Snowfall measurements in the Arctic using lidar and radar data

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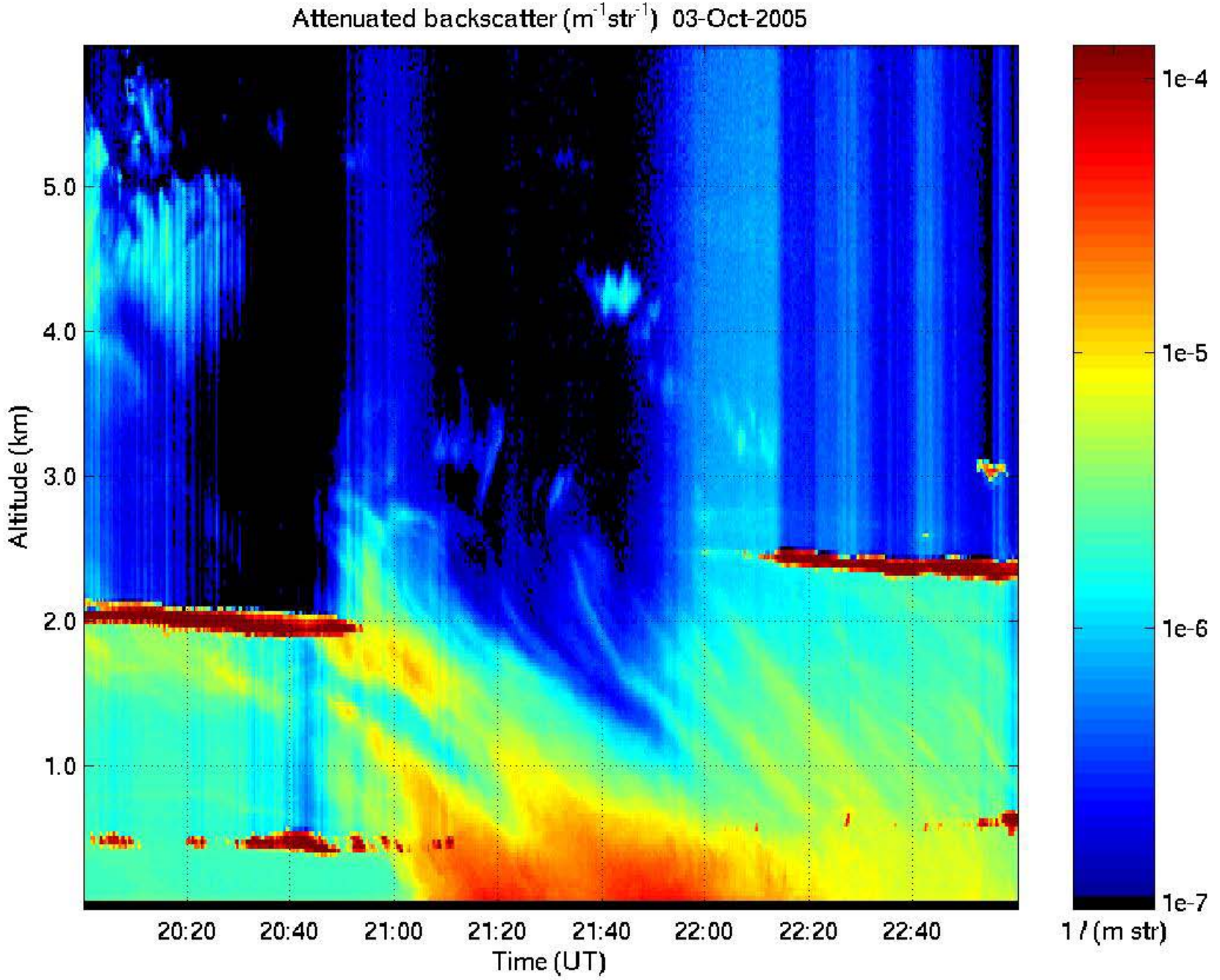
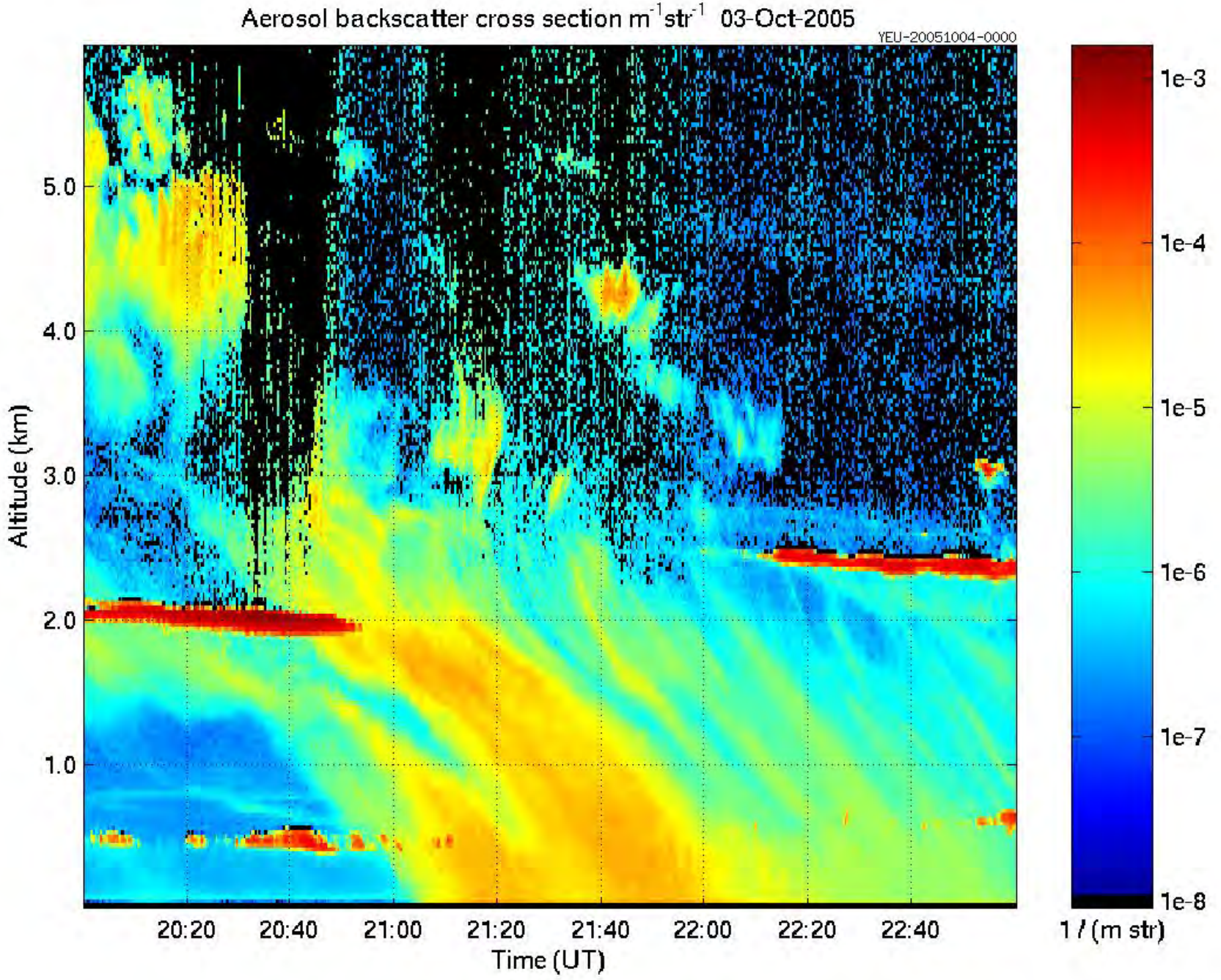
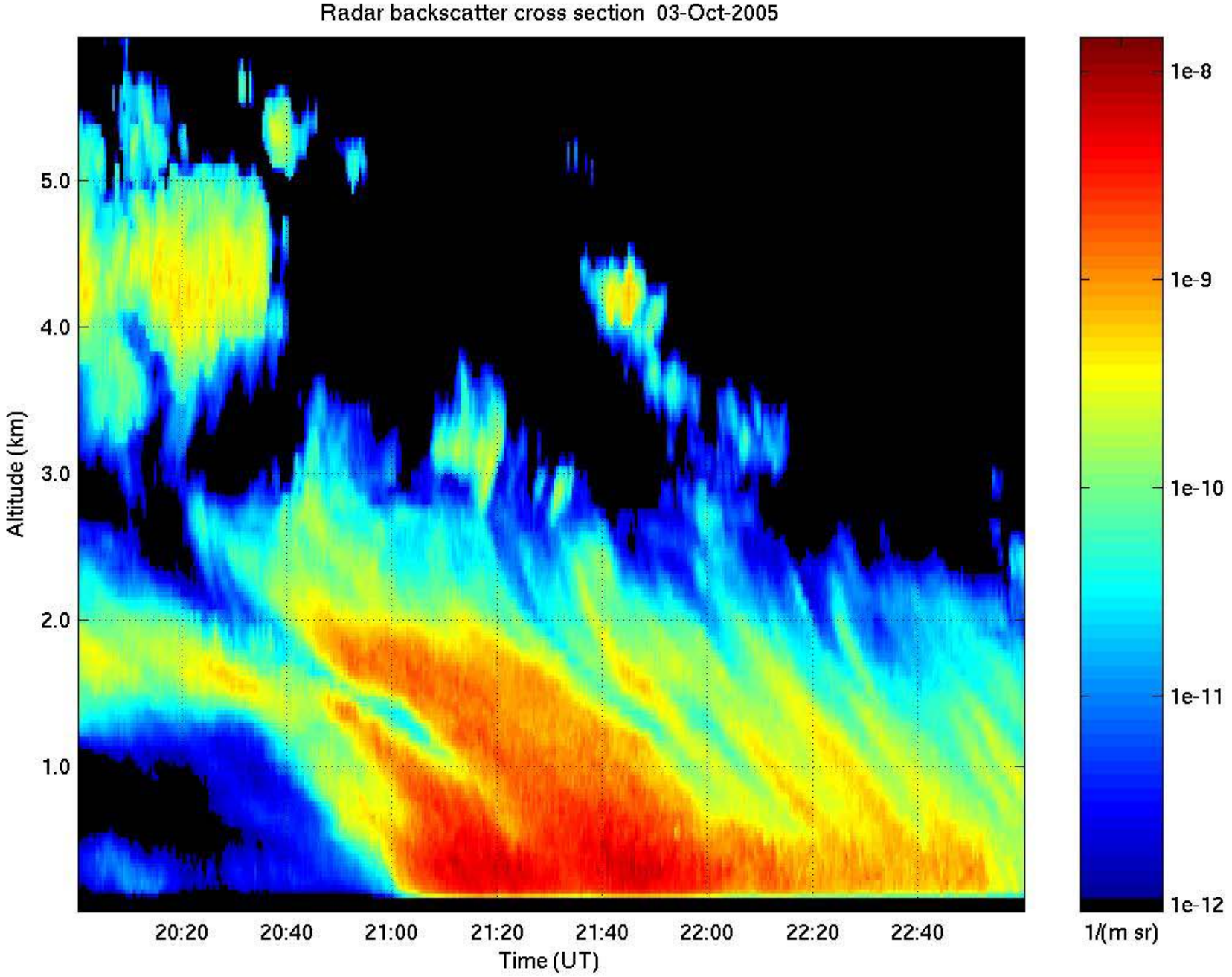

