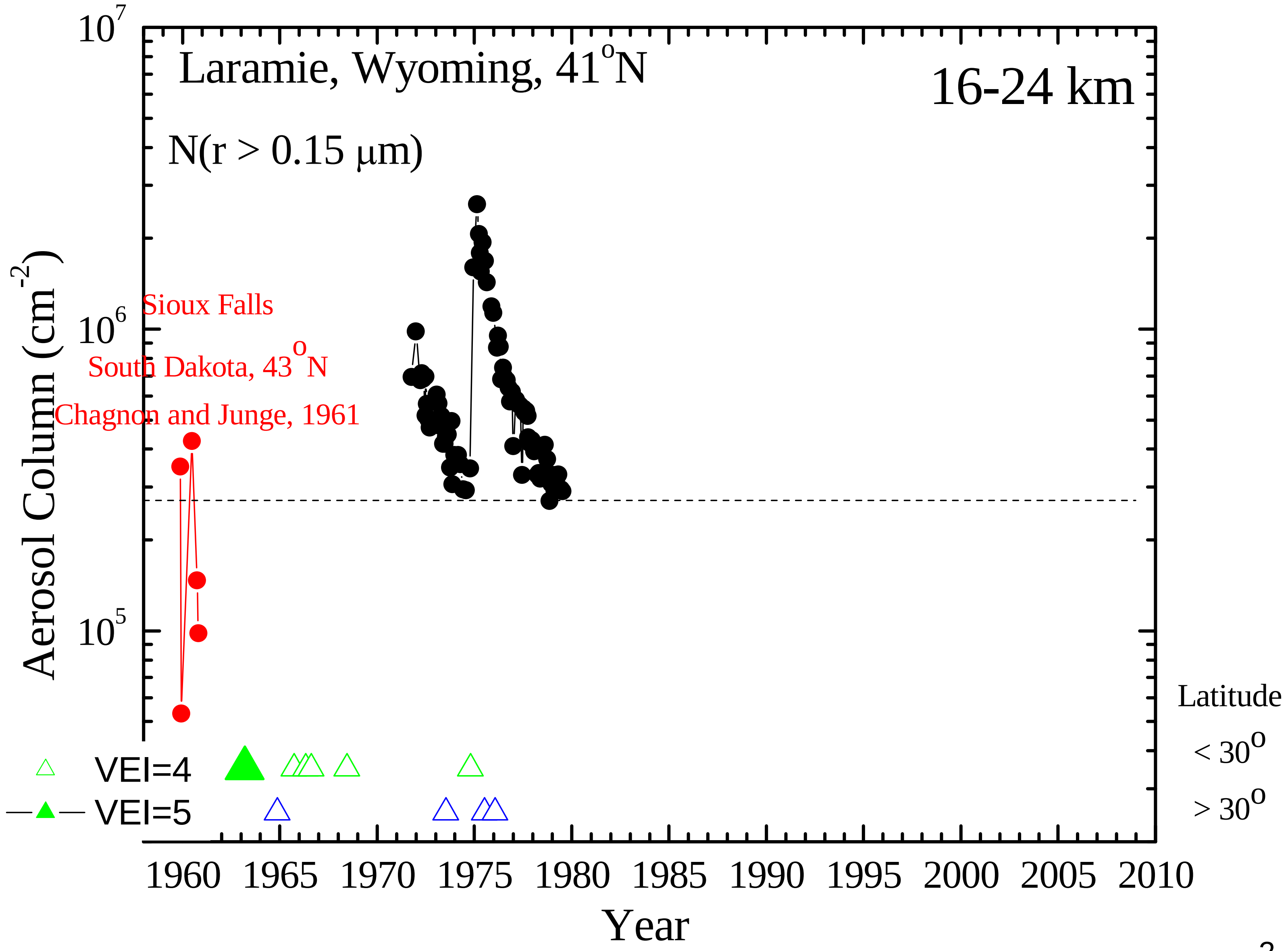
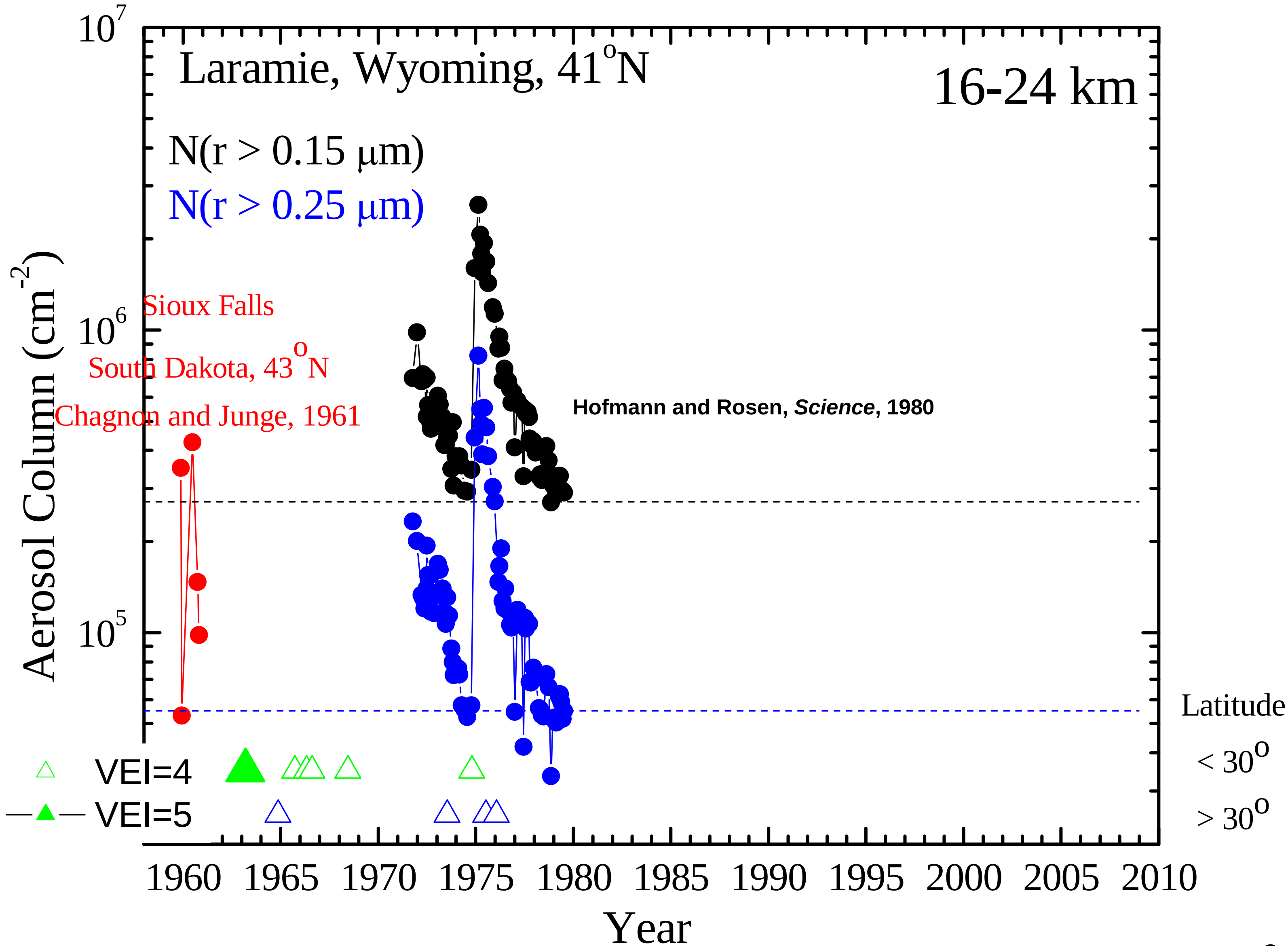
Stratospheric Aerosol from Pole to Pole: Balloonborne In Situ Observations

Terry Deshler, Dept. of Atmospheric Science, University of Wyoming

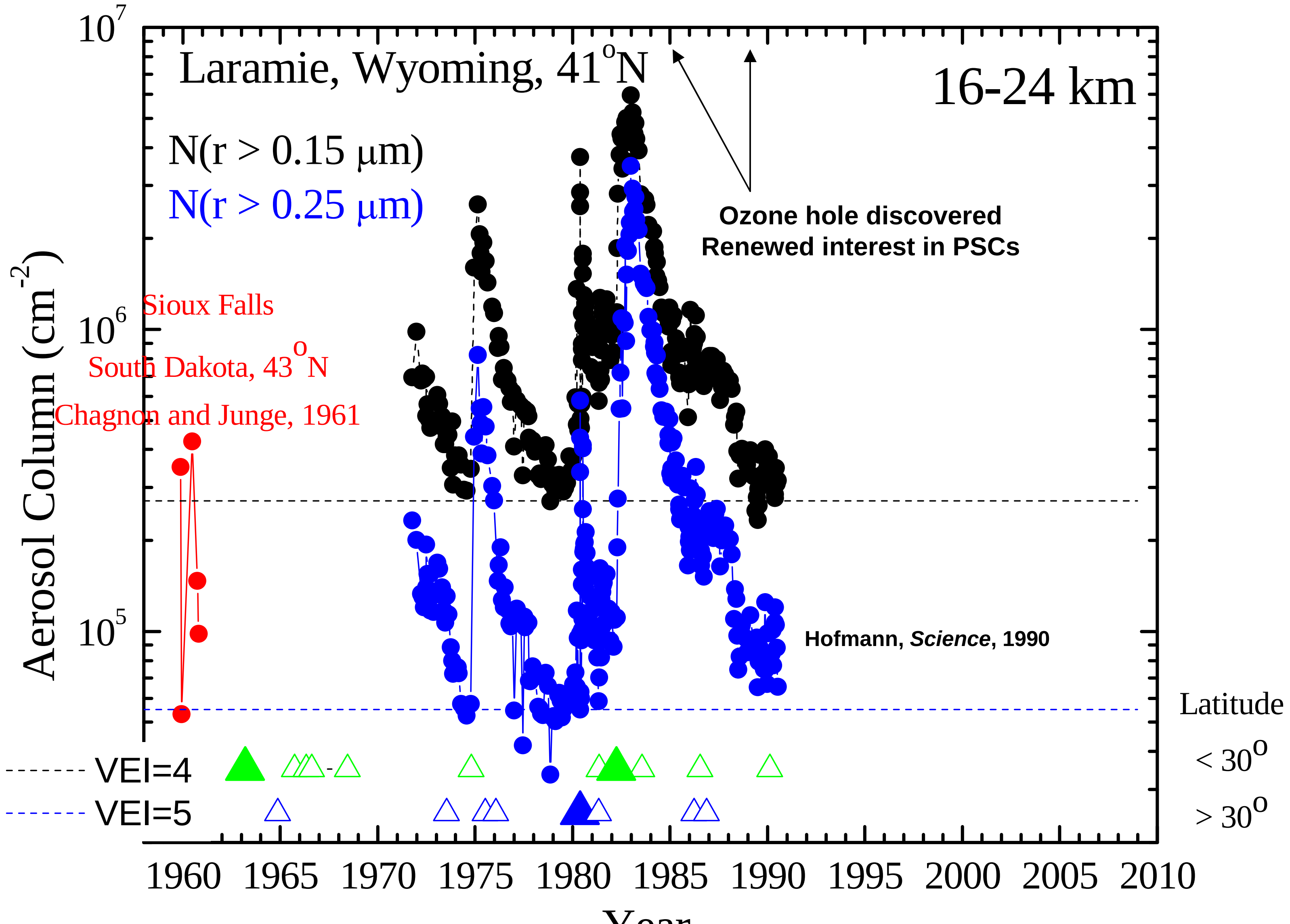
- 1) Early measurements – 25° aerosol counter, 1.0 l/min, 0.15 and 0.25 µm.
- 2) Mid latitude stratospheric aerosol – long term record
- 2) Polar Stratospheric Clouds –
  - New aerosol counter – 40°, 10.0 l/min, 0.15 – 10.0 µm
  - Antarctic PSCs
  - Arctic PSCs.
- 4) Tropical stratospheric aerosol - Brazil, Australia, Niger.



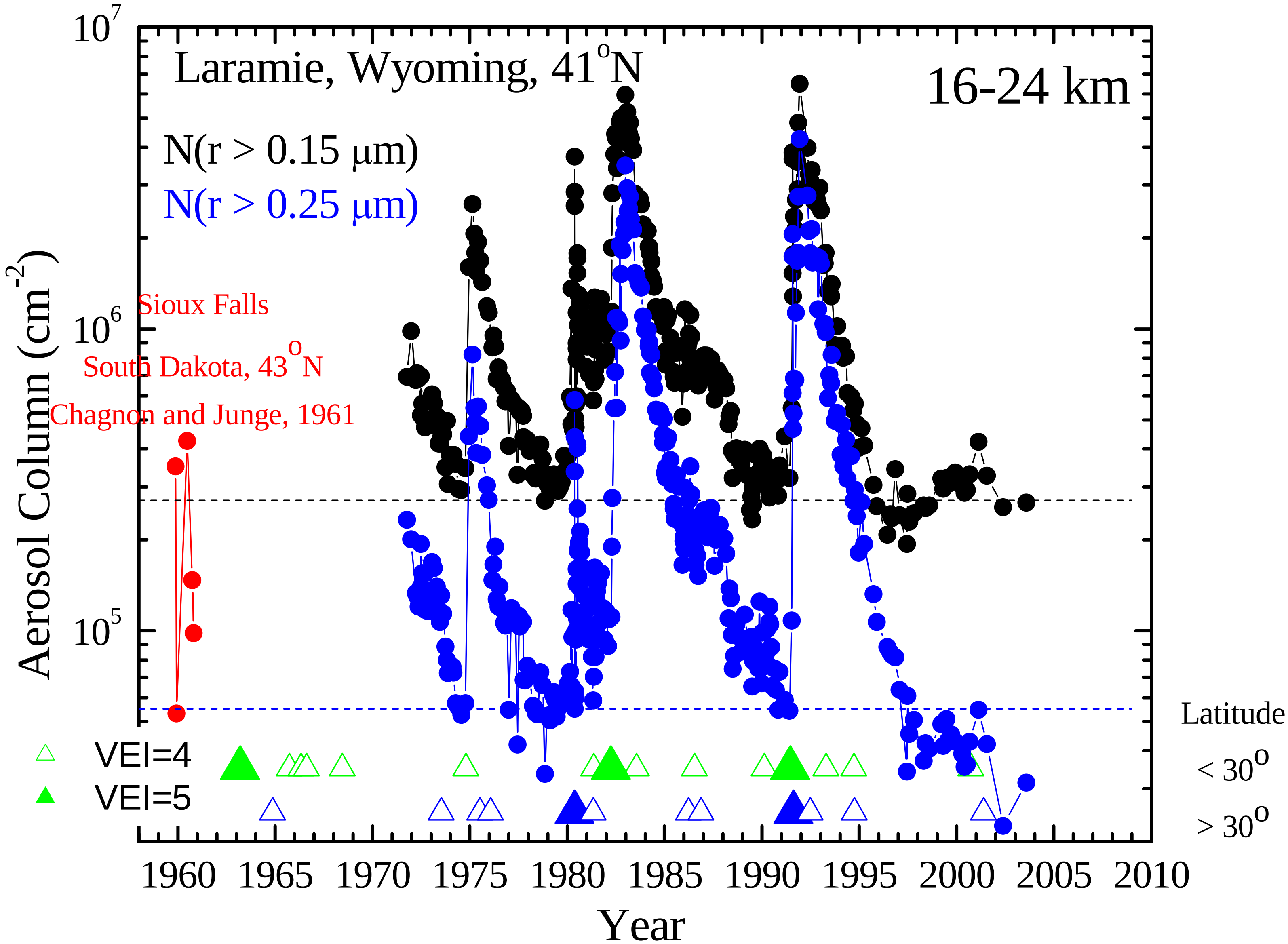
Laramie, Wyoming, 41°N
16-24 km
N(r > 0.15 μm)
Aerosol Column (cm-2)
10^7
10^6
10^5
Sioux Falls
South Dakota, 43°N
Chagnon and Junge, 1961
VEI=4
VEI=5
Latitude
< 30°
> 30°
1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010
Year

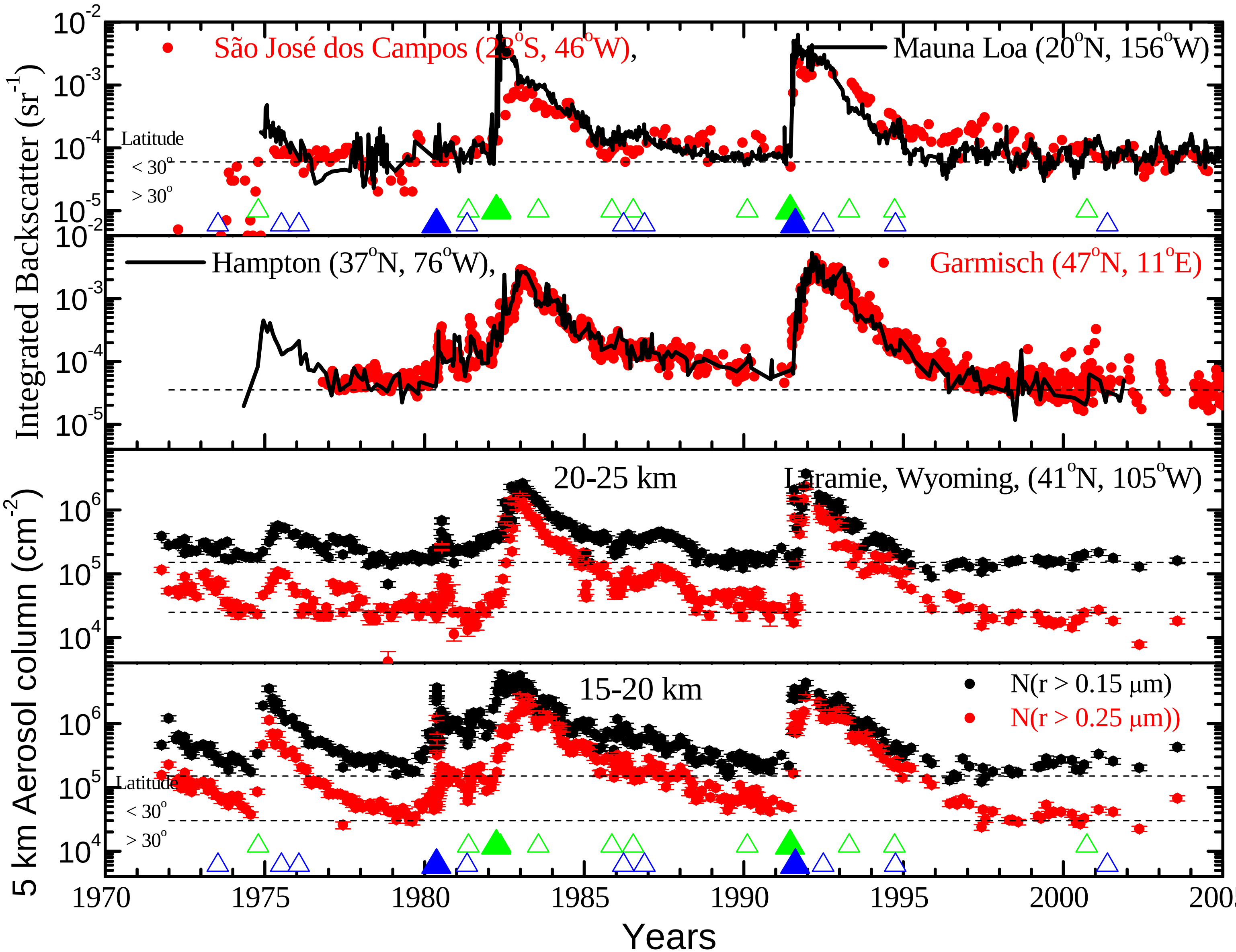


Laramie, Wyoming, 41°N
16-24 km
N(r > 0.15 μm)
N(r > 0.25 μm)
Sioux Falls
South Dakota, 43°N
Chagnon and Junge, 1961
Hofmann and Rosen, *Science*, 1980
Aerosol Column (cm⁻²)
10^7
10^6
10^5
VEI=4
VEI=5
Latitude
< 30°
> 30°
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year



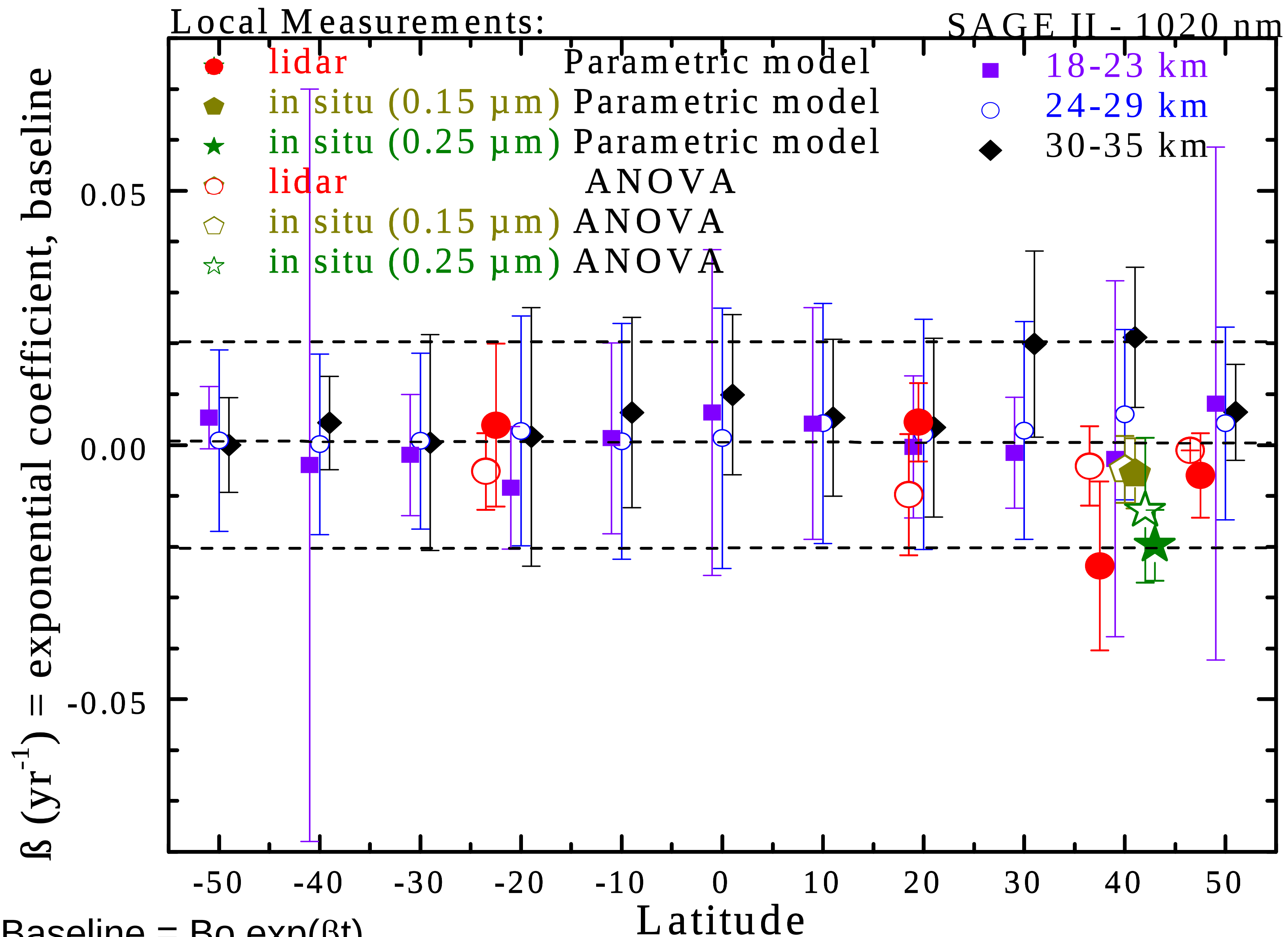
Laramie, Wyoming, 41°N
16-24 km
N(r > 0.15 μm)
N(r > 0.25 μm)
Ozone hole discovered
Renewed interest in PSCs
Sioux Falls
South Dakota, 43°N
Chagnon and Junge, 1961
Hofmann, *Science*, 1990
Aerosol Column (cm^{-2})
10^7
10^6
10^5
VEI=4
VEI=5
Latitude
< 30°
> 30°
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year


Laramie, Wyoming, 41°N
16-24 km
N(r > 0.15 µm)
N(r > 0.25 µm)
Sioux Falls
South Dakota, 43°N
Chagnon and Junge, 1961
Aerosol Column (cm-2)
10^7
10^6
10^5
VEI=4
VEI=5
Latitude
< 30°
> 30°
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year

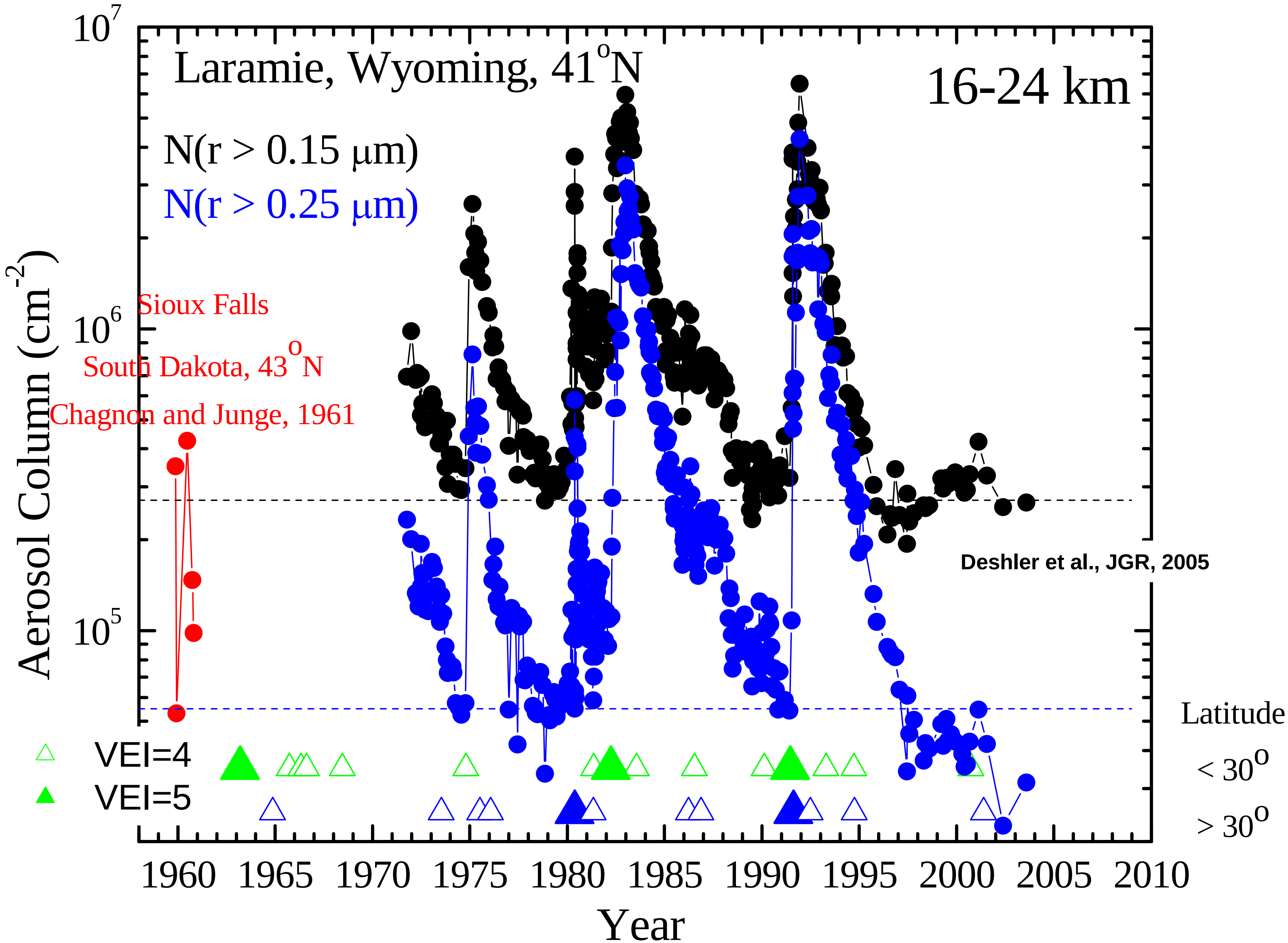


São José dos Campos (23°S, 46°W),
Mauna Loa (20°N, 156°W)
Latitude
< 30°
> 30°
Hampton (37°N, 76°W),
Garmisch (47°N, 11°E)
Integrated Backscatter (sr^{-1})
20-25 km
Laramie, Wyoming, (41°N, 105°W)
15-20 km
N(r > 0.15 μm)
N(r > 0.25 μm))
5 km Aerosol column (cm^{-2})
Years

