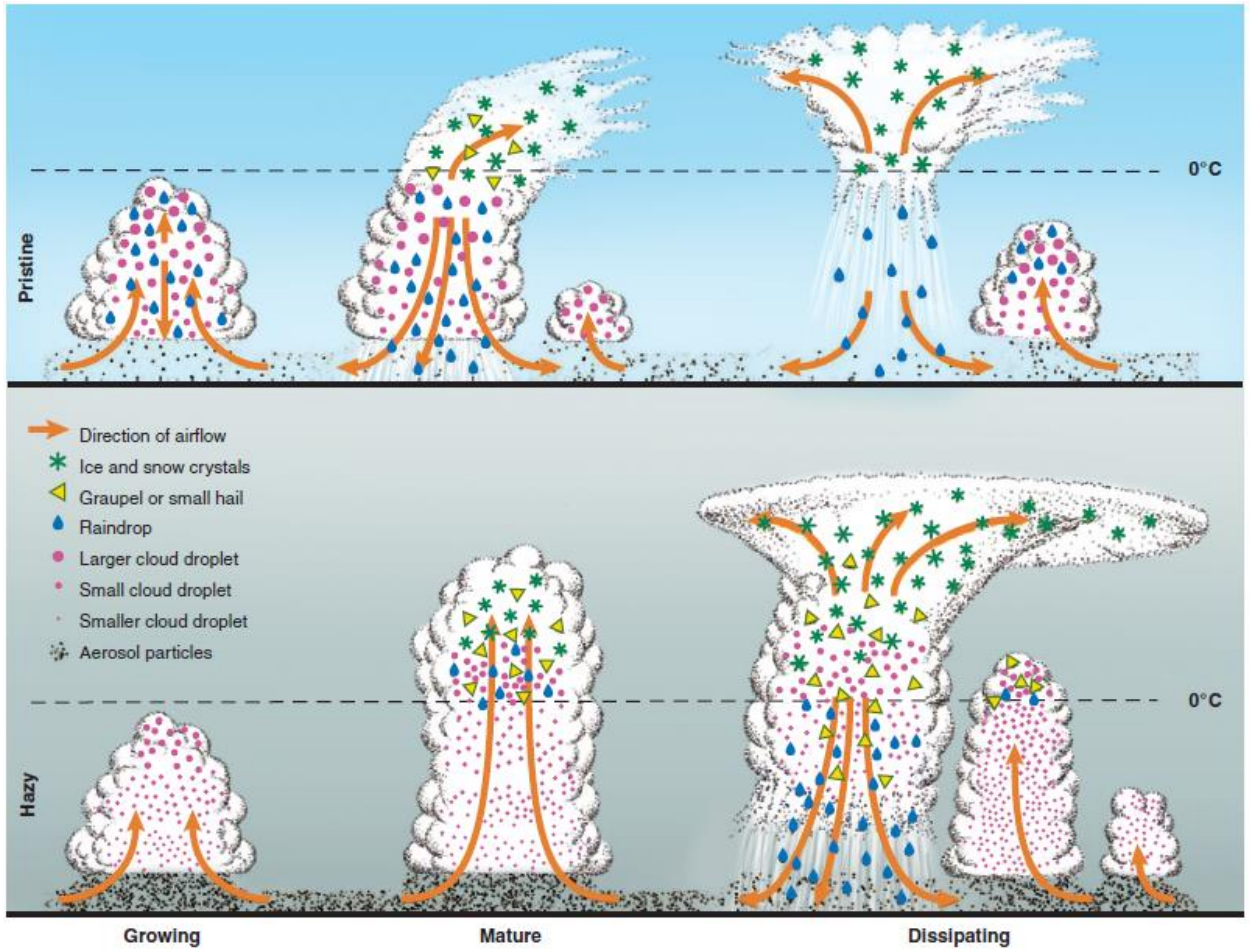
Inventory and Overview of Microphysical Observations from TCu sampling

Presented by J. W. Strapp

Boulder HIWC-2022 Workshop, 29-30 Nov. 2023

Review of HIWC-2022 first order hypothesis



From Rosenfeld et al. 2008

- Polluted clouds nucleate smaller drops, and warm rain is suppressed
- In heavy forest fire smoke cases, warm rain can be practically shut off (Rosenfeld, 1999)
- Pollution delays the precipitation of cloud water, ***so that more water can ascend to altitudes where the temperature is colder than 0 C*** (Rosenfeld et al. 2008)

- Additional cloud water that eventually freezes releases latent heat of fusion and re-invigorates instability and leads to higher and longer lasting clouds

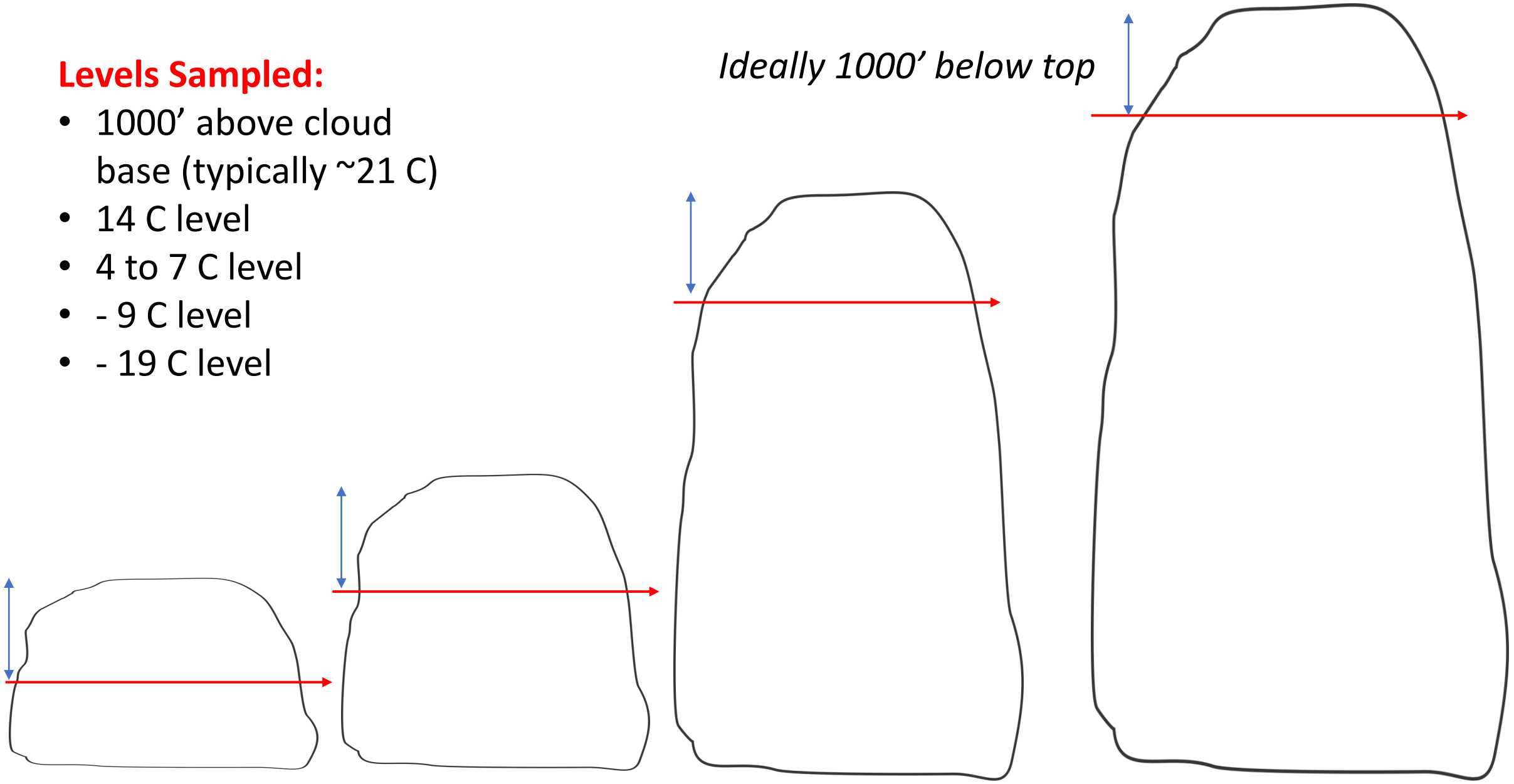
- If the above hypothesis is correct, the datasets collected in HAIC-HIWC, HIWC RADAR 1 and 2, in clean atmospheres may have reduced TWC aloft relative to clouds in polluted areas

- **We are therefore looking for evidence of warm rain suppression in the HIWC-2022 dataset.**

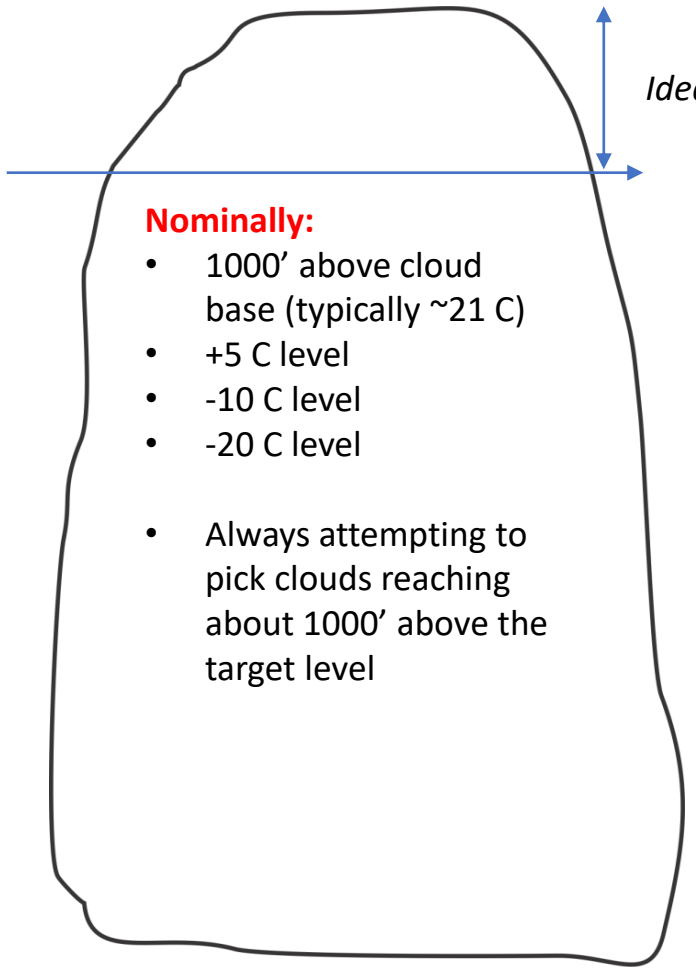
Levels Sampled:

- 1000’ above cloud base (typically ~21 C)
- 14 C level
- 4 to 7 C level
- - 9 C level
- - 19 C level

Ideally 1000’ below top



Inventory of good TCu runs



Nominally:

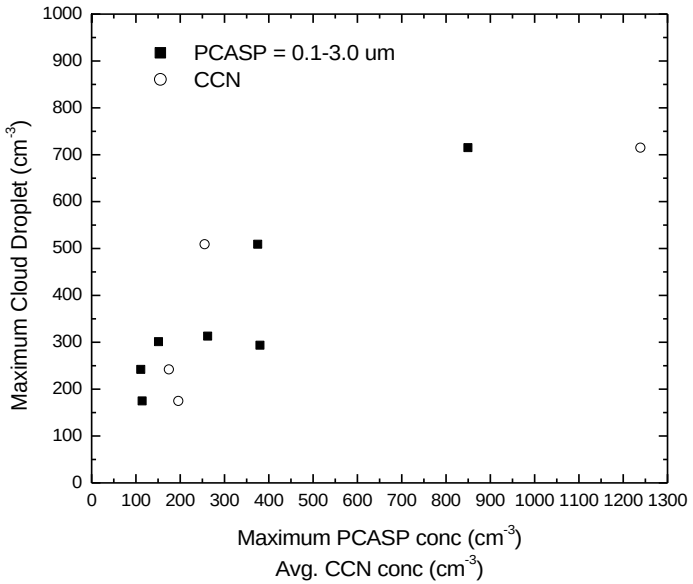
- 1000’ above cloud base (typically ~21 C)
- +5 C level
- -10 C level
- -20 C level

- Always attempting to pick clouds reaching about 1000’ above the target level

		Above-Base ~ +21 C		Below FZ1 ~ +14 C		Below FZ2 ~+4 to +7 C		Above FZ1 ~ -9 C		Above FZ2 ~ -19 C	
Flight	date	good runs	SATav	nruns	SATav	good runs	SATav	nruns	SATav	good runs	SATav
3	8-Jul-22	0	23.7								
4	10-Jul-22	5	22.7					4	-8.5	0	-19.1
5	14-Jul-22	3	23.0								
6	16-Jul-22										
7	18-Jul-22										
8	22-Jul-22	2	20.6								
9	24-Jul-22	4	20.9			2	4.7	5	-9.4	4	-18.1
10	26-Jul-22	0	20.9	5	13.7	4	4.1	5	-9.6	6	-19.8
11	27-Jul-22	3	21.3			5	7.0	5	-8.0		
12	30-Jul-22	5	21.6	3	14.5			5	-9.9	3	-18.4
	totals	**22**		**8**		**11**		**24**		**13**	
	Total runs	**78**									

Summary, 1000’ above cloud base

1. Comparison of maximum cloud droplet conc. (CDCs) to PCASP maximum aerosol number conc. (ANC)
- For each day, pick the highest CDC and below base ANC



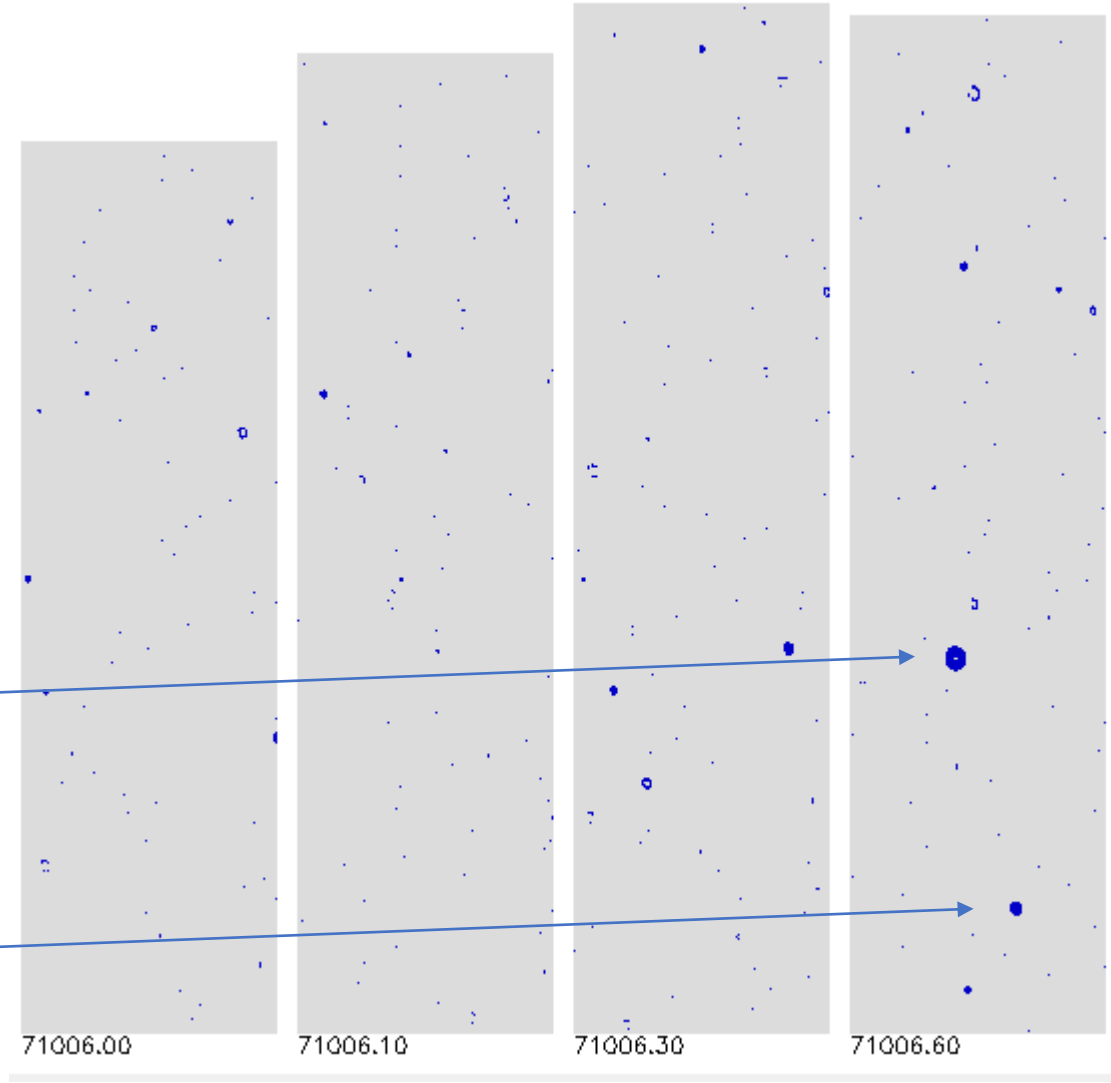
- My rough analysis, but shows increase in CDC with increasing aerosol
- Only two days with cloud base max CDC > 300 cm^{-3}:
  - 22-Jul, 509 cm^{-3} CDC
  - 30-Jul, 715 cm^{-3} CDC

- Based on ANC, two last days seem to be the highest aerosol:
  - 27-Jul, 250 cm^{-3} PCASP max, 741 cm^{-3} CCN
    - No 1000’ above cloud base runs
    - No point on graph to left
  - 30-Jul, PCASP max 850 cm^{-3} , CCN 1240 cm^{-3}

Summary, 1000’ above cloud base

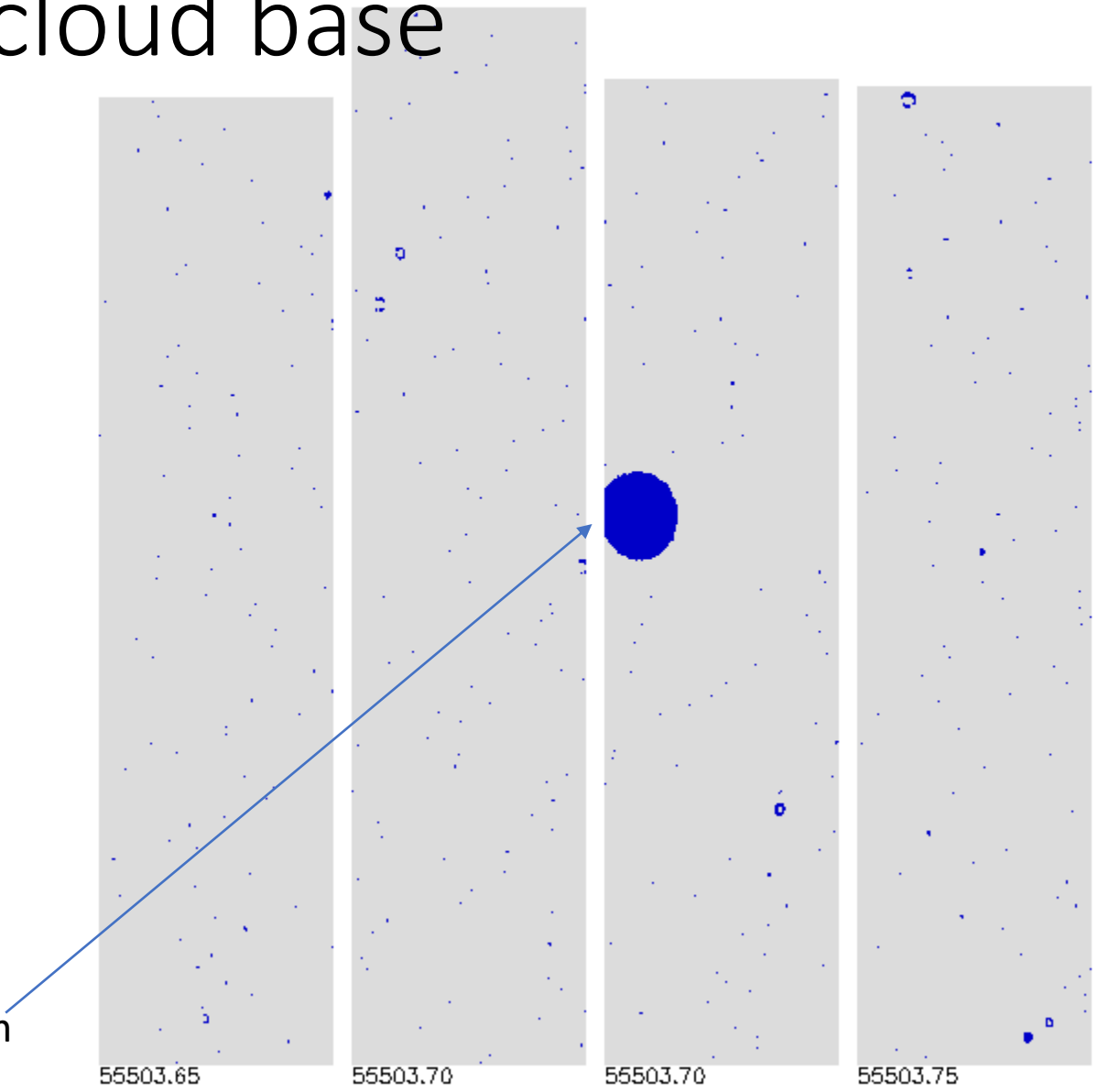
2. Assessment of existence of drops > 50 µm in tail of distribution

- Somewhat hard to do without a very careful analysis. This assessment is a subjective estimate based on inspection of all 2D-S vertical channel image buffers
- Example at right is for 8-Jul, during CDPmax run
- Seed embryos for coalescence?