Attenuated backscatter ($m^{-1}str^{-1}$) 03-Oct-2005
Altitude (km)
5.0
4.0
3.0
2.0
1.0
20:20
20:40
21:00
21:20
21:40
22:00
22:20
22:40
Time (UT)
1e-4
1e-5
1e-6
1e-7
1 / (m str)


Aerosol backscatter cross section m-1str-1 03-Oct-2005
YEU-20051004-0000
Altitude (km)
5.0
4.0
3.0
2.0
1.0
20:20
20:40
21:00
21:20
21:40
22:00
22:20
22:40
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)


Radar backscatter cross section 03-Oct-2005
Altitude (km)
5.0
4.0
3.0
2.0
1.0
20:20
20:40
21:00
21:20
21:40
22:00
22:20
22:40
Time (UT)
1e-8
1e-9
1e-10
1e-11
1e-12
1/(m sr)

Lidar-Radar Measurement of Effective Diameter

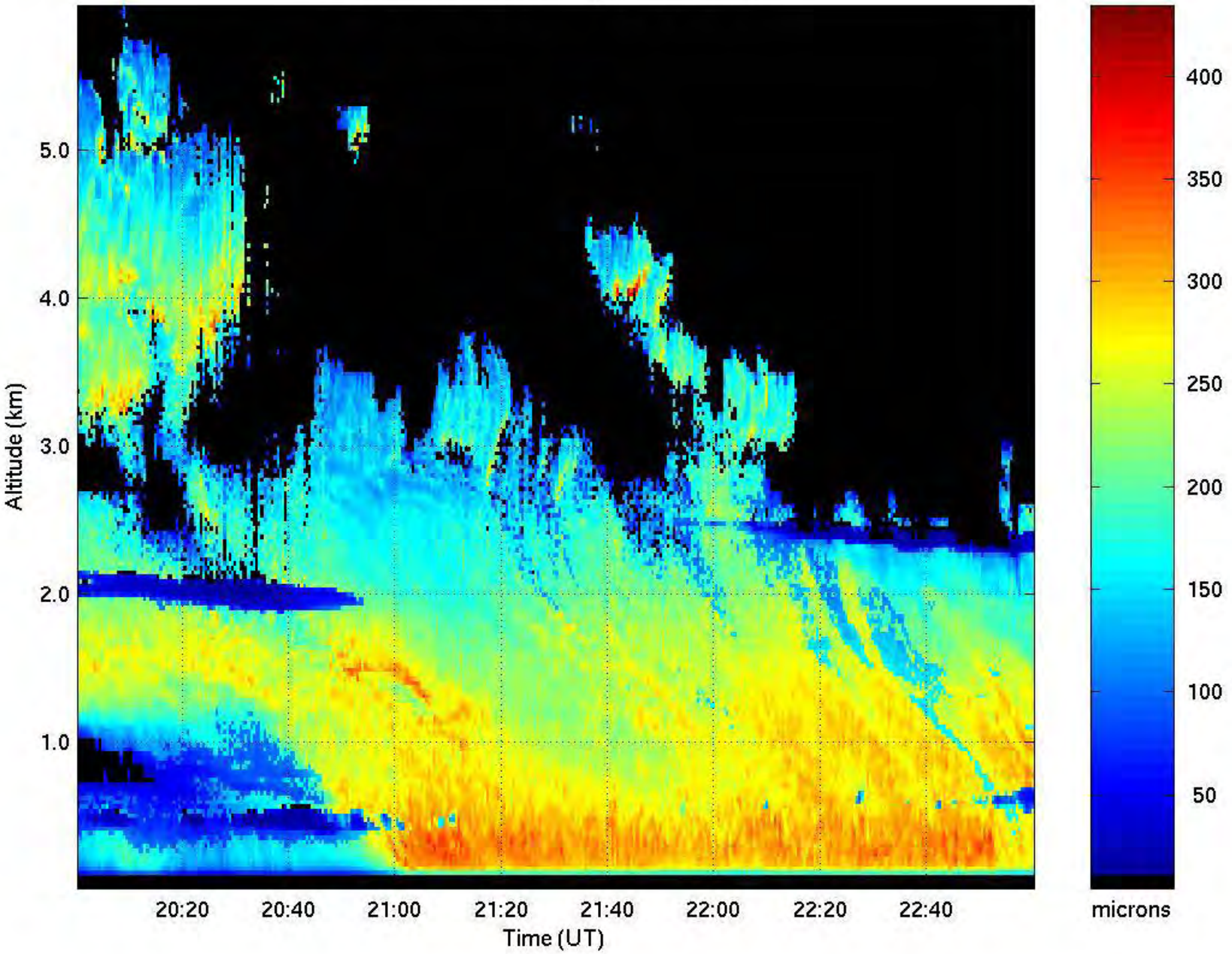
Radar scattering cross section ~ $\langle \text{Mass}^2 \rangle \sim \rho \langle \text{Volume}^2 \rangle \sim D^6$

Lidar scattering cross section ~ $\langle \text{Area} \rangle \sim D^2$

$$D_{eff\_prime} \sim \sqrt[4]{\left(\frac{\langle \text{Radar scattering cross section} \rangle}{\langle \text{Lidar scattering cross section} \rangle} \right)}$$

