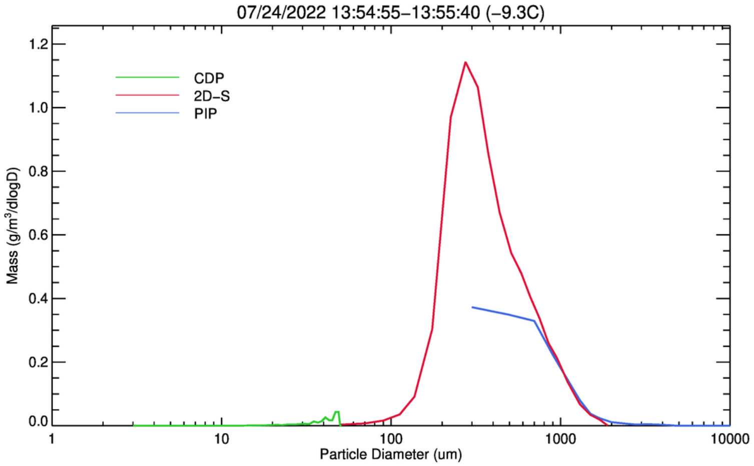

07/24/2022 13:49:45–13:50:25 (–18.0C)
CDP
2D–S
PIP
Mass (g/m^3/dlogD)
Particle Diameter (um)
0
1
2
3
4
1
10
100
1000
10000

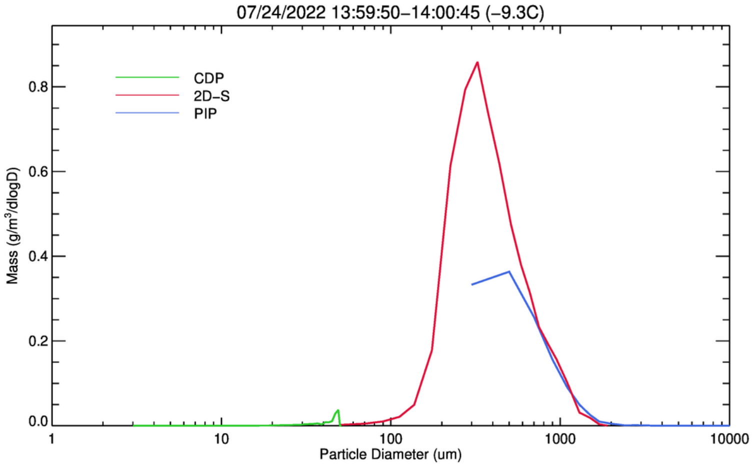

07/24 -9 C
Mixed phase,
graupel and drops
2 0 2 2 - 0 7 - 2 4   1 3 : 5 3 : 5 9
All liquid
2 0 2 2 - 0 7 - 2 4   1 3 : 5 9 : 0 5
Graupel, small ice,
cloud droplets
2 0 2 2 - 0 7 - 2 4   1 4 : 0 9 : 3 1
Large graupel,
cloud droplets
2 0 2 2 - 0 7 - 2 4   1 4 : 1 4 : 3 5


57912.58
57912.58
57912.61
57912.61
57912.61
57912.09
57912.13
57912.18
57912.20
57912.24
58183.01
58183.01
58183.01
58183.03
58183.03
58183.11
58183.14
58183.17
58183.20
58183.23
58311.58
58311.58
58311.58
58311.59
58311.59
58311.47
58311.65
58311.70
58311.83
58311.97
58663.12
58663.12
58663.12
58663.12
58663.12
58663.15
58663.20
58663.25
58663.27
58663.33

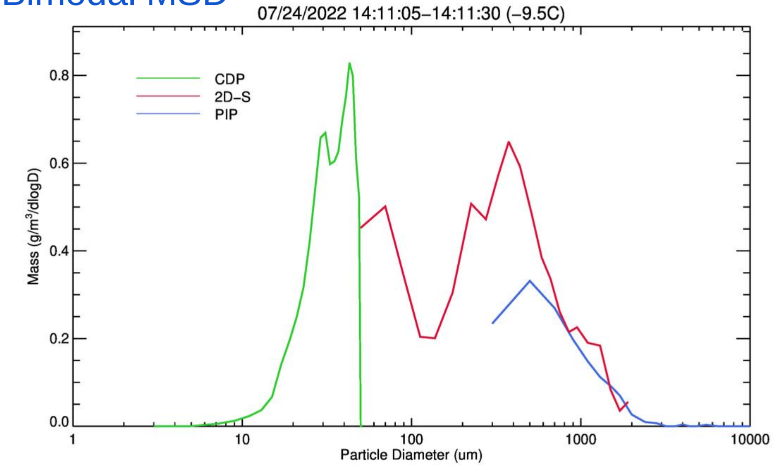


07/24/2022 (−9.3C)
2D−S
CDP
2D−S_Max = 325/L
CDP_Max = 1/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
07/24/2022 (−9.3C)
2D−S
CDP
2D−S_Max = 279/L
CDP_Max = 0/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
07/24/2022 (−9.5C)
2D−S
CDP
2D−S_Max = 1617/L
CDP_Max = 88/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
07/24/2022 (−9.3C)
2D−S
CDP
2D−S_Max = 879/L
CDP_Max = 45/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time