Summary, 1000’ above cloud base

- Some cloud base runs contained quite large drops that seemed out of place with the rest of the spectrum
- These were always from clouds with obscured tops (i.e. tops could have been higher than 1000’ above aircraft)
- Could also have been seeded from unknown neighbouring clouds
- Example at right is for 22-Jul, my comments from DC-8 video say “ (top) obscured, messy”
- Would not use these cases to generalize. **Cases of obscured top were not used**

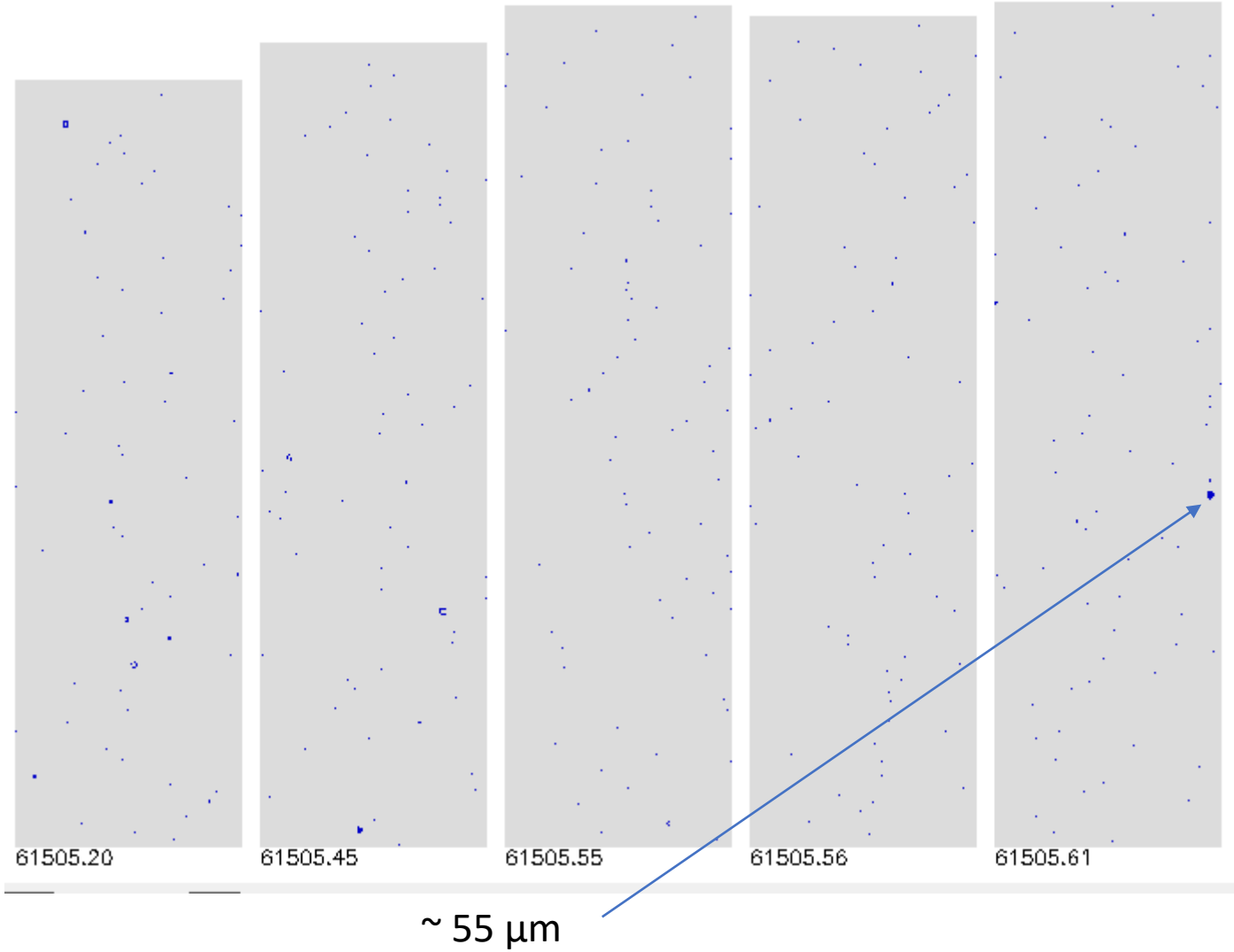


Summary, 1000’ above cloud base, high CDC

- The highest droplet concentration cases may have had the smallest droplets

- 30-Jul: CDCmax= 715 cm^{-3}
- 22-Jul: CDCmax= 509 cm^{-3}

- 30-Jul case shown at right
  - Visually, smaller droplet 2D-S images than majority of cases (need to check MVD)
  - But still the occasional larger droplet



Summary #1

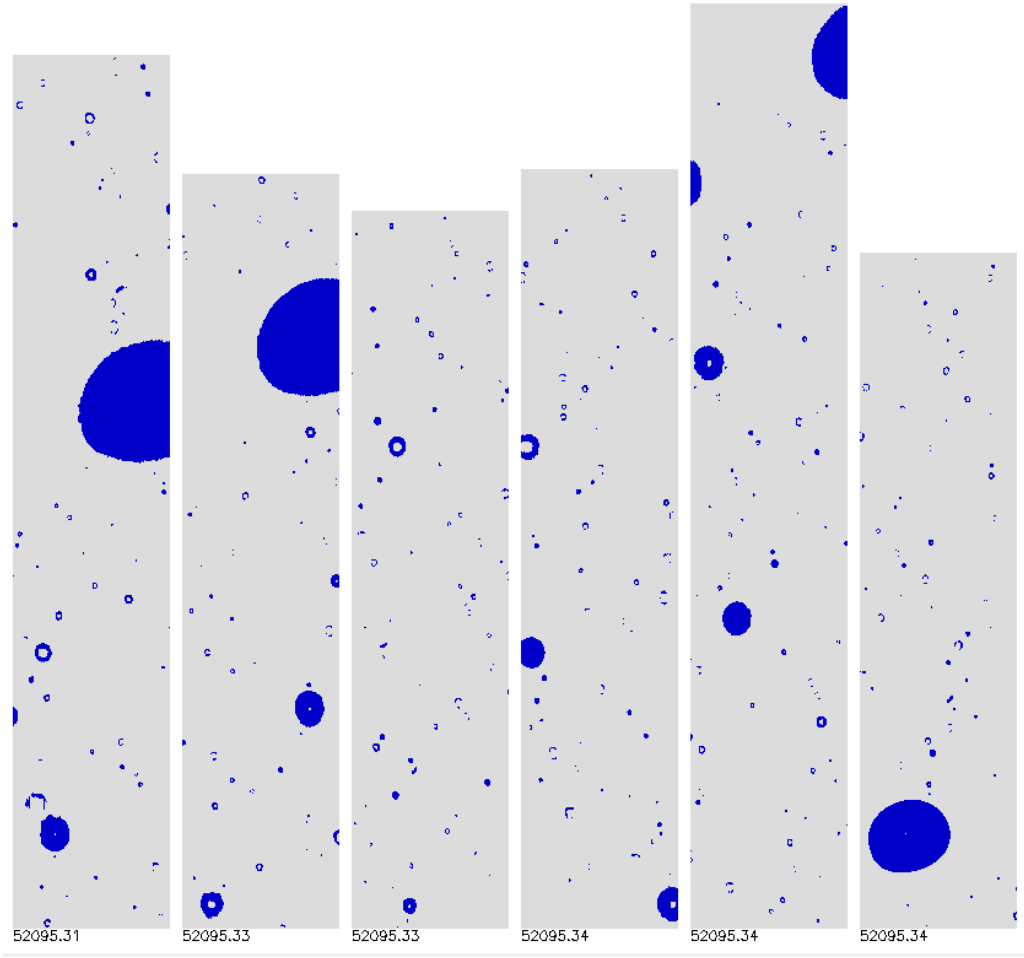
Cloud level	# of flts / runs	Observation
1000’ above base	5 / 23	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)

+ 5 C: Series below Freezing Level Altitude

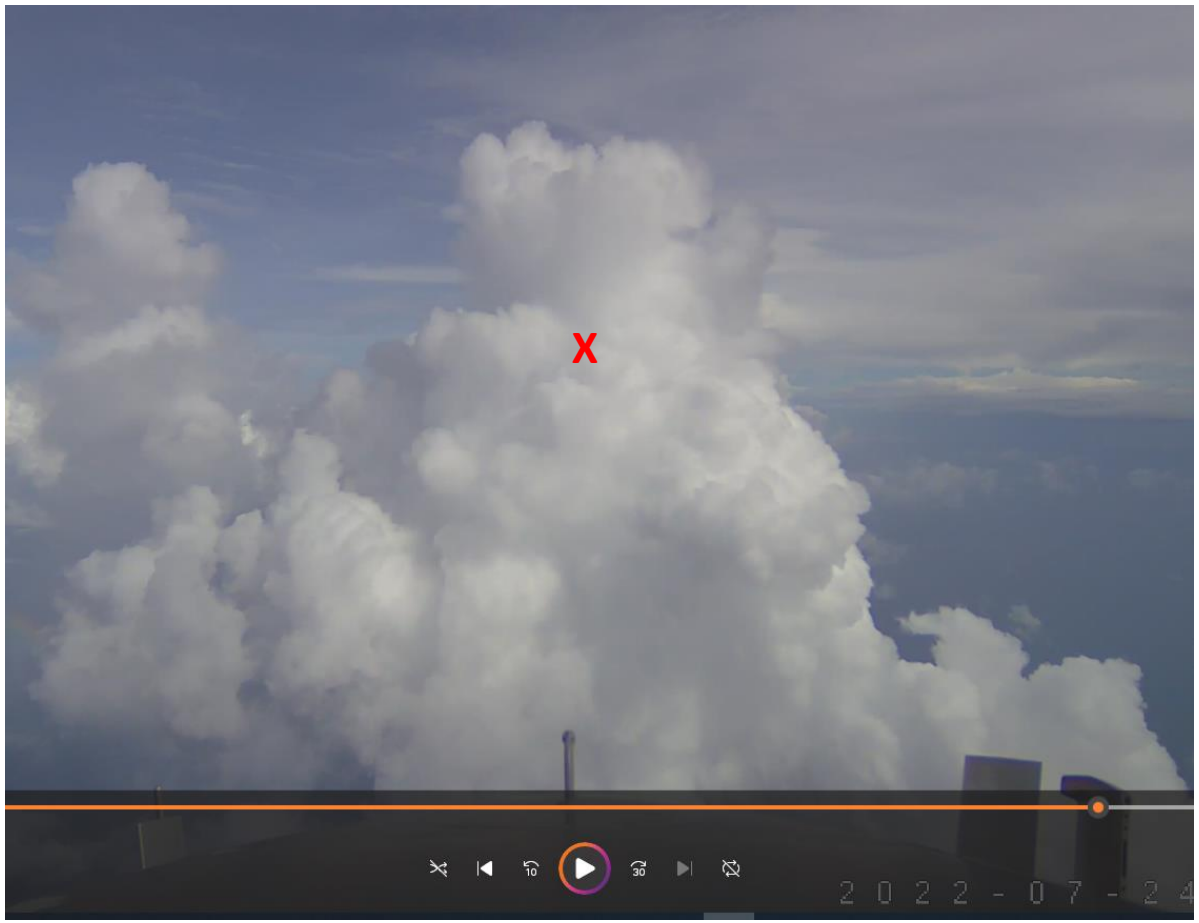
Cloud level	# of flts / Runs	Observation
1000’ above base	5 / 23	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)
+4 to +7 C (“~+5 C”)	3 / 11	• Two low ANC flights, one medium

~ + 5 C
Cloud of 24-Jul-2022

- **Example 1: 24-Jul, ~+5 C, low aerosol**
  - 2D-S shown at right
  - CDPavg= 20.7 cm^{-3}, 0.18 gm^{-3}
  - Isolated cloud, very good location to top; next slide shows frame from video
  - Shown right: Mid-cloud in area with cloud droplets, drops to about 1 mm
  - next slide shows a little later with more cloud drops versus droplets
  - No seeding of particles from above cloud
  - Warm rain process active
  - No indication of melting ice

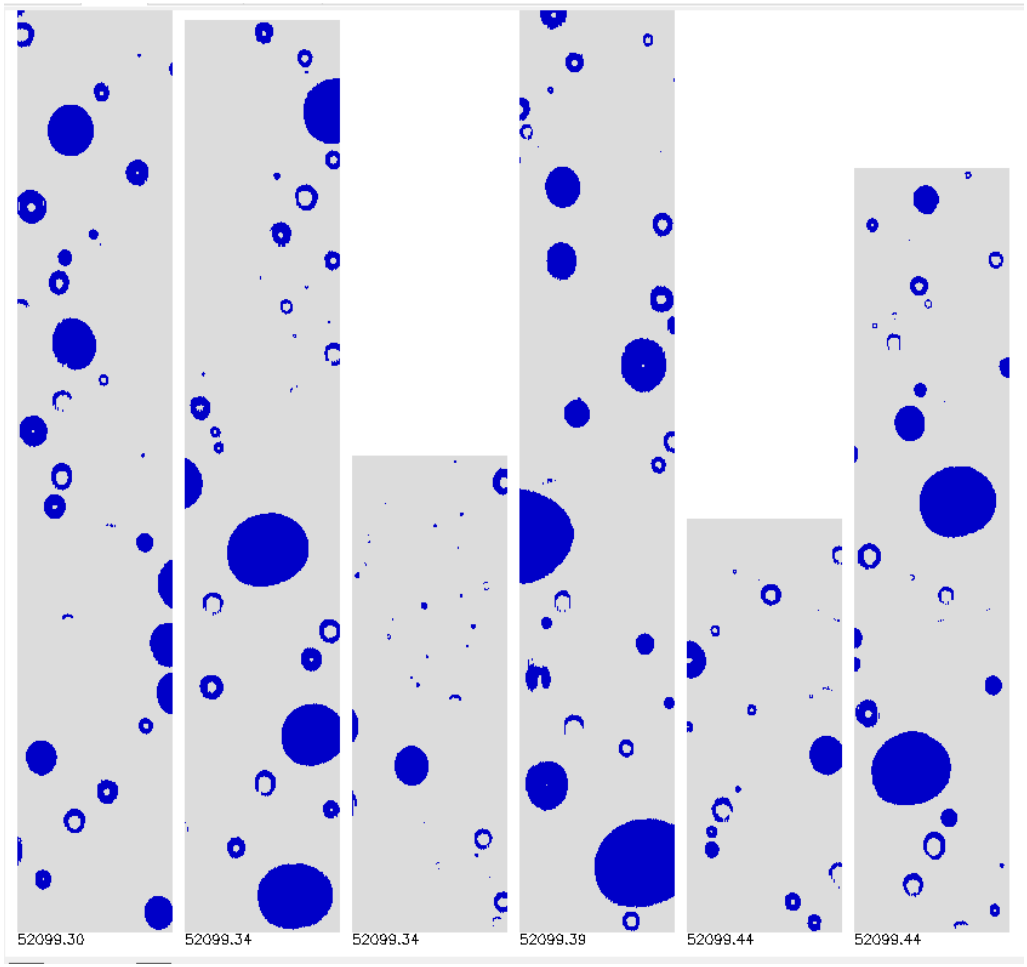


~ + 5 C
Cloud of 24-Jul-2022



14:28:07-14:28:25

Another frame towards exit side



+5 C added

Cloud level	# of flts / Runs	Observation
1000’ above base	5 / 23	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)
+4 to +7 C (~ +5 C)	3 / 11	• Two low ANC flights, one medium • All three days had warm rain developing or developed • No clouds showed evidence of melting ice from aloft • Medium ANC may had higher drop concentrations, different degree of development of warm rain to be checked.

+14 C: A supplementary altitude below Freezing Level Altitude

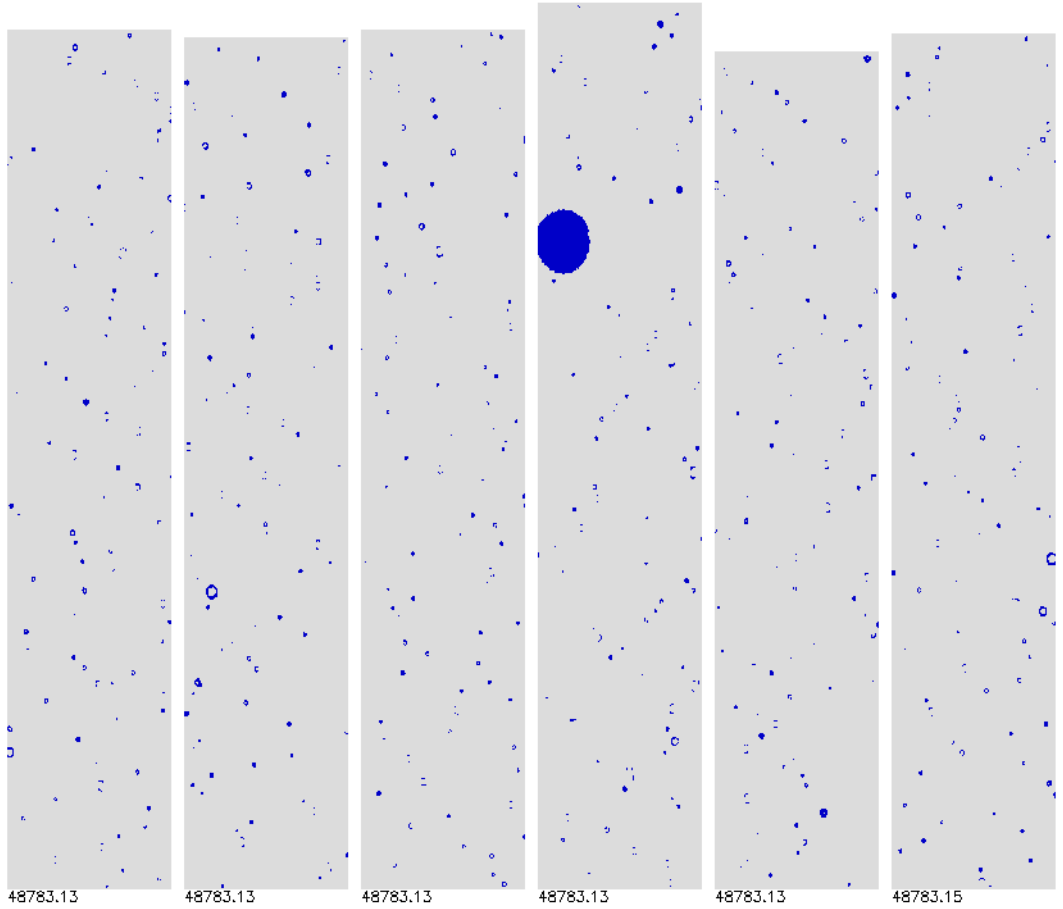
Cloud level	# of flts / Runs	Observation
1000’ above base	5 / 23	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)
+4 to +7 C (~ +5 C)	3 / 11	• Two low ANC flights, one medium • All three days had warm rain developing or developed • No clouds showed evidence of melting ice from aloft • Medium ANC may had higher drop concentrations, different level of warm rain to be checked.
+14 C	2 / 5	

+14 C
Cloud of 26-Jul-2022

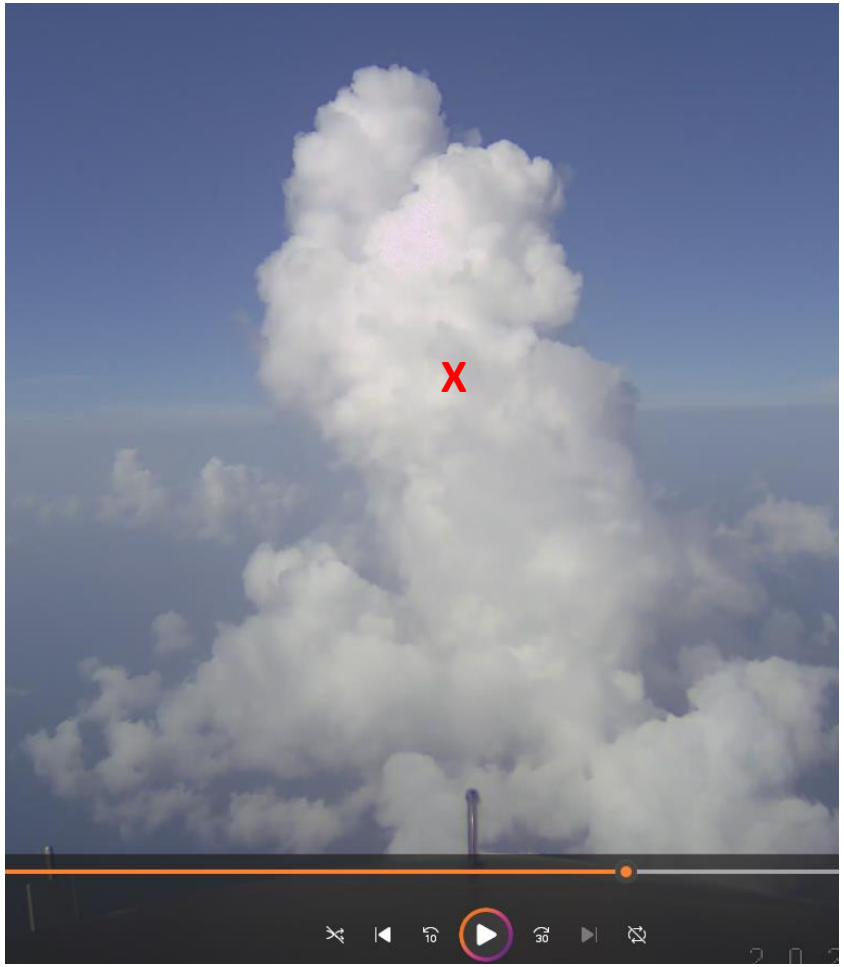
- **26-Jul: ~+14 C, (low aerosol)**
  - Isolated cloud, good location to top; next slide shows frame from DC-8 video
  - 2D-S image frame to right
  - CDPavg: 61.6 cm^{-3}, 0.61 gm^{-3}
  - Displaying some general development of the spectrum to larger sizes since base. Lots of 30+ µm size droplets, maybe max ~55 µm within general population (TBD)
  - The occasional large drop present, maximum in this run to about 600 µm.

  - Warm rain process getting started? Coalescence creating large occasional drop?
  - No indication of melting ice

  - Other 4 clouds this day at this altitude have developing drop spectra with very similar observations. Maximum occasional drop size about 1 mm.



+14 C
Cloud of 26-Jul-2022



13:32:54-13:33:07

+14 C added

Cloud level	# of flts / Runs	Observation
1000’ above base	5 / 23	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)
+4 to +7 C (~ +5 C)	3 / 11	• Two low ANC flights, one medium • All three days had warm rain developing or developed • No clouds showed evidence of melting ice from aloft • Medium ANC may had higher drop concentrations, different maturity of warm rain to be checked.
+14 C	1 / 5	• Starting to develop broader small droplet spectrum with 30 + µm droplets, and occasional large isolated drops to 1 mm

-9 C: First level above freezing level altitude

Cloud level	# of flts / Runs	Observation
1000’ above base	5 / 23	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)
+4 to +7 C (~ +5 C)	3 / 11	• Two low ANC flights, one medium • All three days had warm rain developing or developed • No clouds showed evidence of melting ice from aloft • Medium ANC may had higher drop concentrations, different maturity of warm rain to be checked.
+14 C	1 / 5	• Starting to develop broader small droplet spectrum with 30 + µm droplets, and occasional large isolated drops to ~ 1 mm
- 9 C	5 / 24	

-9 C: First level above freezing level altitude

- This is where big variations were observed. Quick summary below:

Flight	Glaciated runs	Mixed Phase runs	Liquid only runs
10-Jul-22	0	3	1
24-Jul-22	2	3	0
26-Jul-22	0	4	1
27-Jul-22	0	4	1
30-Jul-22	0	4	1
Totals	2	18	4

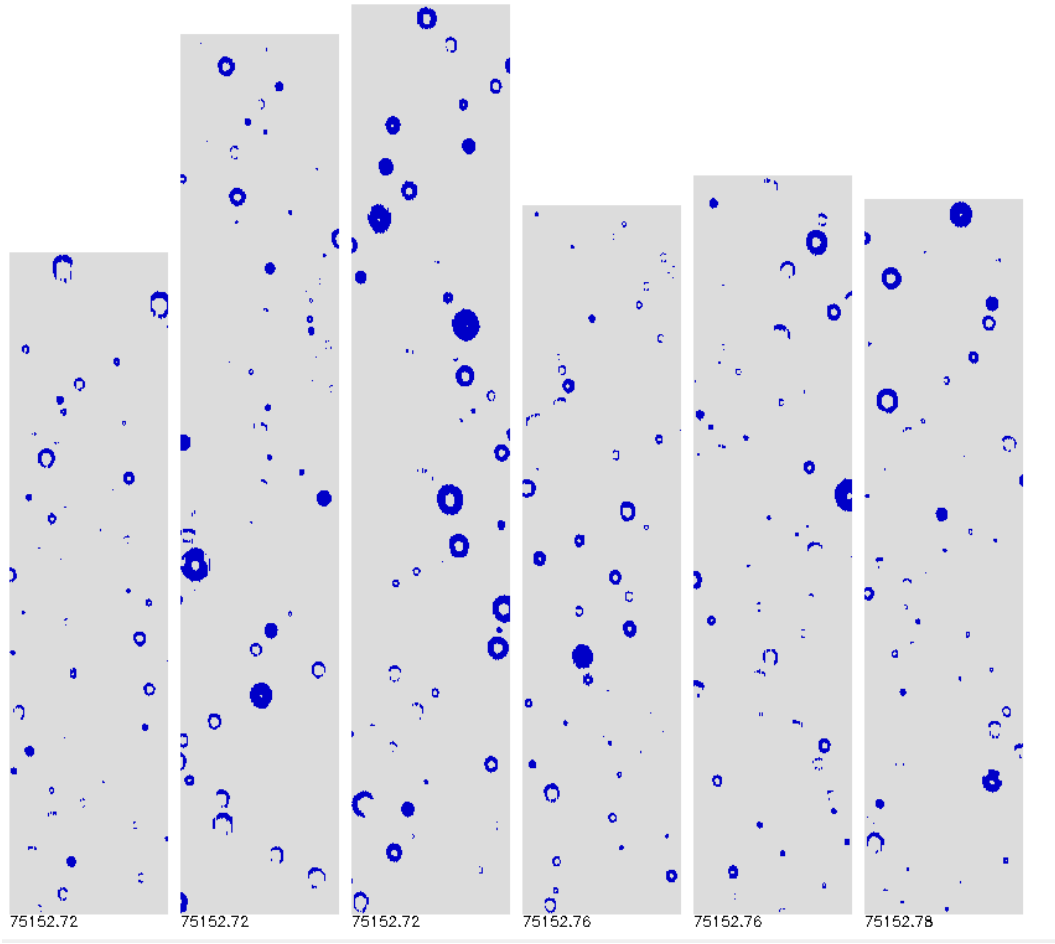
-9 C, Liquid-only runs; Cloud of 10-Jul-2022

- **Example 1: 10-Jul: -8.4 C, low aerosol**
  - Congested cloud, under overcast; good location to top; next slide shows frame from DC-8 video
  - 2D-S image frame to right
  - CDPavg: 23.3 cm^{-3}, 0.17 gm^{-3}

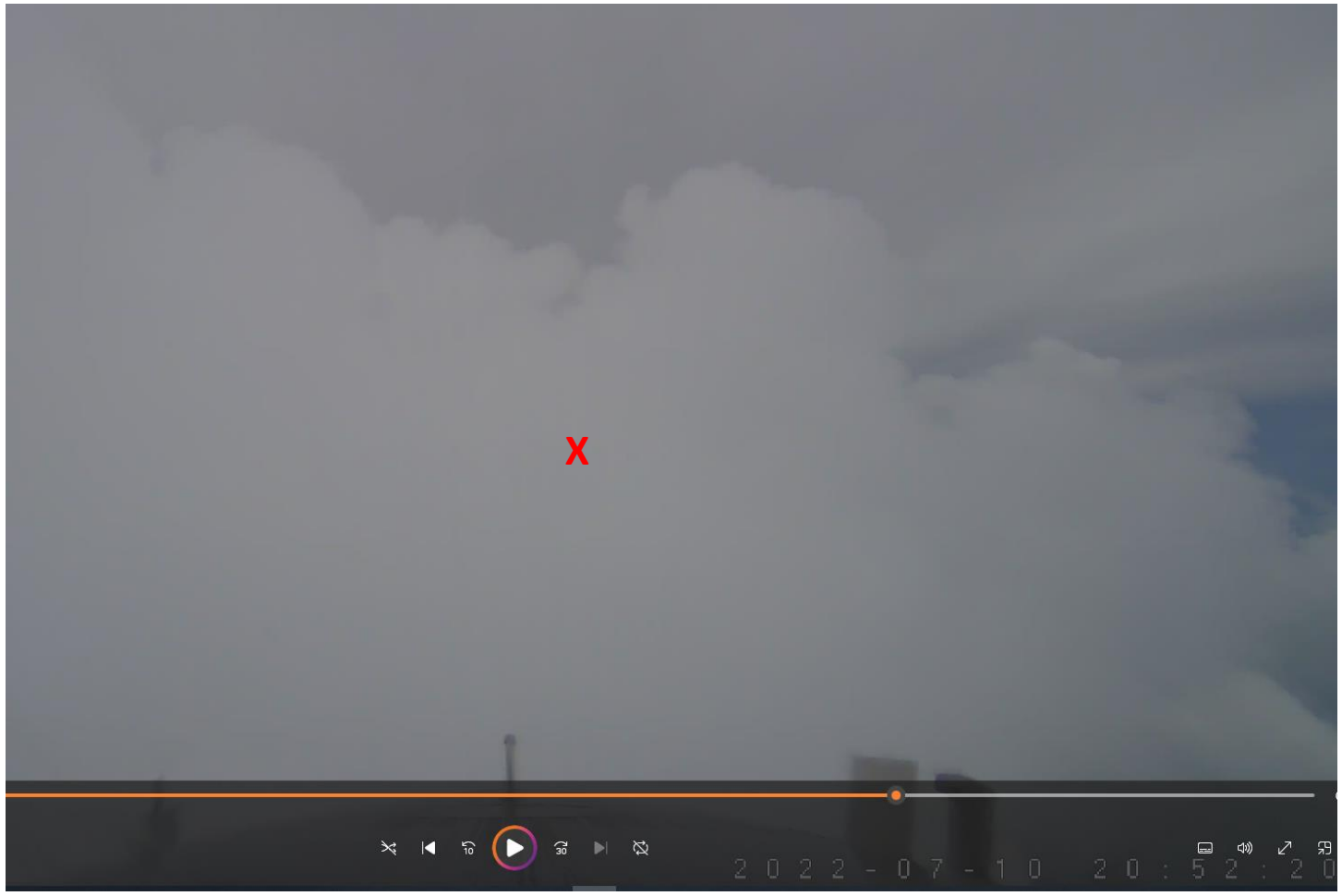
  - Dominated by zones of SLD (image right)
  - Sometimes a mainly small droplet population shows very large isolated drops (next page)
  - No evidence of small ice or graupel

  - Warm rain process at -8 C.

