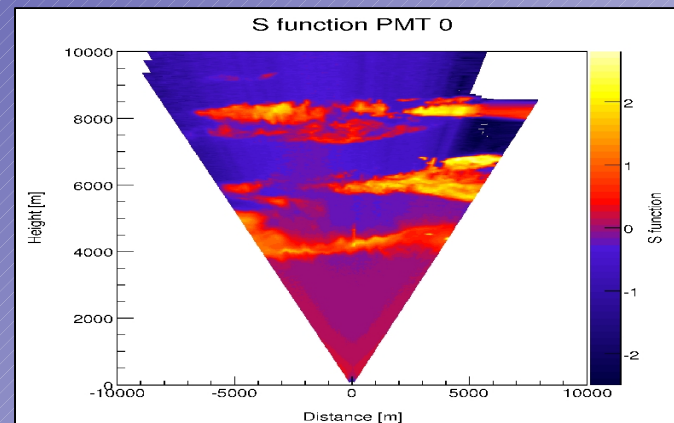


Atmospheric monitoring systems for the

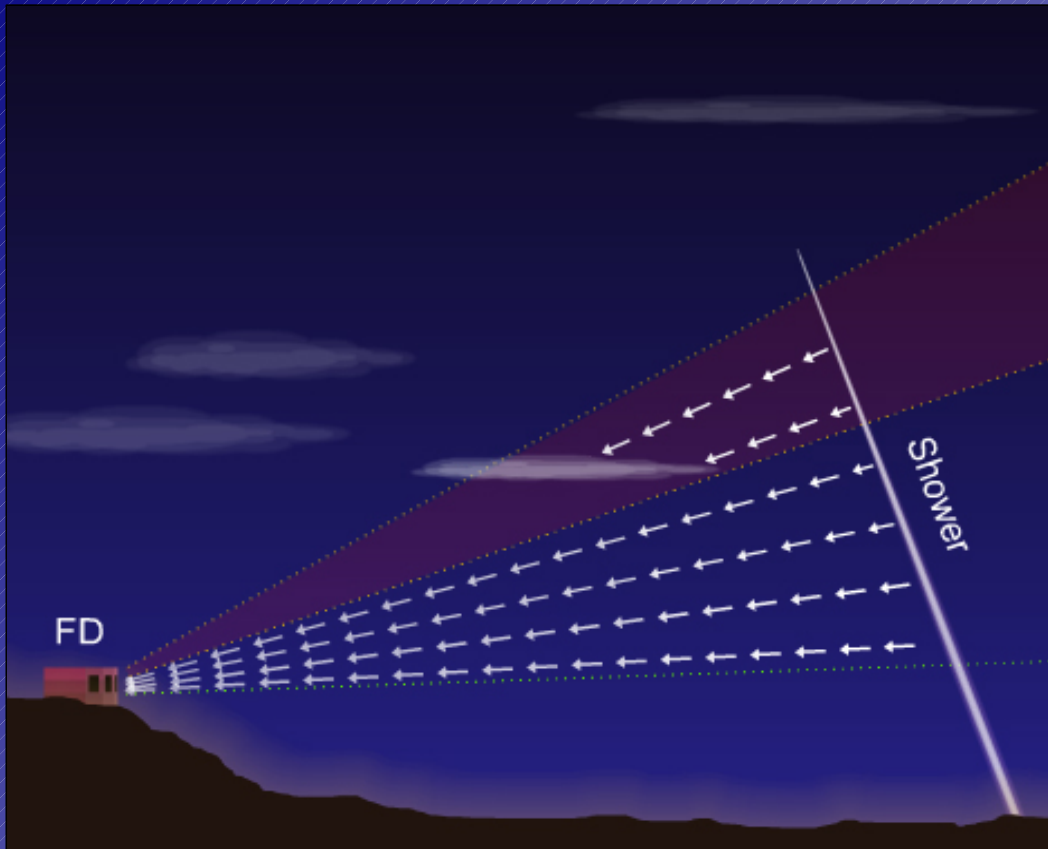
AUGER Observatory

Roberto Mussa - INFN Torino

1) The Molecular Atmosphere



Atmospheric optical properties



Photons emitted at the passage of the shower:

$$\frac{dN_{em}}{dX} = Y(P, T, h) \frac{dE}{dX}$$

$Y(P, T, h)$: Fluorescence Yield (see Arqueros)

$$\text{Grammage} : X(h) = \int_h^\infty \rho(z) dz$$

Photons arriving at FD window:

$$\frac{dN_{FD}(x)}{dX} = \frac{dN_{em}}{dX} T(x) \frac{A_{FD}}{|x|^2}$$

Transmission: $T(x) = e^{-\tau}$

Optical Depth (OD): $\tau = \int_0^x \alpha(r) dr = \tau_{molec} + \tau_{clouds} + \tau_{aerosol}$

Attenuation coefficient: $\alpha = \sigma * N(x)$

Attenuation Length: $\Lambda = 1/\alpha$

Outline of the lectures

1) Ideal conditions : the Rayleigh atmosphere

State parameters, horizontal+vertical profiles

Weather stations and radiosondes

Definition of optical parameters

Rayleigh scattering vs θ , T , P , h , λ

Mie scattering vs θ , λ

2) Cloud Detection

Sky variance

IR cameras

LIDAR techniques

3) Aerosol Measurements

LIDAR : monostatic, bistatic (CLF), Raman

Inversion techniques

Angular distribution of aerosols: APF

Angstrom index determination: HAM, FRAM, StarMon

Disclaimer:

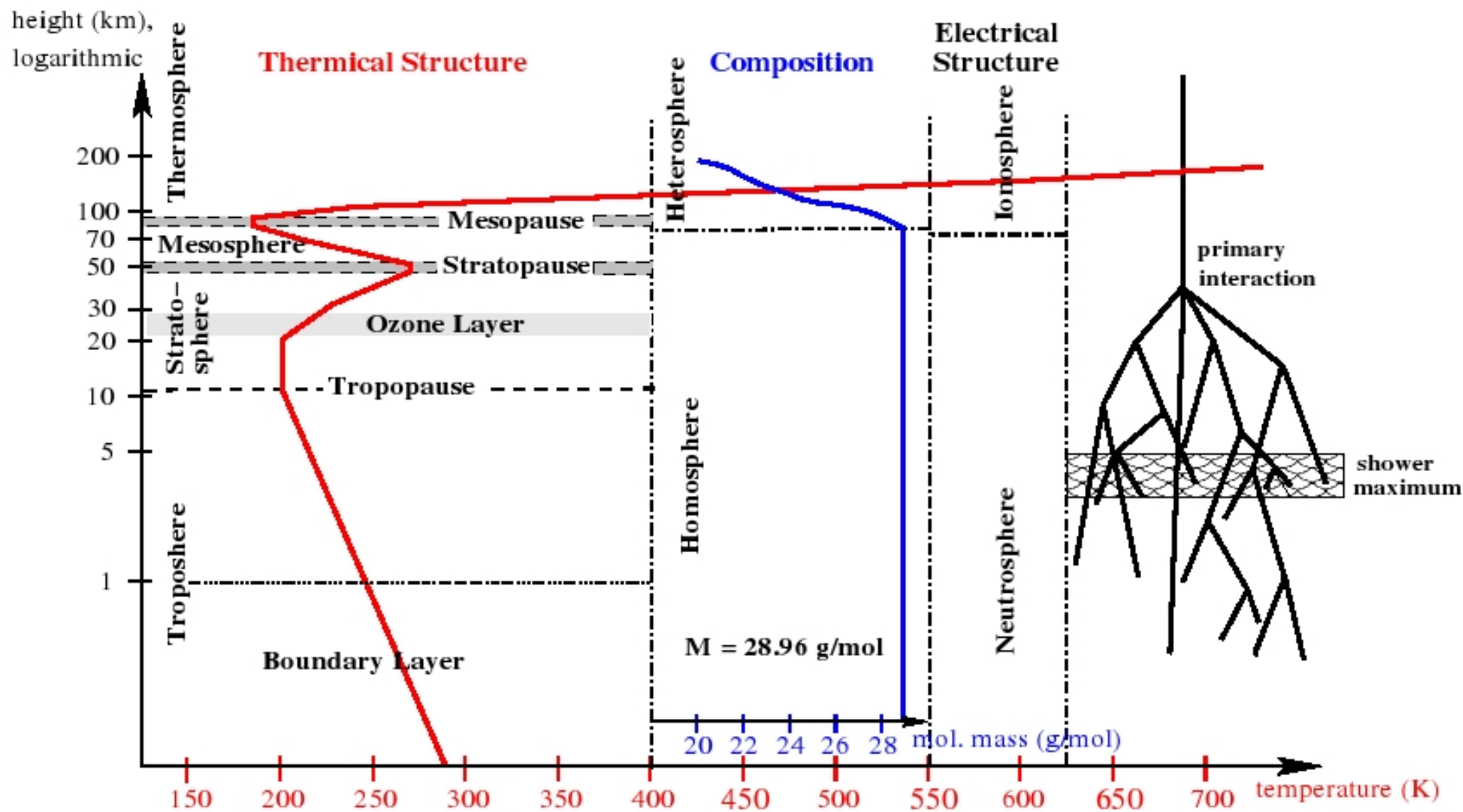
These lessons will mostly cover atmospheric physics topics that are relevant to studies on ultraenergetic cosmic rays.

I will not speak about:

- how to form a cloud or a rainbow
- why rain or hail droplets fall
- why aerosols are harmful to ozone layer
- how cosmic rays can trigger lightning

Moreover, state-of-the-art techniques for atmospheric physics cannot be used in the proximity of fluorescence detectors without affecting their performance. This limits and puts unique challenges on the design of such devices.

Atmosphere: basics



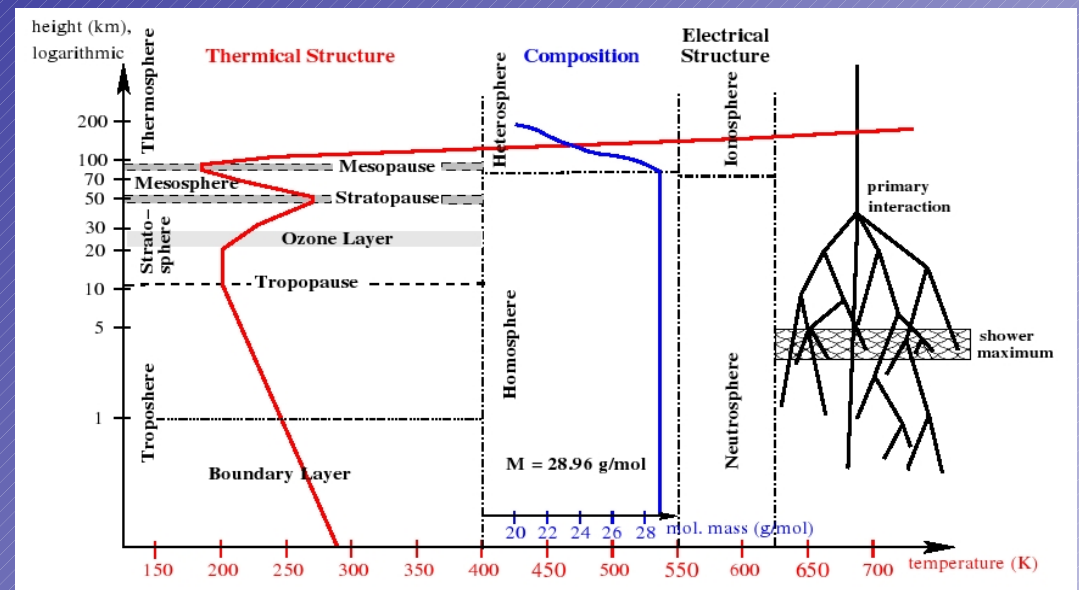
Atmosphere: basics

Gaseous mixture with floating upper boundary.

90% of the mass is contained below 18 km above sea level (a.s.l.)

1% is left above 32 km a.s.l.

Parameters to describe this gas mixture: temperature, pressure, density, and humidity.



Homosphere: 0-100 km

constant chemical composition, main components are well mixed

Troposphere (0 to 12-15 km):

the sphere where changes happen

Planetary Boundary Layer (PBL):

region where aerosols usually mix, being continuously dragged by earth rotation

Atmosphere: composition

Most components are ideally mixed, and the relative density changes are negligible.