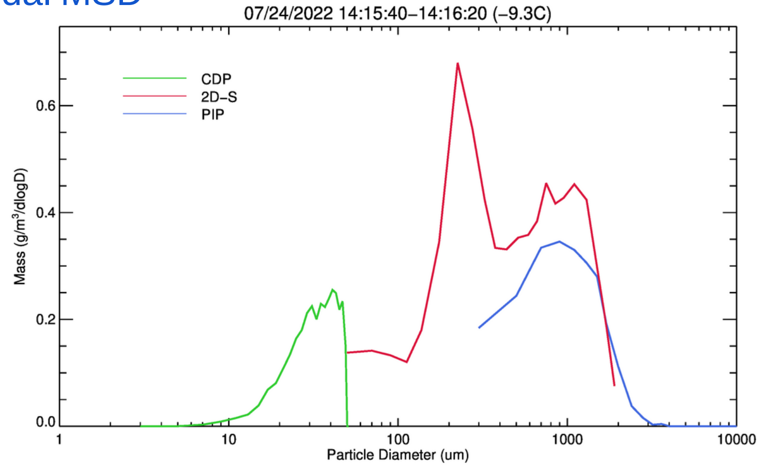




Bimodal MSD

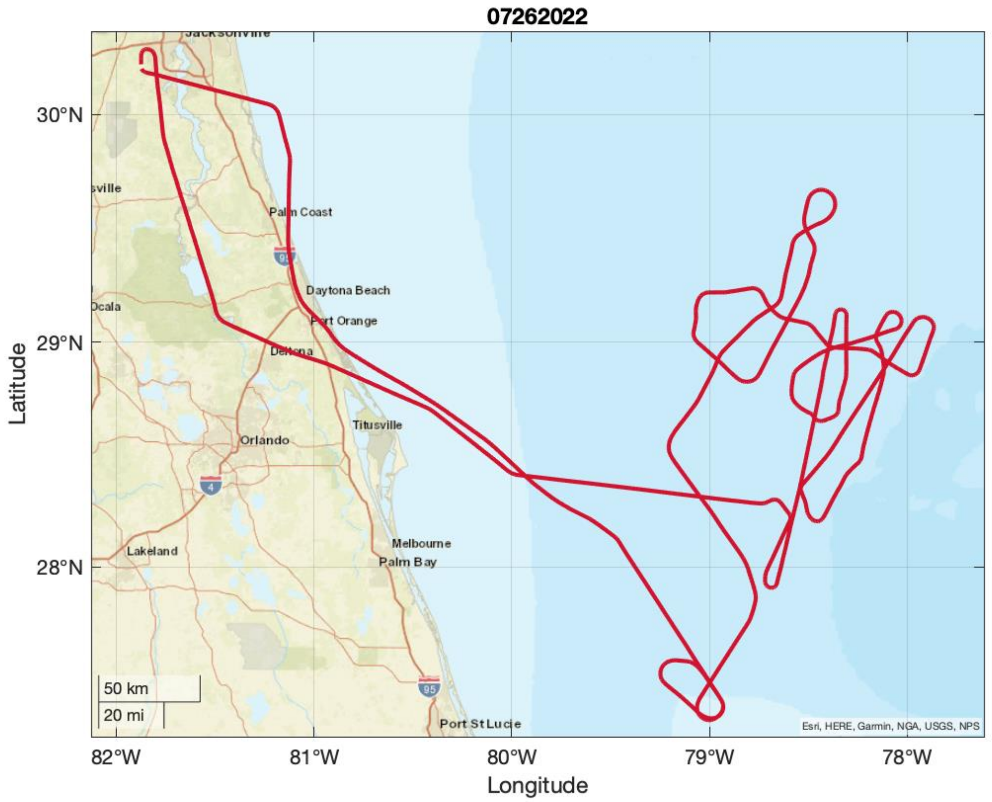


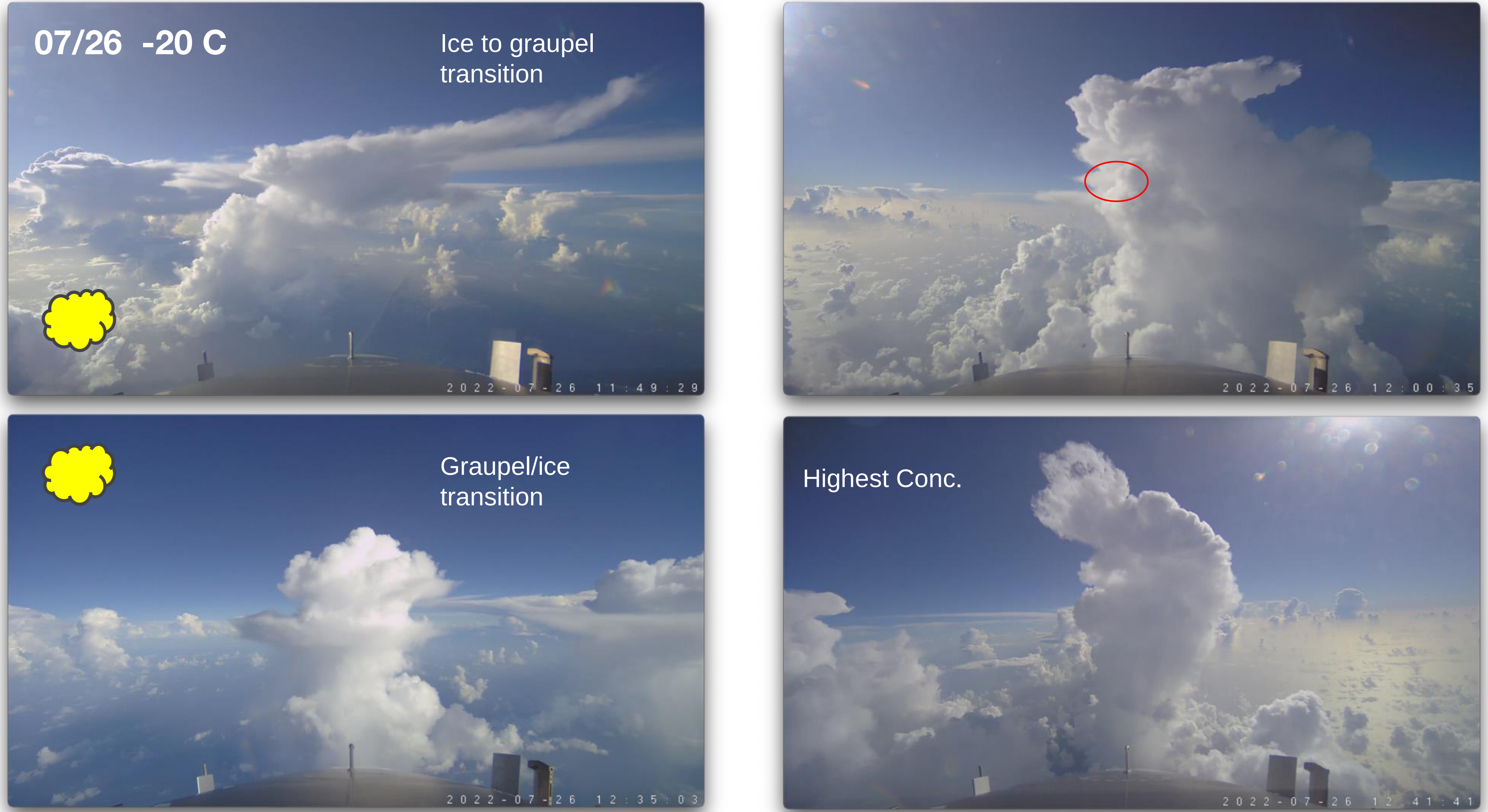
Multi-modal MSD

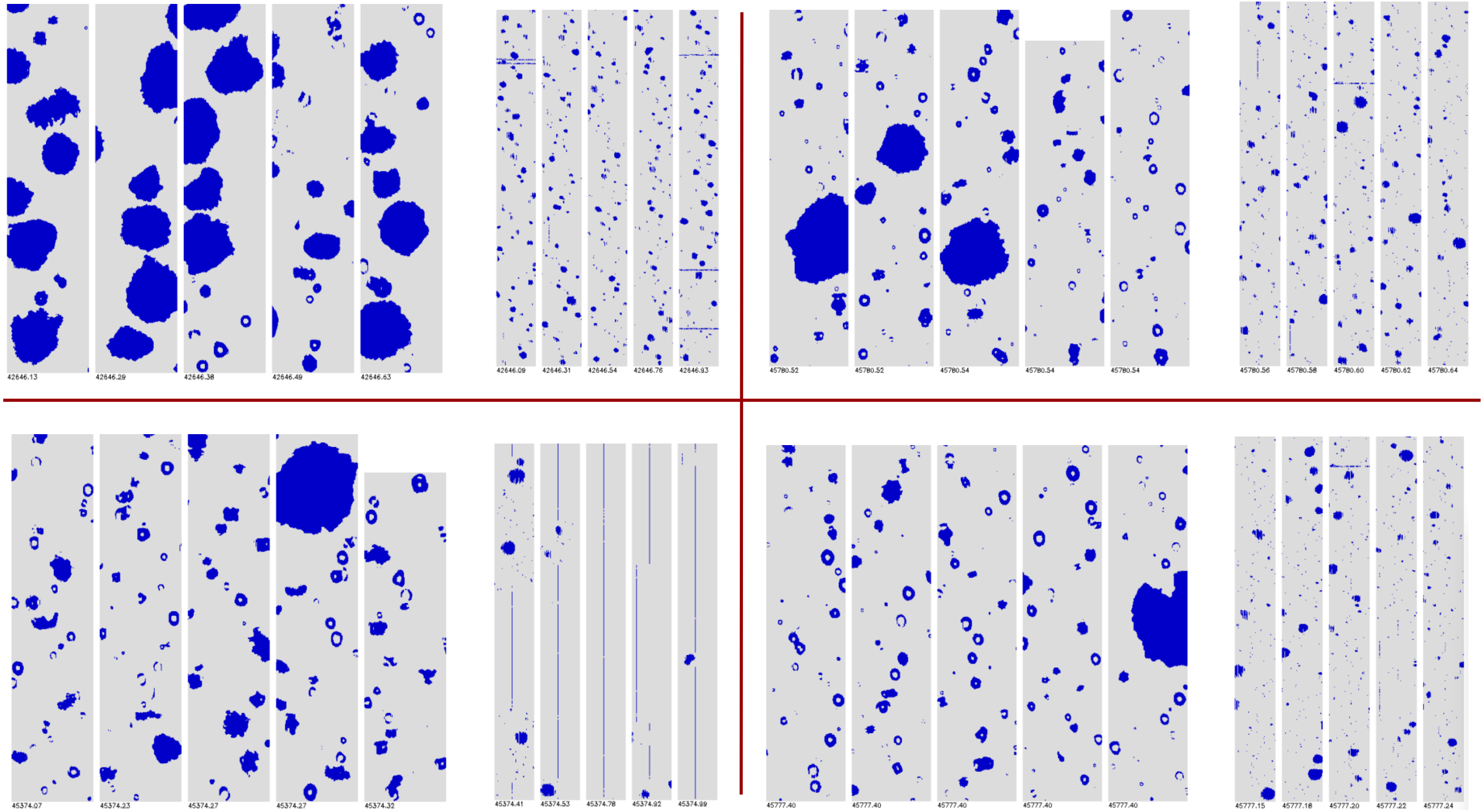


July 26, 2022

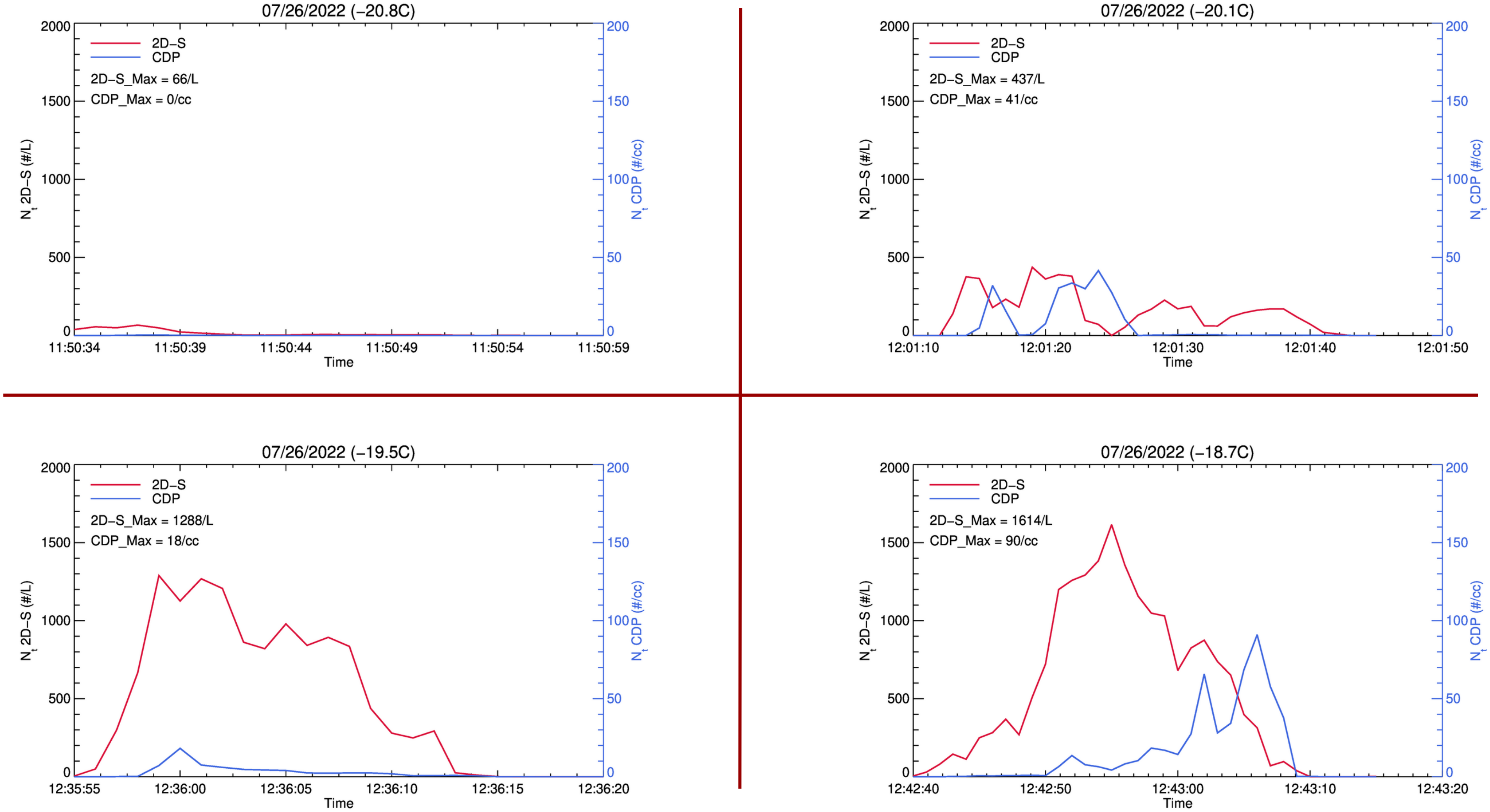
- **-20 C**: 8 cloud penetrations
  - Clear air above
  - Some clouds have glaciated appearance, others not
  - Sharp transitions from small ice to graupel
- **-10 C**: 5 cloud penetrations
  - Mix of liquid, small ice, and graupel varies for each cloud pass
- Poor imagery on the PIP, large aggregates/graupel/drops identifiable



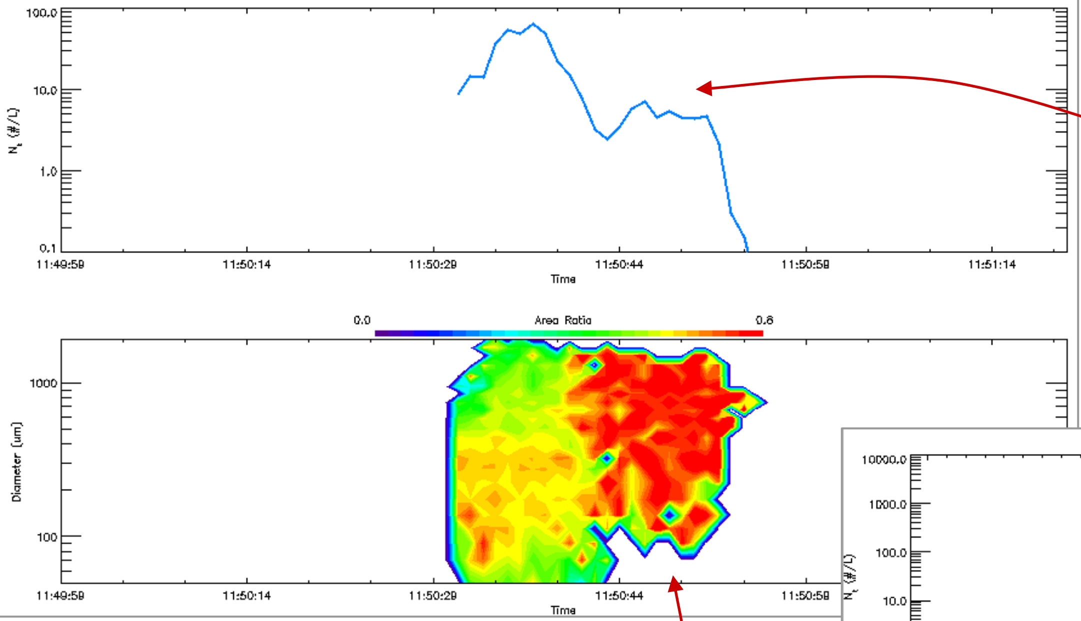

07/26 -20 C
Ice to graupel
transition
2022-07-26 11:49:29
2022-07-26 12:00:35
Graupel/ice
transition
2022-07-26 12:35:03
Highest Conc.
2022-07-26 12:41:41