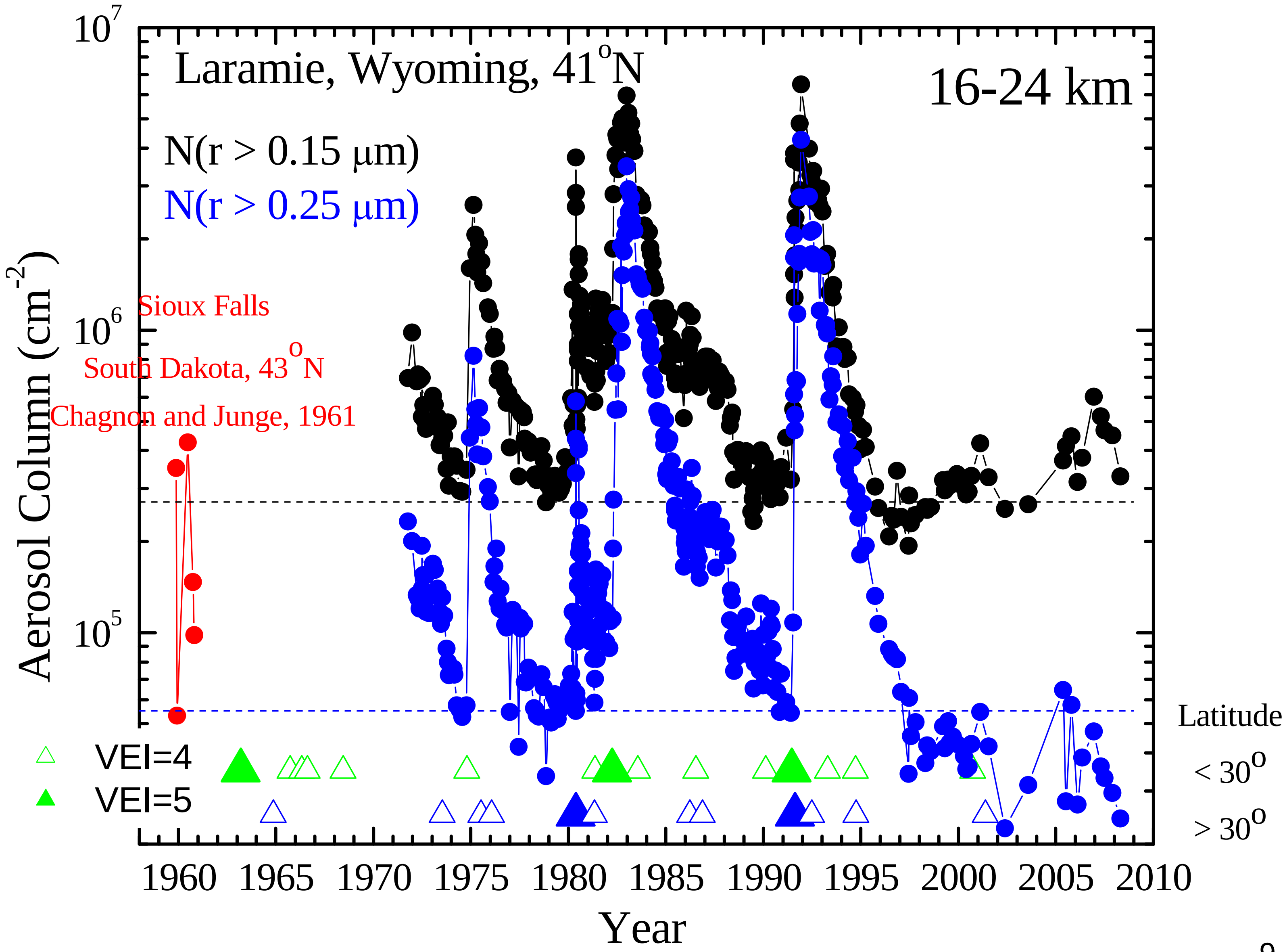
(SPARC ASAP, 2006; Deshler et al., JGR, 2005)



Baseline = Bo exp(βt)



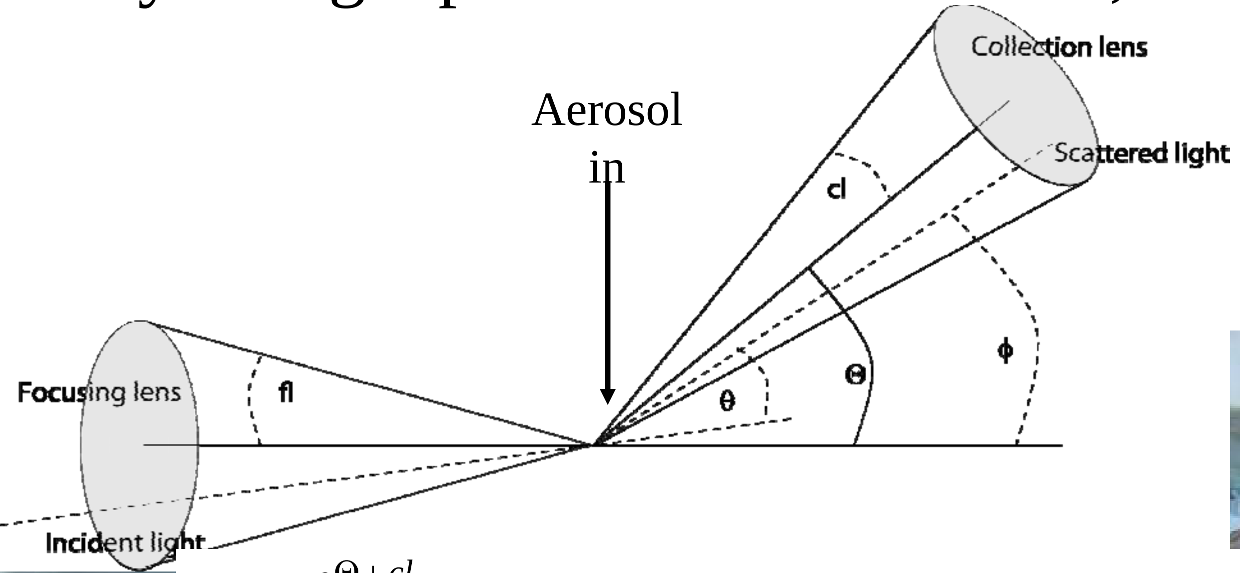
Laramie, Wyoming, 41°N
16-24 km
N(r > 0.15 μm)
N(r > 0.25 μm)
Sioux Falls
South Dakota, 43°N
Chagnon and Junge, 1961
Deshler et al., JGR, 2005
Aerosol Column (cm-2)
10^7
10^6
10^5
VEI=4
VEI=5
Latitude
< 30°
> 30°
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year

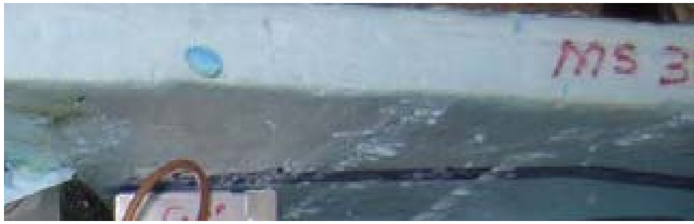

Laramie, Wyoming, 41°N
16-24 km
N(r > 0.15 μm)
N(r > 0.25 μm)
Sioux Falls
South Dakota, 43°N
Chagnon and Junge, 1961
Aerosol Column (cm^{-2})
10^7
10^6
10^5
VEI=4
VEI=5
Latitude
< 30°
> 30°
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year

Polar Stratospheric Clouds

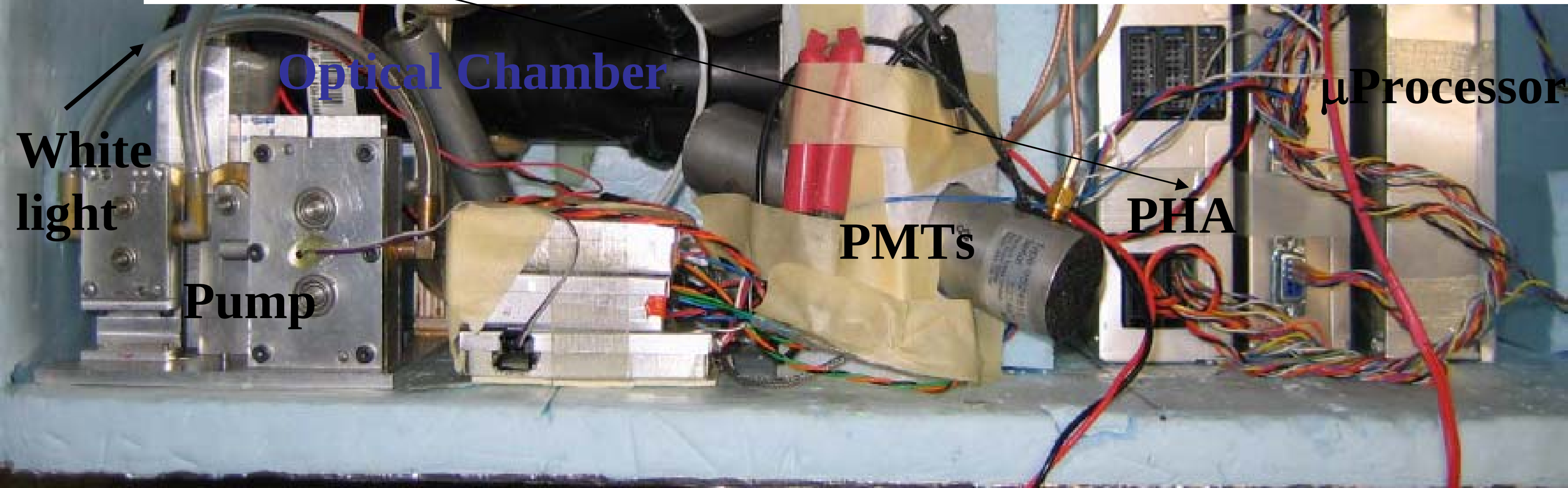
- Diversion into instrumentation
- Antarctic PSCs
- Arctic PSCs

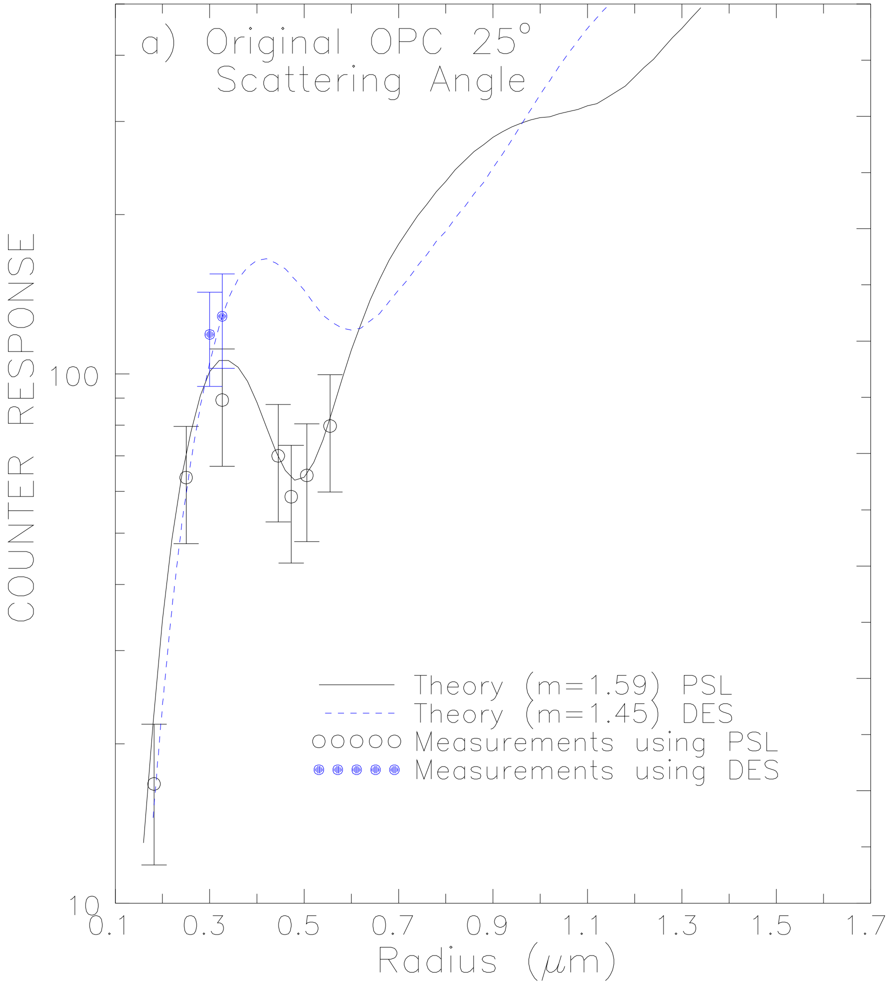
Wyoming Optical Particle Counter, r > 0.2 - 10.0 μm

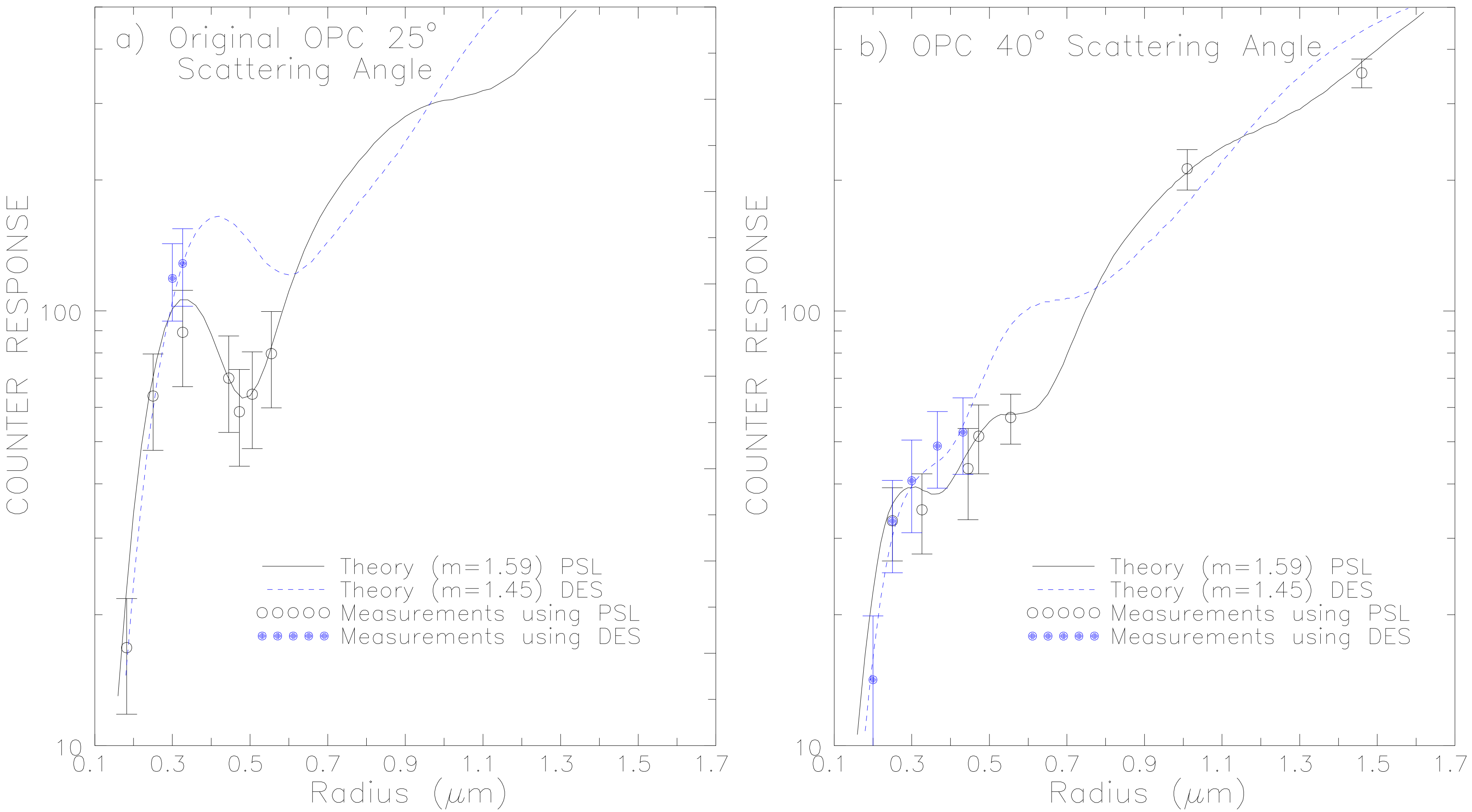




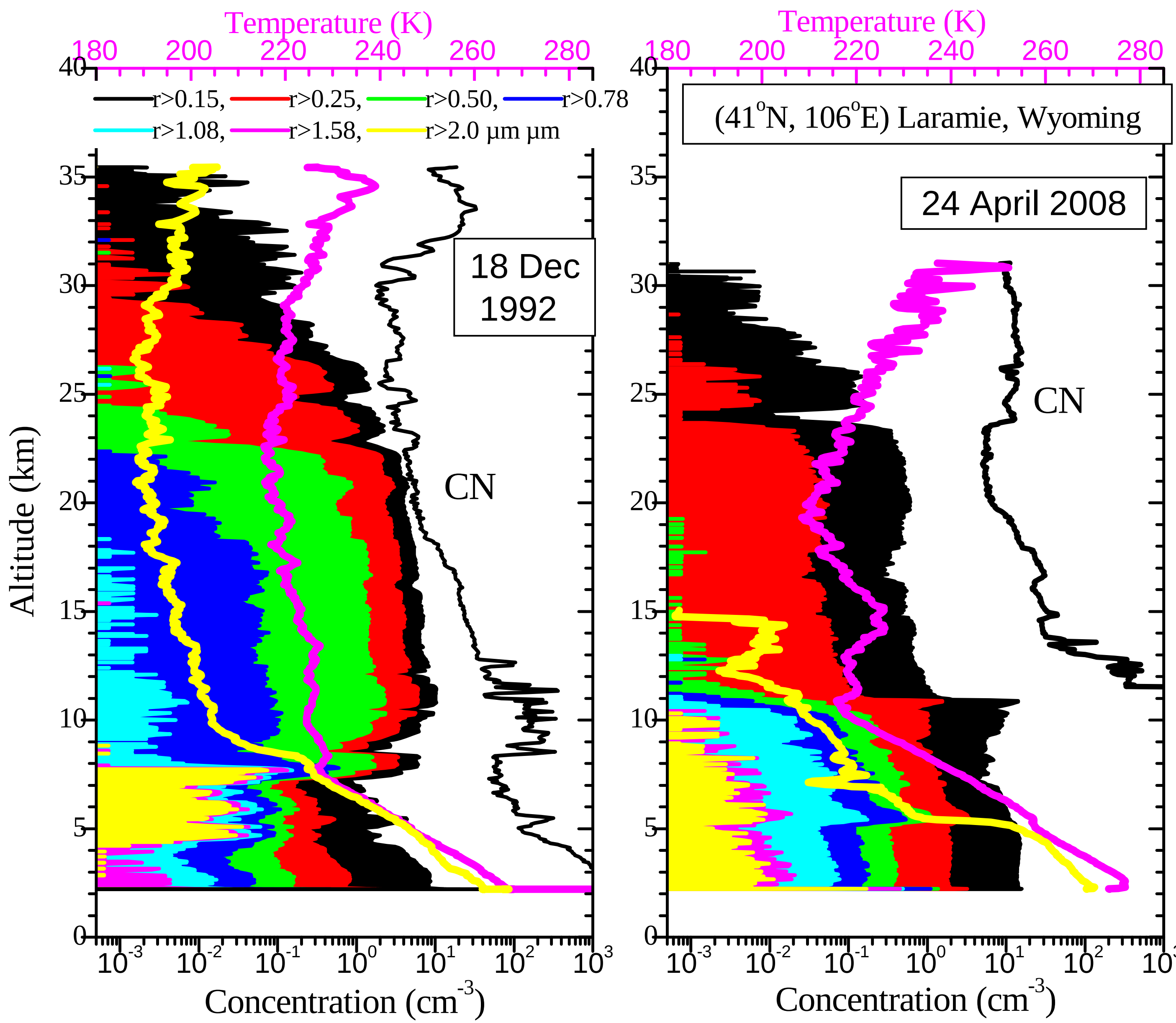
$$CR = \int_{\Theta - cl_2}^{\Theta + cl_2} \mathrm{cl}(\phi)\,d\phi \int_{\phi - fl_2}^{\phi + fl_2} \mathrm{fl}(\phi,\theta)\,d\theta \int_{0.3\mu\,m}^{0.7\mu\,m} \left(\frac{\lambda}{2\pi}\right)^2 \left[\mathrm{i}_1(x,m,\theta) + \mathrm{i}_2(x,m,\theta)\right] \mathrm{I}(\lambda)\,\mathrm{QE}(\lambda)\,d\lambda$$




a) Original OPC 25°
Scattering Angle
COUNTER RESPONSE
100
10
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
Radius (μm)
Theory (m=1.59) PSL
Theory (m=1.45) DES
Measurements using PSL
Measurements using DES



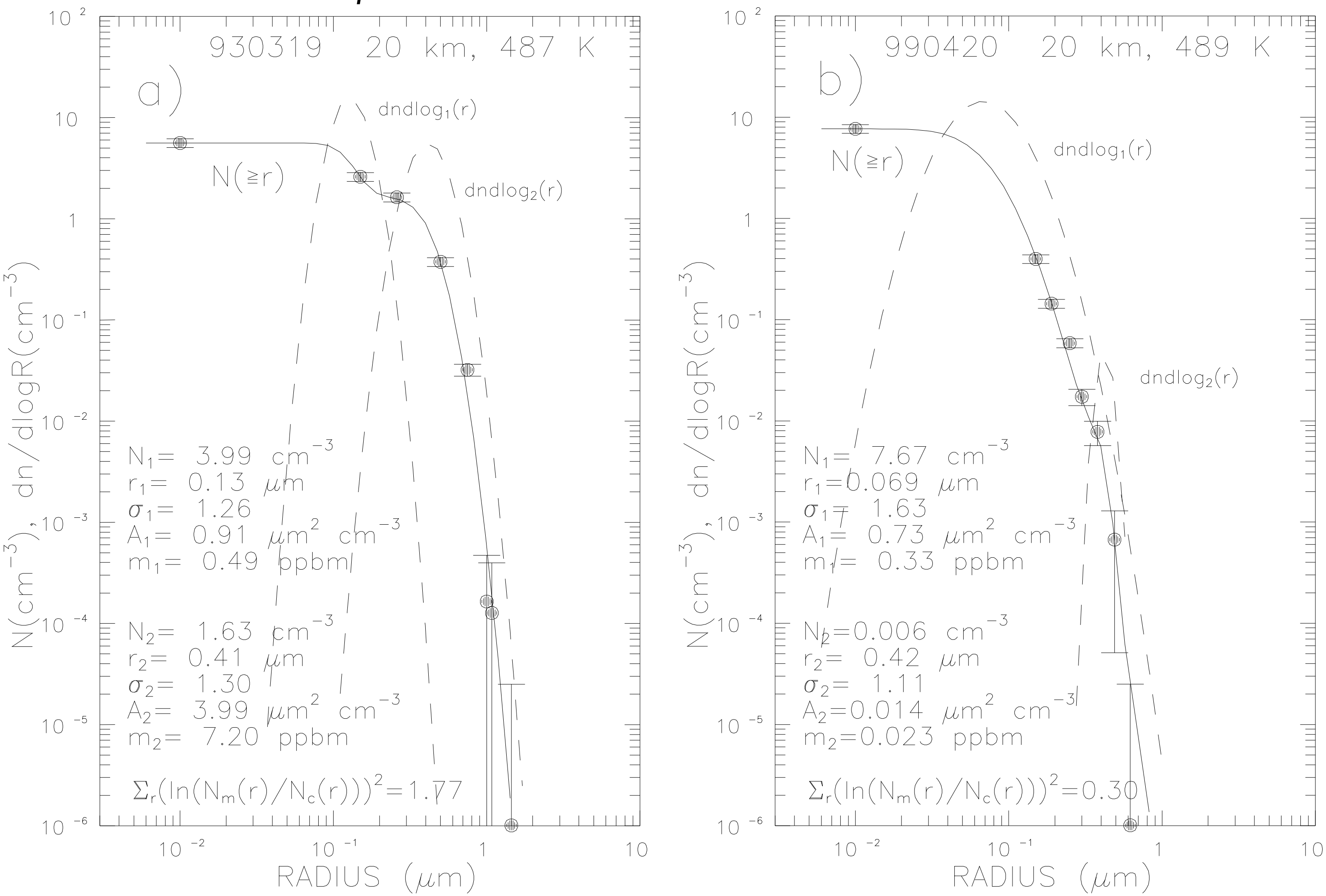
a) Original OPC 25°
Scattering Angle
COUNTER RESPONSE
100
10
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
Radius (μm)
Theory (m=1.59) PSL
Theory (m=1.45) DES
Measurements using PSL
Measurements using DES
b) OPC 40° Scattering Angle
COUNTER RESPONSE
100
10
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
Radius (μm)
Theory (m=1.59) PSL
Theory (m=1.45) DES
Measurements using PSL
Measurements using DES



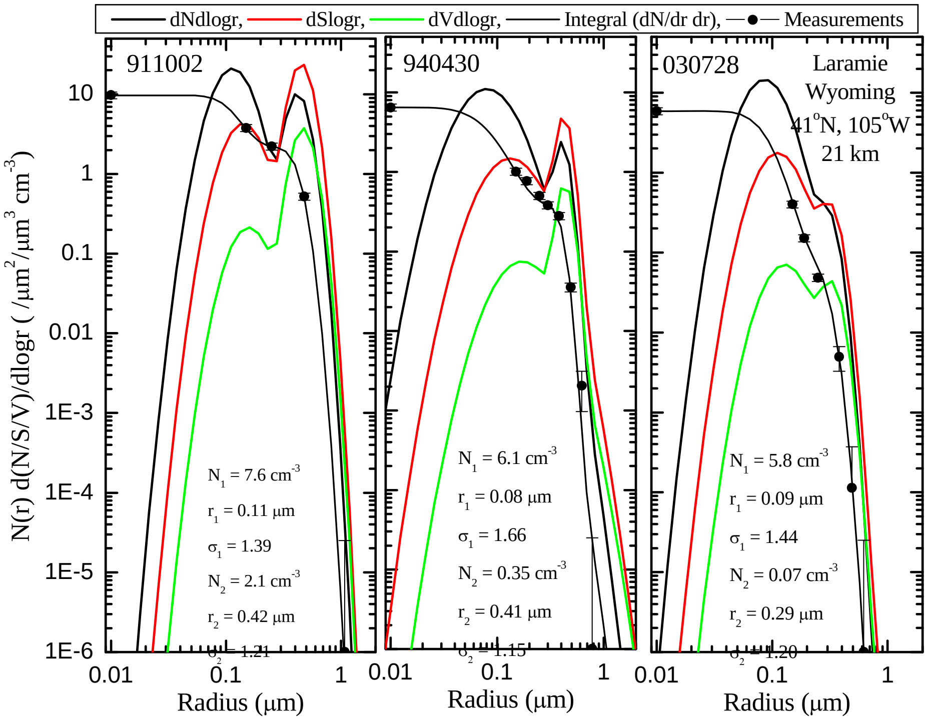
Temperature (K)
180
200
220
240
260
280
r>0.15,
r>0.25,
r>0.50,
r>0.78
r>1.08,
r>1.58,
r>2.0 µm µm
18 Dec 1992
CN
Altitude (km)
Concentration (cm-3)
Temperature (K)
(41oN, 106oE) Laramie, Wyoming
24 April 2008
CN
Concentration (cm-3)

Aerosol Size distributions

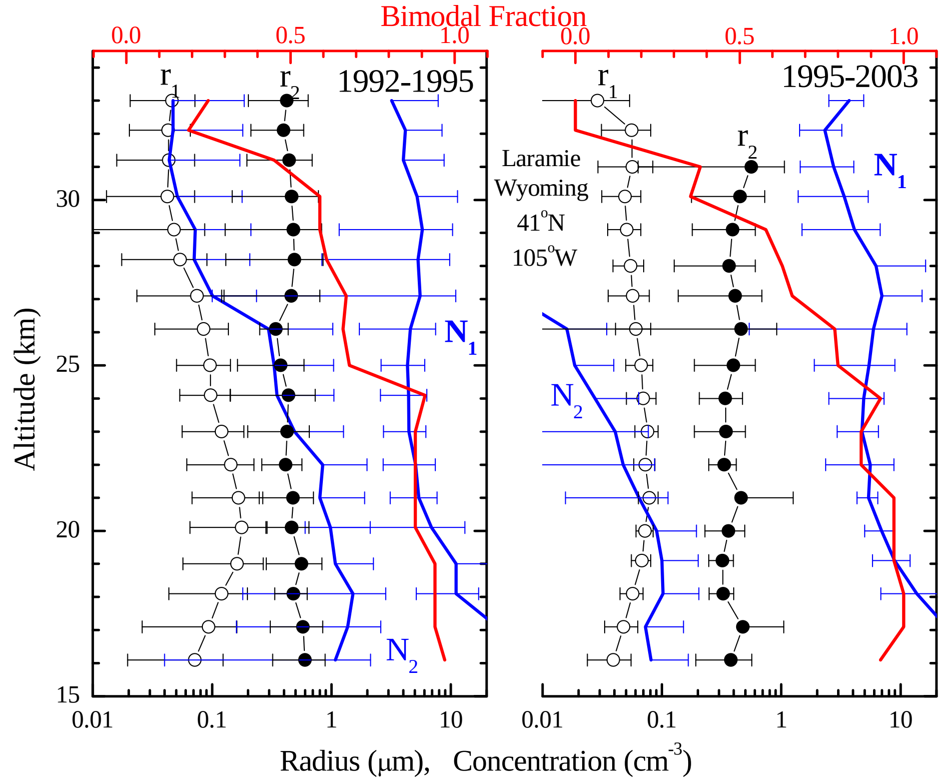
$$N(>r) = \sum_i \int_r^\infty \frac{N_i}{\sqrt{2\pi}\ln\sigma_i} \exp\left(\frac{-\ln^2[a/r_i]}{2\ln^2\sigma_i}\right) d\ln a$$