  - Other 4 clouds this day have mixed-phase. The liquid portions all include SLD.

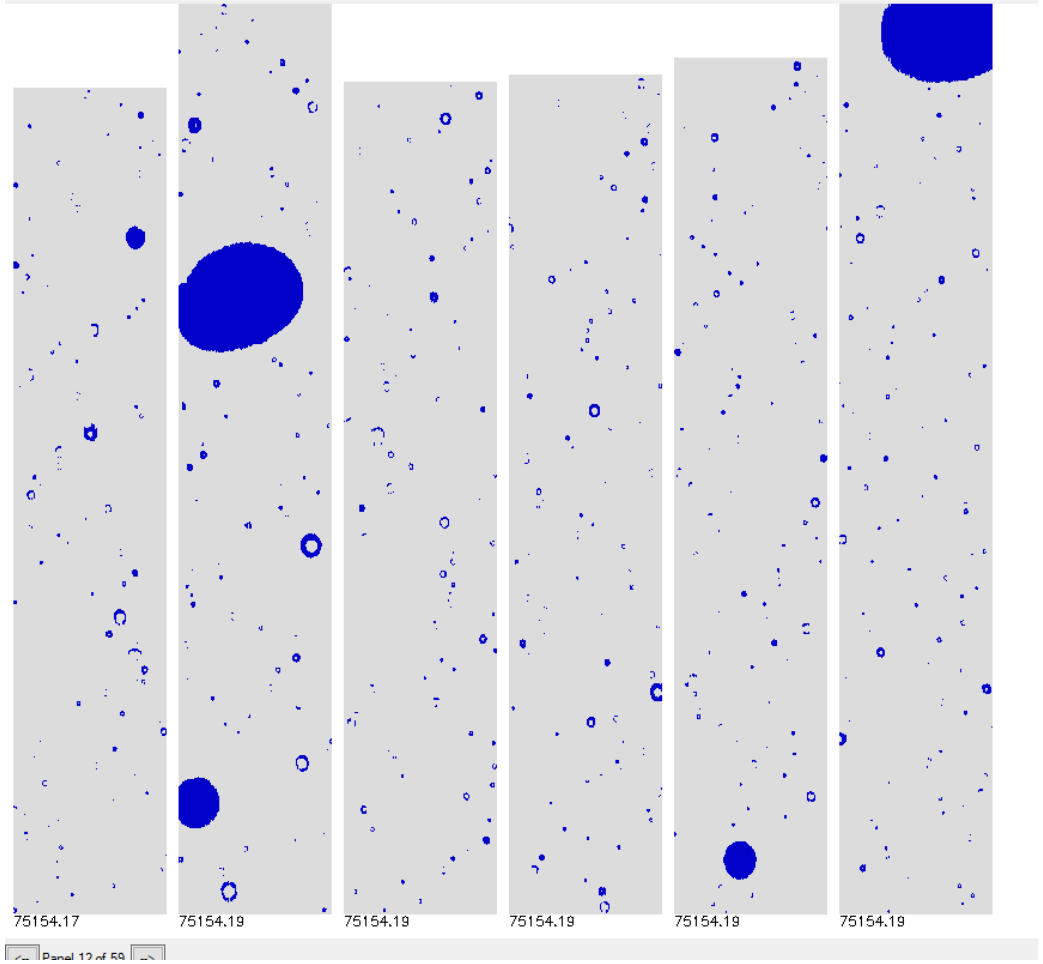


-9 C, Liquid-only runs; Cloud of 10-Jul-2022



20:52:29-20:52:43

- Occasional very large drop



-9 C: liquid-only runs added

Cloud level	# of flts / Runs	Observation
1000’ above base	5 / 23	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)
+4 to +7 C (~ +5 C)	3 / 11	• Two low ANC flights, one medium • All three days had warm rain developing or developed • No clouds showed evidence of melting ice from aloft • Medium ANC may had higher drop concentrations, different maturity of warm rain to be checked.
+14 C	1 / 5	• Starting to develop broader small droplet spectrum with 30 + µm droplets, and occasional large isolated drops to ~ 1 mm
- 9 C	5 / 24	• 4 of 24 are essentially liquid only, with SLD, and drops up to about 1 mm

-9 C – Summary of 2D-S observations for mixed-phase runs

- This is where big variations were observed. Quick summary of -9 C mixed-phase runs below (excludes 4 liquid only, and 2 glaciated):

	Dominated by		
Flight	**LWC/SLD+ graupel**	**LWC+ small ice**	**Variable Zones (LWC+graupel+ small ice)**
10-Jul-22	2	0	1
24-Jul-22	2	0	1
26-Jul-22	2	0	2
27-Jul-22	2	1	1
30-Jul-22	4	0	0
Totals	**12**	**1**	**5**

-9 C
Occurrence of graupel

- Graupel was observed during every -9 C run that was not purely liquid (i.e. 22 of 22 runs)
- Sometimes the runs were primarily composed of LWC/SLD and graupel (i.e. very little or no small ice)
- Therefore, there were no cases of small ice with no graupel present.

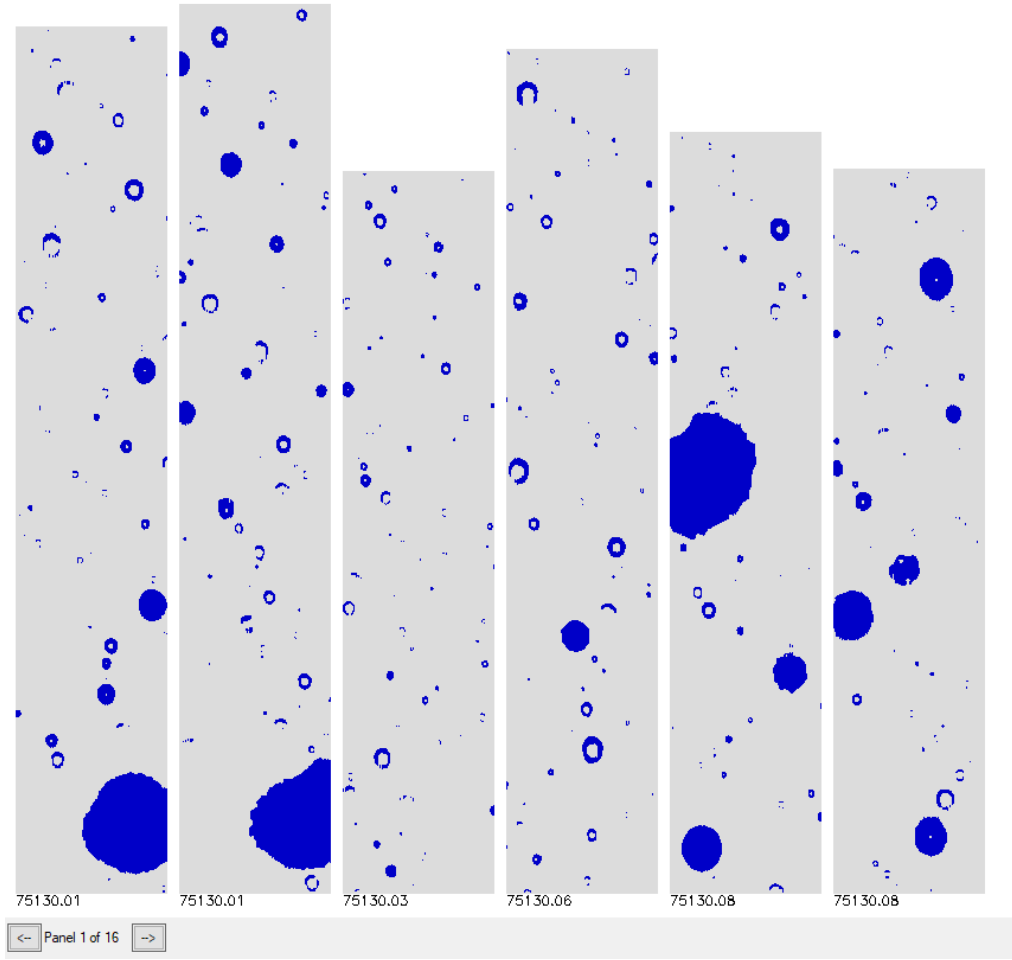
- Number of runs dominated by liquid cloud + graupel (table on previous slide): 12 of the 18 mixed-phase runs

-9 C, graupel and LWC/SLD Cloud of 10-Jul-2022

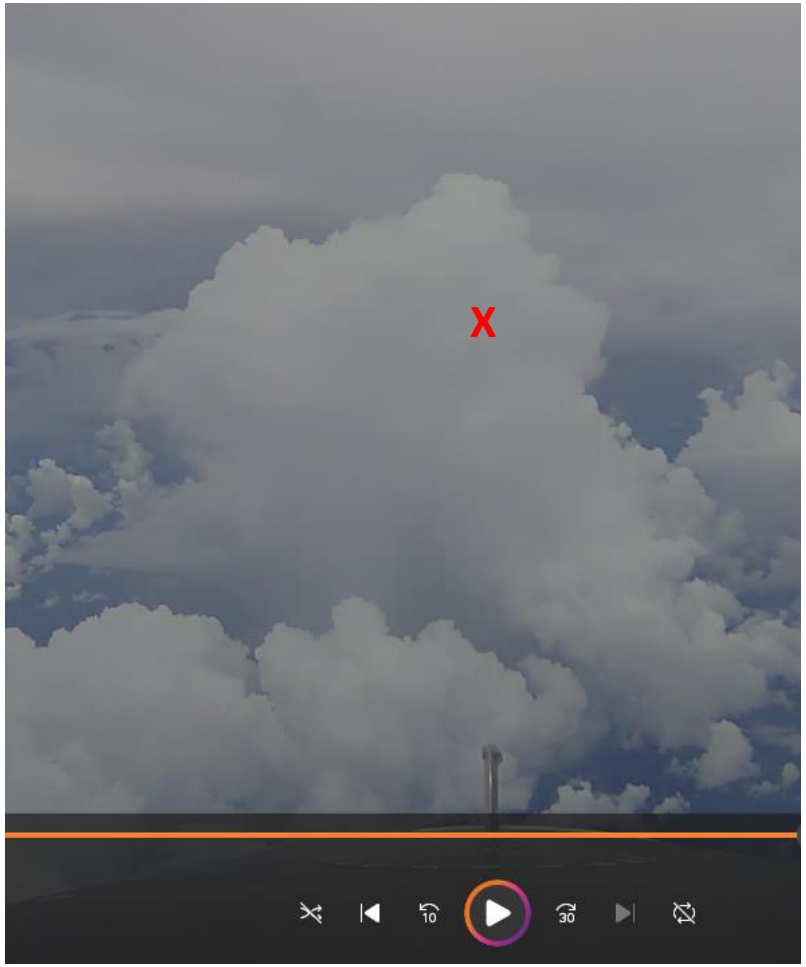
- **Example 1: 10-Jul: -8.8 C, low aerosol**
  - Good location to top; next slide shows frame from DC-8 video, overcast above
  - 2D-S image frame to right
  - CDPavg: 31.5 cm^{-3}, 0.14 gm^{-3}
  - SLD with large drops (image right), estimated to 400 µm
  - Graupel estimated to ~ 1 mm
  - Very few small ice particles
  - Some zones dominated by SLD, or SLD and large drops (next slide)

  - Warm rain process at -9 C.

  - Other 2 mixed-phase clouds this day: one dominated by LWC and graupel, the other had variable zones

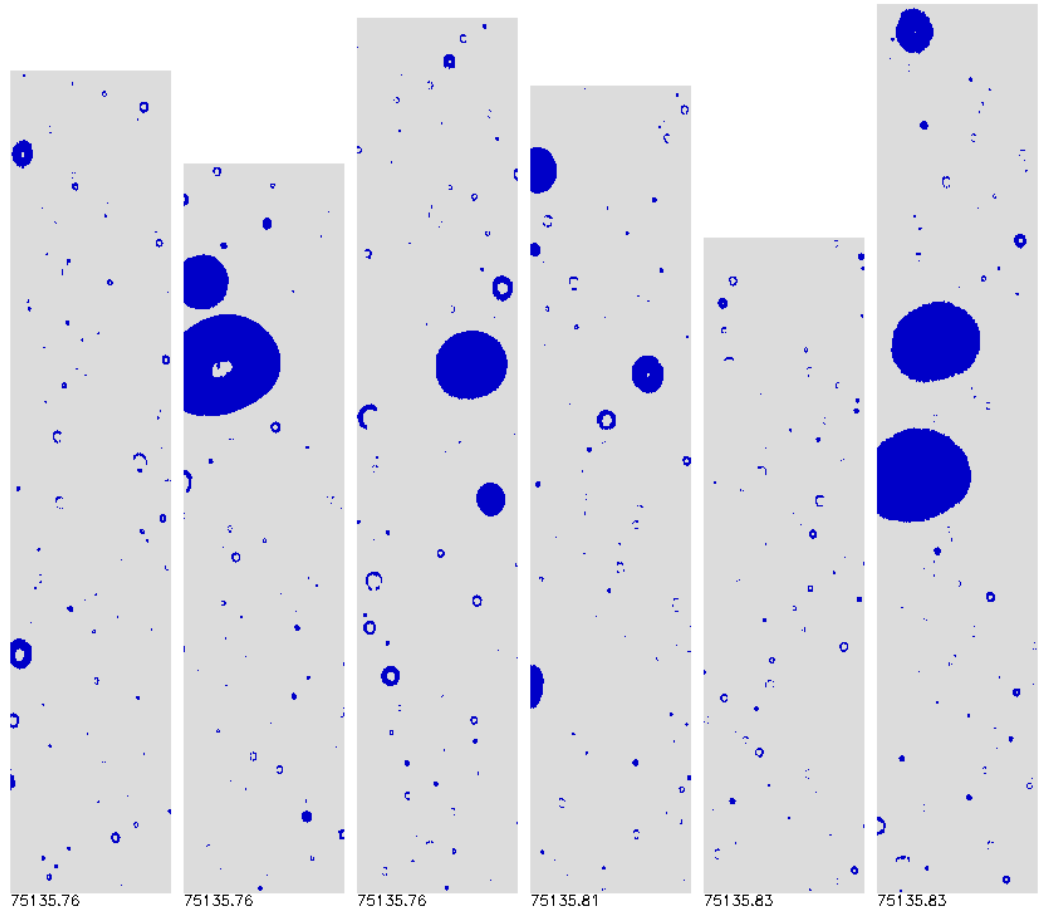


-9 C, graupel and LWC/SLD, Cloud of 10-Jul-2022

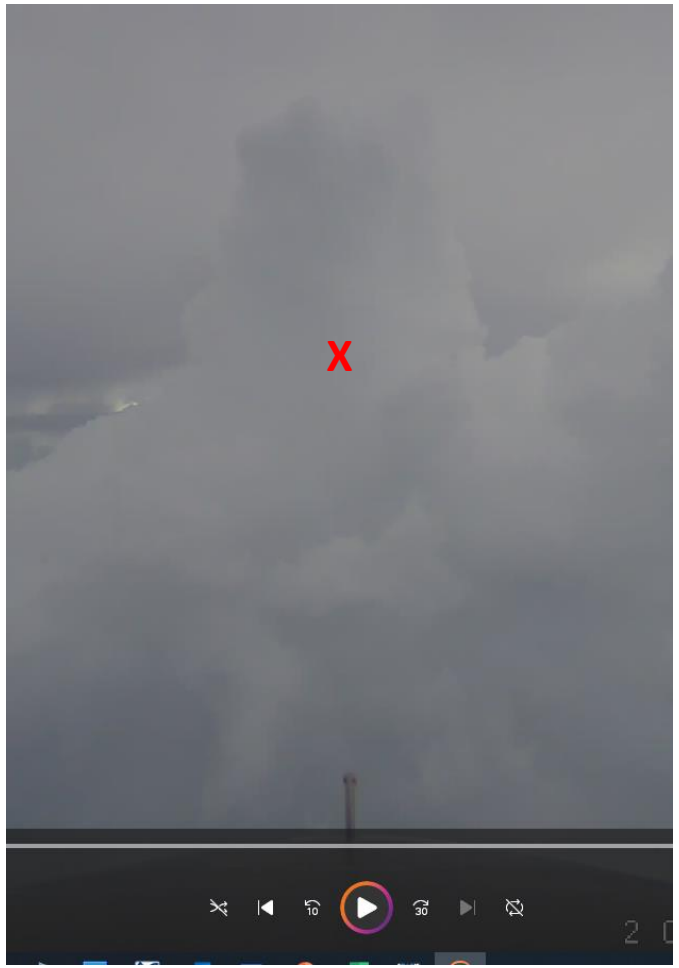


20:52:10-20:52:20

Zone with SLD + large drops (prior to freezing?)

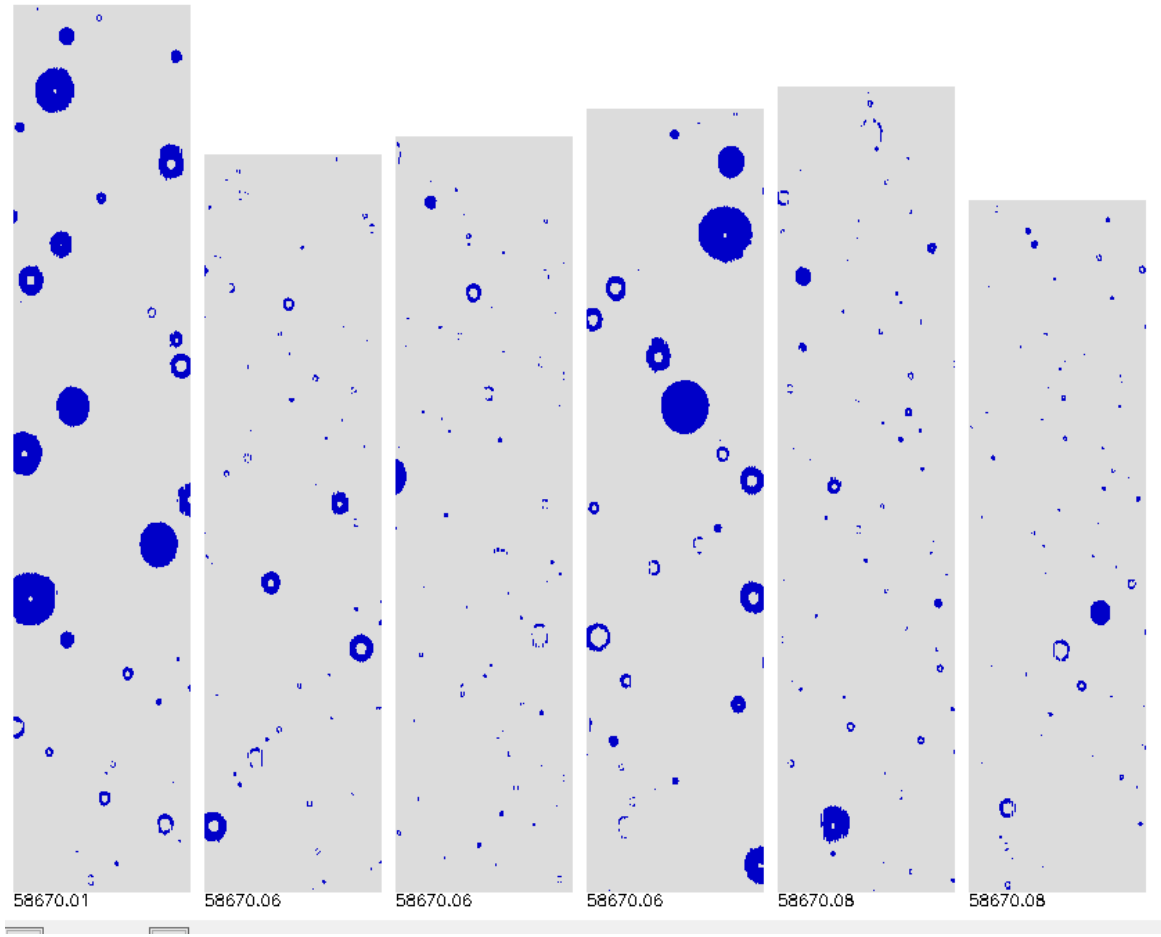


-9 C, graupel and LWC/SLD, Cloud of 30-Jul-2022



16:17:32-16:17:53

Zone with small droplets and SLD only



-9 C, mixed-phase, LWC/SLD+graupel added

Cloud level	# of flts / Runs	Observation
1000’ above base	5 / 23	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)
+4 to +7 C (~ +5 C)	3 / 11	• Two low ANC flights, one medium • All three days had warm rain developing or developed • No clouds showed evidence of melting ice from aloft • Medium ANC may had higher drop concentrations, different maturity of warm rain to be checked.
+14 C	1 / 5	• Starting to develop broader small droplet spectrum with 30 + µm droplets, and occasional large isolated drops to ~ 1 mm
- 9 C	5 / 24	• 4 of 24 are essentially liquid only, with SLD, and drops to about 1 mm • 18 are mixed-phase, 12 of which are dominated by droplet and drops + graupel