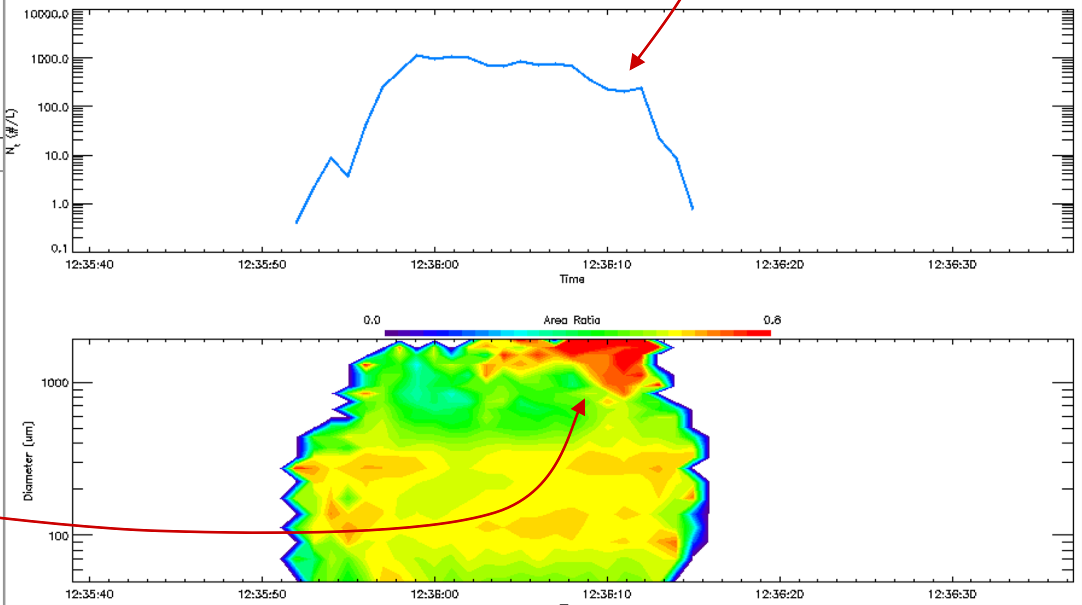
42646.13
42646.29
42646.38
42646.49
42646.63
42646.09
42646.31
42646.54
42646.76
42646.93
45780.52
45780.52
45780.54
45780.54
45780.54
45780.56
45780.58
45780.60
45780.62
45780.64
45374.07
45374.23
45374.27
45374.27
45374.32
45374.41
45374.53
45374.78
45374.92
45374.99
45777.40
45777.40
45777.40
45777.40
45777.40
45777.15
45777.18
45777.20
45777.22
45777.24



07/26/2022 (−20.8C)
2D−S
CDP
2D−S_Max = 66/L
CDP_Max = 0/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
11:50:34
11:50:39
11:50:44
11:50:49
11:50:54
11:50:59
Time
07/26/2022 (−20.1C)
2D−S
CDP
2D−S_Max = 437/L
CDP_Max = 41/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
12:01:10
12:01:20
12:01:30
12:01:40
12:01:50
Time
07/26/2022 (−19.5C)
2D−S
CDP
2D−S_Max = 1288/L
CDP_Max = 18/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
12:35:55
12:36:00
12:36:05
12:36:10
12:36:15
12:36:20
Time
07/26/2022 (−18.7C)
2D−S
CDP
2D−S_Max = 1614/L
CDP_Max = 90/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
12:42:40
12:42:50
12:43:00
12:43:10
12:43:20
Time



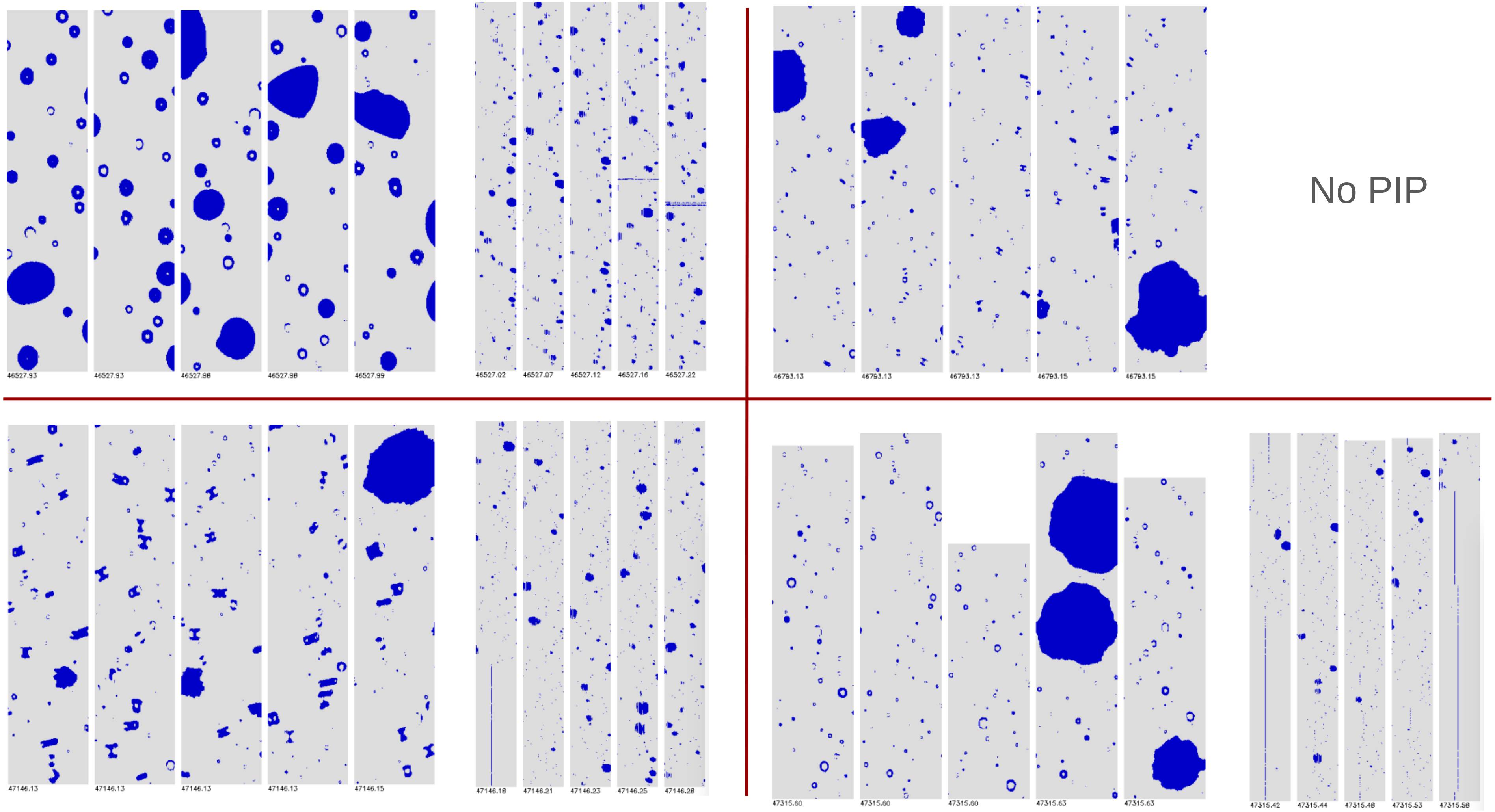
Both cases show a drop in total concentration with the transition to graupel

