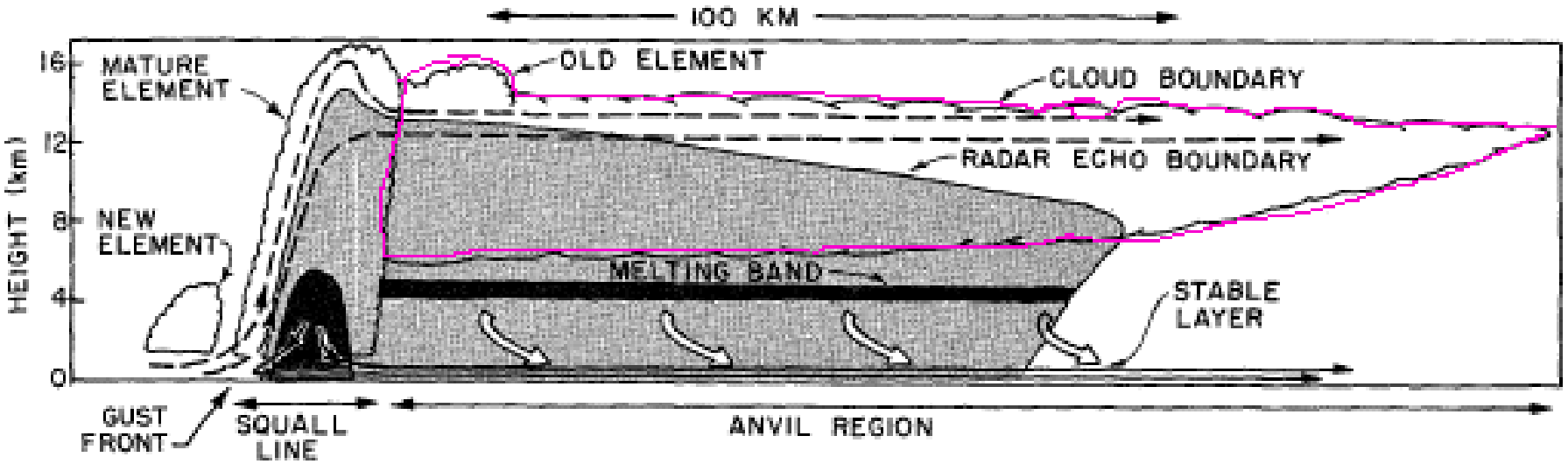
TROPICAL CIRRUS

Andrew Heymsfield
NCAR



After Houze, 1977

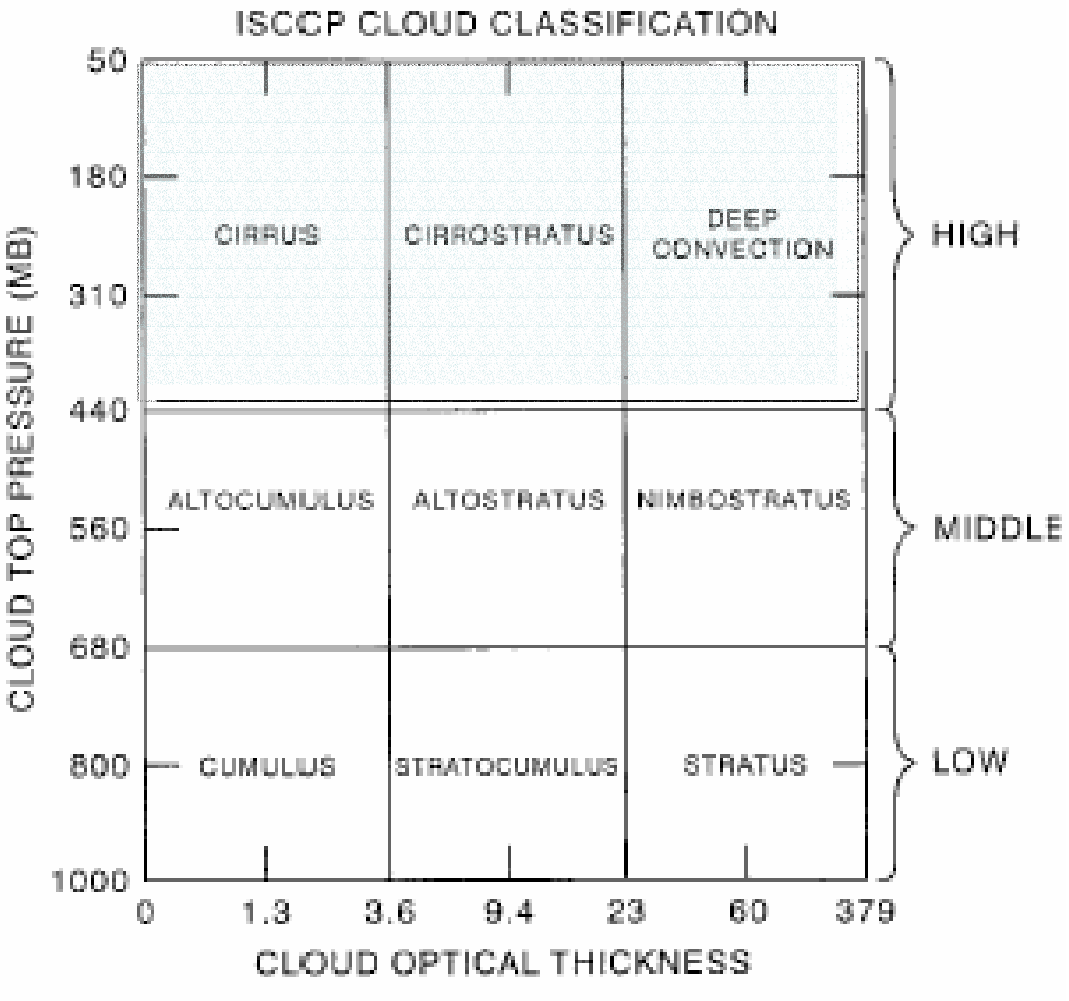
Outline

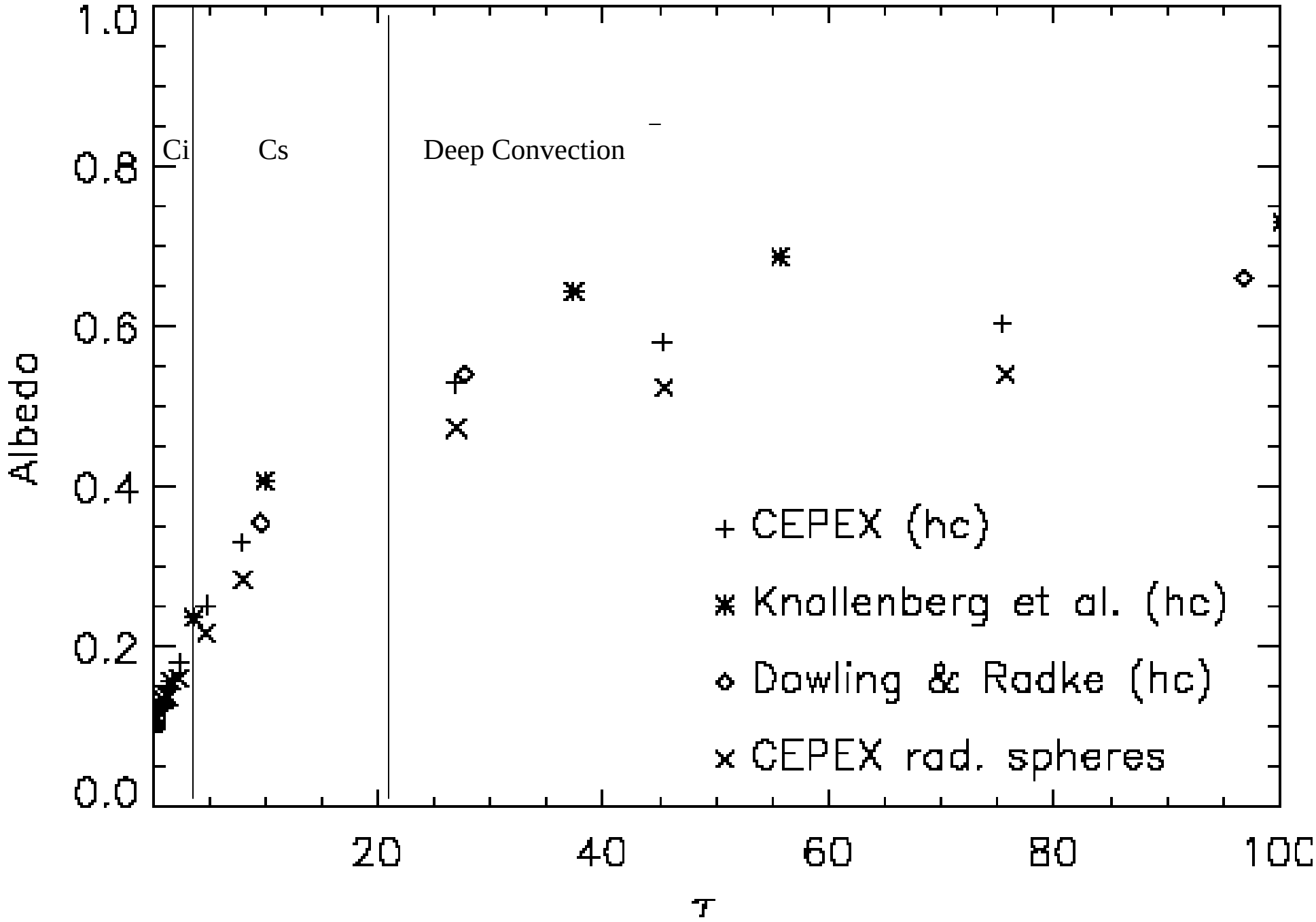
- Three “categories” of tropical cirrus
- Radiative Properties
- Possible Microphysics-Climate Interactions
- Overview of in-situ PSD measurements to date

  Thin, intermediate and thick cirrus.

  Comparison to synoptically-generated, midlatitude cirrus
- Ice Particle Habits
- Summary and Conclusion

Tropical Cirrus Types and Large-Scale Properties


ISCCP CLOUD CLASSIFICATION
CLOUD TOP PRESSURE (MB)
50
180
310
440
560
680
800
1000
CIRRUS
CIRROSTRATUS
DEEP CONVECTION
ALTOCUMULUS
ALTOSTRATUS
NIMBOSTRATUS
CUMULUS
STRATOCUMULUS
STRATUS
HIGH
MIDDLE
LOW
0
1.3
3.6
9.4
23
60
379
CLOUD OPTICAL THICKNESS



Heymsfield et al. (1998)

Cloud type amounts (%)	Tropical	Northern midlatitudes	Southern midlatitudes	North polar	South polar
Cumulus	0.0 (12.3)	1.6 (10.7)	1.4 (15.1)	4.2 (3.6)	6.2 (2.2)
Stratocumulus	0.0 (10.7)	0.8 (10.9)	0.9 (16.8)	3.8 (7.7)	5.2 (4.0)
Stratus	0.0 (0.8)	0.2 (2.2)	0.2 (2.1)	1.3 (5.2)	1.1 (2.5)
Altocumulus	0.9 (6.1)	7.6 (3.2)	8.3 (2.8)	12.1 (0.6)	14.4 (0.1)
Altostratus	0.1 (4.7)	5.0 (4.2)	7.1 (4.2)	10.6 (1.4)	12.5 (0.3)
Nimbostratus	0.0 (1.0)	1.6 (1.7)	1.6 (1.2)	3.3 (1.5)	2.9 (0.2)
Cirrus	15.6	13.8	9.2	8.7	8.7
Cirrostratus	5.5	6.9	7.6	2.4	3.4
Deep convective	2.7	3.3	3.0	0.9	0.8

α=15%
α=50%

Rossow and Schiffer (1999)

Possible Climate-Microphysics Interactions

Cirrus Influence on SW and LW Radiative Fluxes, 11 deg N to 11 deg S (Based on Hartmann et al., 1992)

Quantity (June to August 1985, Dec to Feb, 1986)	Average Flux, W/m^2
Outgoing Long Wave Radiation	
Thin Cirrus	11.0
Thick Cirrus	13.3
SW Radiation	
Thin Cirrus	6.3
Thick Cirrus	28.5
Net Radiation (OLR-SW)	
Thin Cirrus	4.6
Thick Cirrus	-8.8

Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Niño

V. Ramanathan & W. Collins

Scripps Institution of Oceanography and California Space Institute, University of California at San Diego, La Jolla, California 92093, USA

Observations made during the 1987 El Niño show that in the upper range of sea surface temperatures, the greenhouse effect increases with surface temperature at a rate which exceeds the rate at which radiation is being emitted from the surface. In response to this 'super greenhouse effect', highly reflective cirrus clouds are produced which act like a thermostat, shielding the ocean from solar radiation. The regulatory effect of these cirrus clouds may limit sea surface temperatures to less than 305 K.

Ramanathan and Collins (1991)

Radiative energy budget (W m $^{-2}$) at the TOA over 30 days (December 5, 1992 -- January 3, 1993)

Fluxes	FC	GMS1	GMS2	M0	E0
Q_{LW} (TOA)	-198.8	-200.4	-205.1	-194.8	-171.7
Q_{SW} (TOA)	269.5	294.4	274.4	273.5	243.9
	ISCCP	Collins A/C	Minnis	CRM	CRM (k/M fallspeed)

Wu and Moncrief (1999)

EXAMPLES OF TROPICAL CIRRUS/CONVECTIVE CLOUD TYPES

SUBVISUAL CIRRUS

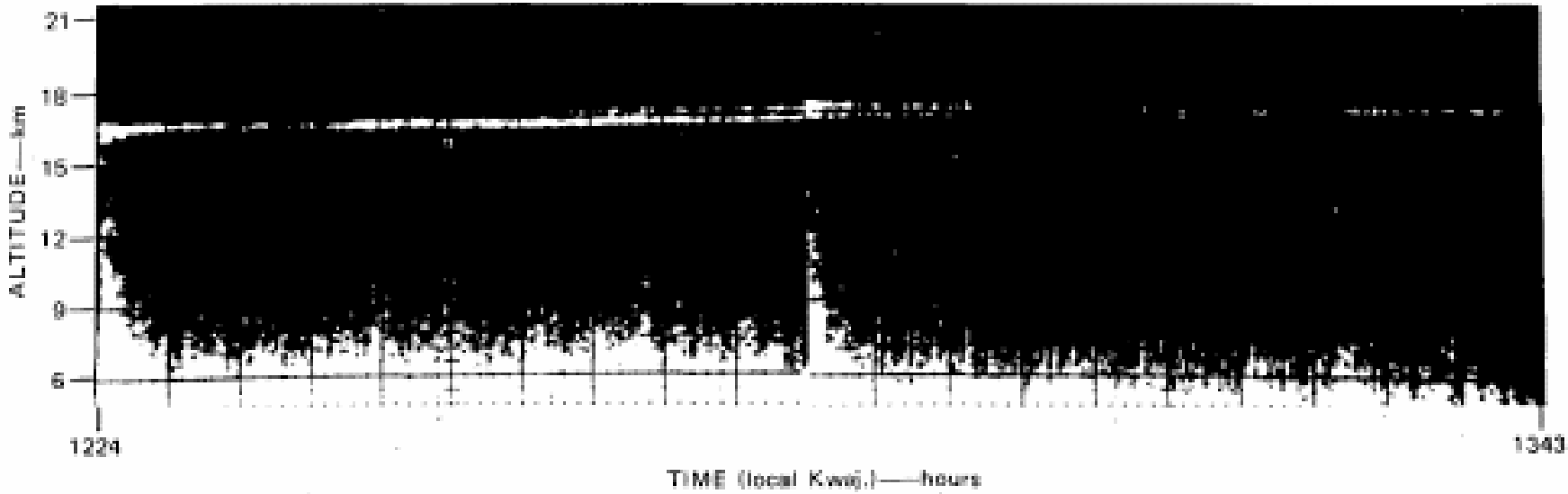
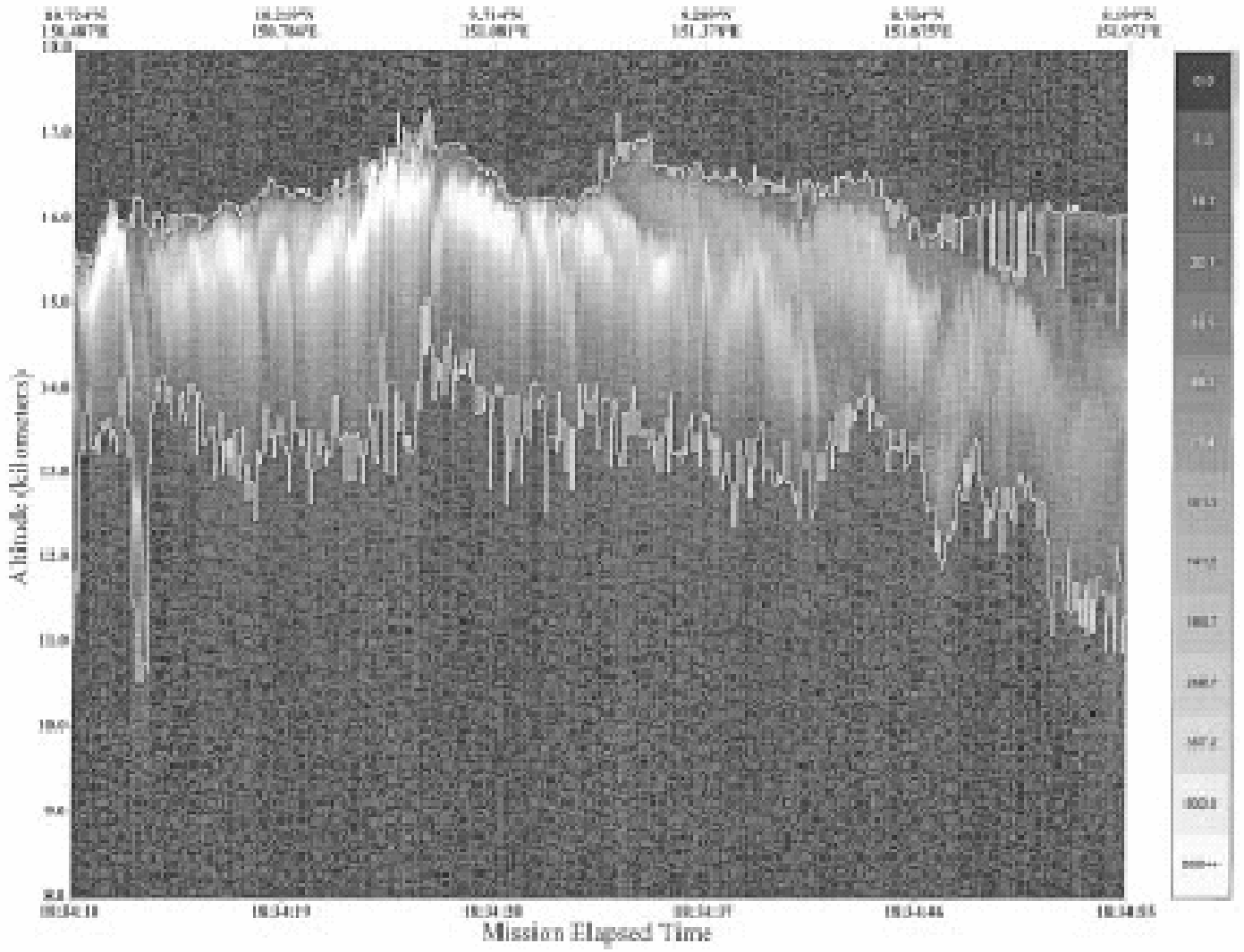
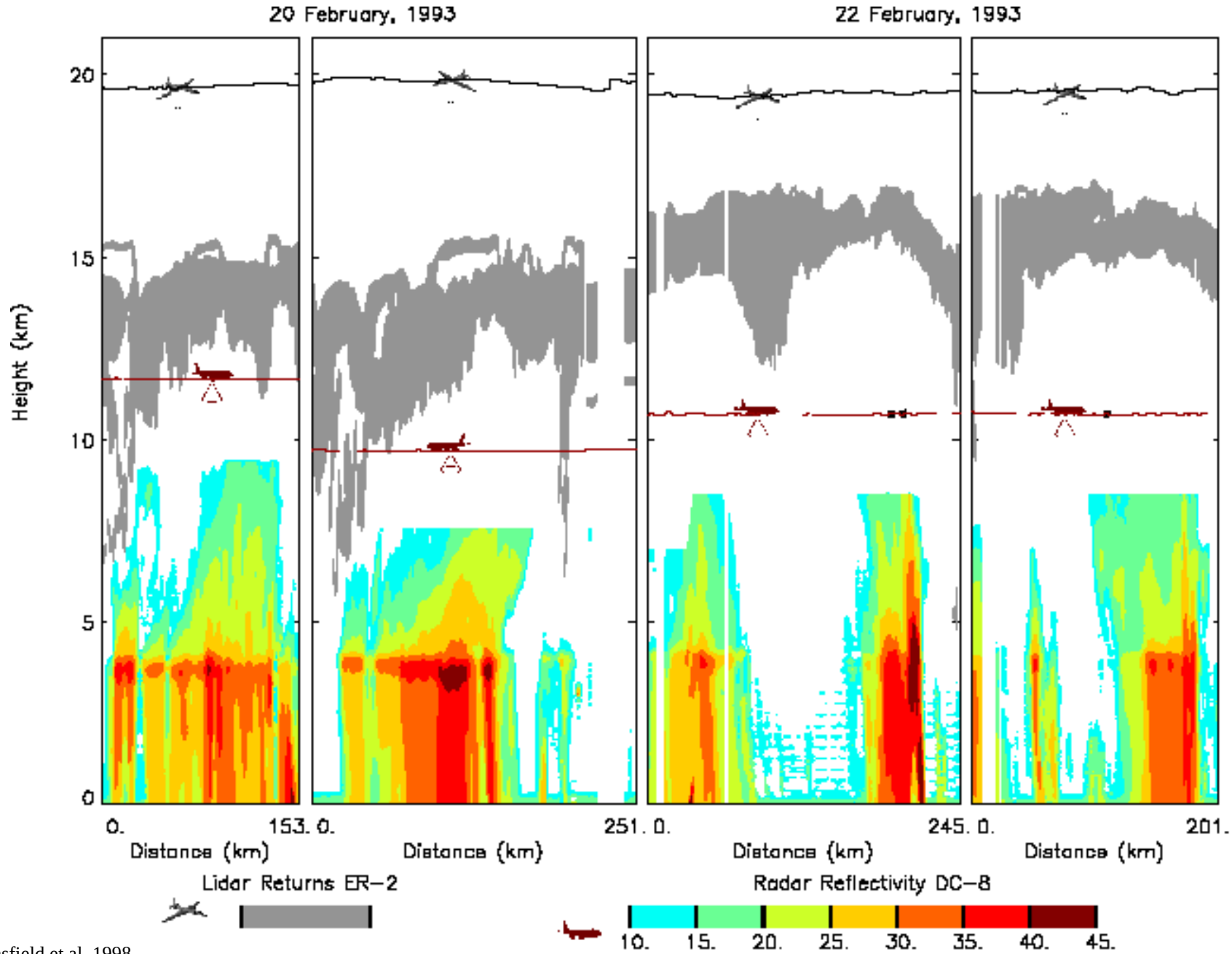


FIG. 1. Analog height/time displays of lidar observed cirrus layer on 17 December 1973. The cirrus appears as a white horizontal line between 16–17 km. Other white areas are produced by "noise" or aerosol particles. (Courtesy of Dr. Ed Uthe).