Changes are due to:

Ozone, in stratosphere

Water vapor, in troposphere

Aerosols, in PBL

COMPOSITION OF THE ATMOSPHERE			
Gas	Symbol	% by weight	% by volume
Nitrogen	N ₂	75.52	78.09
Oxygen	O ₂	23.15	20.95
Argon	A	1.28	0.93
Carbon dioxide	CO ₂	0.046	0.035
Neon	Ne	0.012	0.0018
Helium	He	0.0007	0.0005
Methane	CH ₄	0.0008	0.00015
Krypton	Kr	0.003	0.0001
Ozone	O ₃	0-0.01	Variable
Water vapour	H ₂ O	0-4	Variable

Atmosphere parameters at sea level

To calculate the air density we can use the state equation for ideal gases:

$$PV = nRT$$

Constants

N. of molecules per mole

$$N_{\text{Avogadro}} = 6.02214 \cdot 10^{23} \text{ mol}^{-1}$$

Boltzmann constant:

$$k_{\text{Boltzmann}} = 1.38065 \cdot 10^{-23} \text{ J K}^{-1}$$

Universal Gas Constant

$$R = k_{\text{Boltzmann}} N_{\text{Avogadro}} = 8.314472 \text{ J K}^{-1} \text{ mol}^{-1}$$

STP conditions:

$$T_{\text{stp}} = 273.15 \text{ K}, P_{\text{stp}} = 101325 \text{ Pa}$$

Molar volume at STP :

$$V_{\text{mol}} = R (T_{\text{stp}} / P_{\text{stp}}) = 22.414 \text{ dm}^3 \text{ mol}^{-1}$$

Molar density of dry air

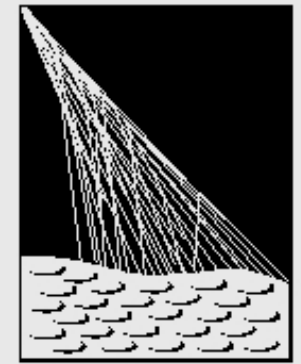
$$M_{\text{air}} = 28.96 \text{ g mol}^{-1}$$

Density of dry air at STP: $\rho(T_{\text{stp}}, P_{\text{stp}}) = 1.292 \text{ kg m}^{-3}$

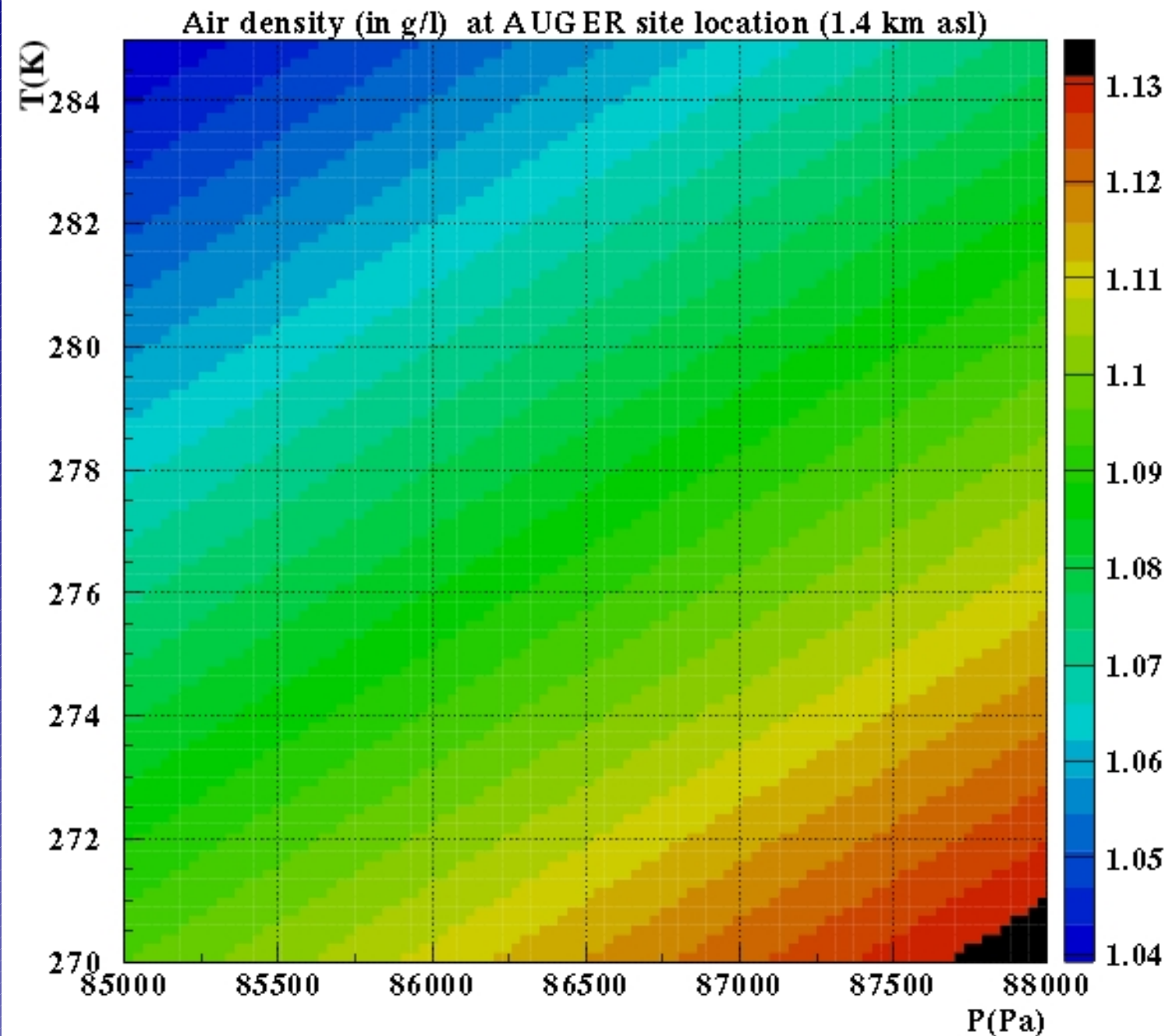
$$N(T_{\text{stp}}, P_{\text{stp}}) = 2.6868 \cdot 10^{25} \text{ molecules/m}^{-3}$$

Density of *standard atmosphere* $N_s(T=288.15, P_{\text{stp}}) = 2.5474 \cdot 10^{25} \text{ molecules/m}^{-3}$

Atmosphere: density at ground



PIERRE
AUGER
OBSERVATORY



Altitudes of FD sites (asl):

Los Leones	1.42 km
Los Morados	1.42 km
Loma Amarilla	1.48 km
Coihueco	1.72 km

Weather stations for ground measurements

5 stations:

- 1 at each FD site
- 1 in the center of the array



Measurements:

- pressure
- temperature
- humidity
- wind speed
- wind direction

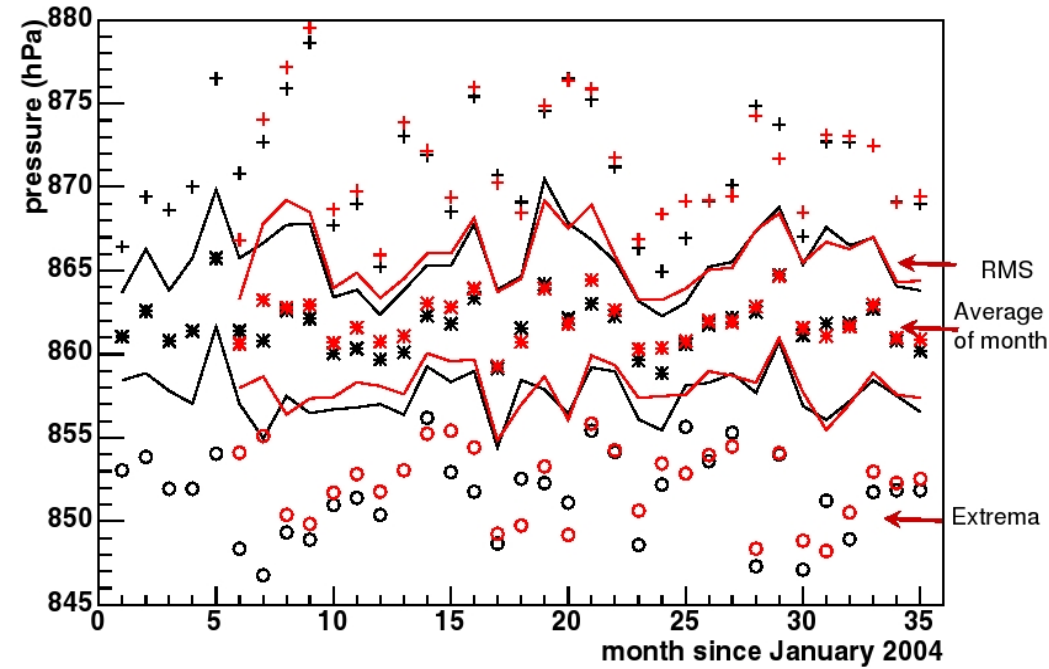




Ground values for P, T, ρ

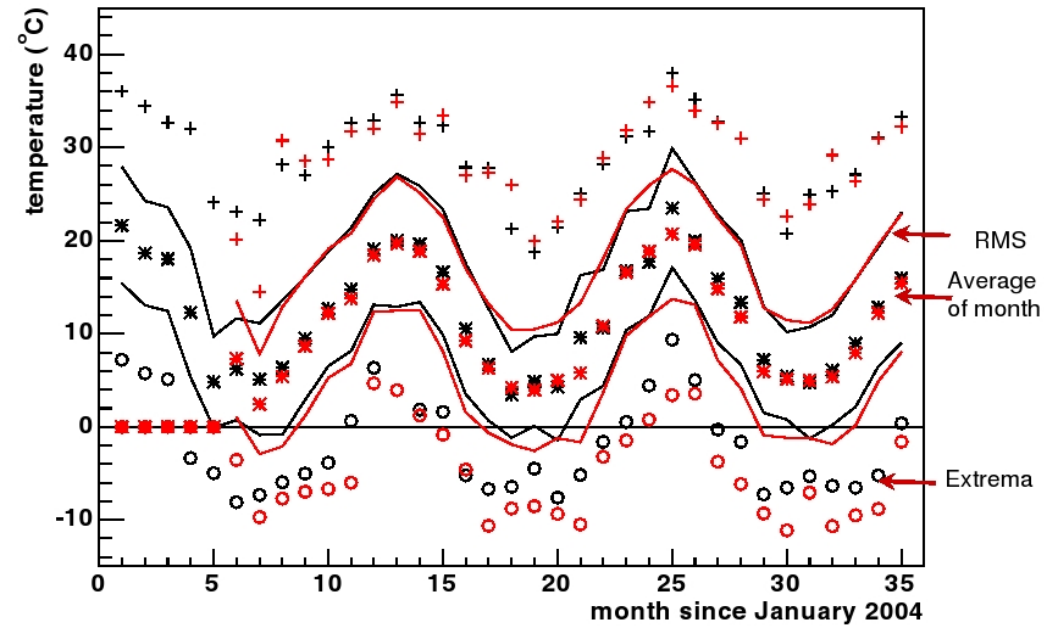
Pressure

LL: black; CLF: red



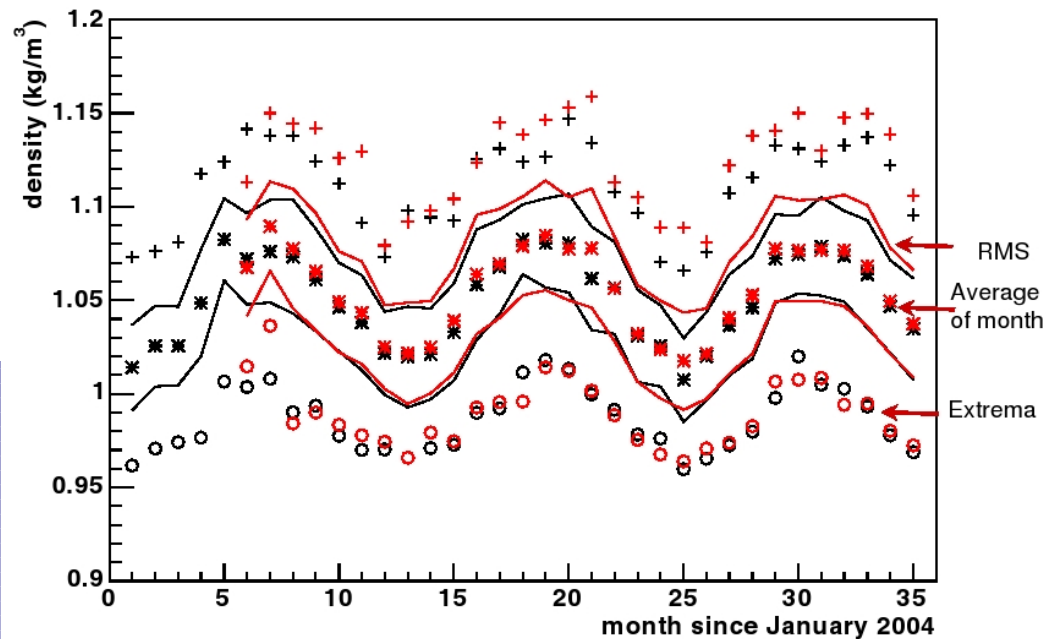
Temperature

LL: black; CLF: red



Density

LL: black; CLF: red

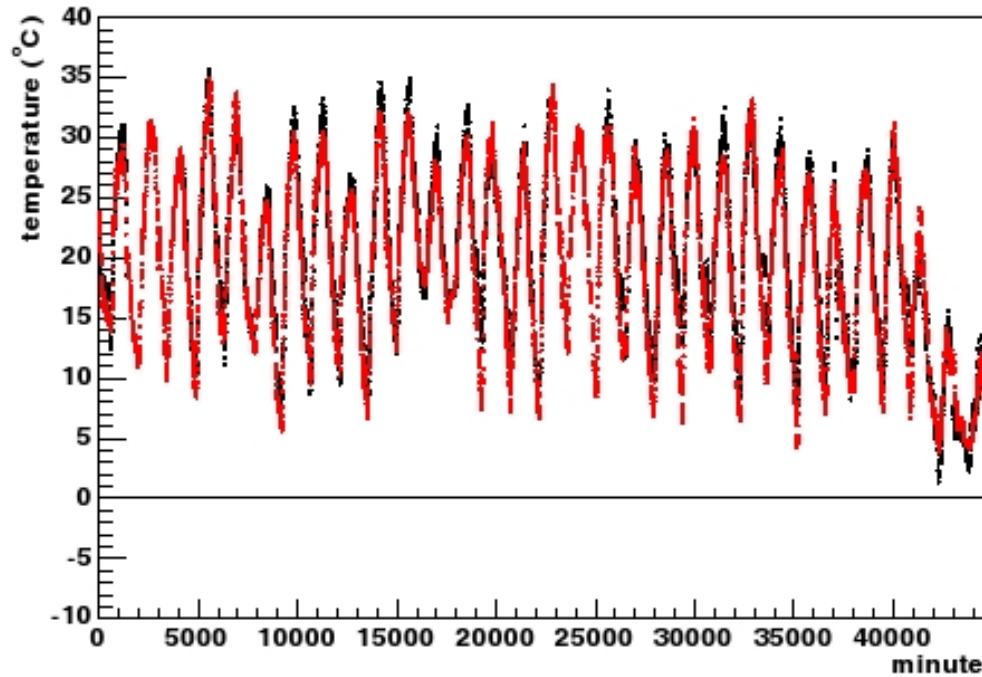


3 years of data in each plot (2004-2006)