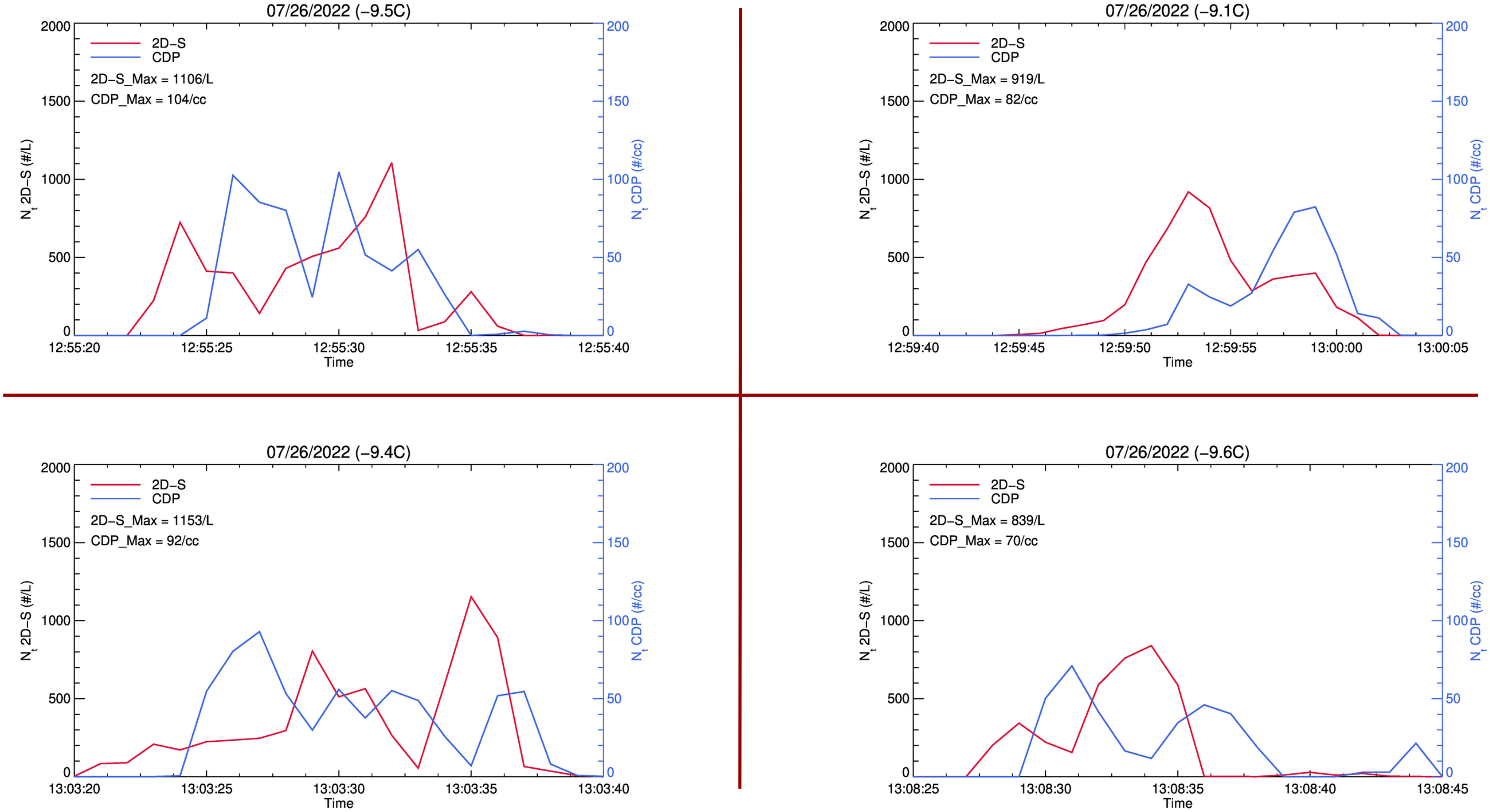


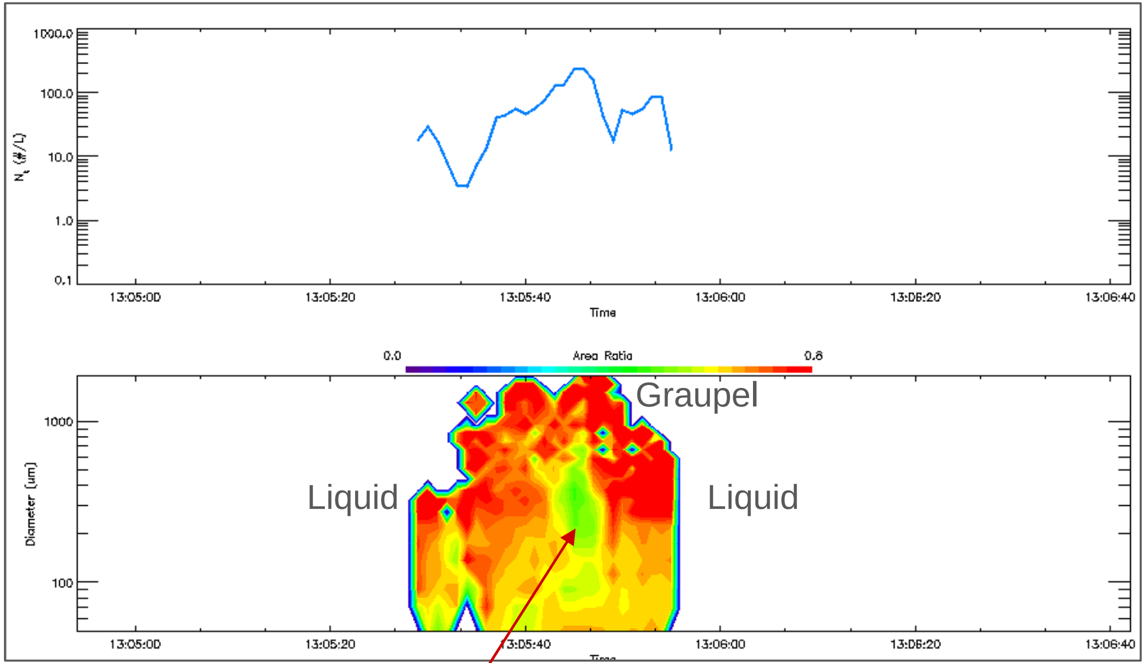
Full graupel transition

Large graupel only


07/26 -10 C
Mostly liquid
2022-07-26 12:55:01
Graupel and mixed-phase small ice
2022-07-26 12:58:27
Mixed phase Ice core, liquid edges
2022-07-26 13:02:53
Graupel and rain, no small ice
2022-07-26 13:07:33


No PIP
46527.93
46527.93
46527.98
46527.98
46527.99
46527.02
46527.07
46527.12
46527.16
46527.22
46793.13
46793.13
46793.13
46793.15
46793.15
47146.13
47146.13
47146.13
47146.13
47146.15
47146.18
47146.21
47146.23
47146.25
47146.28
47315.60
47315.60
47315.60
47315.63
47315.63
47315.42
47315.44
47315.48
47315.53
47315.58

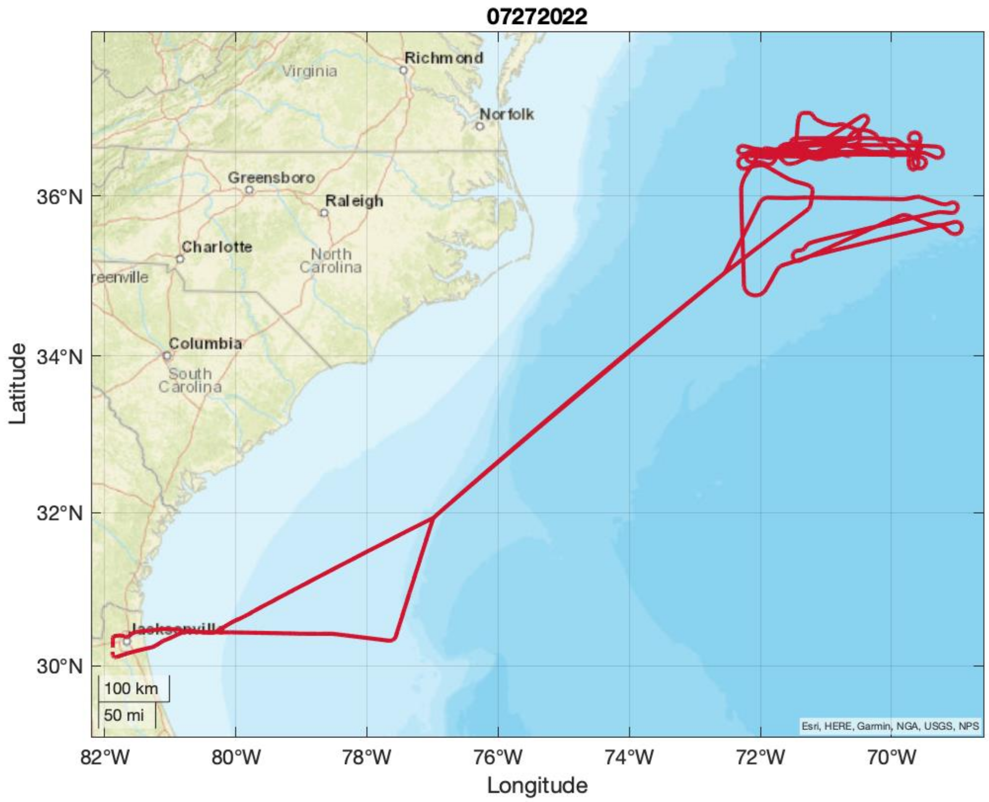

07/26/2022 (−9.5C)
2D−S
CDP
2D−S_Max = 1106/L
CDP_Max = 104/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
12:55:20
12:55:25
12:55:30
12:55:35
12:55:40
07/26/2022 (−9.1C)
2D−S
CDP
2D−S_Max = 919/L
CDP_Max = 82/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
12:59:40
12:59:45
12:59:50
12:59:55
13:00:00
13:00:05
07/26/2022 (−9.4C)
2D−S
CDP
2D−S_Max = 1153/L
CDP_Max = 92/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
13:03:20
13:03:25
13:03:30
13:03:35
13:03:40
07/26/2022 (−9.6C)
2D−S
CDP
2D−S_Max = 839/L
CDP_Max = 70/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
13:08:25
13:08:30
13:08:35
13:08:40
13:08:45

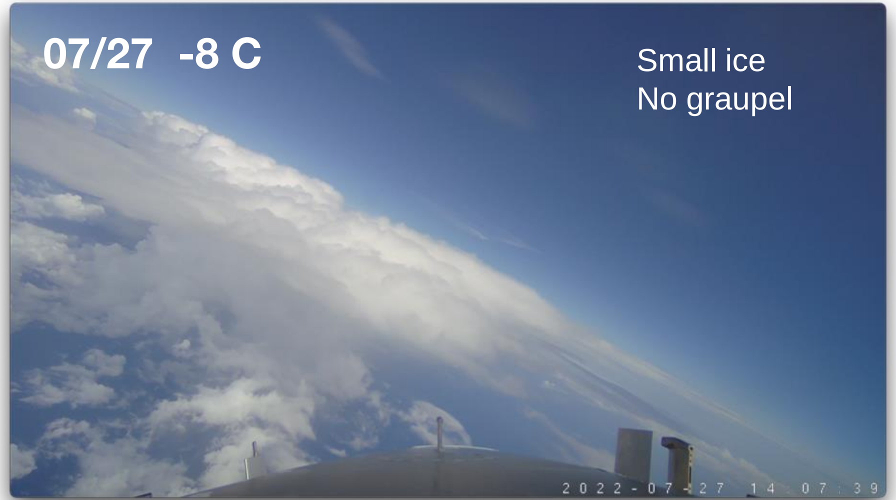


Medium-sized low density particles surrounded by liquid drops and graupel

July 27, 2022

- **-8 C**: 5 cloud penetrations
    - Clouds appear capped
    - Broad low-topped cloud with small columns and needles
    - Other convective clouds still fully liquid or contain frozen drops and graupel
- **-20 C**: No clouds
- PIP OK