Evolution Pinatubo Aerosol

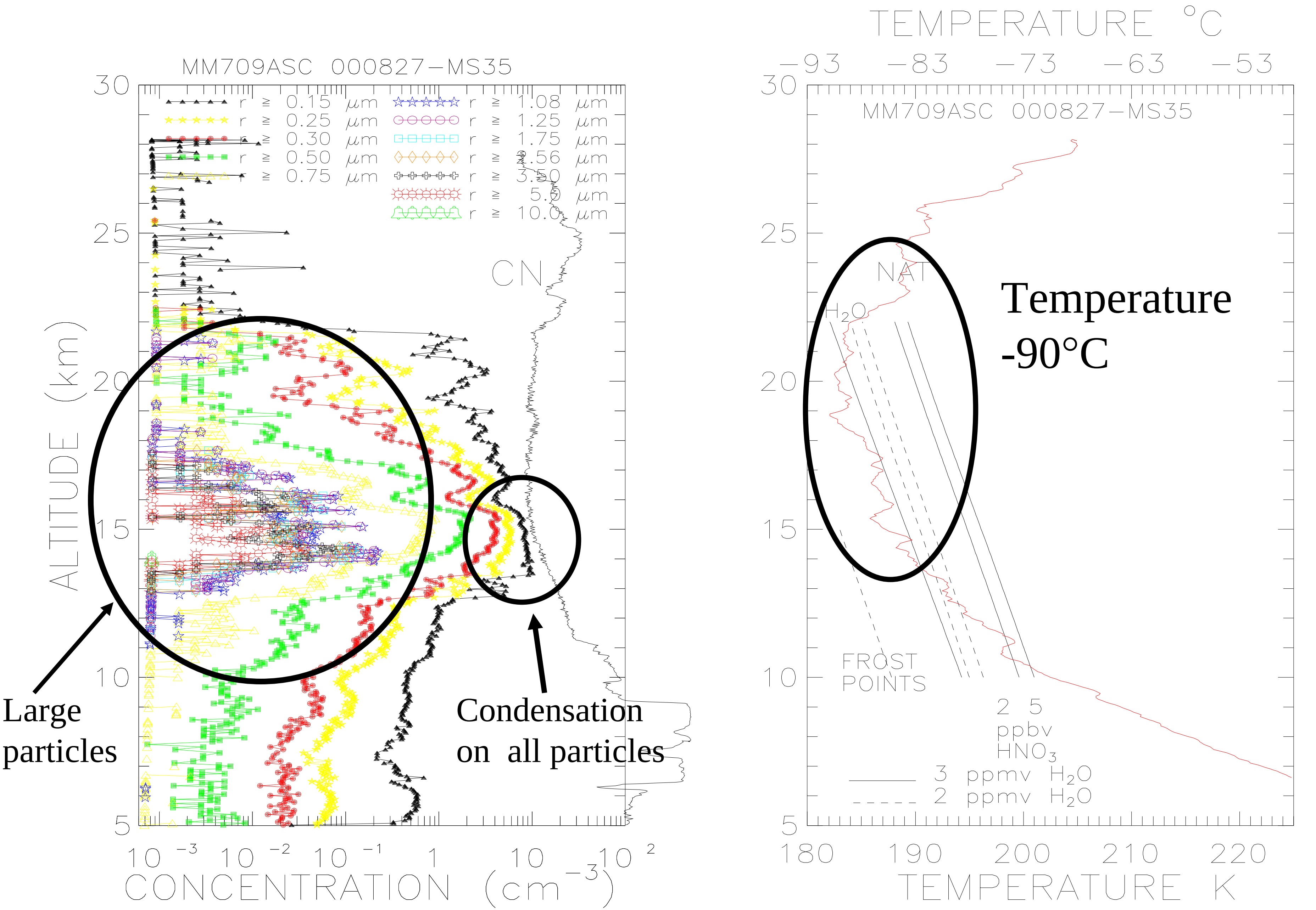


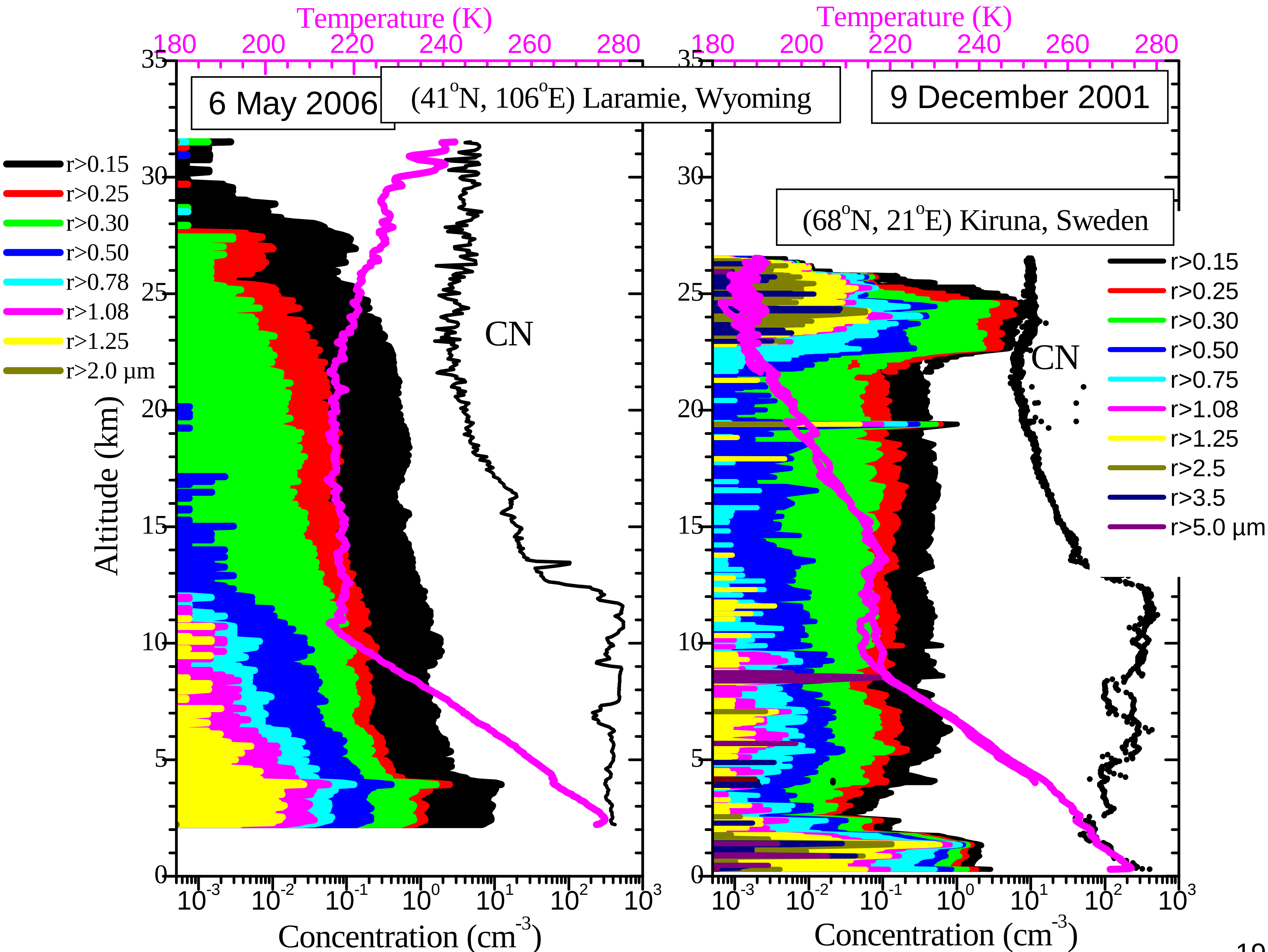
$$N(>r) = \sum_i \int_r^{\infty} \frac{N_i}{\sqrt{2\pi}\ln\sigma_i} \exp\left(\frac{-\ln^2[a/r_i]}{2\ln^2\sigma_i}\right) d\ln a$$



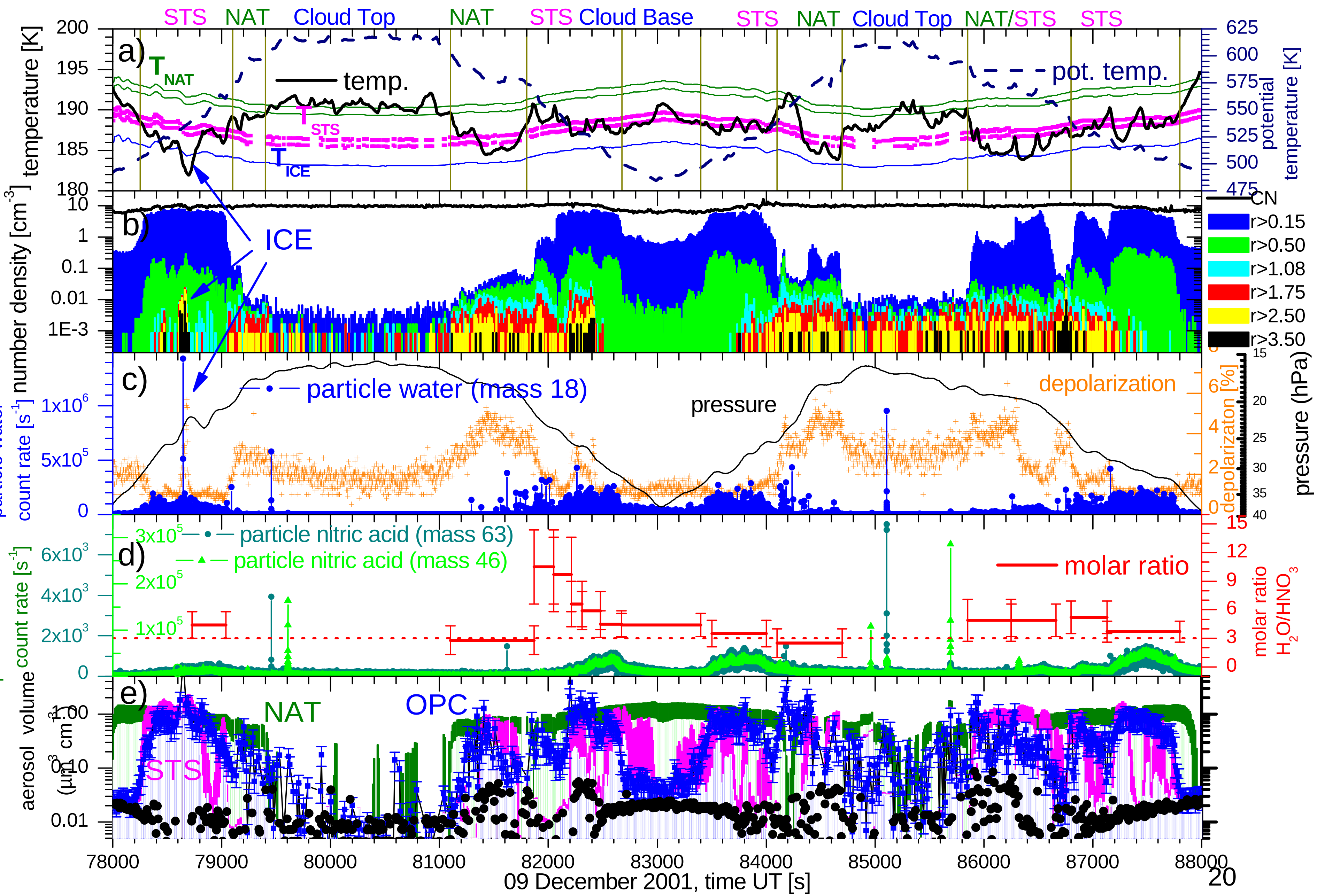
Monte Carlo simulations using Poisson counting uncertainty and pulse width broadening lead to uncertainties of 20% for distribution width, 30% for median radii and 40% for surface area and volume.

Antarctic Polar Stratospheric Clouds

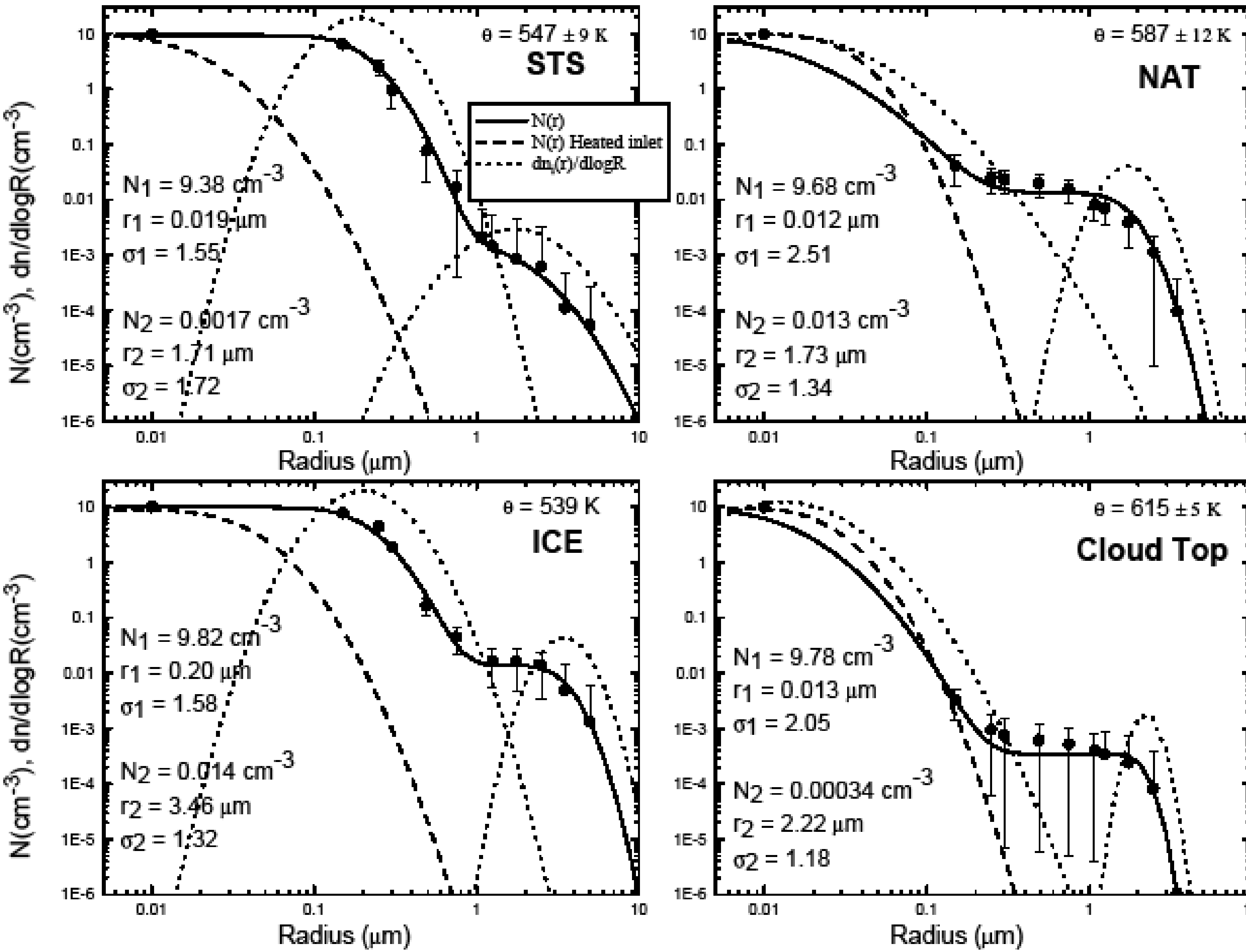




Temperature (K)
180
200
220
240
260
280
6 May 2006
(41°N, 106°E) Laramie, Wyoming
r>0.15
r>0.25
r>0.30
r>0.50
r>0.78
r>1.08
r>1.25
r>2.0 µm
CN
Altitude (km)
35
30
25
20
15
10
5
0
10-3
10-2
10-1
100
101
102
103
Concentration (cm-3)
Temperature (K)
180
200
220
240
260
280
9 December 2001
(68°N, 21°E) Kiruna, Sweden
r>0.15
r>0.25
r>0.30
r>0.50
r>0.75
r>1.08
r>1.25
r>2.5
r>3.5
r>5.0 µm
CN
Concentration (cm-3)



Deshler et al., JGR, 2005

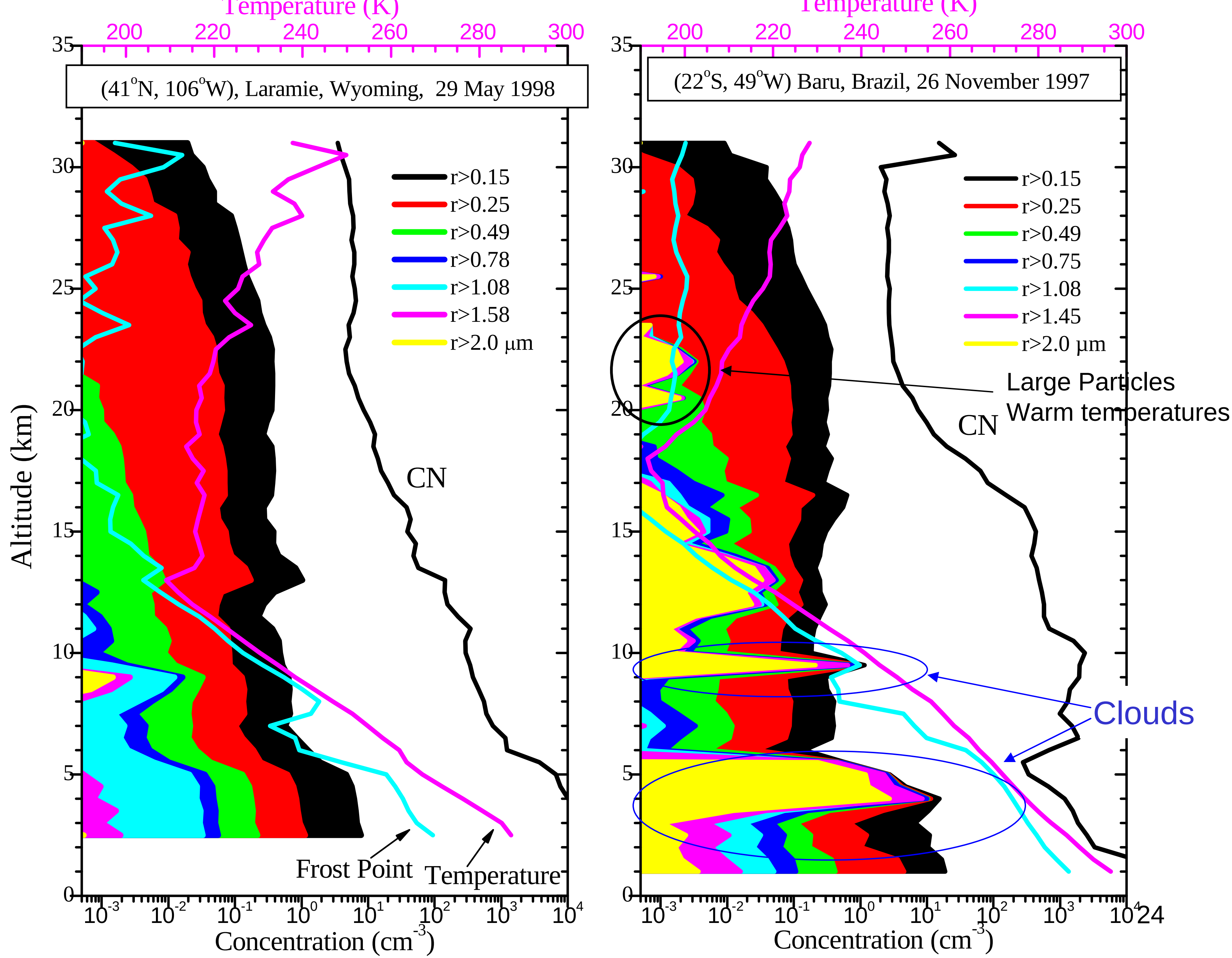

θ = 547 ± 9 K
STS
N(r)
N(r) Heated inlet
dn_i(r)/dlogR
N1 = 9.38 cm-3
r1 = 0.019 μm
σ1 = 1.55
N2 = 0.0017 cm-3
r2 = 1.71 μm
σ2 = 1.72
θ = 587 ± 12 K
NAT
N1 = 9.68 cm-3
r1 = 0.012 μm
σ1 = 2.51
N2 = 0.013 cm-3
r2 = 1.73 μm
σ2 = 1.34
θ = 539 K
ICE
N1 = 9.82 cm-3
r1 = 0.20 μm
σ1 = 1.58
N2 = 0.014 cm-3
r2 = 3.46 μm
σ2 = 1.32
θ = 615 ± 5 K
Cloud Top
N1 = 9.78 cm-3
r1 = 0.013 μm
σ1 = 2.05
N2 = 0.00034 cm-3
r2 = 2.22 μm
σ2 = 1.18
N(cm-3), dn/dlogR(cm-3)
Radius (μm)
10
1
0.1
0.01
1E-3
1E-4
1E-5
1E-6
0.01
0.1
1
10

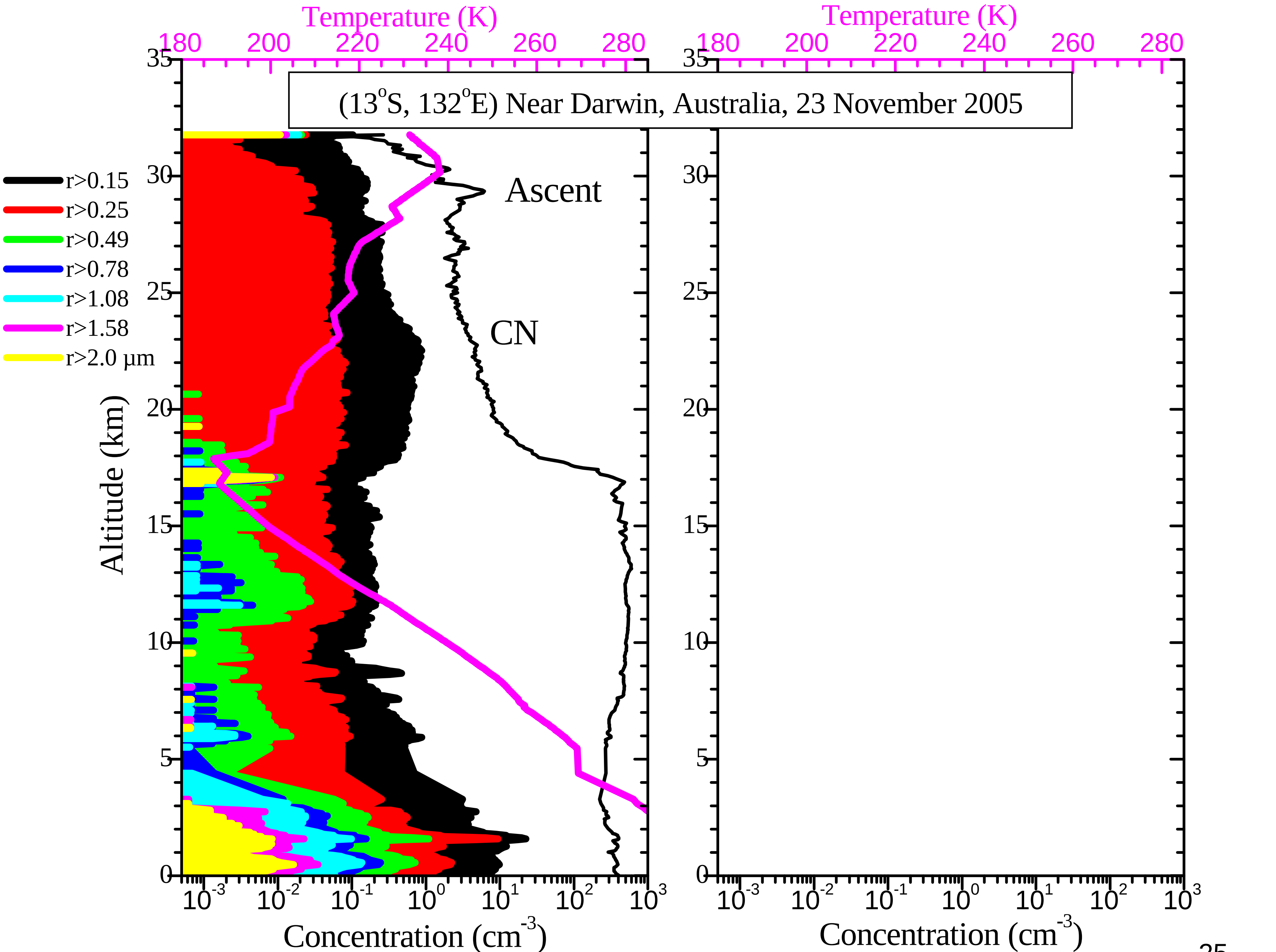
Conclusions

- Mid latitude aerosol
  - Early record dominated by 3 major eruptions (Fuego, El Chichón, Pinatubo). Non volcanic background was difficult to determine.
  - Record since Pinatubo, longest volcanically quiescent period in modern record, through 2005 suggests no long term trend in stratospheric aerosol.
  - Large particle mode, though weak, exists even in non-volcanic aerosol.
  - Measurements since 2005 don’t maintain the stability seen up to that point.
- Polar Stratospheric Aerosol
  - In situ measurements provide best measurements of PSC surface area.
  - Probably only method capable of detecting low concentrations of relatively large particles.
  - PSCs can be identified as STS, NAT, Ice by size distribution.
  - Major unknown: How do nitric acid trihydrate (NAT) particles nucleate?
- Tropical Stratospheric Aerosol
  - What is origin of large particles above the tropopause?