Heymsfield (1986)



LITE (Platt et al. (1999)

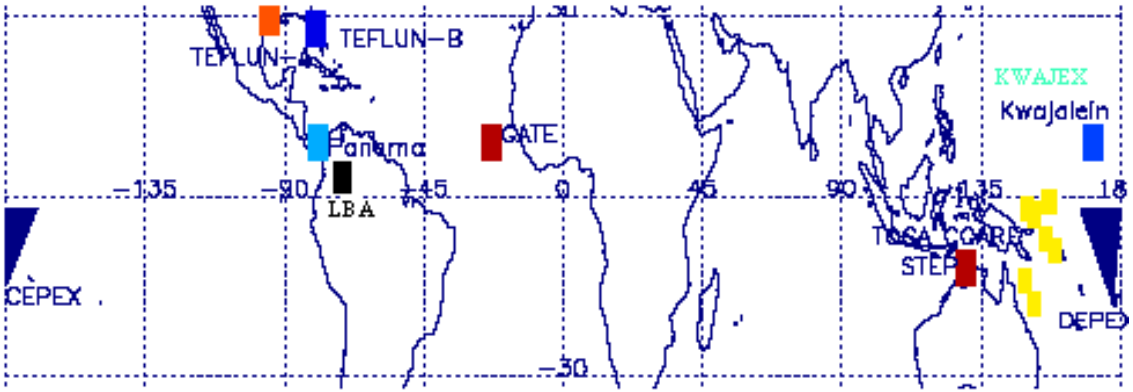


Heymsfield et al. 1998

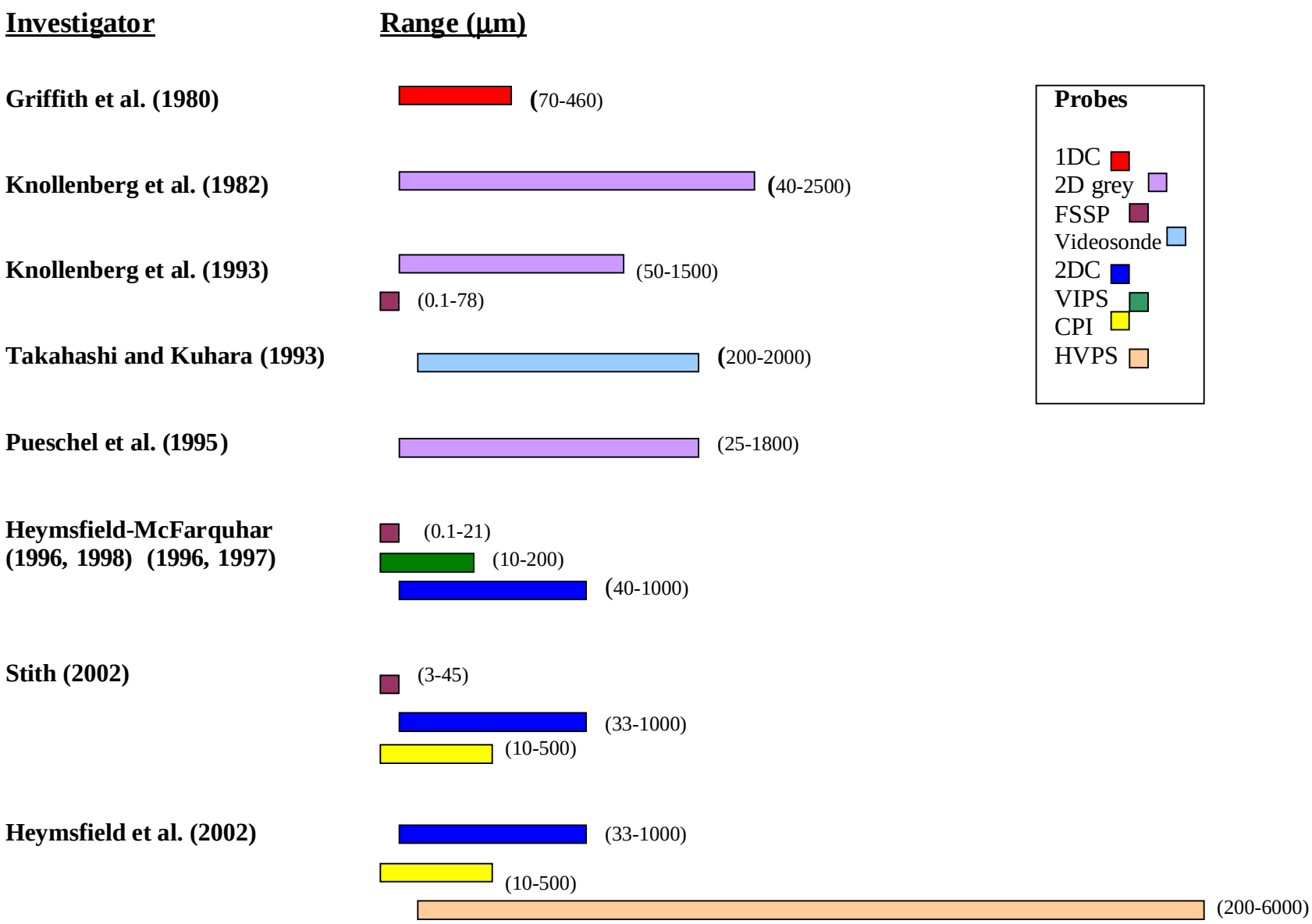
Figure 8: Vertical slice (from the ER-2 height to the ocean surface) showing ER-2 lidar and DC-8 radar data corresponding to the periods in Fig. 5. Gray shading between about 11 and 17 km represents cloud layers detected by 1.064 μm lidar on the ER-2; occultation of the lidar beam occurred at an optical depth of approximately 4, corresponding to the bottom of the grey shaded region. Colorized shading shows radar reflectivities (dBZ) measured by the DC-8. Track of the DC-8 is plotted at times when the 2D probe indicated that ice particles were present. Dark green horizontal segments with arrows at the DC-8 level show locations where the aircraft encountered upward vertical motions in excess of 2 m s^{-1}

Tropical Ice Cloud Studies

Study	Location
Griffith et al. (1980)	Africa
Knollenberg et al. (1982)	Panama
Heymsfield (1986)	Kwajalein
Knollenberg et al. (1993)	Australia
Takahashi and Kuhara (1993)	Ponape
Pueschel et al. (1995)	W. Pacif.
Heymsfield and McFarquhar (1996)	Cen. Pacif.
McFarquhar and Heymsfield (1996)	
McFarquhar and Heymsfield (1997)	
Heymsfield et al. (1998)	
McFarquhar et al. (2000)	Kwajalein
Stith et al. (2002)	Brazil, Kwaj.
Heymsfield et al. (2002)	Brazil, Kwaj.
ABFM, Dye et al.	Florida



Tropical Ice Cloud Studies



Tropical Ice Cloud Studies

- Griffith et al(1980)

  IWCs increased downwards

- Knollenberg et al.(1982,1993)

  Reported IWCs in cold anvils were order hundredths g/m^{-3}

- Takahashi and Kuhara (1993)

  Used sondes to characterize PSDs and habits

•Pueschel et al. (1995)

Observations in typhoon

•Heymsfield McFarquhar (1996, 1998)

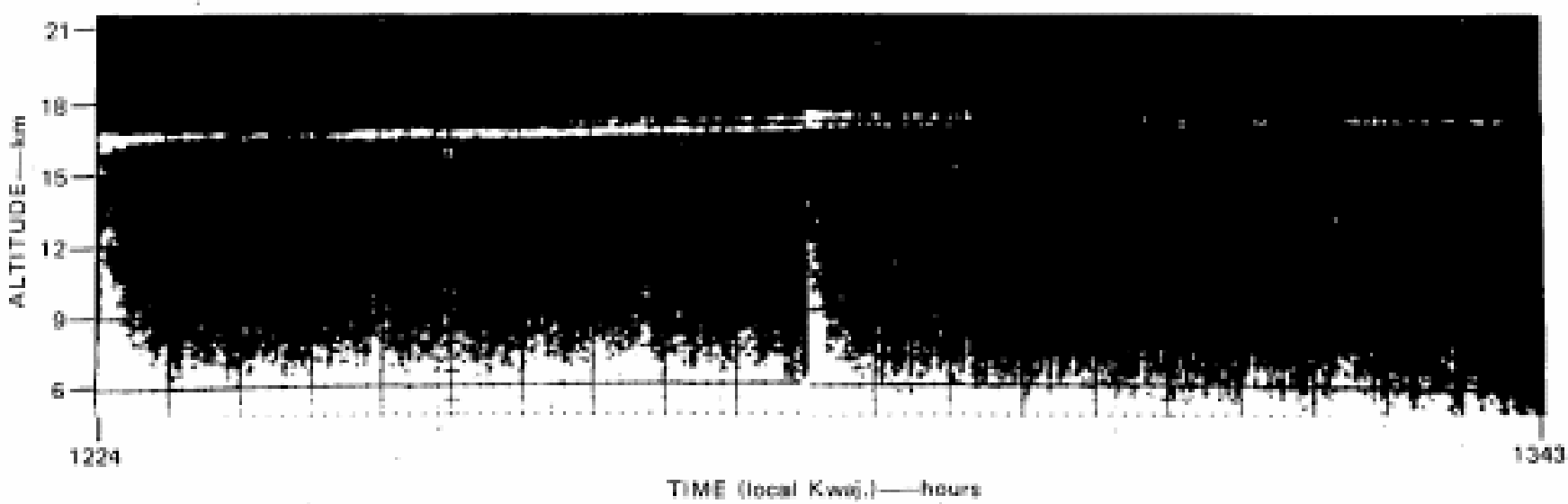
Characterized average IWCs
Inferred cause of high albedos in tropical ice clouds

•McFarquhar-Heymsfield (1996,1997)

Characterized PSDs in 3 anvils
Developed param. For PSDs

- Stith et al (2002)
  - Characterized the updraft and stratiform regions of Florida, Brazil and Kwajalein Clouds (TRMM)
- Heymsfield et al. (2002)
  - Characterized the anvil and stratiform ice cloud regions of Florida, Brazil and Kwajalein Clouds (TRMM)
- APE-THESEO ( )
- Dye et al. (2000)
  - Airborne Field Mill Project

Thin Cirrus



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Heymsfield (1986)

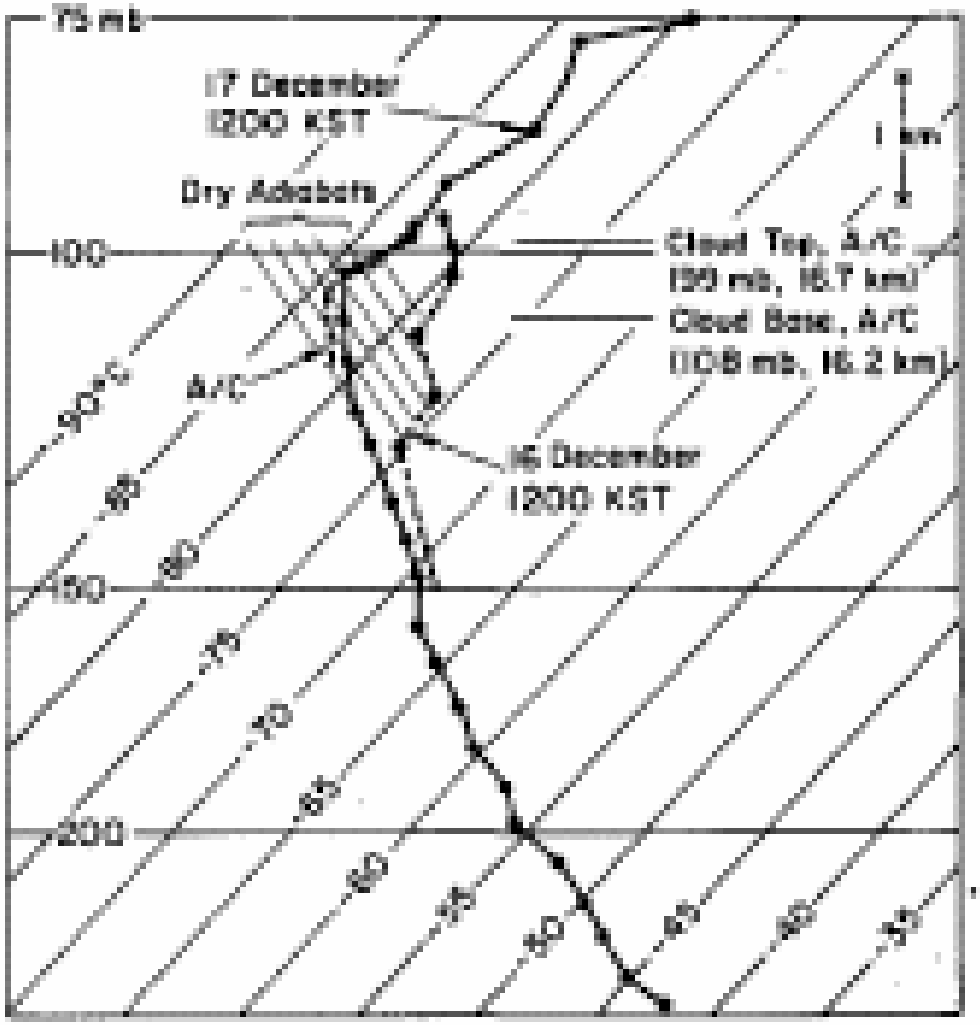


FIG. 2. Soundings taken by rawinsonde on 16 and 17 December 1973 and from the aircraft on 17 December 1973. Locations of cirrus cloud base and top from aircraft measurements are shown at right.

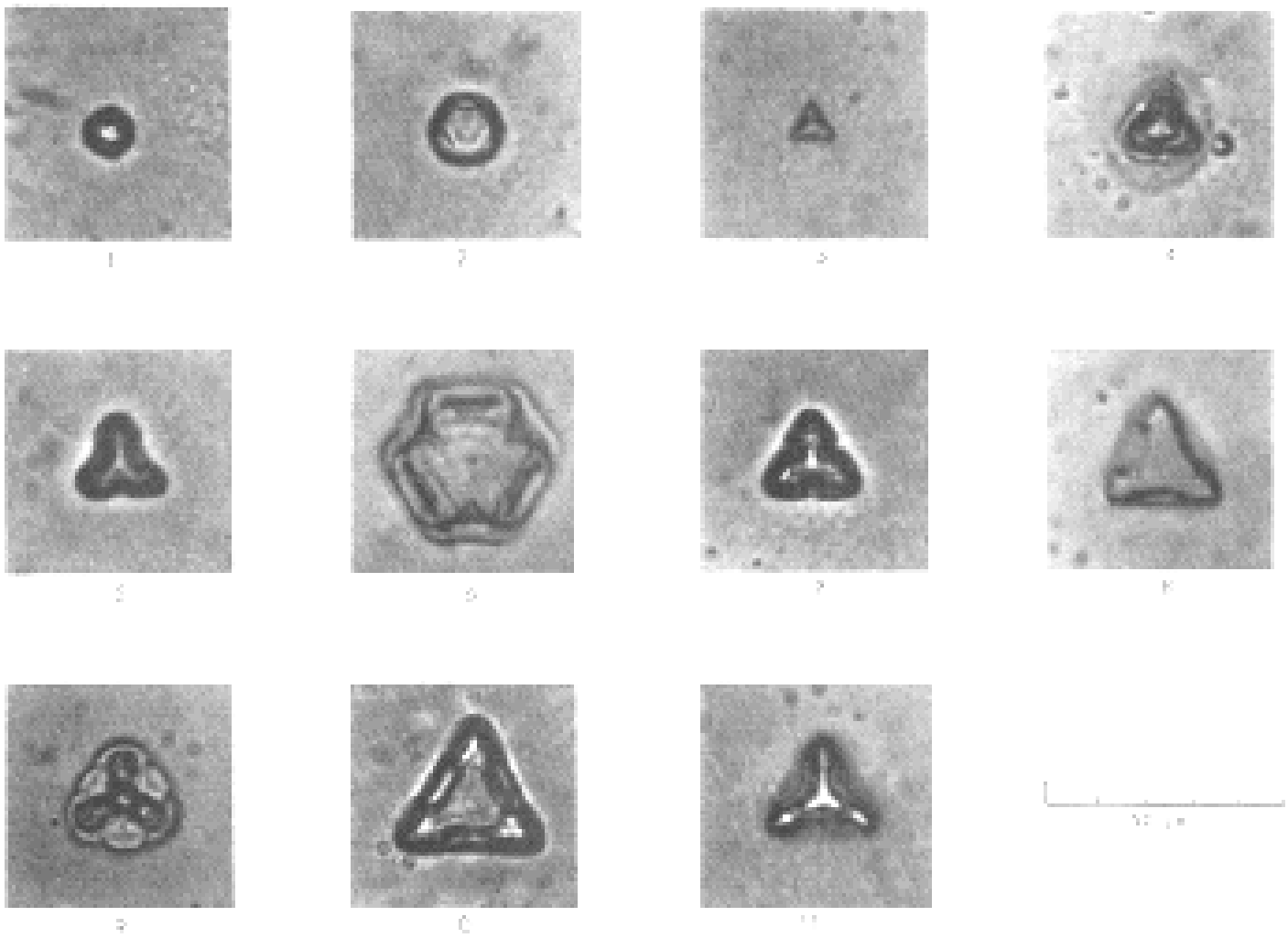


FIG. 3. Examples of trigonal ice crystal shapes observed in the cirrus layer.