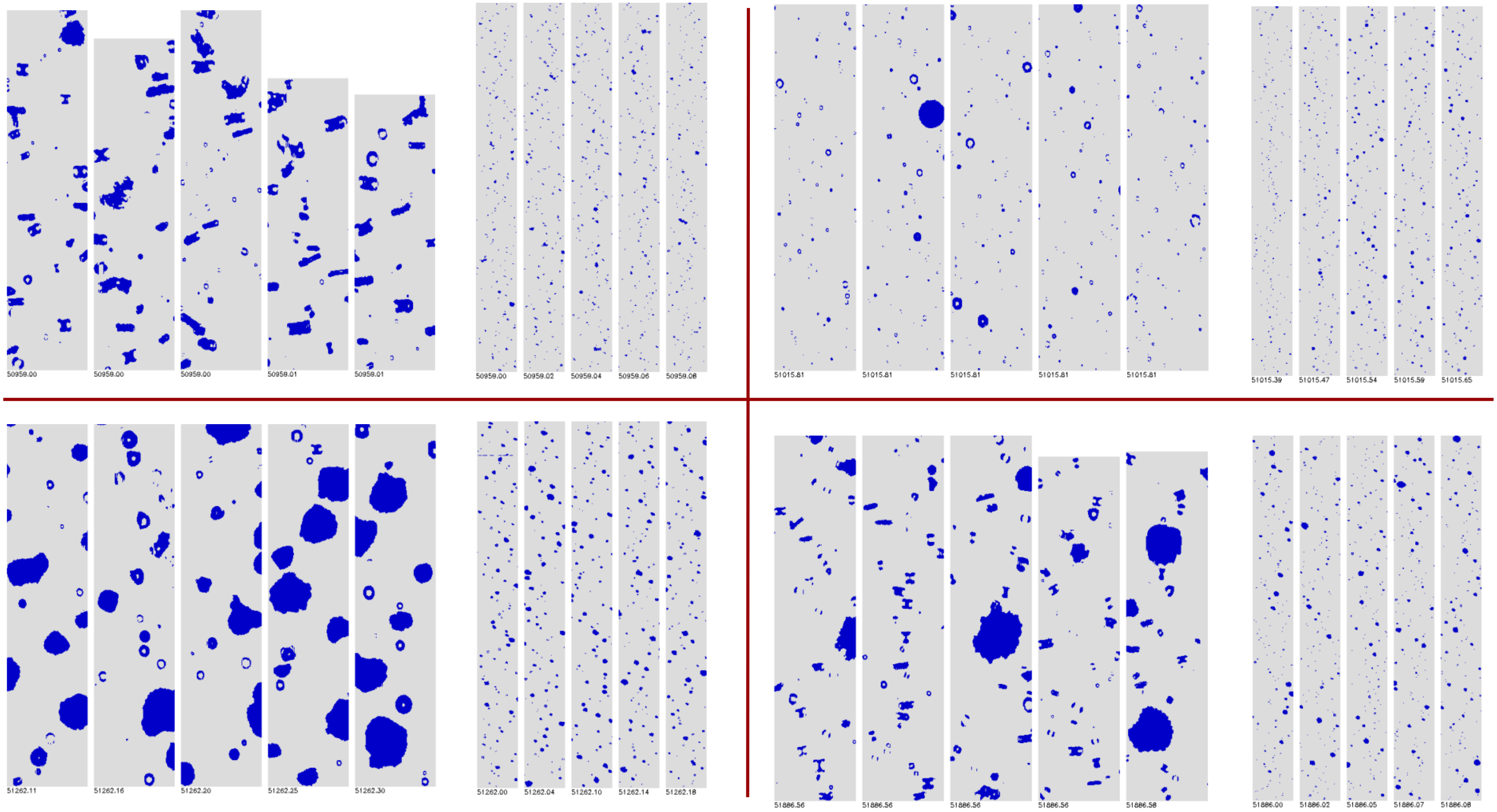


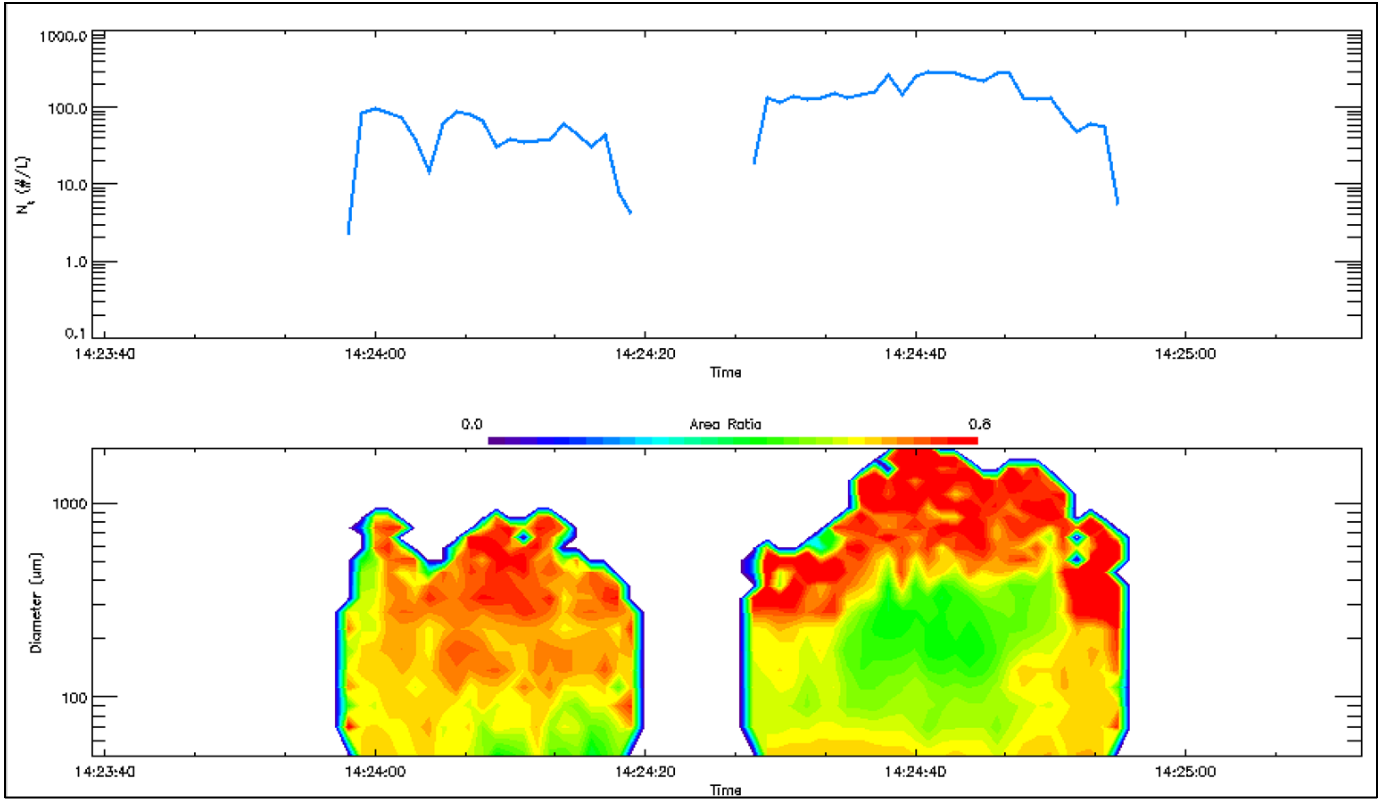

07/27 -8 C
Small ice
No graupel
2022-07-27 14:07:39


Liquid only
2022-07-27 14:09:57


Liquid, then
graupel
2022-07-27 14:12:41


Ice columns
and graupel
H-M?
2022-07-27 14:22:47

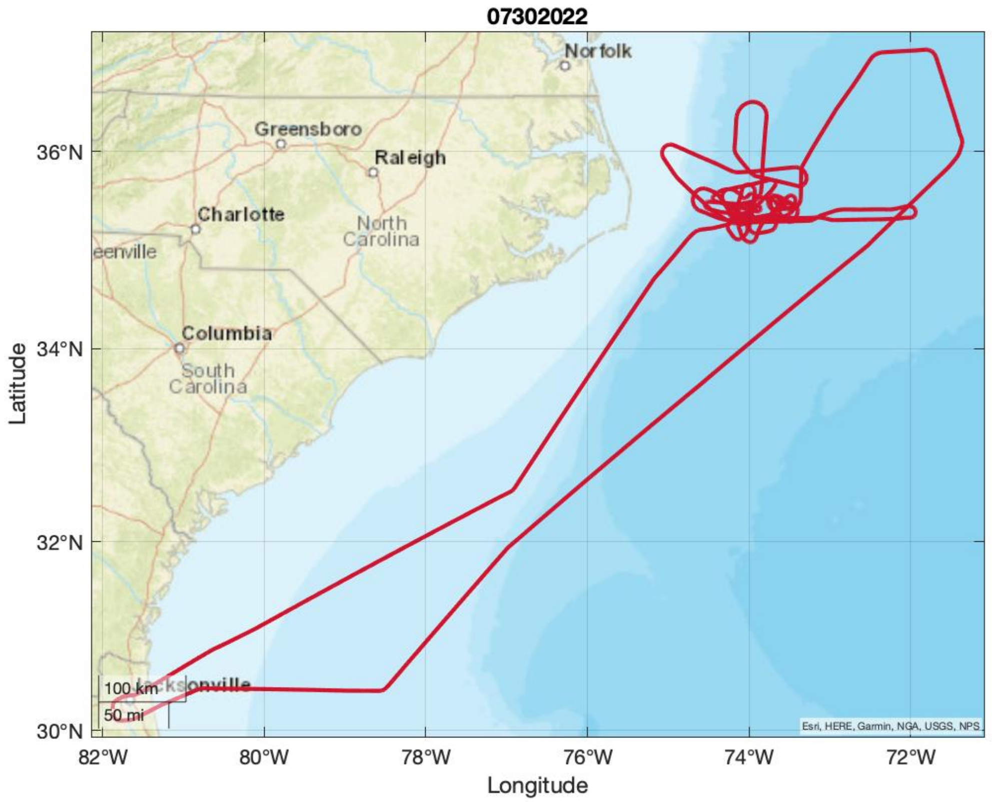

50959.00
50959.00
50959.00
50959.01
50959.01
50959.00
50959.02
50959.04
50959.06
50959.08
51015.81
51015.81
51015.81
51015.81
51015.81
51015.39
51015.47
51015.54
51015.59
51015.65
51262.11
51262.16
51262.20
51262.25
51262.30
51262.00
51262.04
51262.10
51262.14
51262.18
51886.56
51886.56
51886.56
51886.56
51886.58
51886.00
51886.02
51886.05
51886.07
51886.08

