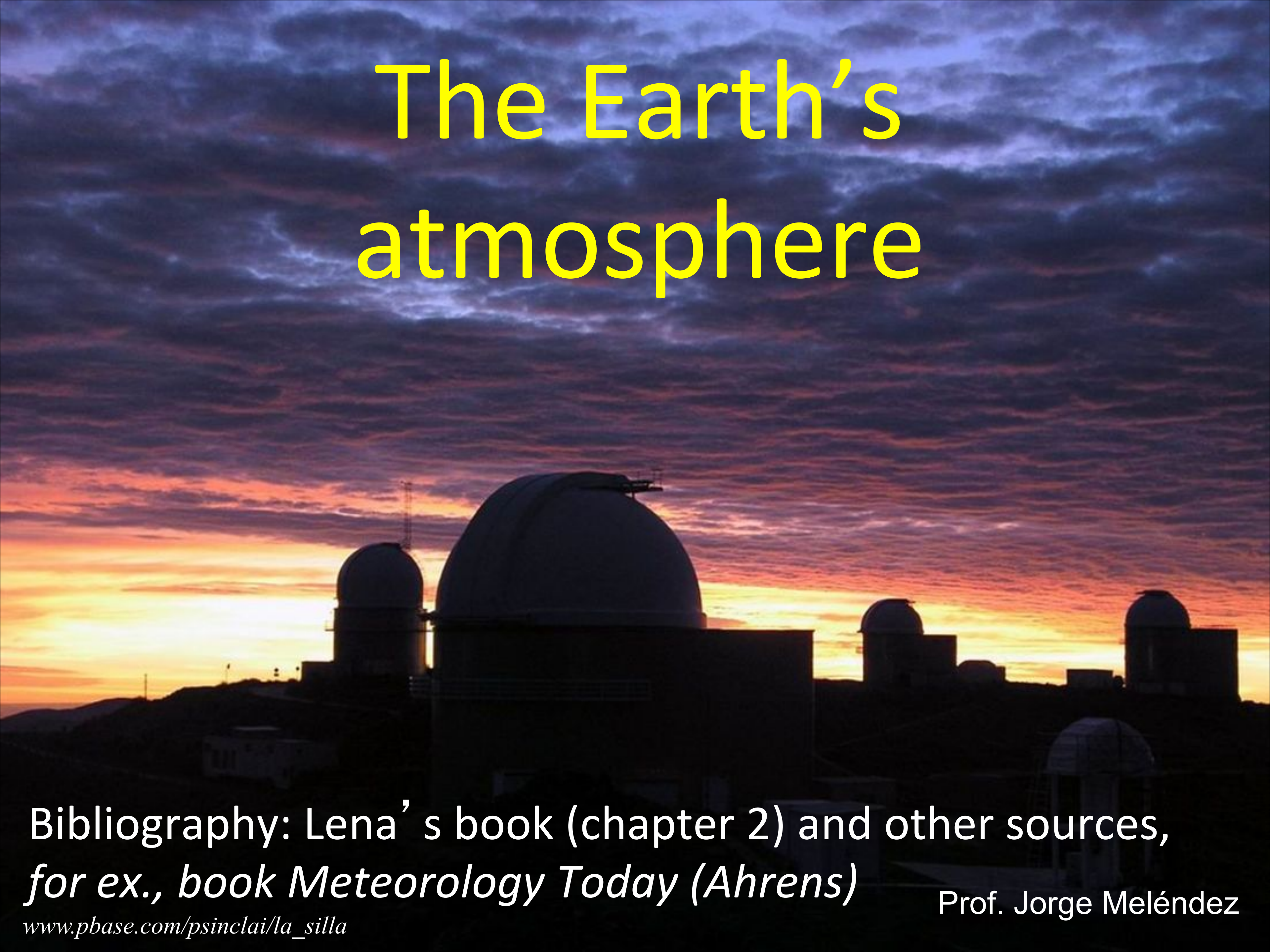
The Earth's atmosphere



Bibliography: Lena's book (chapter 2) and other sources, *for ex., book Meteorology Today (Ahrens)*

Prof. Jorge Meléndez

www.pbase.com/psinclai/la_silla

Points to discuss at the beginning of the class

- What is the Earth atmosphere?
- Temperature profile?
- Pressure profile?
- Composition profile?
- What are the main problems for observational astronomy?