T_{ground} in summer

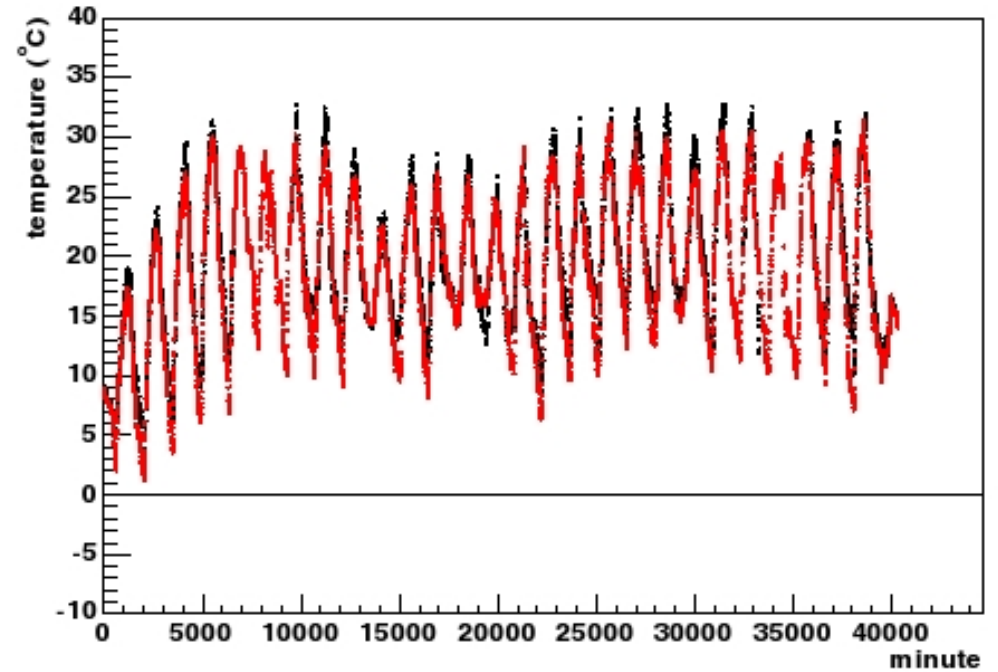
Large day-night variations, typically 10 to 30 C, common in desert areas

LL: black; CLF: red



January 2005

LL: black; CLF: red

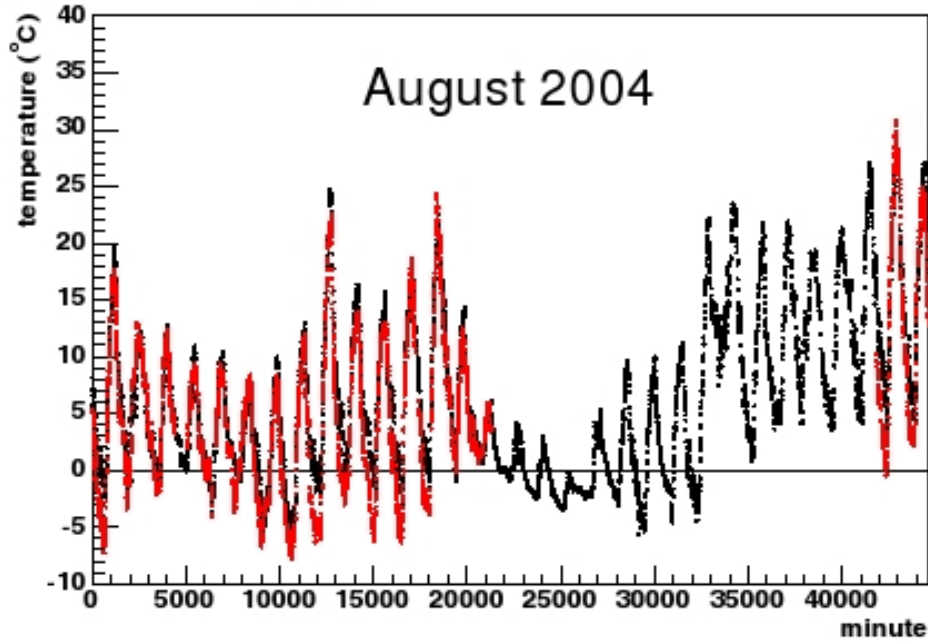


February 2005

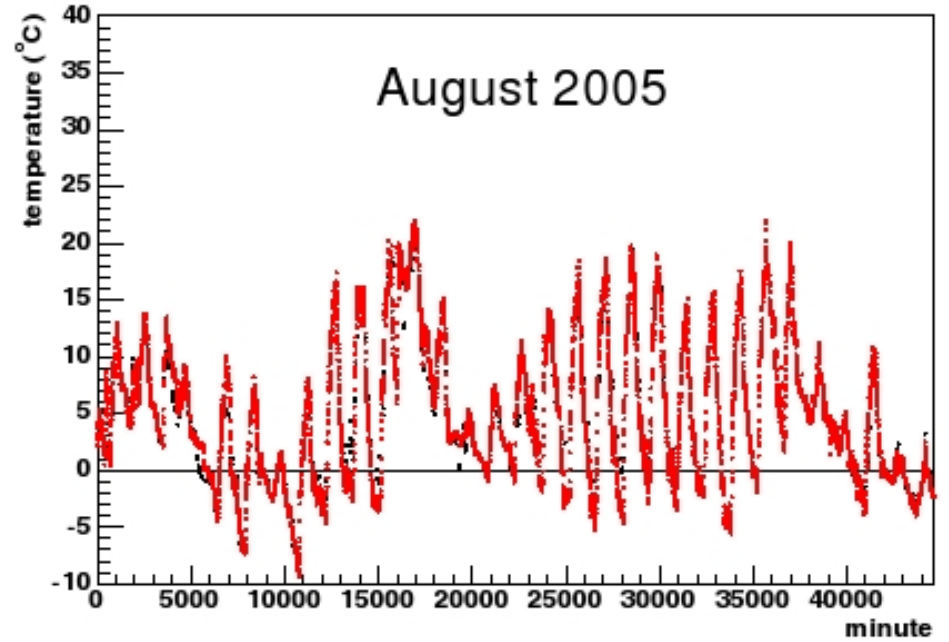
T_{ground} in winter

Temperature

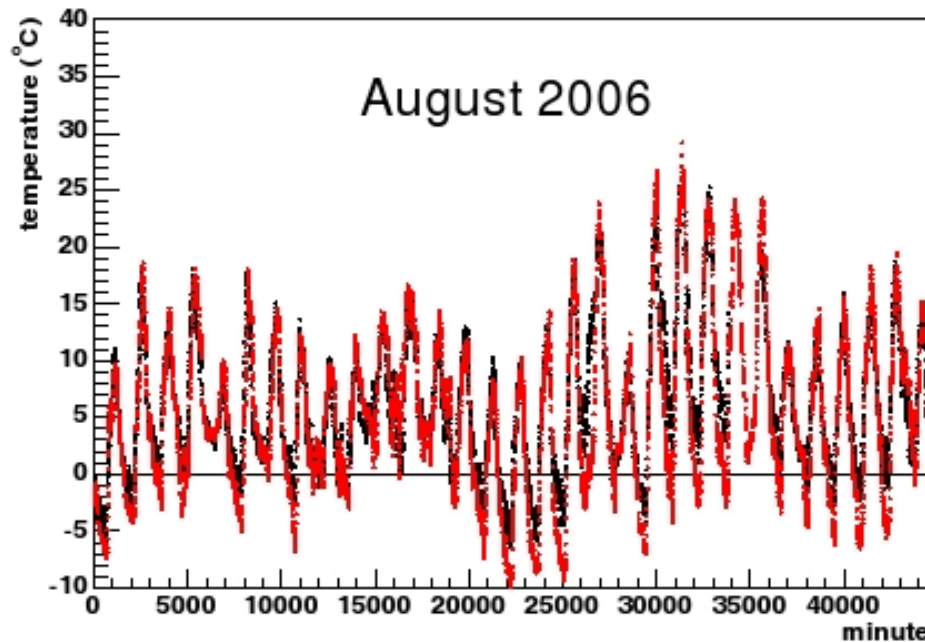
LL: black; CLF: red



LL: black; CLF: red



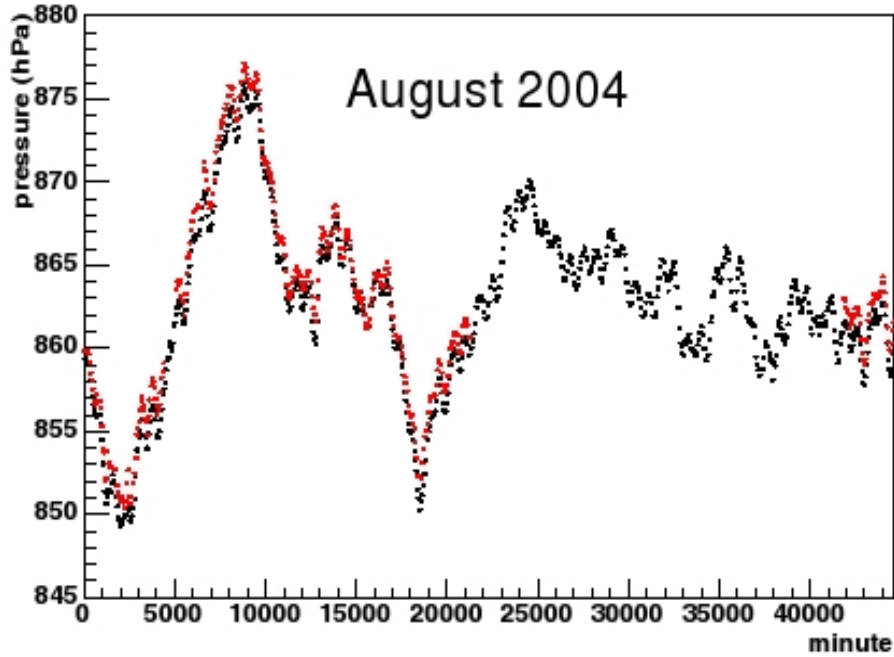
LL: black; CLF: red



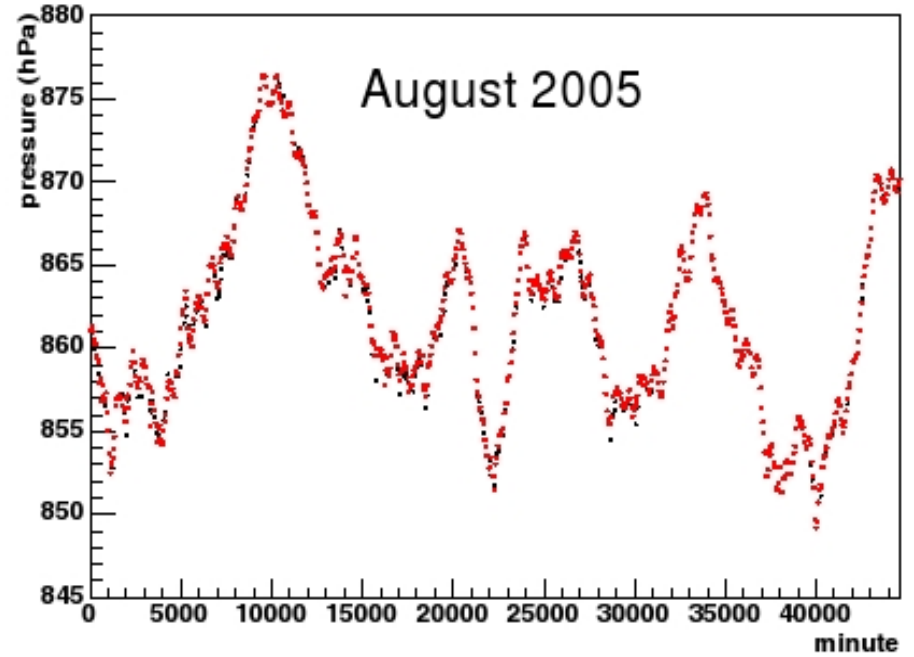
P_{ground} in winter

Pressure

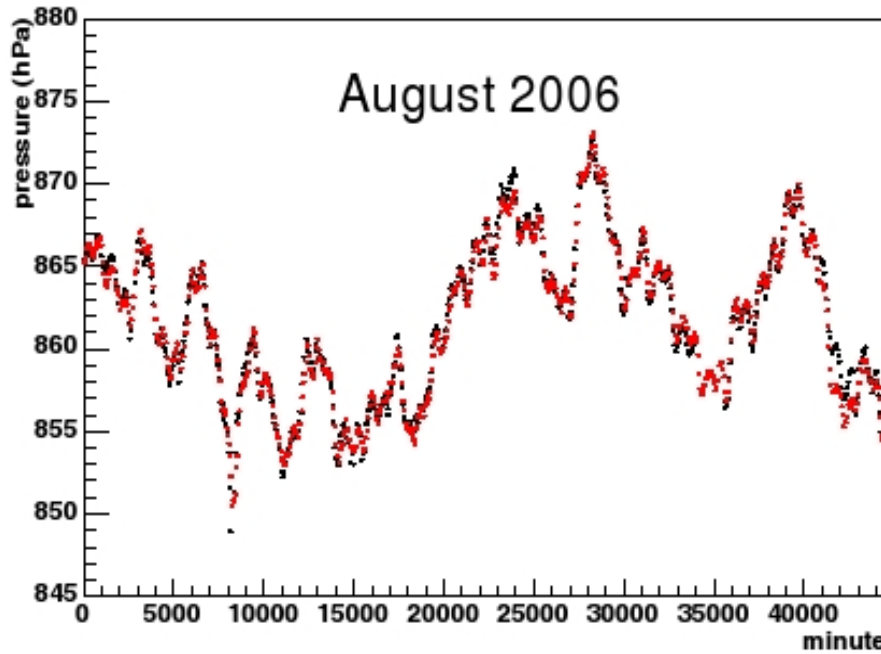
LL: black; CLF: red



LL: black; CLF: red



LL: black; CLF: red



Vertical profiles

Hydrostatic equation

$$\frac{dP}{dz} = -\rho g = -\frac{gM_{air}P}{RT}$$

$dS/dz = 0$ adiabatic conditions:

$$\gamma = C_p/C_v = (5+f)/(3+f) = 7/5$$

($f=2$ for N_2, O_2 ; $f=0$ for rare gases)

$$PV^\gamma = \text{const} \longrightarrow PT^{-\frac{\gamma}{\gamma-1}} = \text{const}$$

Dry Air Lapse Rate

$$\frac{dT}{dz} = -\frac{gM_{air}}{R} \left(\frac{\gamma - 1}{\gamma} \right) = -9.8 \text{ }^\circ\text{K/km}$$

Environmental Lapse Rate

$$\langle dT/dz \rangle = -6.5 \text{ }^\circ\text{K/km}$$

(depends on the amount of water vapor)