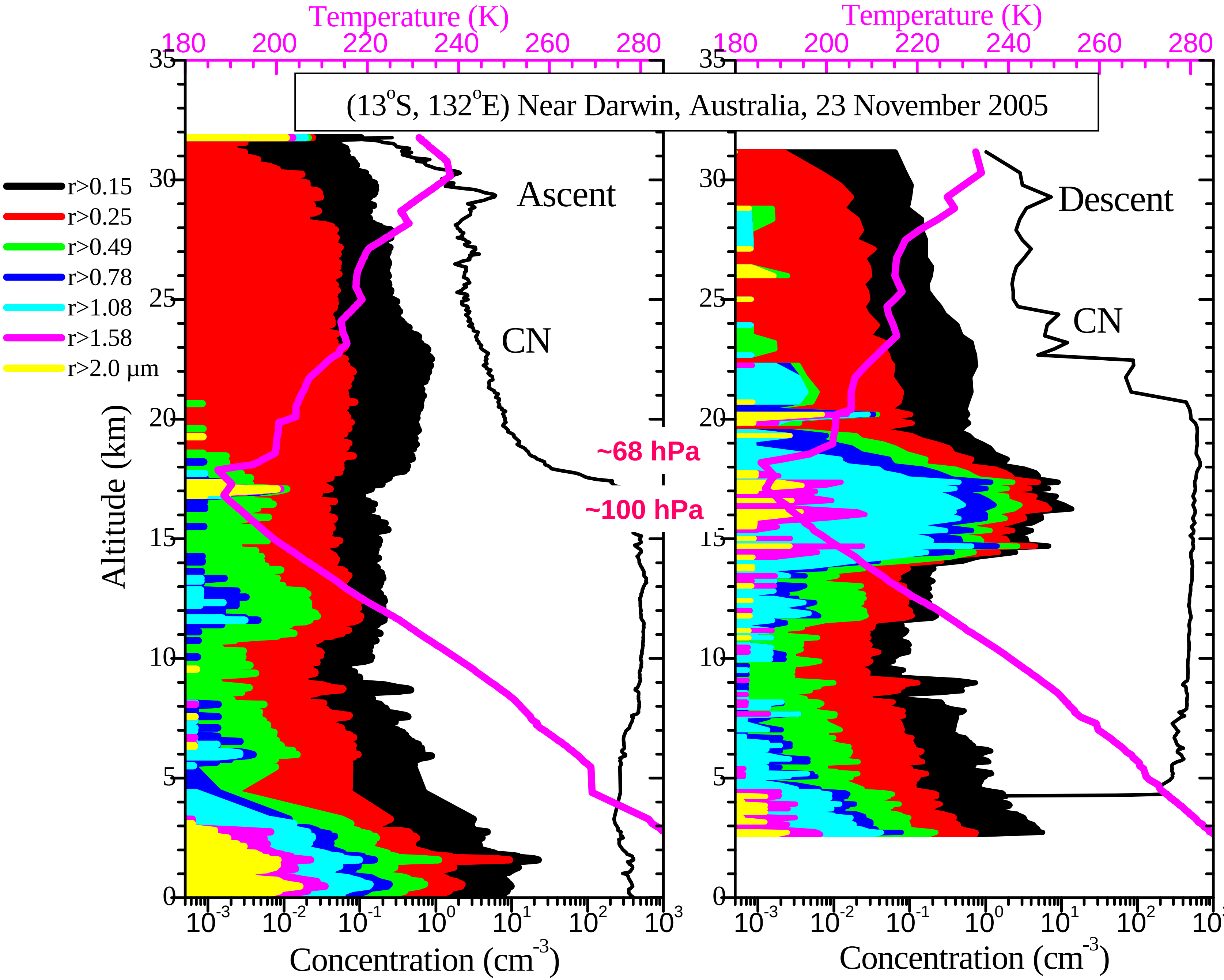
Tropical Stratospheric Aerosol

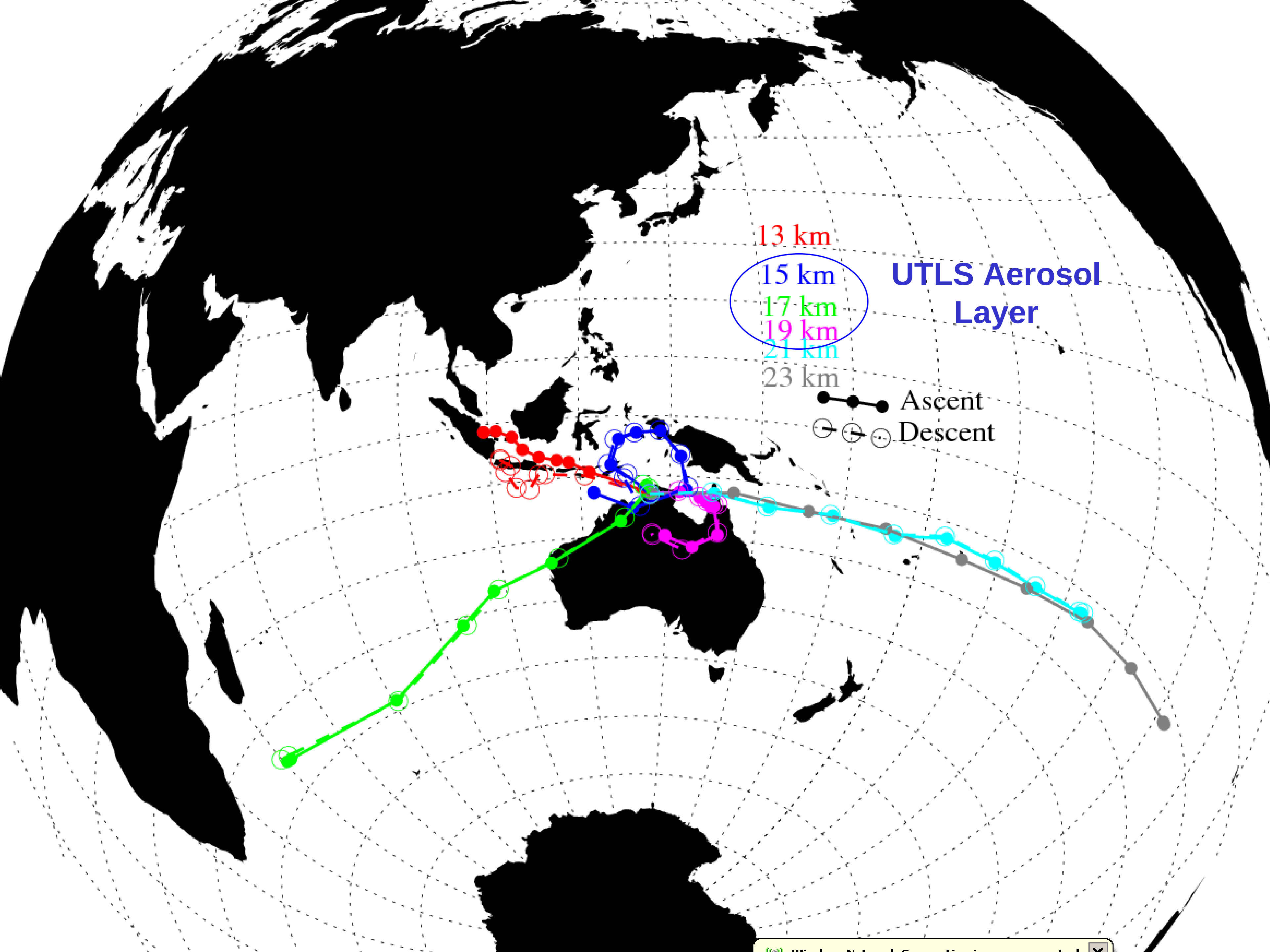
- Baru, Brazil, 23°S
- Darwin, Australia, 13°S
- Niamey, Niger, 13°N


Temperature (K)
(41°N, 106°W), Laramie, Wyoming, 29 May 1998
r>0.15
r>0.25
r>0.49
r>0.78
r>1.08
r>1.58
r>2.0 µm
CN
Frost Point
Temperature
Altitude (km)
Concentration (cm⁻³)
Temperature (K)
(22°S, 49°W) Baru, Brazil, 26 November 1997
r>0.15
r>0.25
r>0.49
r>0.75
r>1.08
r>1.45
r>2.0 µm
Large Particles
Warm temperatures
CN
Clouds
Concentration (cm⁻³)

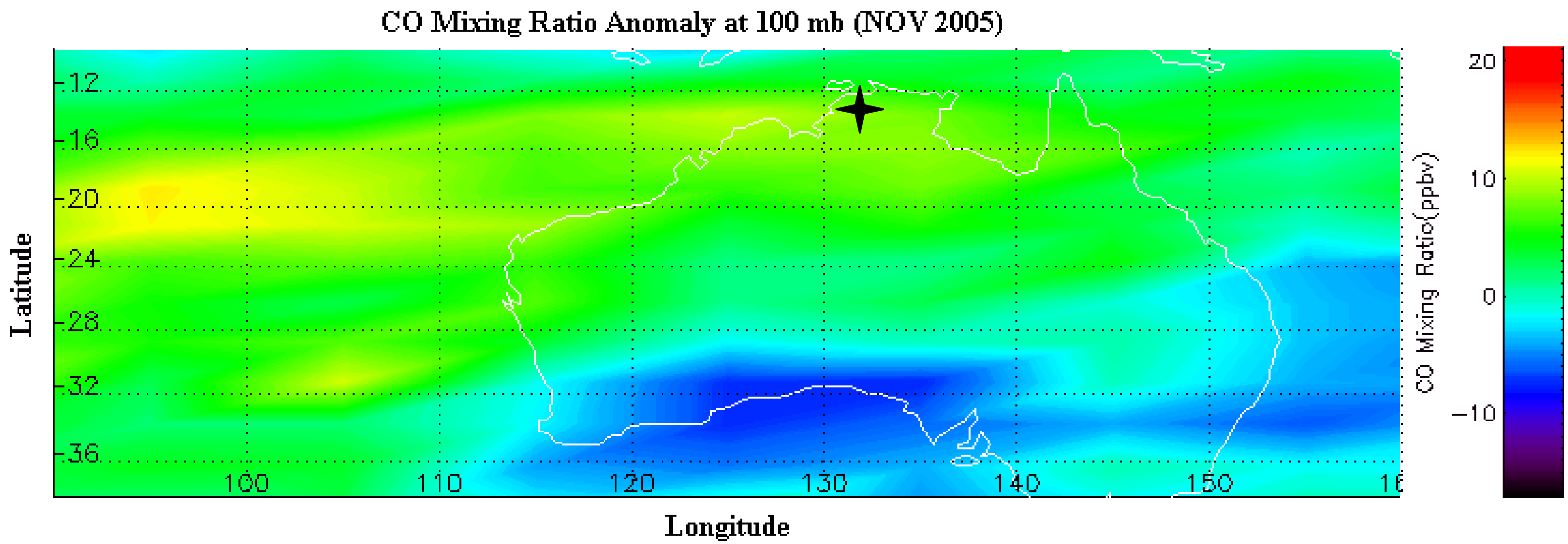


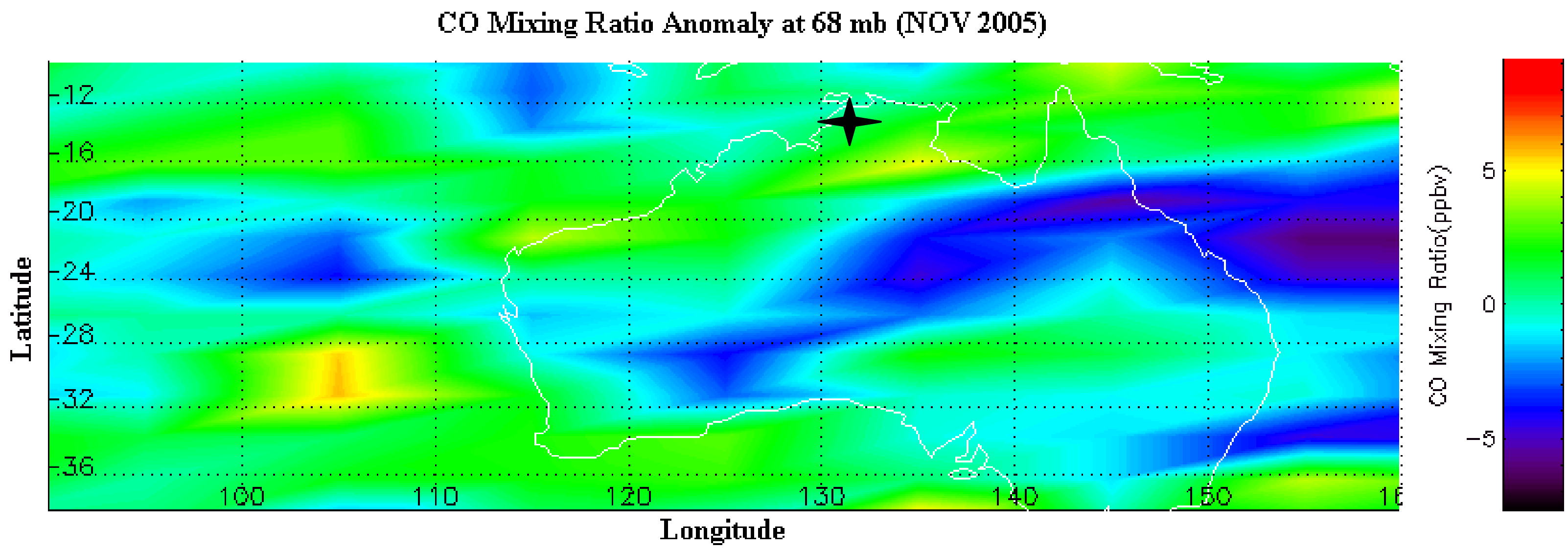
Temperature (K)
180 200 220 240 260 280
(13°S, 132°E) Near Darwin, Australia, 23 November 2005
r>0.15
r>0.25
r>0.49
r>0.78
r>1.08
r>1.58
r>2.0 μm
Ascent
CN
Altitude (km)
0 5 10 15 20 25 30 35
10^-3 10^-2 10^-1 10^0 10^1 10^2 10^3
Concentration (cm^-3)
Temperature (K)
180 200 220 240 260 280
Concentration (cm^-3)


(13°S, 132°E) Near Darwin, Australia, 23 November 2005
Temperature (K)
180 200 220 240 260 280
Temperature (K)
180 200 220 240 260 280
r>0.15
r>0.25
r>0.49
r>0.78
r>1.08
r>1.58
r>2.0 µm
Altitude (km)
Ascent
CN
Descent
CN
~68 hPa
~100 hPa
0 5 10 15 20 25 30 35
Concentration (cm-3)
Concentration (cm-3)

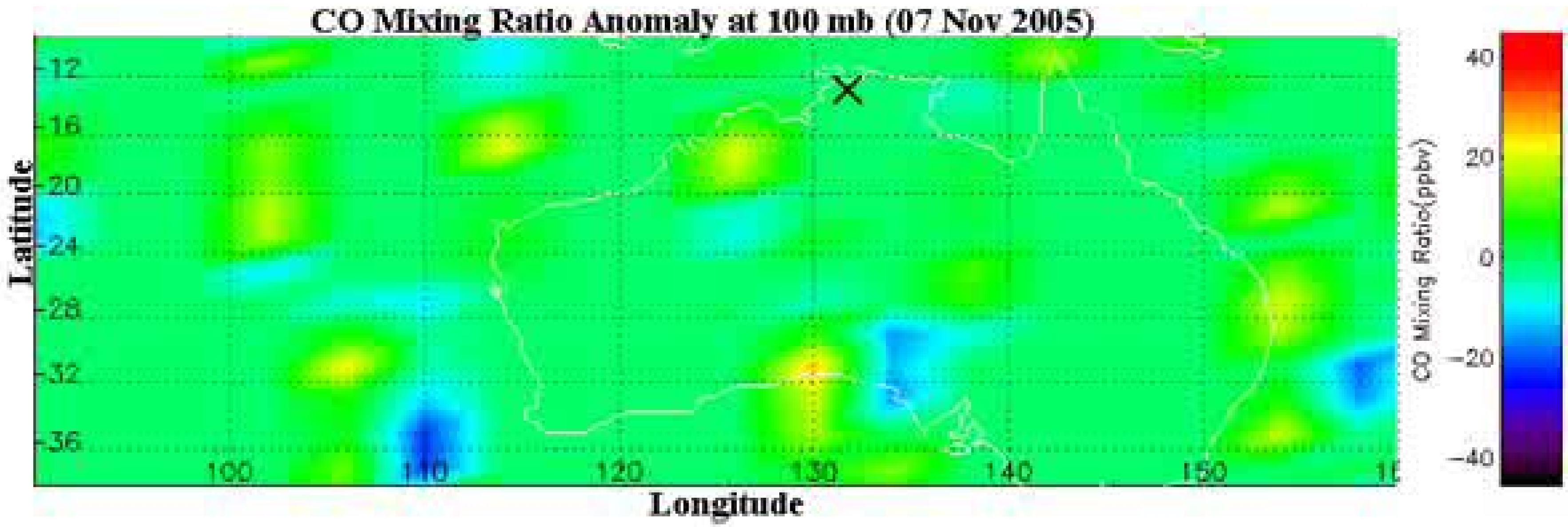

13 km
15 km
17 km
19 km
21 km
23 km
UTLS Aerosol Layer
Ascent
Descent

November 2005 average of AURA MLS CO measurements at 100 and 68 hPa

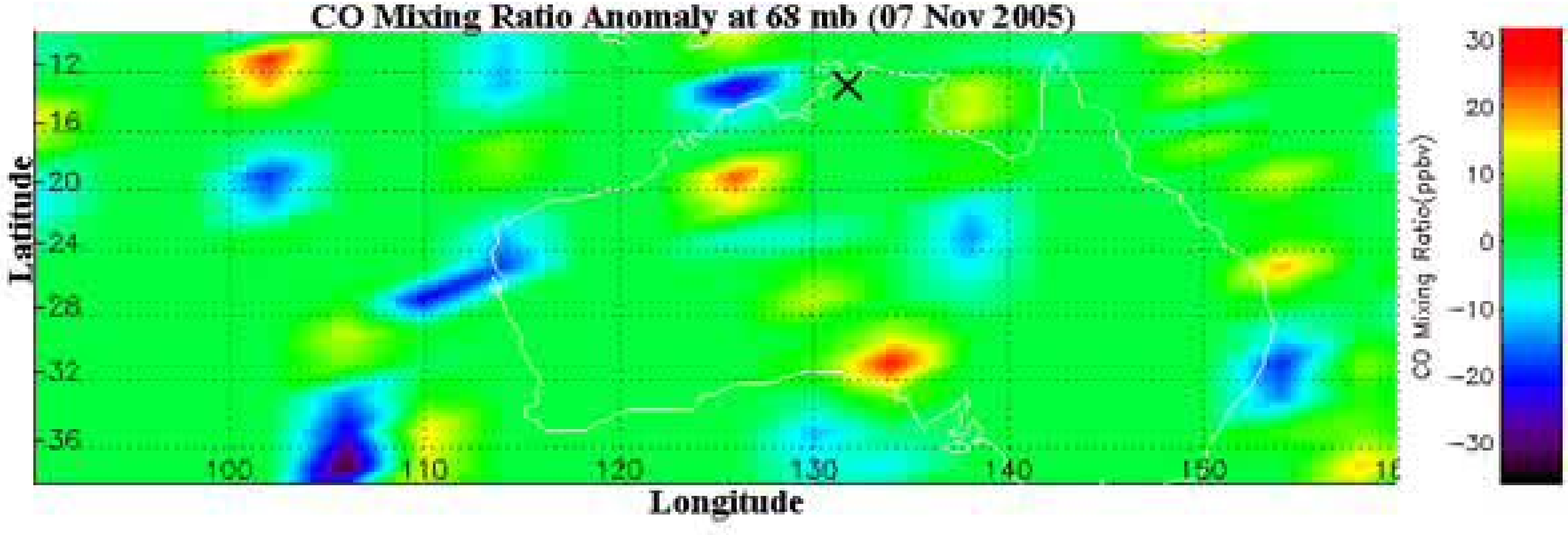


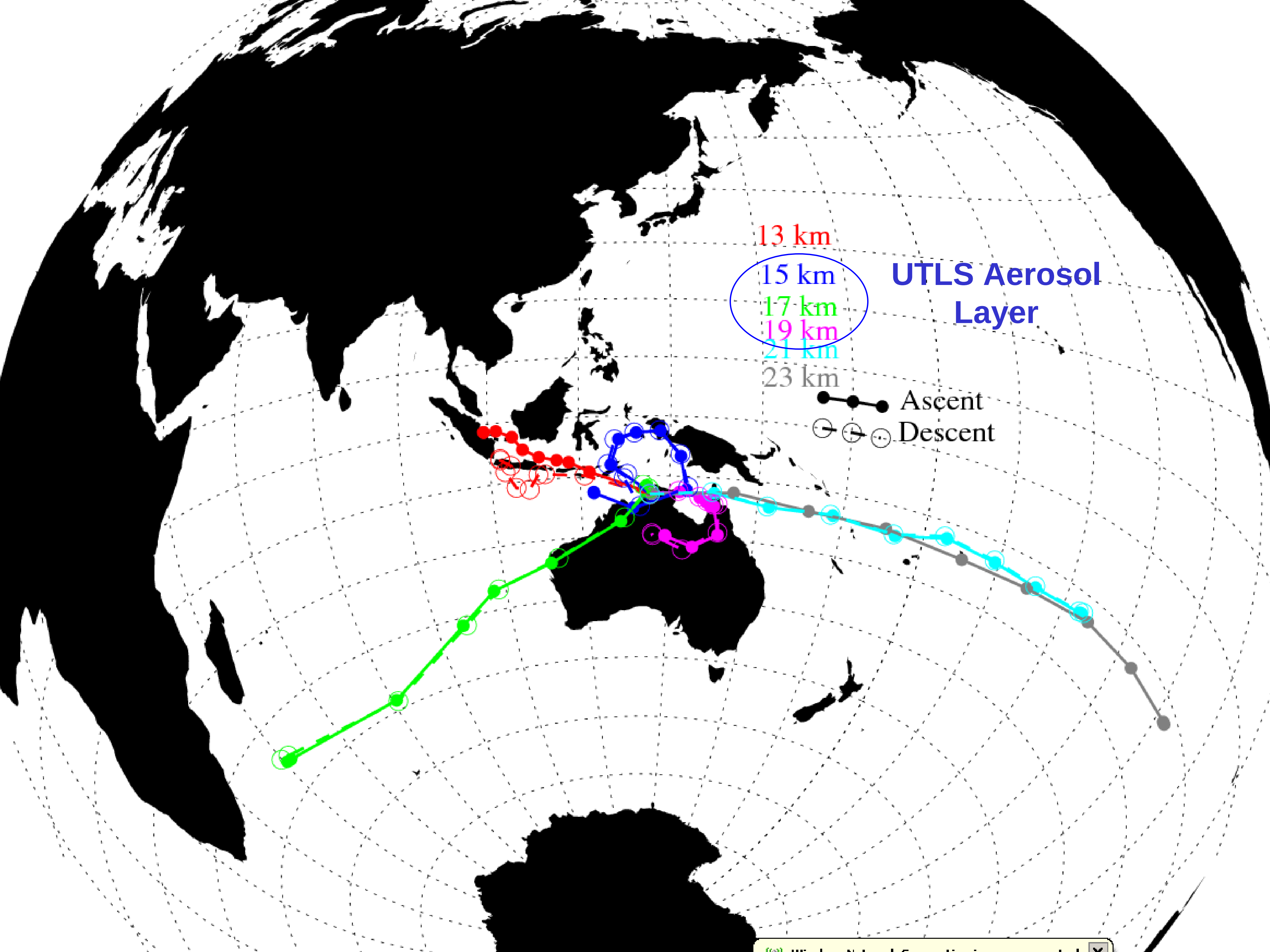


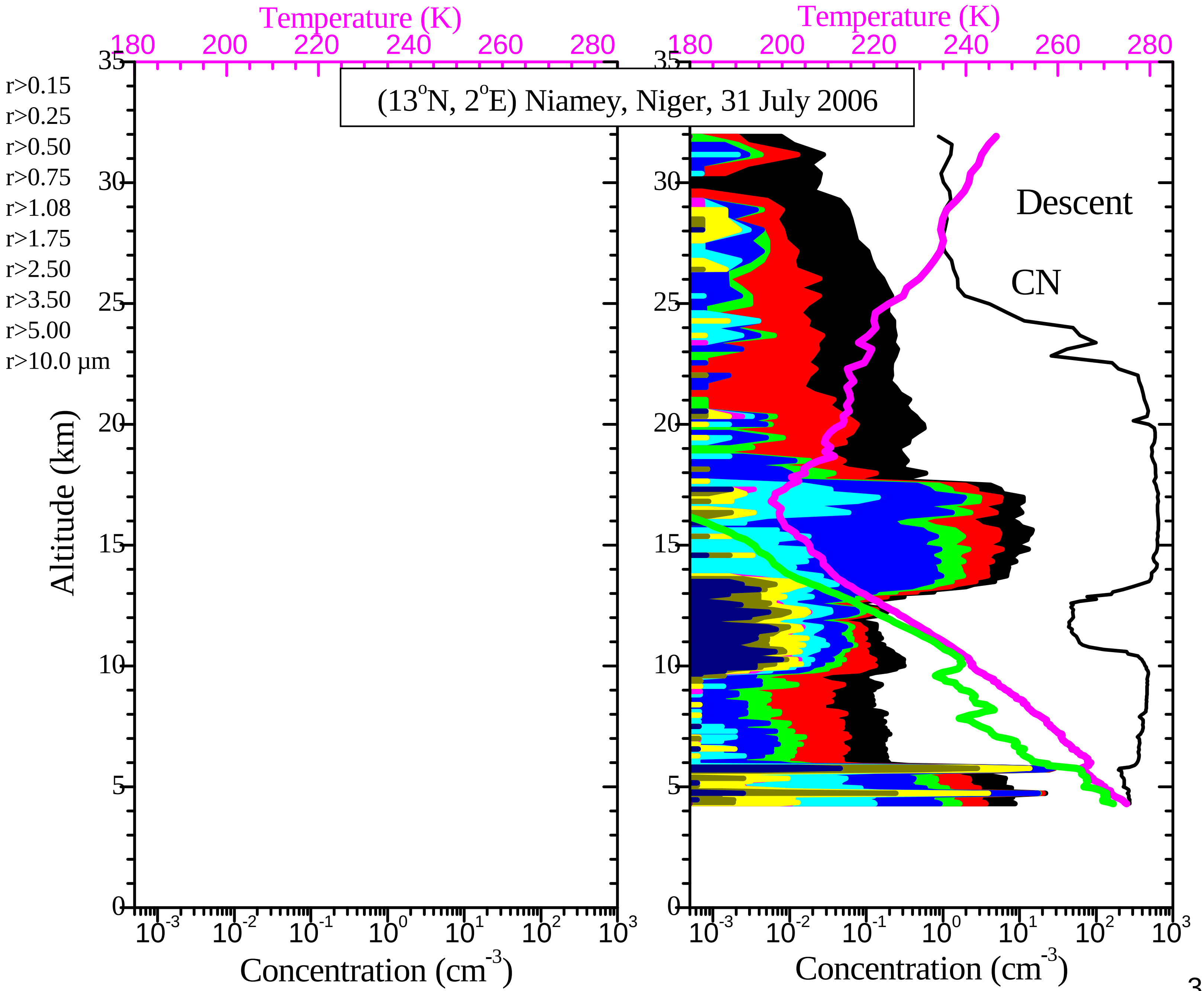
Grid Size 2° Latitude X 4° Longitude

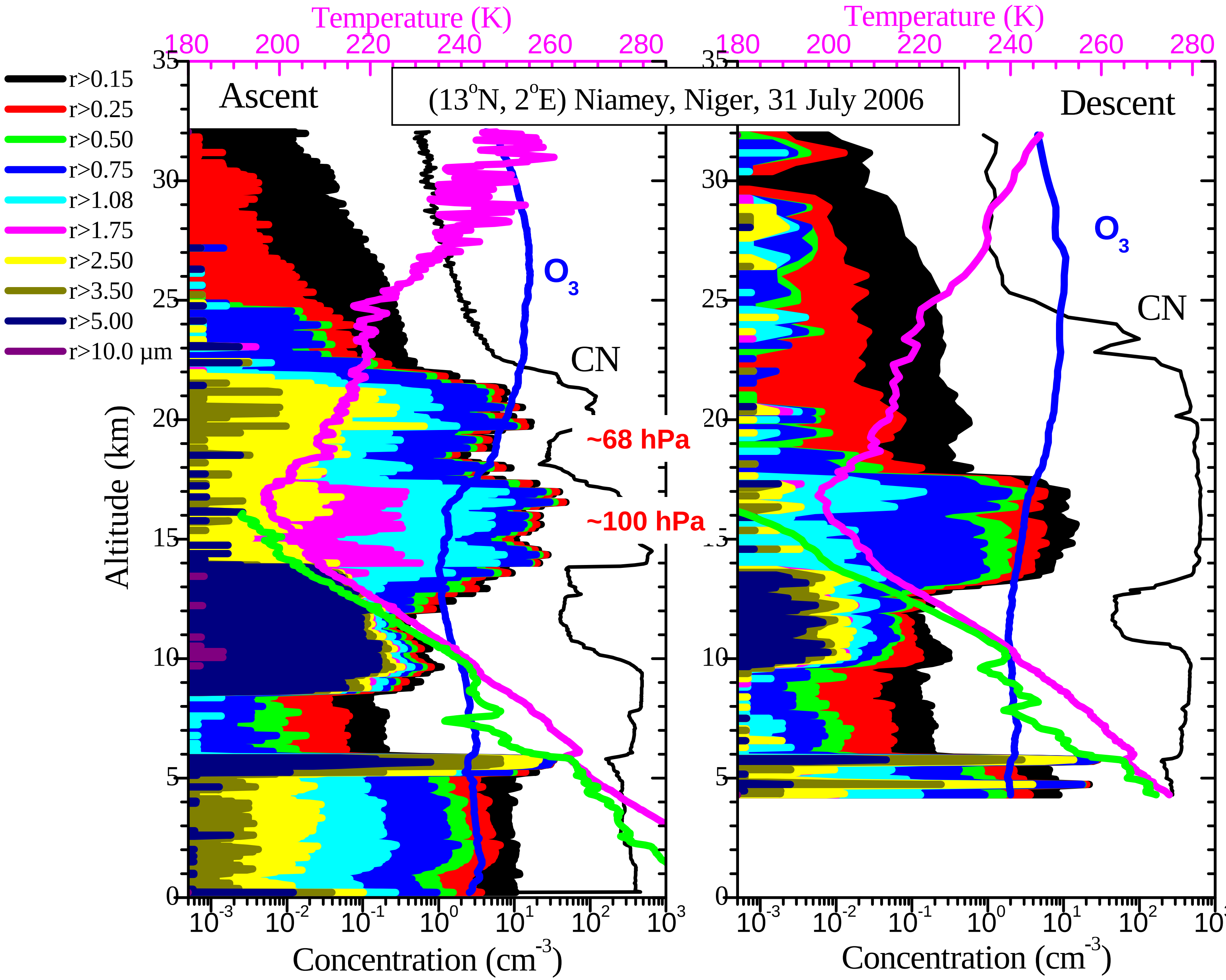


Grid Size 2° Latitude X 4° Longitude



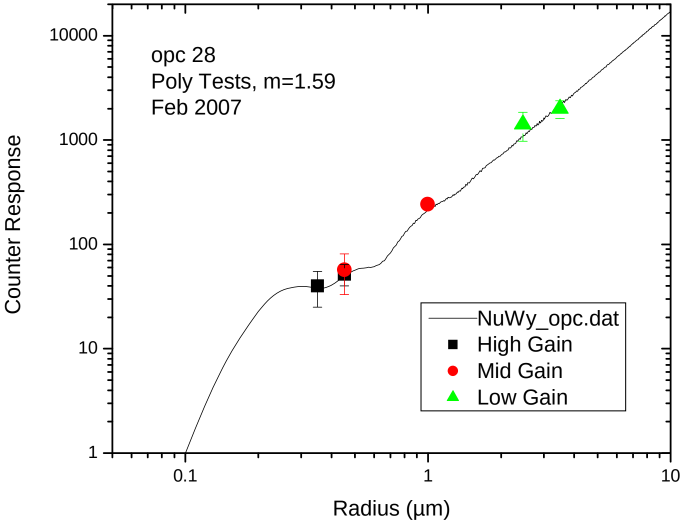

13 km
15 km
17 km
19 km
21 km
23 km
UTLS Aerosol Layer
Ascent
Descent

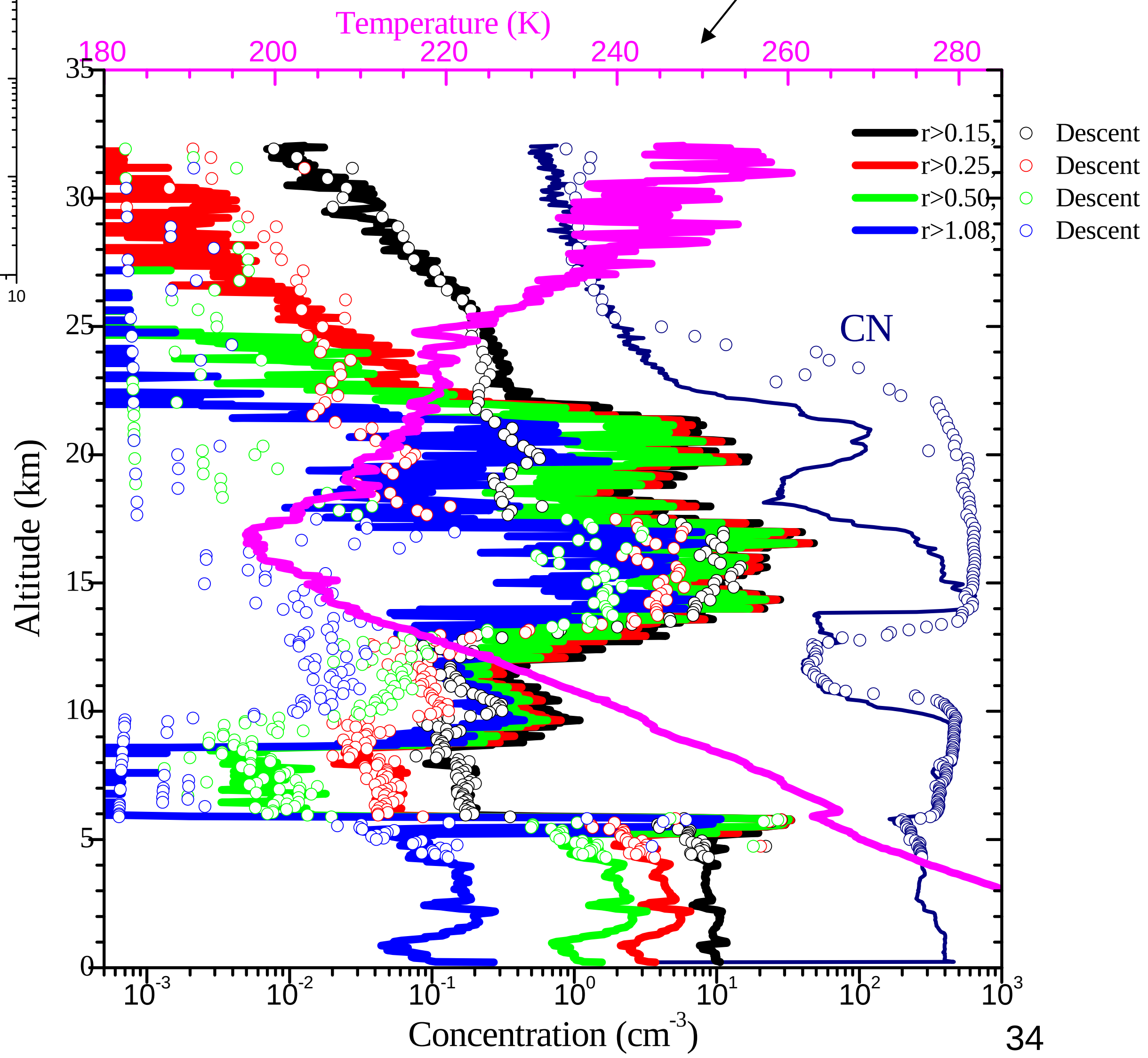

Temperature (K)
180 200 220 240 260 280
(13°N, 2°E) Niamey, Niger, 31 July 2006
r>0.15
r>0.25
r>0.50
r>0.75
r>1.08
r>1.75
r>2.50
r>3.50
r>5.00
r>10.0 µm
Altitude (km)
0 5 10 15 20 25 30 35
Descent
CN
10^-3 10^-2 10^-1 10^0 10^1 10^2 10^3
Concentration (cm^-3)