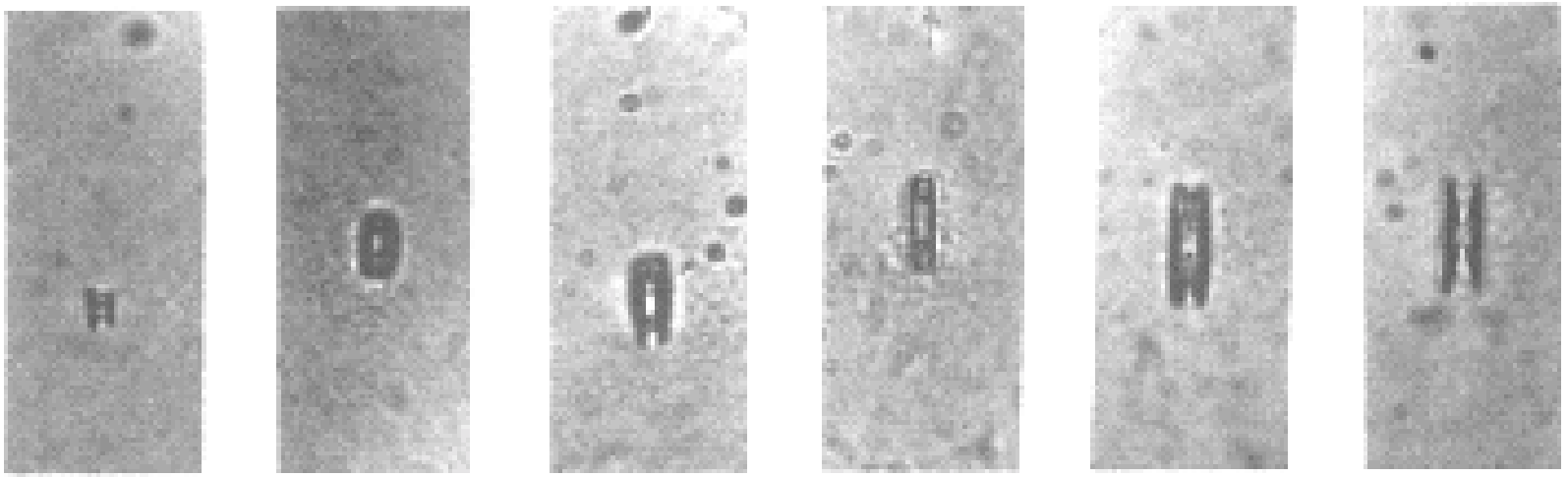
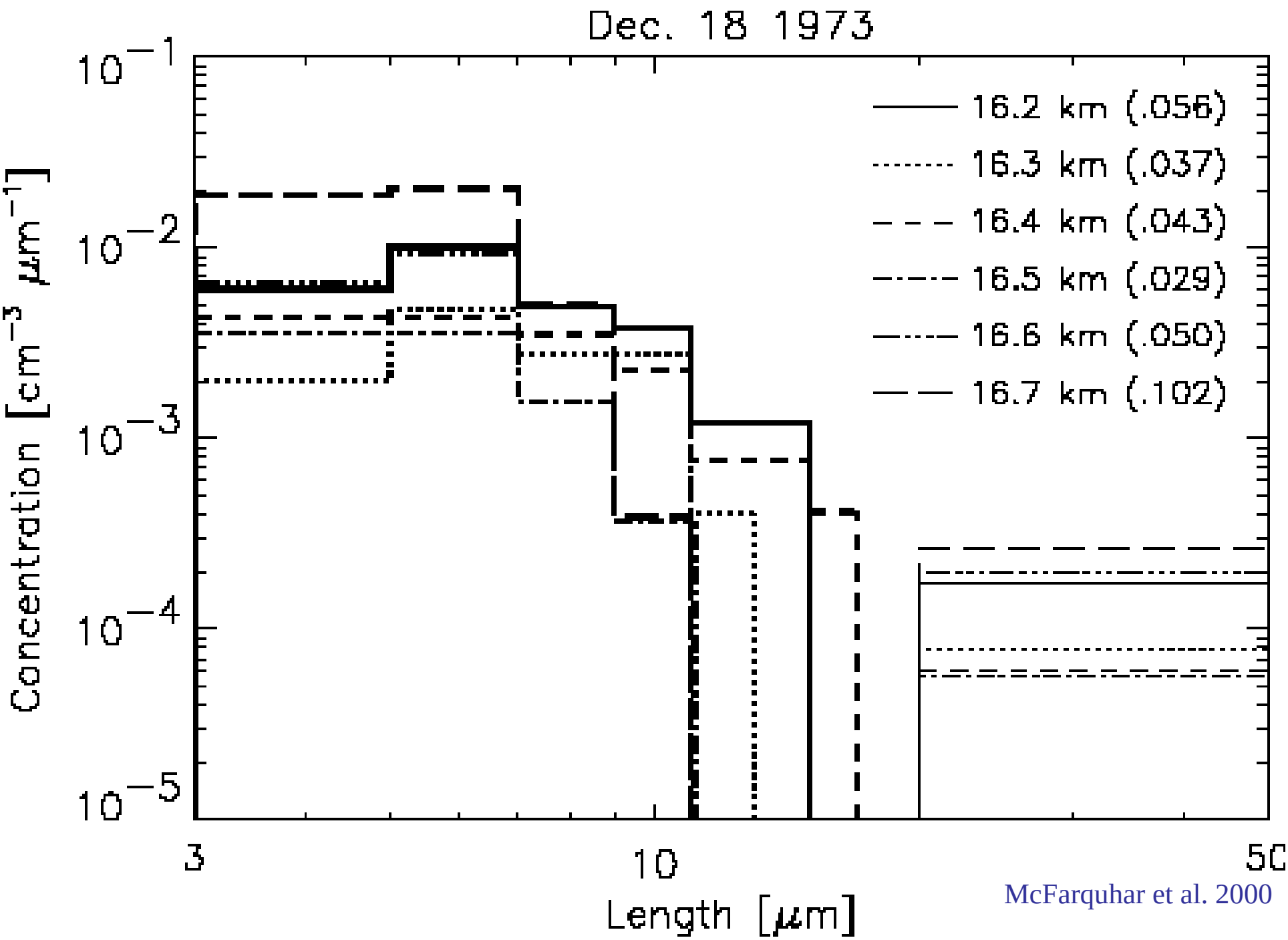
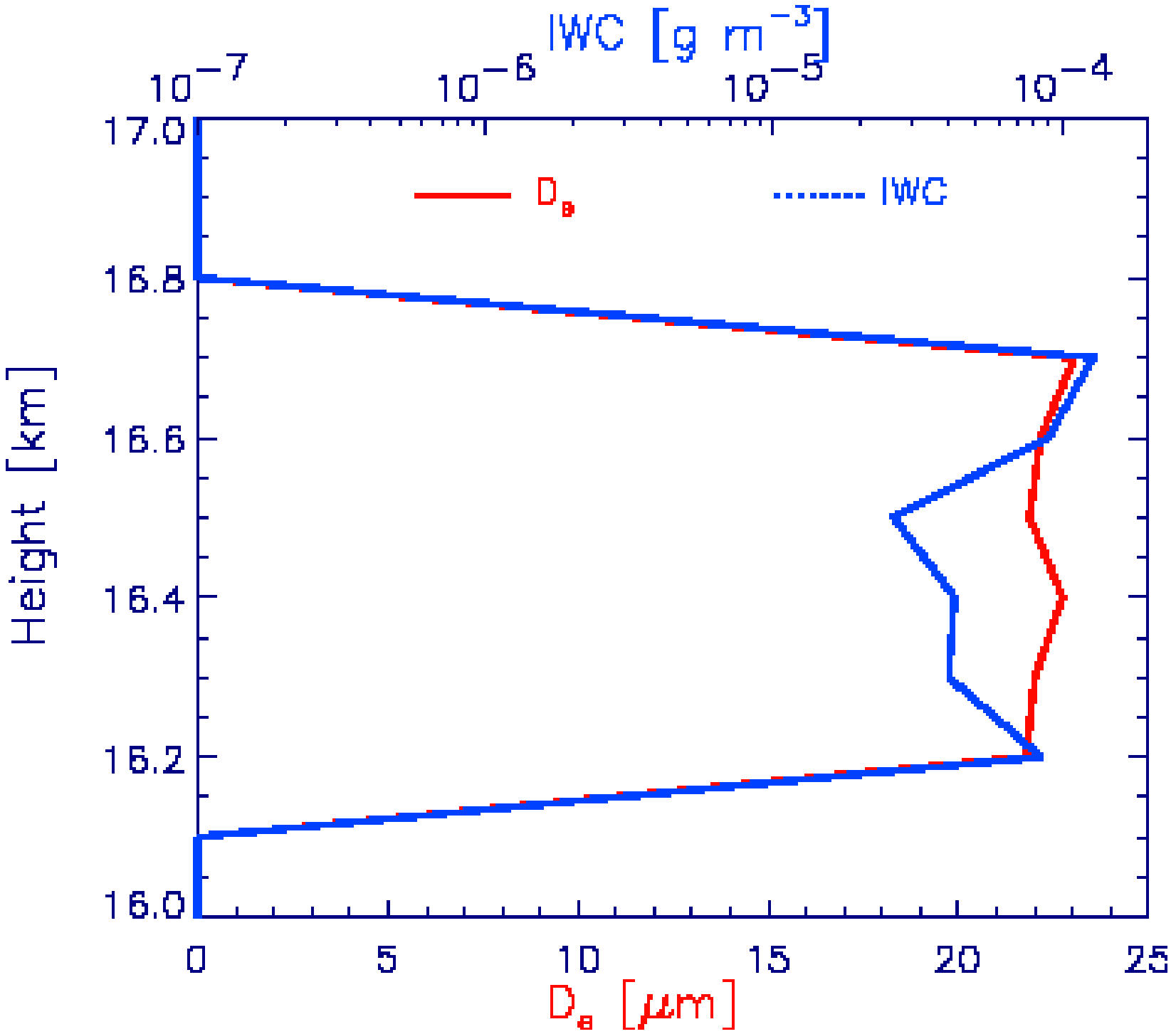


TABLE 1. Concentrations measured by the ASSP.

Altitude (km)	Concentration (cm^{-3})
16.8	0.0
16.7	0.093
16.6	0.044
16.5	0.027
16.4	0.041
16.3	0.036
16.2	0.051
16.1	0.0



McFarquhar et al. 2000


IWC [g m^{-3}]
10^{-7}
10^{-6}
10^{-5}
10^{-4}
17.0
16.8
16.6
16.4
16.2
16.0
Height [km]
D_e
IWC
0
5
10
15
20
25
D_e [μm]

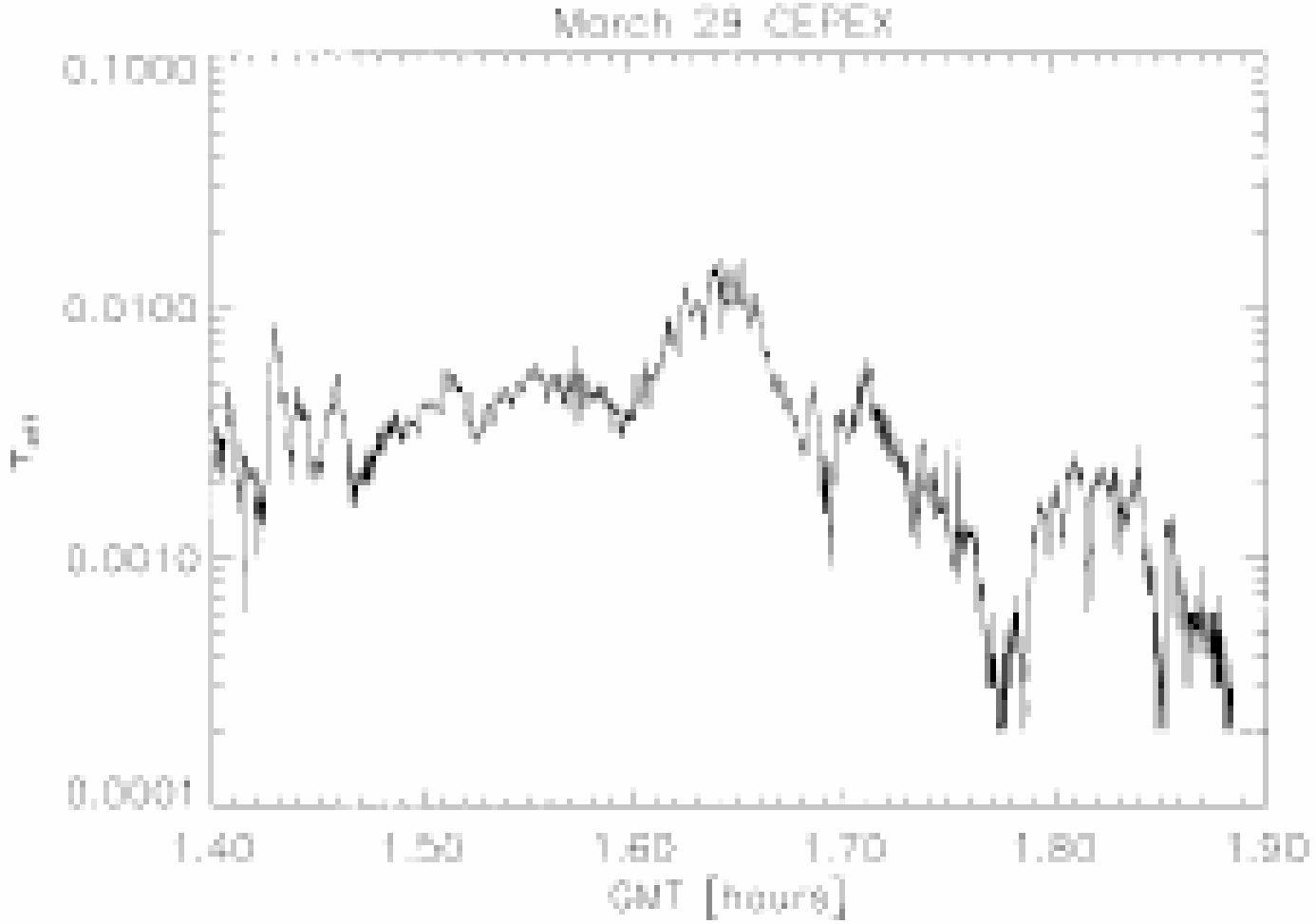
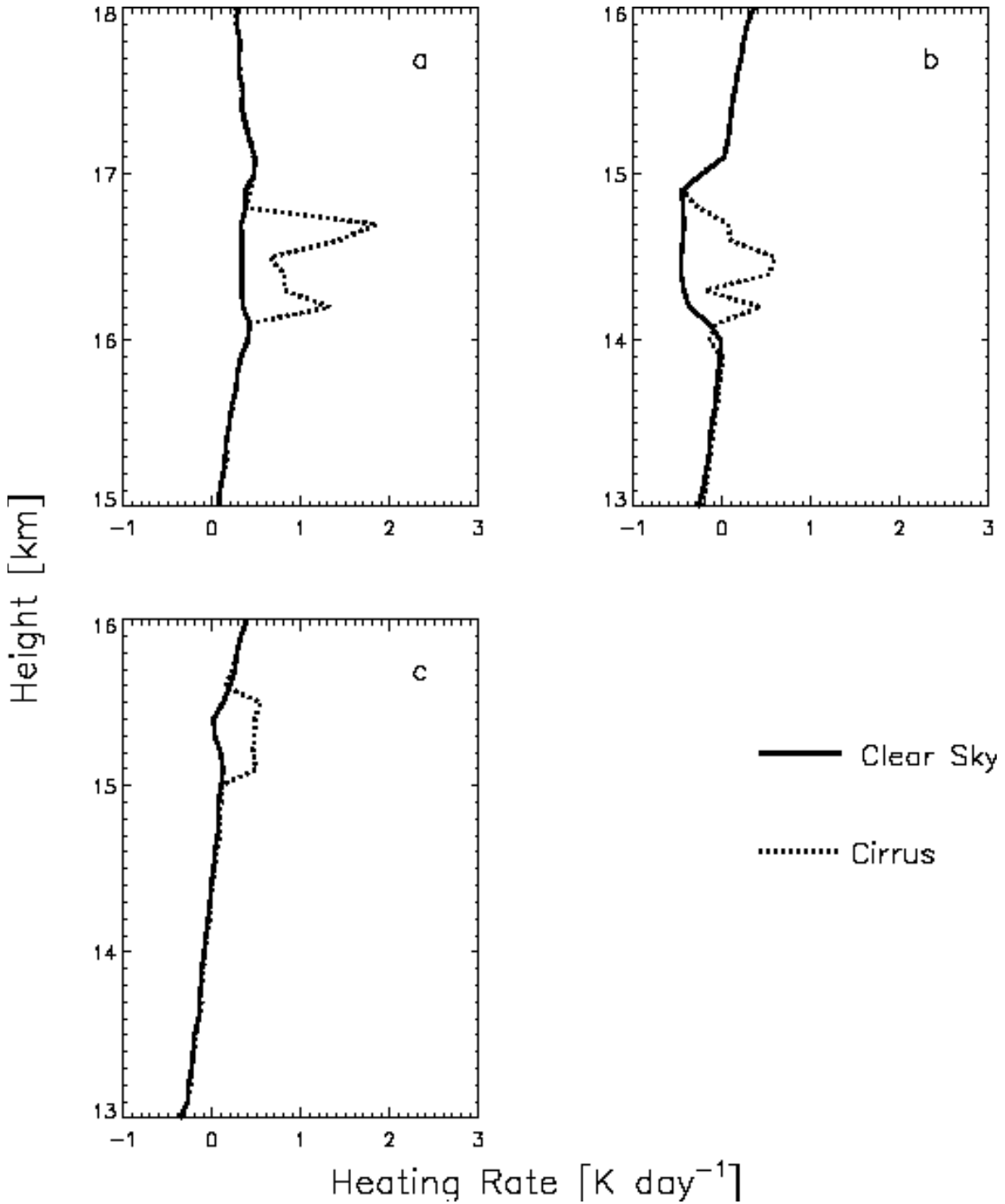


FIG. 6. Temporal variation of effective optical thickness, derived from CLS lidar measurements, for thin tropopause cirrus sampled on 0024 to 0154 UTC (GMT) 29 Mar 1993 during CEPEX at 2°S and 171°E.


a
b
c
Height [km]
Heating Rate [K day^{-1}]
Clear Sky
Cirrus

Cirrostratus

Kwajalein Vertical Profile

Microphysical data on April 5, 1974

Penetration	Altitude (km)	Temperature (°C)	IWC (g m^{-3})	$\overline{D}_m$ (μm)	D_{max} (μm)	
1	12.9	-58	4.510E-04	103.4	1190 (1680)	
2	12.1	-52	4.318E-03	110.0	1165 (1680)	
3	11.4	-44	5.396E-04	102.2	1195 (1680)	
4	10.4	-37	2.274E-02	129.3	1419 (2100)	
5	9.7	-30	8.940E-02	169.8	1815 (2100)	
6	9.0	-24	1.493E-01	157.7	1756 (2100)	
7	8.1	-19	4.292E-02	140.9	1587 (2100)	
8	7.3	-14	1.335E-01	230.5	2048 (2100)	
9	6.6	-9	1.056E-01	204.8	2049 (2100)	