- 9 C, Occurrence of small ice

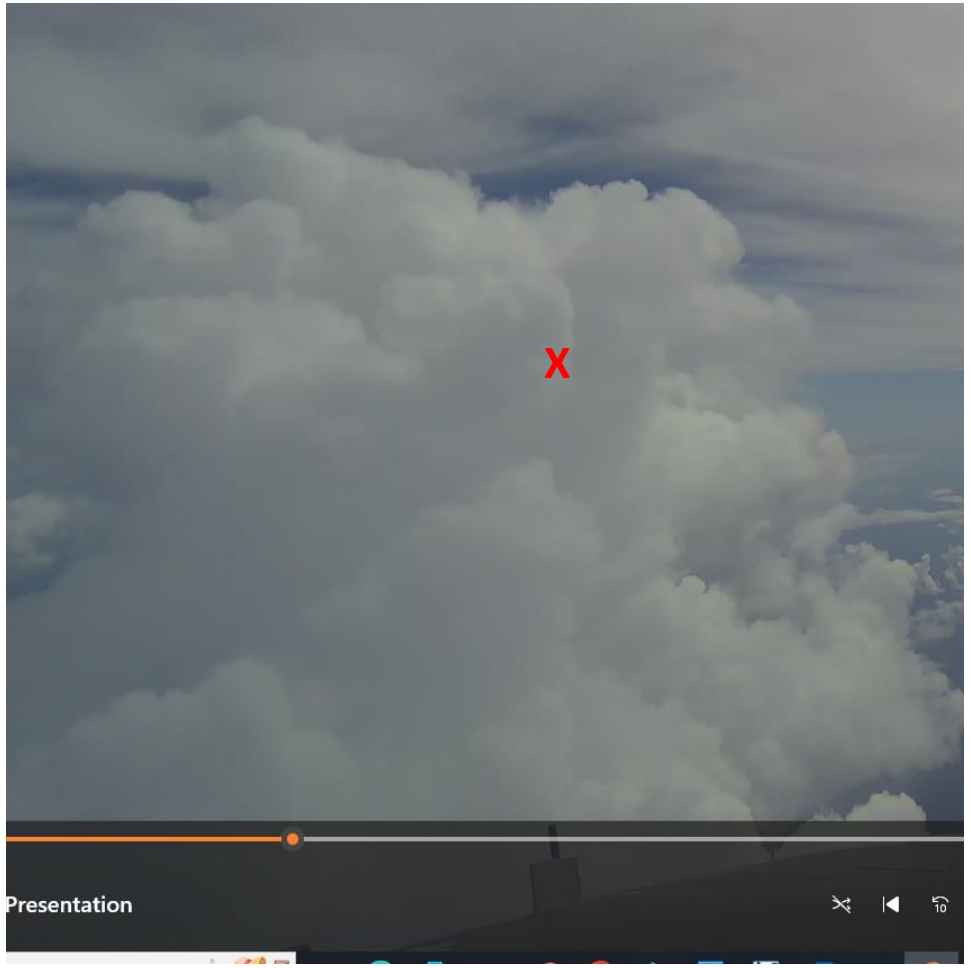
- Low concentrations of small ice were sometimes observed, but what was notable was the appearance of high concentration of small ice in concentrated zones, and the glaciation of that zone
- concentrated small ice zones were observed in 5 of the 16 mixed-phase runs

-9 C, Occurrence of small ice, Cloud of 10-Jul-2022

- **Example 1: 10-Jul: -9.2 C, low aerosol**
  - Good location to top; at right shows frame from DC-8 video, DC-8 turned a bit to left for run
  - CDPavg: 15.1 cm^{-3}, 0.14 gm^{-3} (unreliable in small ice)
  - 2D-S image frames next slide
  - Entry side, SLD + graupel (next slide)
  - inside: start of some small ice (next slide)
  - Towards exit side: small ice glaciated cloud (next slide)
  - Graupel estimated to max ~ 1 mm overall
  - Small ice appears to glaciate cloud

  - Other 2 mixed-phase cloud this day dominated by SLD + graupel

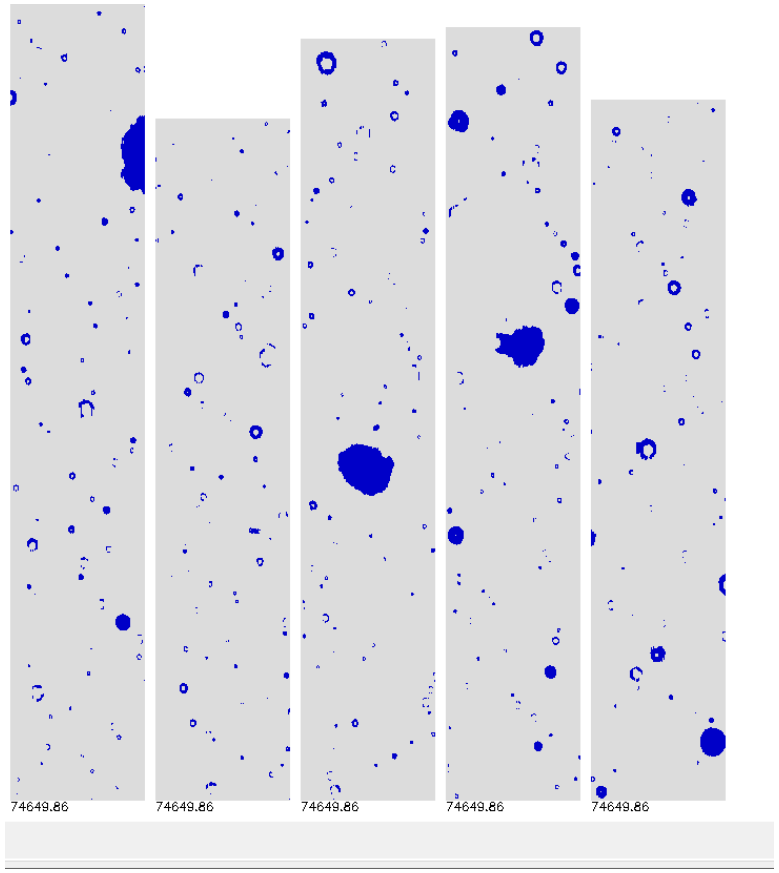
Run along 11 o'clock bearing



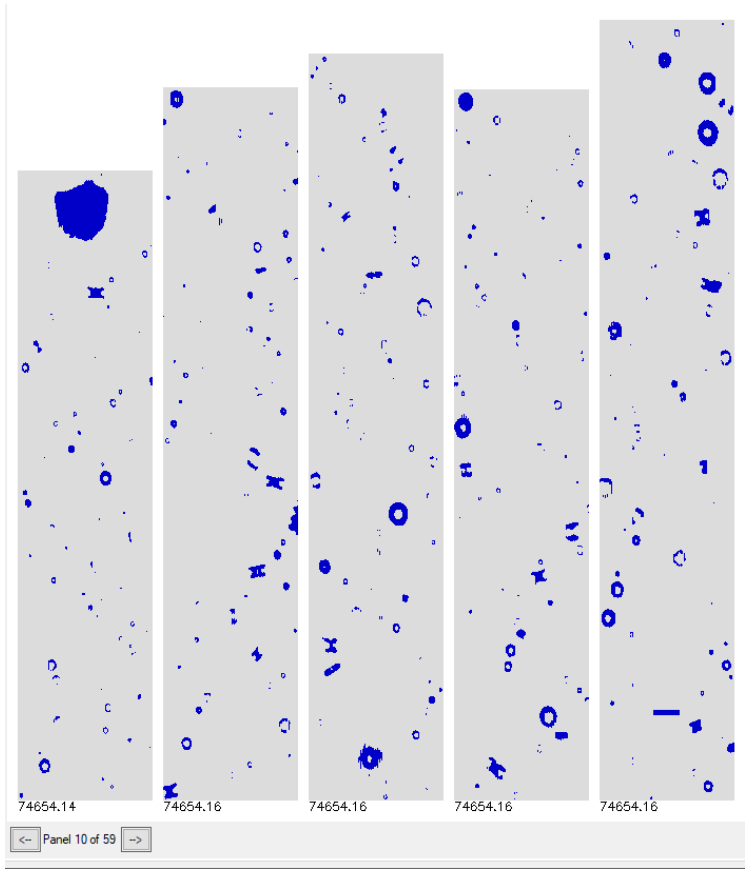
20:44:25-20:44:32

-9 C, Occurrence of small ice, Cloud of 10-Jul-2022

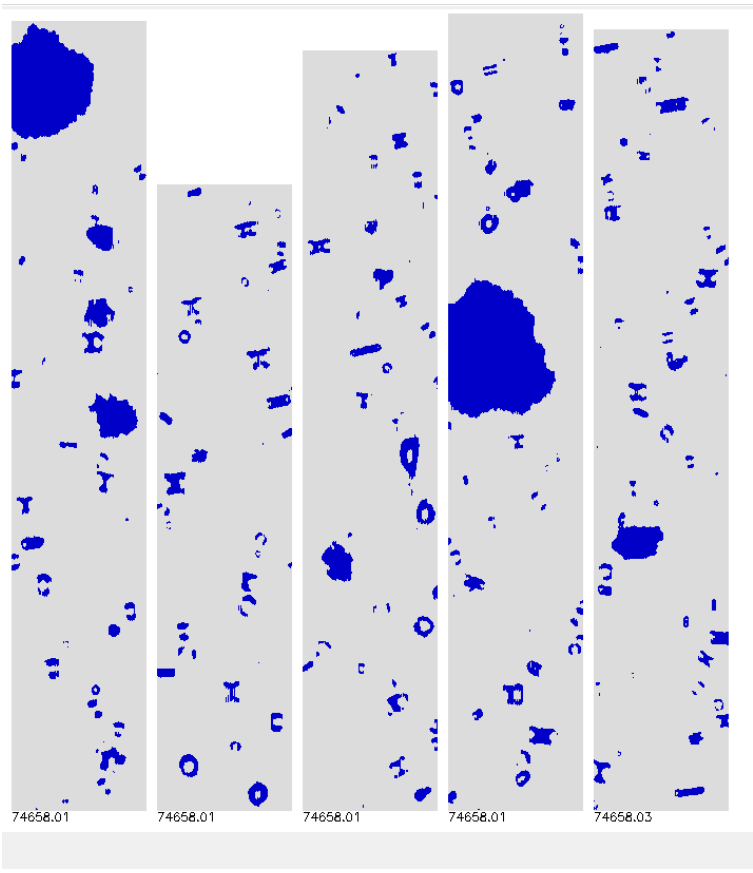
Zone of droplets, SLD + graupel on entry



Zone of Droplets, graupel, some small ice



Zone dominated by small ice, prob. glaciated



-9 C, mixed-phase, small ice occurrence added

Cloud level	# of flts / Runs	Observation
1000’ above base	5 / 23	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)
+4 to +7 C (~ +5 C)	3 / 11	• Two low ANC flights, one medium • All three days had warm rain developing or developed • No clouds showed evidence of melting ice from aloft • Medium ANC may had higher drop concentrations, different maturity of warm rain TBD.
+14 C	1 / 5	• Starting to develop broader small droplet spectrum with 30 + µm droplets, and occasional large isolated drops to ~ 1 mm
- 9 C	5 / 24	• 4 of 24 are essentially liquid only, with SLD, and drops to about 1 mm • 18 are mixed-phase, 12 of which are dominated by droplet and drops + graupel, and 6 of which are overall being dominated at least partially by zones of glaciating small ice particles

- 9 C, Glaciated cloud runs

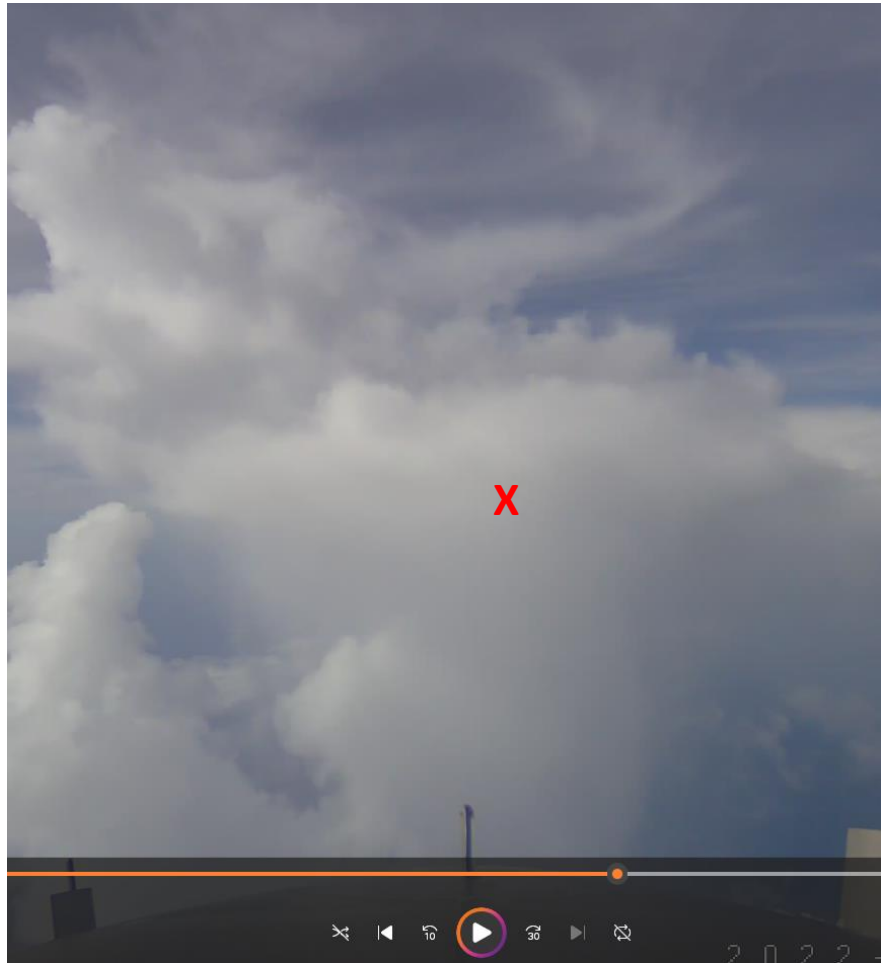
- 2 of the 25 cloud runs at -9 C were glaciated as far as could be determined (no significant LWC)
- Both were on 24-Jul

-9 C, glaciated run, Cloud of 24-Jul-2022

- **24-Jul: -7.9 C**, shown at right
  - Good location to top; at right shows frame from DC-8 video, DC-8 turned a bit to left for run
  - Fuzzy top; cloud could be collapsing; did not cross higher cloud behind
  - Fairly long crossing (44 s)
  - Particles looked quite uniform across the entire width (next slide), albeit with some size variation according to location
  - Probably rimed particles, but large semi-circular graupel is not obvious anywhere; more like heavily rimed crystals

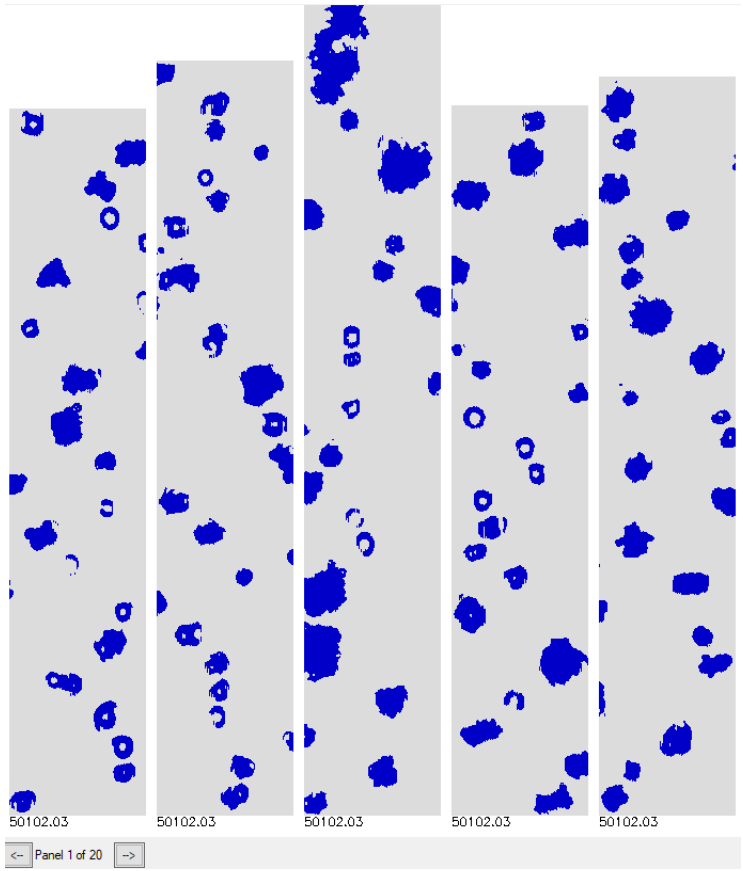
  - Second glaciated cloud this day has similar looking data. Another fuzzy-topped cloud with more cauliflower looking tops nearby

Collapsing top?

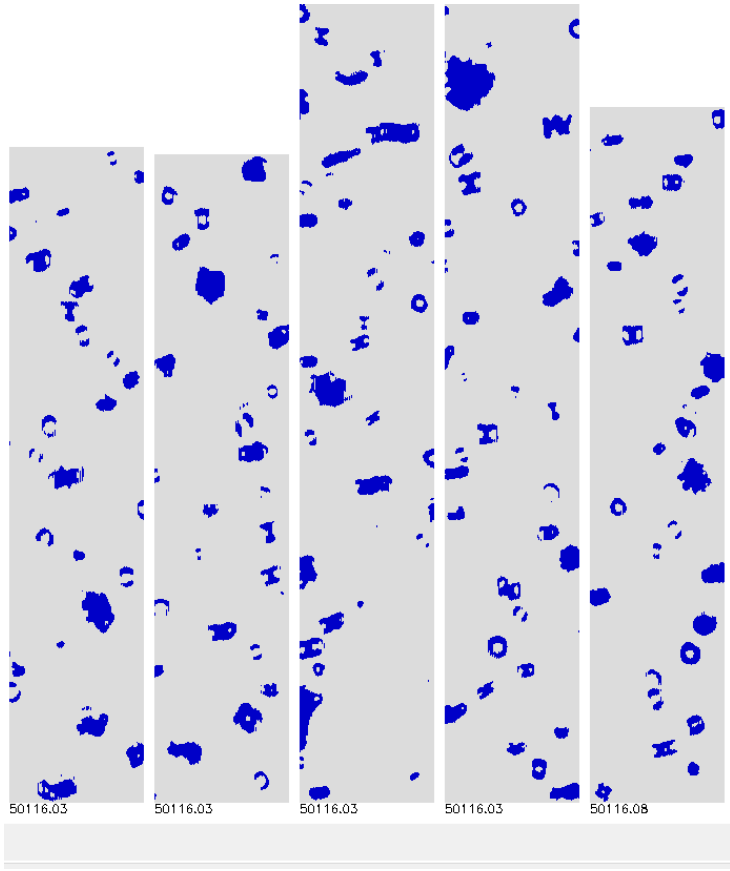


-9 C, glaciated run, Cloud of 24-Jul-2022

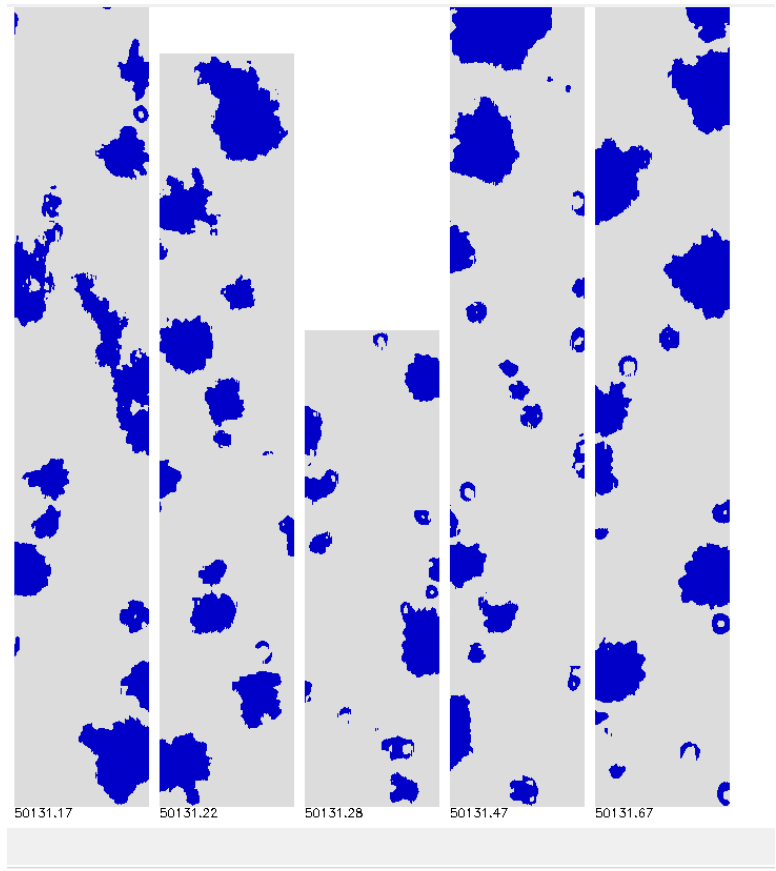
Entry side



Middle



Exit side



-9 C, mixed-phase, glaciated cloud added

Cloud level	# of flts / Runs	Observation
1000’ above base	5 / 23	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)
+4 to +7 C (~ +5 C)	3 / 11	• Two low ANC flights, one medium • All three days had warm rain developing or developed • No clouds showed evidence of melting ice from aloft • Medium ANC may had higher drop concentrations, different maturity of warm rain TBD.
+14 C	1 / 5	• Starting to develop broader small droplet spectrum with 30 + µm droplets, and occasional large isolated drops to ~ 1 mm
- 9 C	5 / 24	• 4 of 24 are essentially liquid only, with SLD, and drops to about 1 mm • 18 are mixed-phase, 12 of which are dominated by droplet and drops + graupel, and 6 of which are overall being dominated at least partially by zones of glaciating small ice particles • **2 of 24 are glaciated, with concentrations of small – medium sized ice and large rimed ice crystals; graupel less “round”**

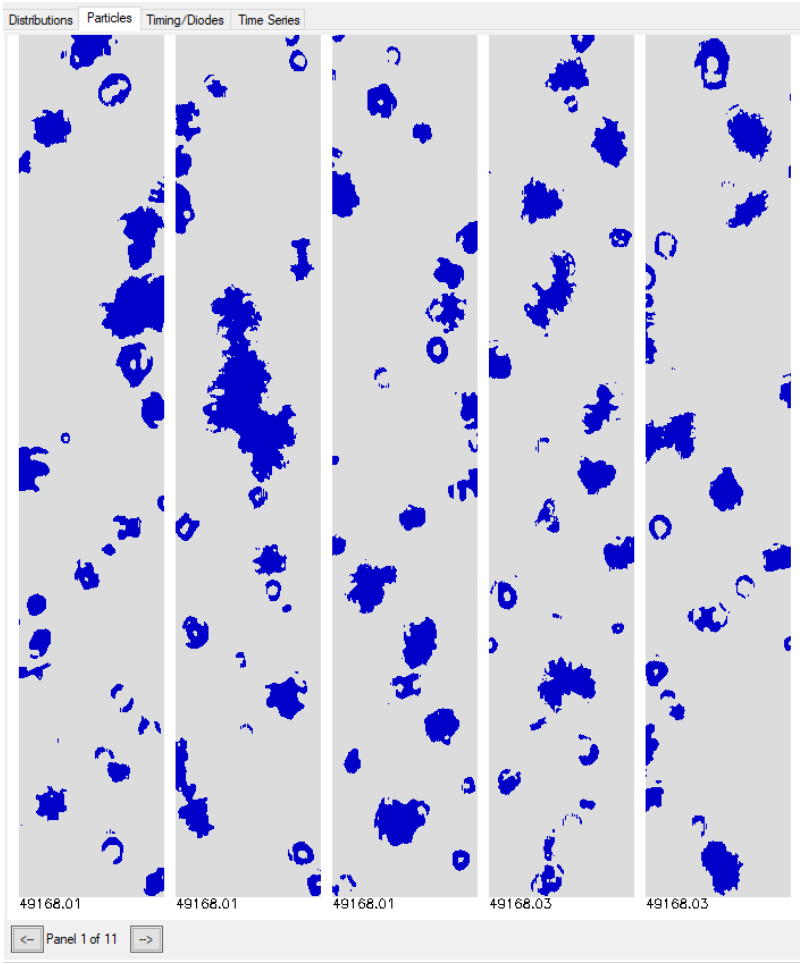
-19 C level

Cloud level	# of flts / Runs	Observation
1000’ above base	5 / 23	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)
+4 to +7 C (~ +5 C)	3 / 11	• Two low ANC flights, one medium • All three days had warm rain developing or developed • No clouds showed evidence of melting ice from aloft • Medium ANC may had higher drop concentrations, different maturity of warm rain TBD.
+14 C	1 / 5	• Starting to develop broader small droplet spectrum with 30 + µm droplets, and occasional large isolated drops to ~ 1 mm
- 9 C	5 / 24	• 4 of 24 are essentially liquid only, with SLD, and drops to about 1 mm • 18 are mixed-phase, 12 of which are dominated by droplet and drops + graupel, and 6 of which are overall being dominated at least partially by zones of glaciating small ice particles • 2 of 24 are glaciated, with concentrations of small – medium sized ice and large rimed ice crystals; little evidence of graupel
-19 C	**3 / 13**	• 7 glaciated, 4 substantially mixed-phase, 2 mixed-phase with trace LWC

-19 C, Glaciated Cloud of 24-Jul-2022

- **24-Jul: -17.9 C**, shown at right
  - Good location to top; at right shows frame from DC-8 video, DC-8 turned a bit to left for run
  - Fuzzy top; cloud could be collapsing
  - Particles looked quite uniform across the entire width, albeit with some size variation according to location
  - Dry growth from crystals ? , aggregates, no small droplets
  - No obvious hard graupel (rare case without)

  - Second glaciated cloud from the same day, had similar looking data, also with no obvious hard graupel.