Most observations are performed on the ground

We must know the Earth atmosphere to understand the limitations for ground observations

O P D - Estação Meteorológica

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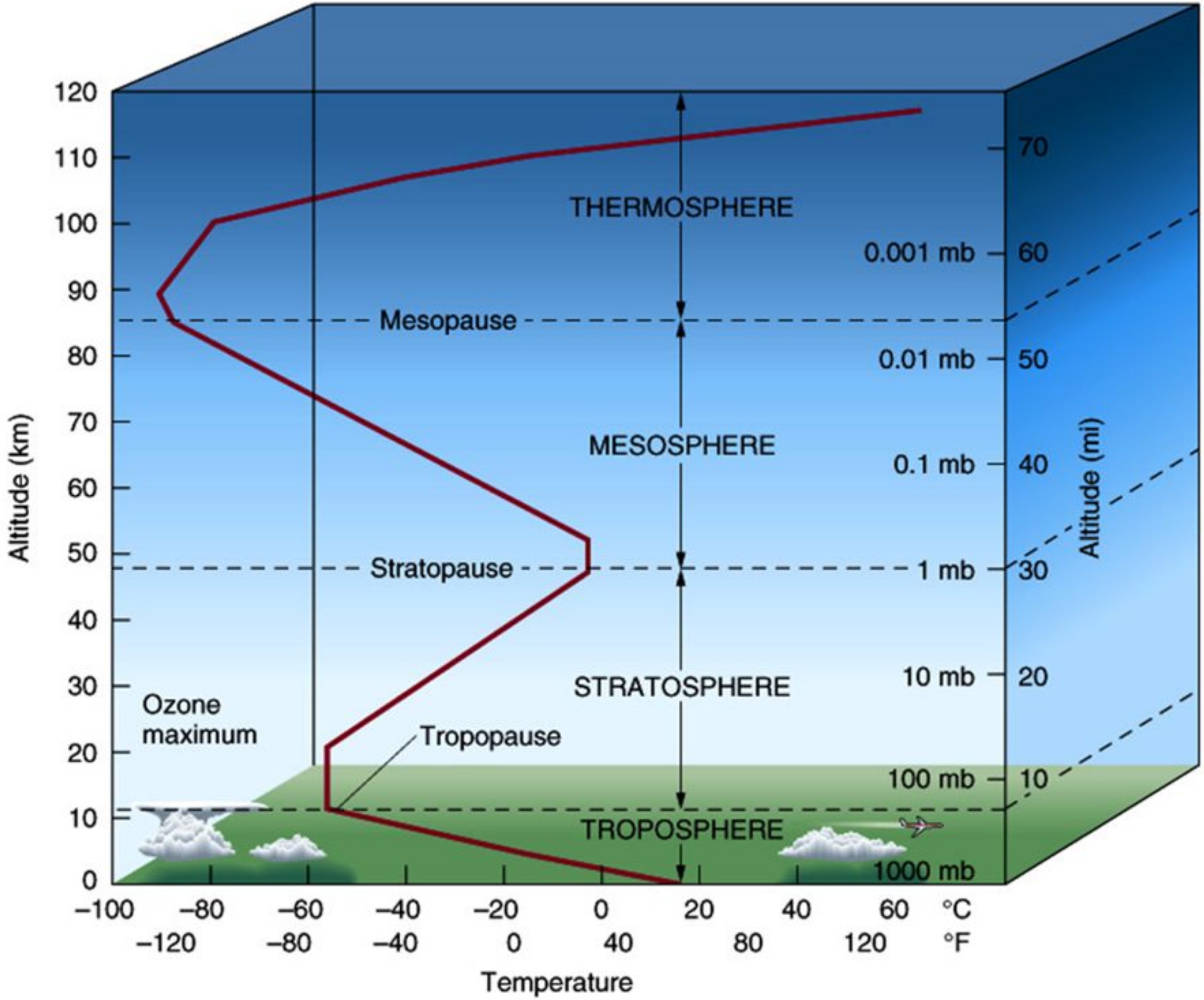
Earth's atmosphere is a fine layer of gas that surrounds Earth and that is kept by gravity

• FIGURE 1.2 The earth's atmosphere as viewed from space. The atmosphere is the thin blue region along the edge of the earth.