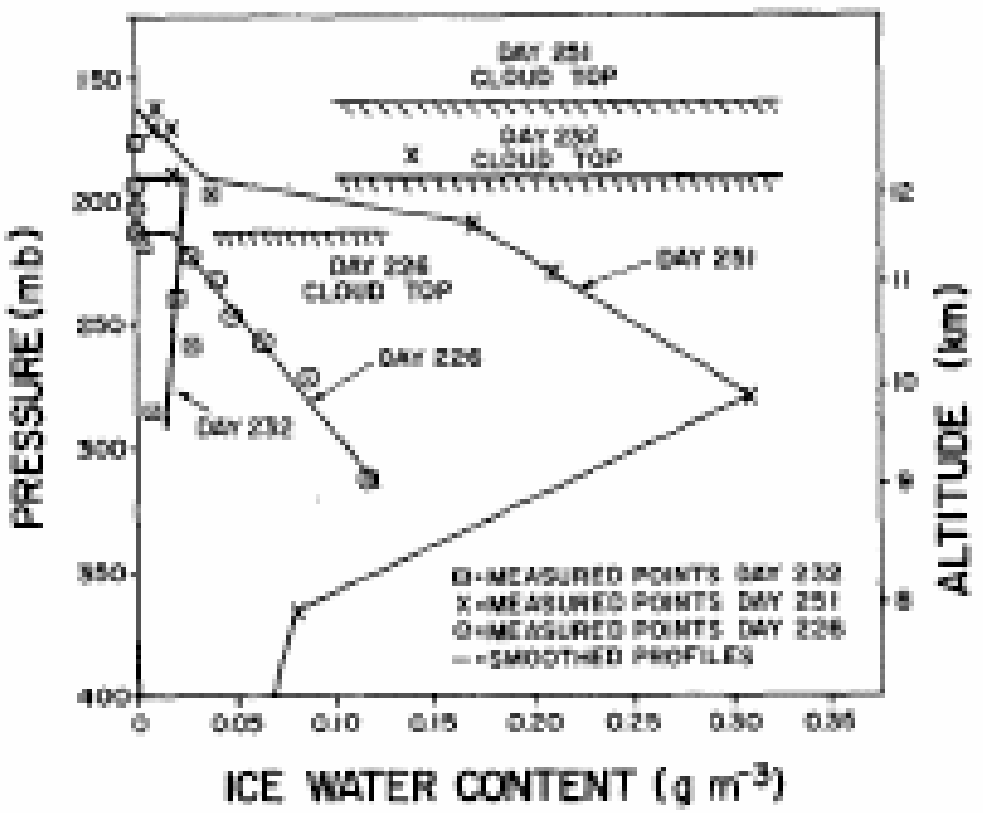
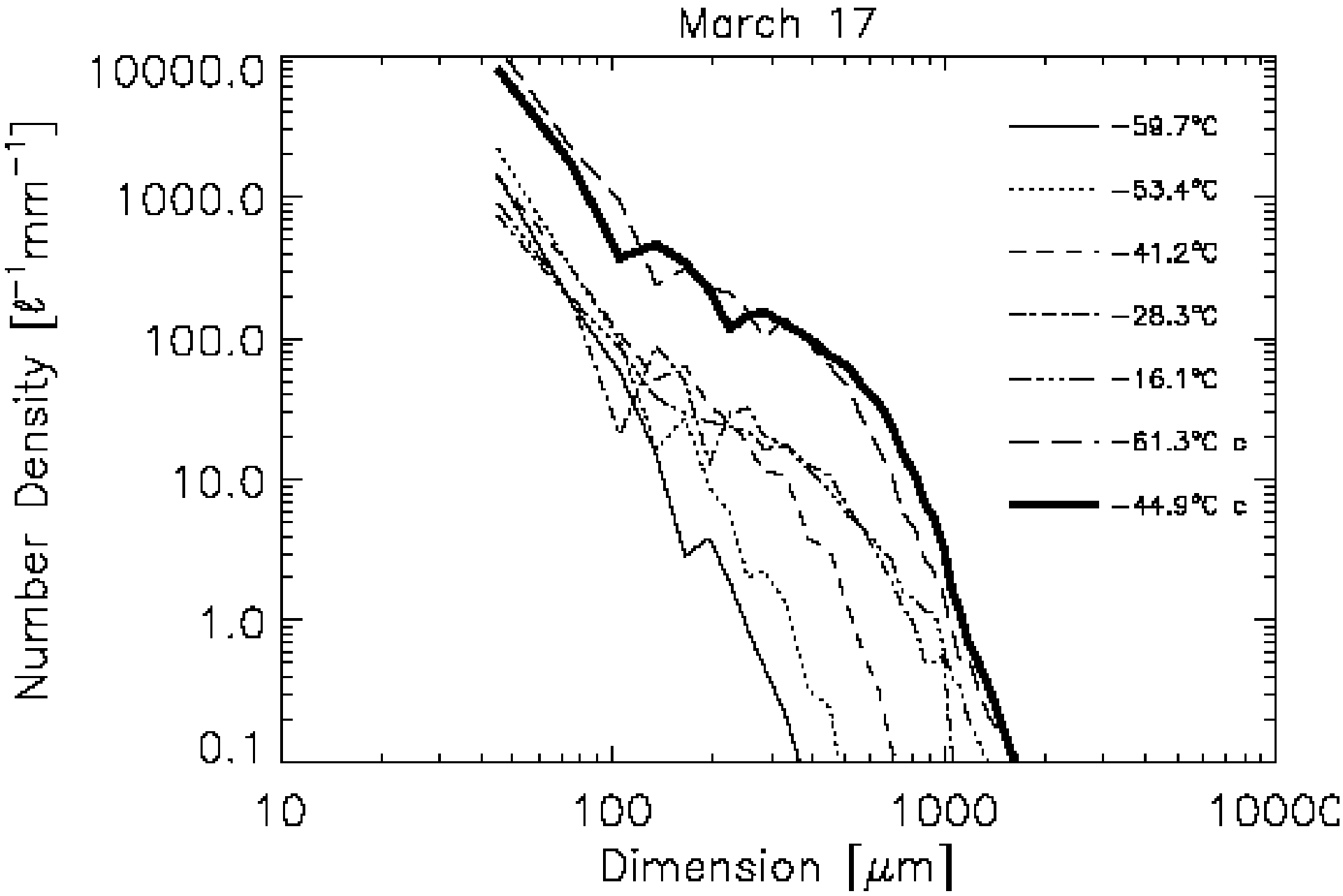
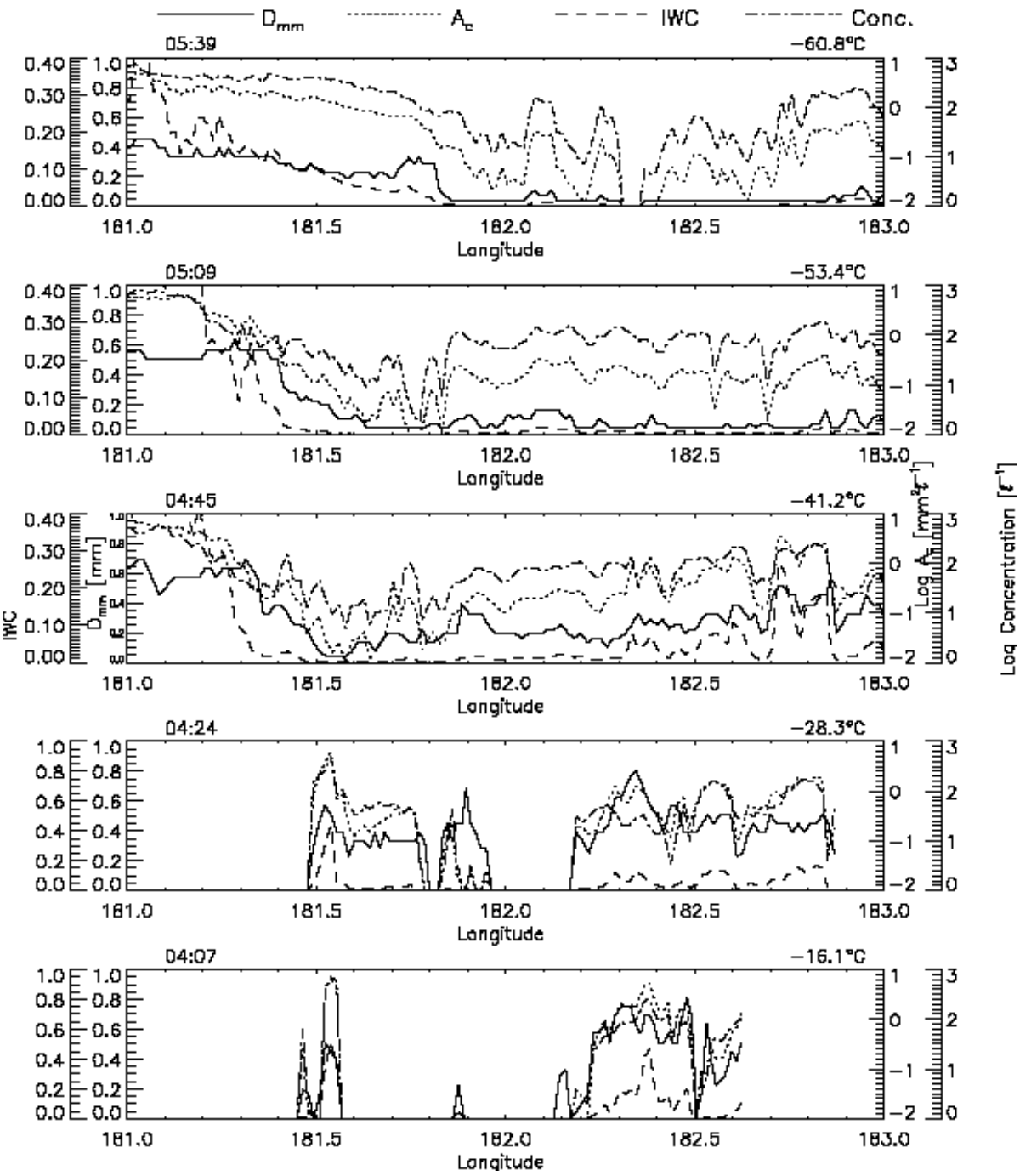


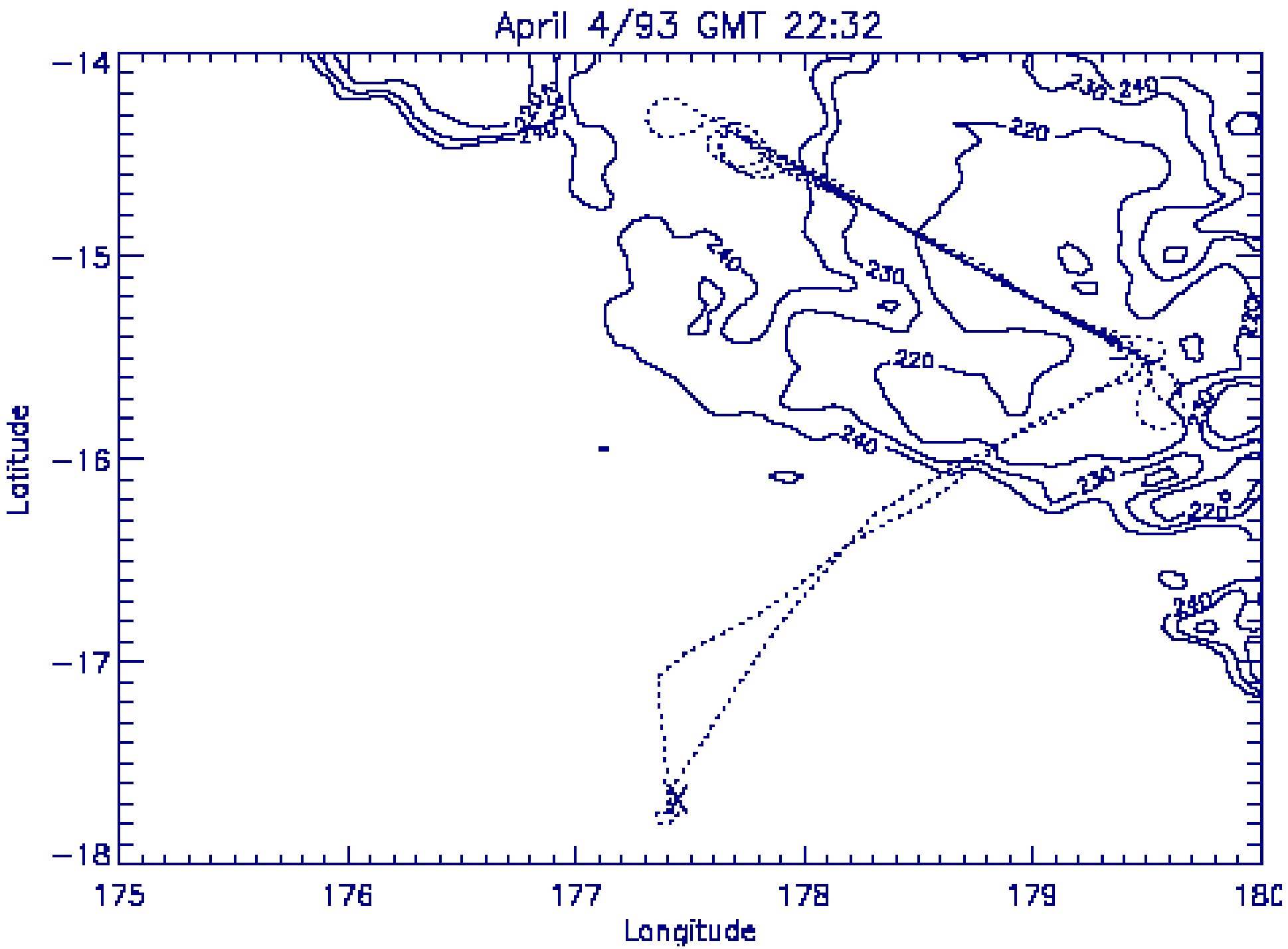
FIG. 4. Vertical structure of ice water content for the three case studies.

GATE Griffith et al. (1980)

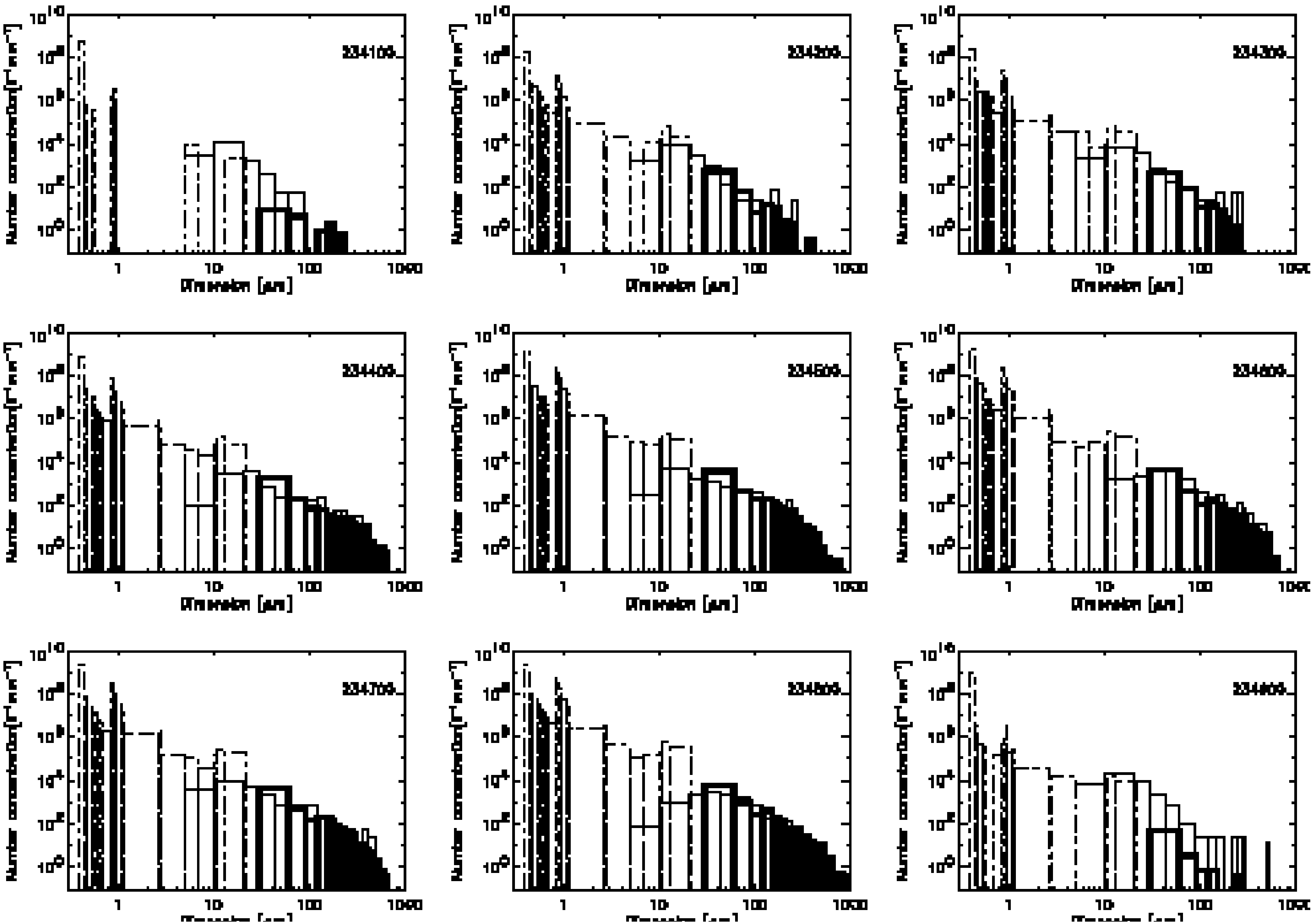


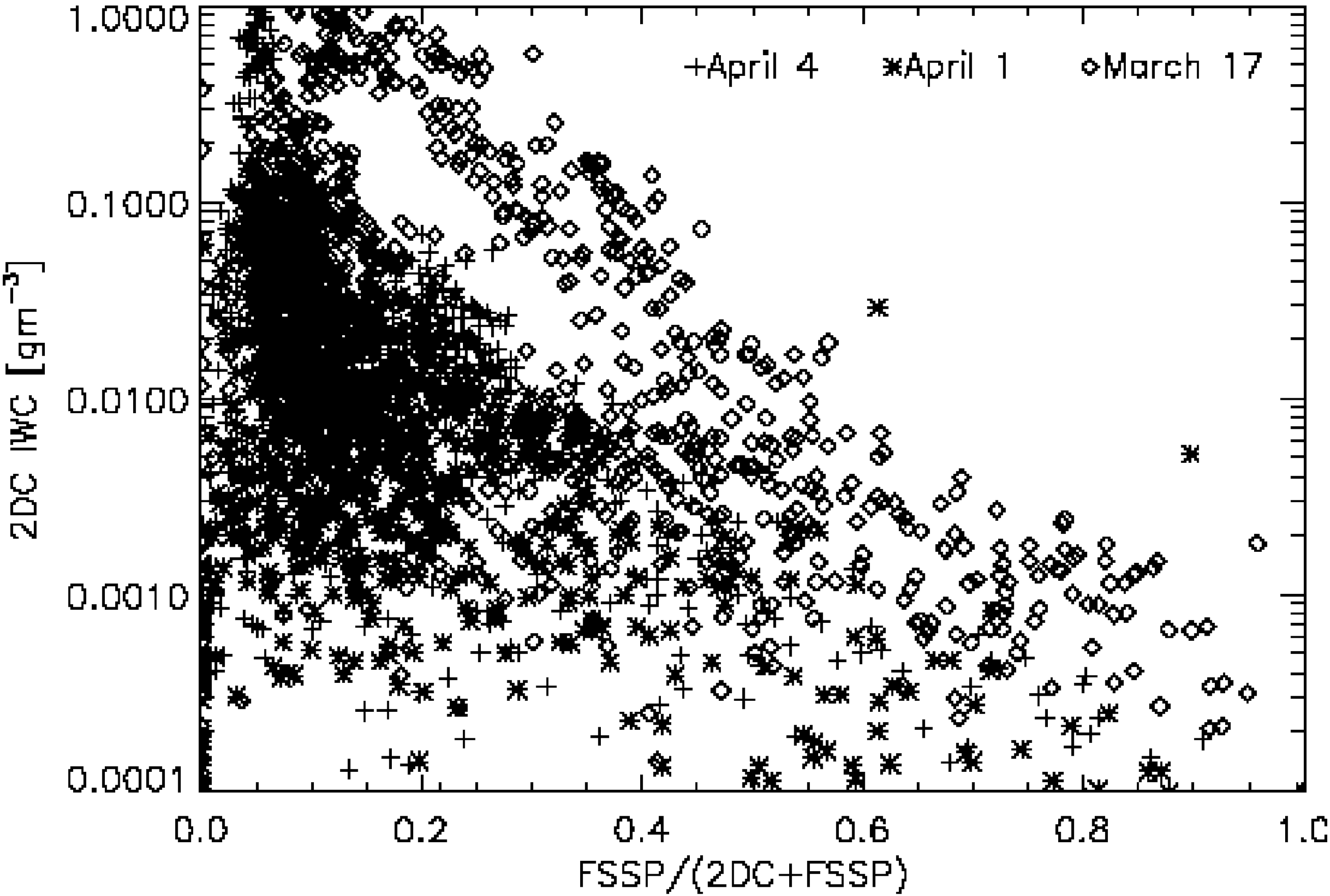
McFarquhar and Heymsfield (1997)

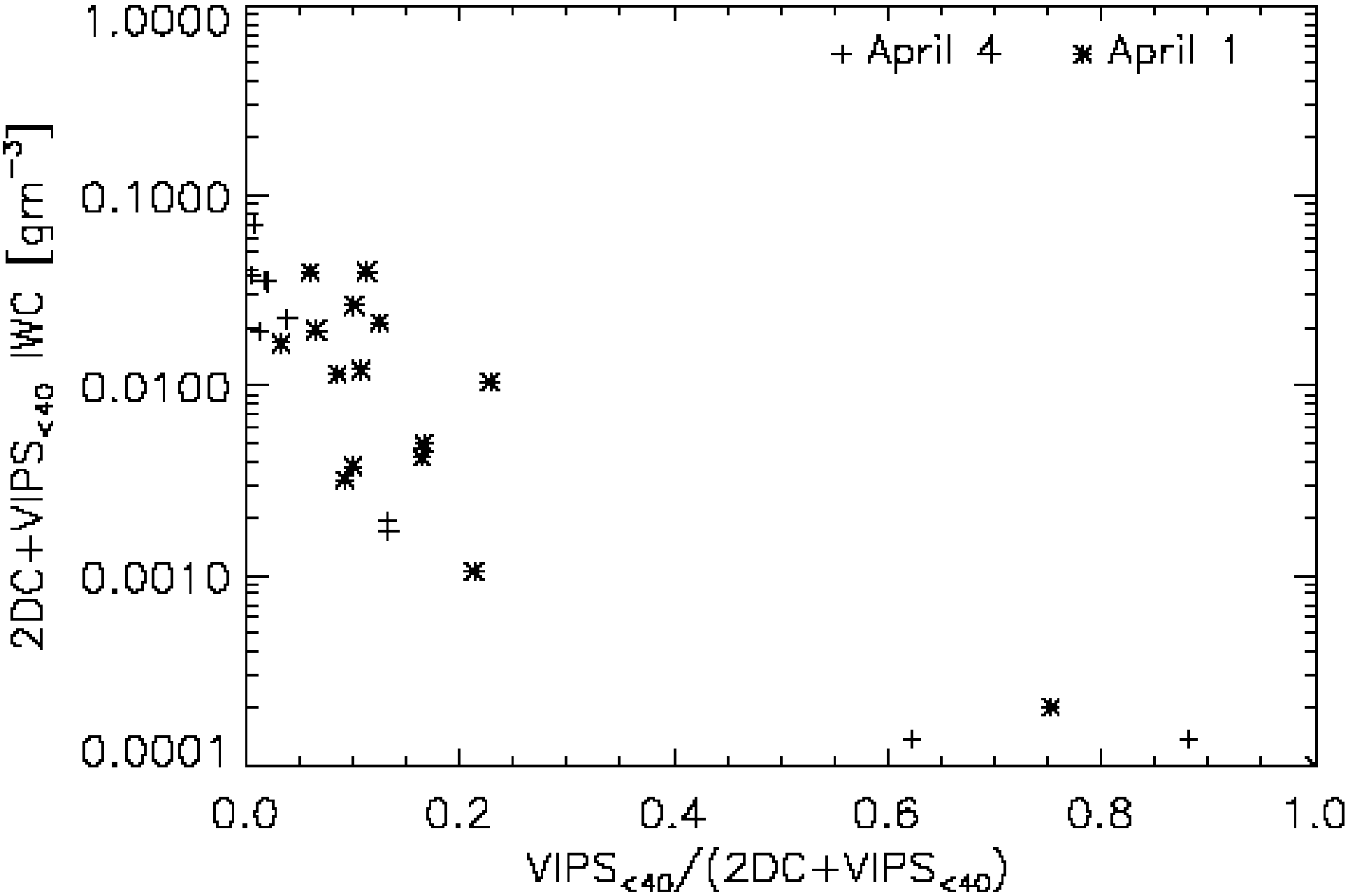

March 17
D_{mm}
A_c
IWC
Conc.
05:39
−60.8°C
05:09
−53.4°C
04:45
−41.2°C
04:24
−28.3°C
04:07
−16.1°C
Longitude
181.0
181.5
182.0
182.5
183.0
IWC
D_{mm} [mm]
Log A_c [$mm^2 \ell^{-1}$]
Log Concentration [ℓ^{-1}]