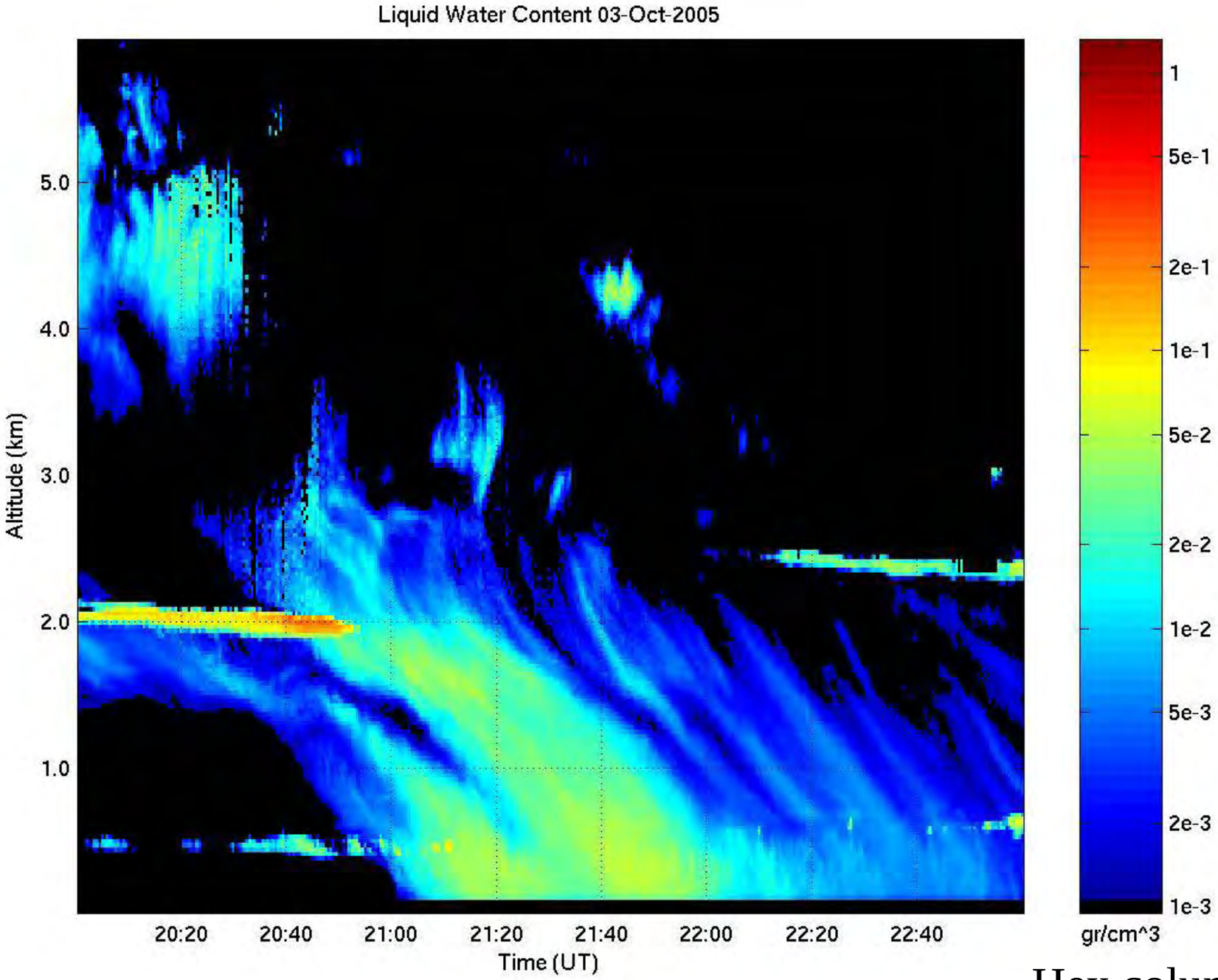
Notice that this differs for the usual definition:

$$D_{eff} = \frac{\langle \text{Particle volume} \rangle}{\langle \text{Particle area} \rangle}$$


Particle effective diameter prime 03-Oct-2005
Altitude (km)
5.0
4.0
3.0
2.0
1.0
20:20
20:40
21:00
21:20
21:40
22:00
22:20
22:40
Time (UT)
400
350
300
250
200
150
100
50
microns

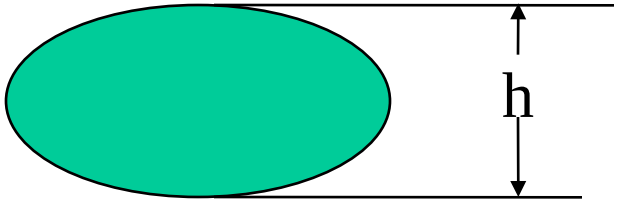
Problem:
Ice crystals are not spherical

Photos by Kenneth Libbrecht


Liquid Water Content 03-Oct-2005
Altitude (km)
5.0
4.0
3.0
2.0
1.0
20:20
20:40
21:00
21:20
21:40
22:00
22:20
22:40
Time (UT)
1
5e-1
2e-1
1e-1
5e-2
2e-2
1e-2
5e-3
2e-3
1e-3
gr/cm^3

Hex columns

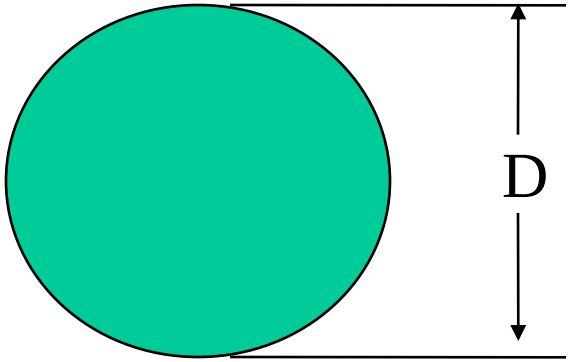
Spheroid model to represent measureable properties of a snowflake



Side view

$h = a D^{\zeta}$ (Auer and Veal)

mass = $\pi/6\ D^2 h$



Top view

projected area = $\pi/4\ D^2$

We assume a modified Gamma distribution

$N(D) \sim D^{\alpha} \exp(-bD^{\gamma})$

Radar backscatter ~ particle concentration <mass^2>

Lidar extinction ~ particle concentration <projected area>

Fall Velocity ~ F(mass, projected area)

The size distribution and the spheroid model are used to compute the observable quanities:

Integrating over the size distribution N(D) to derive D'_{eff}

$$D'_{eff} = \sqrt[4]{\frac{9\langle V^2\rangle}{\pi\langle A\rangle}} = \sqrt[4]{\frac{\int a^2 D^4 D^{2\zeta} N(D)dD}{\int D^2 N(D)dD}} = \sqrt[4]{\frac{2\lambda^4 \beta_{radar}}{\pi^3 k^2_{ice} \beta_s}}$$

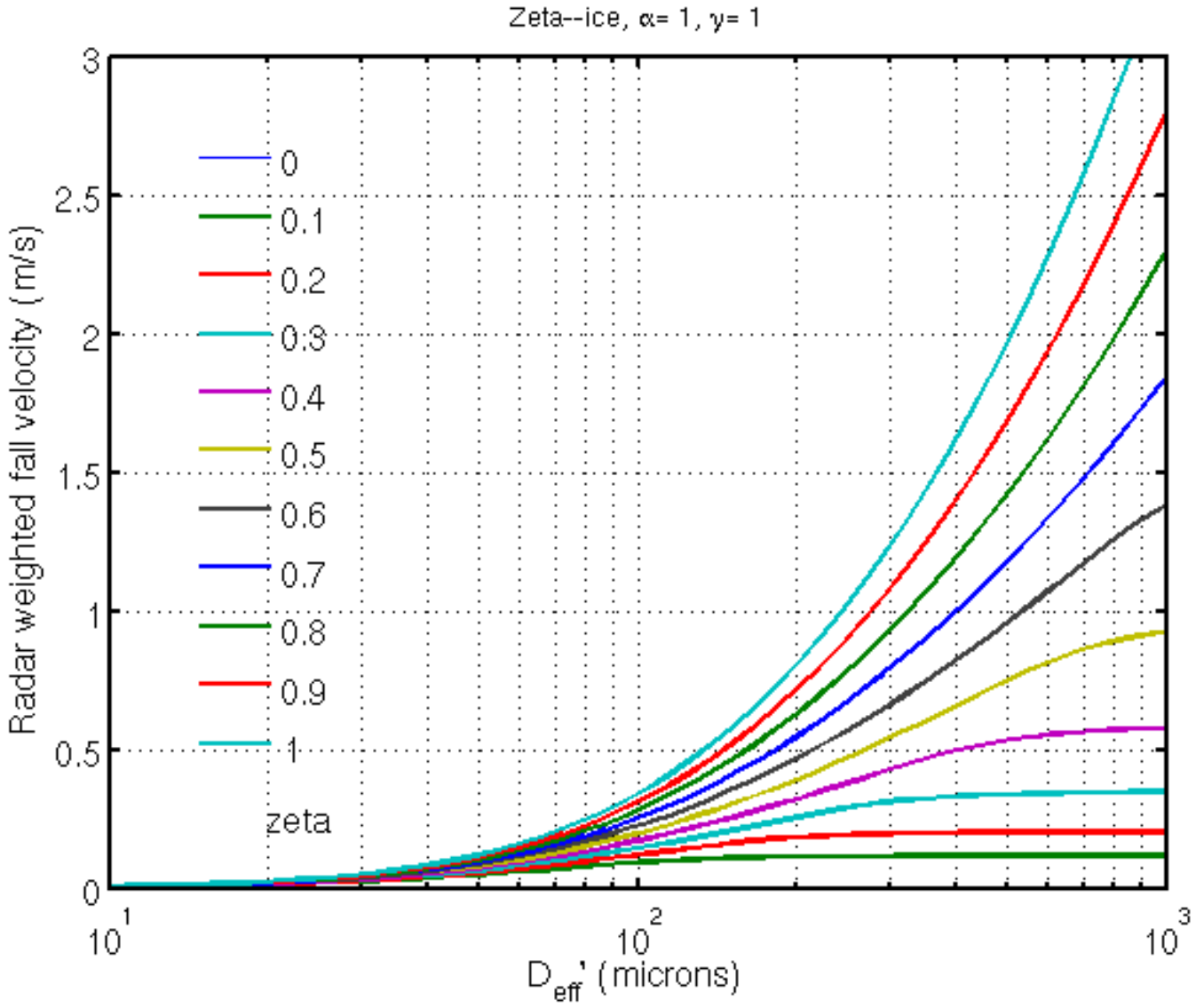
Radar reflectivity weighted fall velocity:

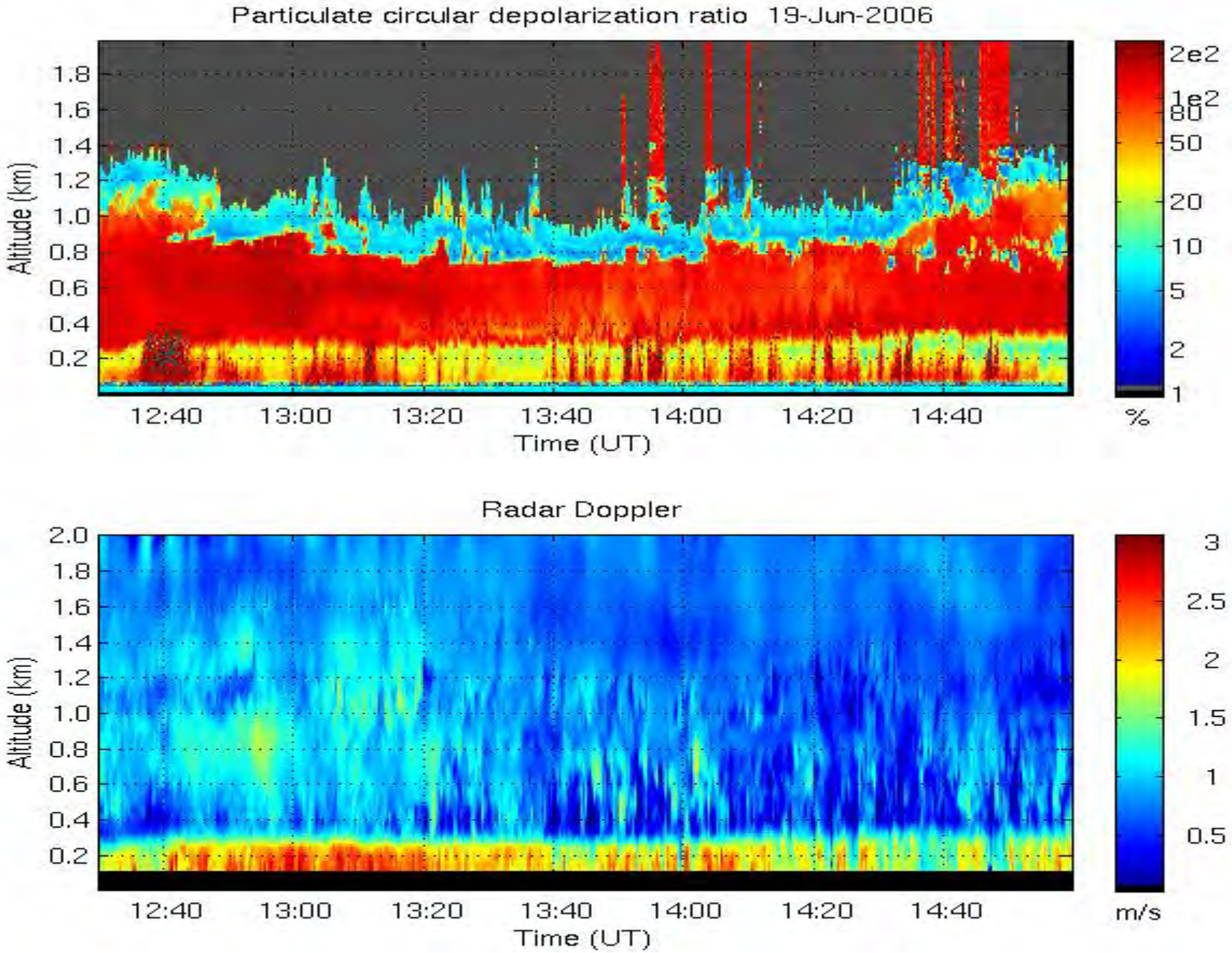
$$\langle V_f\rangle = \frac{\int V_f \; D^4 D^{2\zeta} N(D)dD}{\int D^4 D^{2\zeta} N(D)dD}$$

Fall velocity is parameterized in terms of X, the Best # :

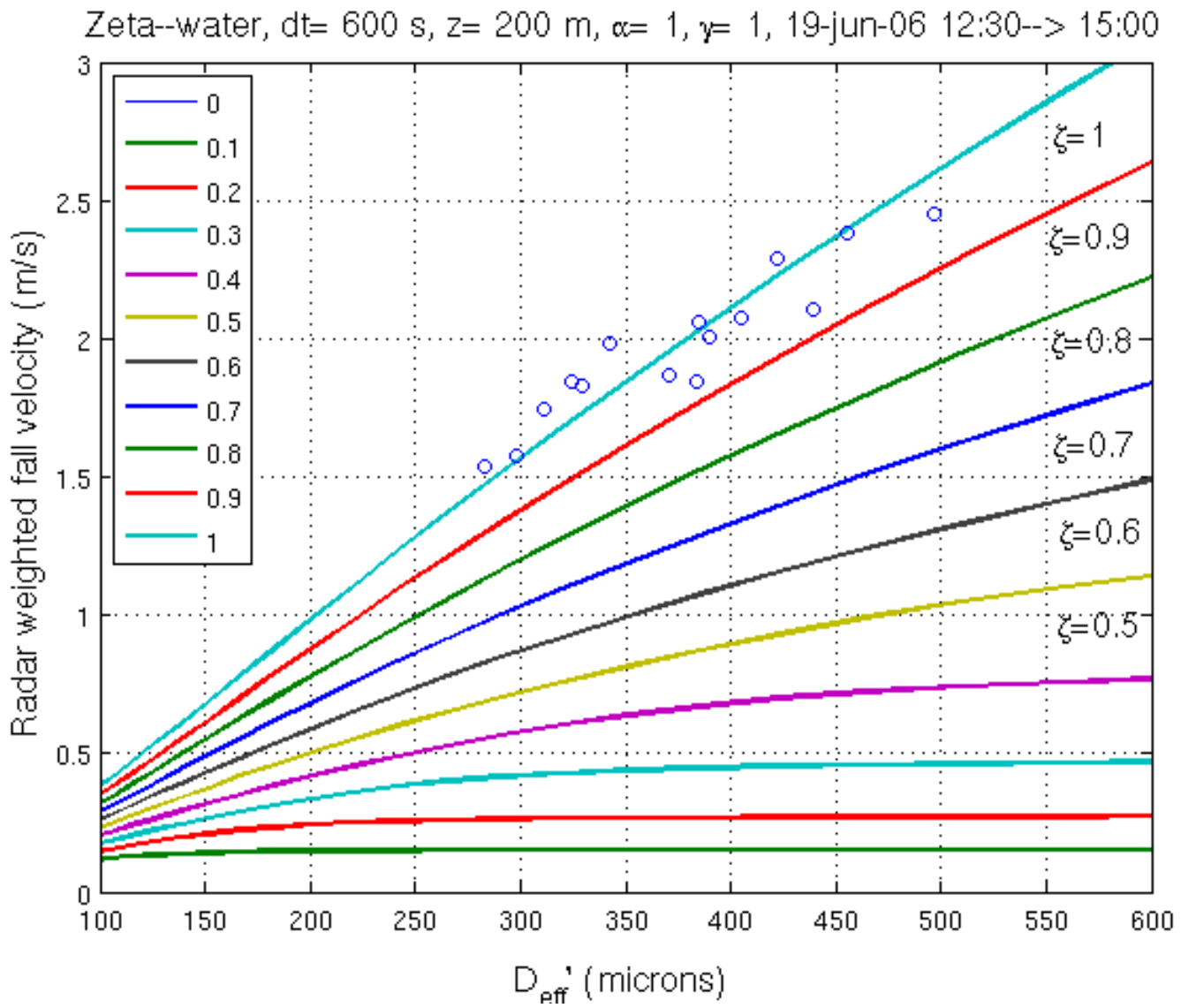
$$V_f = (\eta/(\rho_{air} D))\{(d^2_o/4)[(1+C_1 X^{1/2})^{1/2} - a_o X^{bo}\}$$