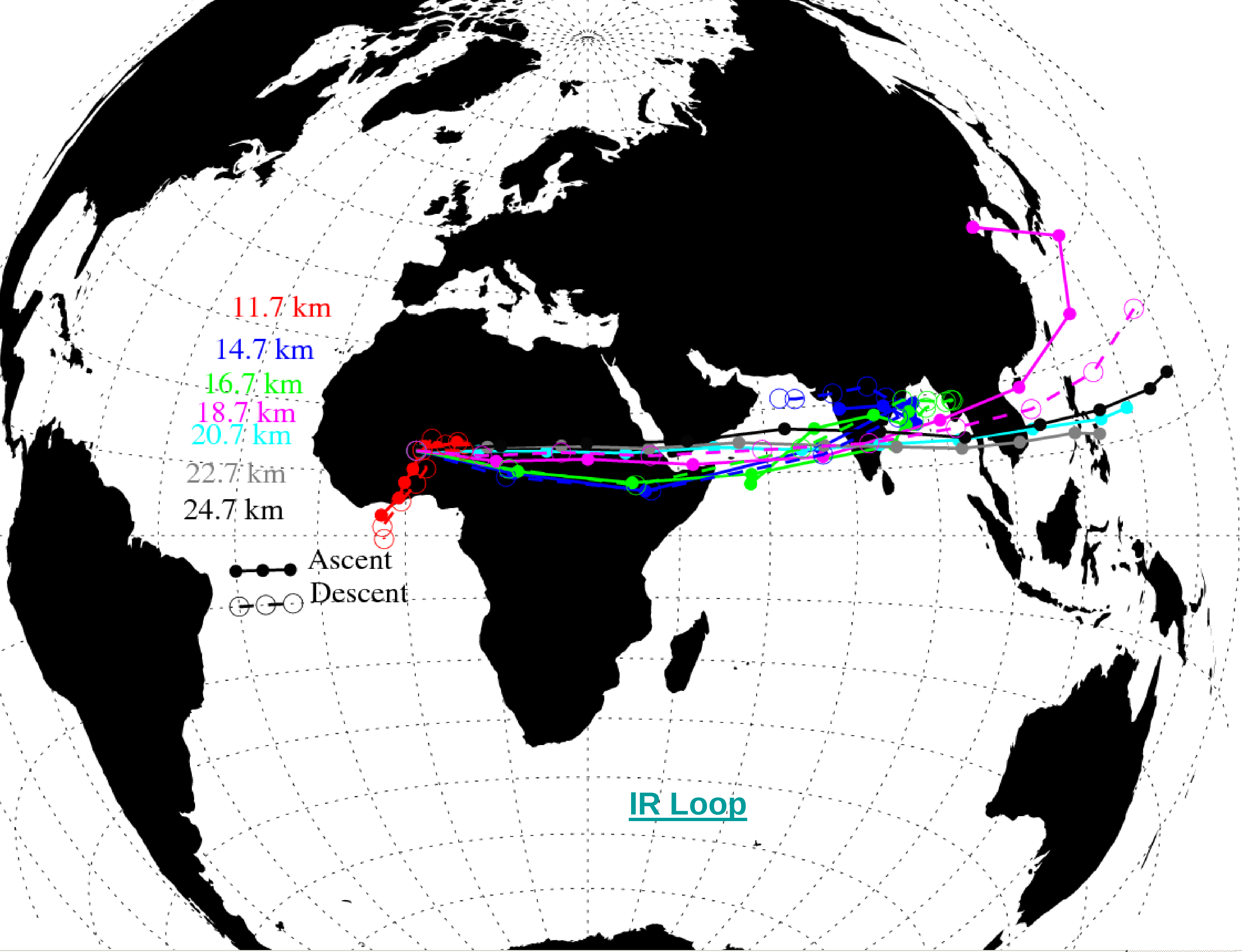


Temperature (K)
180
200
220
240
260
280
Temperature (K)
180
200
220
240
260
280
r>0.15
r>0.25
r>0.50
r>0.75
r>1.08
r>1.75
r>2.50
r>3.50
r>5.00
r>10.0 µm
Ascent
(13°N, 2°E) Niamey, Niger, 31 July 2006
Descent
O_3
O_3
CN
CN
~68 hPa
~100 hPa
Altitude (km)
35
30
25
20
15
10
5
0
Concentration (cm^{-3})
Concentration (cm^{-3})
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

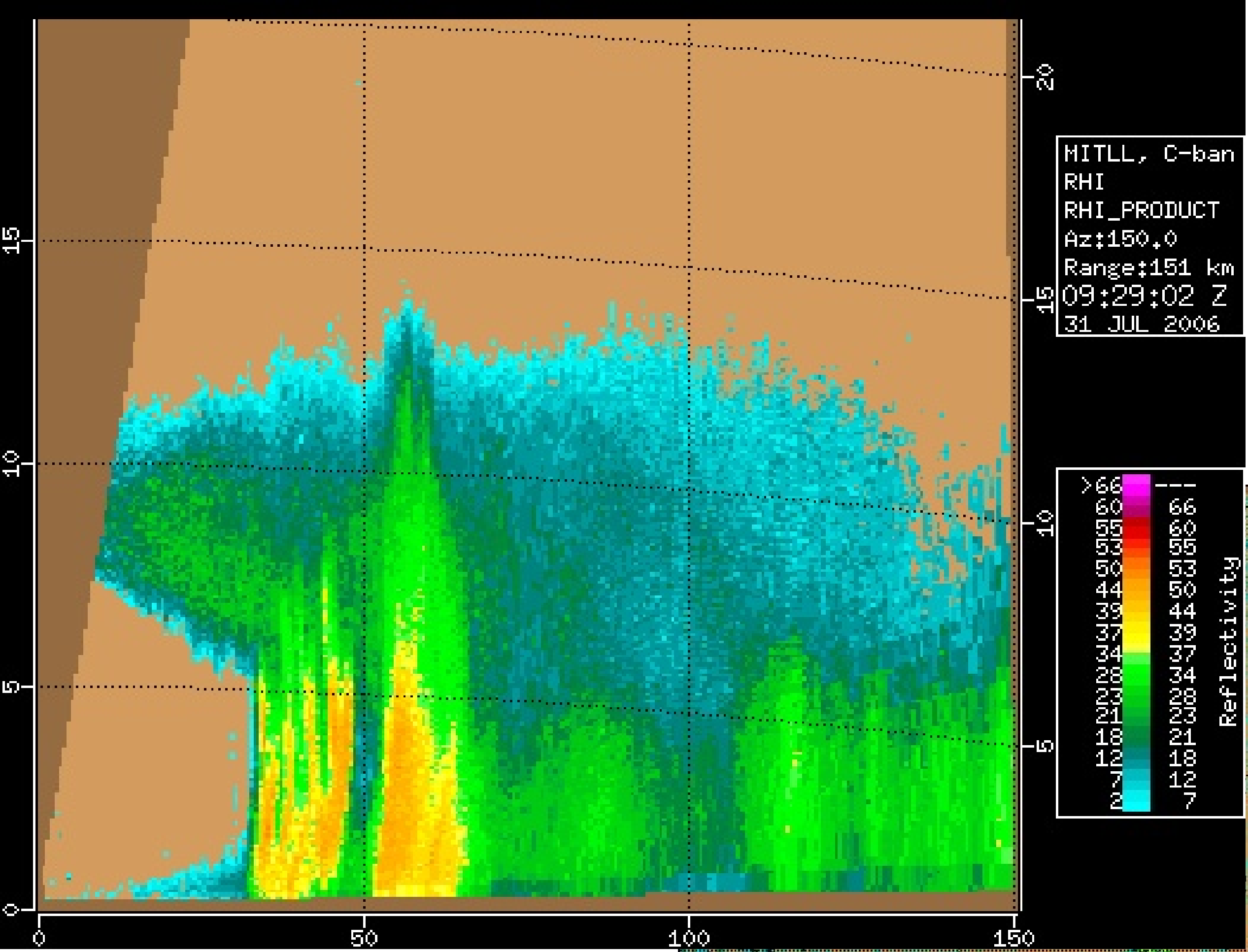
Instrument checks
Post flight lab
Ascent/Descent comparison

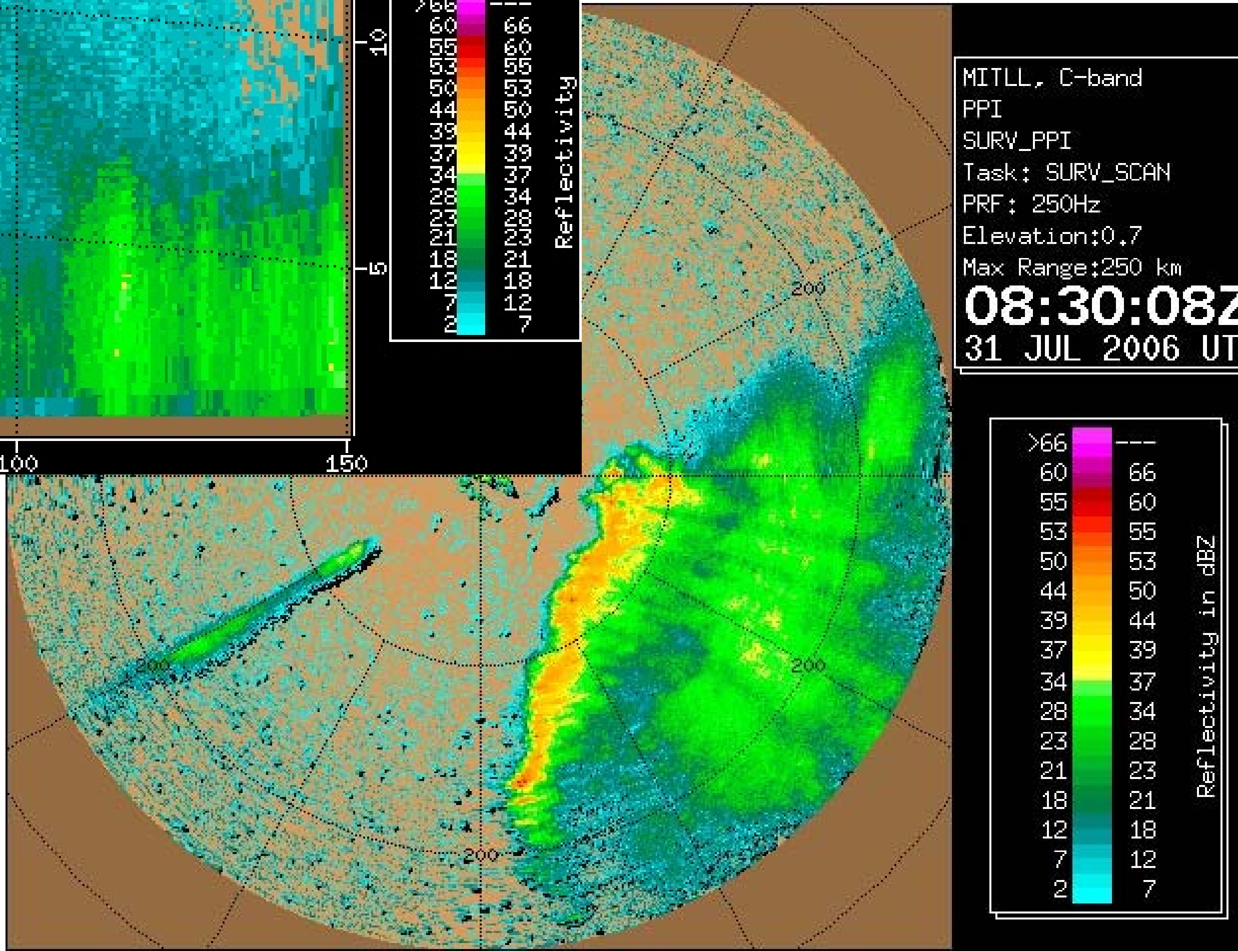




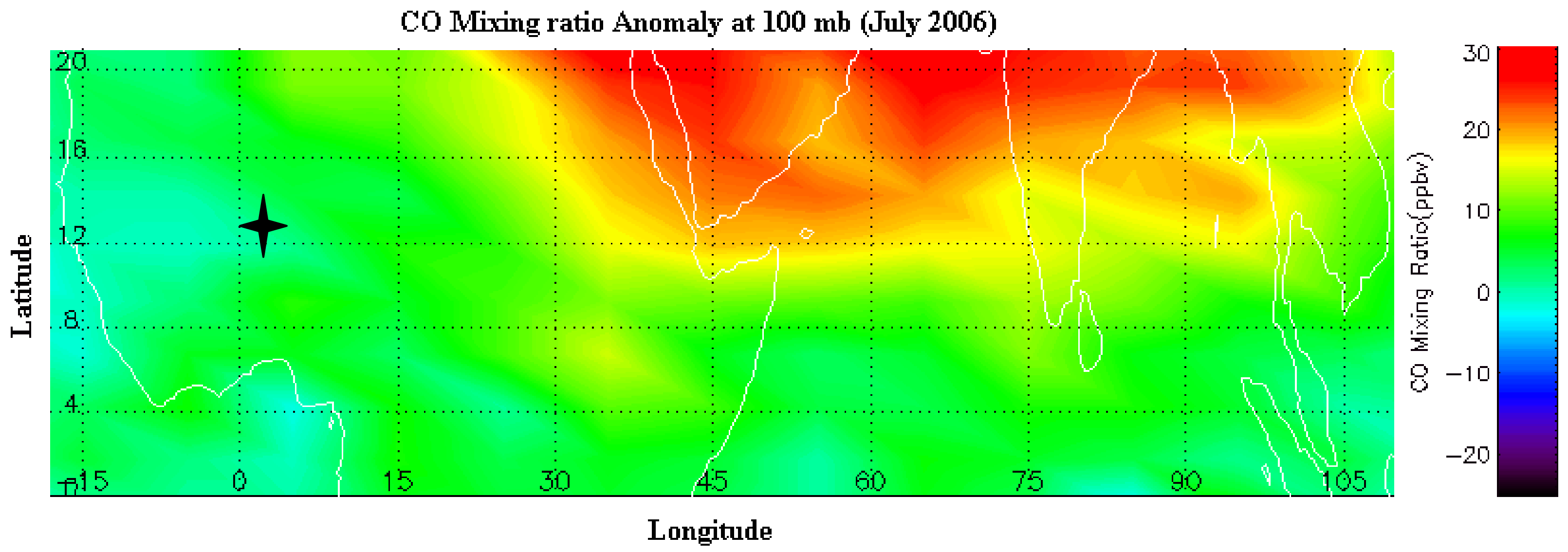

11.7 km
14.7 km
16.7 km
18.7 km
20.7 km
22.7 km
24.7 km
Ascent
Descent
IR Loop

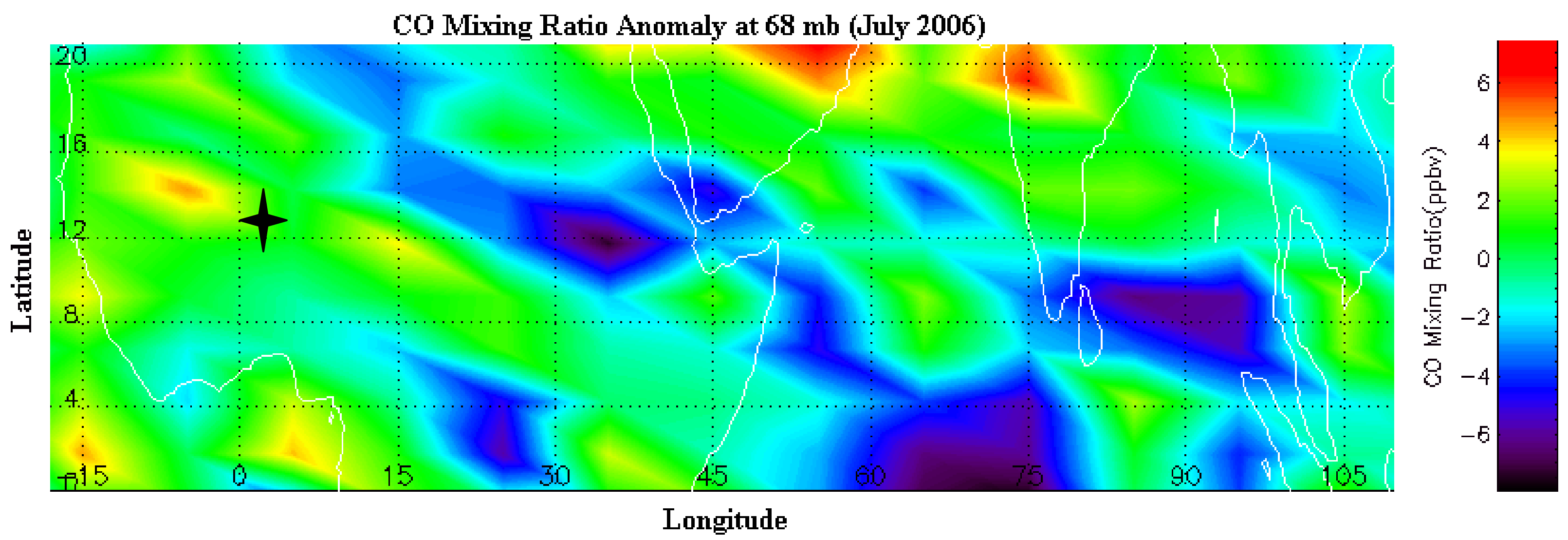
Radar Images compliments of Earl Williams