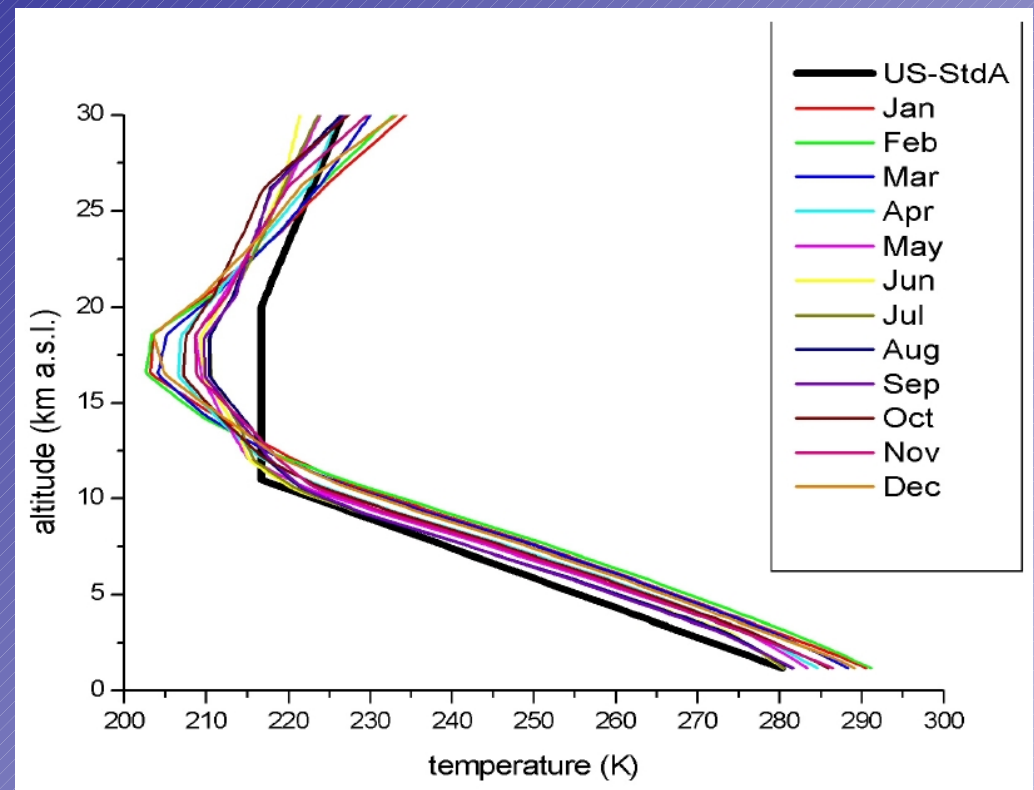
Modeling the Molecular Atmosphere

Many attempts to use already existing data:

- US Standard Atmosphere for desert areas

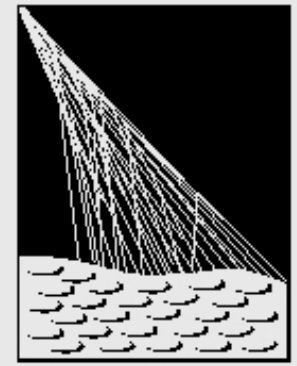
- Regular balloon launches in Cordoba and Santa Rosa

Inadequate to describe Auger atmosphere.