Structure of Earth's atmosphere



burro.cwru.edu/Academics/Astr201/Atmosphere/atmosphere1.html

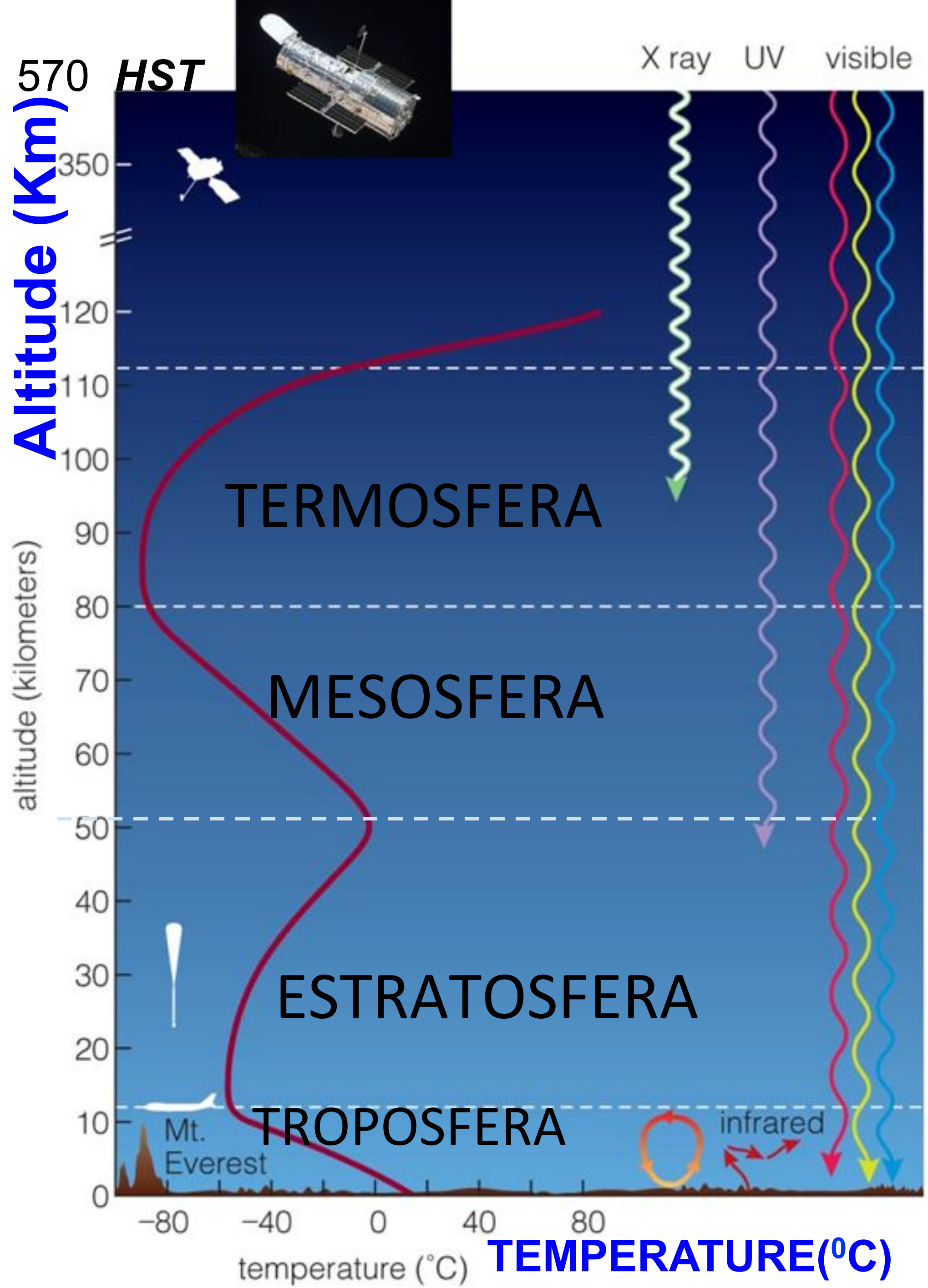
Temperature profile

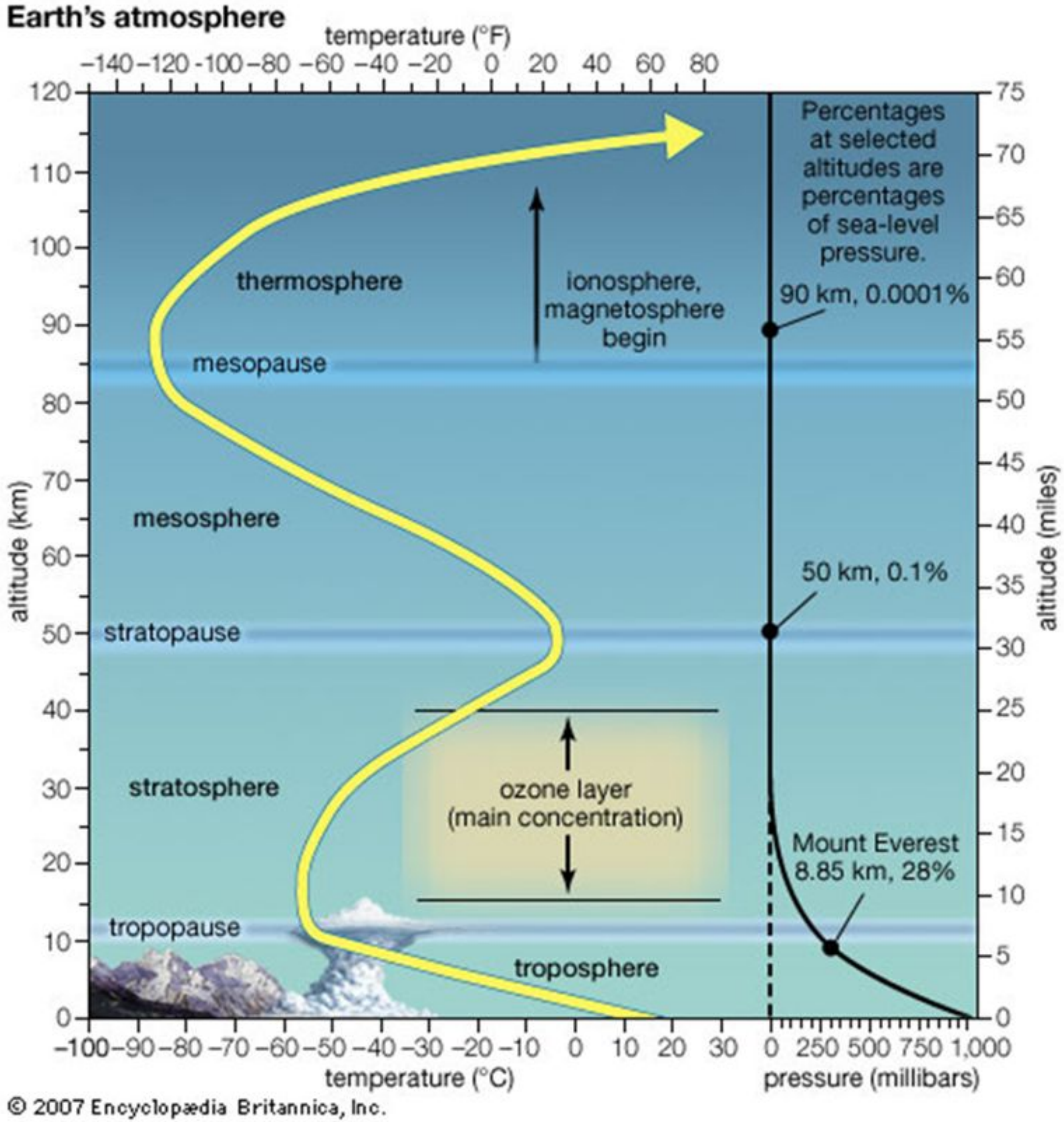
Solar UV light and X-rays heat and ionize gas

Ozone decreases

Warm by ozone UV absorption

Warm by the ground and convection





Pressure:

decrease exp. with height z

$$P(z) = P_0 \exp(-z/H)$$

H: height scale ($=RT_m/M_0g$)