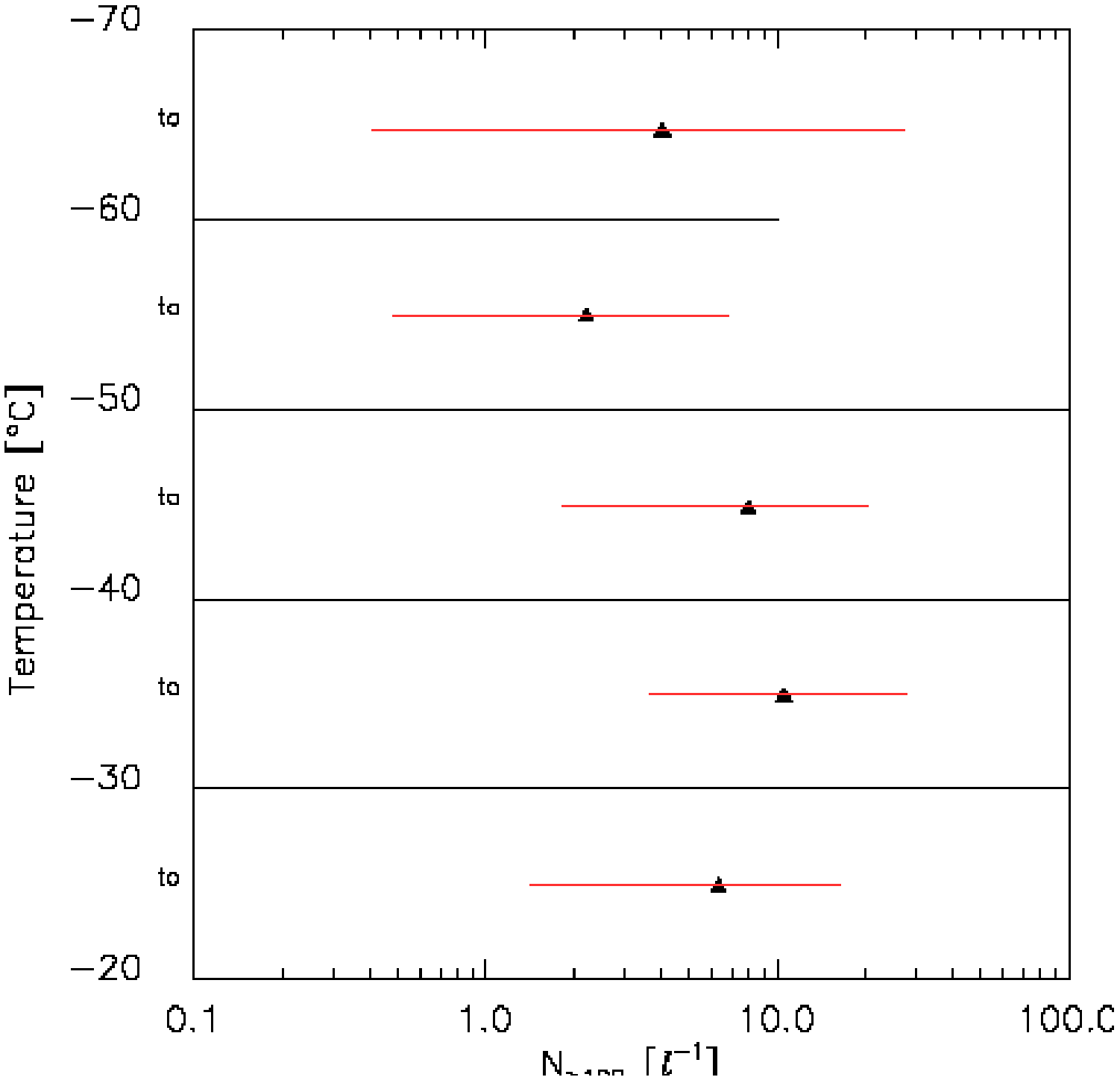

April 4/93 GMT 22:32
Latitude
Longitude
-14
-15
-16
-17
-18
175
176
177
178
179
180
240
230
220
240
230
220
240
230
220
240

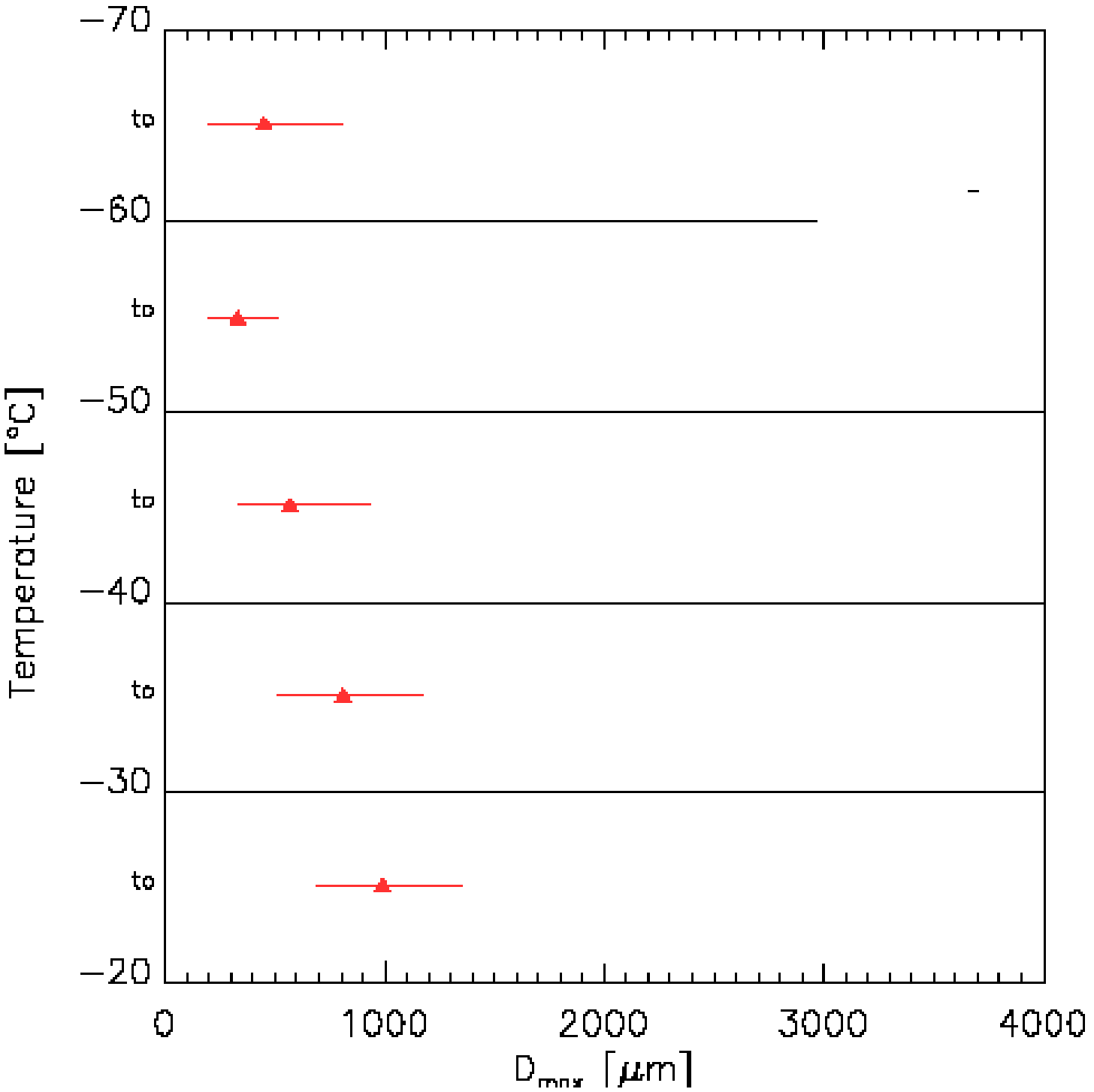
April 4

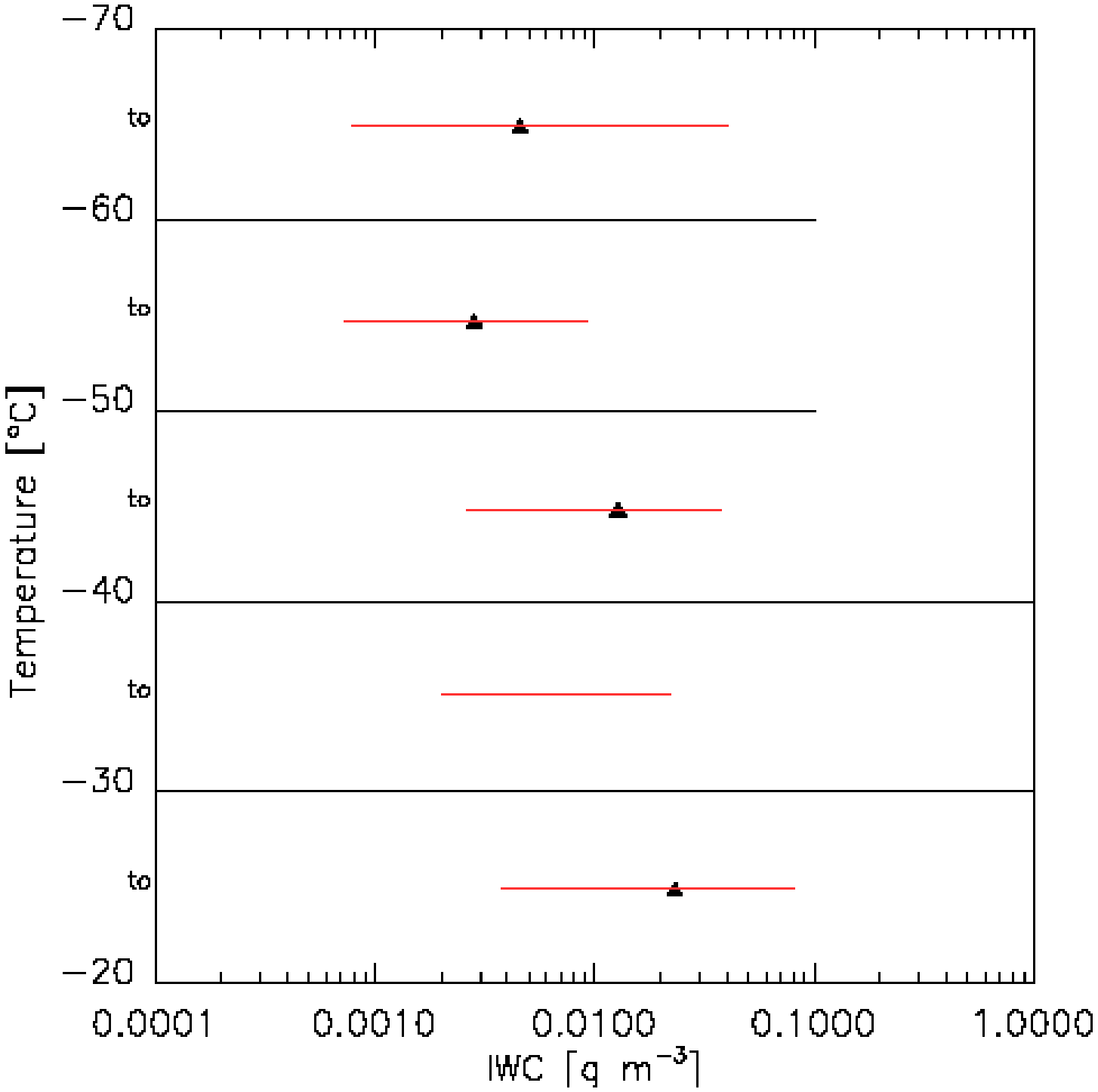



1.0000
0.1000
0.0100
0.0010
0.0001
2DC IWC [gm^{-3}]
+April 4
*April 1
◇March 17
0.0
0.2
0.4
0.6
0.8
1.0
FSSP/(2DC+FSSP)


1.0000
0.1000
0.0100
0.0010
0.0001
0.0
0.2
0.4
0.6
0.8
1.0
+ April 4
* April 1
2DC+VIPS<40 IWC [gm-3]
VIPS<40/(2DC+VIPS<40)


−70
−60
−50
−40
−30
−20
Temperature [°C]
to
to
to
to
to
0.1
1.0
10.0
100.0


−70
to
−60
to
−50
to
−40
to
−30
to
−20
Temperature [°C]
0
1000
2000
3000
4000
D_{max} [μm]


−70
to
−60
to
−50
to
−40
to
−30
to
−20
Temperature [°C]
0.0001
0.0010
0.0100
0.1000
1.0000
IWC [g m^{-3}]

Deep Convection (Thick Cirrus)

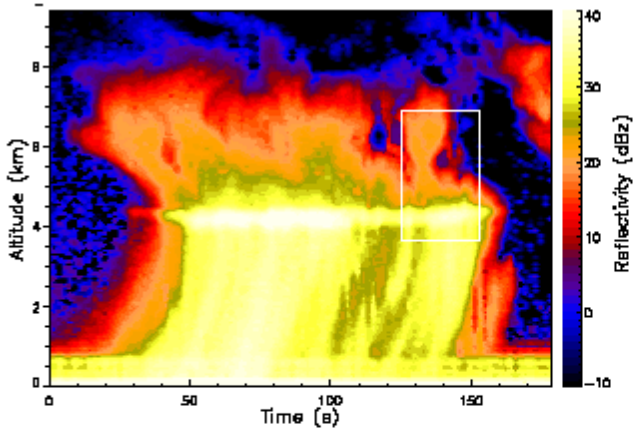
FIG. 2. LITE position–height image of MCS1 at 532-nm wavelength, together with regions to the north and south of MCS1. Lat = N, long = E, GMT = UTC h:min:s on 10 Sep 1994. The key gives the relative backscatter intensity (arbitrary).

LITE (Platt et al. (1999)

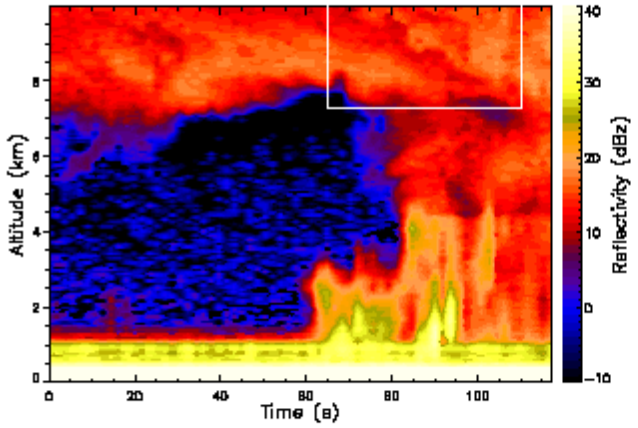
TRMM Spiral Descents

Date	Location	Times (UTC)	Alt (m)	Temp (° C)	$\frac{d(Alt)}{dt}$ (m s^{-1})	Loops (#)	Op. Depth (Average)
980805	Fla[1]	213251 215040	7923 3632	-19 0	2.7	6	
980217	Brazil	194224 195601	10042 4602	-38 0	6.7	4	
980219	Brazil[2]	201335 201934	9091 4379	-10 2	4.8	3	
980818	Kwajalein	035139 040701	8508 5695	-26 -5	3.1	7	28
980819	Kwajalein	220448 225000	9050 3370	-14 7	1.3	23	36
980822	Kwajalein	212049 220451	11205 6083	-50 -16	1.6	14	23
980823	Kwajalein	031450 034550	10341 6094	-42 -9	2.3	10	25
980830	Kwajalein	201056 203730	7376 3685	-18 6	2.3	13	29
		205332 212120	7319 3685	-17 5	2.2	13	25
980911	Kwajalein	194955 203121	10065 4514	-39 7	2.2	11	29