-19 C, Glaciated Cloud of 24-Jul-2022

13:39:25-13:39:35

-19 C , Mixed-Phase, Cloud of 30-Jul-2022

- **24-Jul: -17.9 C**, shown at right
  - Good location to solid top; at right shows frame from DC-8 video, DC-8 in turn to line up with ~ 10:30 o'clock pass
  - Particles looked quite uniform across the entire width, albeit with some size variation according to location
  - CDPmax 101 cm^{-3}, 0.4 gm^{-3}
  - Cloud droplet across entire cloud (no glaciation)
  - A little bit of SLD on both edges of cloud
  - Small/medium, and large ice, some large graupel

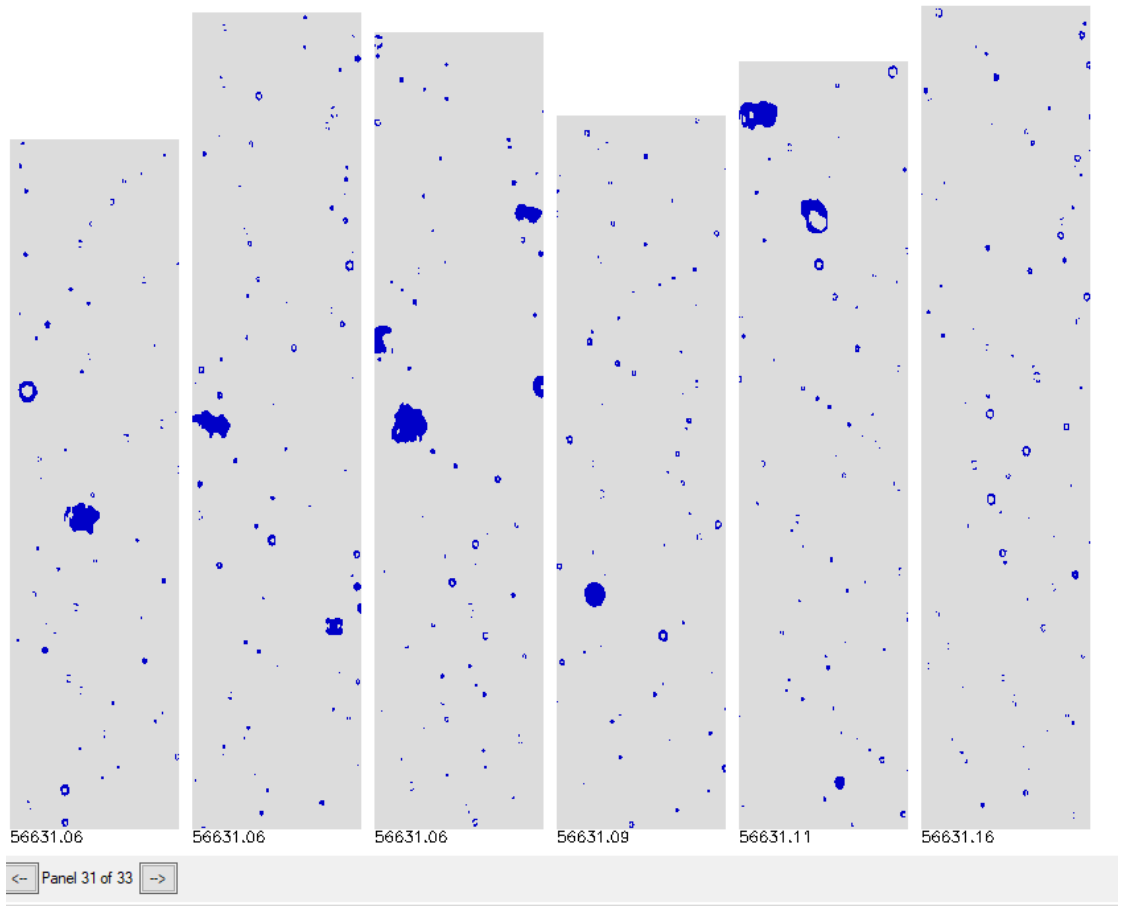
  - Other two runs from this day: one with broad mixed-phase, the other with patchy LWC and zones of glaciation, both with small-medium ice and graupel.

DC-8 in turn to line up

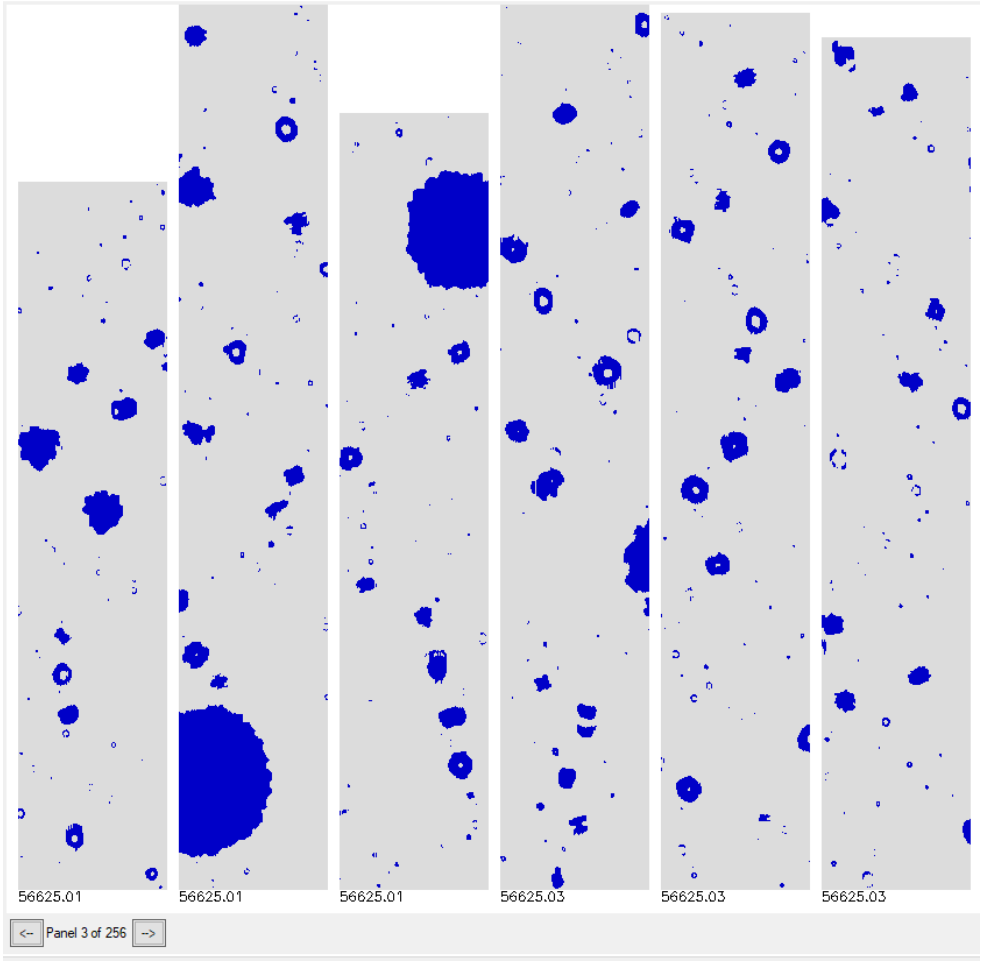
15:43:42-15:43:55

-19 C , Mixed-Phase, Cloud of 30-Jul-2022

A little bit of SLD on cloud edge



Droplets, small-medium ice and large graupel



-19 C level, glaciated and mixed phase added Final Overview Summary

Cloud level	# of flts / Runs	Observation
1000’ above base	5 / 22	• Coalescence embryos ≥ ~50 µm always present • Warm rain undeveloped (not surprisingly)
+4 to +7 C (~ +5 C)	3 / 11	• Two low ANC flights, one medium • All three days had warm rain developing or developed • No clouds showed evidence of melting ice from aloft • Medium ANC may had higher drop concentrations, different maturity of warm rain TBD.
+14 C	2 / 8	• Starting to develop broader small droplet spectrum with 30 + µm droplets, and occasional large isolated drops to ~ 1 mm
- 9 C	5 / 24	• 4 of 24 are essentially liquid only, with SLD, and drops to about 1 mm • 18 are mixed-phase, 12 of which are dominated by droplet and drops + graupel, and 6 of which are overall being dominated at least partially by zones of glaciating small ice particles • 2 of 24 are glaciated, with little evidence of graupel, and high concentrations of small ice
-19 C	**3 / 13**	• 7 glaciated, 4 substantially mixed-phase, 2 mixed-phase with trace LWC • 2 of the glaciated runs the only ones without obvious hard graupel • Dominant observation was a mix of small-medium sized ice and graupel • 3 of the 4 substantially mixed phase cases were from 30-Jul (high aerosol)

Questions relative to first order hypothesis

Warm Rain

1. Were coalescence embryos (≥ 50 μm) indeed present in cloud base runs ?
2. Was the warm rain observed at +5 C significant in terms of depleting TWC advected aloft?
3. Is it possible to see a difference in warm rain production between low and high aerosol cases

Ice production and precipitation development

1. Ice dominates the cloud by -20 C and arguably even by -9 C.
    - Are natural ice nuclei sufficient in concentration to account for the concentrations of small ice and graupel? Can Hallet-Mossop ice multiplication explain sudden appearance of glaciating small ice?
2. Does the cloud have any memory of warm rain by this point? (e.g. does the existence of large drops coming through the freezing level affect the initiation of ice in the cloud)
3. Are there any differences in cloud ice microphysics for low and high aerosol cases?

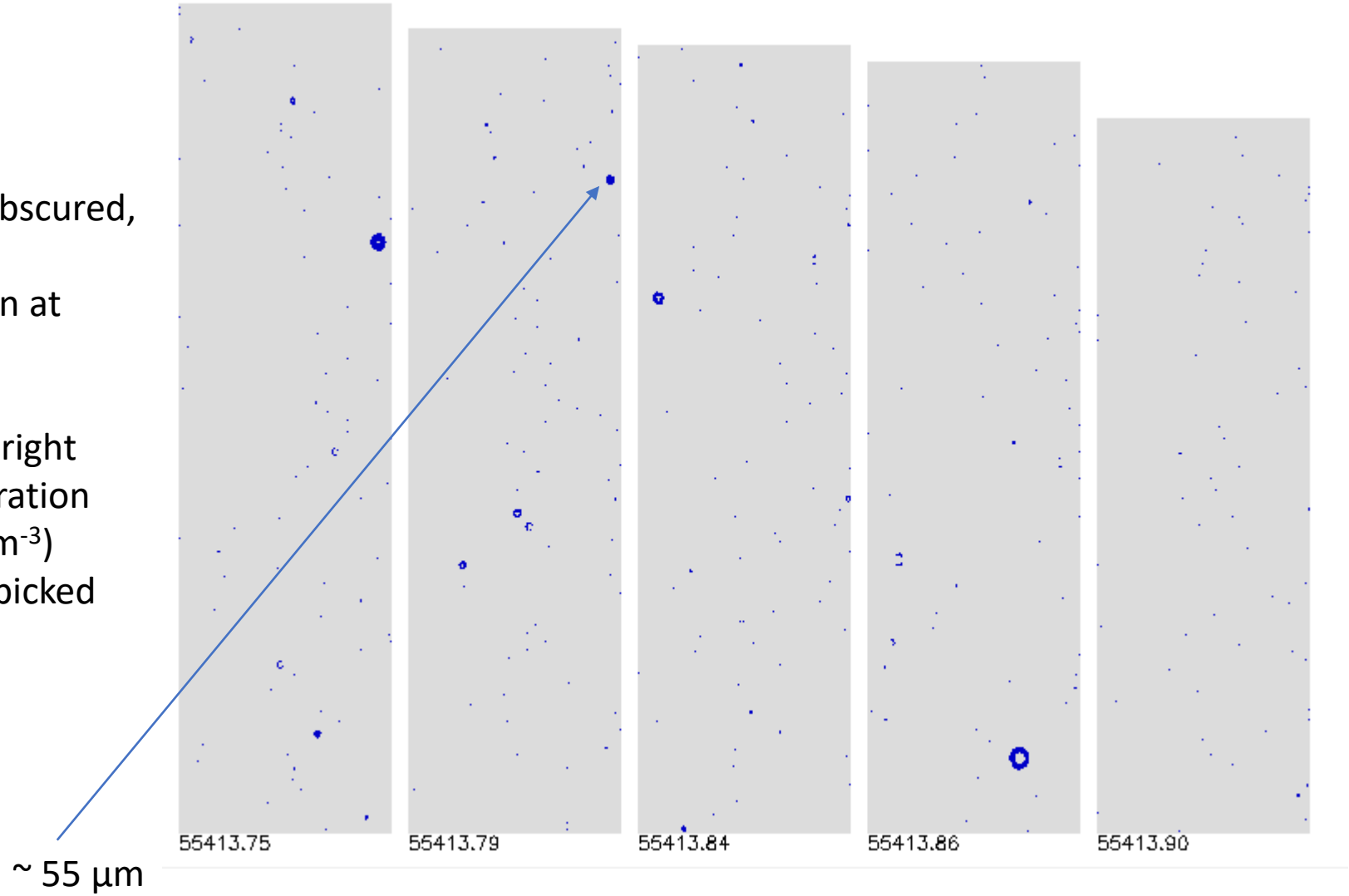
End of presentation

- Additional slides for documentation, but not used in presentation, follow

22-Jul case, 1000’ above cloud base, high CDC

- 30-Jul: CDCmax= 715 cm^{-3}
- **22-Jul:**
  - CDCmax= 509 cm^{-3} (top obscured, some drizzle)
  - CDCmax= **483** cm^{-3} (shown at right)

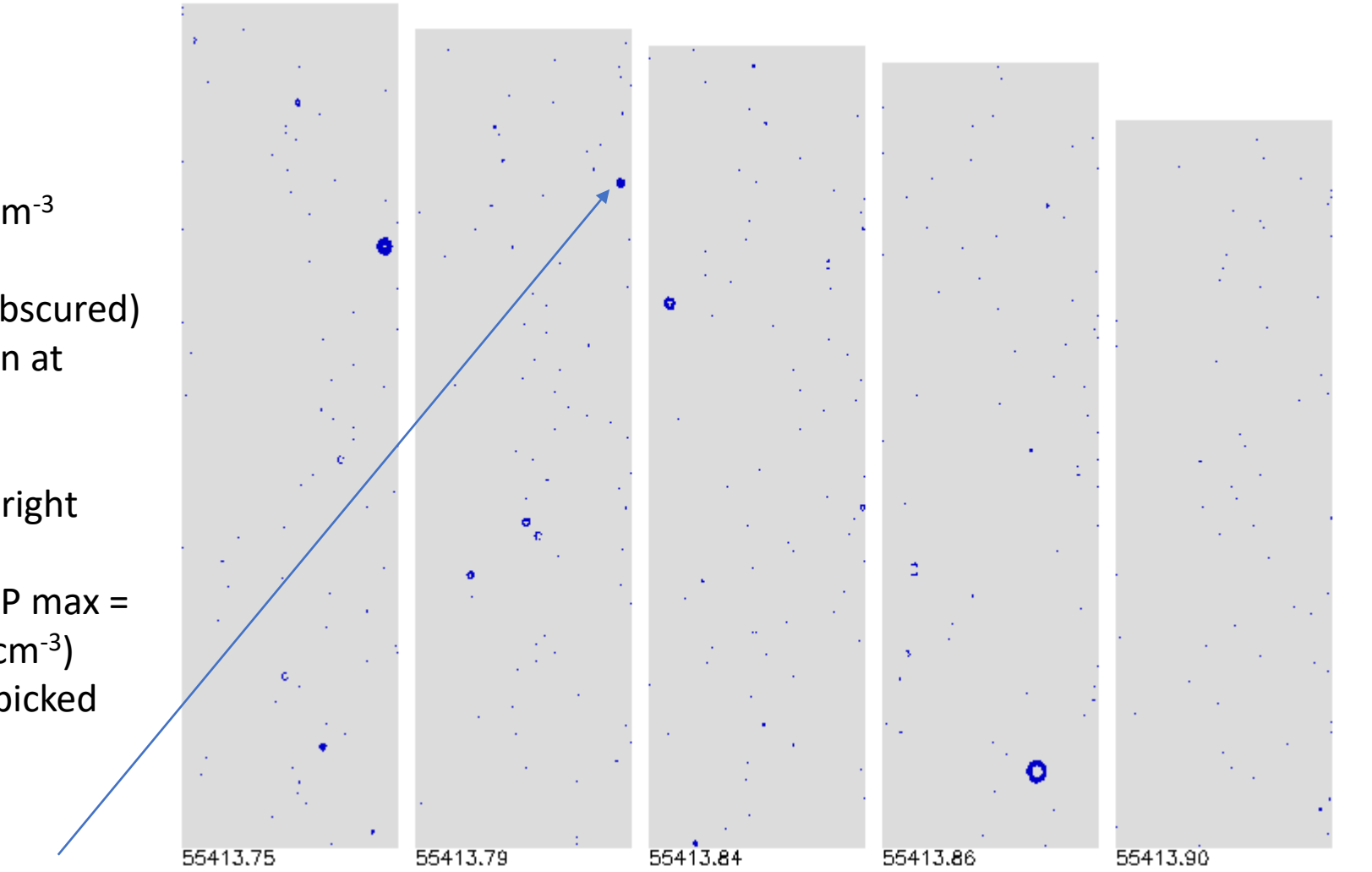
- **22-Jul 483 cm^{-3}** case shown at right
  - Medium aerosol concentration case (PCASP max = 375 cm^{-3})
  - But still odd larger drop; picked this frame to illustrate



27-Jul case, 1000’ above cloud base, high CDC

- 30-Jul: CDCmax= 715 cm^{-3}
- 22-Jul:
  - CDCmax= 509 cm^{-3}, 483 cm^{-3}
- 27-Jul:
  - CDCmax= 423 cm^{-3} (top obscured)
  - CDCmax= 414 cm^{-3}, shown at right (top visible)

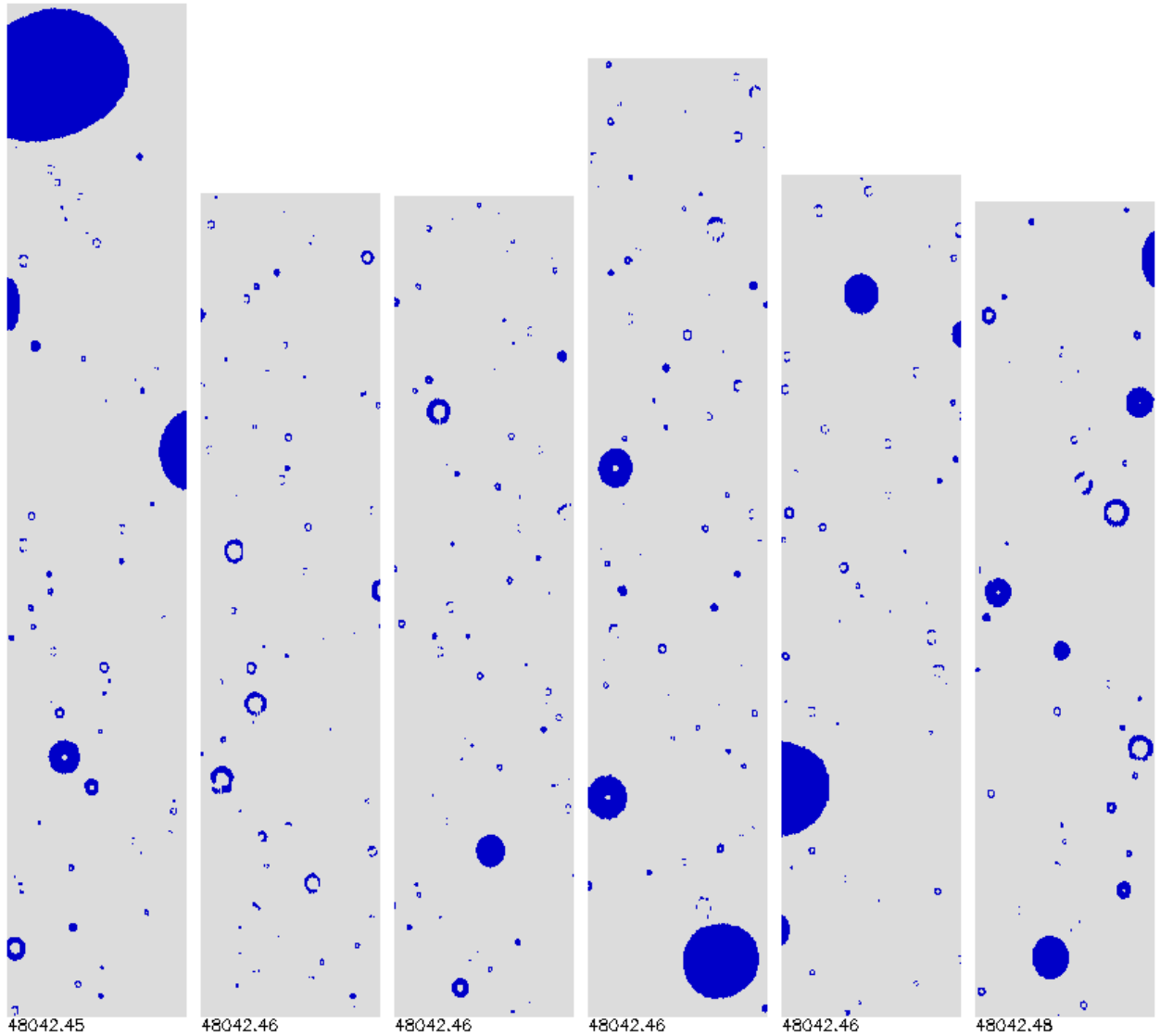
- **27-Jul 414 cm^{-3}** case shown at right
  - Medium-high aerosol concentration case (PCASP max = 250 cm^{-3}, but CCN ~ 740 cm^{-3})
  - But still odd larger drop; picked this frame to illustrate



~ +5 C,
Cloud of 26-Jul-2022

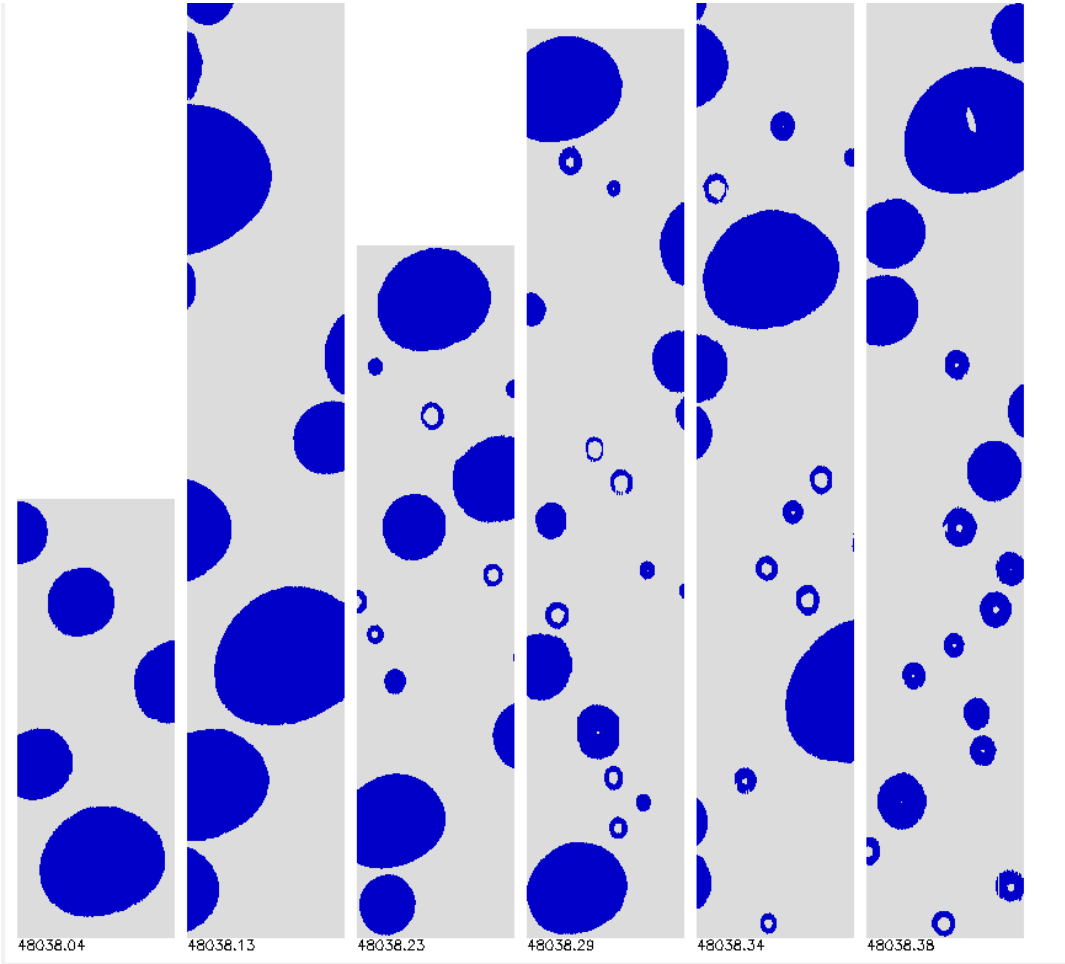
- **26-Jul: ~+3.8 C, low aerosol**
  - 2D-S shown at right
  - Isolated cloud, very good location to top; next slide shows frame from video
  - Mid cloud in area with cloud droplets, drops to about 1 mm
  - next slide also shows rain on entry (leaning?)
  - Warm rain process active
  - No indication of melting ice