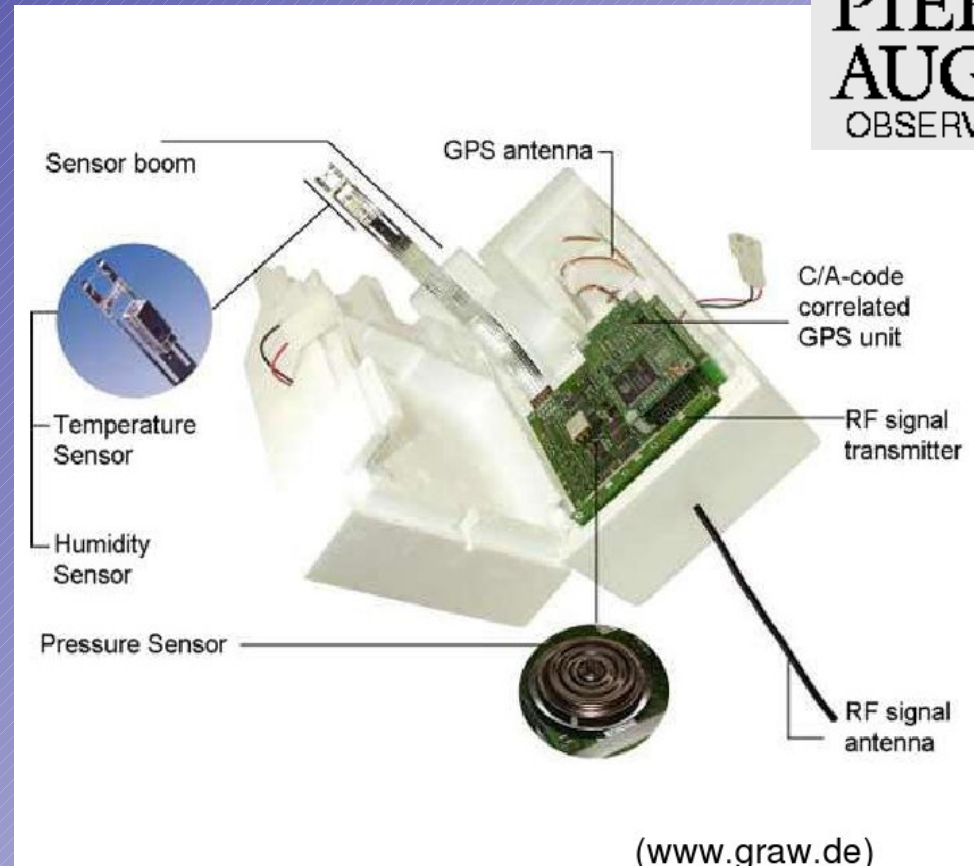


Radiosounding

BLF: Balloon Launching Facility

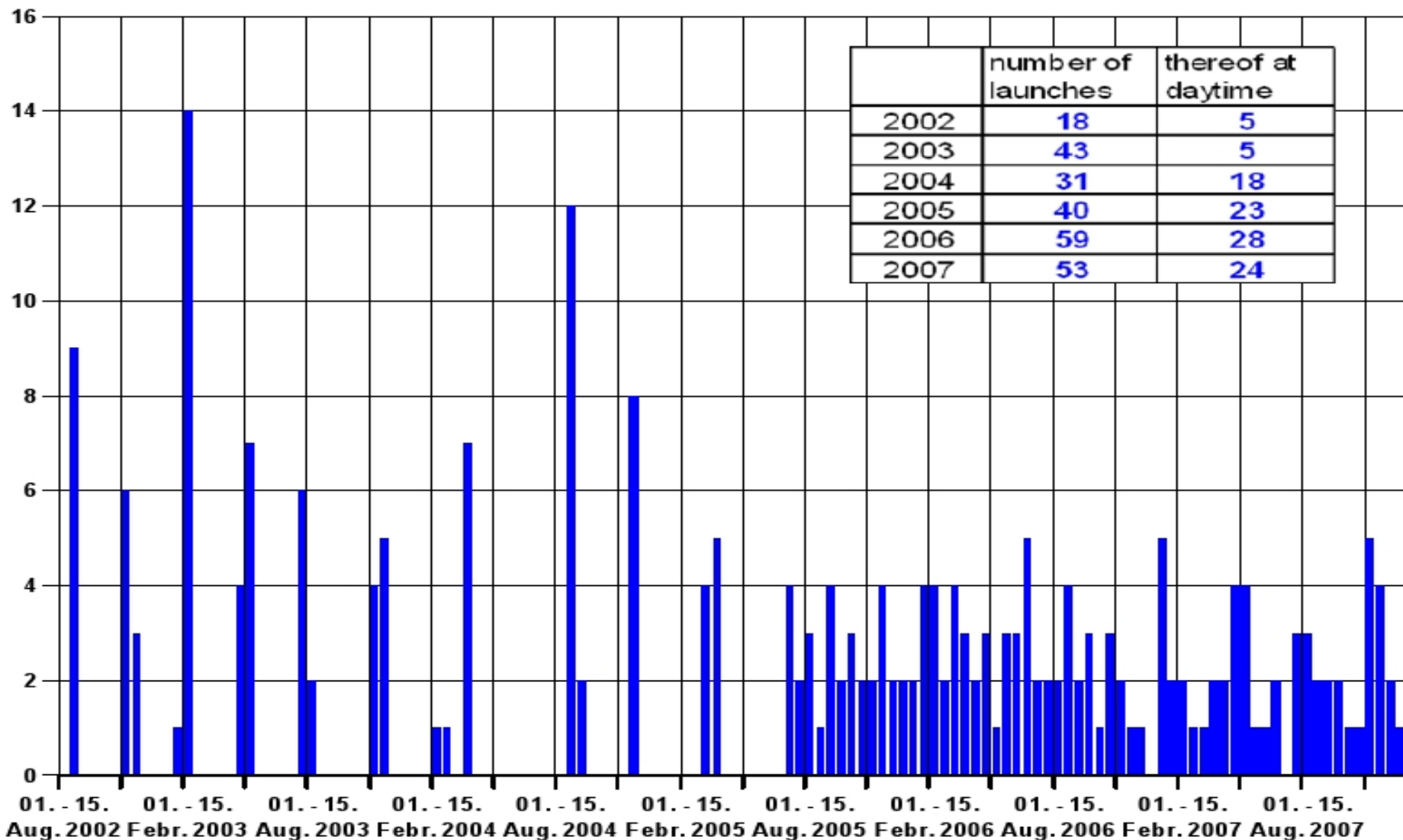


**PIERRE
AUGER
OBSERVATORY**

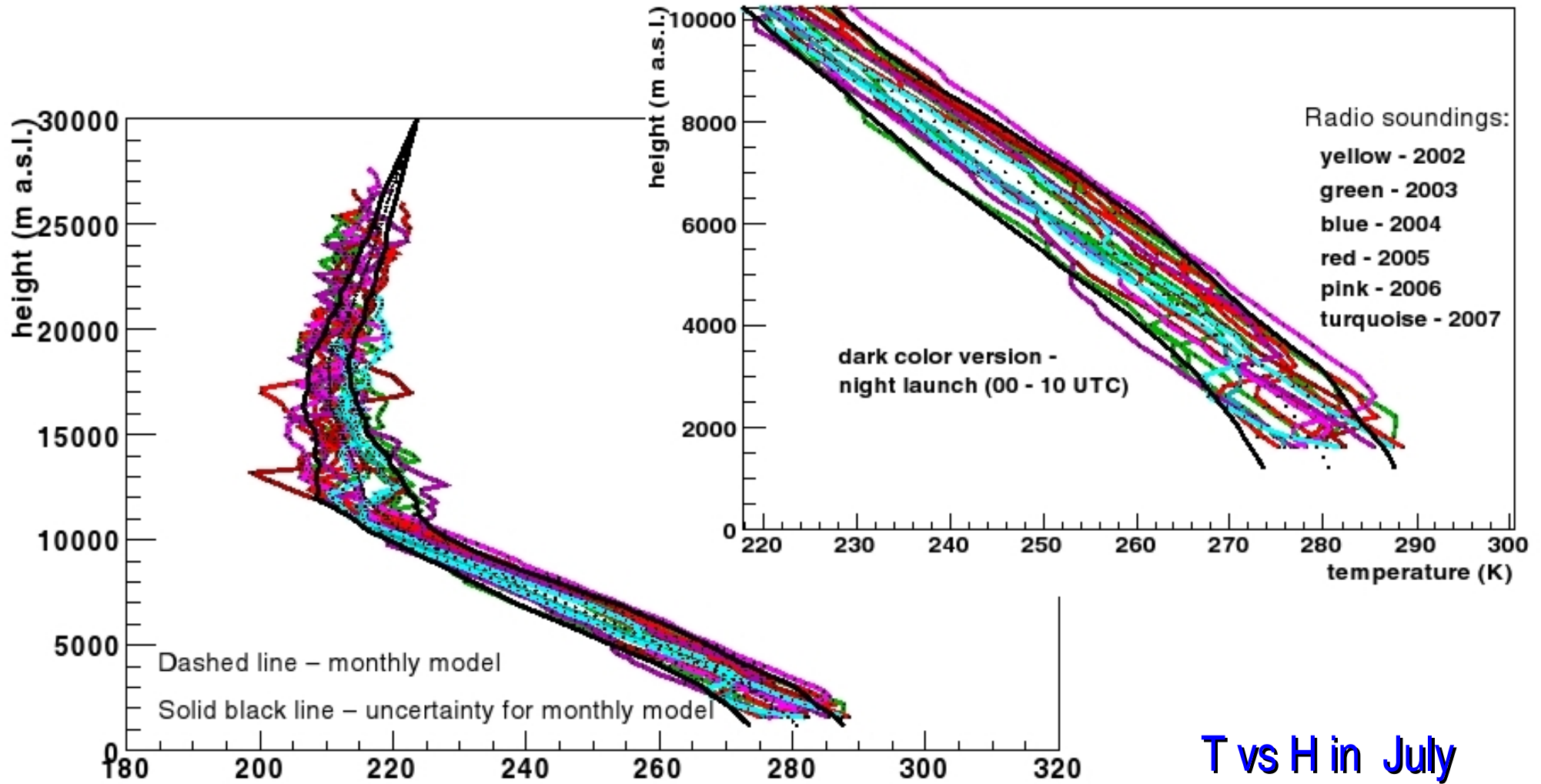


Balloon launches

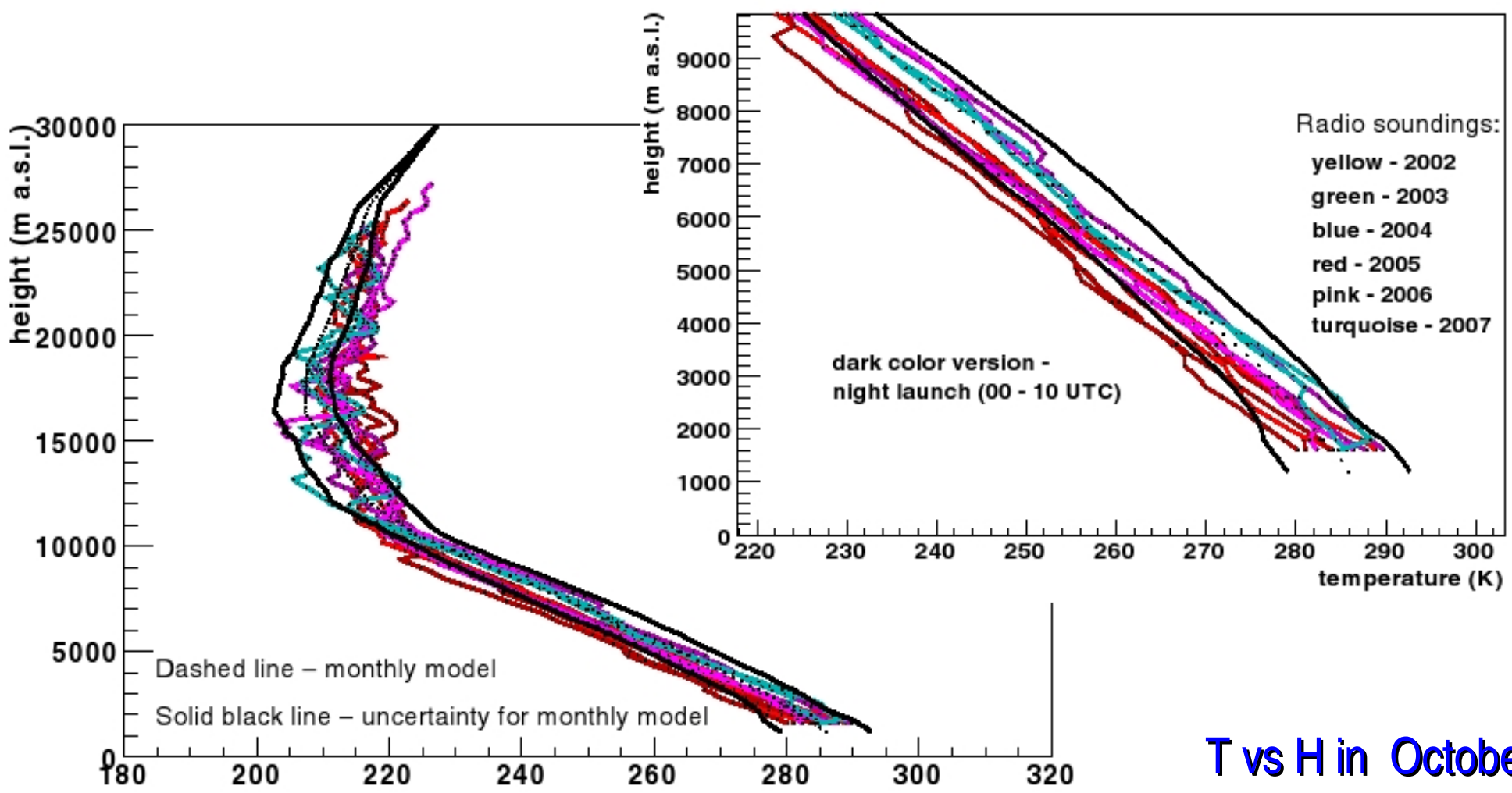
Statistics of Radiosoundings



Temperature vertical profiles

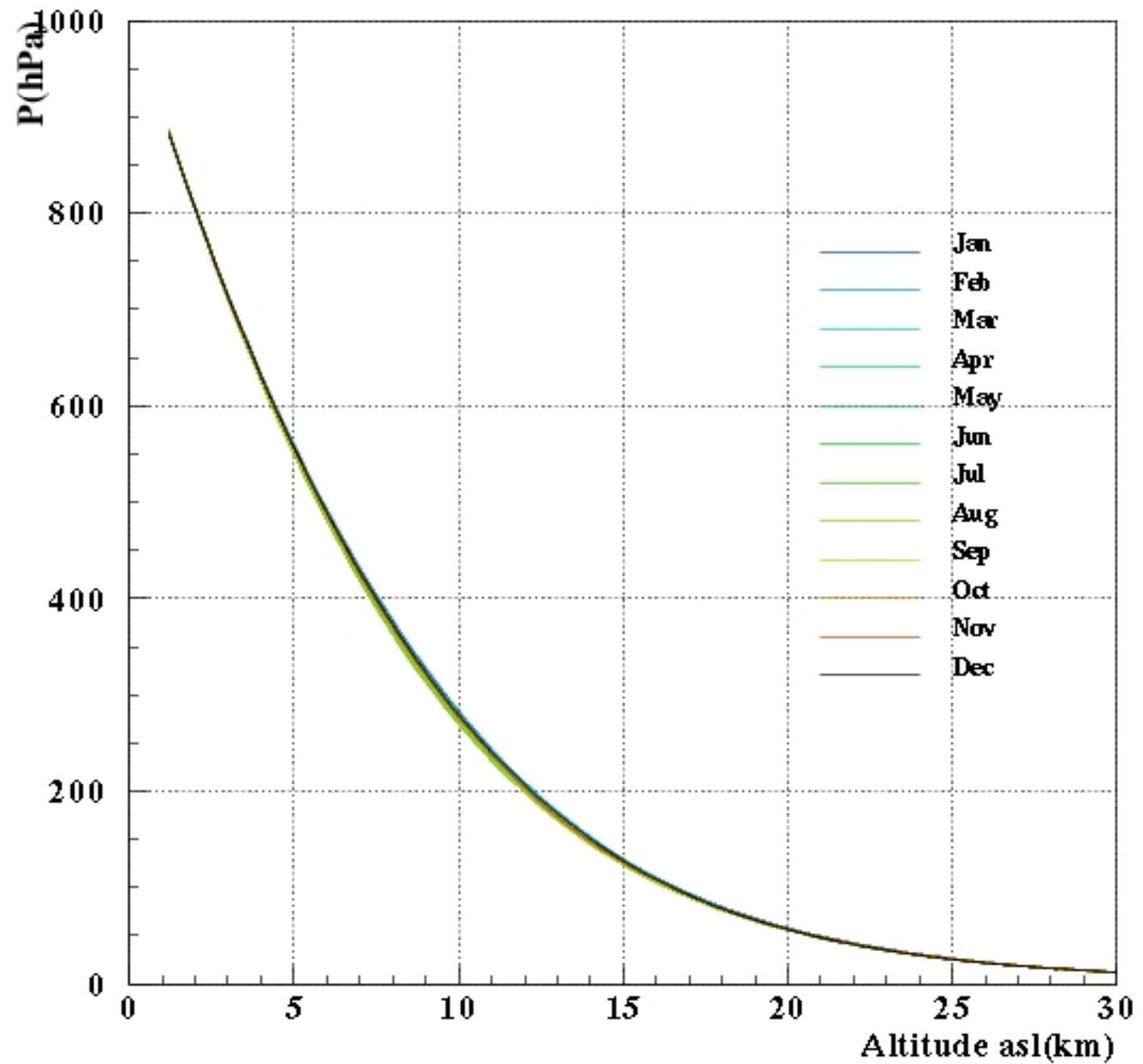


Temperature vertical profiles

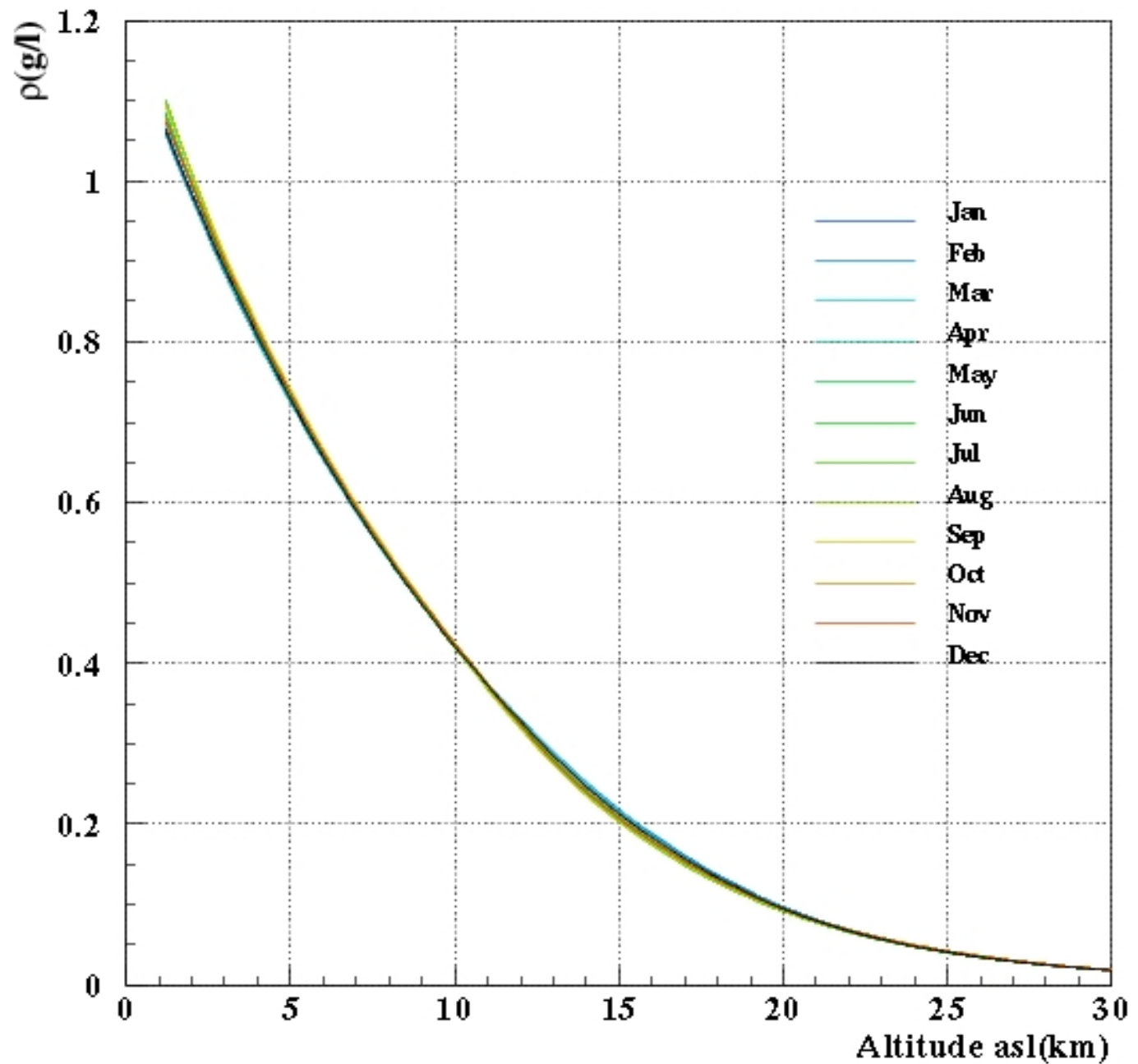


T vs H in October

Pressure vertical profiles : monthly models



Density vertical profiles : monthly models



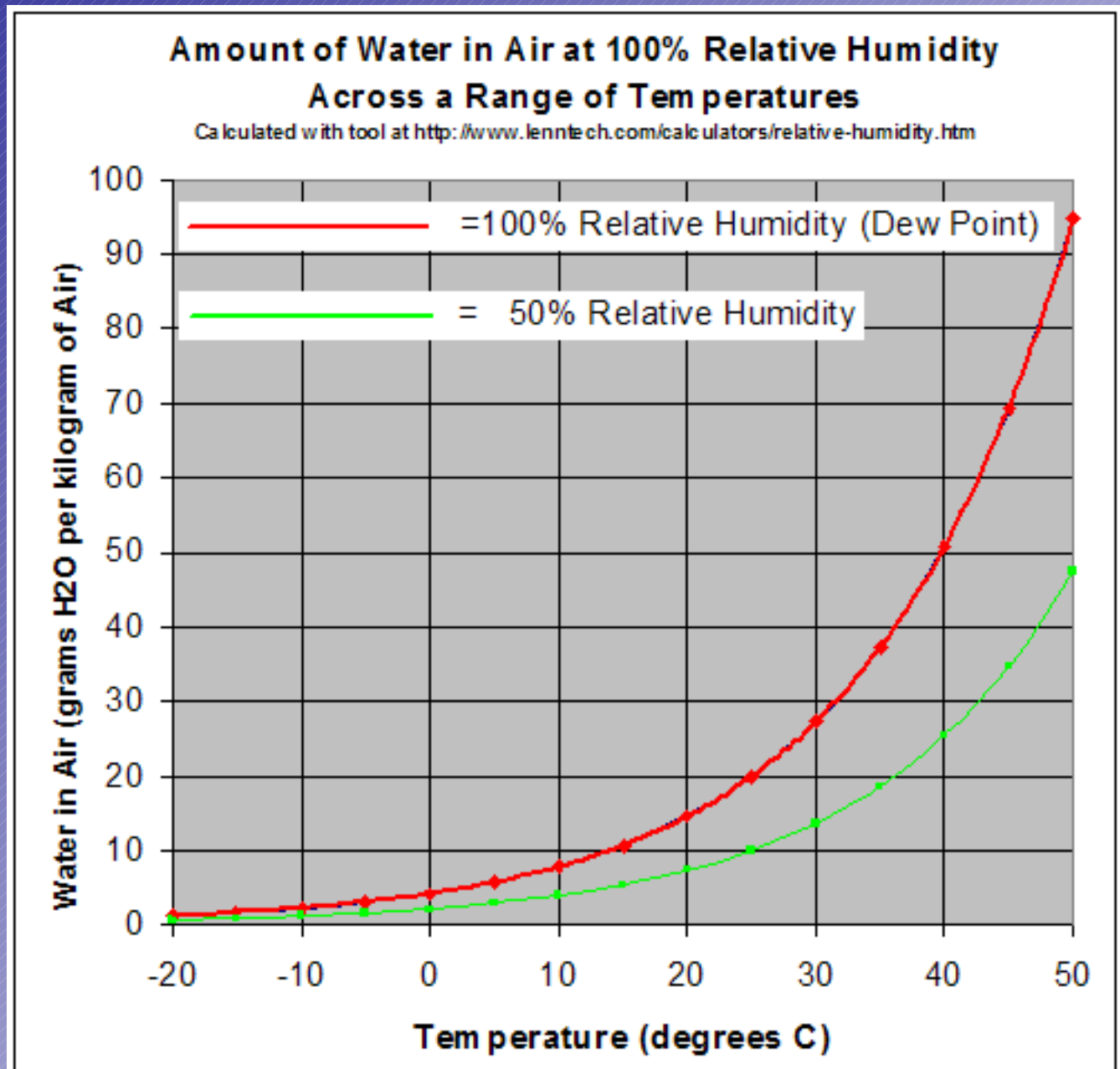
Relative Humidity vs Temperature

Partial pressures of water vapor can be obtained from $P' = \rho RT$

T= 0C, P' = 6 hPa

T= 10C, P' = 12 hPa

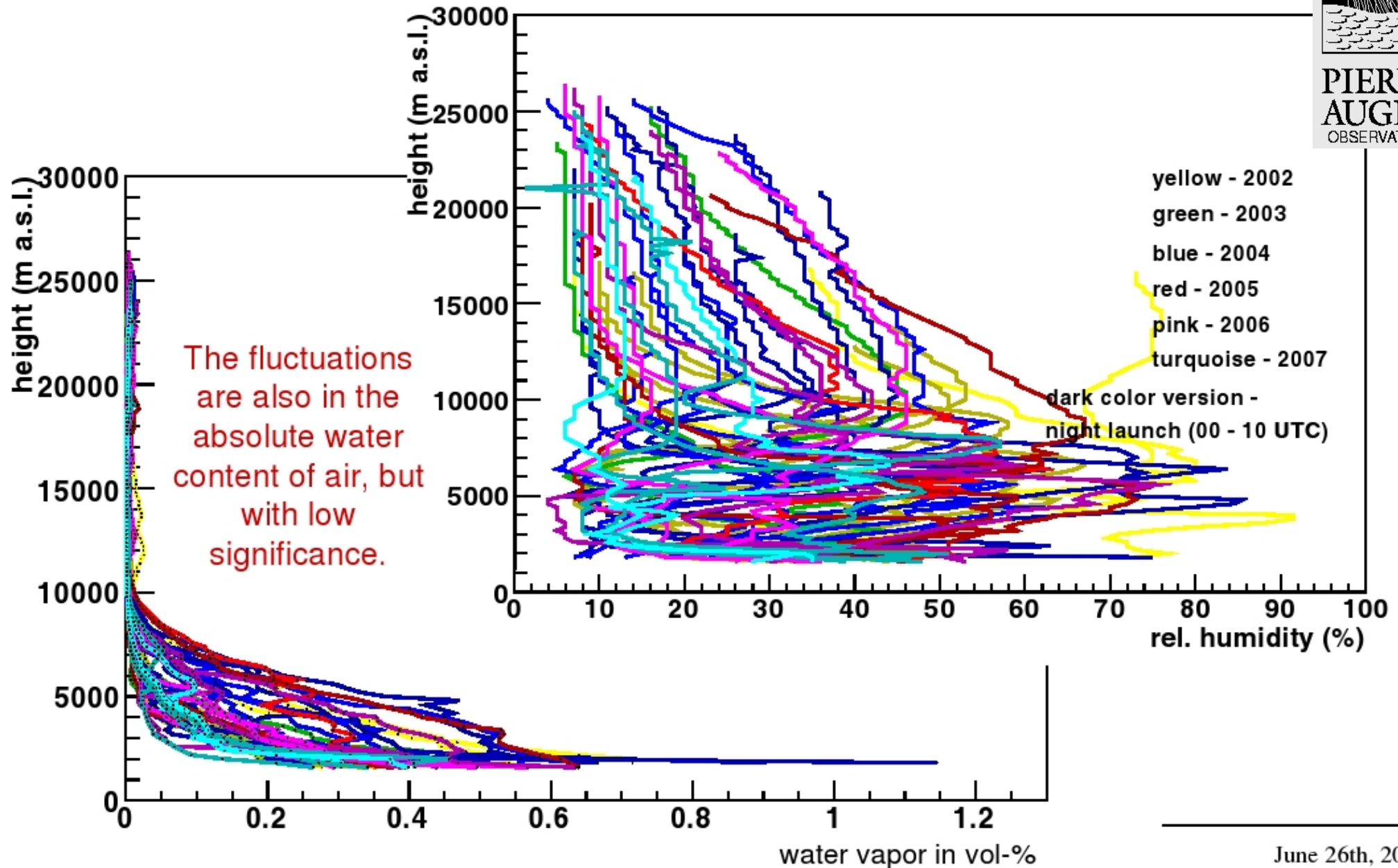
T= 20C, P' = 23 hPa



Humidity measurements : Winter(August)



PIERRE
AUGER
OBSERVATORY

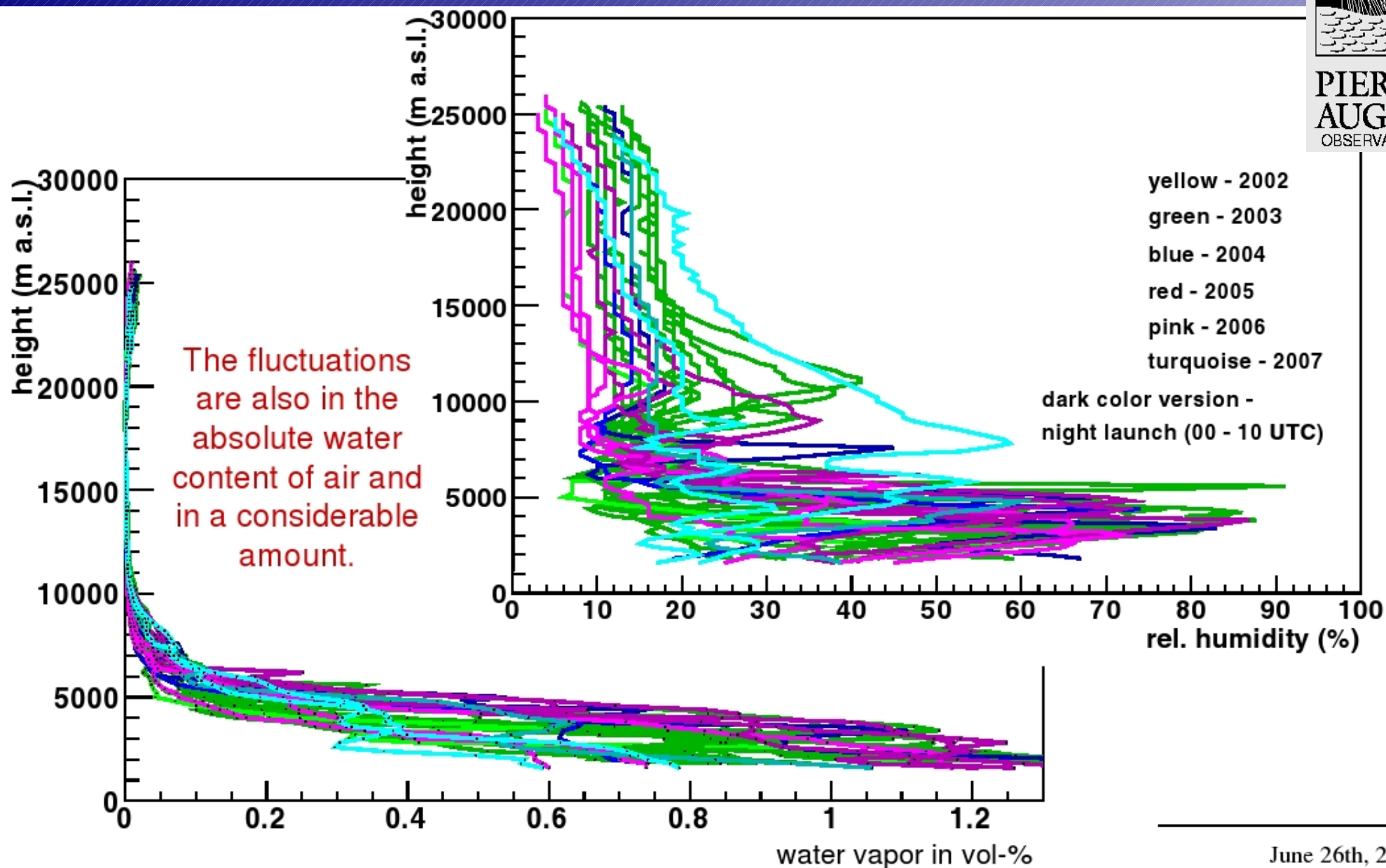