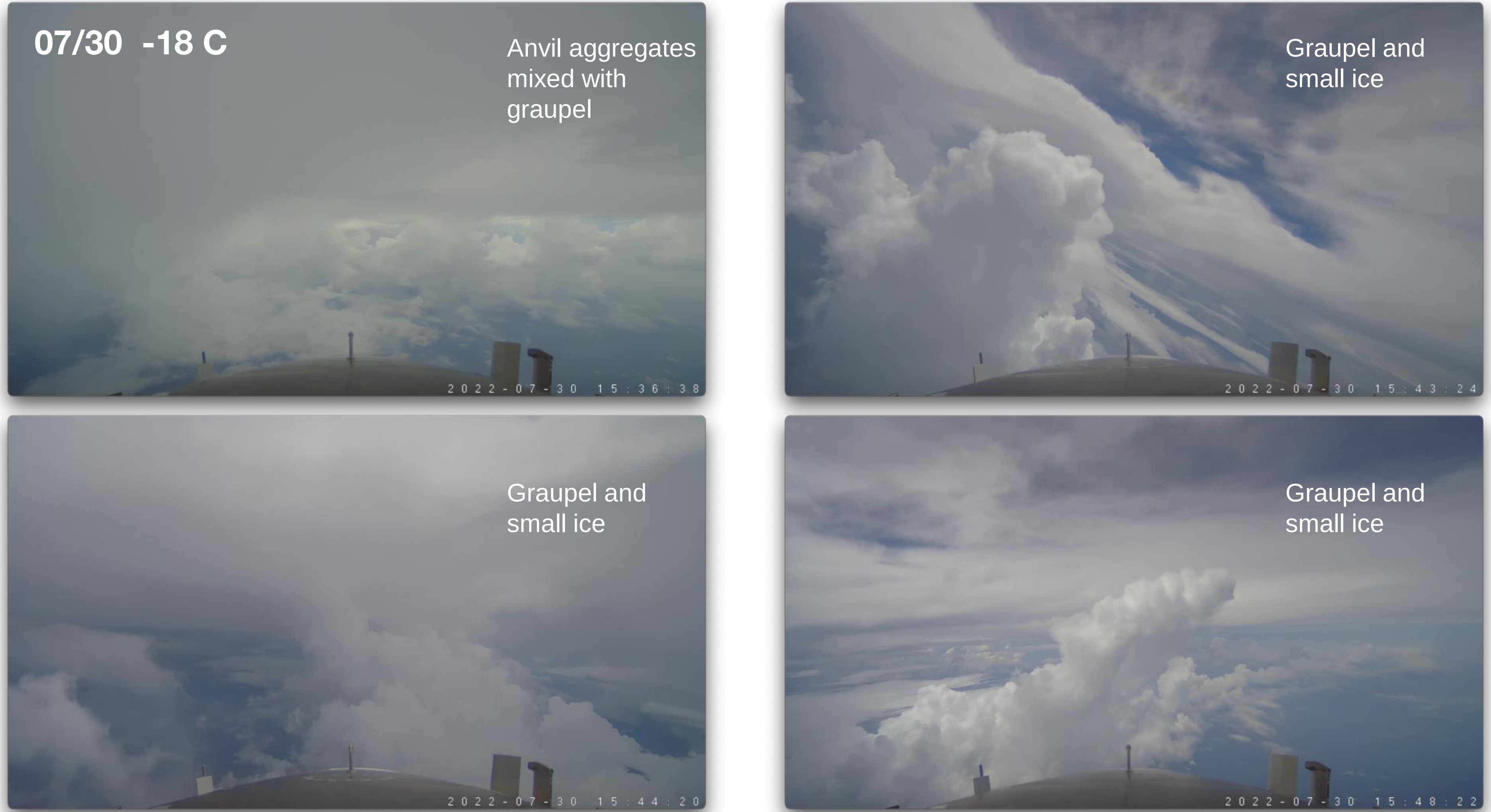


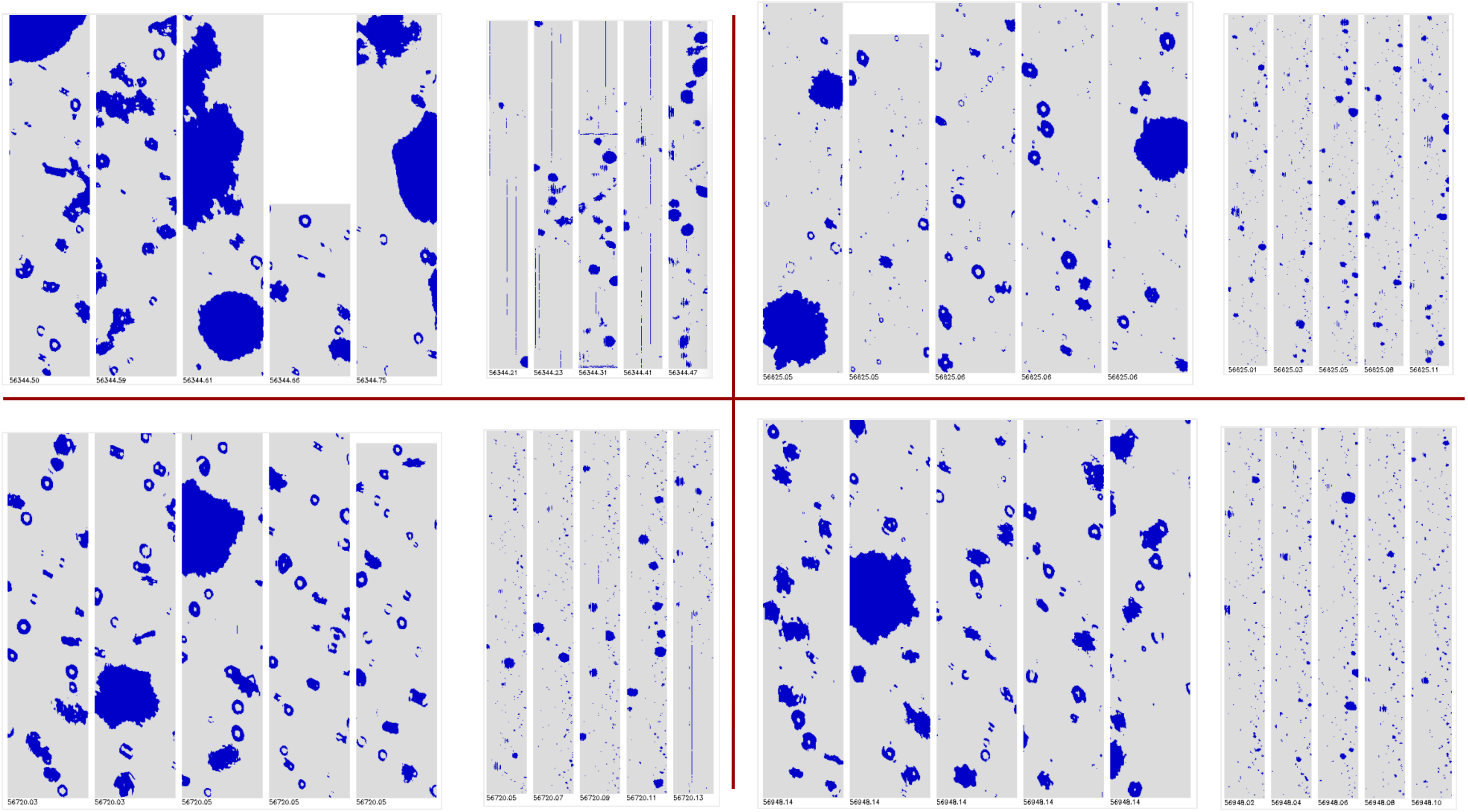
Large graupel, low density small ice

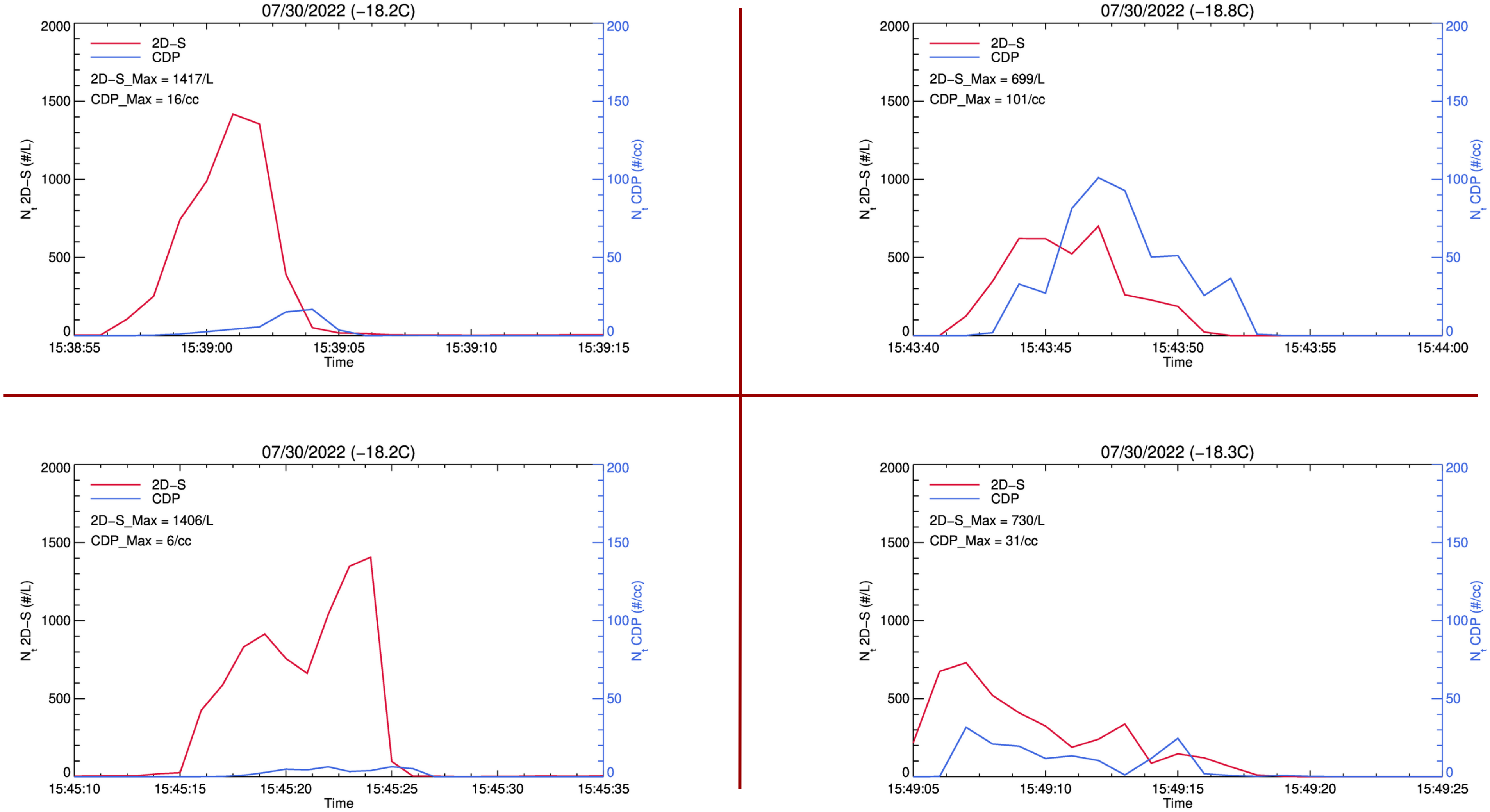
July 30, 2022

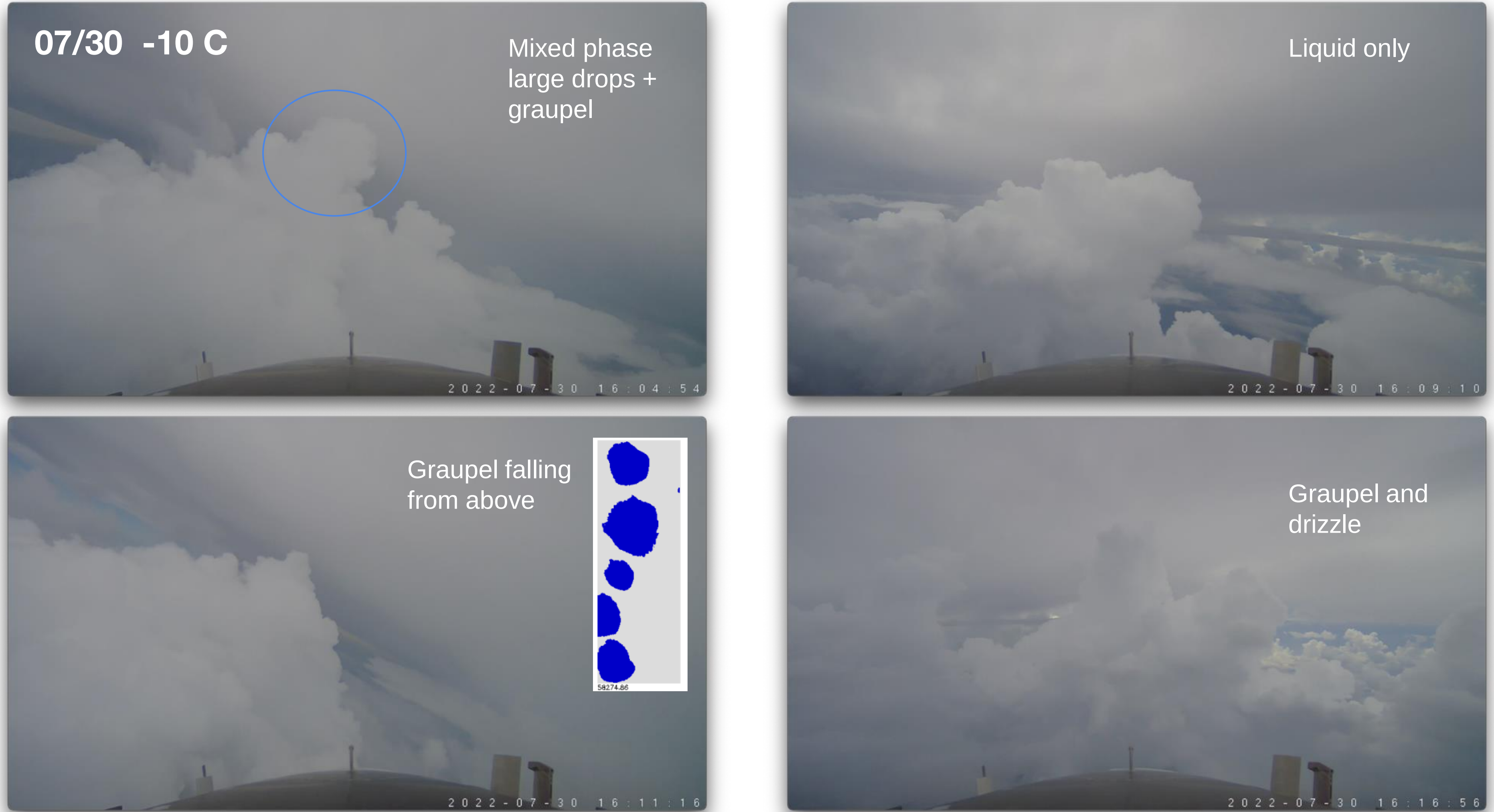
- **-18 C**: 7 cloud penetrations
  - Cirrus anvil deck overhead around -20 C
  - We occasionally flew into this cloud
  - Several clouds mixed anvil/TCu, with large aggregates and some graupel
- **-10 C**: 4 cloud penetrations
  - One case of graupel falling into the cloud from the anvil
- Poor imagery on the PIP, large aggregates identifiable