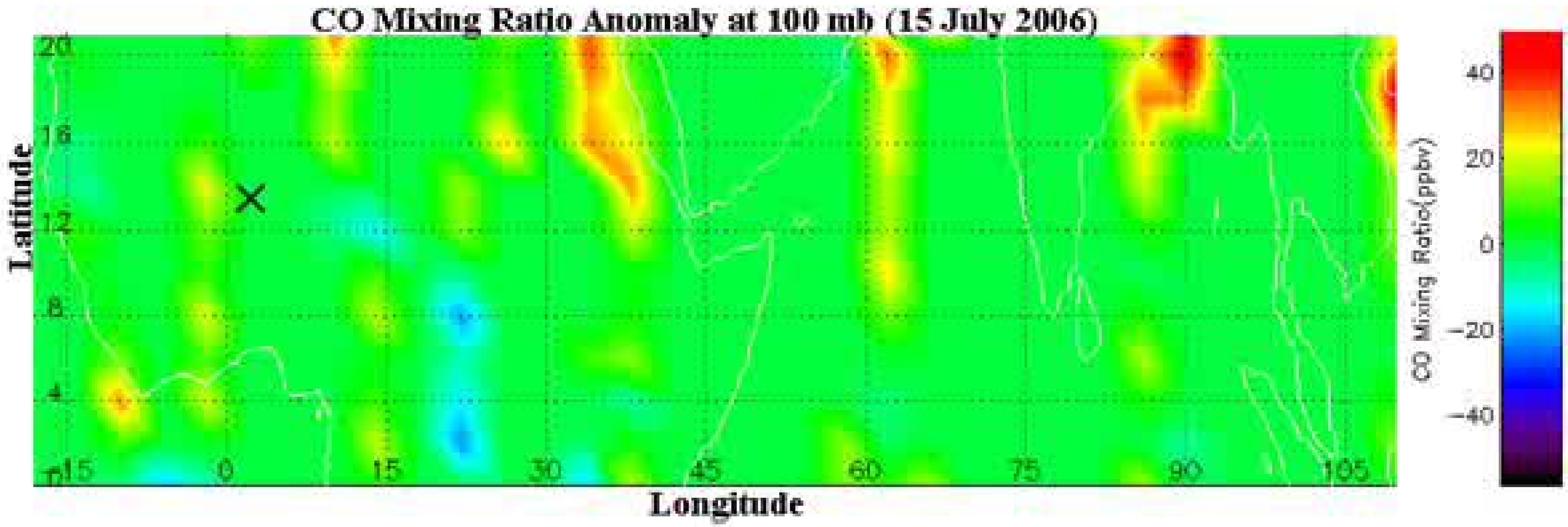


July 2006 average of AURA MLS CO measurements at 100 and 68 hPa

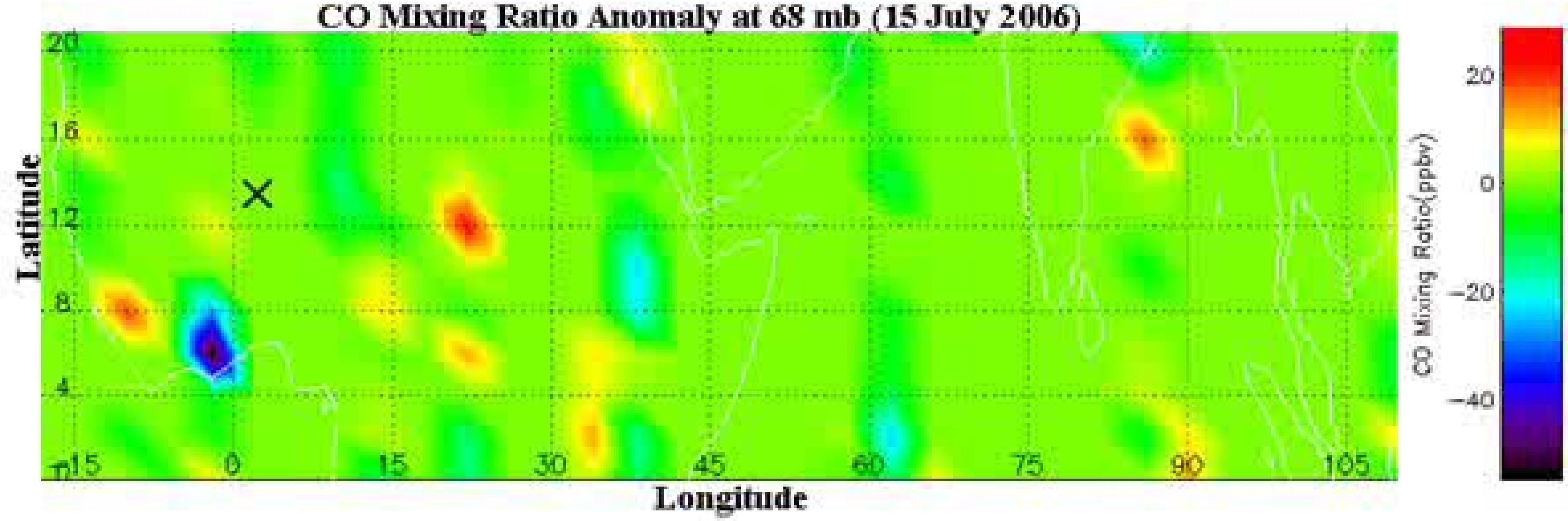


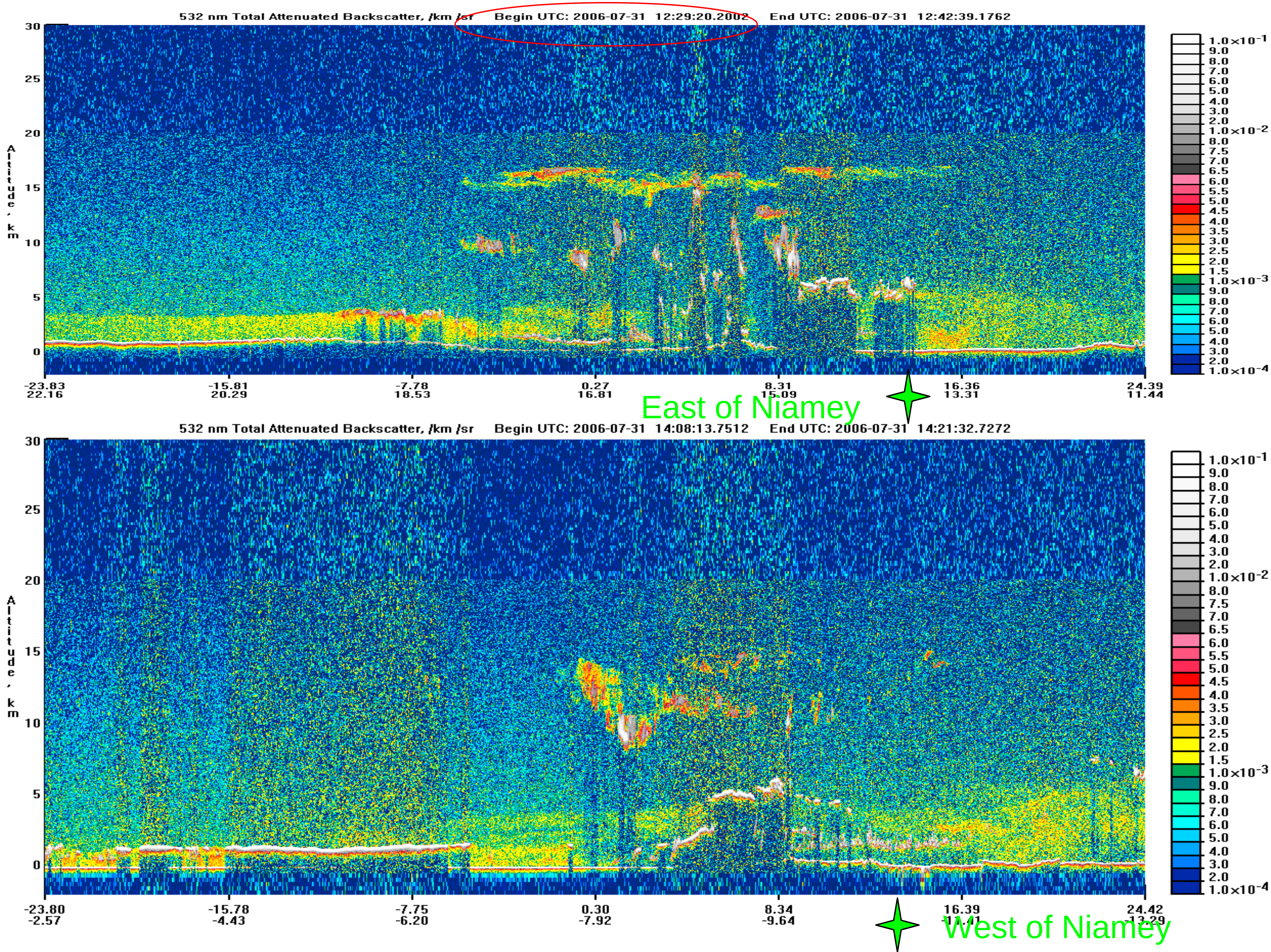


Grid Size 2° Latitude X 4° Longitude

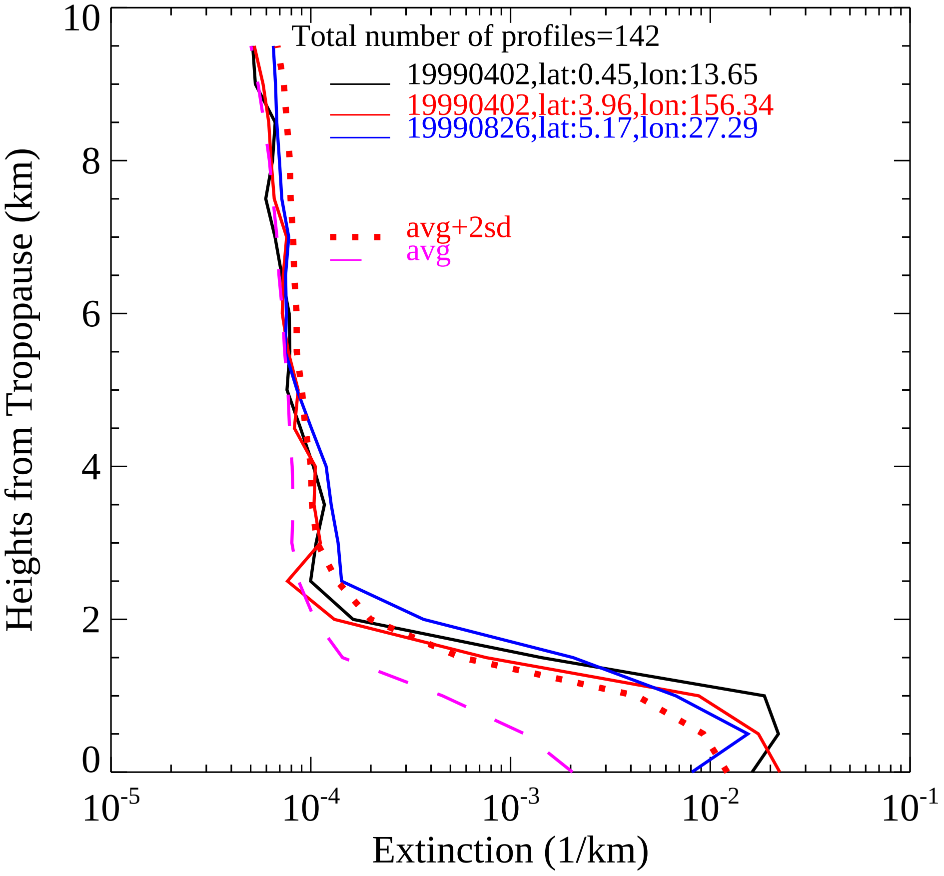


Grid Size 2° Latitude X 4° Longitude

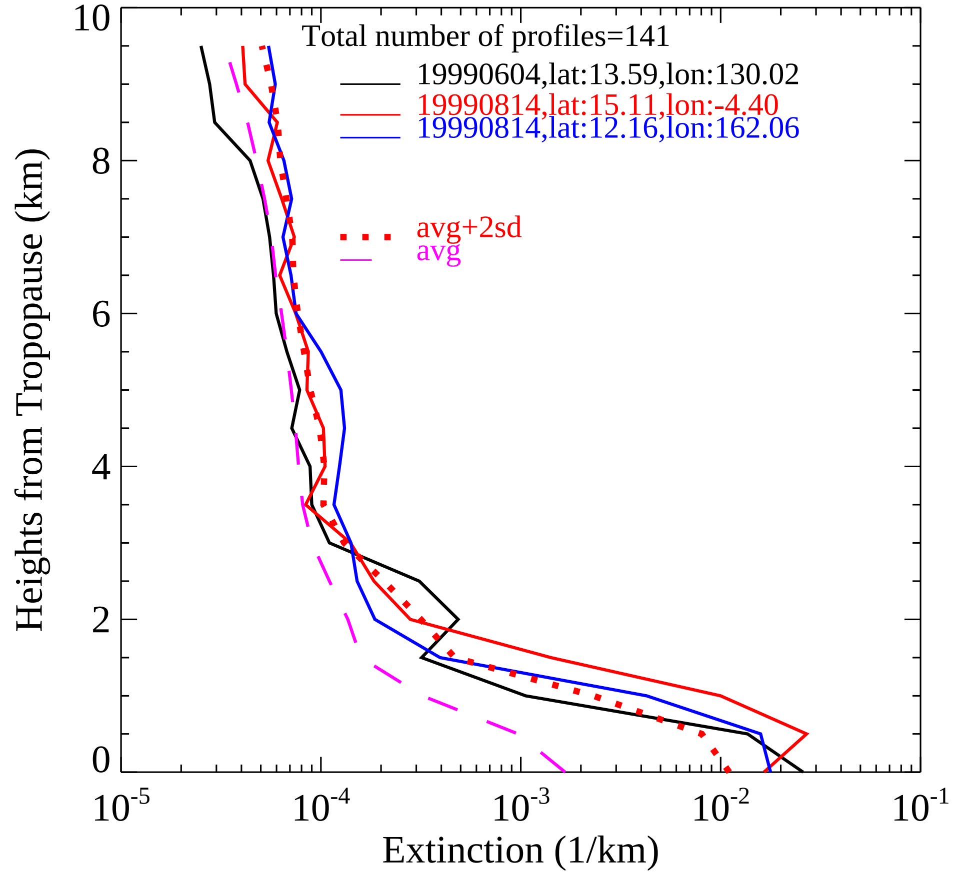



532 nm Total Attenuated Backscatter, /km /sr
Begin UTC: 2006-07-31 12:29:20.2002
End UTC: 2006-07-31 12:42:39.1762
Altitude, km
30
25
20
15
10
5
0
-23.83
22.16
-15.81
20.29
-7.78
18.53
0.27
16.81
8.31
15.09
16.36
13.31
24.39
11.44
East of Niamey
1.0×10⁻¹
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0×10⁻²
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0×10⁻³
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0×10⁻⁴
532 nm Total Attenuated Backscatter, /km /sr
Begin UTC: 2006-07-31 14:08:13.7512
End UTC: 2006-07-31 14:21:32.7272
Altitude, km
30
25
20
15
10
5
0
-23.80
-2.57
-15.78
-4.43
-7.75
-6.20
0.30
-7.92
8.34
-9.64
16.39
24.42
-13.29
West of Niamey

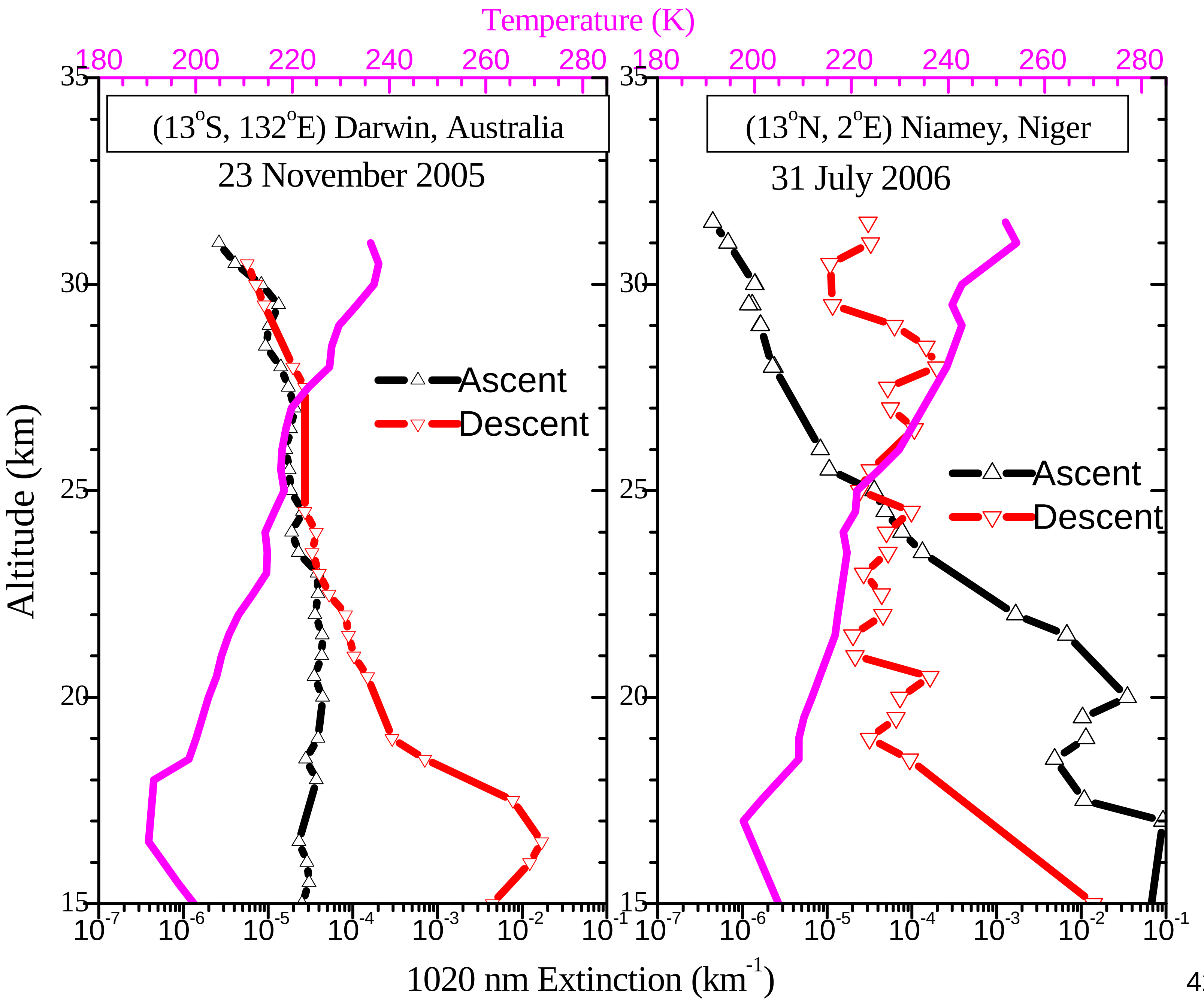
OCT98-MAR99 (0-10S)



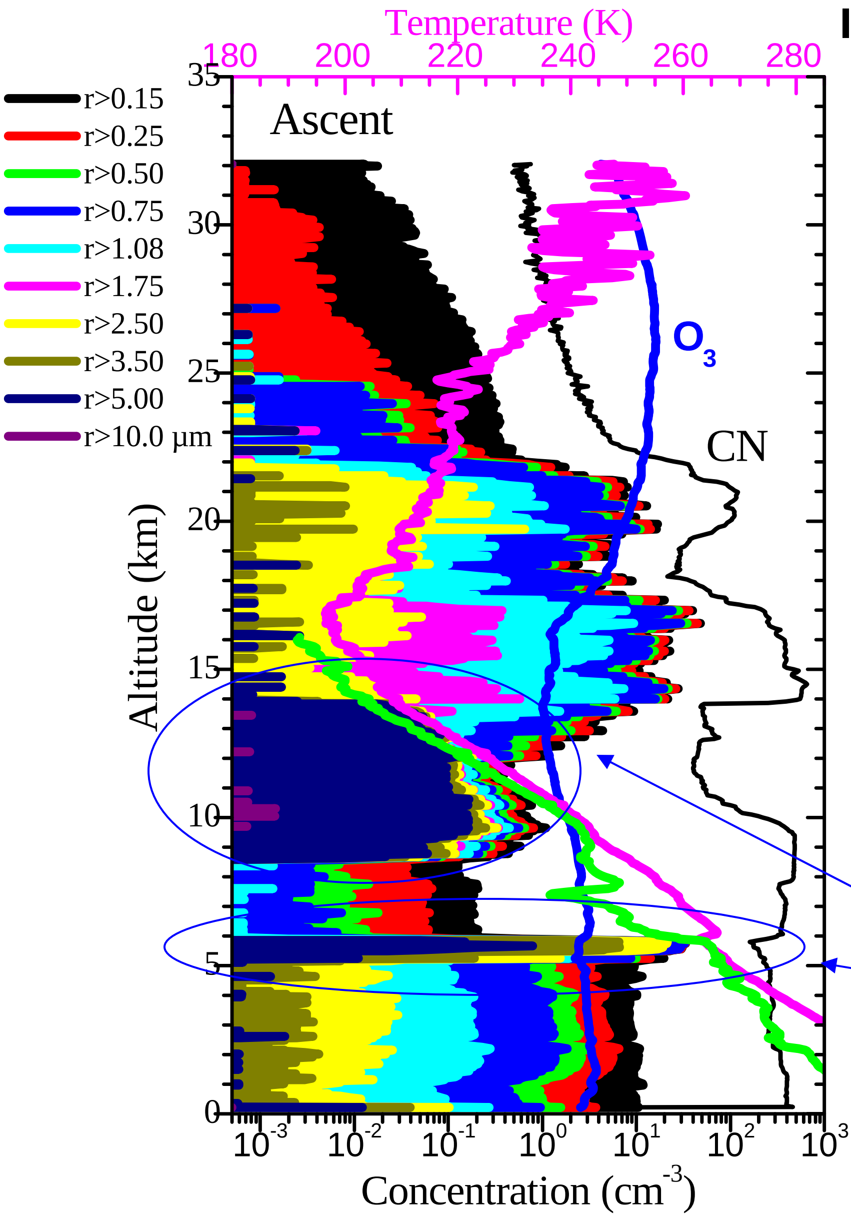
APR-AUG99 (0-10N)



SAGE II data analyzed by Mahesh Kovilakam


Temperature (K)
180
200
220
240
260
280
35
30
25
20
15
(13°S, 132°E) Darwin, Australia
23 November 2005
(13°N, 2°E) Niamey, Niger
31 July 2006
Ascent
Descent
Altitude (km)
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1020 nm Extinction (km^{-1})

Origin of particles r >1 - 4 μm at 3 - 6 km (200 K) above the tropopause?



Instrument mal function - not obvious

- **Two instruments detect same feature**
- **In unperturbed regions ascent and descent agree, post flight checks reveal no problems**

Contamination from flight train – possible but:

- **Not seen before in mid latitudes.**
- **Cannot explain Darwin descent measurements.**
- **For Niger measurements would have to contaminate air space on ascent with both large and small particles and instruments would have to return through the same air on descent. Recall elevated CN on descent beginning at top of elevated aerosol layer.**

Ice, Nitric acid trihydrate?
No, Temperatures too warm
Size distributions do not conform to either: cirrus or other stratospheric (NAT) clouds

Origin of particles between 1 and 4 µm at altitudes of 2 to 6 km (200 K) above the tropopause?

- Volcanic? - No
  - No obvious major recent eruptions for the measurements.
  - For the Nigerian measurements the Ecuadorian eruption is too low and observations exceed expectations from such an eruption.

- Supporting evidence for nearby convection which may penetrate the tropopause?
  - Darwin
    - AURA MLS - elevated CO at 100 and 68 hPa in areas along back trajectories from the measurements.
    - IR satellite record yet to be investigated
  - Niger
    - Severe convection in the region based on IR satellite measurements.
    - AURA MLS – elevated CO near the measurements at both 100 and 68 hPa.
    - CALYPSO and MODIS data no supporting evidence.
- General supporting evidence for instrusions of tropospheric aerosol into lower stratosphere
  - SAGE II shows some evidence, but frequency is low.

The phenomenon is highly local. Large differences in ascent descent profiles are separated by tens of kilometers horizontally

Thank you

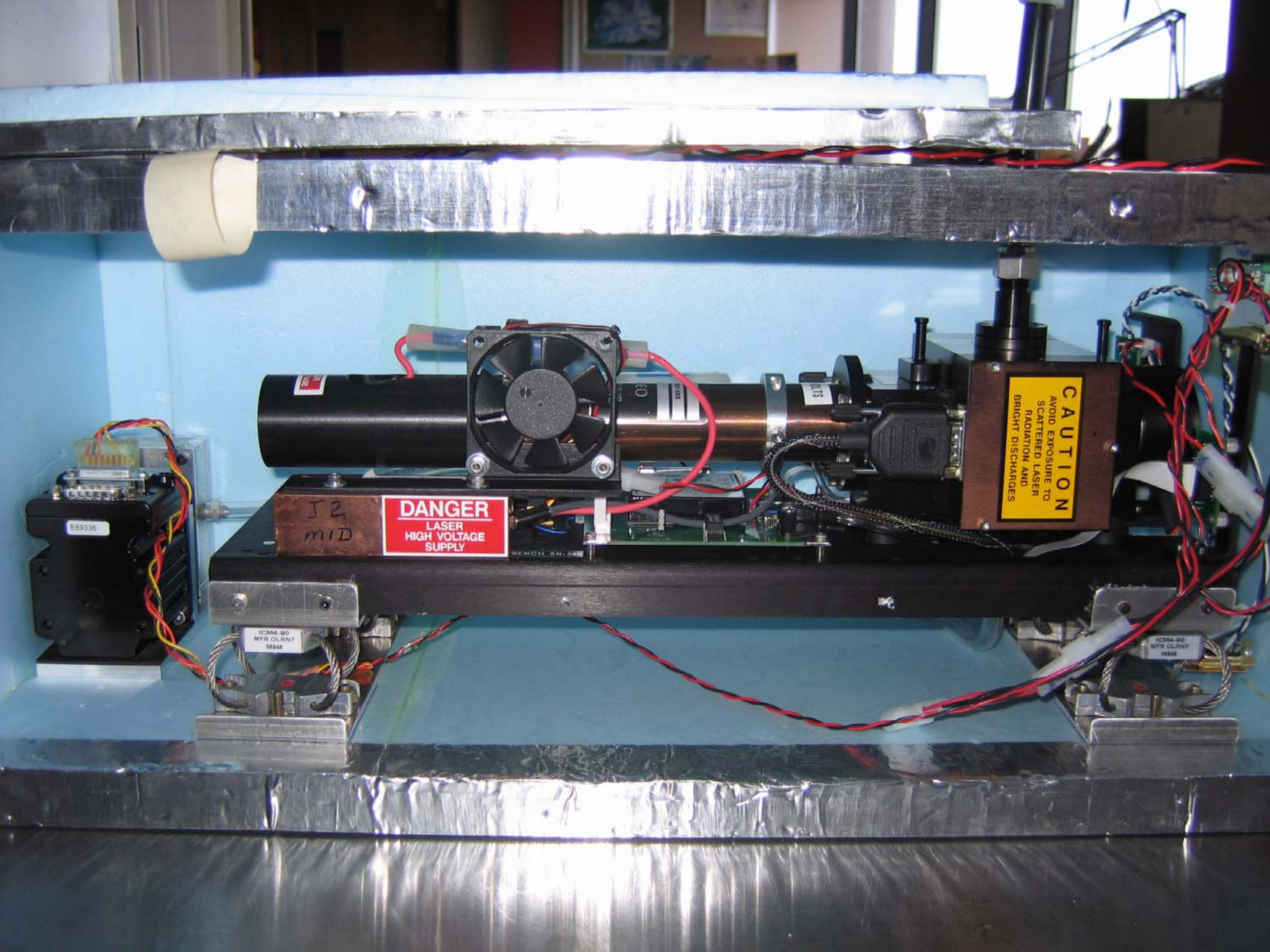
Acknowledgments

- **These measurements over the years have been supported by the National Science Foundation, the National Aeronautics and Space Administration and the Naval Research Laboratory.**

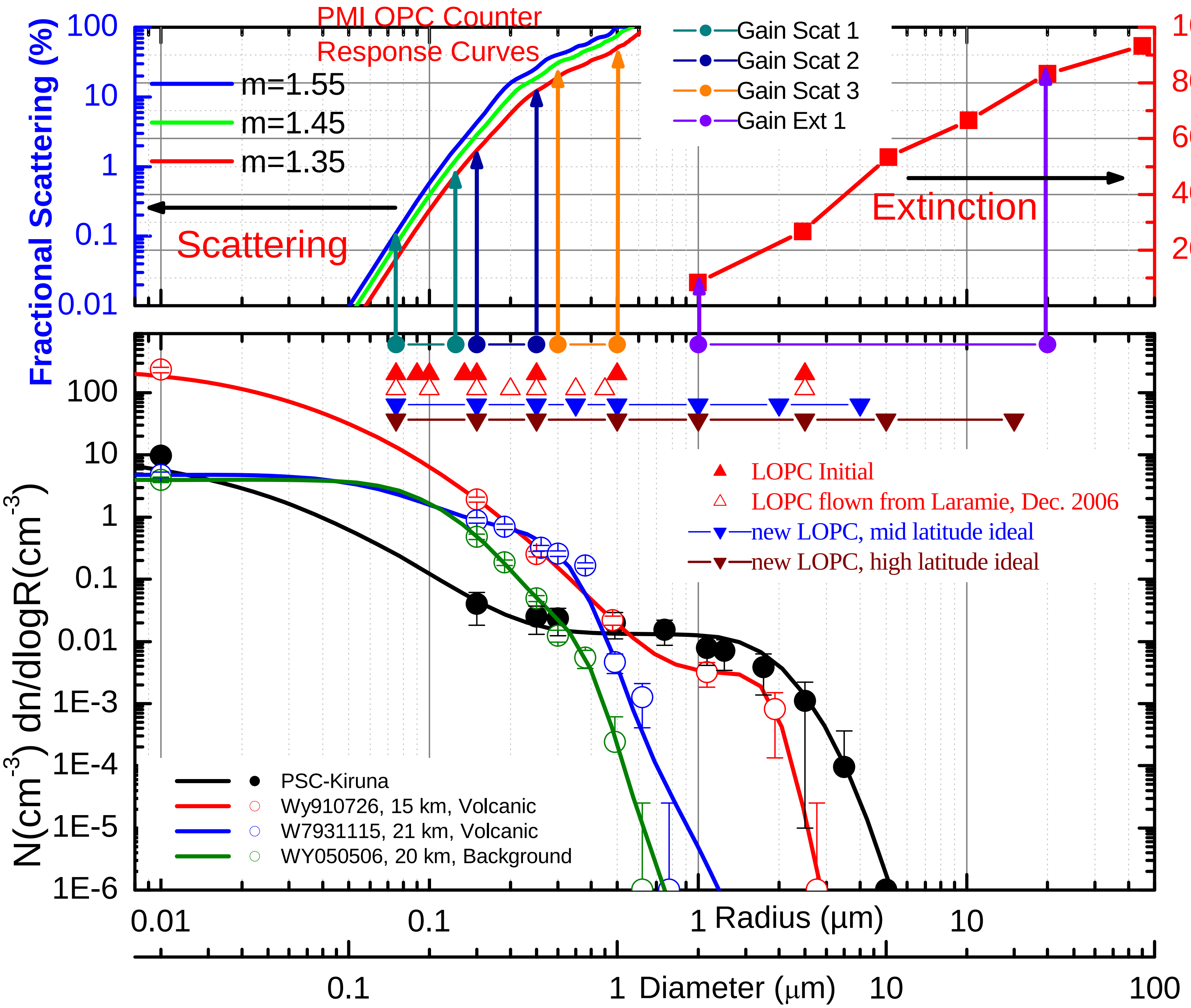
- **Many individuals at the University of Wyoming have contributed to the quality and the longevity of these measurements and we acknowledge their hard work and willingness to spend many an early morning on the Laramie plains waiting for the winds to fall to favorable levels.**

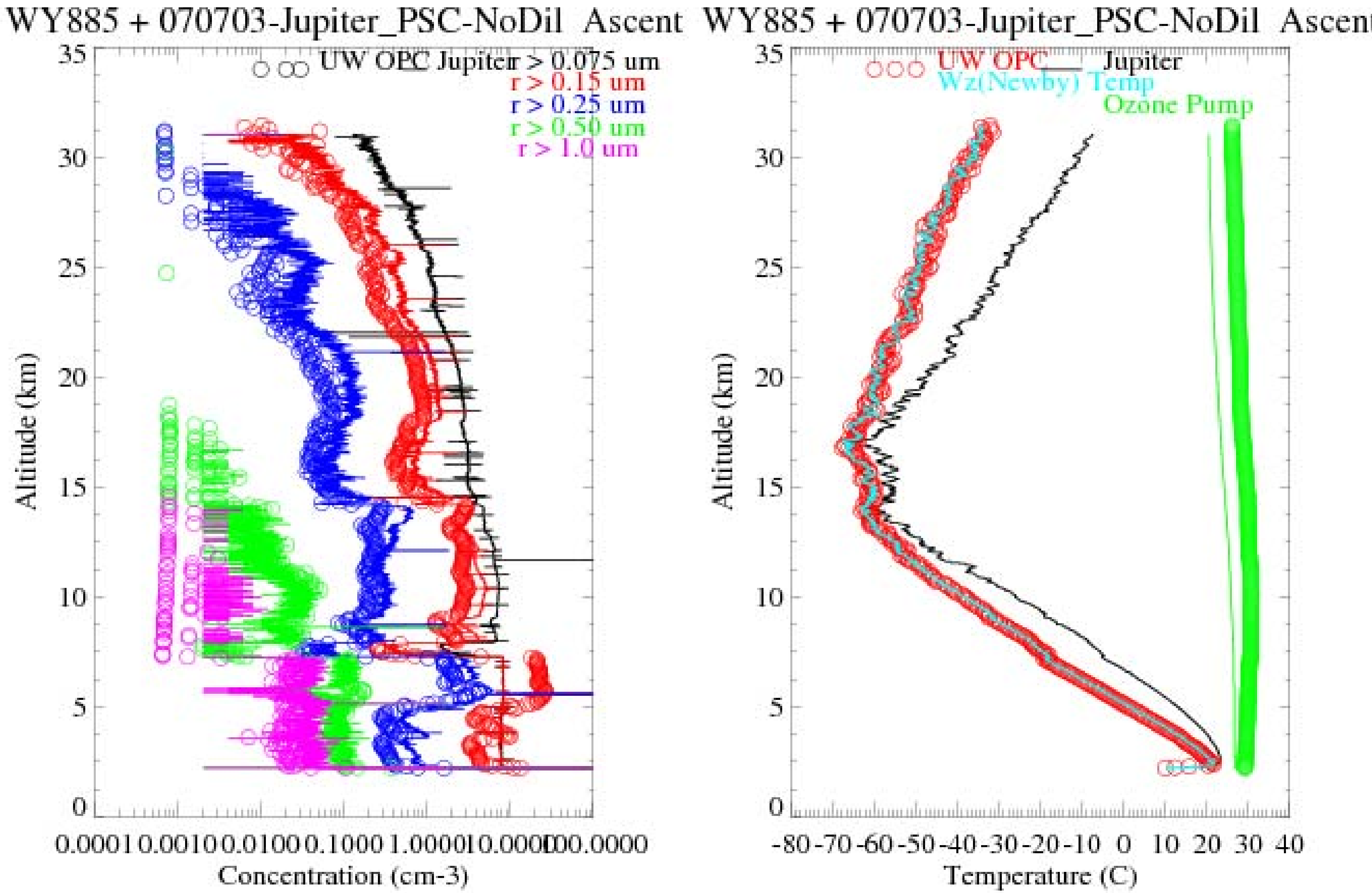
What's new

- A laser based optical counter, manufactured by Particle Metrics Inc.
- Needed to:
  - Expand size measurements to sizes less than 0.15 μm. Size range of new instrument 0.075 – 10.0 μm
  - Reduce the minimum concentration threshold below 0.006 cm-3. Flow rate of new instrument 3 x WOPC -> minimum concentrations will be 0.002 cm-3 for a 10 second measurement.