  - Other 3 clouds this day have very similar observations



~ +5 C,
Cloud of 26-Jul-2022

Left photo: Cloud looks fuzzy on entry, more solid past

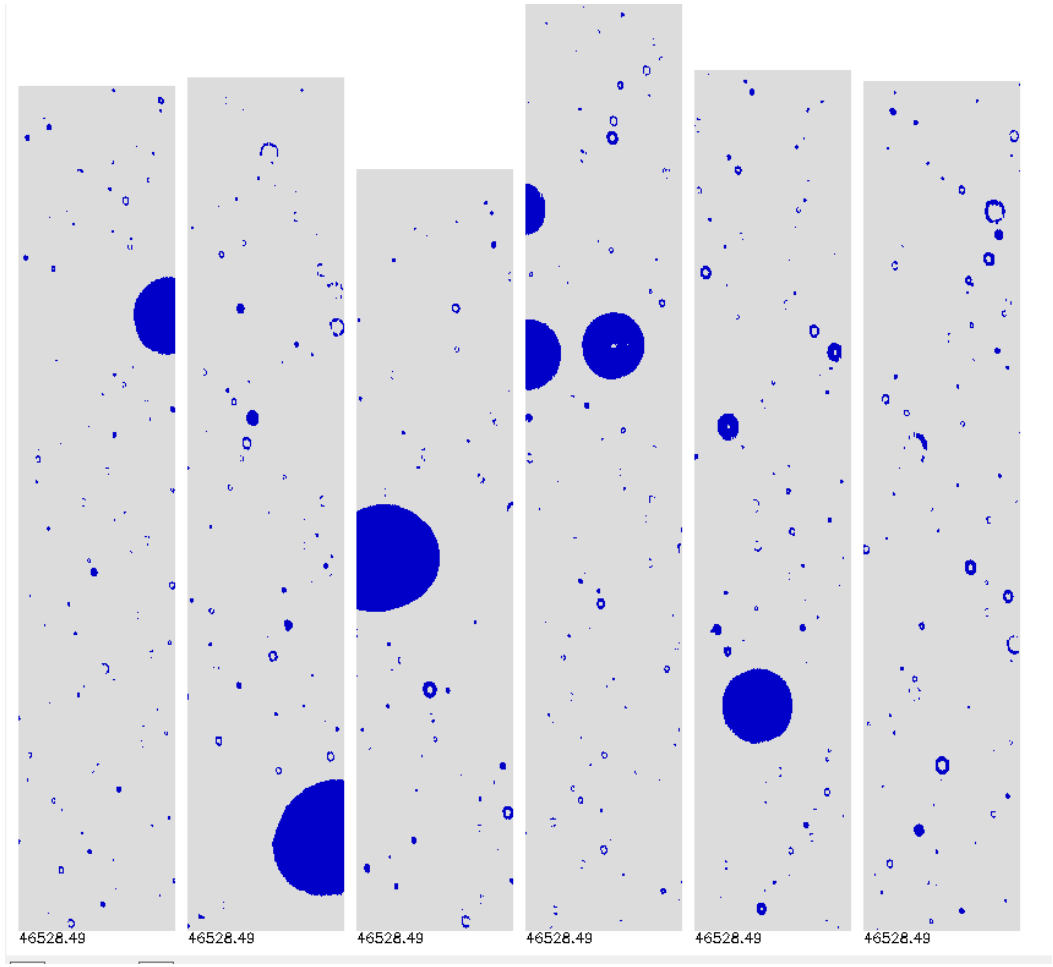


-9 C, Liquid-only runs; Cloud of 26-Jul-2022

- **Case 2: 26-Jul: -9.8 C**, shown at right
  - Isolated cloud, good location to top; did not penetrate cloud in background; next slide shows frame from DC-8 video
  - SLD with large drops (image right)
  - Some zones more SLD-like (image next page)
  - 2D-S imagery poorer than usual
  - No evidence of small ice or graupel

  - Warm rain process at -9 C.

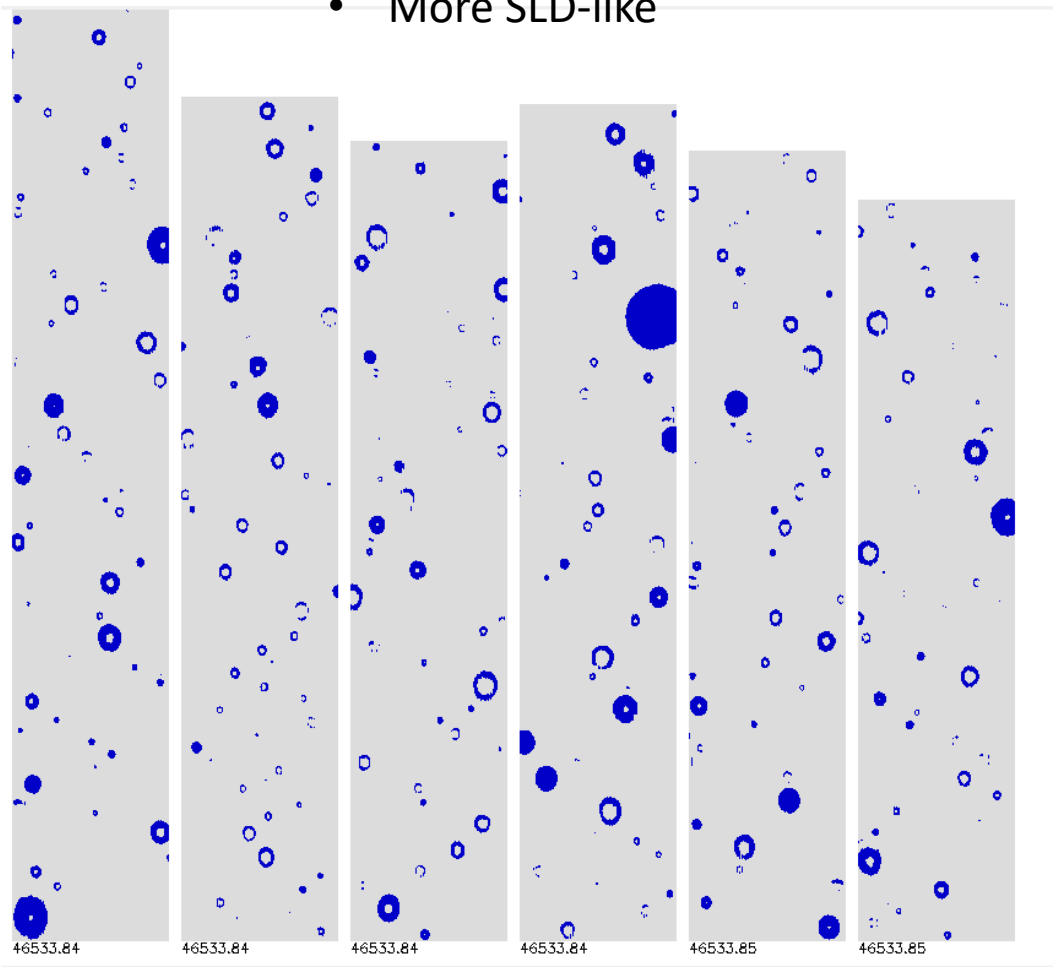
  - Other 4 clouds this day have mixed-phase. The liquid portions all include SLD up to about 0.5 mm.



-9 C, Liquid-only runs; Cloud of 26-Jul-2022

12:55:22-12:55:37

- More SLD-like

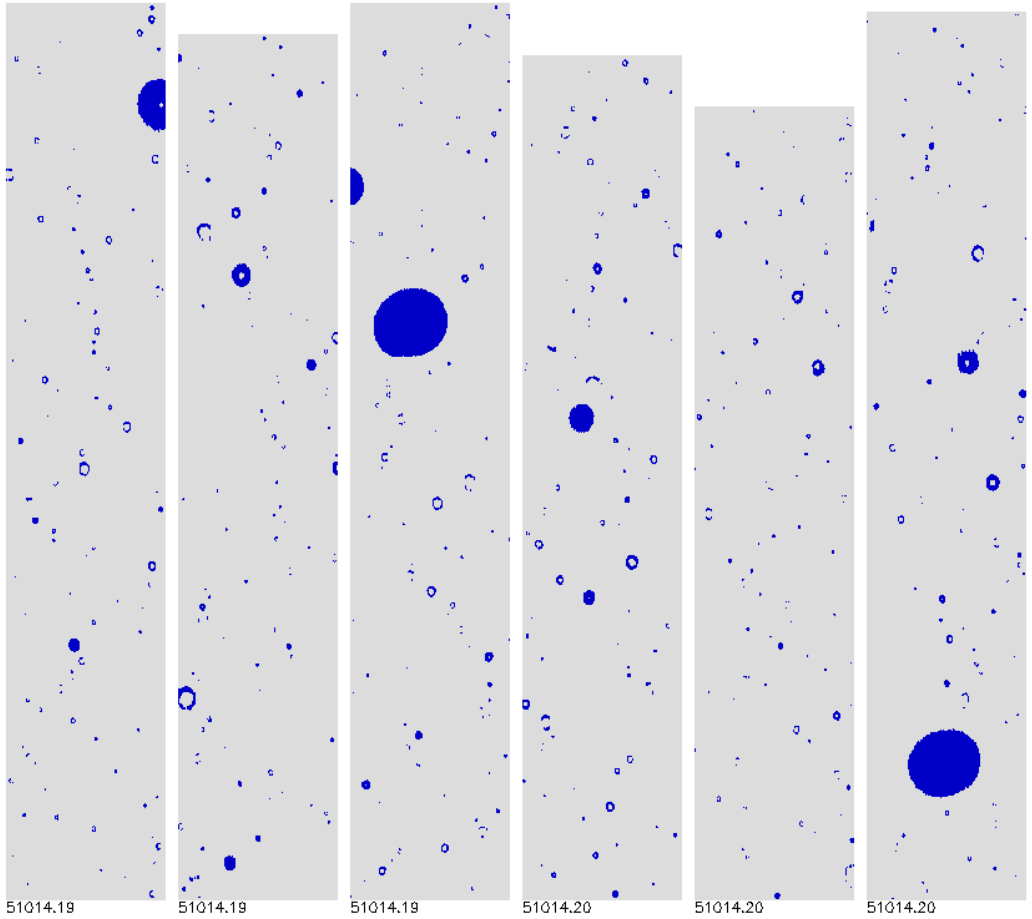


-9 C, Liquid-only runs; Cloud of 27-Jul-2022

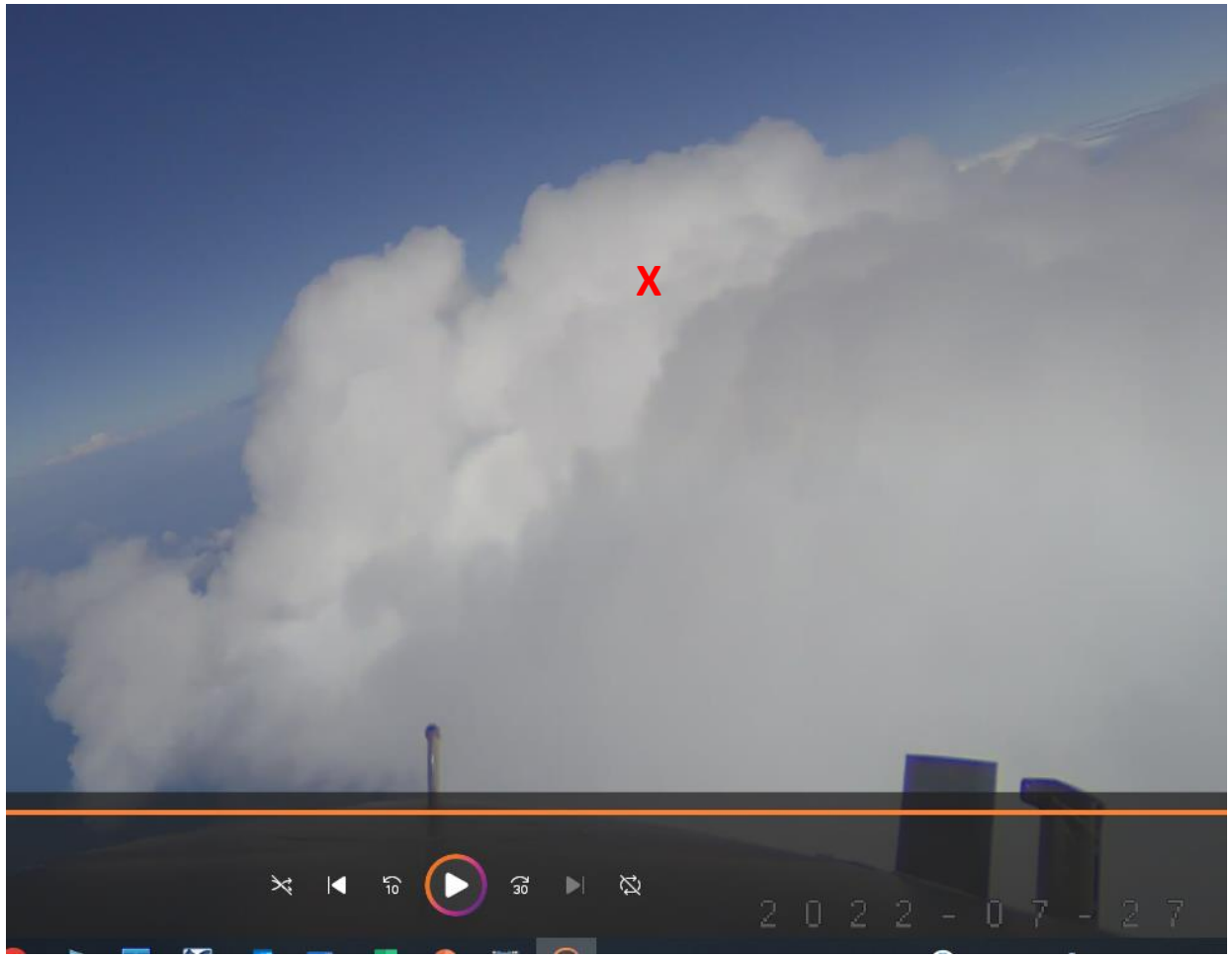
- **Case 3: 27-Jul: -8.6 C**, shown at right
  - Good location to top; next slide shows frame from DC-8 video
  - SLD with large drops (image right)
  - Maybe a very few possible graupel particles, and a very few small ice particles
  - Highly, highly dominated by liquid

  - Warm rain process at -9 C.

  - Other 4 clouds this day have mixed-phase. The liquid portions all include SLD up to about 0.5 mm.

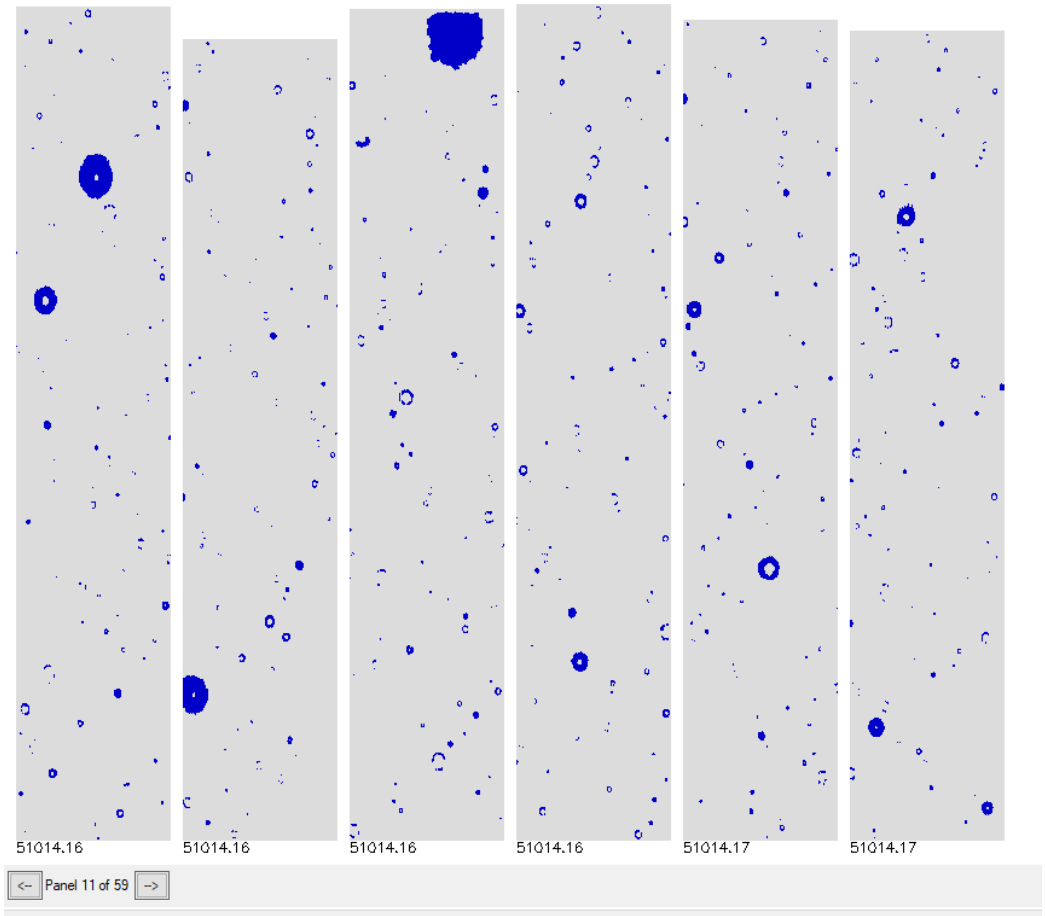


-9 C, Liquid-only runs; Cloud of 27-Jul-2022



14:10:13-14:10:24

Rare frame with a possible graupel particle

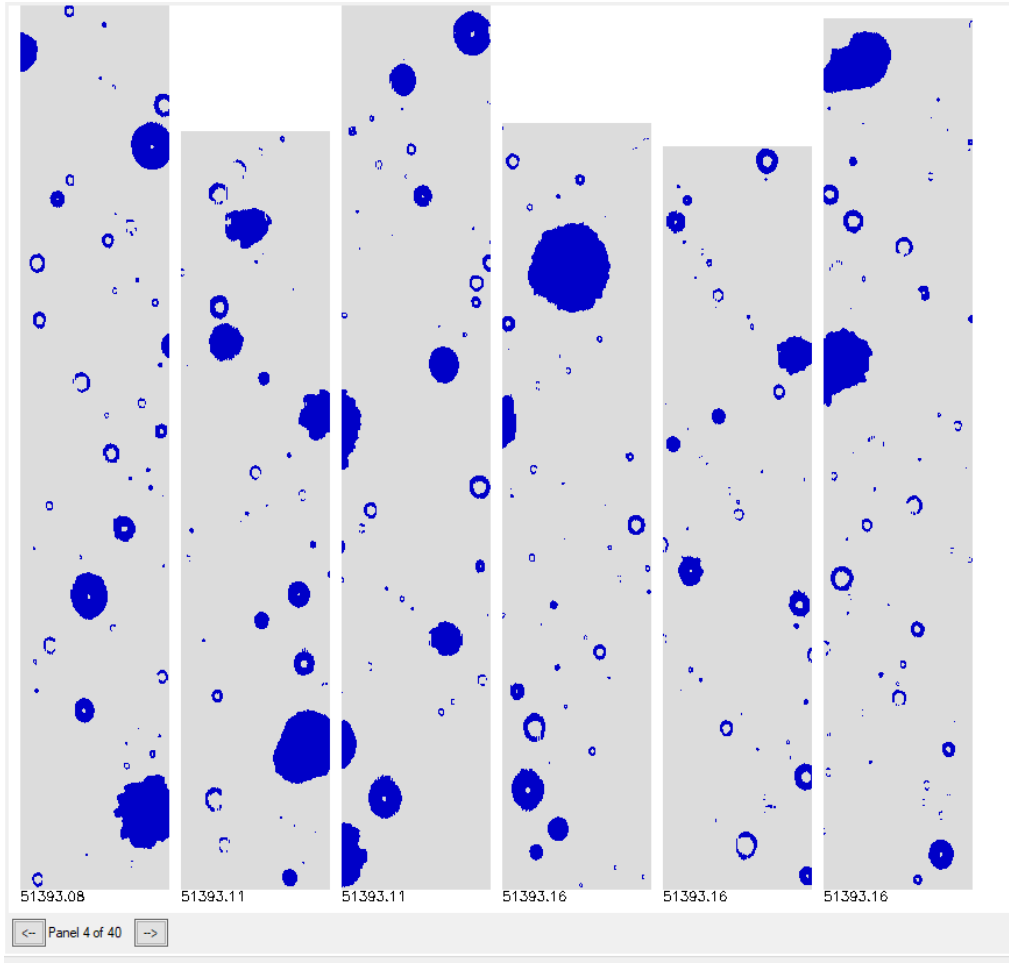


-9 C
Example of graupel and SLD/warm rain, 27-Jul

- **Example 3: 27-Jul: -8.1 C, medium aerosol**
  - Good location to top; next slide shows frame from DC-8 video, no overcast above
  - 2D-S image frame to right
  - CDPavg: 14.6 cm^{-3}, 0.11 gm^{-3}
  - Mixture of SLD, SLD+graupel, and smaller droplet + graupel (SLD+graupel right)
  - Some very large drops to 1 mm on other frames
  - Much of cloud is dominated by LWC and SLD with no graupel (next slide)
  - Graupel estimated to max ~ 1 mm overall
  - Very few small ice particles overall

  - Warm rain process at -8 C.