$$X = (2 \text{ mass } \rho_{air} \text{ g } D^2)/(\text{area } \eta^2)$$

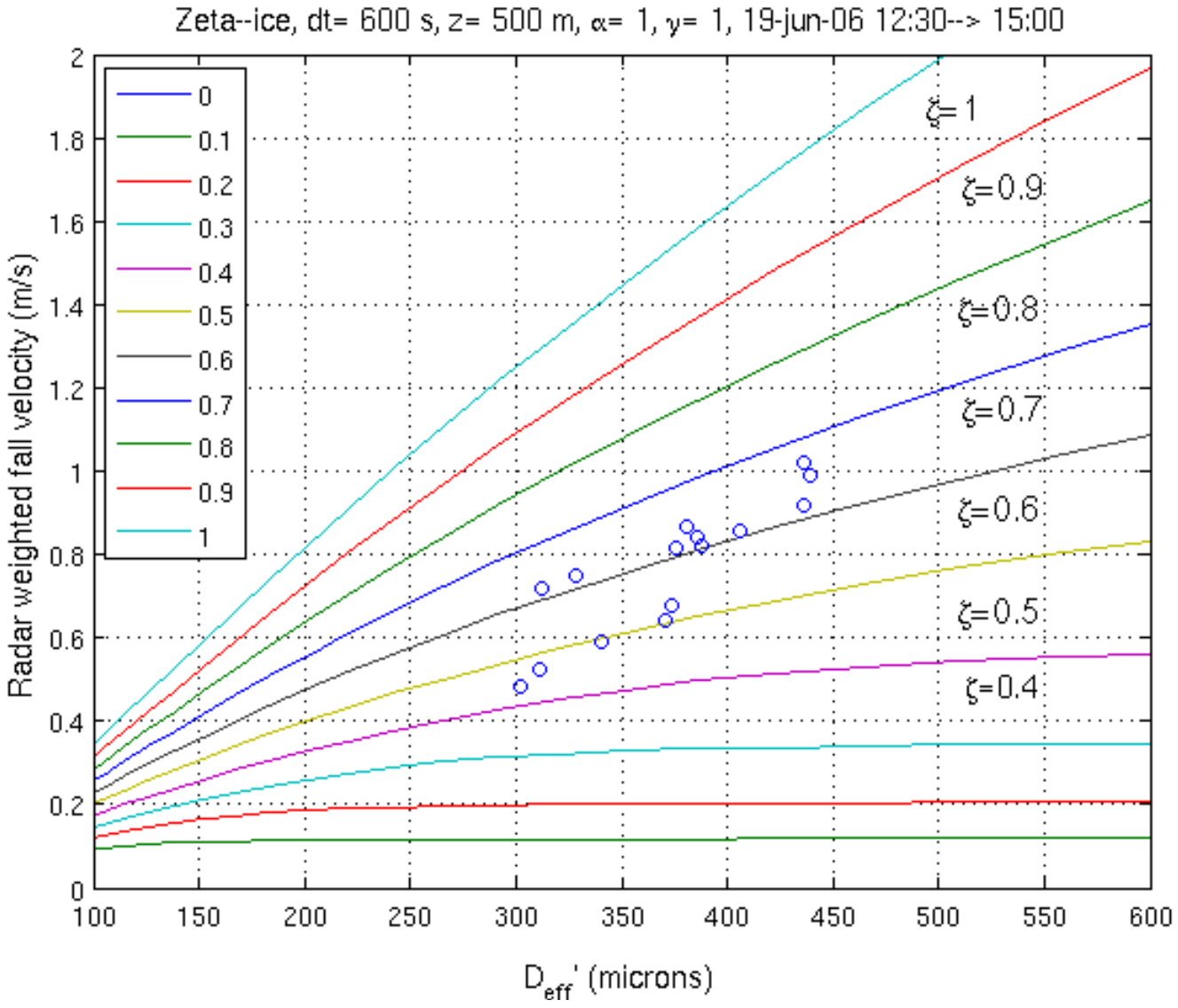

Zeta--ice, α= 1, γ= 1
Radar weighted fall velocity (m/s)
D_eff' (microns)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
zeta
0
0.5
1
1.5
2
2.5
3
10^1
10^2
10^3

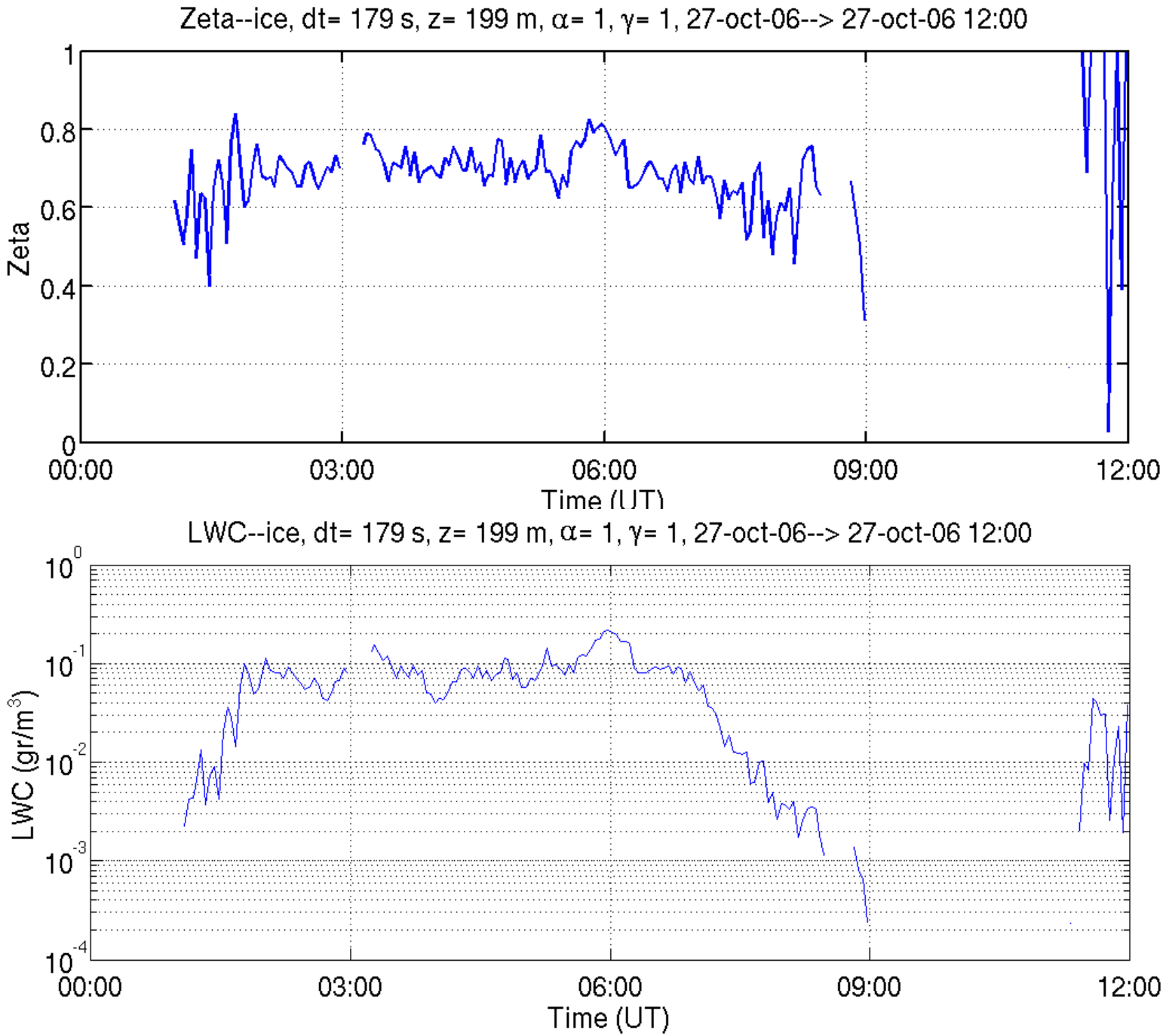

Particulate circular depolarization ratio 19-Jun-2006
Altitude (km)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
12:40
13:00
13:20
13:40
14:00
14:20
14:40
Time (UT)
2e2
1e2
80
50
20
10
5
2
1
%
Radar Doppler
Altitude (km)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
12:40
13:00
13:20
13:40
14:00
14:20
14:40
Time (UT)
3
2.5
2
1.5
1
0.5
m/s

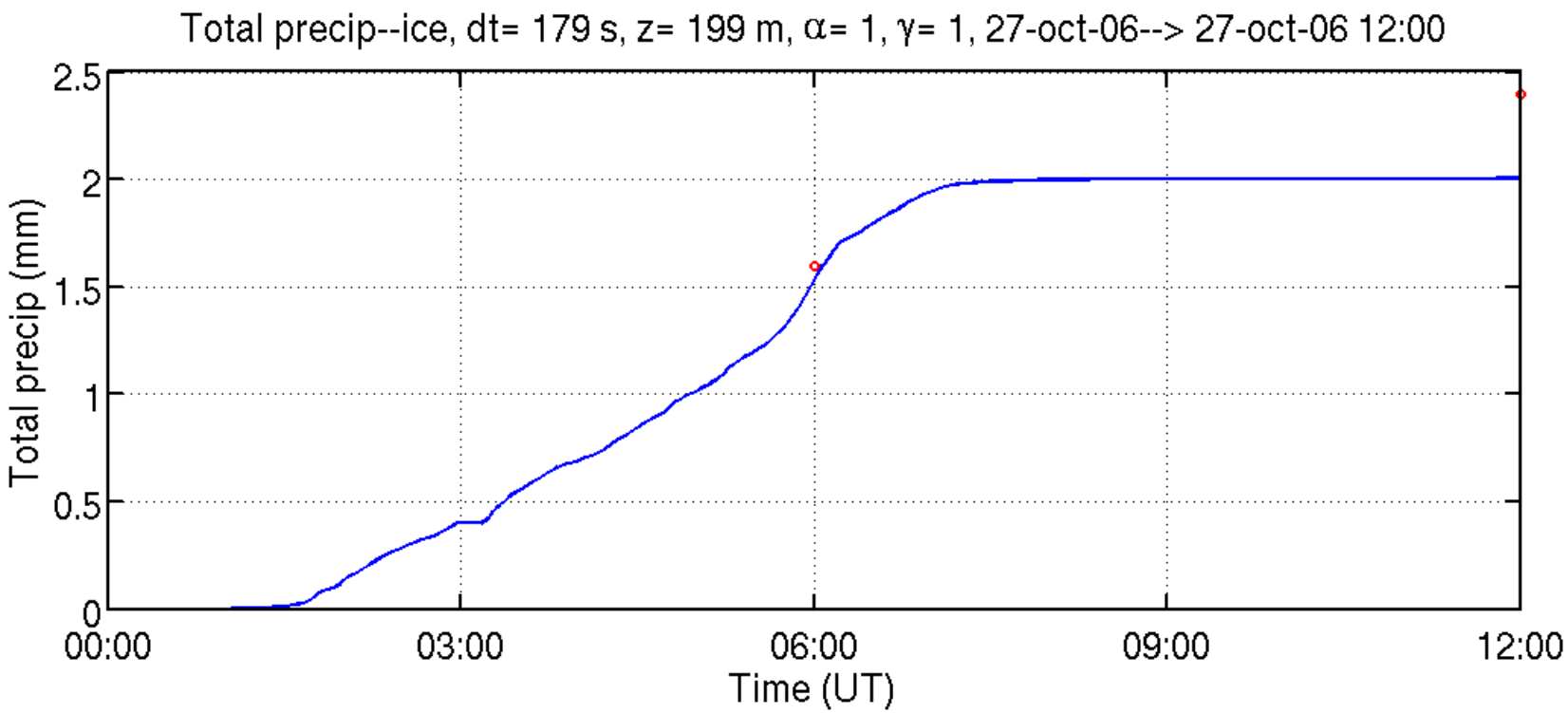
Doppler velocity vs. $D_{eff\ prime}$ below melting layer