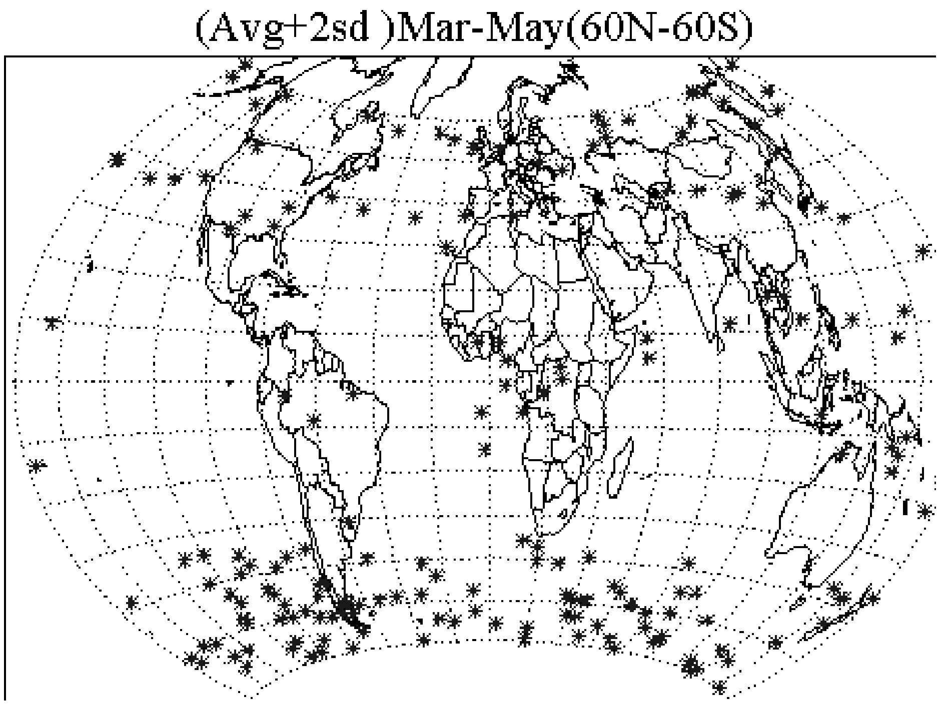


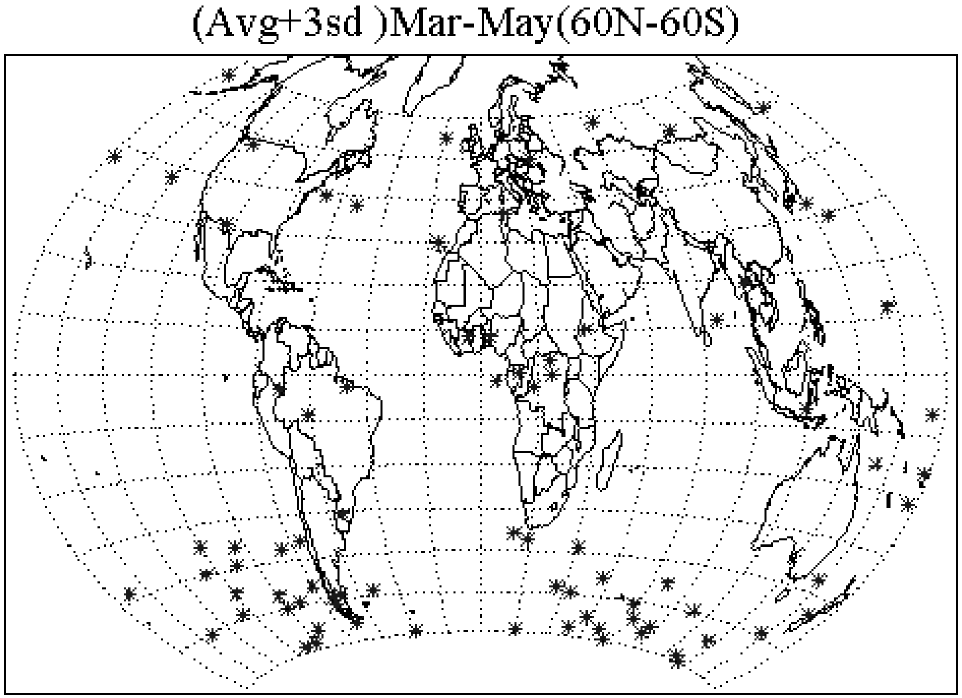
DANGER
LASER
HIGH VOLTAGE
SUPPLY
CAUTION
AVOID EXPOSURE TO
SCATTERED LASER
RADIATION AND
BRIGHT DISCHARGES
J2
MID
E69336

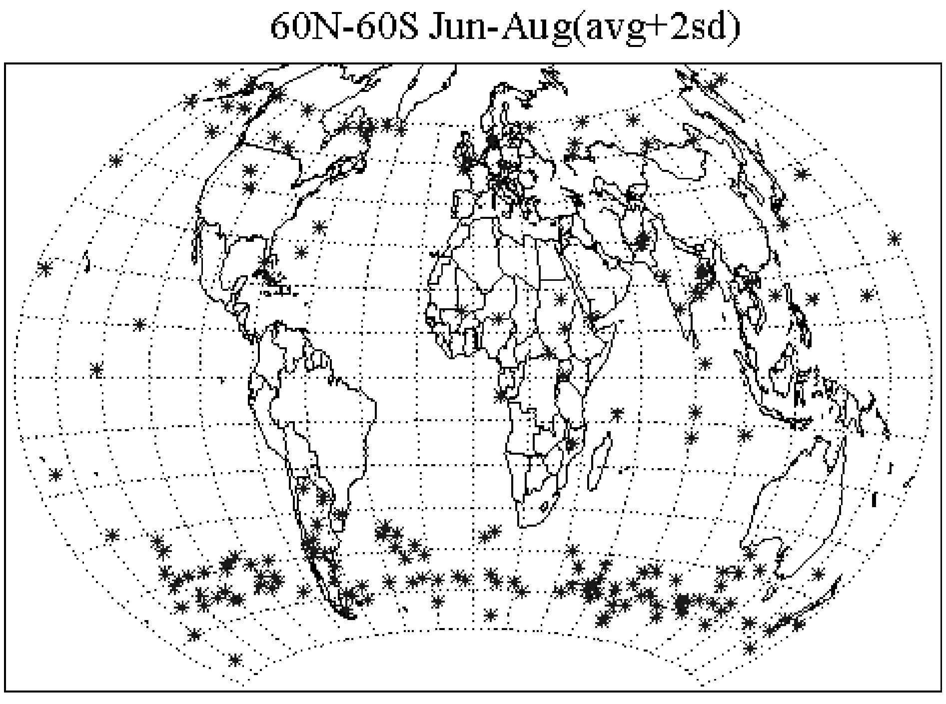

PMI OPC Counter
Response Curves
m=1.55
m=1.45
m=1.35
Scattering
Extinction
Gain Scat 1
Gain Scat 2
Gain Scat 3
Gain Ext 1
Fractional Scattering (%)
Fractional Extinction(%)
LOPC Initial
LOPC flown from Laramie, Dec. 2006
new LOPC, mid latitude ideal
new LOPC, high latitude ideal
PSC-Kiruna
Wy910726, 15 km, Volcanic
W7931115, 21 km, Volcanic
WY050506, 20 km, Background
N(cm^-3) dn/dlogR(cm^-3)
Radius (μm)
Diameter (μm)

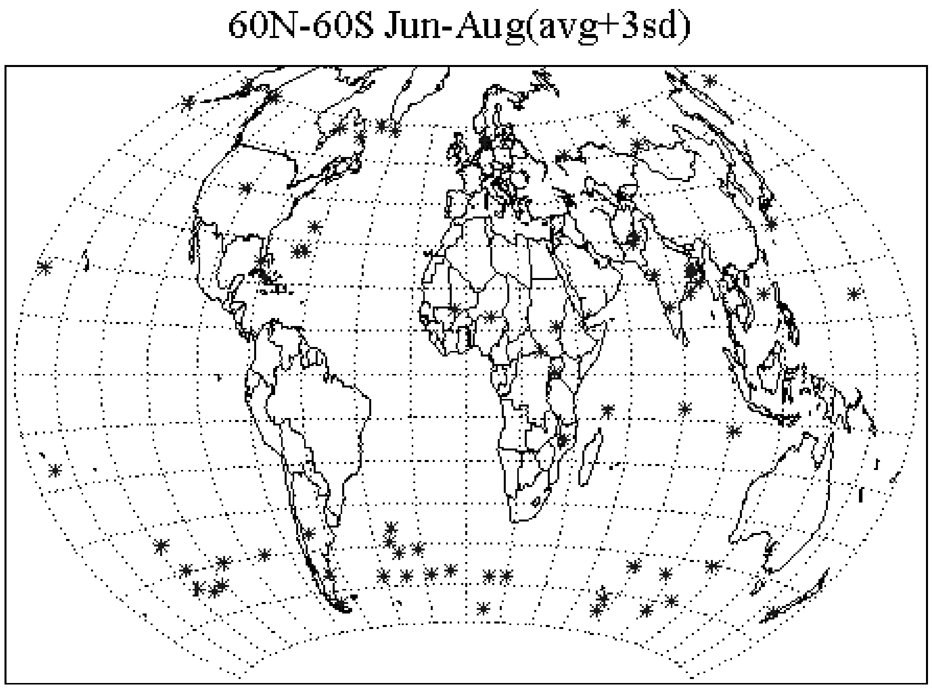


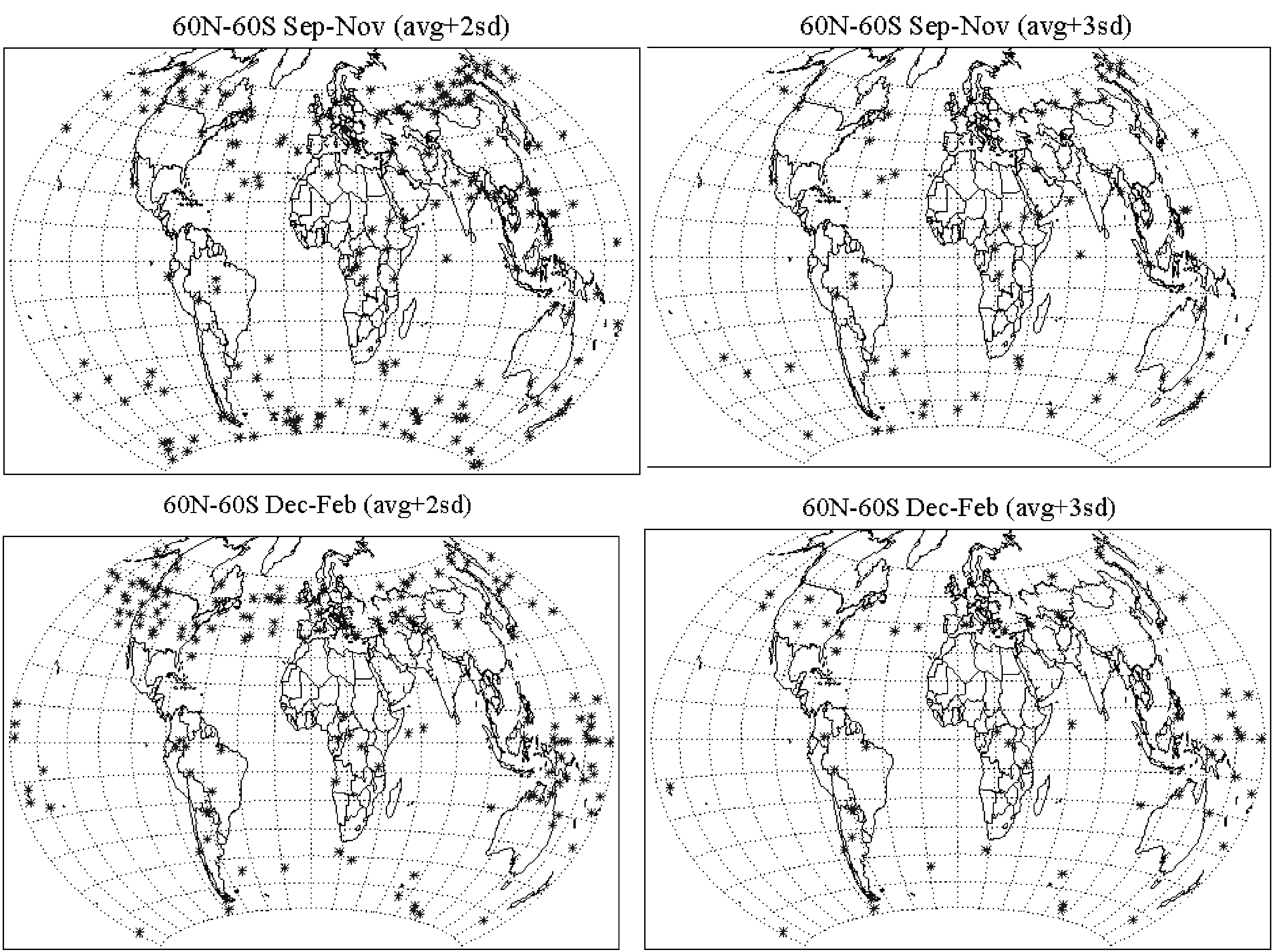
WY885 + 070703-Jupiter_PSC-NoDil Ascent
UW OPC Jupiter
r > 0.075 um
r > 0.15 um
r > 0.25 um
r > 0.50 um
r > 1.0 um
Altitude (km)
Concentration (cm-3)
0.0001 0.0010 0.0100 0.1000 1.0000 10.0000 100.0000
0 5 10 15 20 25 30 35
WY885 + 070703-Jupiter_PSC-NoDil Ascent
UW OPC
Jupiter
Wz(Newby) Temp
Ozone Pump
Altitude (km)
Temperature (C)
-80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40


(Avg+2sd)Mar-May(60N-60S)


(Avg+3sd)Mar-May(60N-60S)


60N-60S Jun-Aug(avg+2sd)


60N-60S Jun-Aug(avg+3sd)

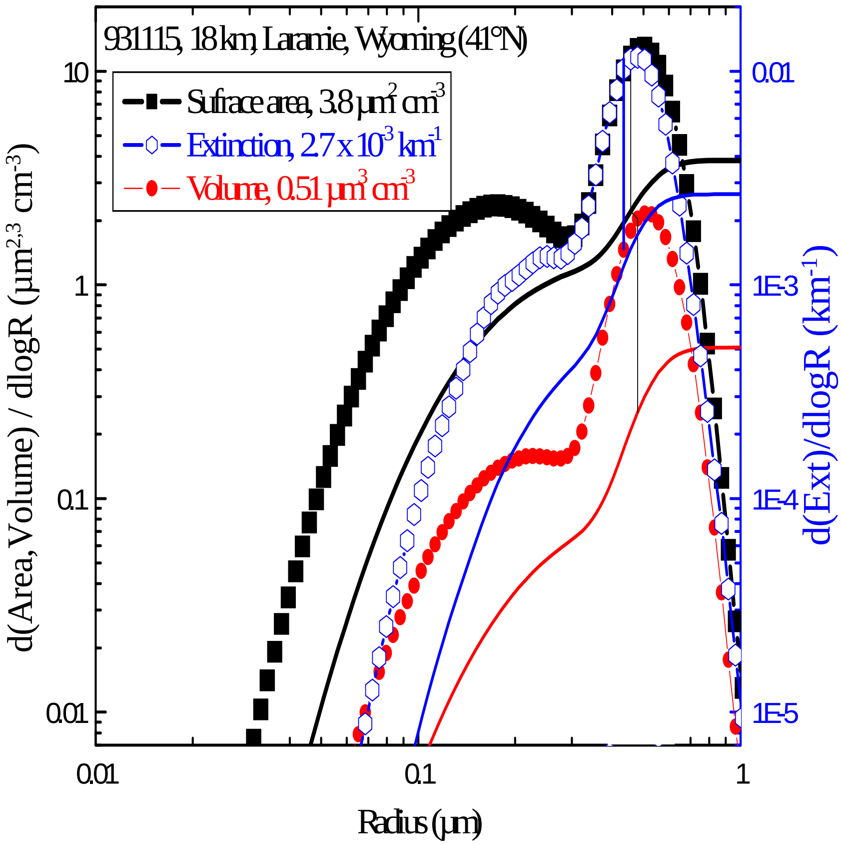

60N-60S Sep-Nov (avg+2sd)
60N-60S Sep-Nov (avg+3sd)
60N-60S Dec-Feb (avg+2sd)
60N-60S Dec-Feb (avg+3sd)

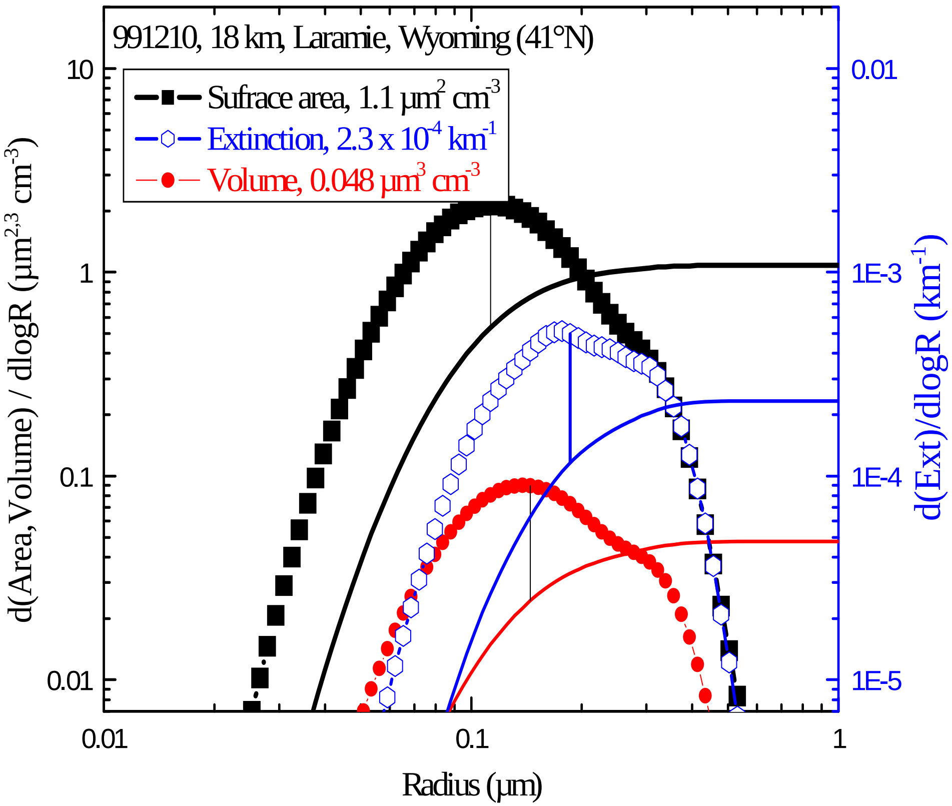
Stratospheric Aerosol Summary

- **Understanding is fairly extensive**
  - Composition well characterized
  - Volcanic and non-volcanic aerosol can be modeled reasonably well
  - Post Pinatubo volcanic quiescence has been long enough to test for long term trends in background stratospheric aerosol

- **Outstanding questions/problems**
  - No SO2 measurements in the upper atmosphere, particularly tropical
  - Tropical UTLS aerosol measurements are limited and confusing
  - Surface area of non-volcanic aerosol is not well characterized by instruments available
  - Formation temperatures for nitric acid trihydrates in polar stratospheric clouds not well characterized
  - We are losing measurement platforms for stratospheric aerosol (No replacement for SAGE, POAM, Langley lidar)

Estimates of differential surface area ($\mu m^2\ cm^{-3}$), , and volume ($\mu m^3\ cm^{-3}$) for in situ measurements in 1993 and 1999





Volcanoes?

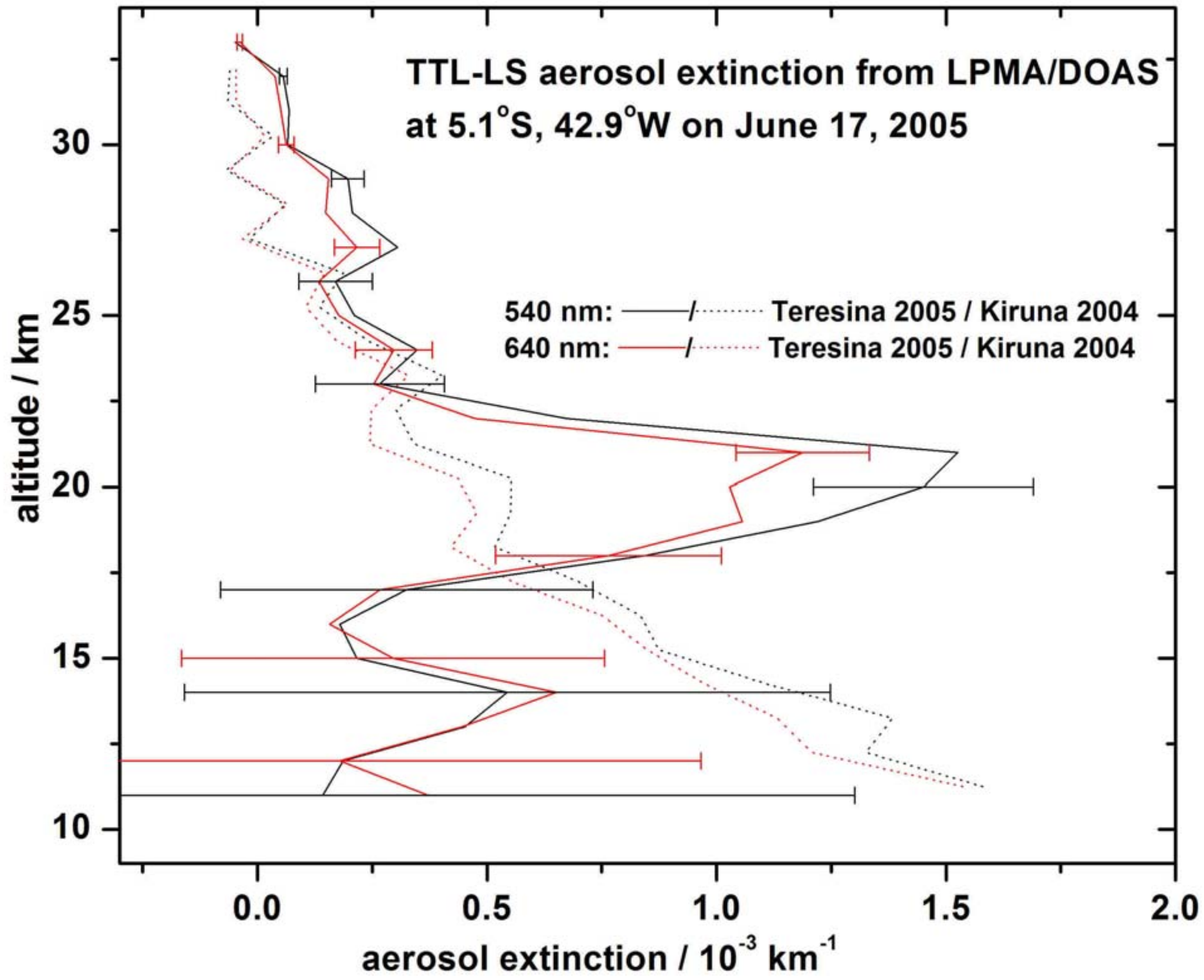
Soufriere Hills, Montserrat Island 20 May 2006 –

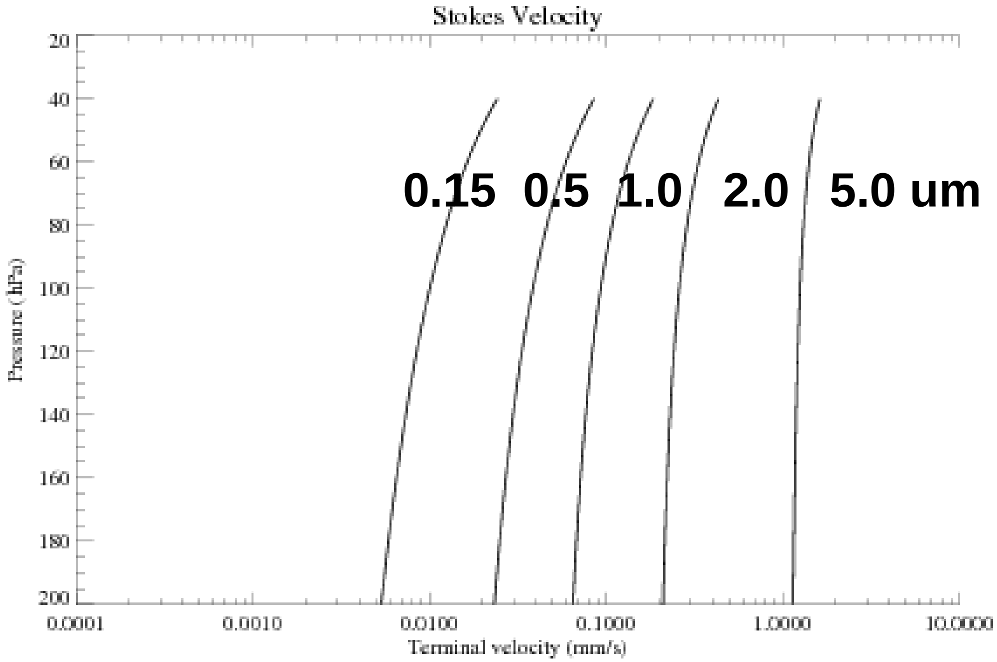
Signature apparent on DMI backscattersondes and OPC flights in August as a thin layer at 20 km. More about this from Francesco Cairo later.

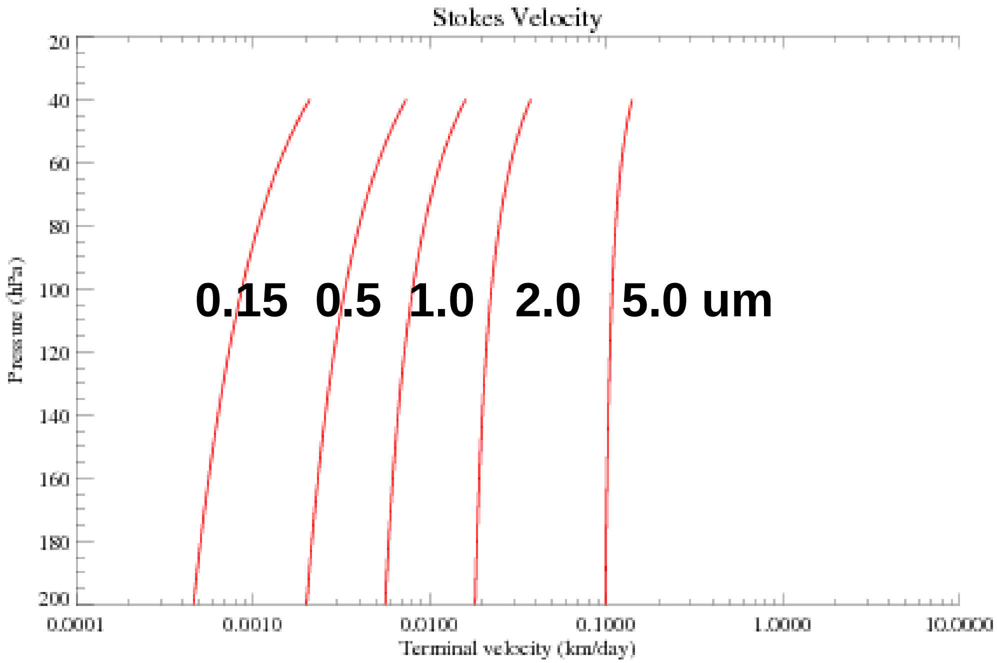
No other significant stratospheric events.