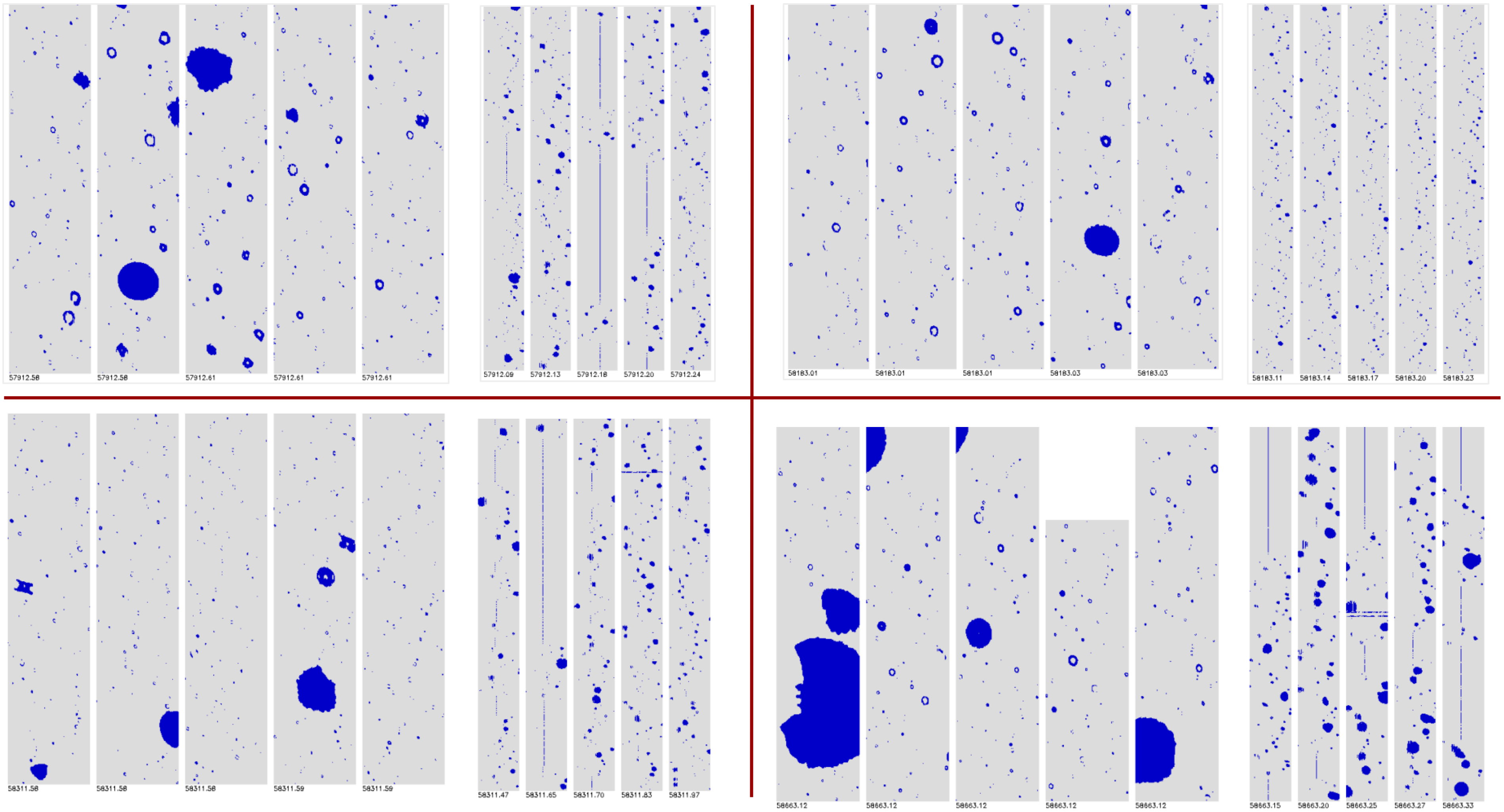



07/30 -18 C
Anvil aggregates mixed with graupel
2022-07-30 15:36:38
Graupel and small ice
2022-07-30 15:43:24
Graupel and small ice
2022-07-30 15:44:20
Graupel and small ice
2022-07-30 15:48:22


56344.50
56344.59
56344.61
56344.66
56344.75
56344.21
56344.23
56344.31
56344.41
56344.47
56625.05
56625.05
56625.06
56625.06
56625.06
56625.01
56625.03
56625.05
56625.08
56625.11
56720.03
56720.03
56720.05
56720.05
56720.05
56720.05
56720.07
56720.09
56720.11
56720.13
56948.14
56948.14
56948.14
56948.14
56948.14
56948.02
56948.04
56948.06
56948.08
56948.10


07/30/2022 (−18.2C)
2D−S
CDP
2D−S_Max = 1417/L
CDP_Max = 16/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
15:38:55
15:39:00
15:39:05
15:39:10
15:39:15
Time
07/30/2022 (−18.8C)
2D−S
CDP
2D−S_Max = 699/L
CDP_Max = 101/cc
15:43:40
15:43:45
15:43:50
15:43:55
15:44:00
Time
07/30/2022 (−18.2C)
2D−S
CDP
2D−S_Max = 1406/L
CDP_Max = 6/cc
15:45:10
15:45:15
15:45:20
15:45:25
15:45:30
15:45:35
Time
07/30/2022 (−18.3C)
2D−S
CDP
2D−S_Max = 730/L
CDP_Max = 31/cc
15:49:05
15:49:10
15:49:15
15:49:20
15:49:25
Time


07/30 -10 C
Mixed phase large drops + graupel
2022-07-30 16:04:54
Liquid only
2022-07-30 16:09:10
Graupel falling from above
58274.86
2022-07-30 16:11:16
Graupel and drizzle
2022-07-30 16:16:56


57912.58
57912.58
57912.61
57912.61
57912.61
57912.09
57912.13
57912.18
57912.20
57912.24
58183.01
58183.01
58183.01
58183.03
58183.03
58183.11
58183.14
58183.17
58183.20
58183.23
58311.58
58311.58
58311.58
58311.59
58311.59
58311.47
58311.65
58311.70
58311.83
58311.97
58663.12
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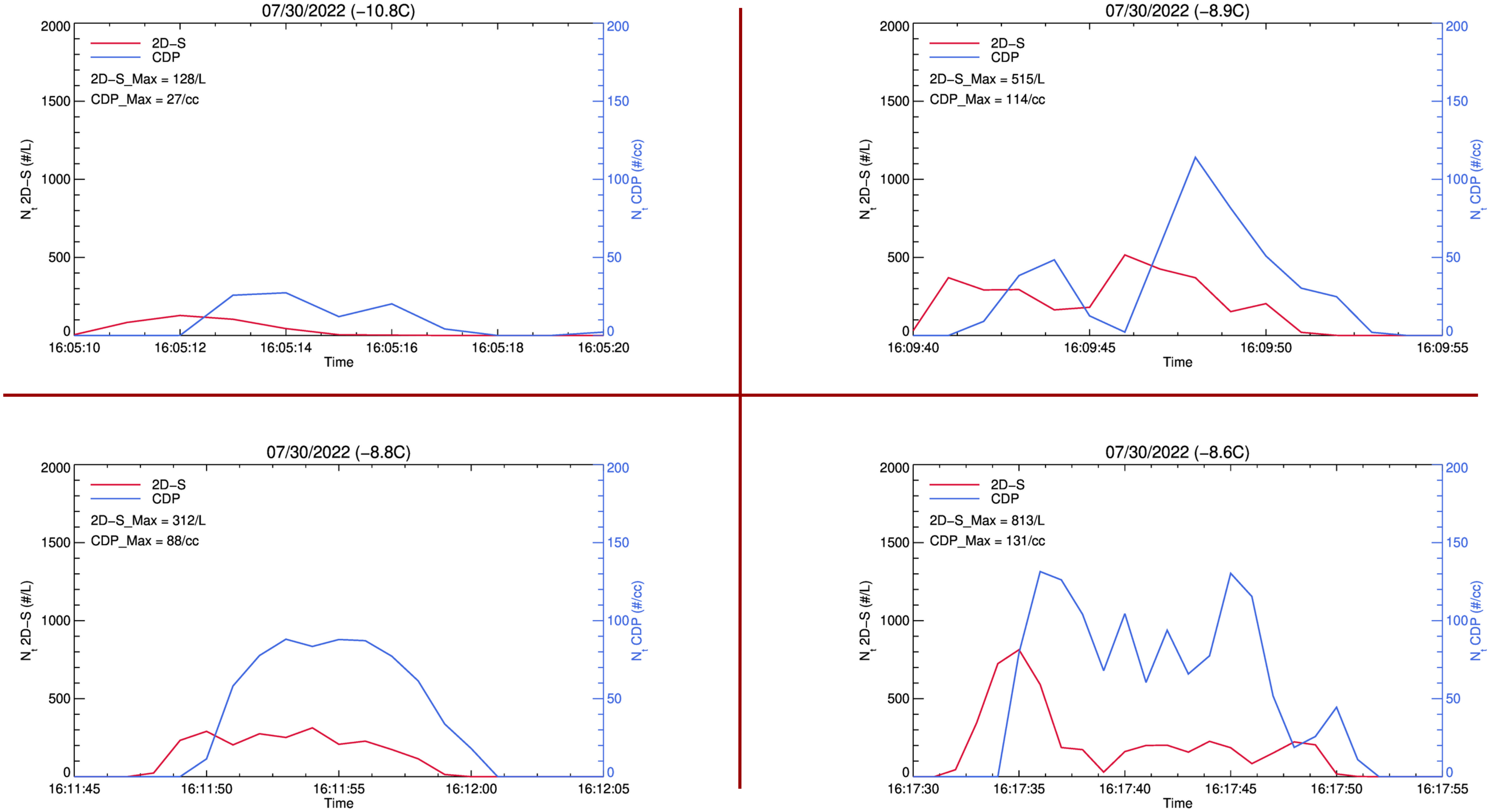
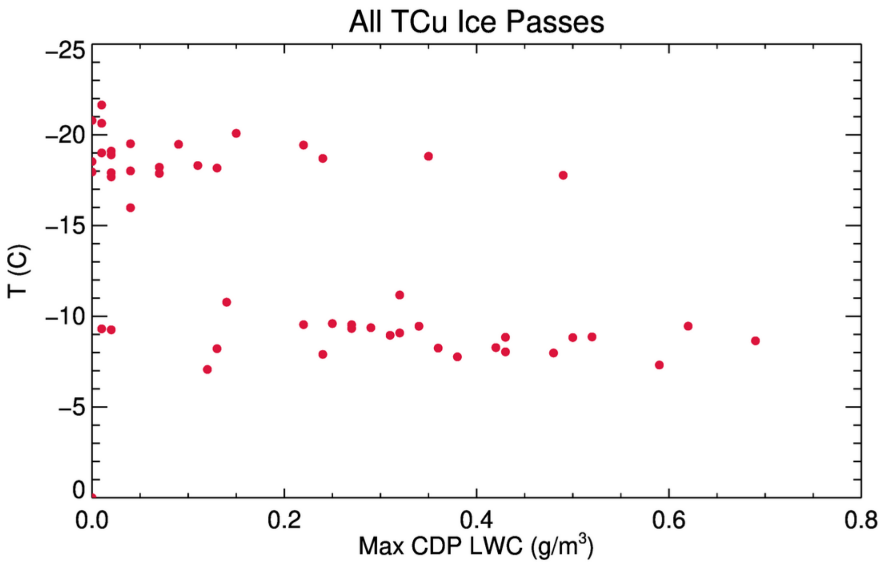
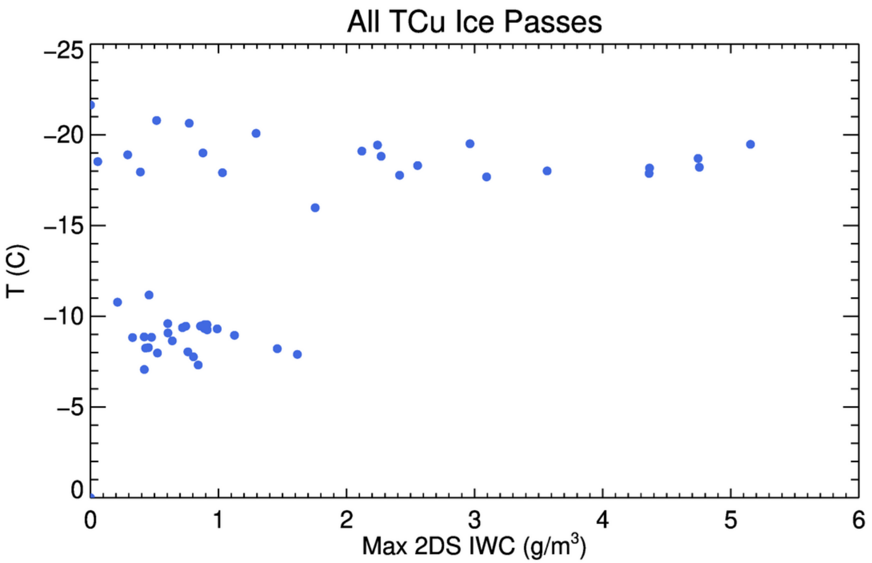
58663.12
58663.12
58663.12
58663.15
58663.20
58663.25
58663.27
58663.33