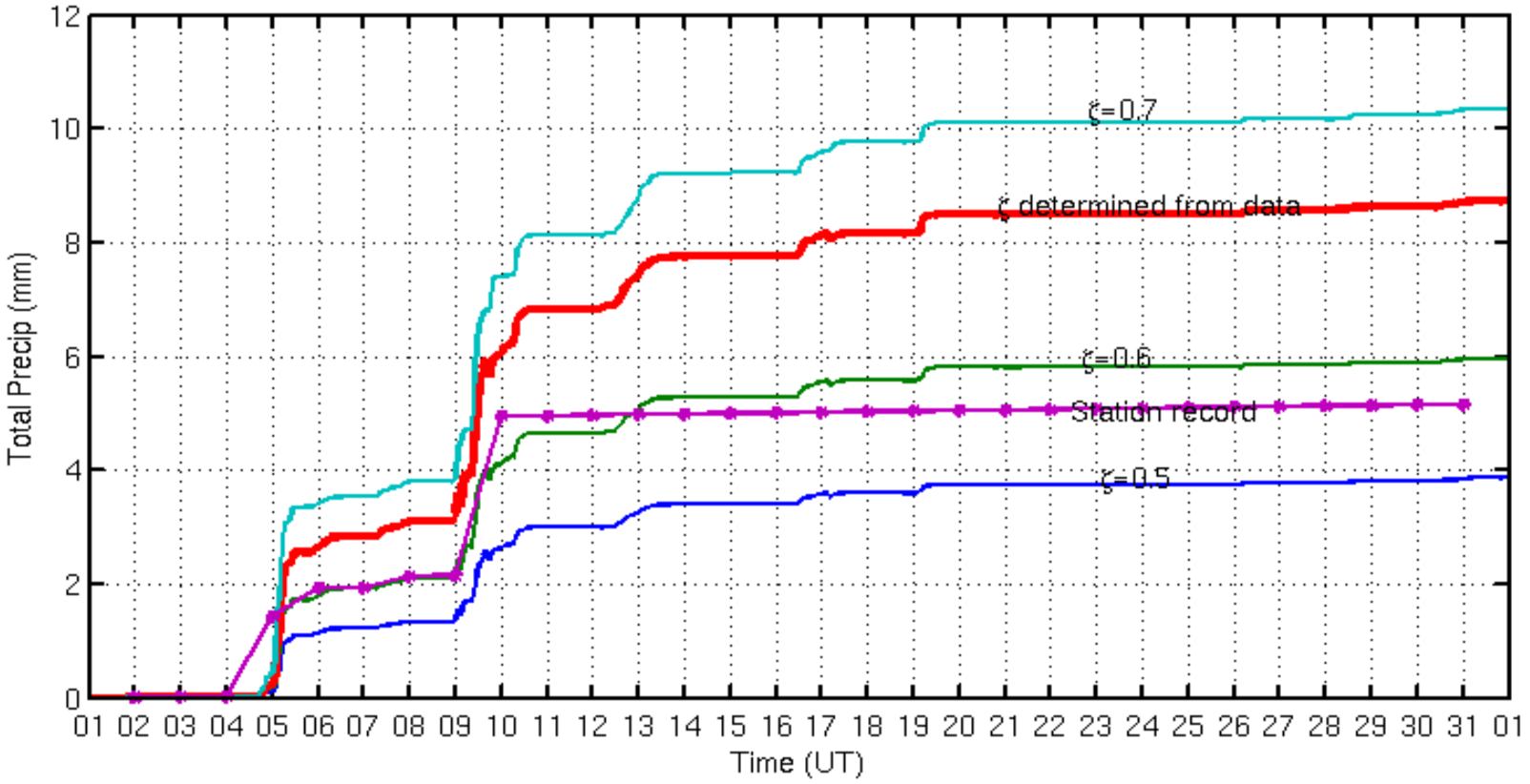
Doppler velocity vs. $D_{eff\ prime}$ in snow layer