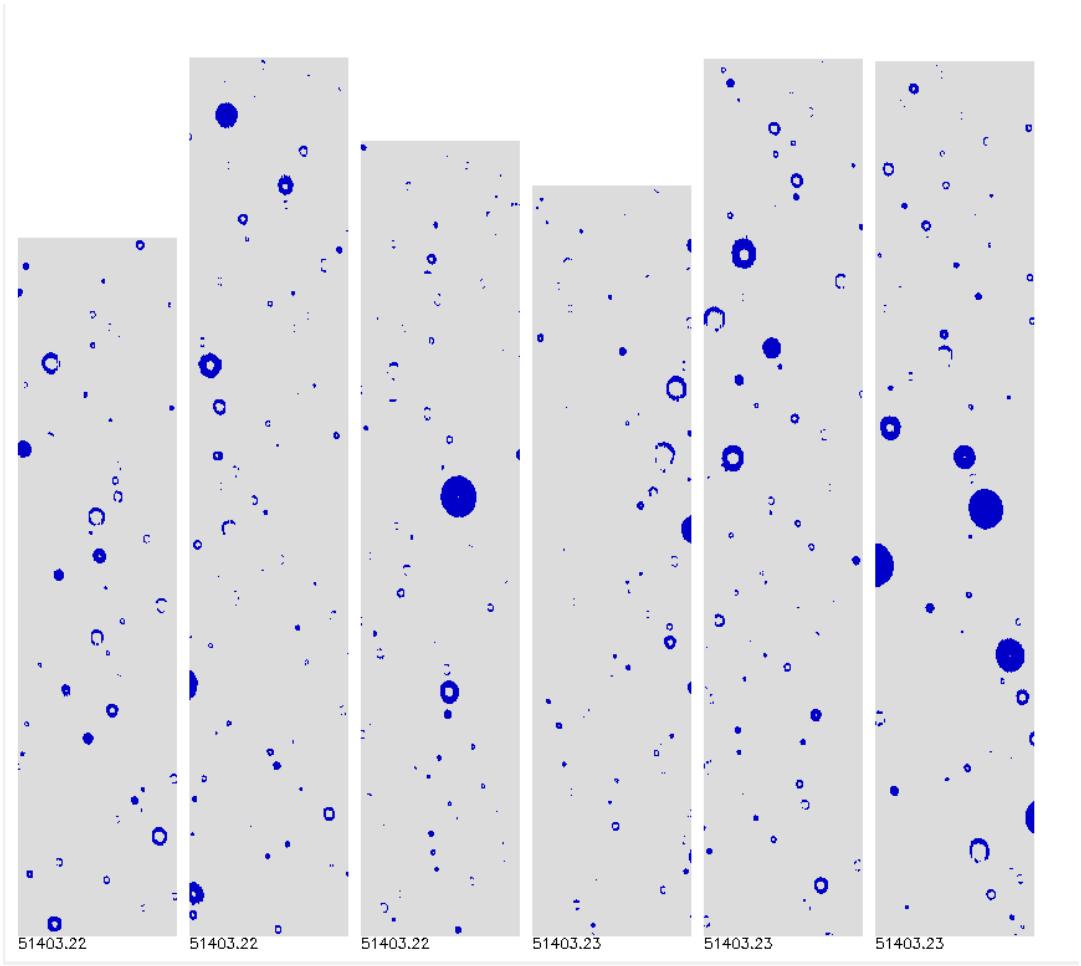
  - Other 3 mixed-phase clouds this day: 1 graupel +SLD, 1 LWC and small ice, 1 variable zones



-9 C
Examples of graupel and SLD/warm rain, 27-Jul

14:16:31-14:16:53

Zone with small droplets and SLD only (much of cloud)



-9 C, Occurrence of small ice, Cloud of 26-Jul-2022

- **Example 3: 10-Jul: -7.9 C**, shown at right
  - Good location to top, top may be colder than usual for -9 C run ; at right shows frame from DC-8 video
  - A real mixture of small droplets + some small ice + graupel, some SLD and small ice, and glaciated small ice growing to medium size.
  - Small ice is ubiquitous, and appears to glaciate cloud

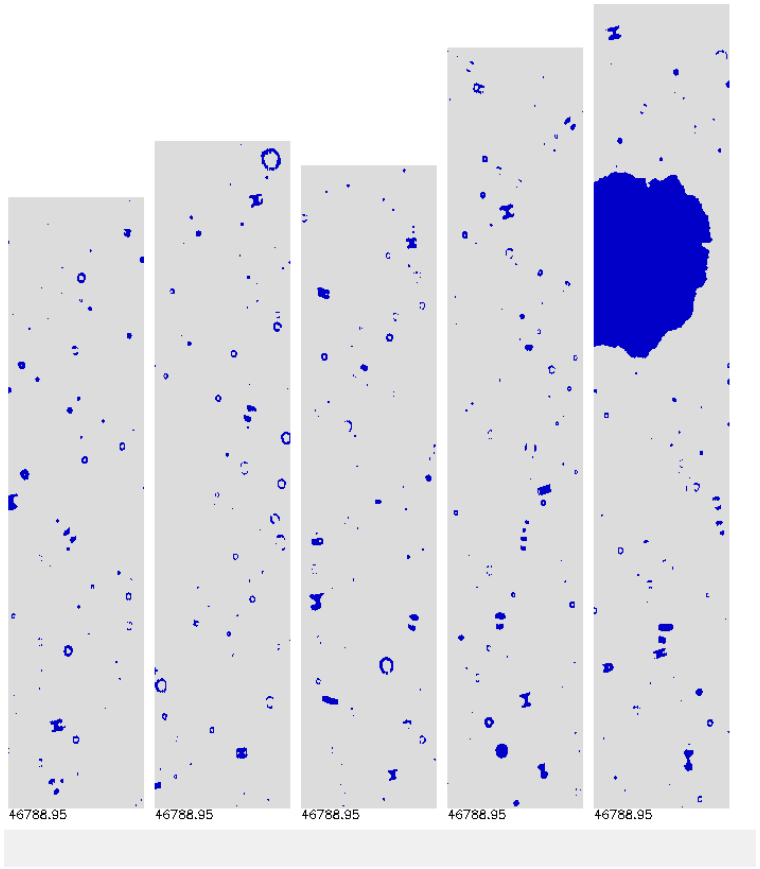
  - Other 3 mixed-phase clouds this day: 2 dominated by SLD + graupel, one mixed small ice like this one

  - Was the ubiquitous ice due to colder cloud top?

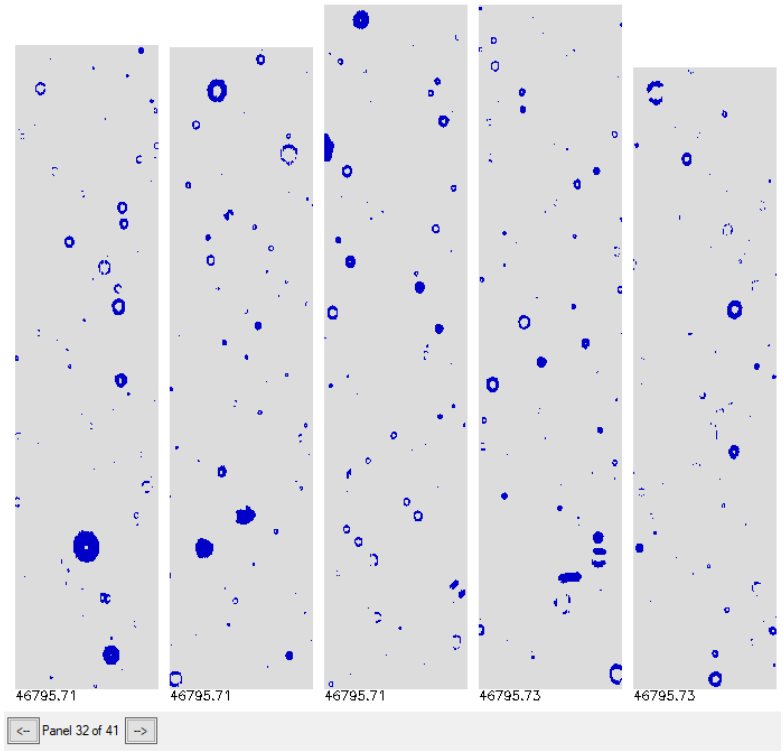
A little taller than usual

-9 C, Occurrence of small ice, Cloud of 10-Jul-2022

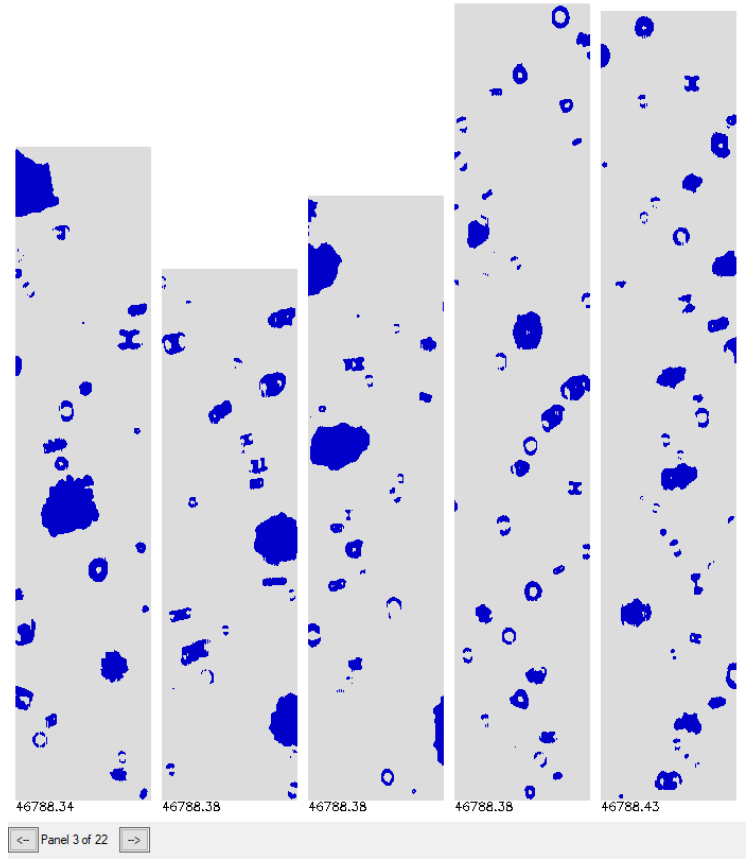
Zone of droplets + graupel + small ice
Most of run looks like this



Zone with droplet/SLD
and some small ice



Zone with predominant small ice
growth, prob. glaciated



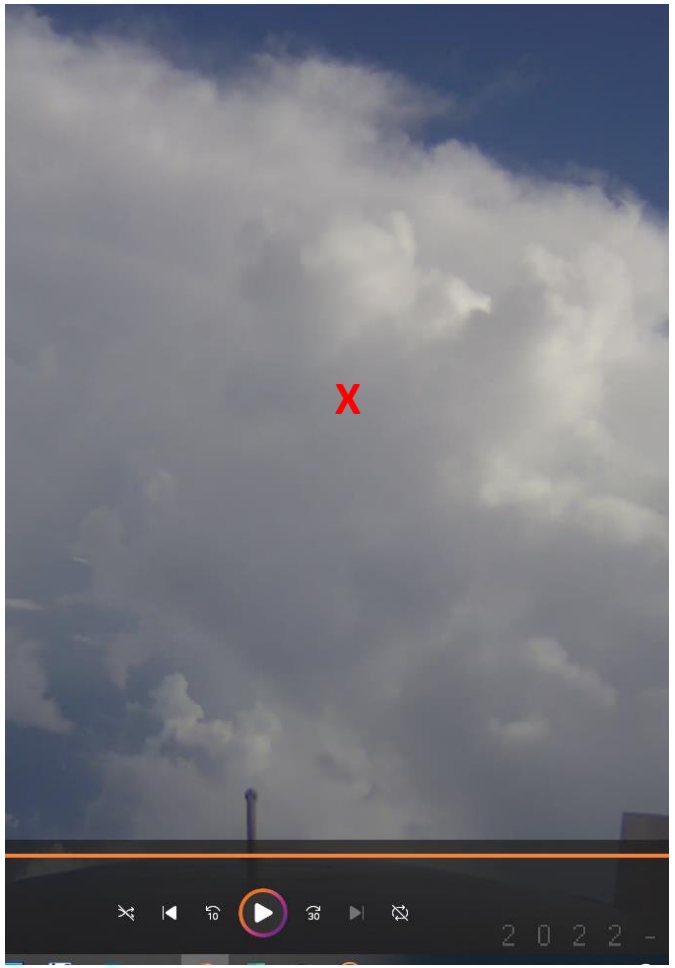
-9 C, Occurrence of small ice, Cloud of 26-Jul-2022 (2)

- **Example 4: 10-Jul: -7.9 C**, shown at right
  - Quasi-good location near top, messy. top may be colder than usual for -9 C run ; at right shows frame from DC-8 video
  - Again, a real mixture of small droplets + some small ice + graupel, some SLD and small ice, and glaciated small ice growing to medium size.
  - Small ice is ubiquitous, and appears to glaciate cloud in zones

  - Other 3 mixed-phase clouds this day: 2 dominated by SLD + graupel, one mixed small ice like this one

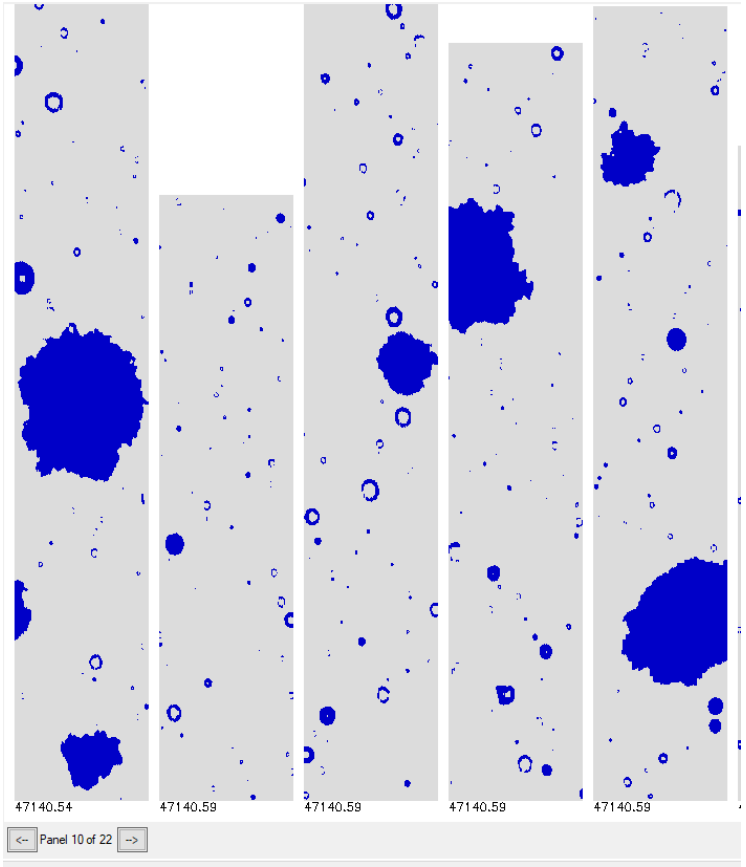
  - Was the ubiquitous ice due to colder cloud top?

Messier than usual

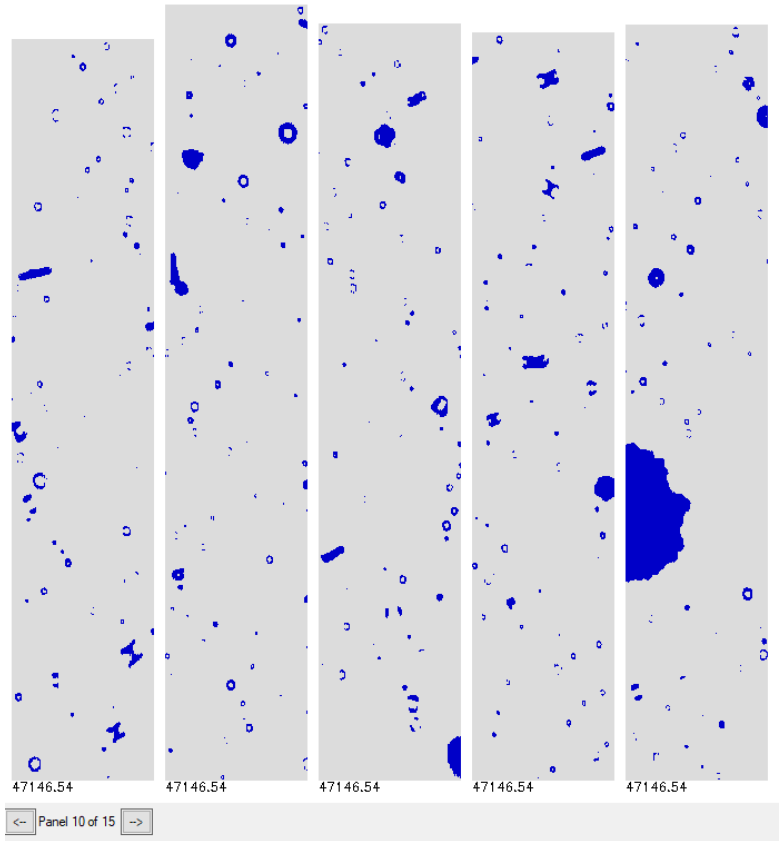


-9 C, Occurrence of small ice, Cloud of 26-Jul-2022

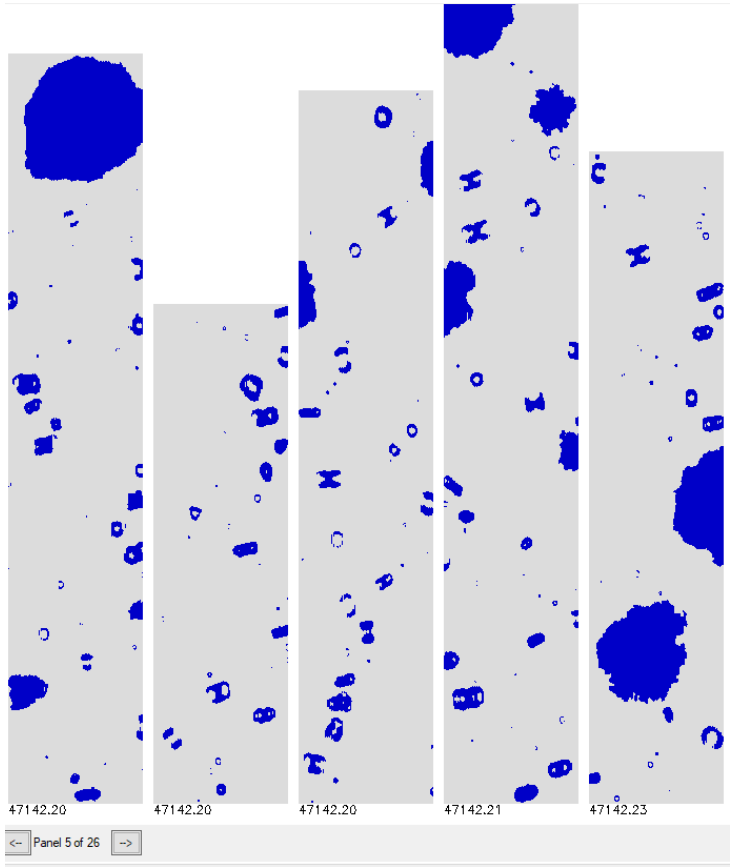
Zone of droplets, SLD, graupel



Zone changing to droplets, graupel, small ice



Zone of graupel, small ice, glaciated?

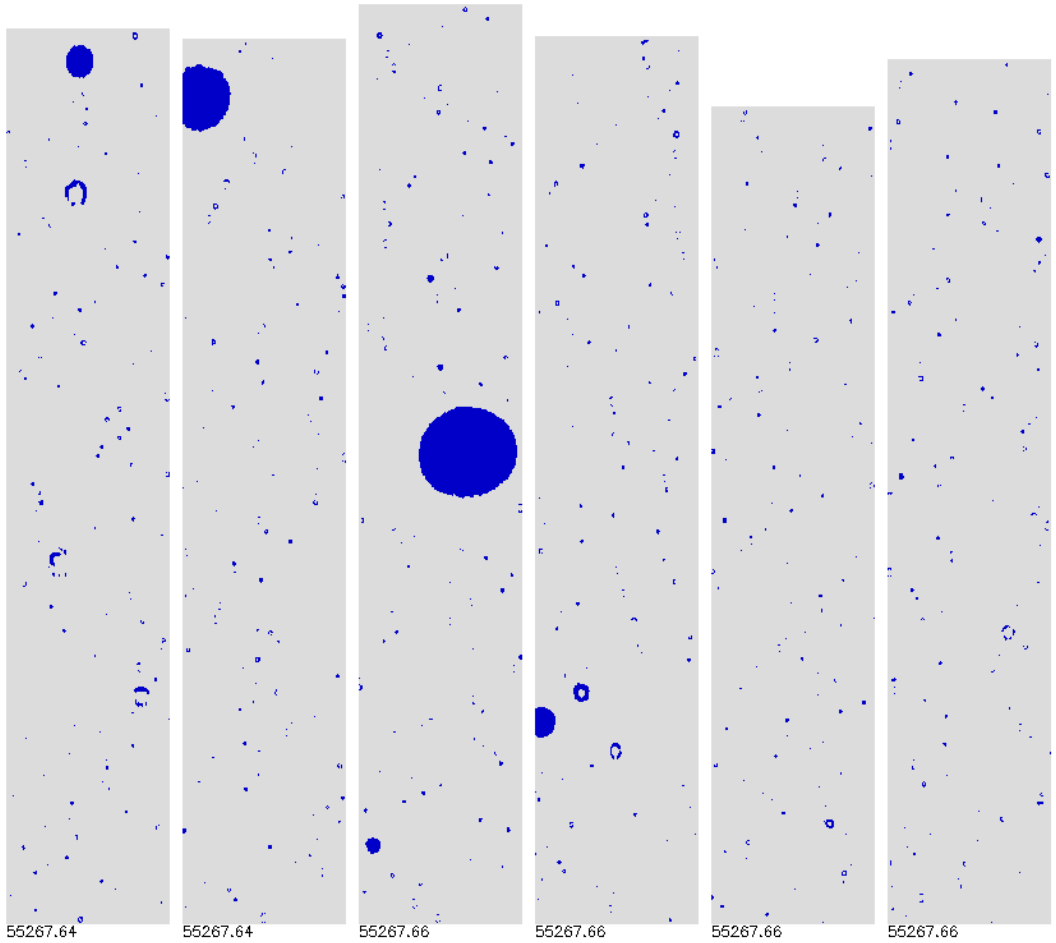


~ + 5 C
Cloud of 27-Jul-2022

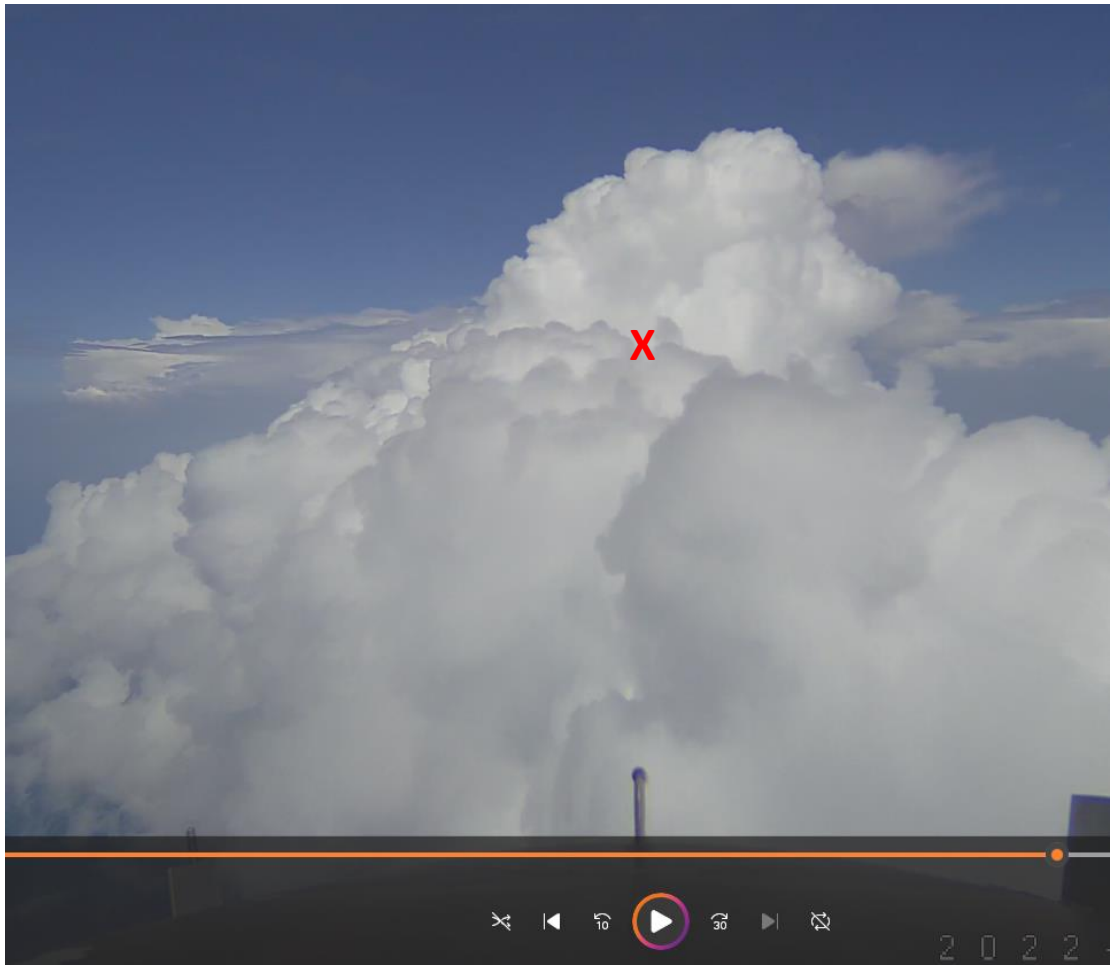
- **Example 2: 27-Jul, ~+7.4 C, medium aerosol**
  - 2D-S shown at right
  - CDPavg = 164cm^{-3}, 0.71 gm^{-3}
  - Isolated cloud, good location to top; next slide shows frame from DC-8 video
  - Cloud dominated by small droplets (larger size than cloud base), but with imbedded large drops – no seeding from above as per video
  - Higher CDP concentration could explain why drops look more isolated

  - Warm rain process getting going
  - No indication of melting ice

  - Other 4 clouds this day have developing drop spectra with similar observations
  - Need to do more careful analysis to see if difference between low-versus-medium aerosol concentration