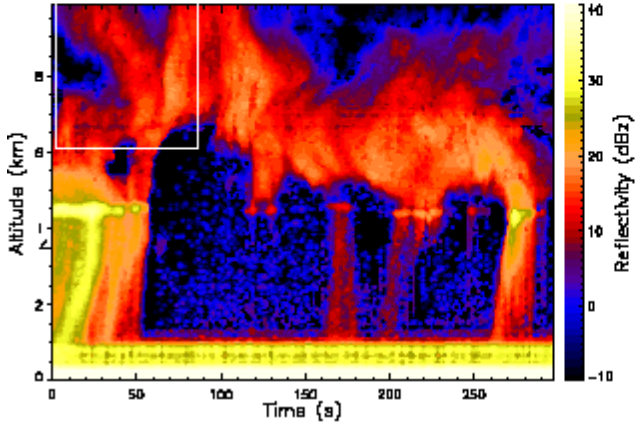
0819

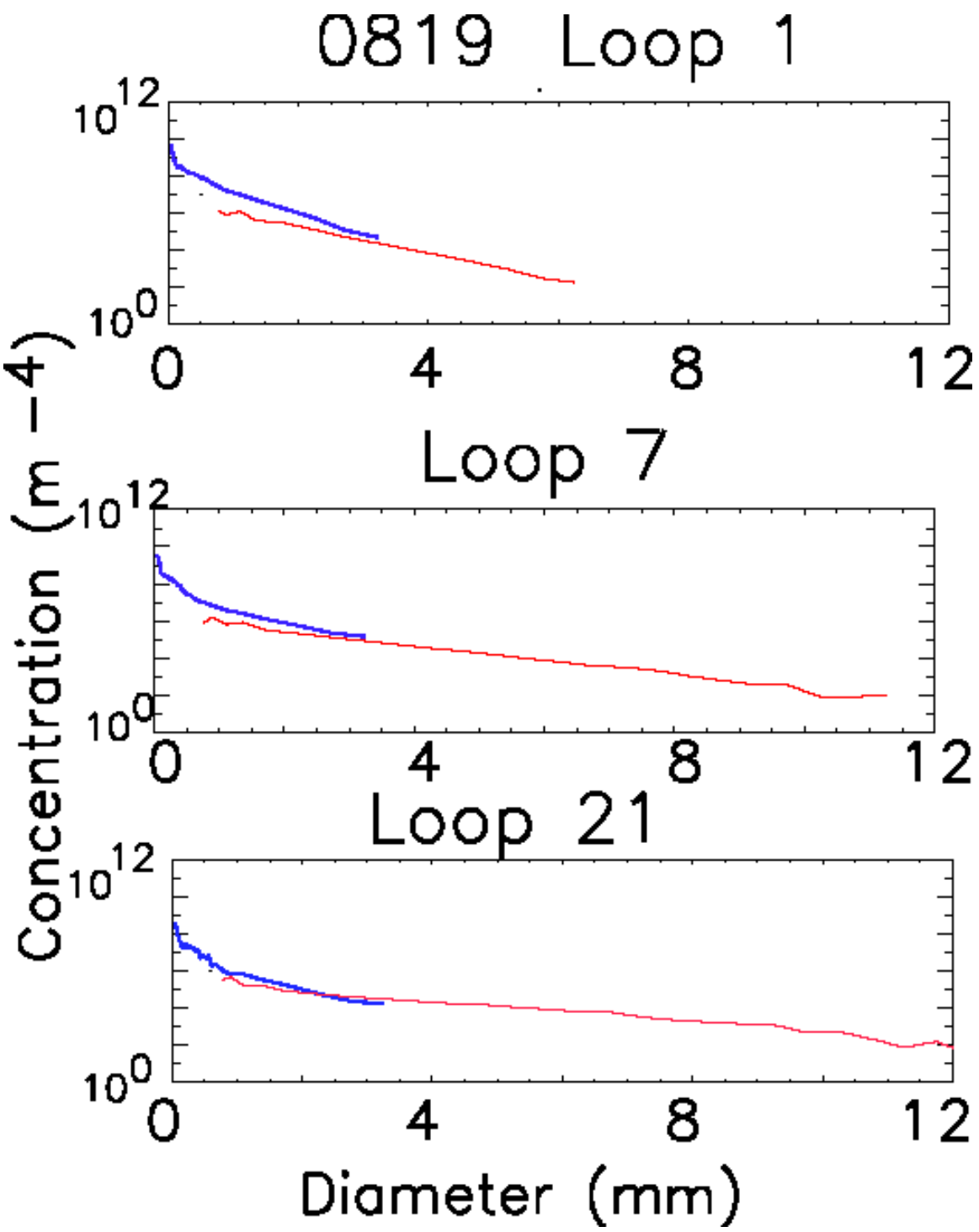


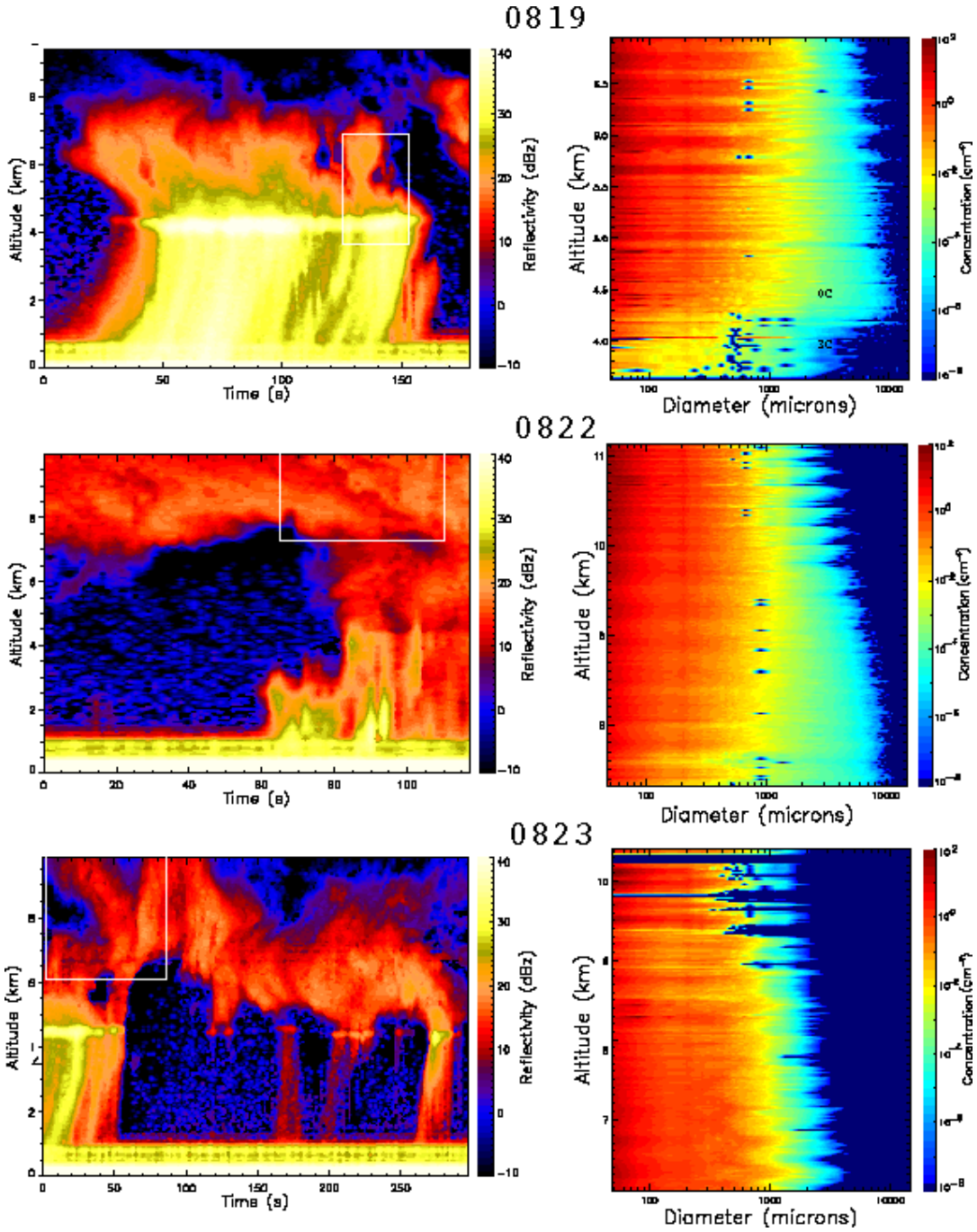
0822

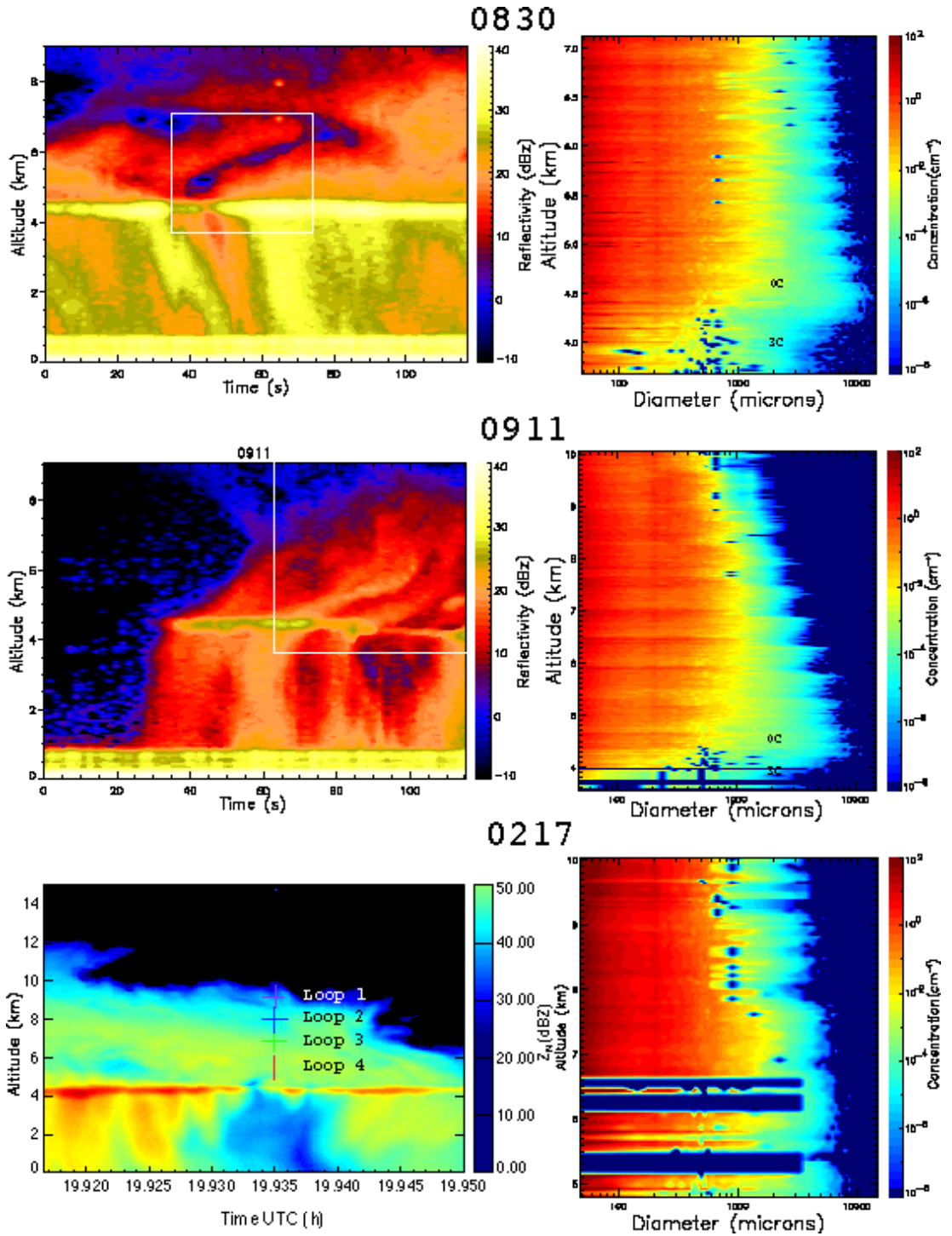


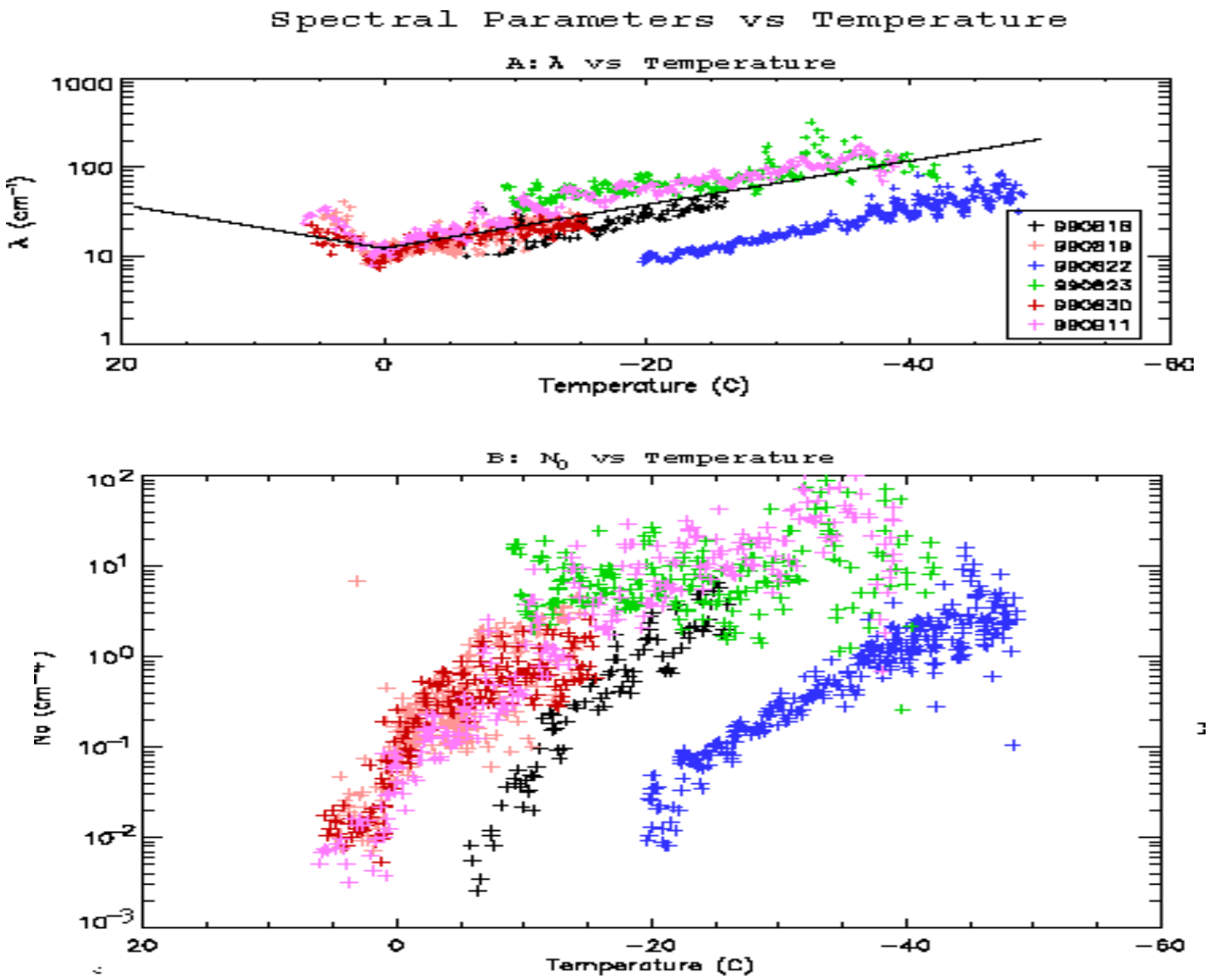
0823

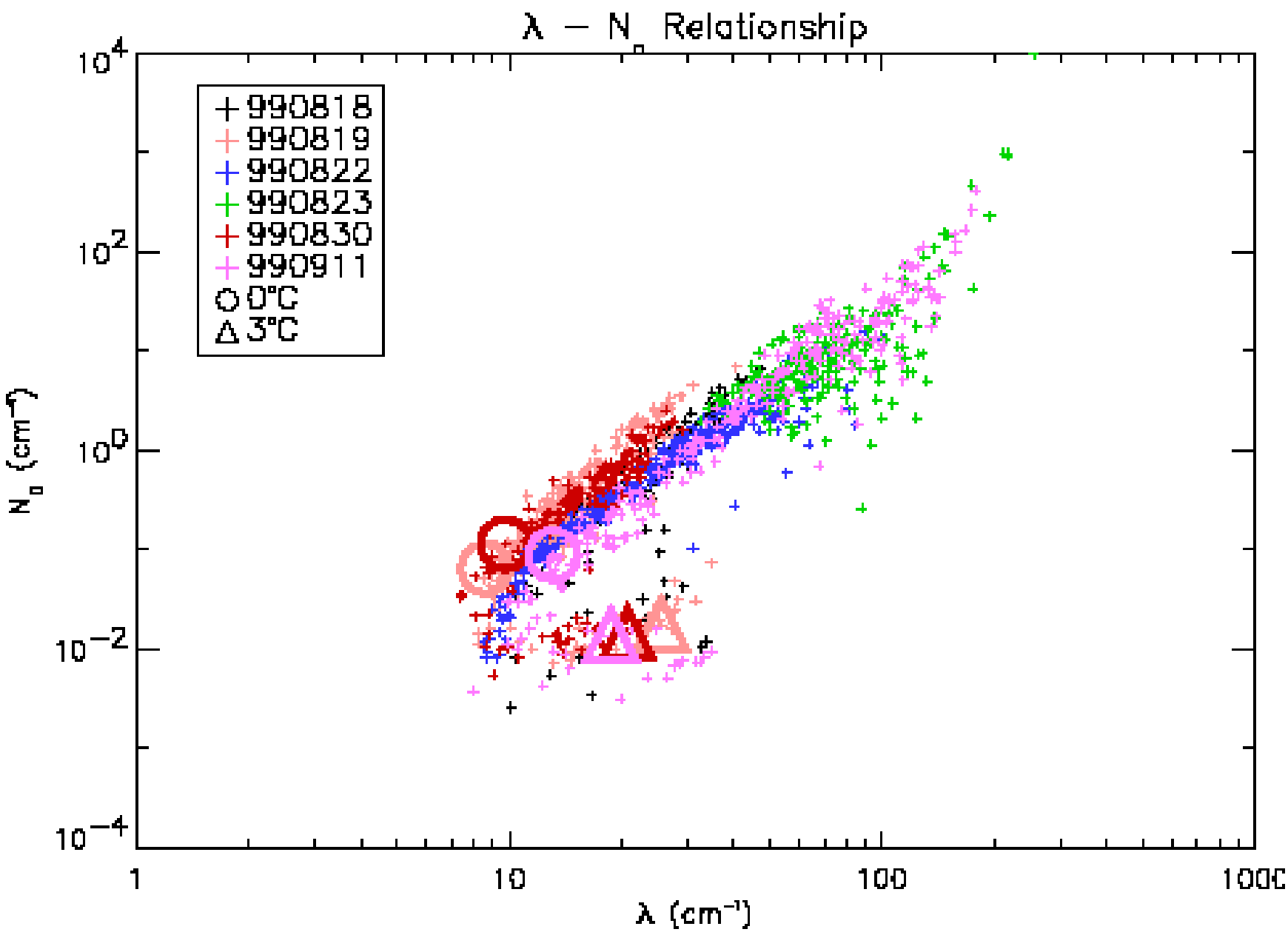


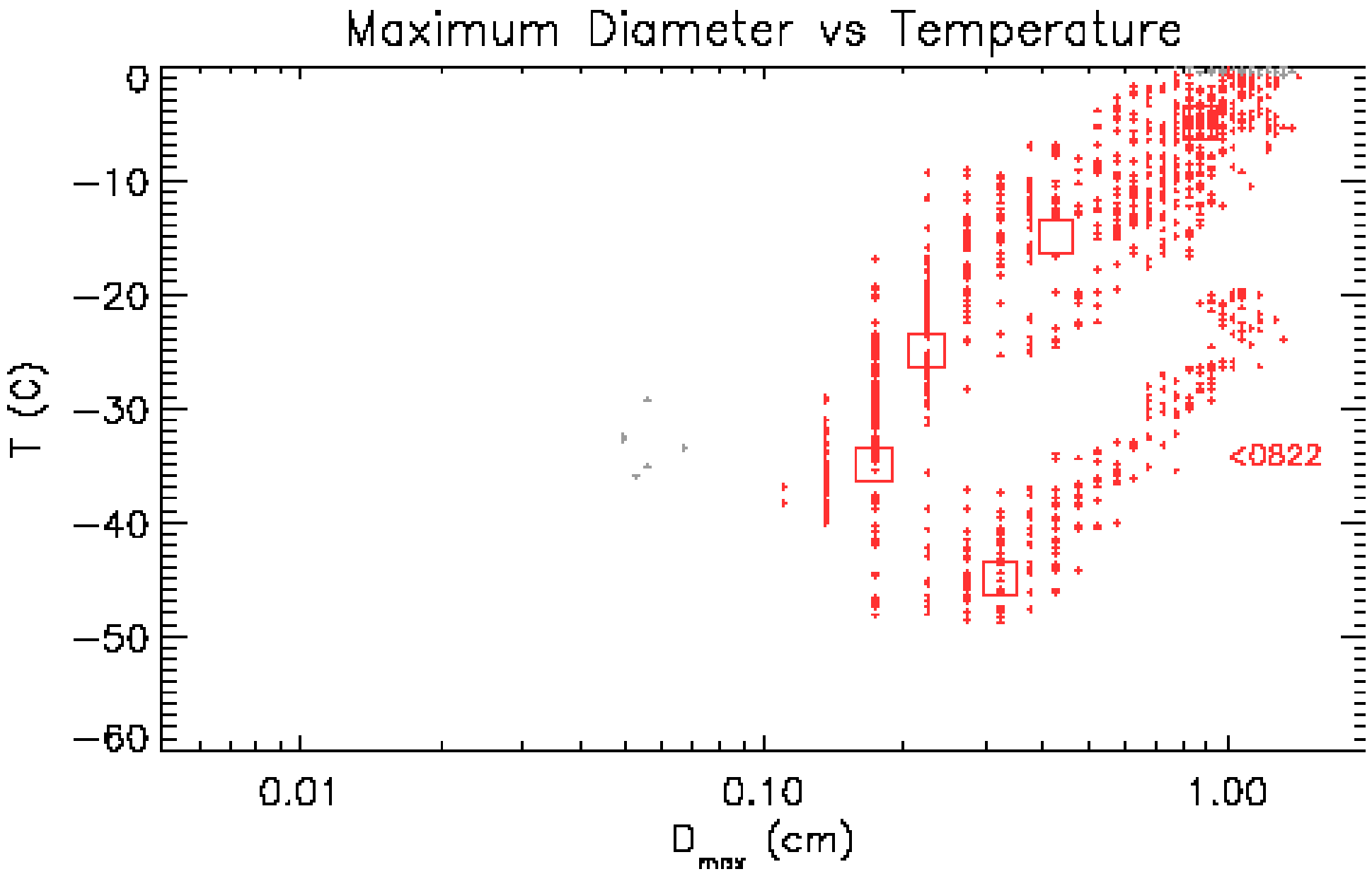

0819 Loop 1
Loop 7
Loop 21
Concentration (m^-4)
Diameter (mm)
10^12
10^0
0
4
8
12

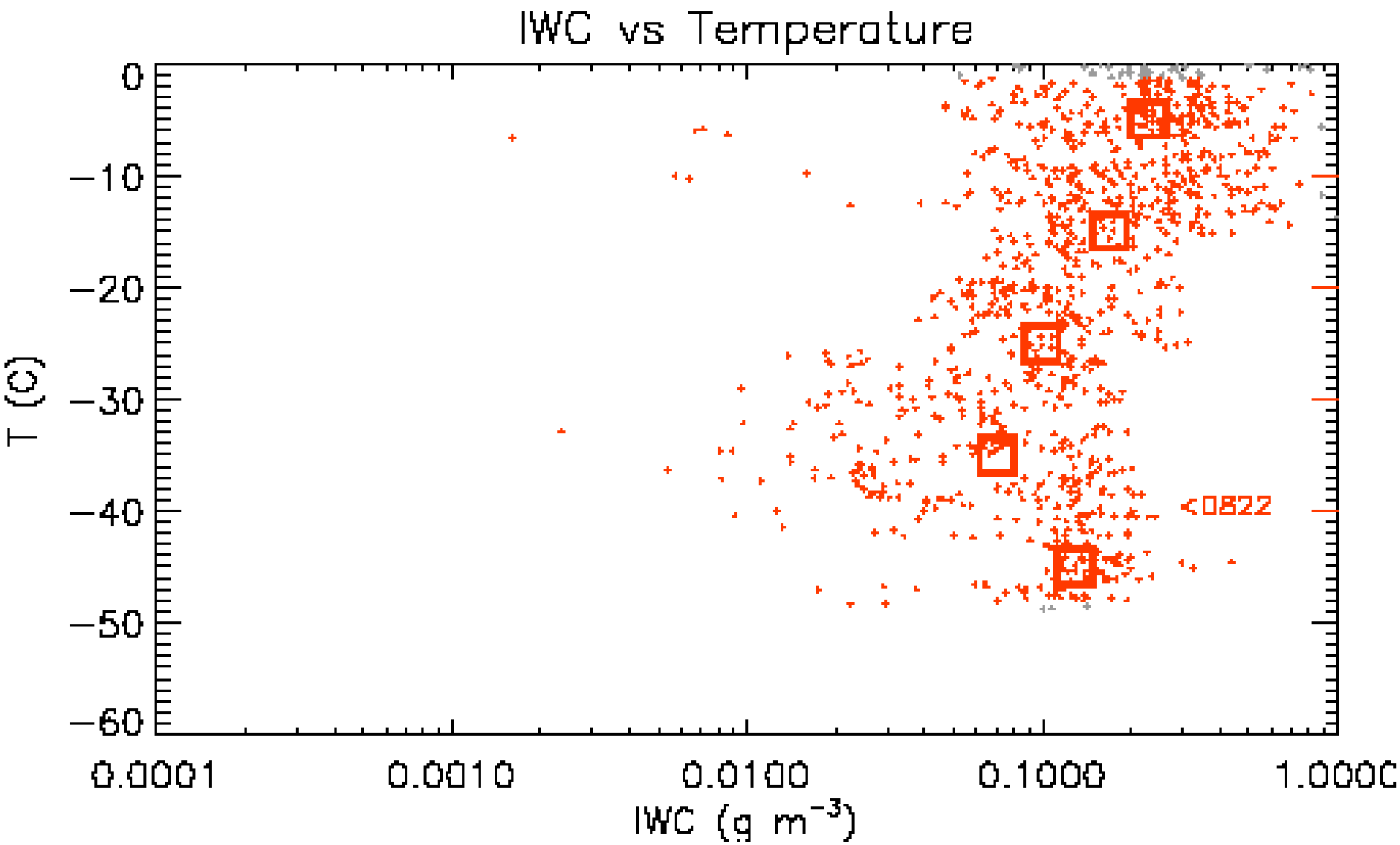

0819
Altitude (km)
Time (s)
Reflectivity (dBz)
Altitude (km)
Diameter (microns)
Concentration (cm⁻³)
0C
-3C
0822
Altitude (km)
Time (s)
Reflectivity (dBz)
Altitude (km)
Diameter (microns)
Concentration (cm⁻³)
0823
Altitude (km)
Time (s)
Reflectivity (dBz)
Altitude (km)
Diameter (microns)
Concentration (cm⁻³)