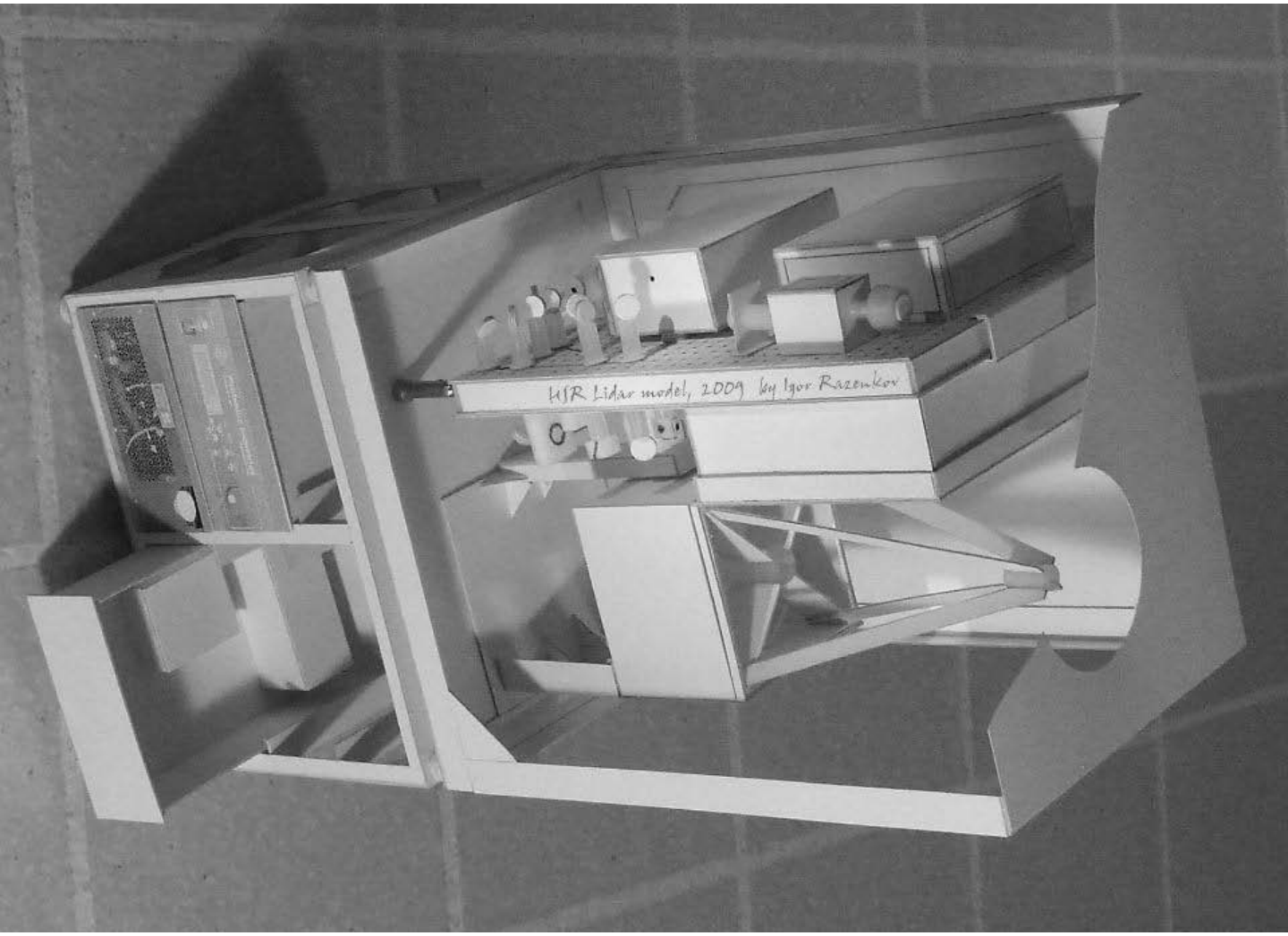


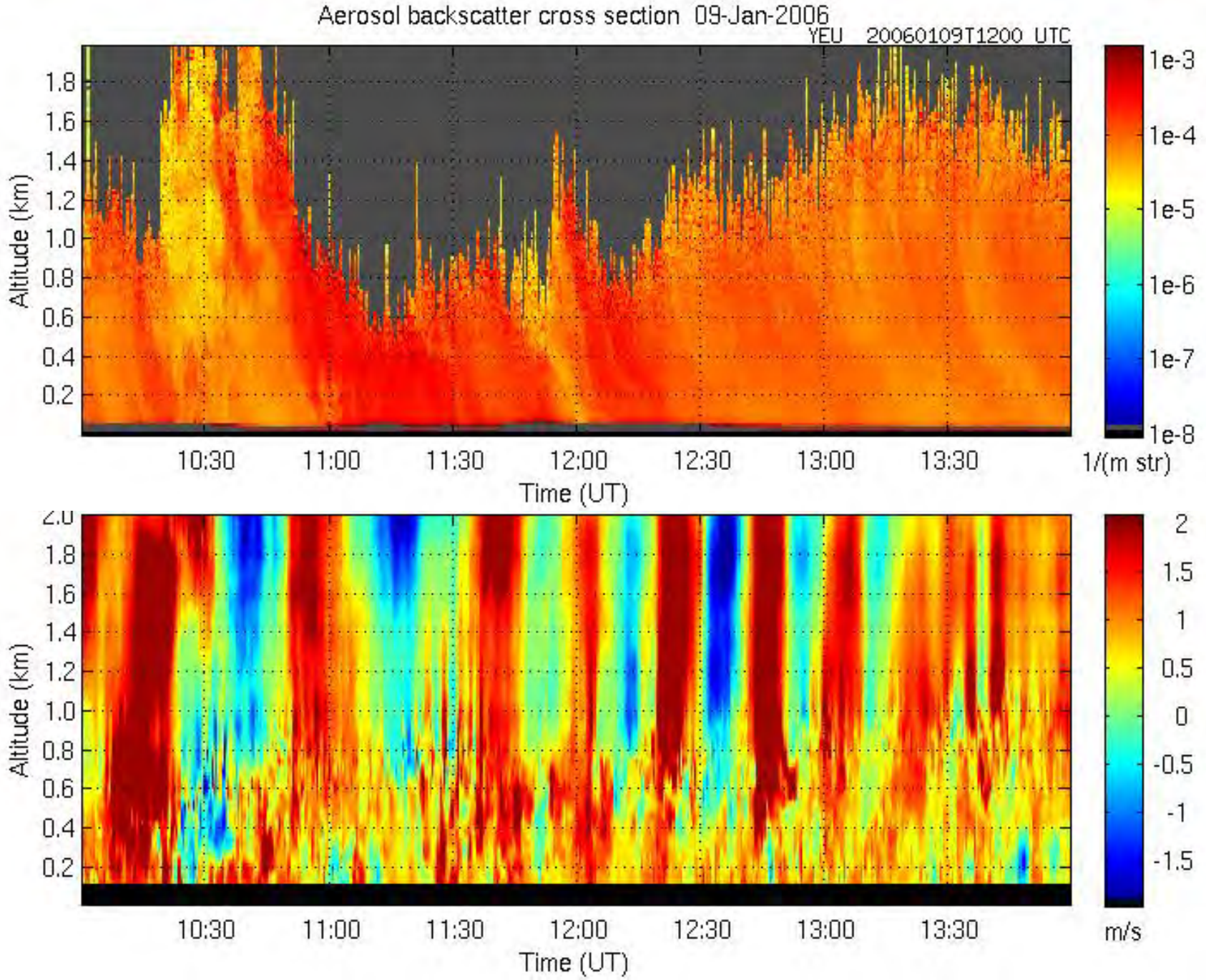

Zeta--ice, dt= 179 s, z= 199 m, α= 1, γ= 1, 27-oct-06--> 27-oct-06 12:00
Zeta
0
0.2
0.4
0.6
0.8
1
00:00
03:00
06:00
09:00
12:00
Time (UT)
LWC--ice, dt= 179 s, z= 199 m, α= 1, γ= 1, 27-oct-06--> 27-oct-06 12:00
LWC (gr/m3)
10^0
10^-1
10^-2
10^-3
10^-4
00:00
03:00
06:00
09:00
12:00
Time (UT)

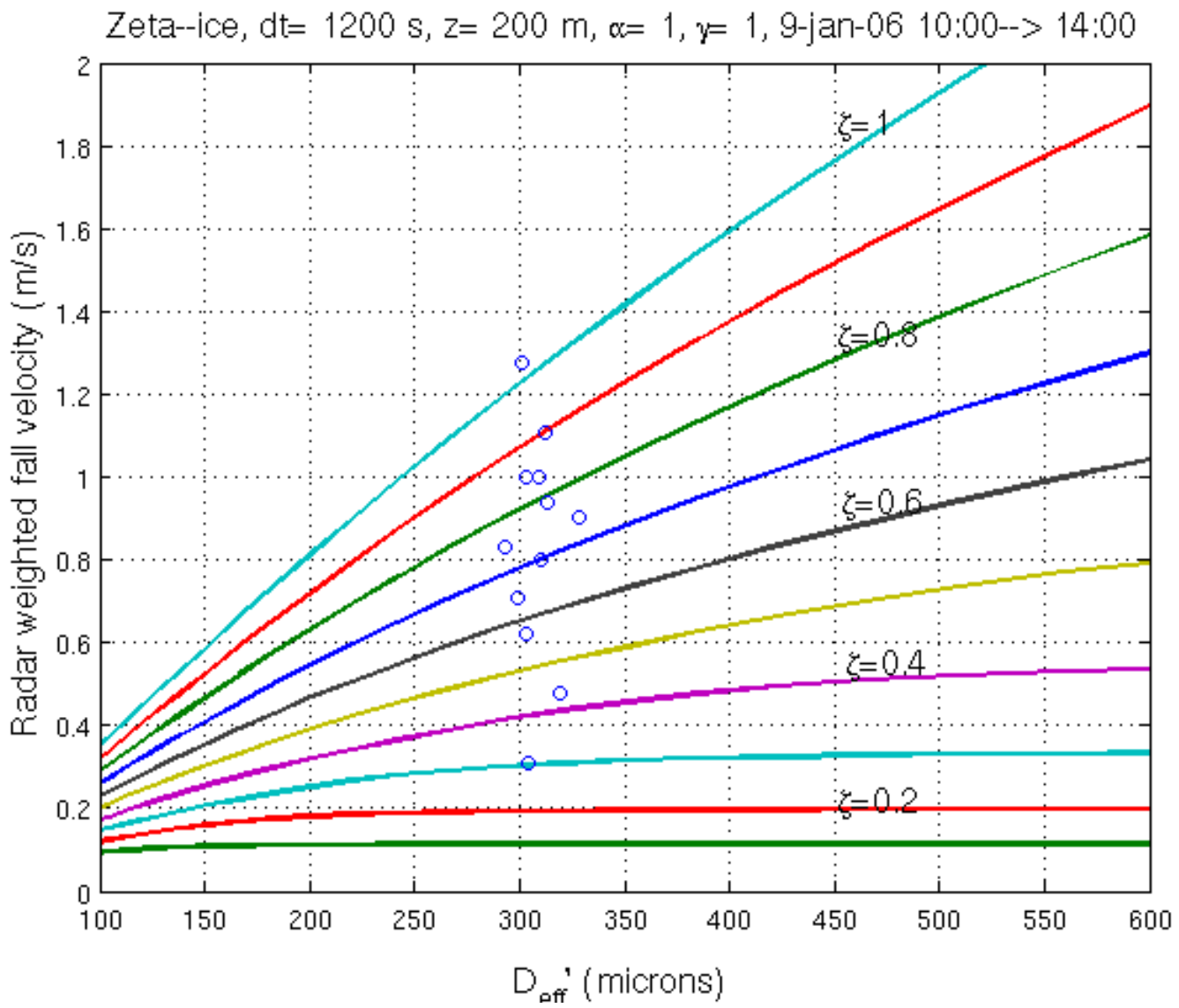

Total precip--ice, dt= 179 s, z= 199 m, α= 1, γ= 1, 27-oct-06--> 27-oct-06 12:00
Total precip (mm)
2.5
2
1.5
1
0.5
0
00:00
03:00
06:00
09:00
12:00
Time (UT)