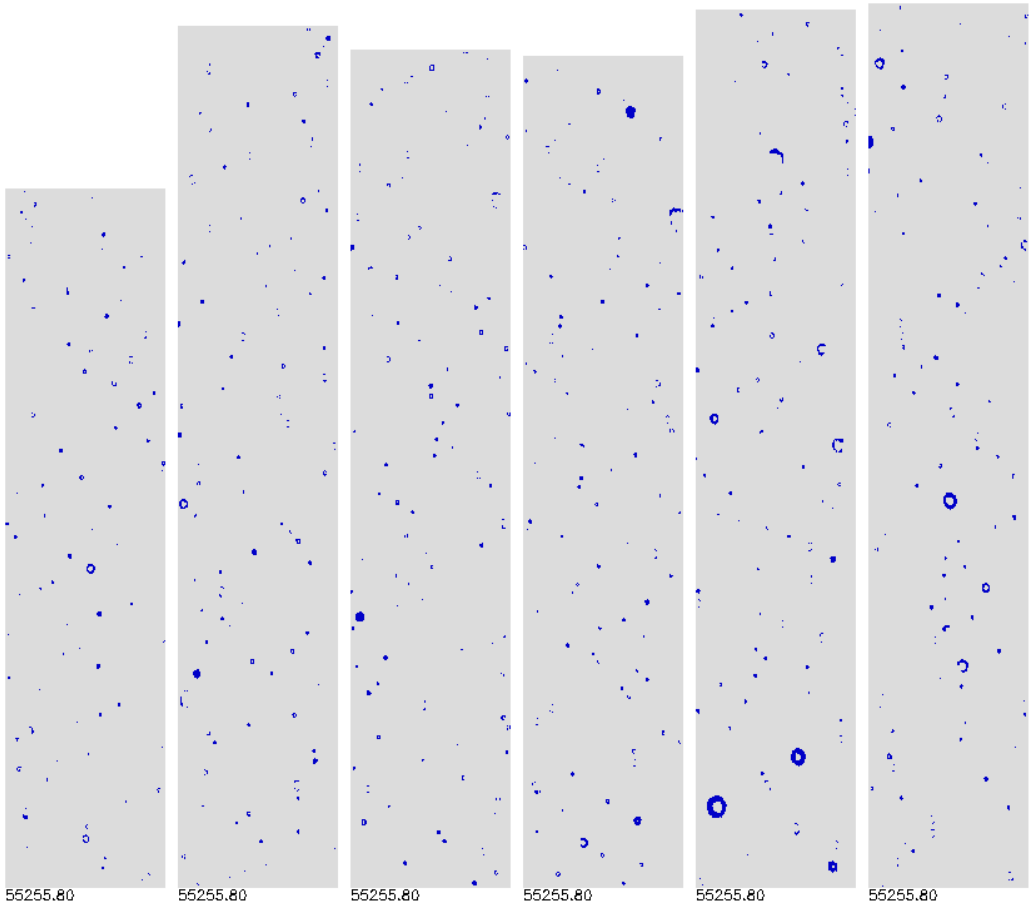


~ + 5 C
Cloud of 27-Jul-2022



15:21:00-15:21:13

Skimming top of lower fuzzy cloud before main entry

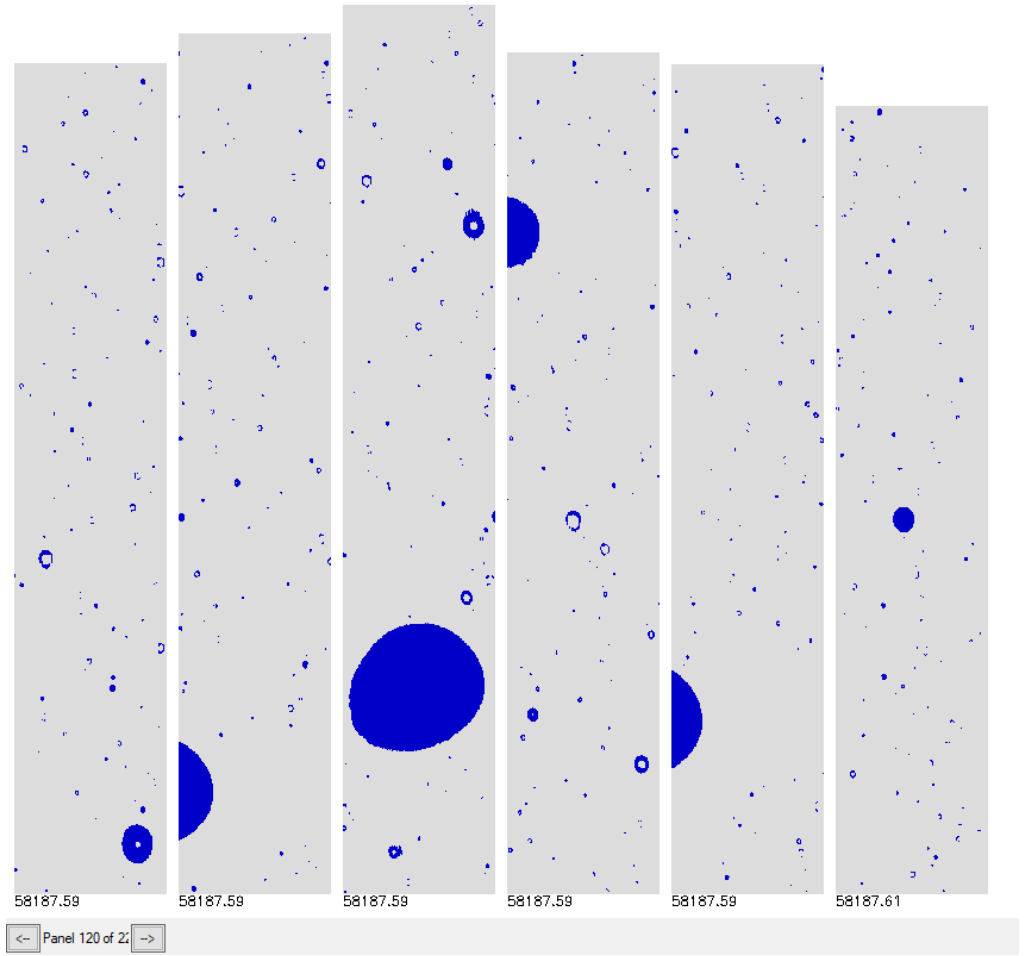


-9 C , Liquid-only runs Cloud of 30-Jul-2022

- **Example 2: 30-Jul: -9.0 C, high aerosol**
  - Congested cloud, under overcast; good location to top; next slide shows frame from DC-8 video
  - 2D-S image frame to right
  - CDPavg: 31.5 cm^{-3}, 0.14 gm^{-3}
  - CDPavgs and maxs about the same as 10-Jul (low aerosol)
  - Dominated by zones of small droplet, SLD (image right). Drops to about 1 mm
  - Sometimes proportionately more SLD (next page)
  - No evidence of small ice or graupel
  - No obvious difference to low aerosol case

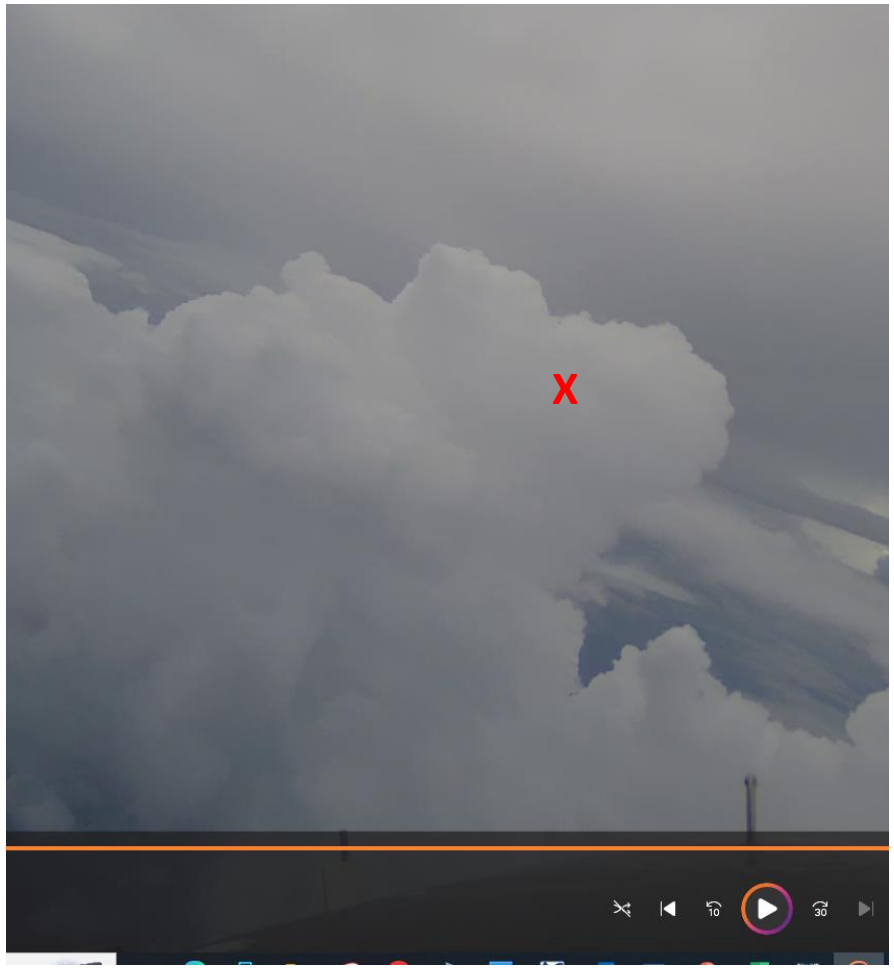
  - Warm rain process at -9 C.

  - Other 4 clouds this day have mixed-phase. The liquid portions all include SLD.



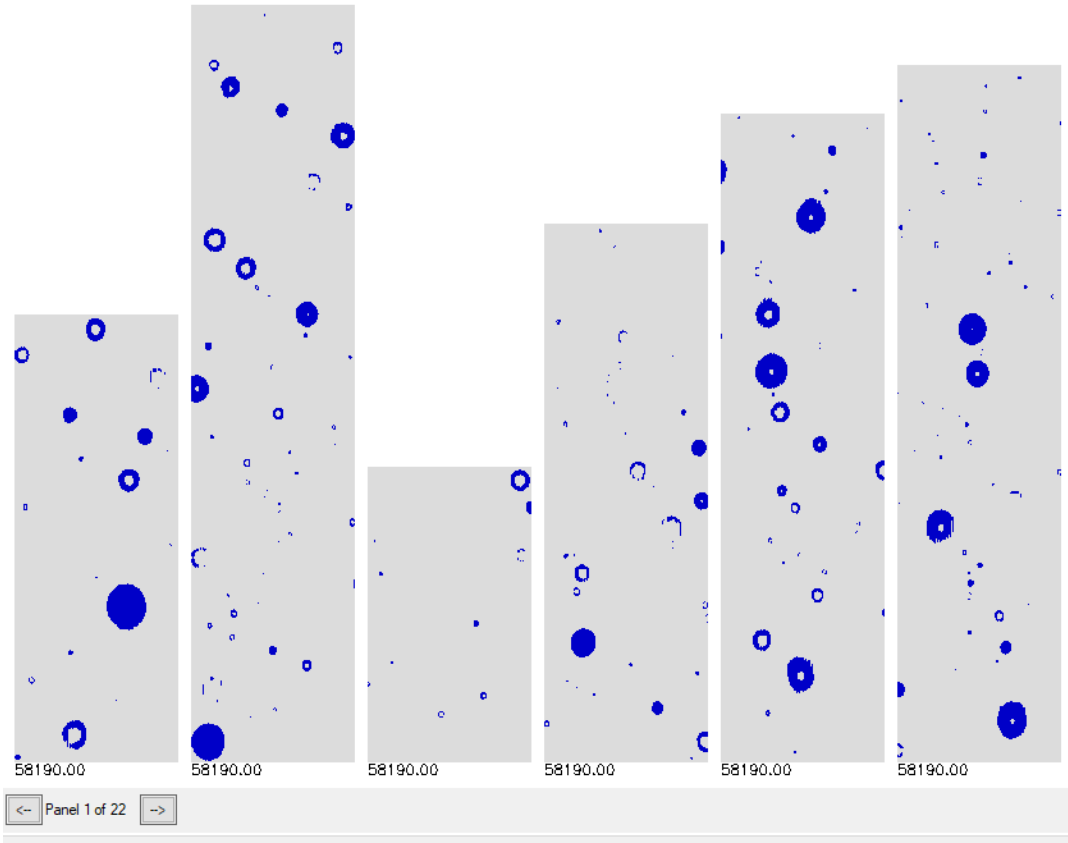
-9 C, Liquid-only runs; Cloud of 30-Jul-2022

- DC-8 in turn to line up, run along about 11 o'clock



16:09:40-16:09:54

- Fewer droplets, more SLD in frame

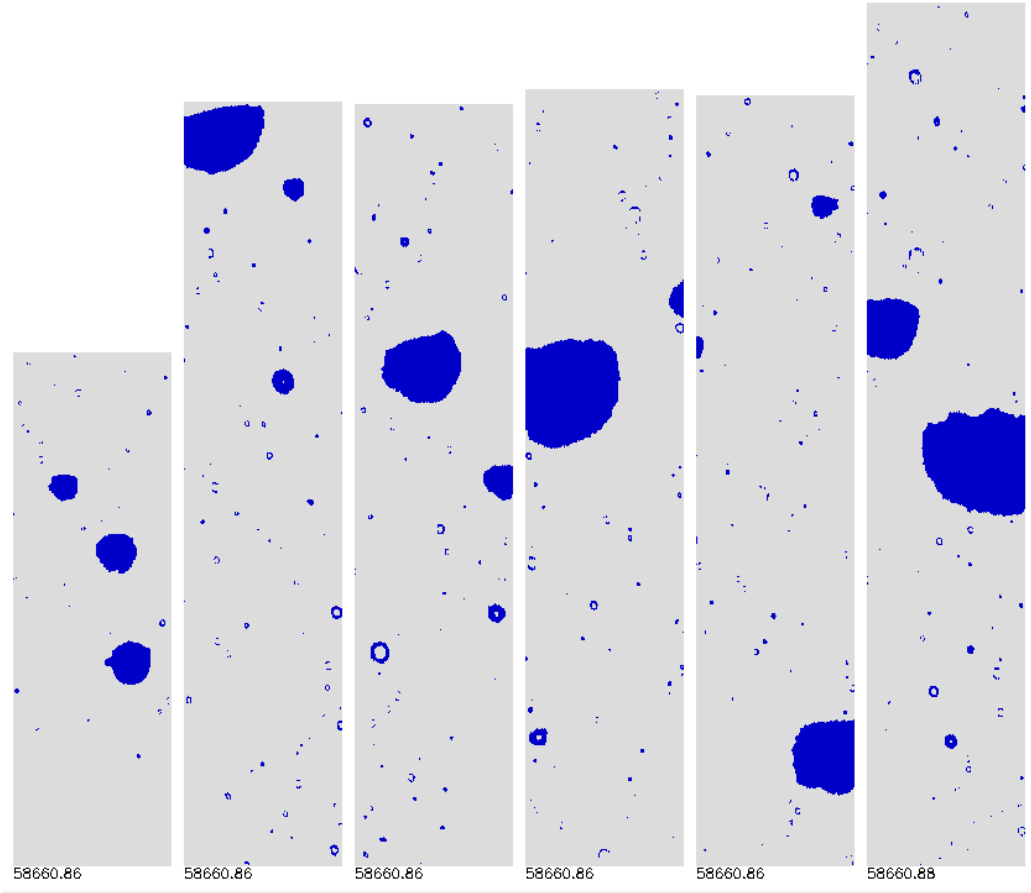


-9 C, graupel and LWC/SLD, Cloud of 30-Jul-2022

- **Example 2: 30-Jul, -8.8 C, high aerosol**
  - Good location to top; next slide shows frame from DC-8 video, overcast above
  - 2D-S image frame to right
  - CDPavg: 59.5 cm^{-3}, 0.21 gm^{-3}
  - Mixture of SLD, SLD+graupel, and smaller droplet + graupel (latter images right, conical graupel?)
  - Graupel estimated to max ~ 1.5 mm overall
  - Very few small ice particles overall
  - Marginally higher small drop concentration than example 1, but not con

  - Warm rain process at ~-9 C.

  - Other 3 mixed-phase clouds this day were all dominated by LWC and graupel, 2 with some small ice

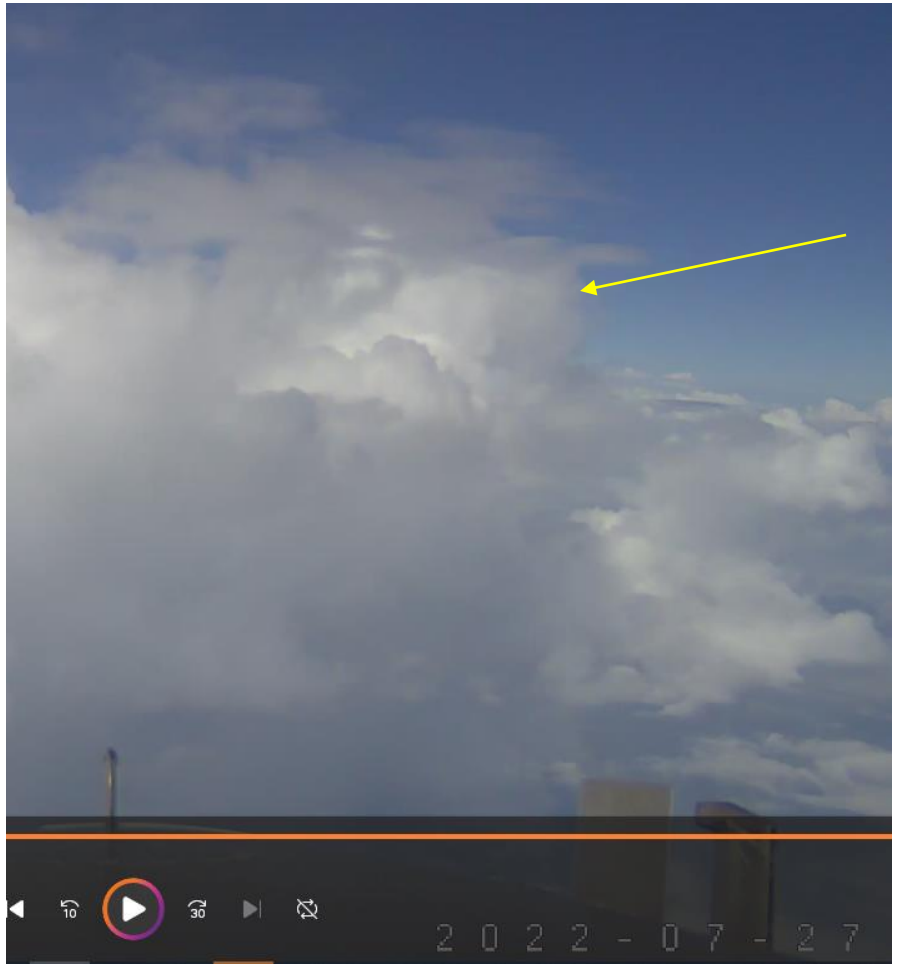


-9 C, Occurrence of small ice, Cloud of 10-Jul-2022

- **Example 2: 27-Jul: -7.6 C, medium aerosol**
  - Good location to top; at right shows early frame from DC-8 video, DC-8 flew towards fuzzy cloud and thenturned to right to line up
  - CDPavg: 20.5 cm^{-3}, 0.18 gm^{-3} (unreliable in small ice)
  - 2D-S image frames next slide
  - Varies from zones dominated by LWC / SLD, to LWC / SLD + graupel and a bit of small ice, to graupel + glaciating small ice
  - Nothing notably different between low aerosol example and this medium aerosol example

  - Other 3 mixed-phase cloud this day: 2 dominated by LWC and graupel, 1 by LWC and small ice.

Cloud from distance



14:24:28-14:24:58

-9 C, Occurrence of small ice, Cloud of 10-Jul-2022

- **Example 2: 27-Jul: -7.6 C, medium aerosol**
  - Good location to top; at right shows early frame from DC-8 video, DC-8 flew towards fuzzy cloud and thenturned to right to line up
  - CDPavg: 20.5 cm^{-3}, 0.18 gm^{-3} (unreliable in small ice)
  - 2D-S image frames next slide
  - Varies from zones dominated by LWC / SLD, to LWC / SLD + graupel and a bit of small ice, to graupel + glaciating small ice
  - Nothing notably different between low aerosol example and this medium aerosol example

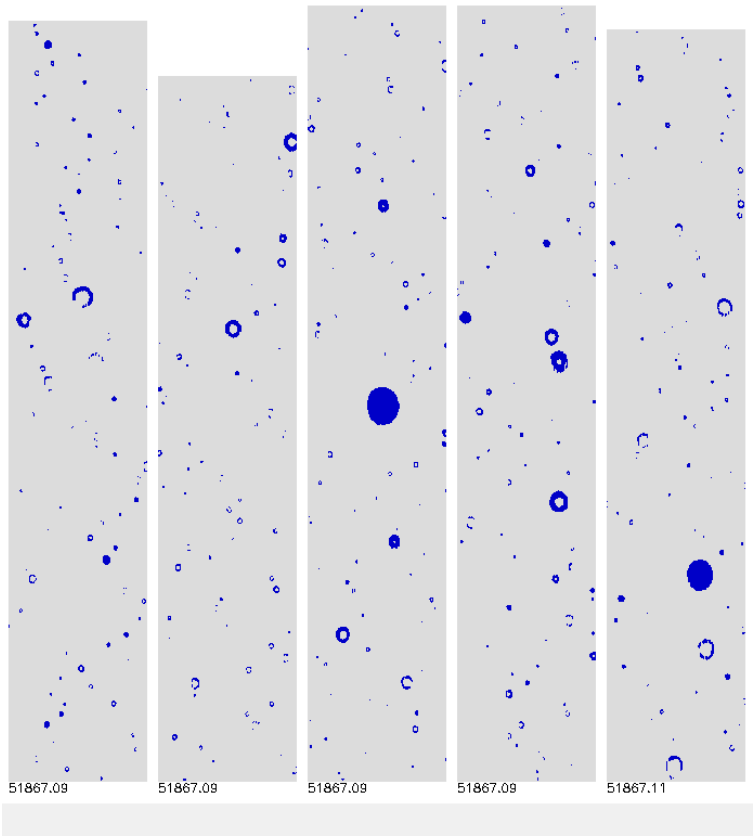
  - Other 3 mixed-phase cloud this day: 2 dominated by LWC and graupel, 1 by LWC and small ice.

Cloud before entry

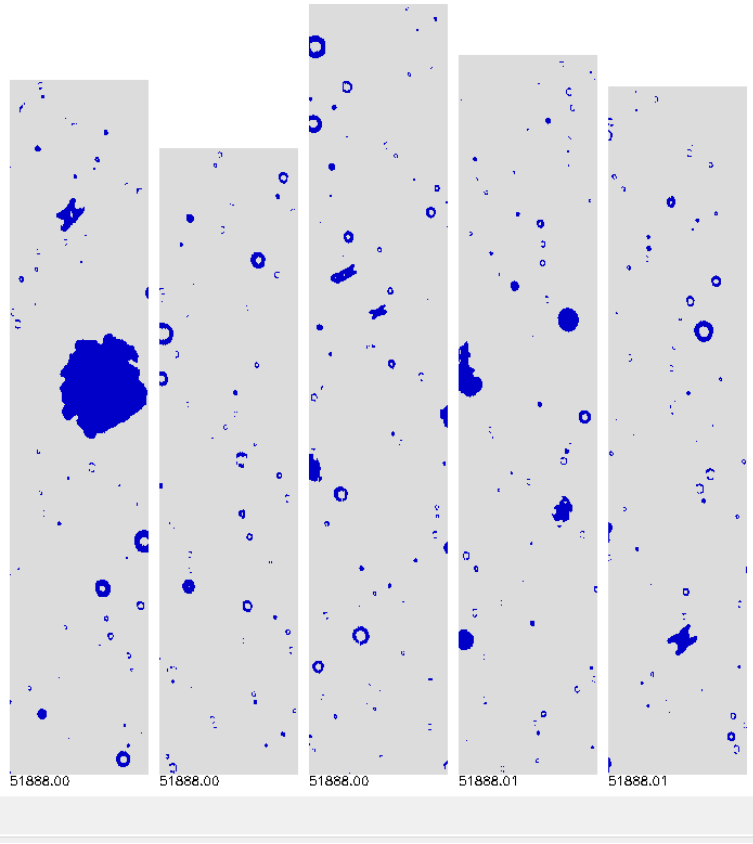
14:24:28-14:24:58

-9 C, Occurrence of small ice, Cloud of 10-Jul-2022

Zone of LWC / SLD on entry



Zone of LWC / SLD, graupel and small ice



Zone dominated by small ice and graupel, prob. glaciated