07/30/2022 (−10.8C)
2D−S
CDP
2D−S_Max = 128/L
CDP_Max = 27/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
07/30/2022 (−8.9C)
2D−S
CDP
2D−S_Max = 515/L
CDP_Max = 114/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
07/30/2022 (−8.8C)
2D−S
CDP
2D−S_Max = 312/L
CDP_Max = 88/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time
07/30/2022 (−8.6C)
2D−S
CDP
2D−S_Max = 813/L
CDP_Max = 131/cc
N_t 2D−S (#/L)
N_t CDP (#/cc)
Time

All flights: LWC (CDP) IWC (crude estimate)

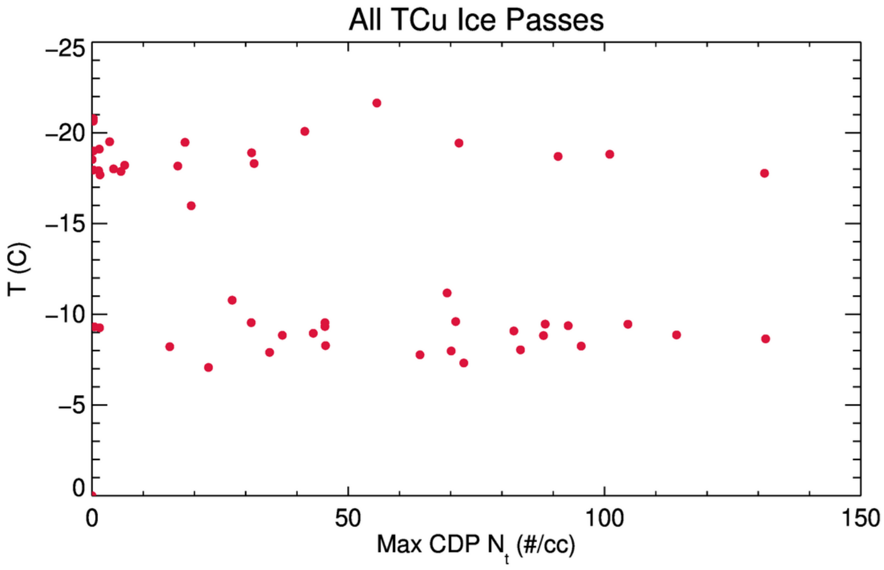


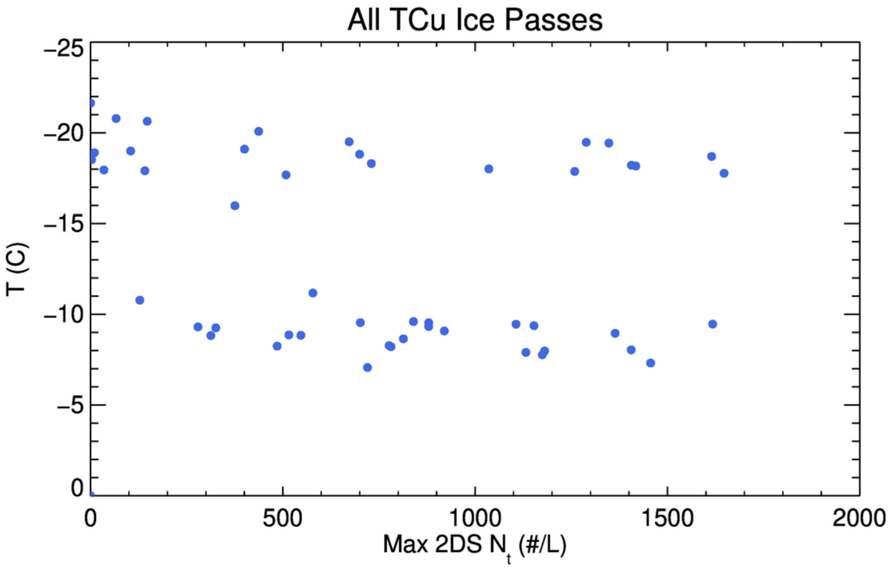


LWC decreases for deeper clouds

IWC increases for deeper clouds

All flights: N_t-CDP and N_t-2DS





Nt < 50um no change with T

Nt > 50um no change with T

Most HIWC-TCu follow what was observed in Lawson et al. 2017

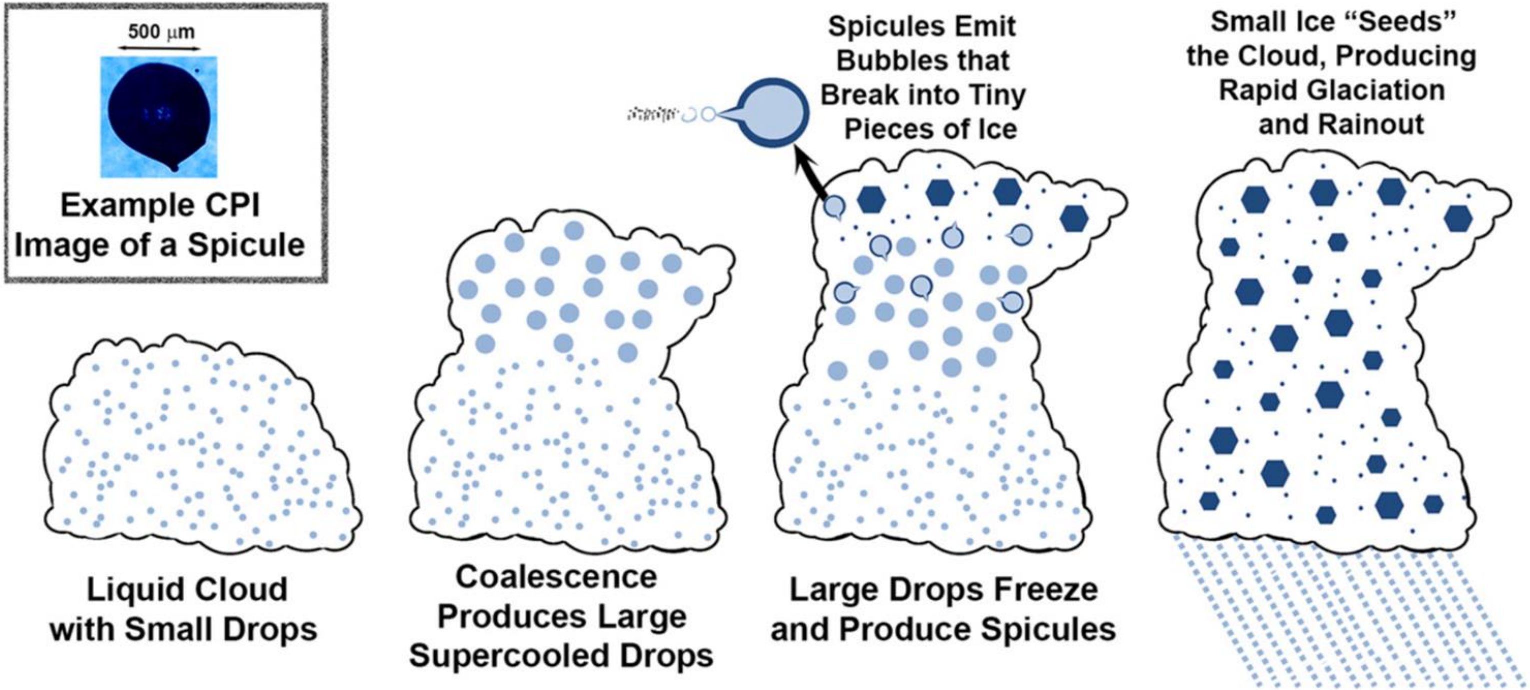


FIG. 11. Schematic diagram showing the evolution of SLDs that produce spicules, which can produce ice cannons that generate tiny ice particles. Collisions between the tiny ice and rapidly falling large supercooled drops results in rapid glaciation. (top left) CPI image of a spicule emitting a bubble that was recorded at 1748:34 UTC 18 Sep 2013 by the Learjet at −9°C.

Summary

- TCu may look outwardly similar, but there are often significant microphysical differences, even among neighbors.
  - Different stages in cloud life cycle
  - Interactions with nearby clouds
  - Local thermodynamic differences

- Evidence for SIP mechanisms actively working in these clouds
  - Droplet breakup
  - Frozen drop riming
  - H-M conditions occasionally present
  - High ice concentrations
  - Do IN concentrations matter with efficient SIP processes?
  - Presence of large drops may enhance SIP, is a clean boundary layer beneficial for ice?

- Does it matter for HIWC?
  - Most of these clouds probably didn't make it to the MCS stage
  - Would clouds that do have significantly different characteristics?