Mount Cleveland on 23 May 2006
Jeffrey N. Williams, Flight Engineer
and NASA Science Officer,
International Space Station Expedition

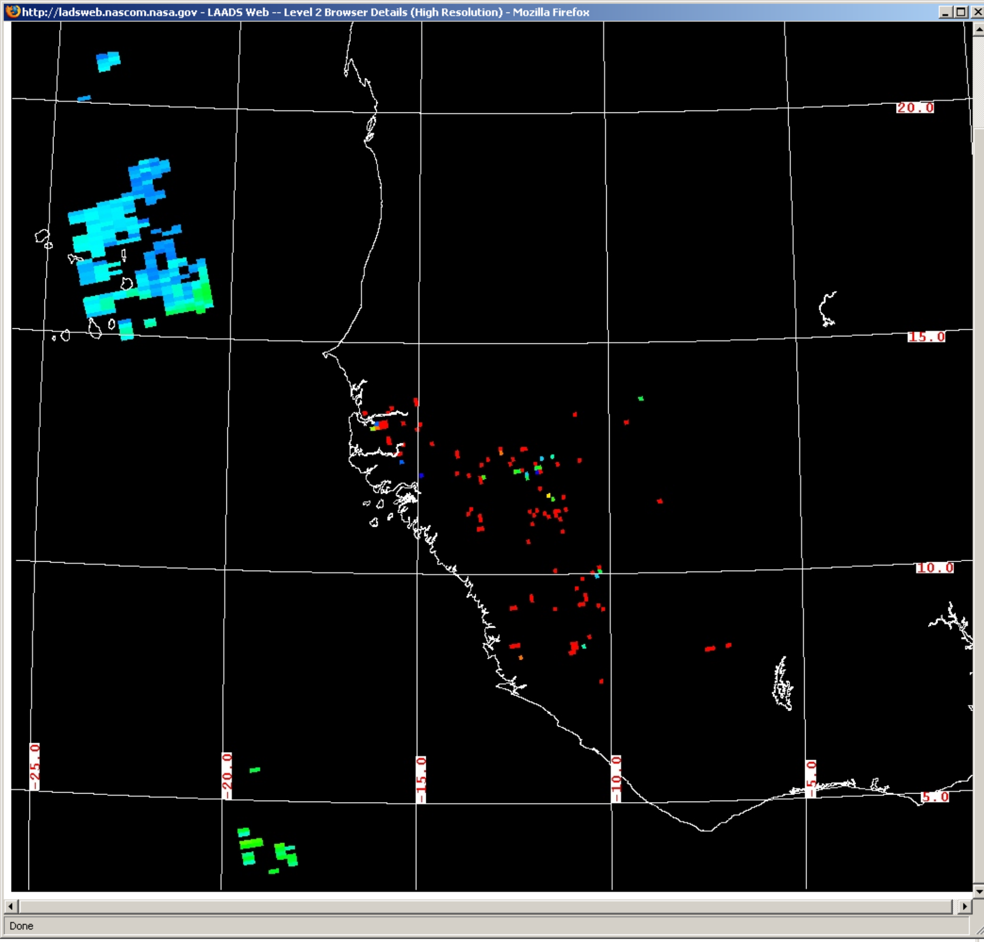
LPMA/DOAS balloon payload, Klaus Pfeilsticker

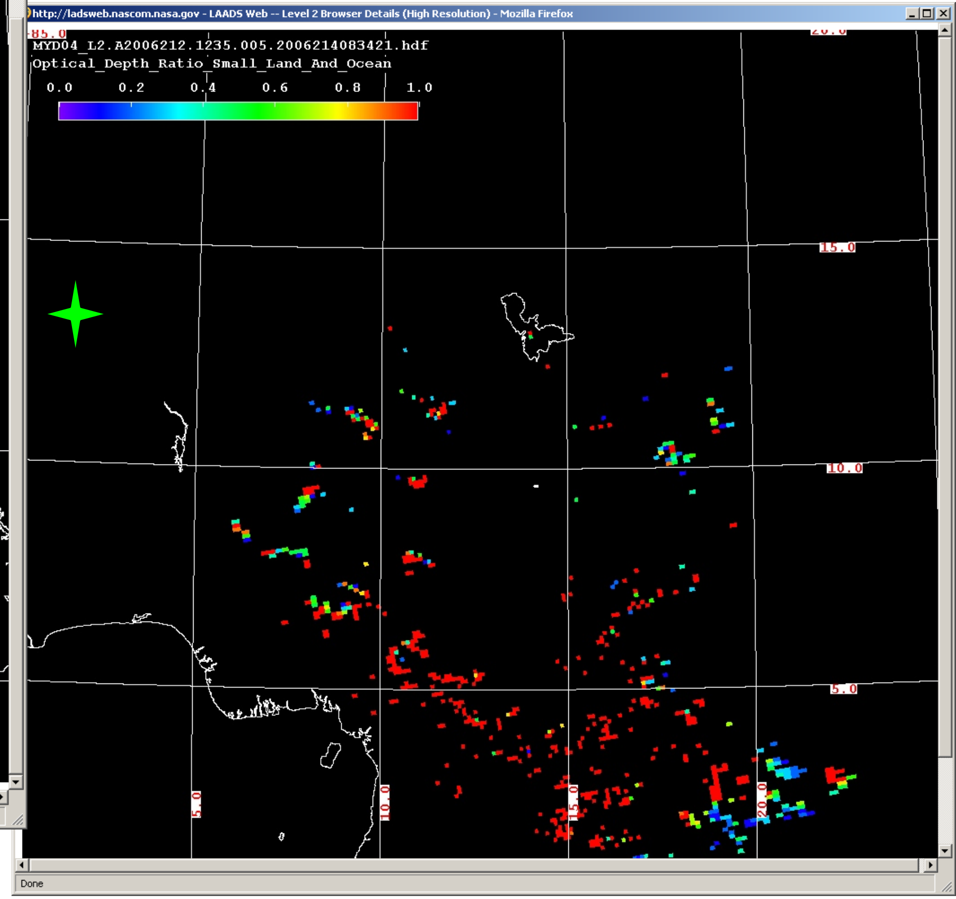



Stokes Velocity
0.15 0.5 1.0 2.0 5.0 um
Pressure (hPa)
Terminal velocity (mm/s)

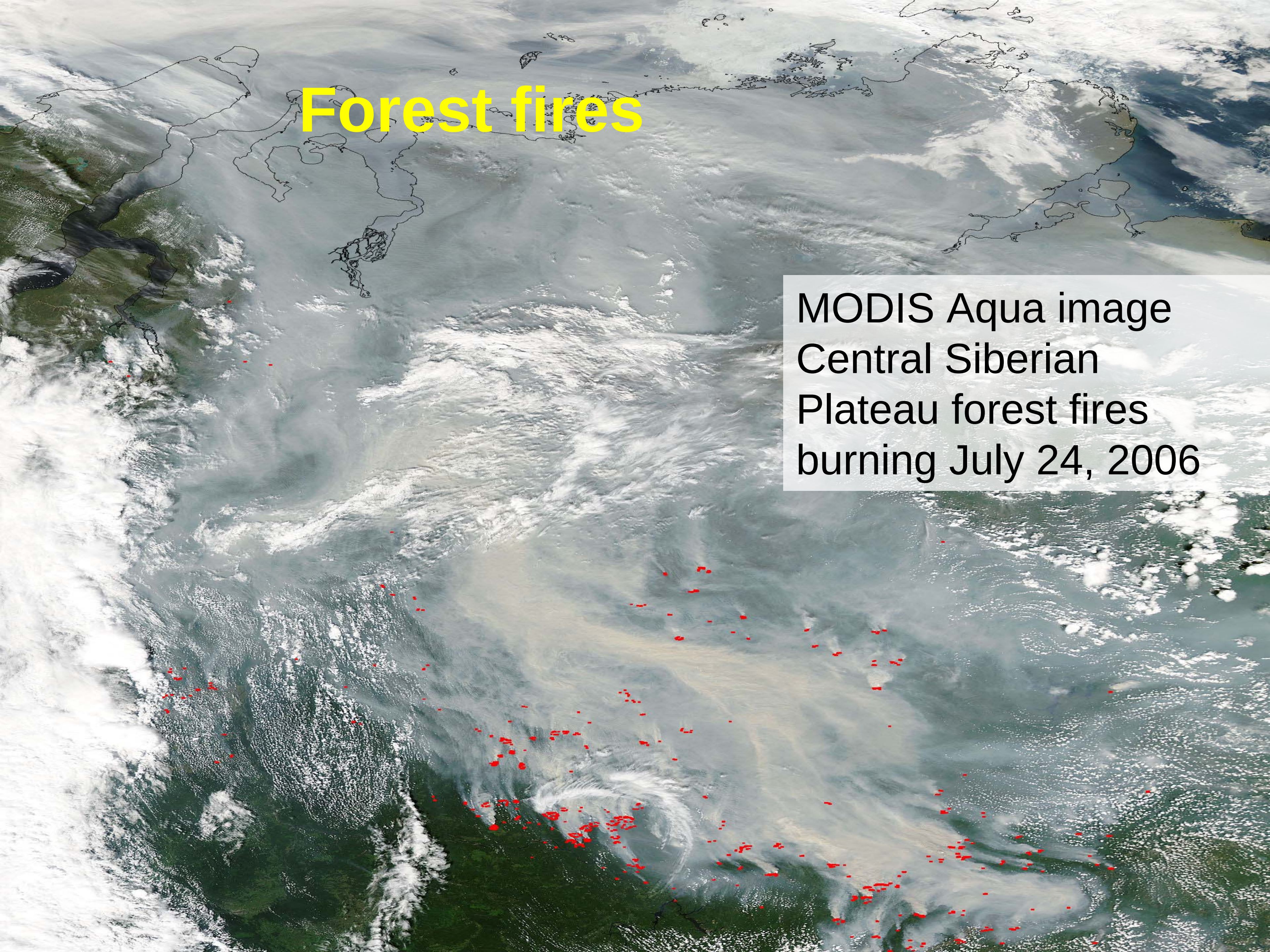

Stokes Velocity
0.15 0.5 1.0 2.0 5.0 um
Pressure (hPa)
Terminal velocity (km/day)

MODIS Optical Depth, 31 July 2006

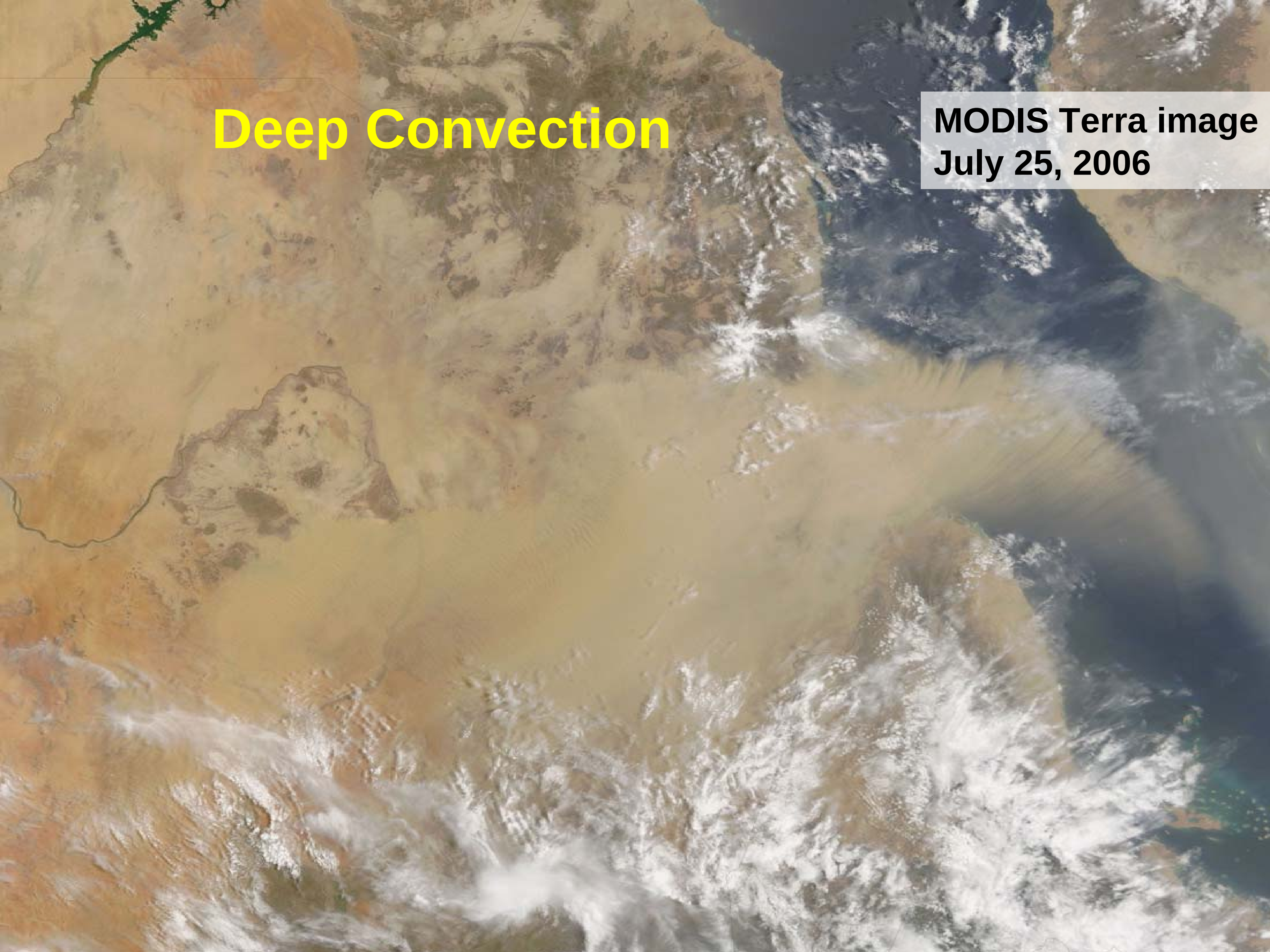




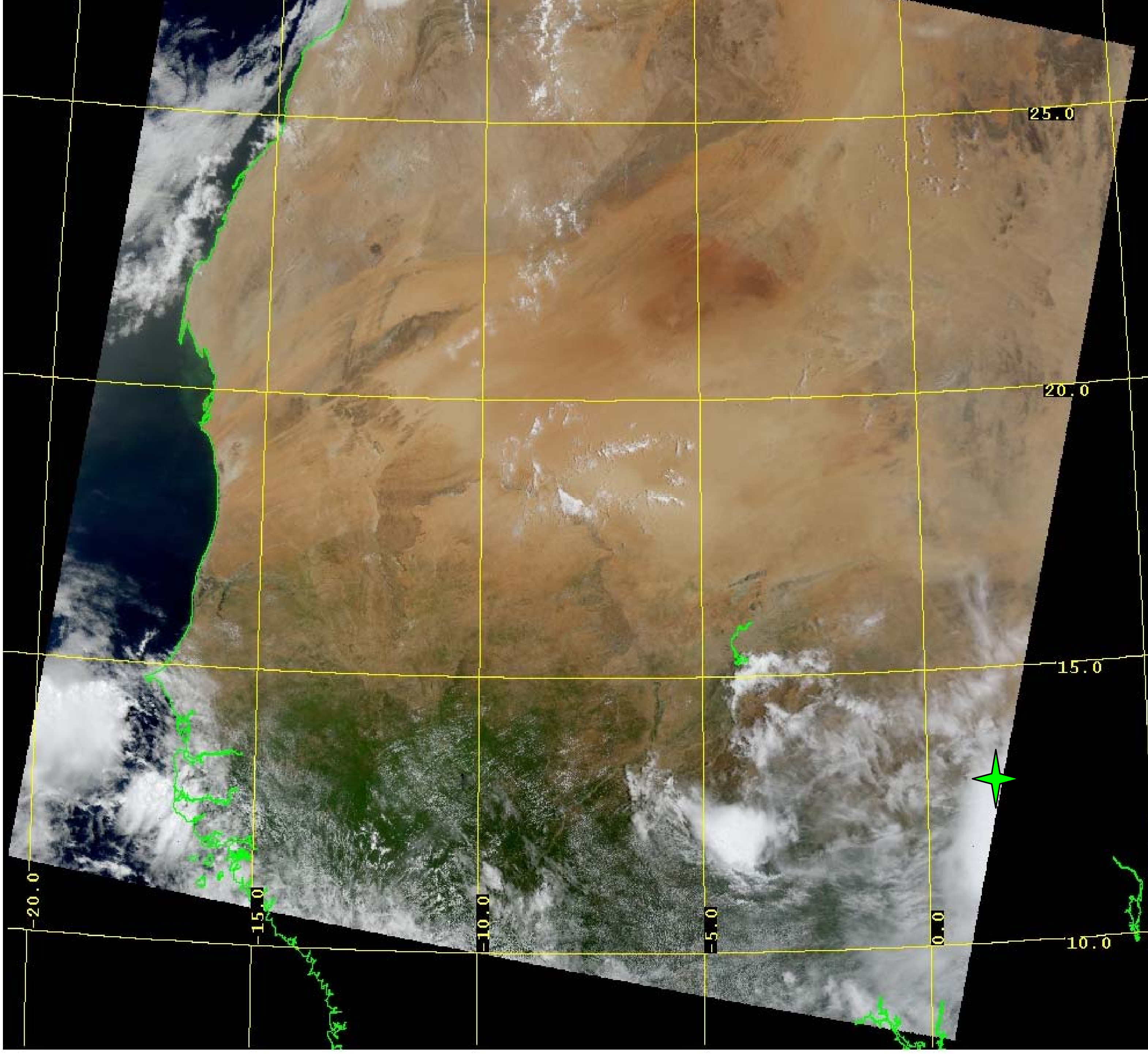
Forest fires

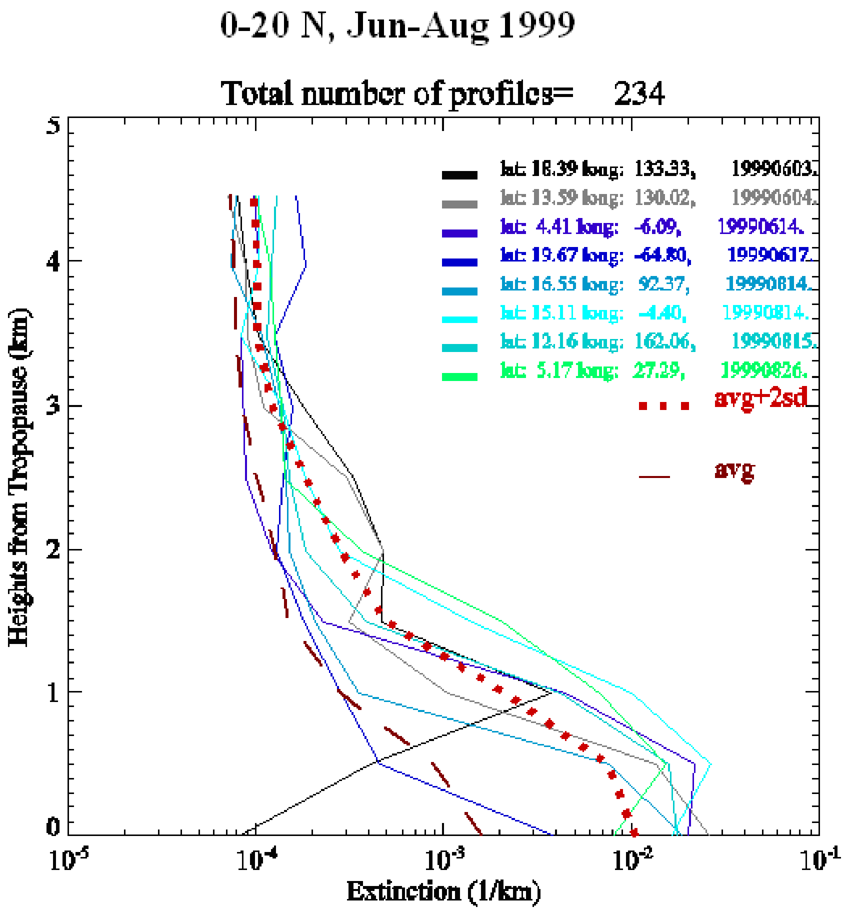


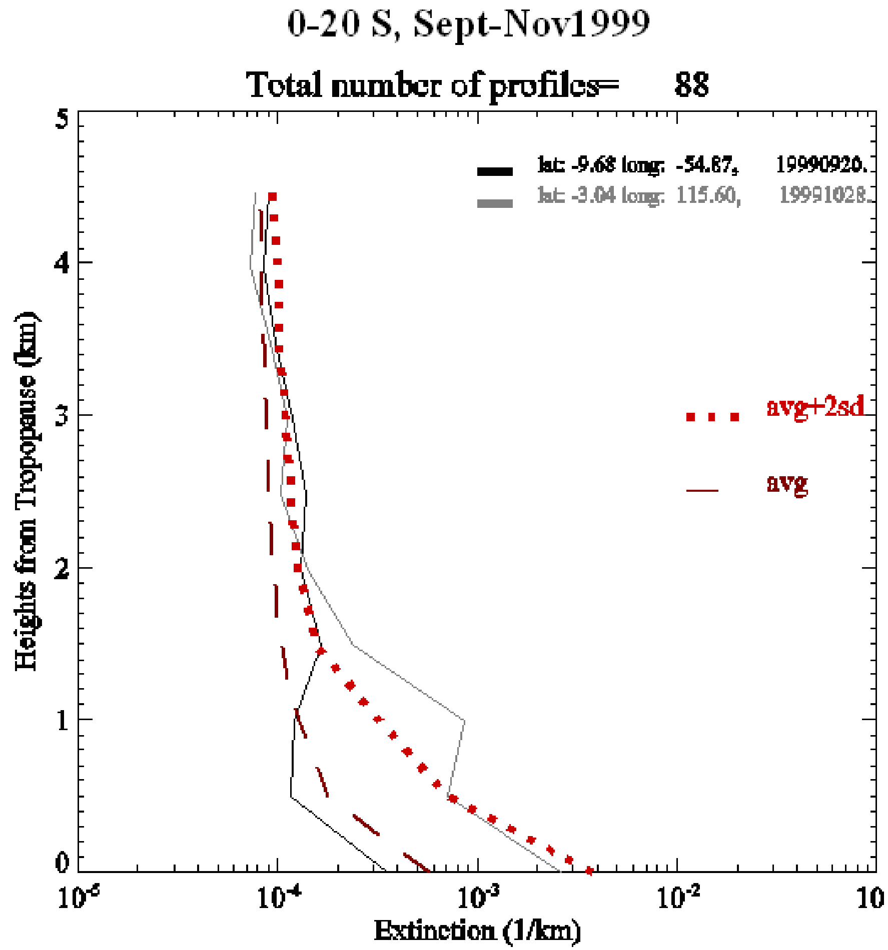
MODIS Aqua image
Central Siberian
Plateau forest fires
burning July 24, 2006


Deep Convection
MODIS Terra image
July 25, 2006

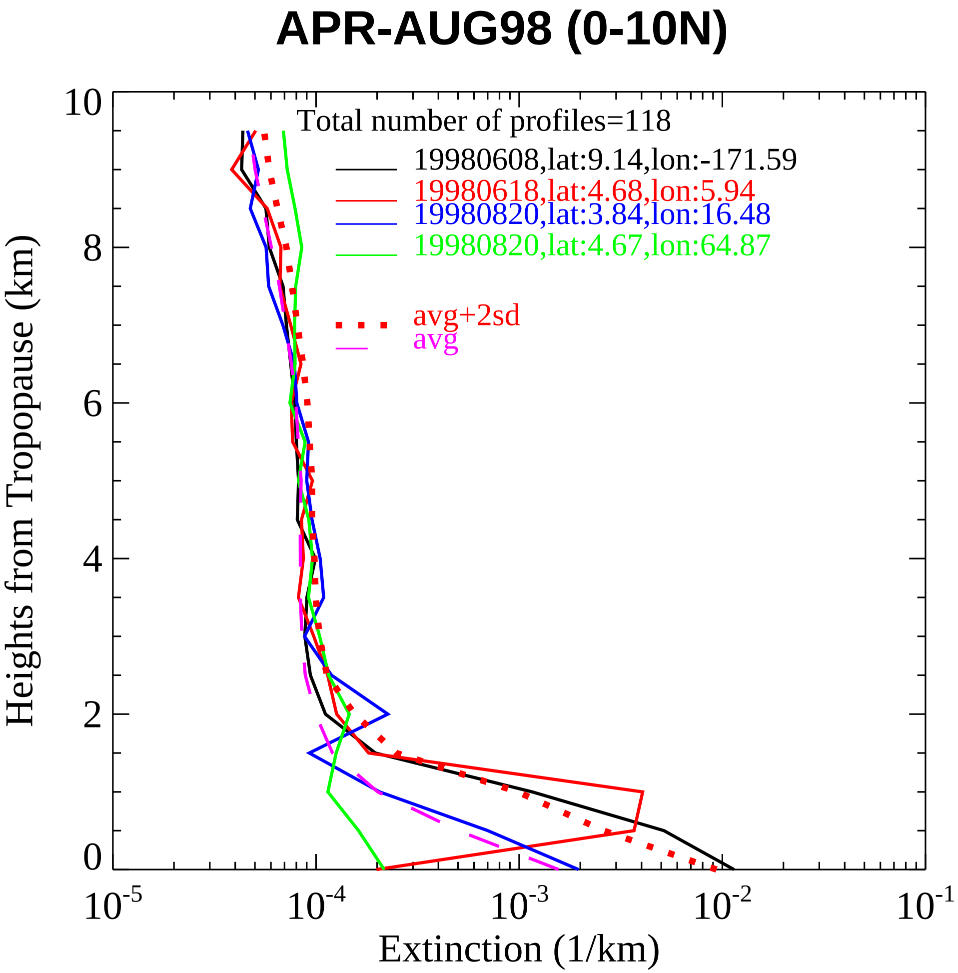
31 July
2006
11:10

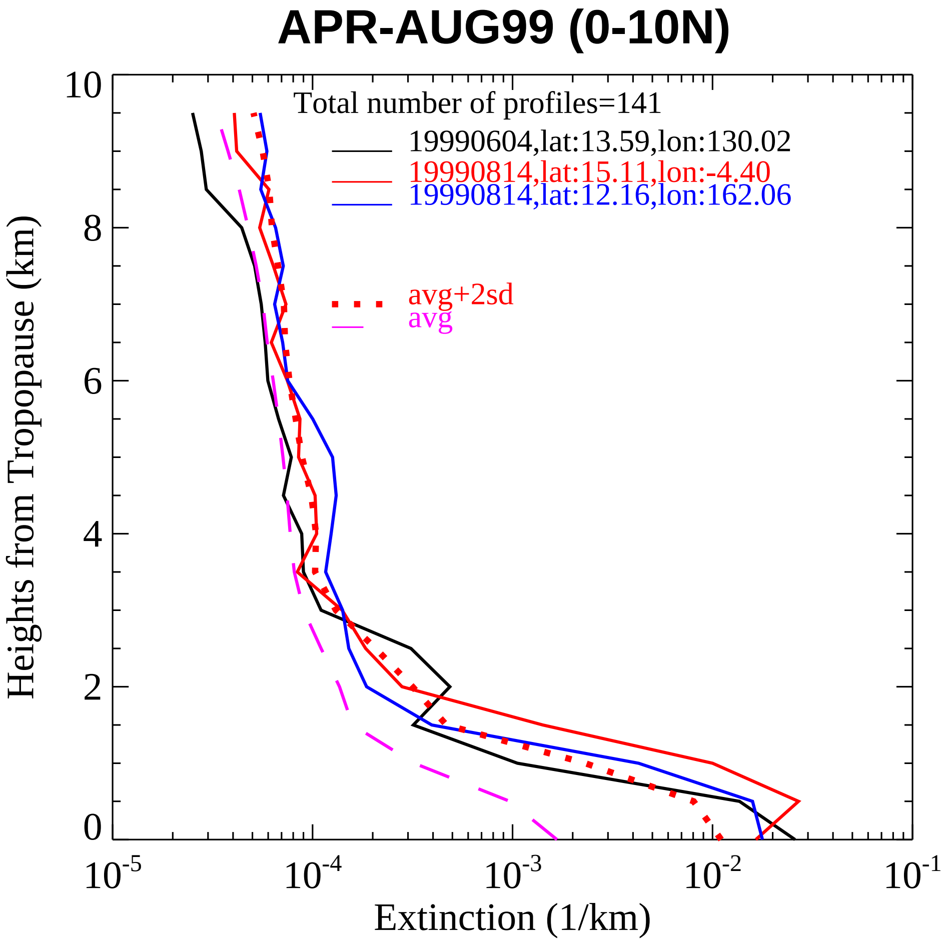




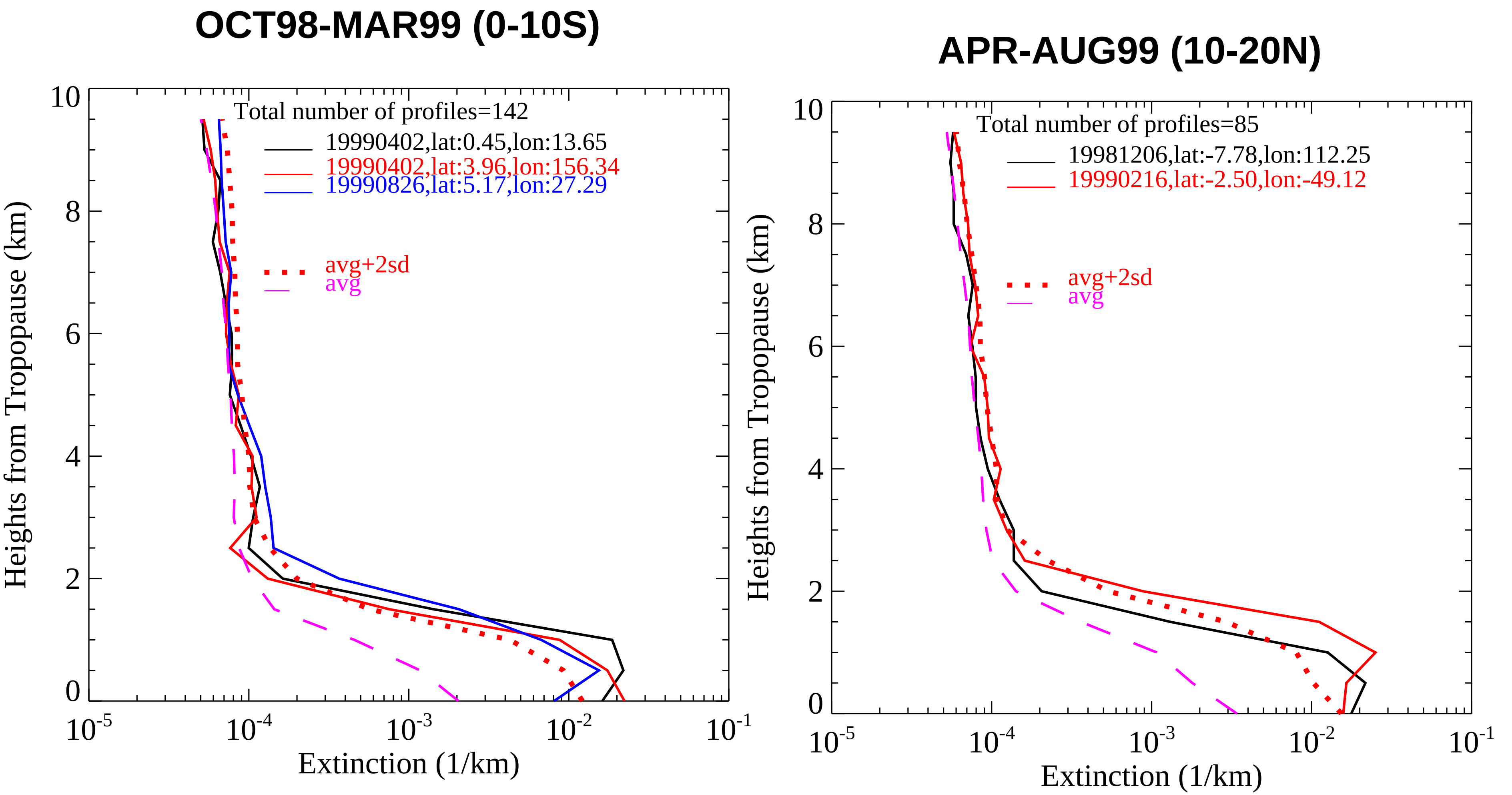


SAGE II data analyzed by Mahesh Kovilakam





SAGE II data analyzed by Mahesh Kovilakam



SAGE II data analyzed by Mahesh Kovilakam