0830
Altitude (km)
Time (s)
Reflectivity (dBz)
Altitude (km)
0C
-3C
Diameter (microns)
Concentration(cm⁻⁴)
0911
0911
Altitude (km)
Time (s)
Reflectivity (dBz)
Altitude (km)
0C
-3C
Diameter (microns)
Concentration (cm⁻⁴)
0217
Loop 1
Loop 2
Loop 3
Loop 4
Altitude (km)
Time UTC (h)
19.920
19.925
19.930
19.935
19.940
19.945
19.950
50.00
40.00
30.00
20.00
10.00
0.00
Z_N (dBZ)
Altitude (km)
Diameter (microns)
Concentration(cm⁻⁴)

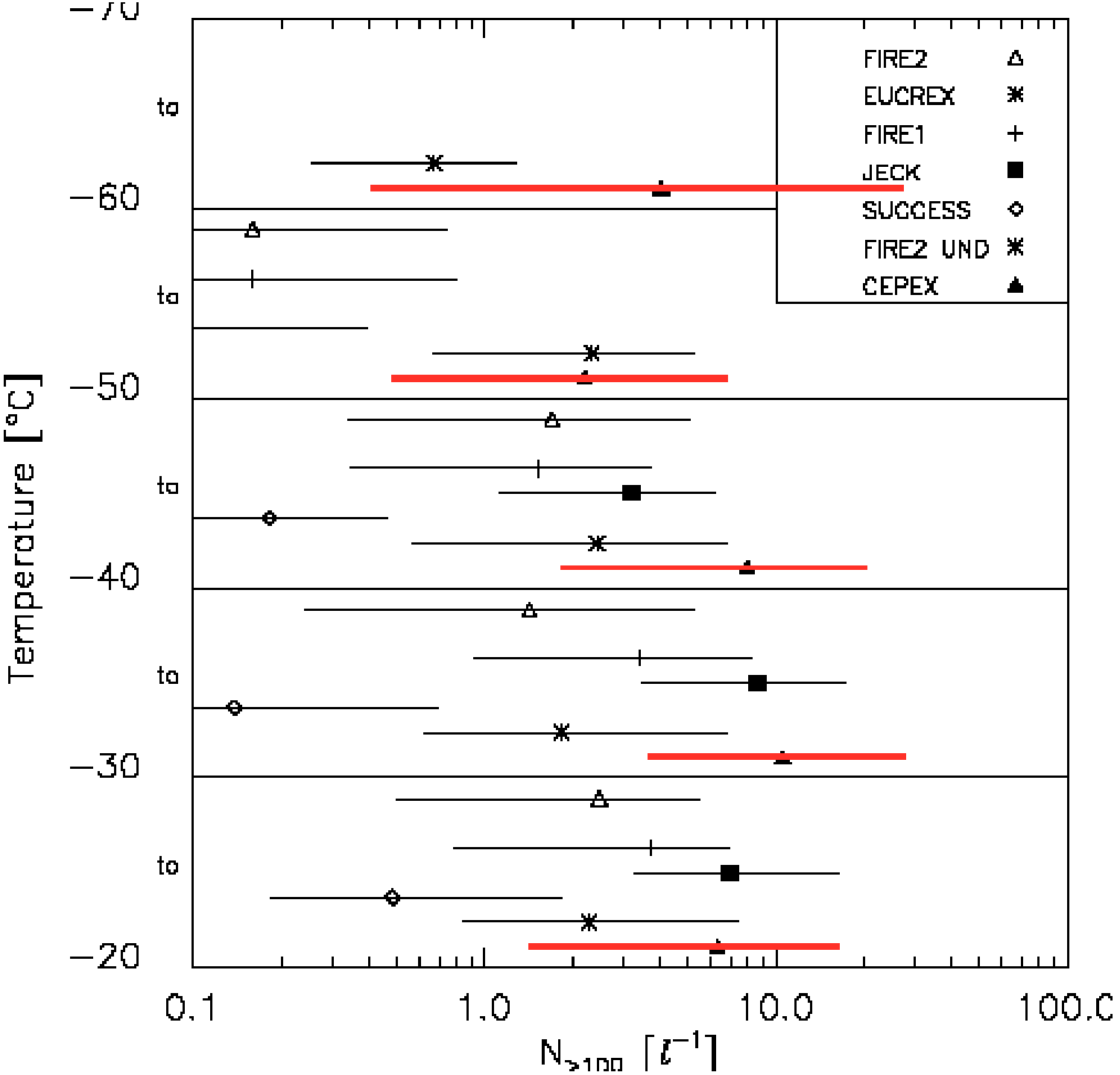

Spectral Parameters vs Temperature
A: λ vs Temperature
λ (cm⁻¹)
1000
100
10
1
20
0
−20
−40
−60
Temperature (C)
990818
990819
990822
990823
990830
990811
B: N0 vs Temperature
N0 (cm⁻⁴)
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
20
0
−20
−40
−60
Temperature (C)

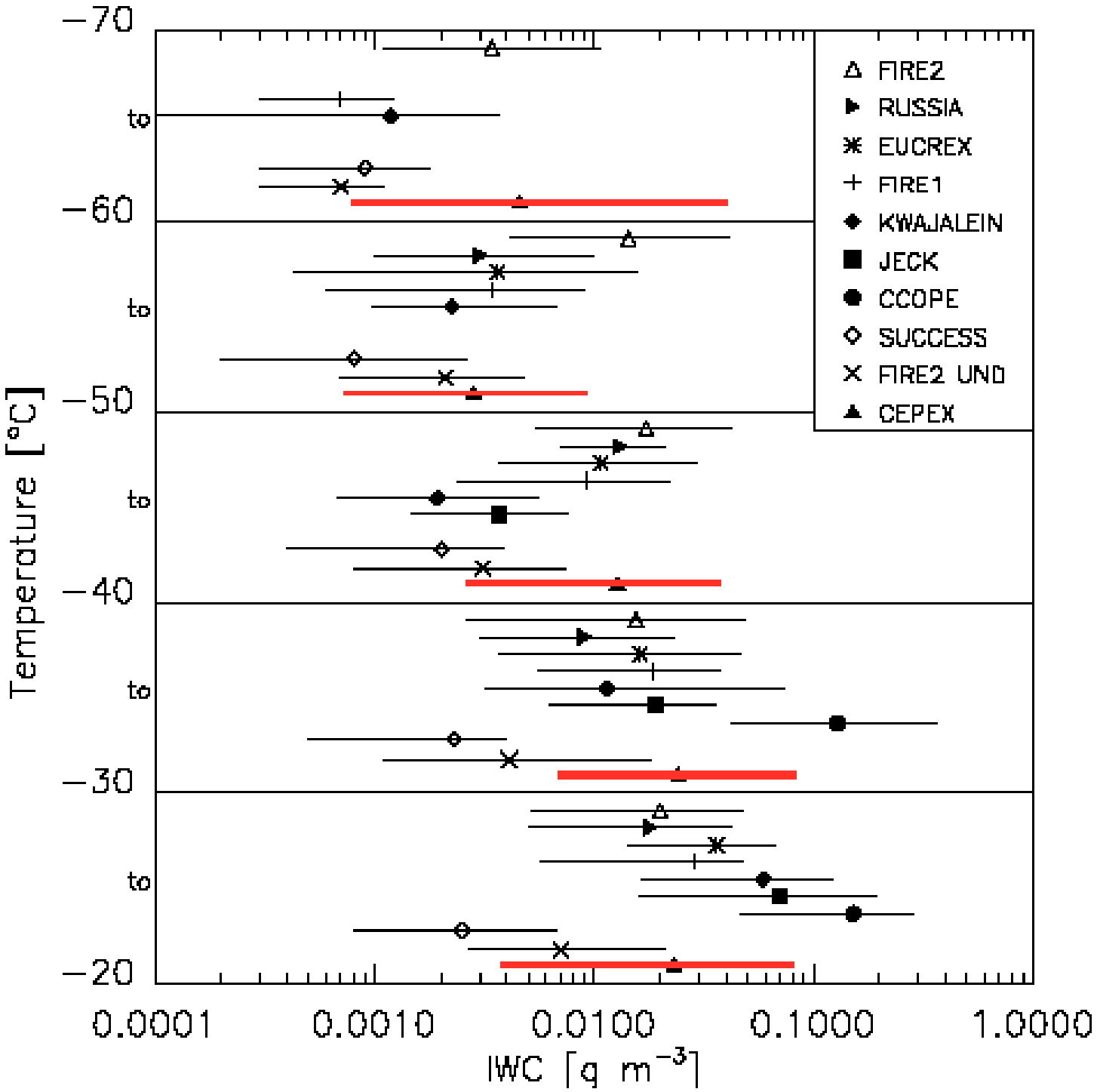

λ — N0 Relationship
990818
990819
990822
990823
990830
990911
0°C
3°C
10^4
10^2
10^0
10^-2
10^-4
N0 (cm^-4)
1
10
100
1000
λ (cm^-1)

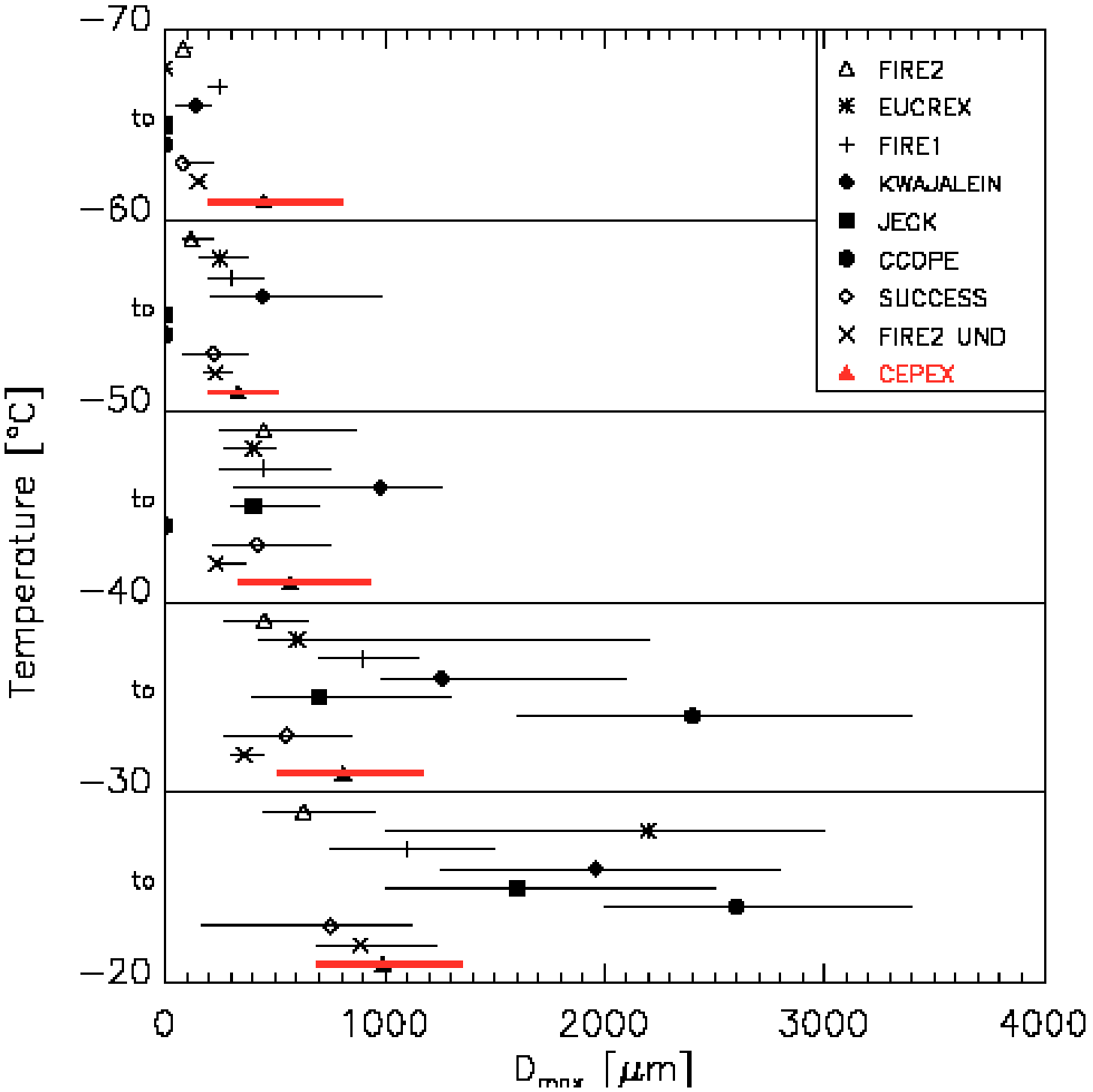

Maximum Diameter vs Temperature
0
−10
−20
−30
−40
−50
−60
T (C)
0.01
0.10
1.00
D max (cm)
<0822

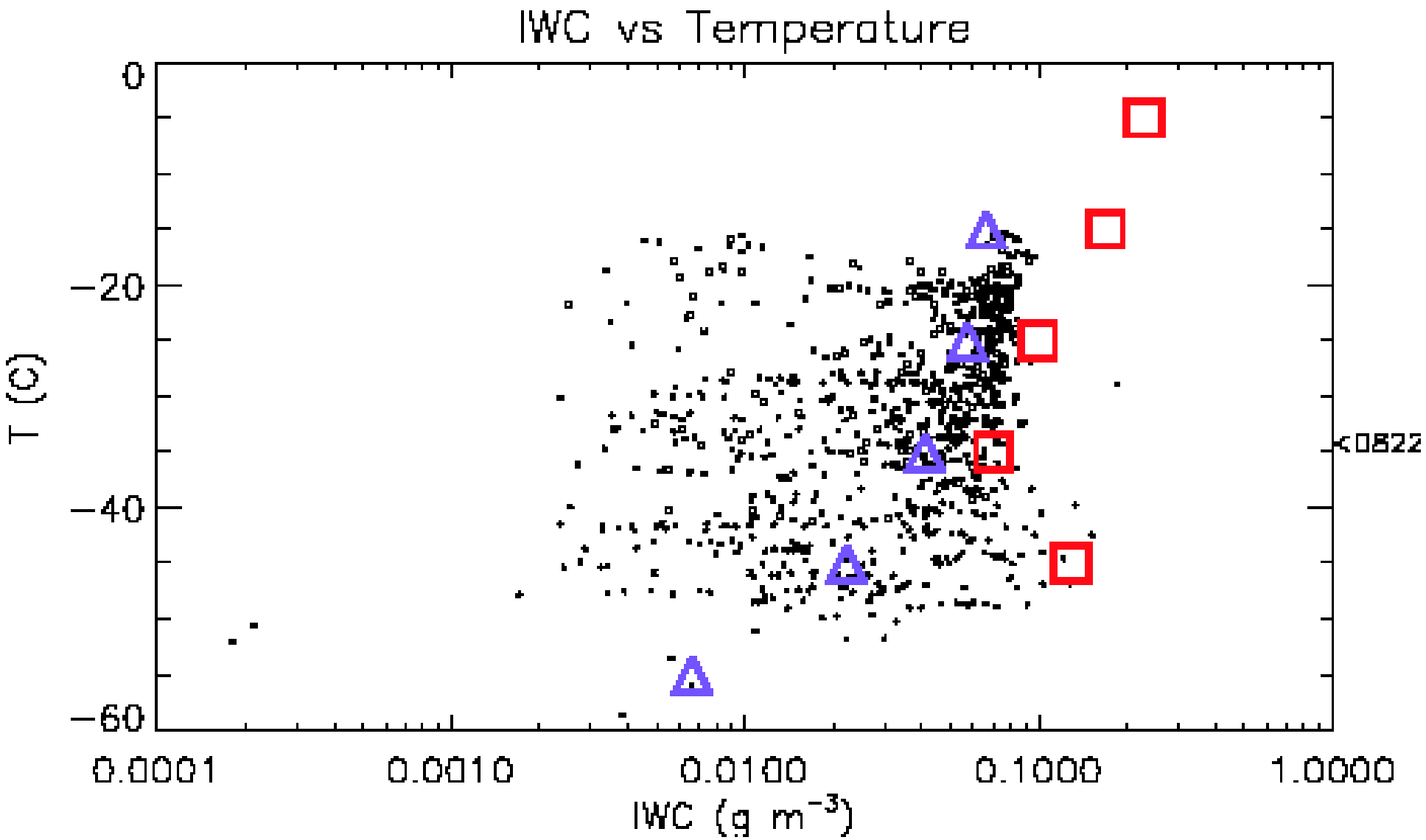

IWC vs Temperature
0
−10
−20
−30
−40
−50
−60
T (C)
0.0001
0.0010
0.0100
0.1000
1.0000
IWC (g m^{-3})
<0822

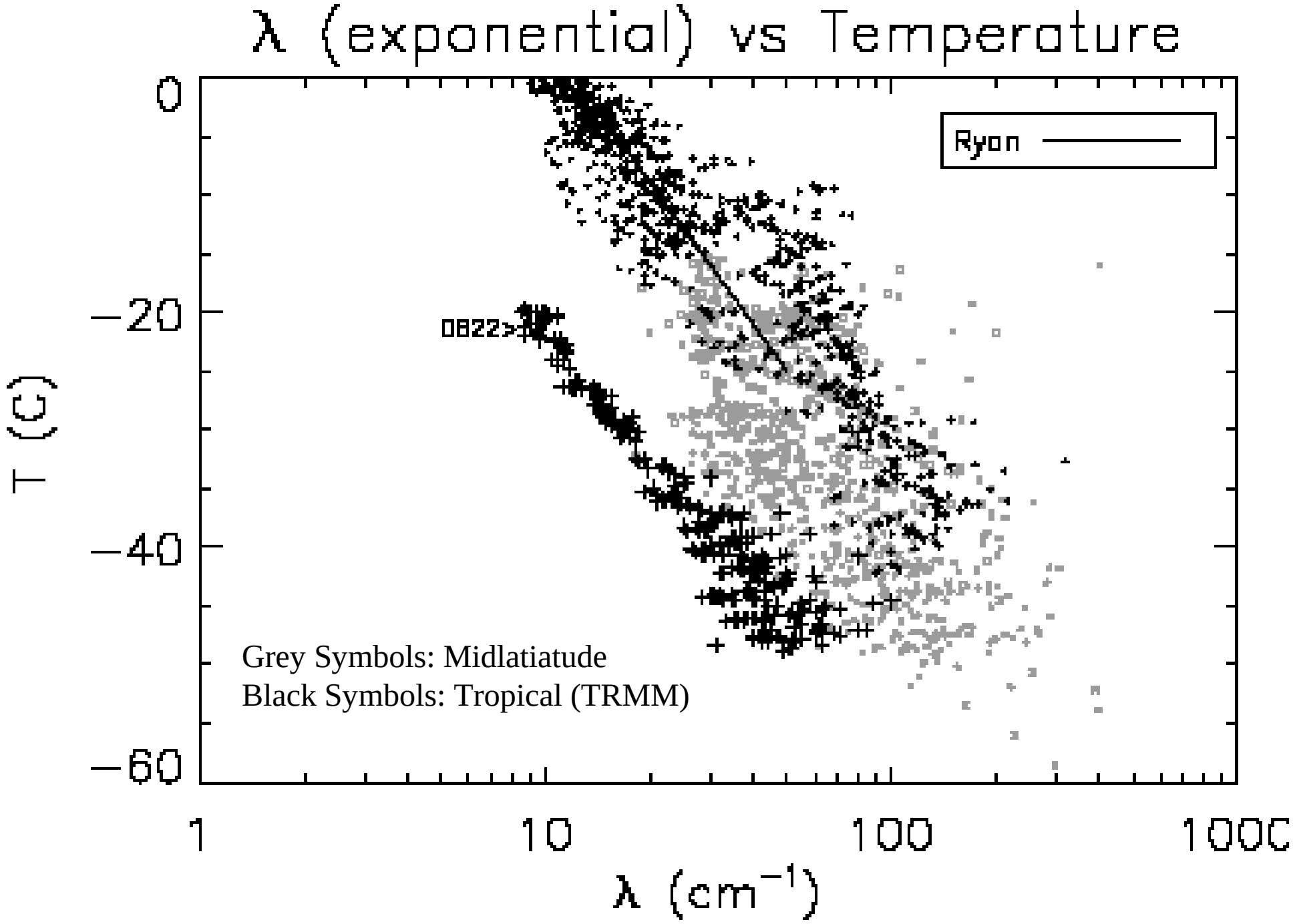
COMPARISON TO MIDLATITUDE OBSERVATIONS


FIRE2
EUCREX
FIRE1
JECK
SUCCESS
FIRE2 UND
CEPEX
−60
−50
−40
−30
−20
Temperature [°C]
0.1
1.0
10.0
100.0
$N_{>100}$ [l^{-1}]