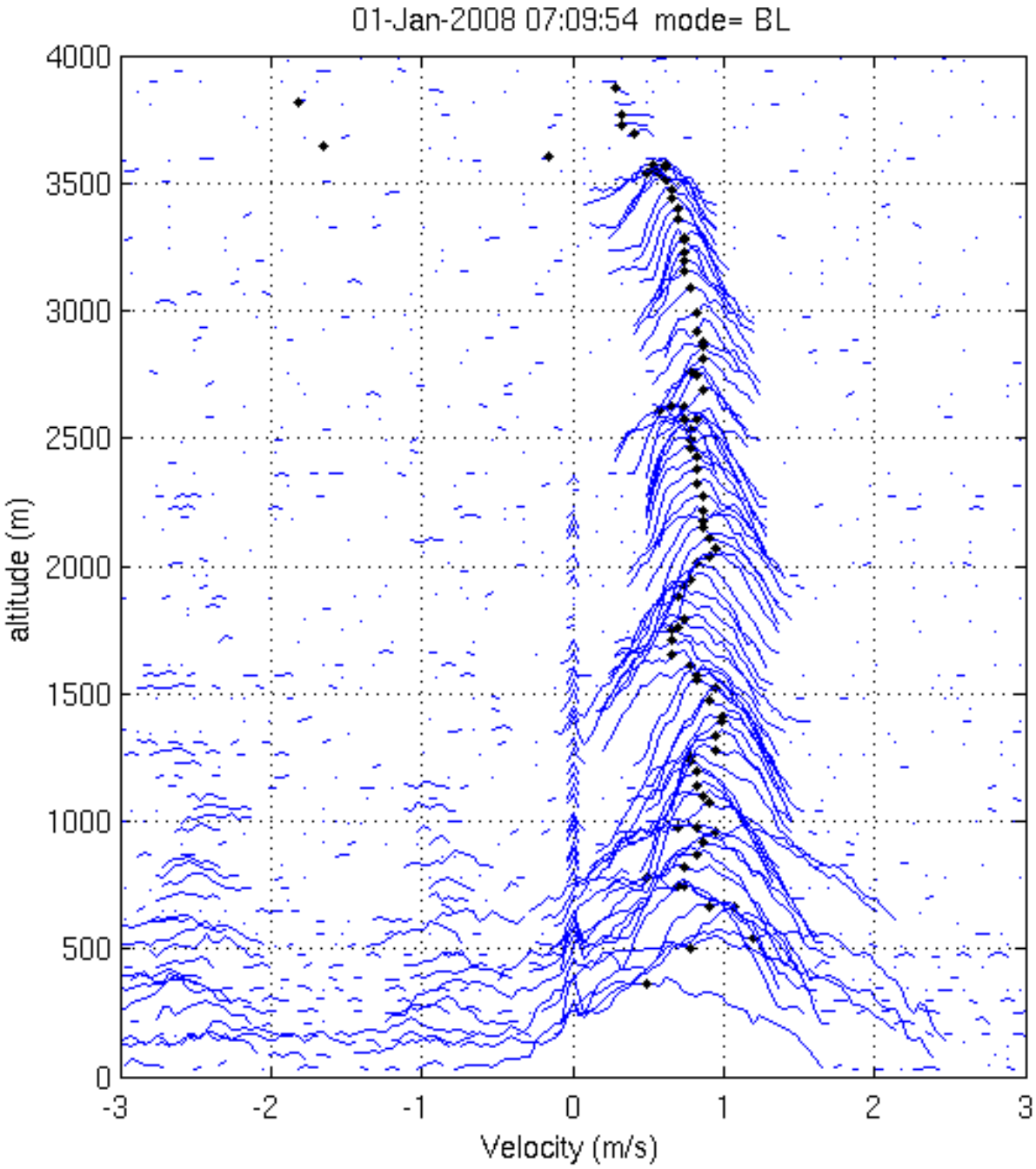
Cumulative snowfall with ζ determined from fall velocity vs D'_{eff} Jan 2007

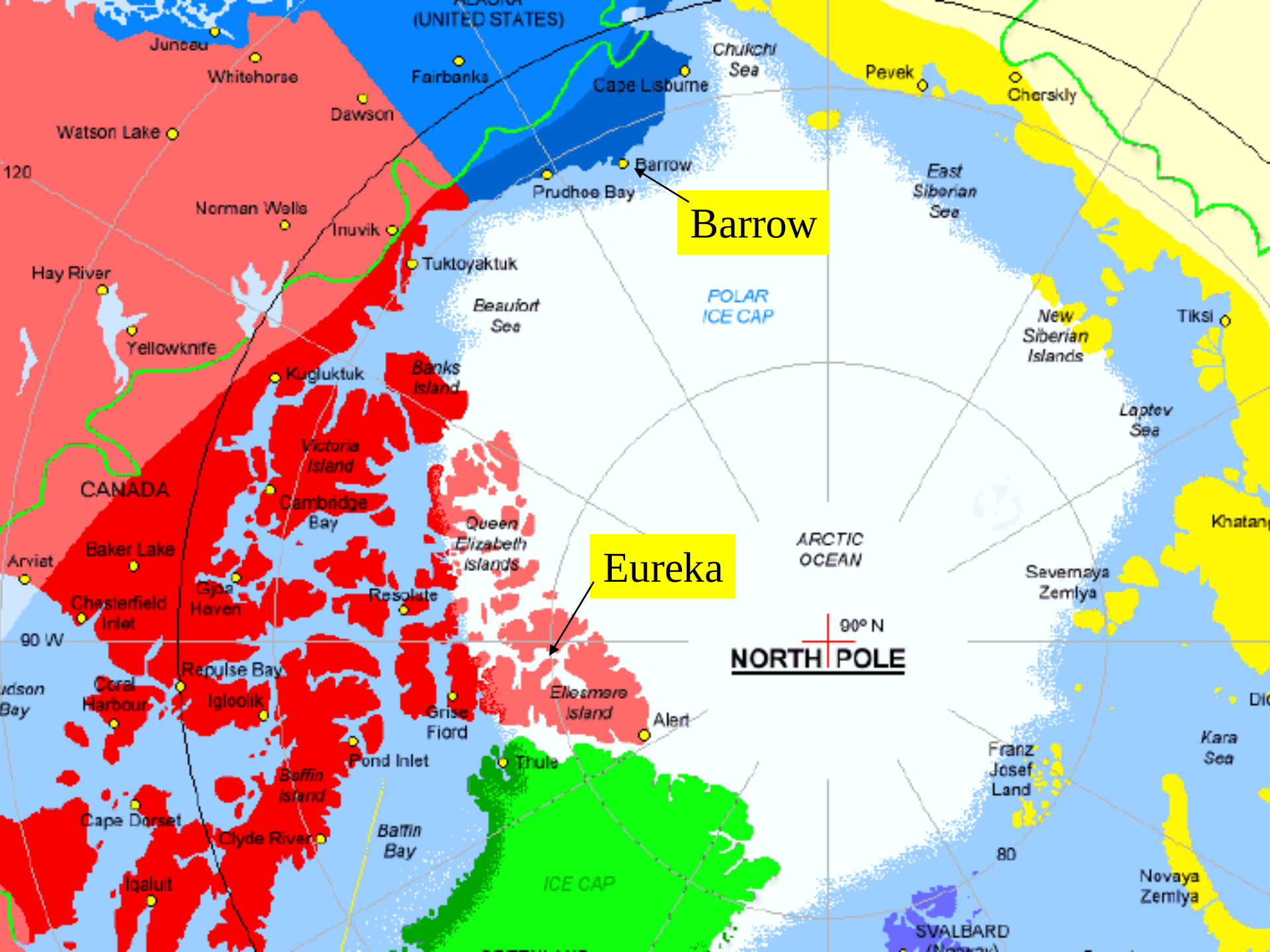



HSR Lidar model, 2009 by Igor Razenkov


Aerosol backscatter cross section 09-Jan-2006
YEU 20060109T1200 UTC
Altitude (km)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
10:30
11:00
11:30
12:00
12:30
13:00
13:30
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1/(m str)
Altitude (km)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
10:30
11:00
11:30
12:00
12:30
13:00
13:30
Time (UT)
2
1.5
1
0.5
0
-0.5
-1
-1.5
m/s


Zeta--ice, dt= 1200 s, z= 200 m, α= 1, γ= 1, 9-jan-06 10:00--> 14:00
Radar weighted fall velocity (m/s)
D_eff' (microns)
ζ=1
ζ=0.8
ζ=0.6
ζ=0.4
ζ=0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
100
150
200
250
300
350
400
450
500
550
600


01-Jan-2008 07:09:54 mode= BL
altitude (m)
4000
3500
3000
2500
2000
1500
1000
500
0
-3
-2
-1
0
1
2
3
Velocity (m/s)


Barrow
Eureka
ALASKA (UNITED STATES)
Juneau
Whitehorse
Fairbanks
Dawson
Watson Lake
Cape Lisburne
Chukchi Sea
Pevek
Cherskiy
Barrow
Prudhoe Bay
East Siberian Sea
120
Norman Wells
Inuvik
Tuktoyaktuk
Hay River
Beaufort Sea
POLAR ICE CAP
New Siberian Islands
Tiksi
Yellowknife
Kugluktuk
Banks Island
Laptev Sea
Victoria Island
CANADA
Cambridge Bay
Queen Elizabeth Islands
ARCTIC OCEAN
Khatanga
Arviat
Baker Lake
Gjoa Haven
Resolute
Severnaya Zemlya
Chesterfield Inlet
90 W
90° N
NORTH POLE
Repulse Bay
Coral Harbour
Igloolik
Ellesmere Island
Grise Fiord
Alert
Pond Inlet
Thule
Kara Sea
Franz Josef Land
Baffin Island
Cape Dorset
Clyde River
Baffin Bay
80
ICE CAP
Iqaluit
Novaya Zemlya
SVALBARD

Total precipitation Jan 07 for assumed values of zeta