June 26th, 2008

Humidity measurements : Summer(February)

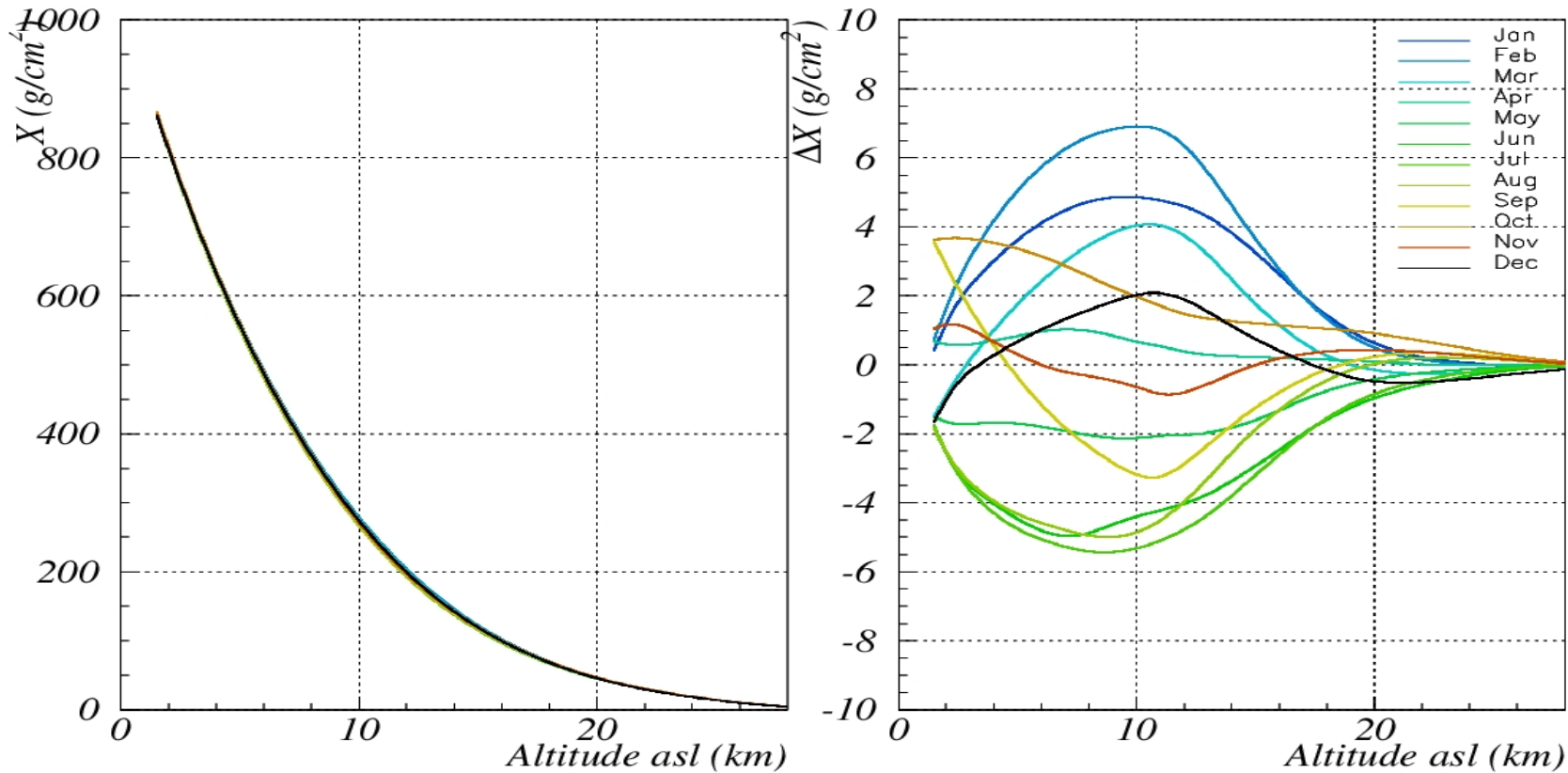


PIERRE
AUGER
OBSERVATORY



June 26th, 2008

Atmosphere: grammage, monthly models



Grammage : $X(h) = \int_h^\infty \rho(z) dz$ is the mass on unit area of the air column above a given height.

Small seasonal variations, mostly peaking in the lower tropopause.

Data shown on the right compare monthly averages to all-year average.

Data taken in Malargue (southern hemisphere, 35 degrees latitude).

Rayleigh scattering

Rayleigh approximation : scattering on small spheres

size of molecules \ll distance between molecules \ll light wavelength
0.1 nm \ll 5 nm \ll 300-400 nm

Rayleigh cross section :

$$\sigma_{Rayleigh} = \frac{24\pi^3}{\lambda^4 N^2} \left| \frac{\epsilon - 1}{\epsilon + 2} \right|^2$$

where N =density of scattering centers, ϵ = dielectric constant and λ = wavelength of the light.