−70
to
−60
to
−50
to
−40
to
−30
to
−20
Temperature [°C]
0.0001
0.0010
0.0100
0.1000
1.0000
IWC [g m^{-3}]
FIRE2
RUSSIA
EUCREX
FIRE1
KWAJALEIN
JECK
CCOPE
SUCCESS
FIRE2 UND
CEPEX

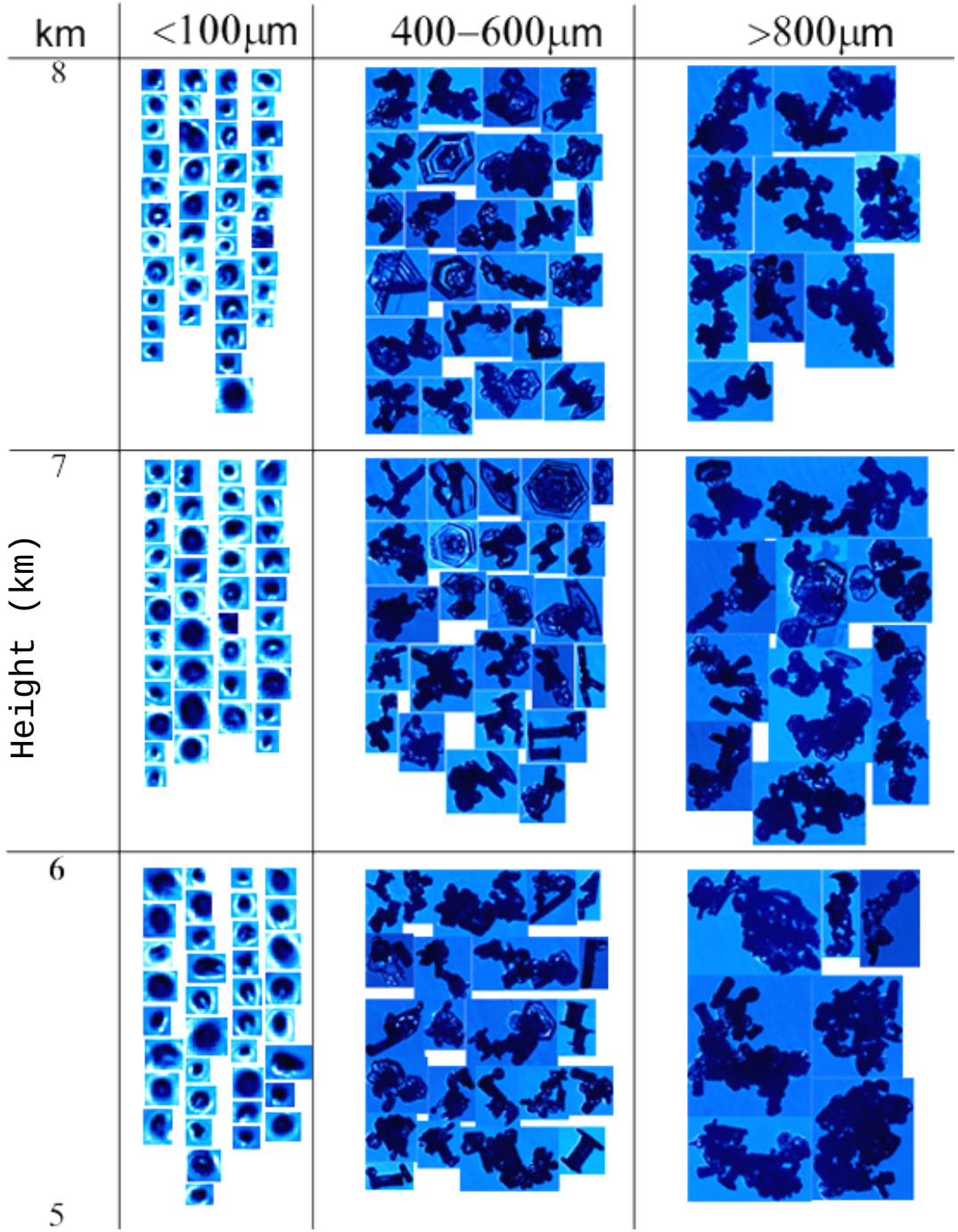

−70
to
−60
to
−50
to
−40
to
−30
to
−20
Temperature [°C]
0
1000
2000
3000
4000
D_{max} [μm]
FIRE2
EUCREX
FIRE1
KWAJALEIN
JECK
CCOPE
SUCCESS
FIRE2 UND
CEPEX

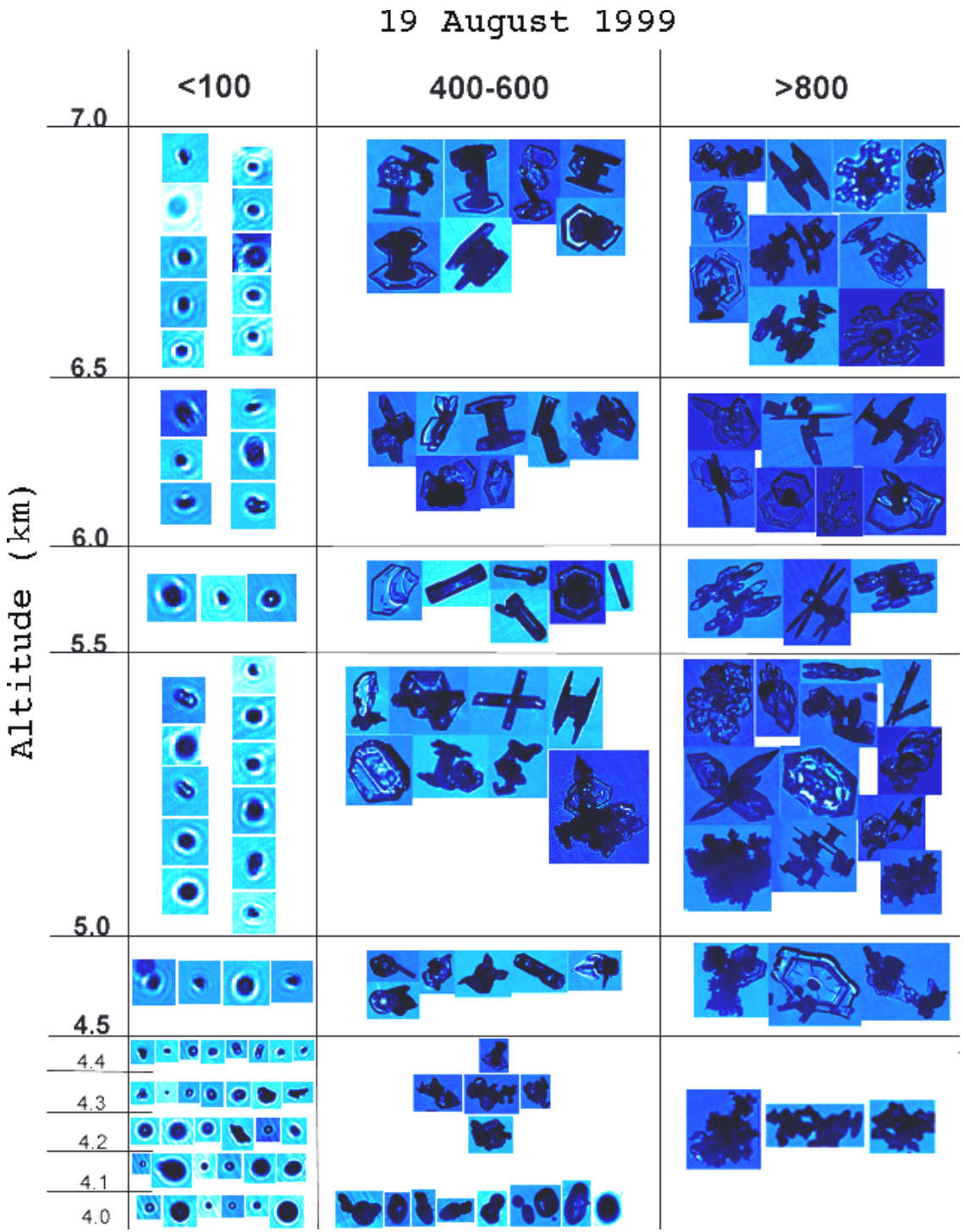

IWC vs Temperature
0
−20
−40
−60
T (C)
0.0001
0.0010
0.0100
0.1000
1.0000
IWC (g m^{-3})
<0822

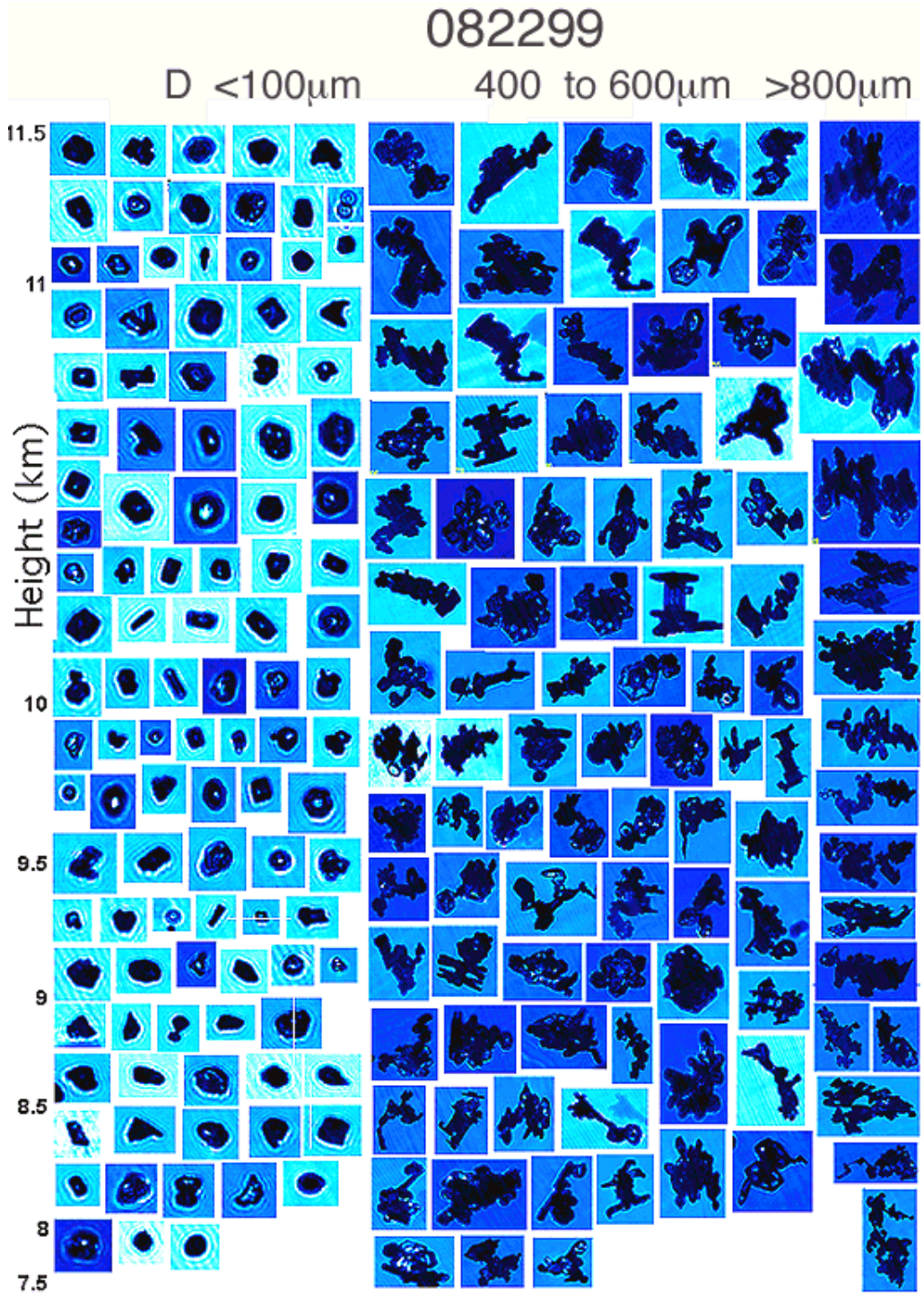

λ (exponential) vs Temperature
0
−20
−40
−60
T (C)
1
10
100
1000
λ (cm⁻¹)
Ryan
0822>
Grey Symbols: Midlatiatude
Black Symbols: Tropical (TRMM)

Particle Habits

090598




19 August 1999
<100
400-600
>800
Altitude (km)
7.0
6.5
6.0
5.5
5.0
4.5
4.4
4.3
4.2
4.1
4.0

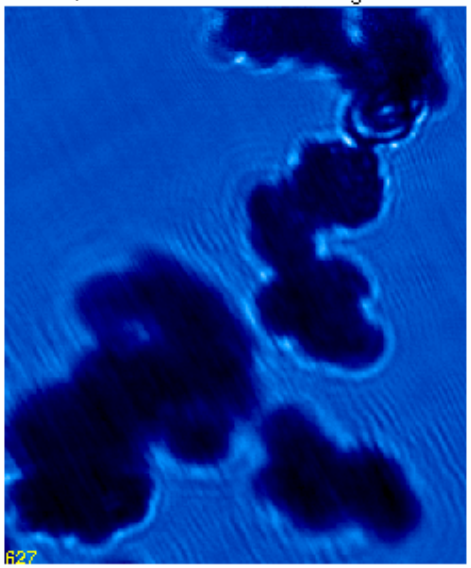

082299
D <100μm
400 to 600μm
>800μm
Height (km)
11.5
11
10
9.5
9
8.5
8
7.5

Airborne Field Mill Project
Florida, 2000, 2001

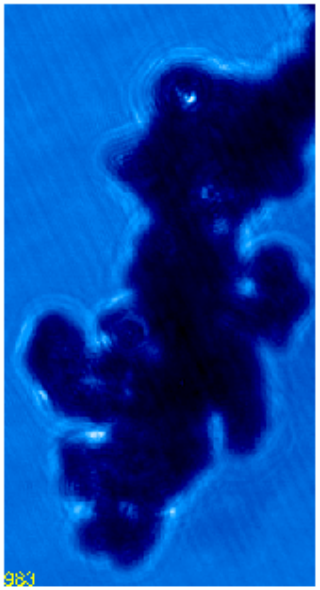
Dye, Willis

6/13/2000 Max Size, <------->200microns len gt 400 AND focus gt 40

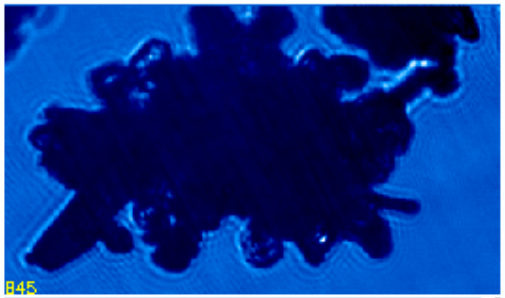
22:48: 2:634



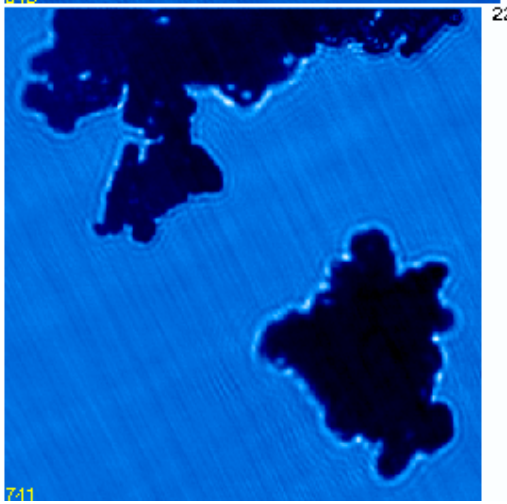
22:48:10:952



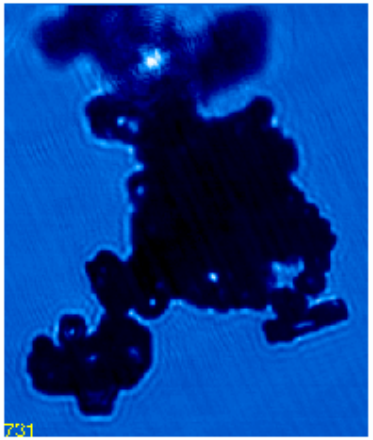
22:48:32:832

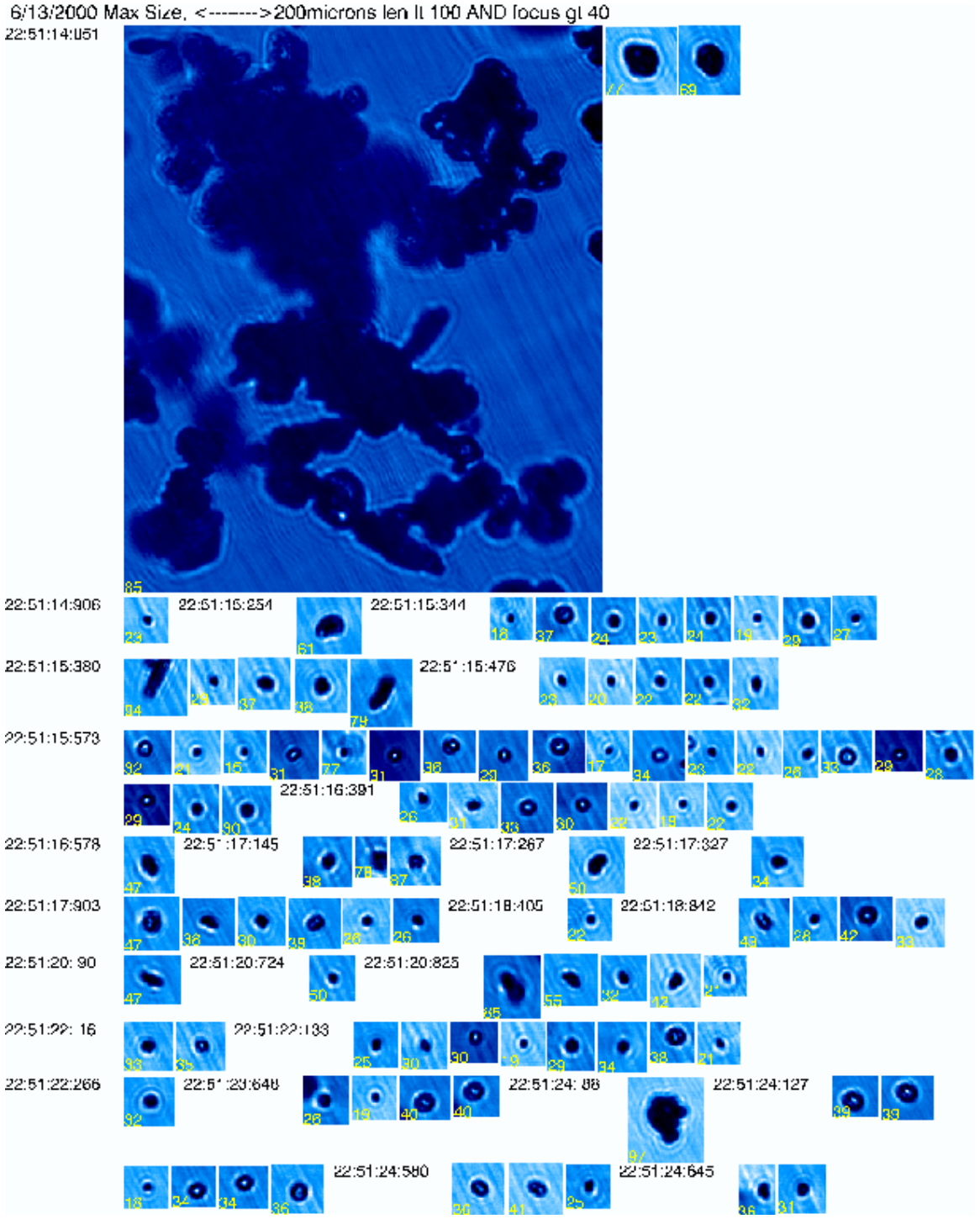


22:48:39: 77



22:48:52:823




6/13/2000 Max Size, <-------->200microns len lt 100 AND focus gt 40
22:51:14:051
22:51:14:906
22:51:15:254
22:51:15:344
22:51:15:380
22:51:15:476
22:51:15:573
22:51:16:391
22:51:16:578
22:51:17:145
22:51:17:267
22:51:17:327
22:51:17:903
22:51:18:405
22:51:18:842
22:51:20: 90
22:51:20:724
22:51:20:825
22:51:22: 16
22:51:22:133
22:51:22:266
22:51:23:648
22:51:24: 88
22:51:24:127
22:51:24:580
22:51:24:645

Summary and Conclusions

- Tropical cirrus properties exhibit considerable variability
- Optical depths and albedos vary widely
- Small particles have the largest influence on microphysical properties at low ice water contents--information lacking in the proximity of updrafts---small particle conc. generally unknown
- Maximum ice crystal sizes can be as large as 1 cm at low temperatures in the proximity of convection--aggregation has a profound influence on the particle size distributions
- The PSDs above several hundred microns were generally well-represented by exponential or gamma distribution fits, and vary in a systematic way.
- The slope parameter was generally a function of temperature and conform to earlier midlatitude observations---knowledge of the form of the PSD in small sizes largely unknown

Summary and Conclusions (continued)

- Ice water contents generally a function of temperature--direct measurements of IWC have not been made and are needed
- Water budget of tropical systems---transport of condensate into the upper troposphere--are needed
- Habits often not the pristine idealized shapes modeled previously