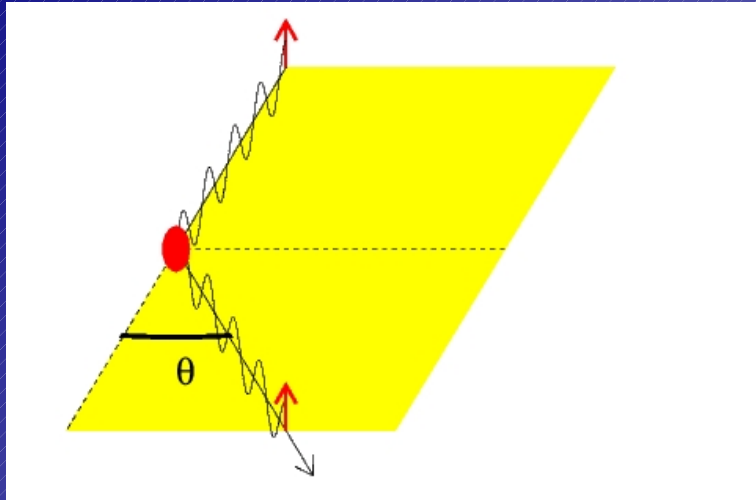
The refractive index = $n = \sqrt{\epsilon}$ is very close to 1 for a dilute gas:

$$\epsilon - 1 = 2(n - 1), \epsilon + 2 = 3$$

Finally:

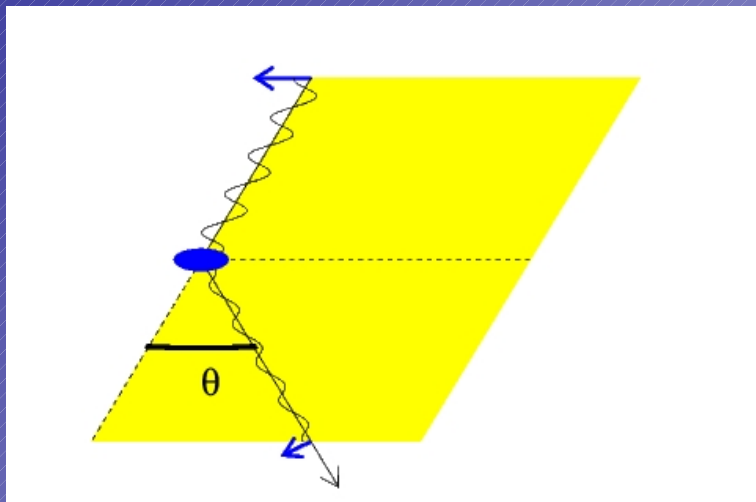
$$\sigma_{Rayleigh} = \frac{32\pi^3}{3\lambda^4} \left| \frac{n - 1}{N} \right|^2$$

Rayleigh scattering : angular distribution



Photon polarization perpendicular to scattering plane:

$$\frac{d\sigma_{\perp}}{d\Omega} = \frac{3\sigma_{Rayleigh}}{16\pi}$$



Photon polarization parallel to scattering plane:

$$\frac{d\sigma_{\parallel}}{d\Omega} = \frac{3\sigma_{Rayleigh}}{16\pi} \cos^2 \theta$$

Photons at 90 degrees are fully polarized

Rayleigh scattering : depolarization effects

If scattering centers are not perfect spheres, depolarization occurs, and a correction to total cross section and angular distribution is needed.

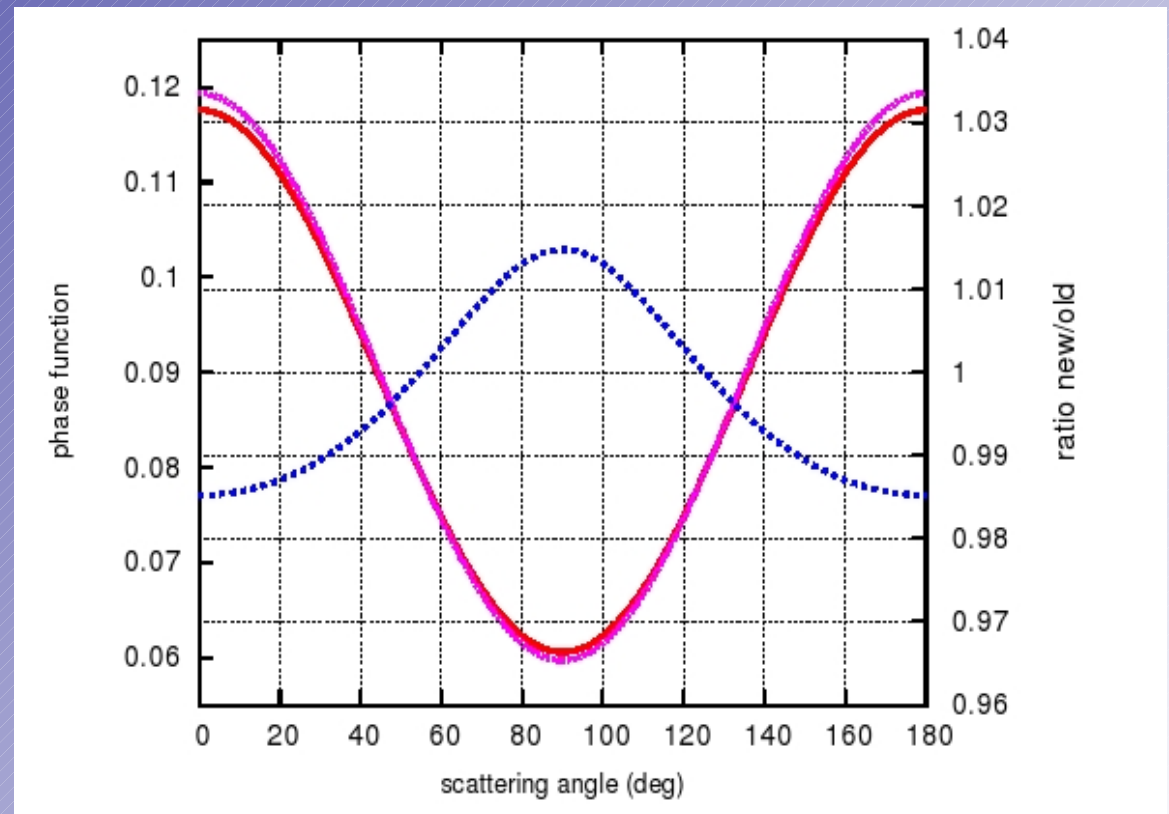
$$\sigma_{Rayleigh} = \frac{32\pi^3}{3\lambda^4} \left| \frac{n-1}{N} \right|^2 \frac{6+3\rho_n}{6-7\rho_n}$$

$$\frac{d\sigma}{d\Omega} = \frac{3\sigma_{Rayleigh}}{16\pi} [a_n(1 + \cos^2 \theta) + b_n \sin^2 \theta]$$

$$a_n = \frac{2-2\rho_n}{2+\rho_n}; b_n = \frac{2\rho_n}{2+\rho_n}$$

Depolarization is smoothly wavelength dependent:

$\rho_n = 0.028$, $\Delta\sigma/\sigma = 4.8\%$
(at 300-400 nm)



Refractive Index vs λ and humidity

Dry standard air : $P = 101325 \text{ Pa}$, $T = 15 \text{ }^\circ\text{C}$

$$(n_s - 1) \times 10^8 = A + B / (130 - v^2) + C / (38.9 - v^2)$$

where: $A = 8\,342.54$, $B = 2\,406\,147$, $C = 15\,998$

and $v = 1 / (\lambda / \mu\text{m})$

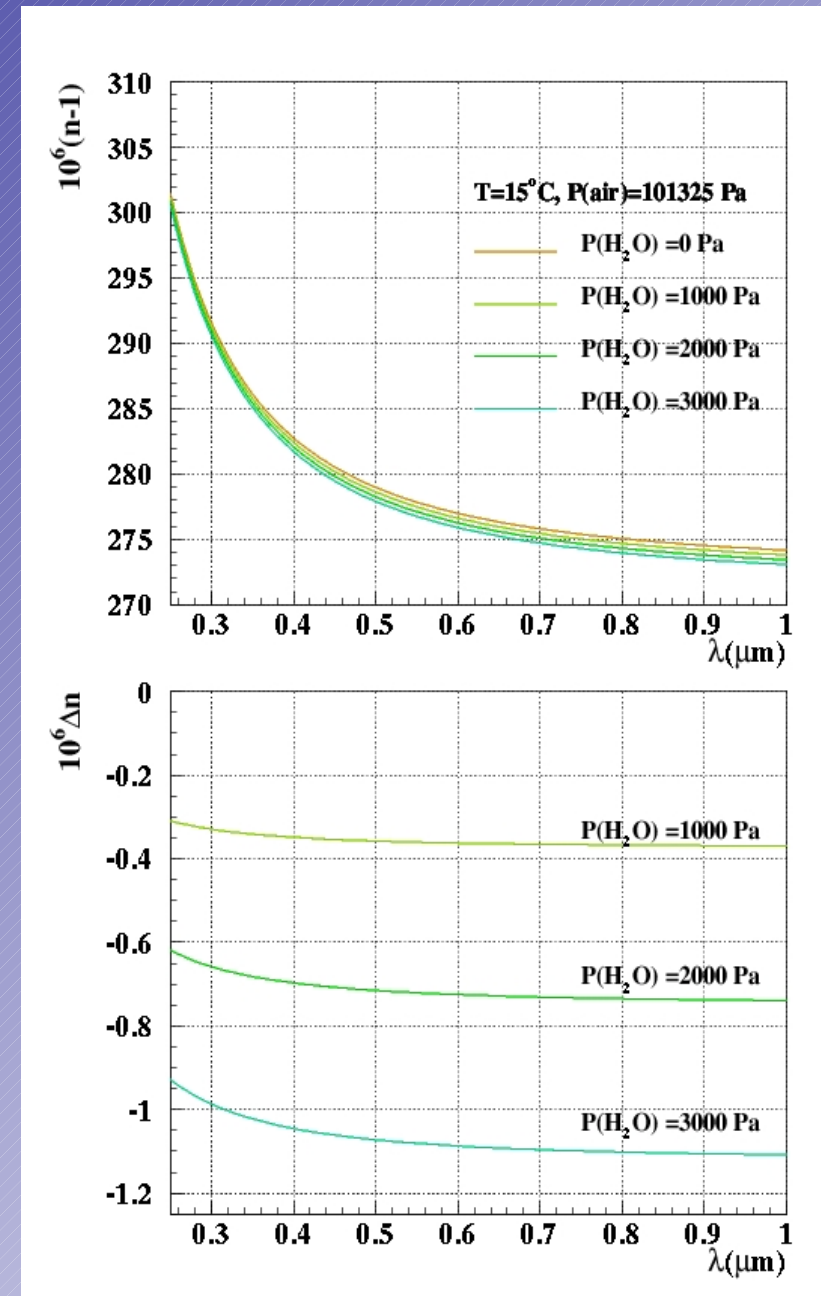
(Birch, Metrologia, 1994, 31, 315)

Correction for *moist air* :

$$\Delta n \times 10^8 = - P(\text{H}_2\text{O}) (3.7345 - 0.0401 v^2) 10^{-2}$$

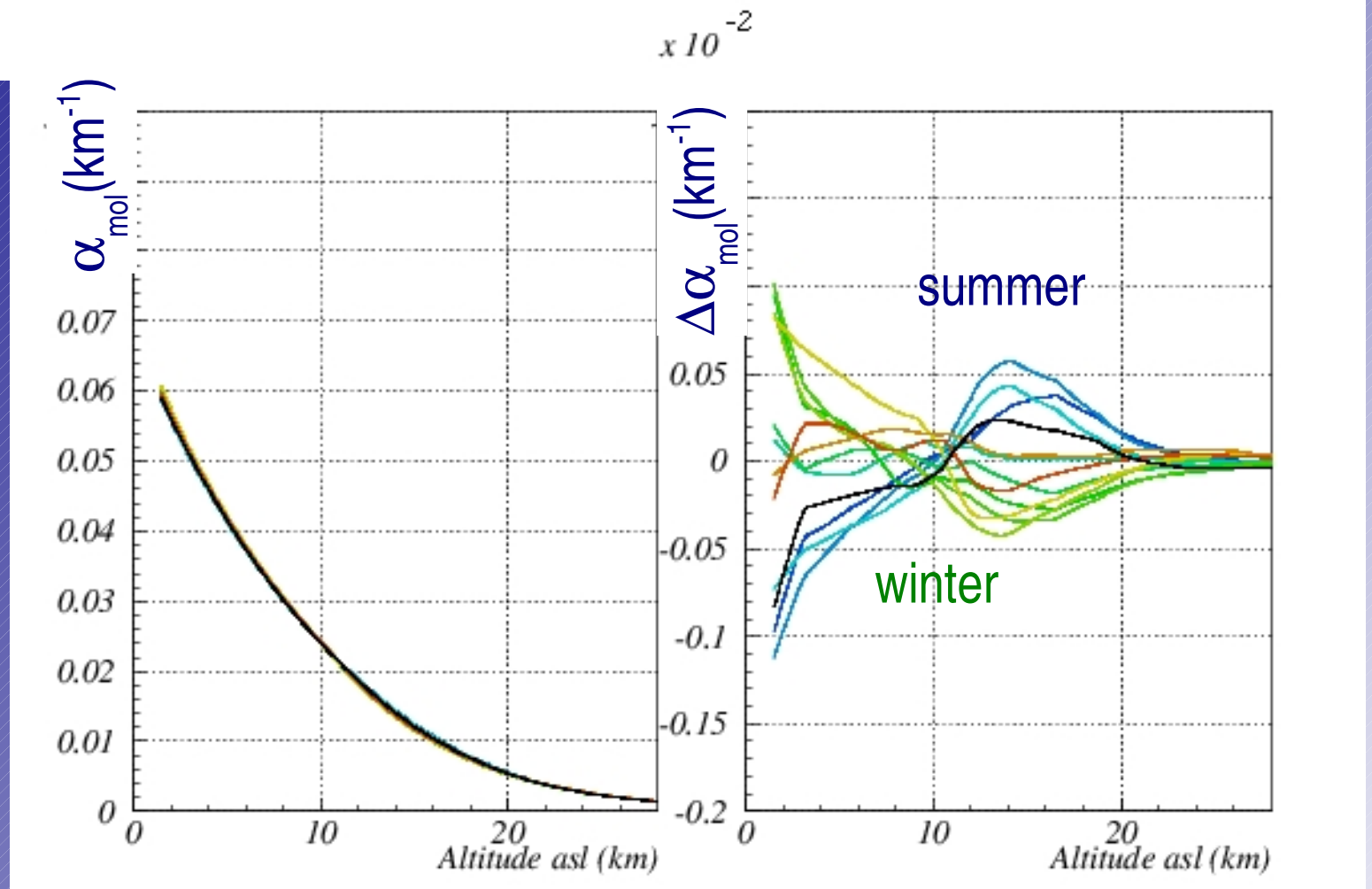
where $P(\text{H}_2\text{O})$ = partial pressure of water vapor,

in Pascal (e.g. 1500 with 1.5% of water vapor)



Attenuation coefficient at 350 nm vs altitude

$$\alpha_{\text{mol}} = \sigma_{\text{Rayleigh}} N(h)$$



Optical properties show little dependence on molecular density variations. Significant variations (even in the short term, even nightly) are instead due to **changes of aerosol contamination** or **cloud coverage**.

Mie scattering

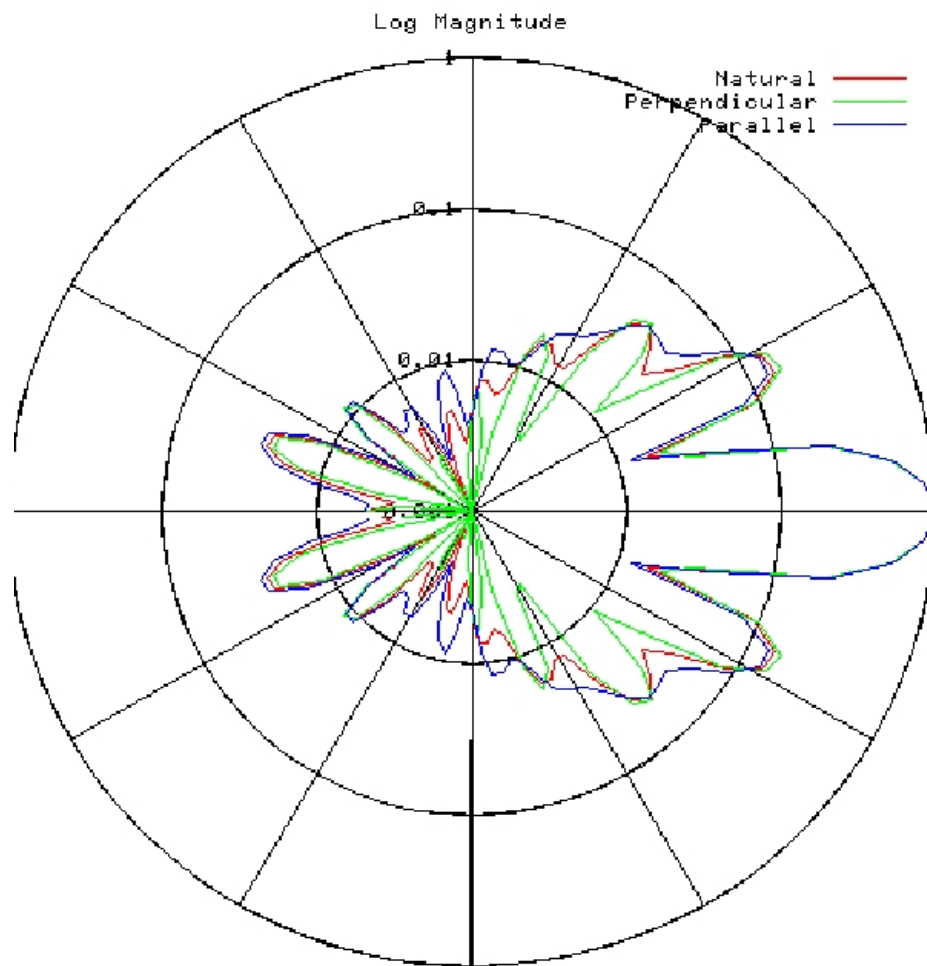
Input Parameters

Sphere Diameter	1.0	microns
Refractive Index of Medium	1.0	
Real Refractive Index of Sphere	1.4	
Imaginary Refractive Index of Sphere	0	
Wavelength in Vacuum	0.355	microns
Concentration	0.01	spheres/micron ³

Calculated results

Wavelength in Medium	0.355	microns
Size Parameter	8.8496	
Average Cosine of Phase Function	0.61327	
Scattering Efficiency	1.9275	
Extinction Efficiency	1.9275	
Backscattering Efficiency	0.41029	
Scattering Cross Section	1.5139	micron ²
Extinction Cross Section	1.5139	micron ²
Backscattering Cross Section	0.32224	micron ²
Scattering Coefficient	15.139	mm ⁻¹
Total Attenuation Coefficient	15.139	mm ⁻¹

size of spheres > light wavelength
1000nm > 300-400 nm
(e.g.: mist)

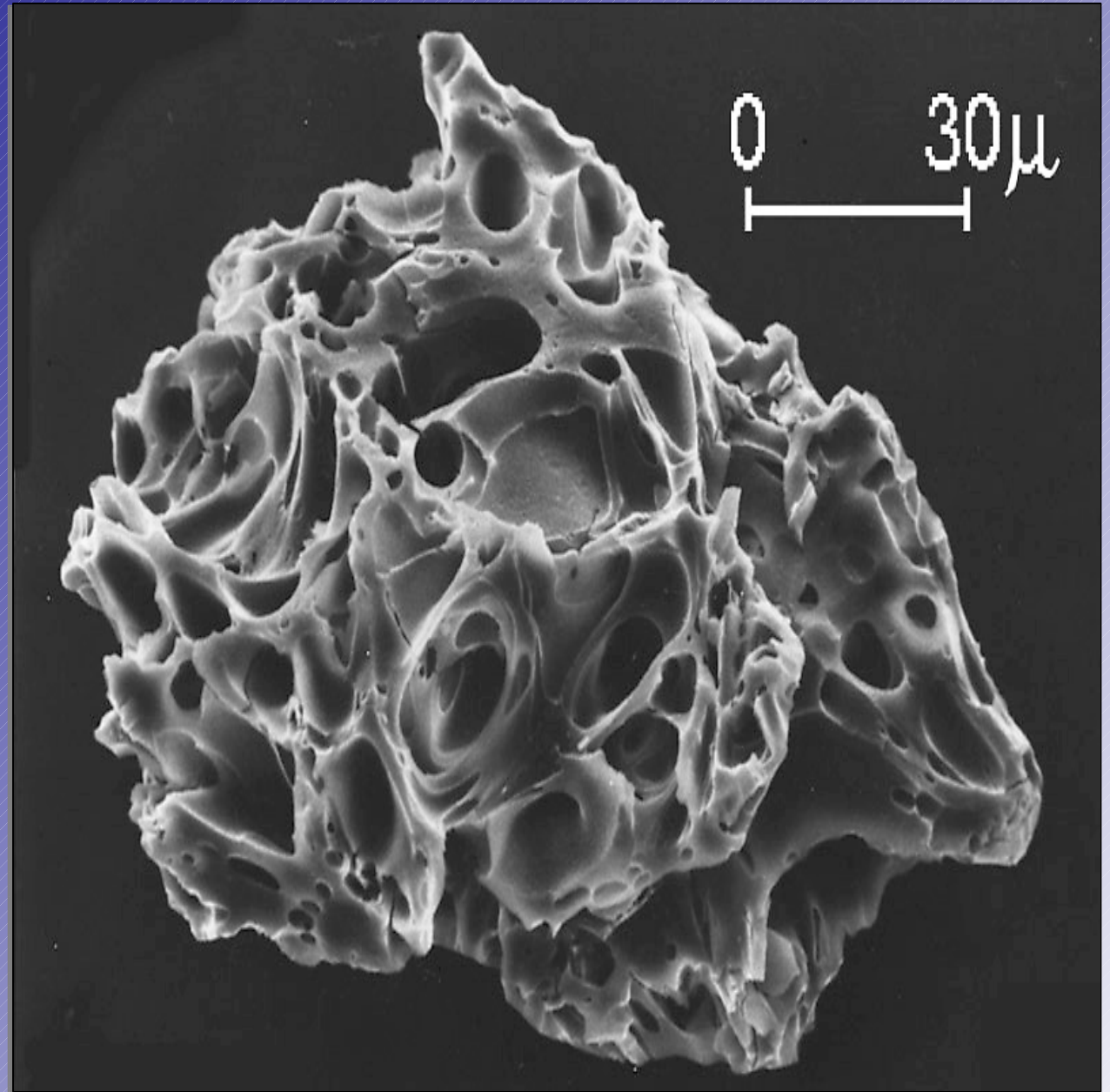


Mie scattering: limits

Typical aerosols for desert areas :

smoke (from landfires),
dust, sand (windborn)

Very irregular shapes,
clearly impossible to
model as spheres



Summary

Molecular atmosphere modeling in AUGER could rely upon existing data
Weather station and radiosonde data since 2004 were analyzed to build seasonal profiles

Daily profiles can differ significantly from monthly averages

Water vapour has significant impact on the lapse rate

Water vapour has small impact on the slant depth

Molecular optical properties are well described by Rayleigh theory

Molecular optical depth has small monthly variations

Water vapor does not significantly affect the air refraction index

.... until it starts condensing in clouds: see next lesson

Mie scattering theory hardly describes most Malargue aerosols

Bibliography

Jackson: *Classical Electrodynamics*, Wiley 1975

Panofsky, Phillips: *Classical Electricity and Magnetism*, Addison-Wesley 1966

Lipson *et al.*: *Optical Physics*, Cambridge 1995

Bucholtz, *Applied Optics* 34, 2765 (1995)

Kovalev, Eichinger: *Elastic Lidar*, Wiley 2004

Atmosphere: refractive indices and heat capacity ratios

	A	n-1	γ
N ₂	28.01348	0.000298	1.404
O ₂	31.9988	0.000271	1.401
Ar	39.948	0.000283	1.668
CO ₂	42.010	0.000410	1.304
Ne	20.1797	0.000067	1.64
He	4.0026	0.000035	1.659
CH ₄	16.0428	0.000444	1.305
Kr	83.798	0.000427	1.666
O ₃	47.9982	-	-
H ₂ O	18.015	0.000256	1.324

COMPOSITION OF THE ATMOSPHERE				
	Gas	Symbol	% by weight	% by volume
	Nitrogen	N ₂	75.52	78.09
	Oxygen	O ₂	23.15	20.95
	Argon	A	1.28	0.93
	Carbon dioxide	CO ₂	0.046	0.035
	Neon	Ne	0.012	0.0018
	Helium	He	0.0007	0.0005
	Methane	CH ₄	0.0008	0.00015
	Krypton	Kr	0.003	0.0001
	Ozone	O ₃	0-0.01	Variable
	Water vapour	H ₂ O	0-4	Variable

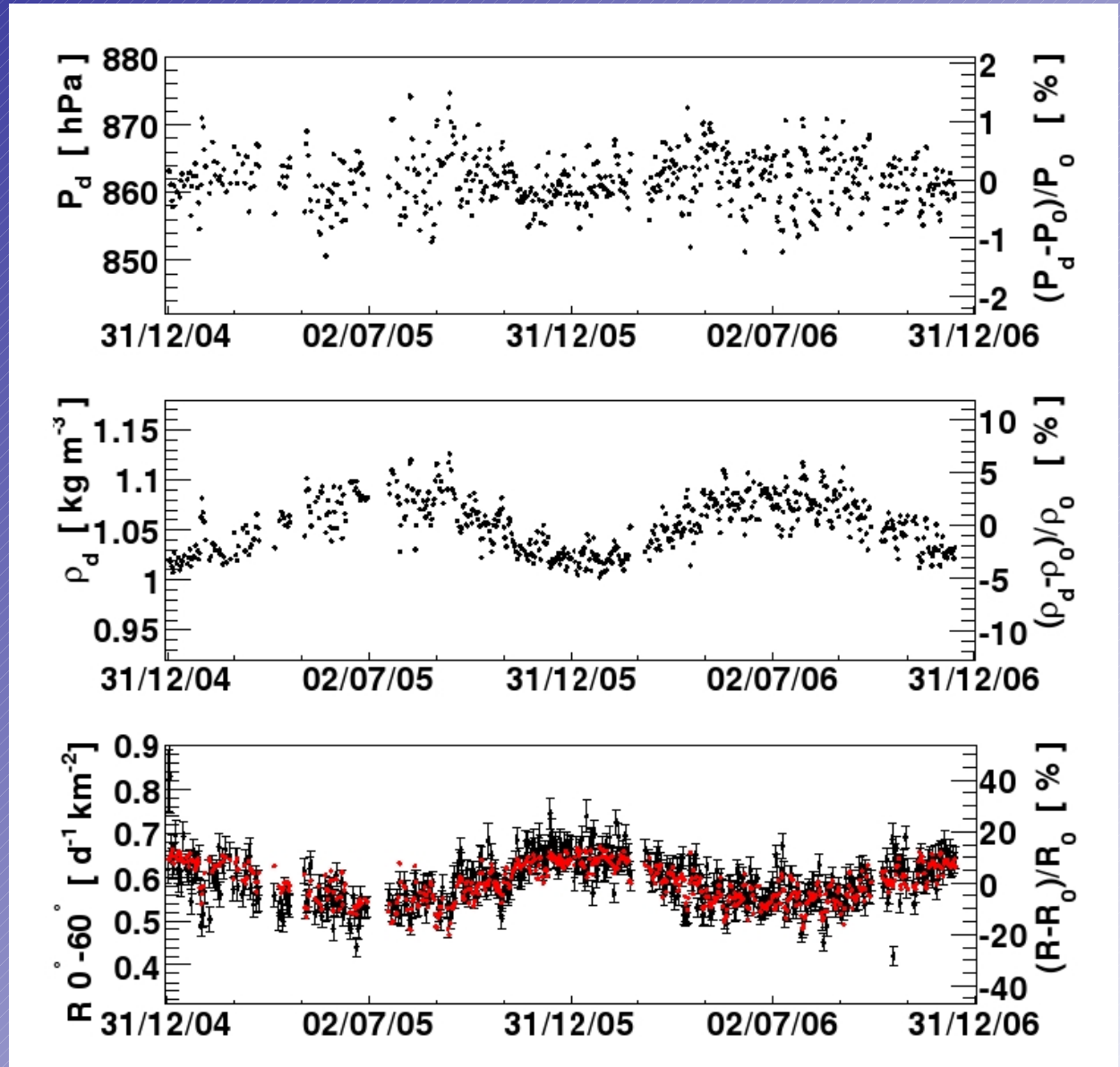
Refraction Index: $n = \sqrt{\epsilon} = 1 + 2\pi \langle \alpha \rangle N$

Mean Polarizability: $\langle \alpha \rangle$

Molecular density: N

Heat capacity ratio: $\gamma = C_p/C_v = (5+f)/(3+f)$

Density effects on tank rates: seasonal



Density effects on tank rates: daily