Chemical composition aprox. constant until 90 km

$$\rho = \frac{MP}{kT}$$

$H = RT_m/M_0g$
(scale height)

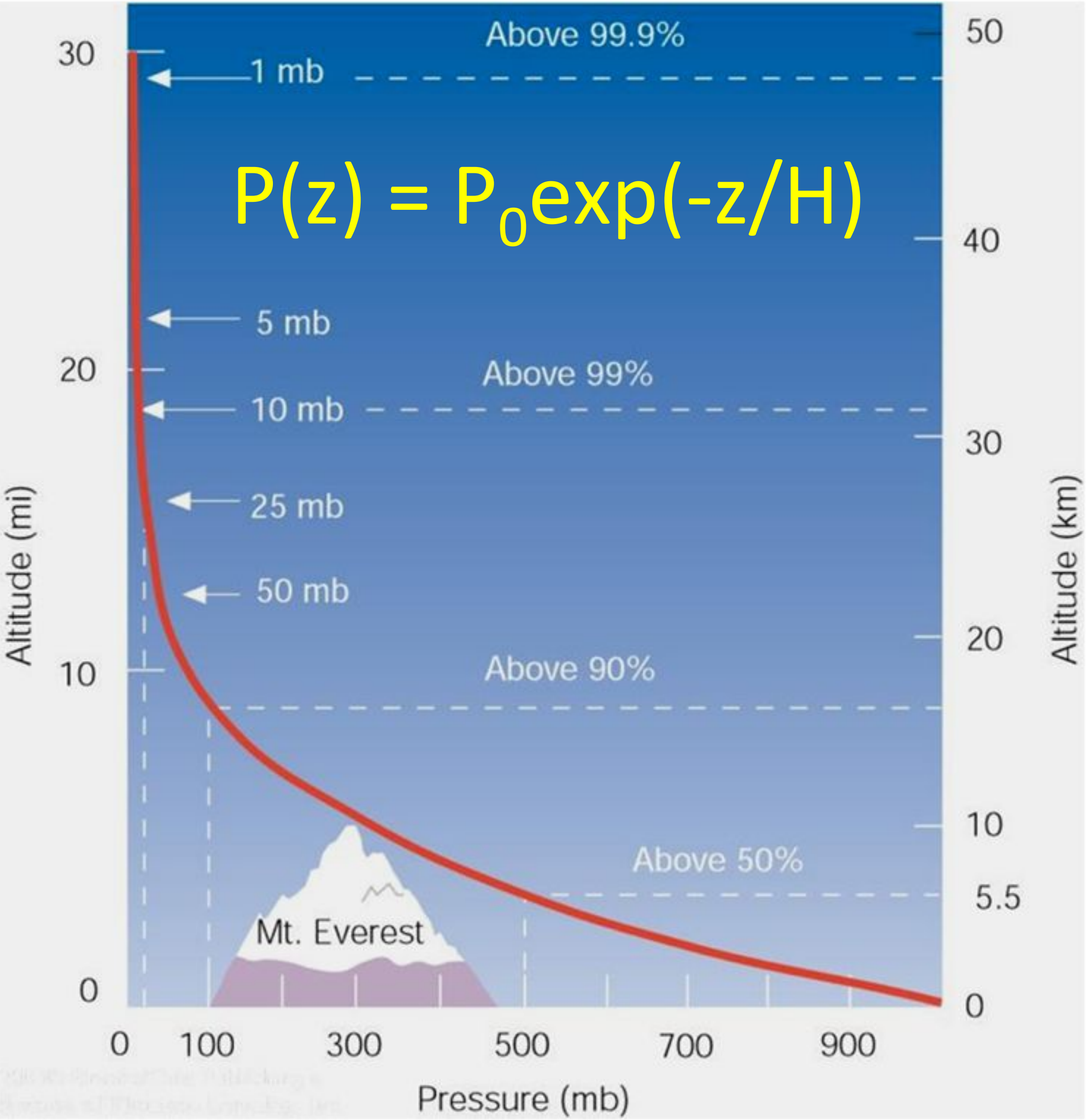
R: gas constant ($8.23\ J\ K^{-1}\ mol^{-1}$)

T_m: mean temp. (0^0 C)

M_0: mean mol. mass (0.029kg)

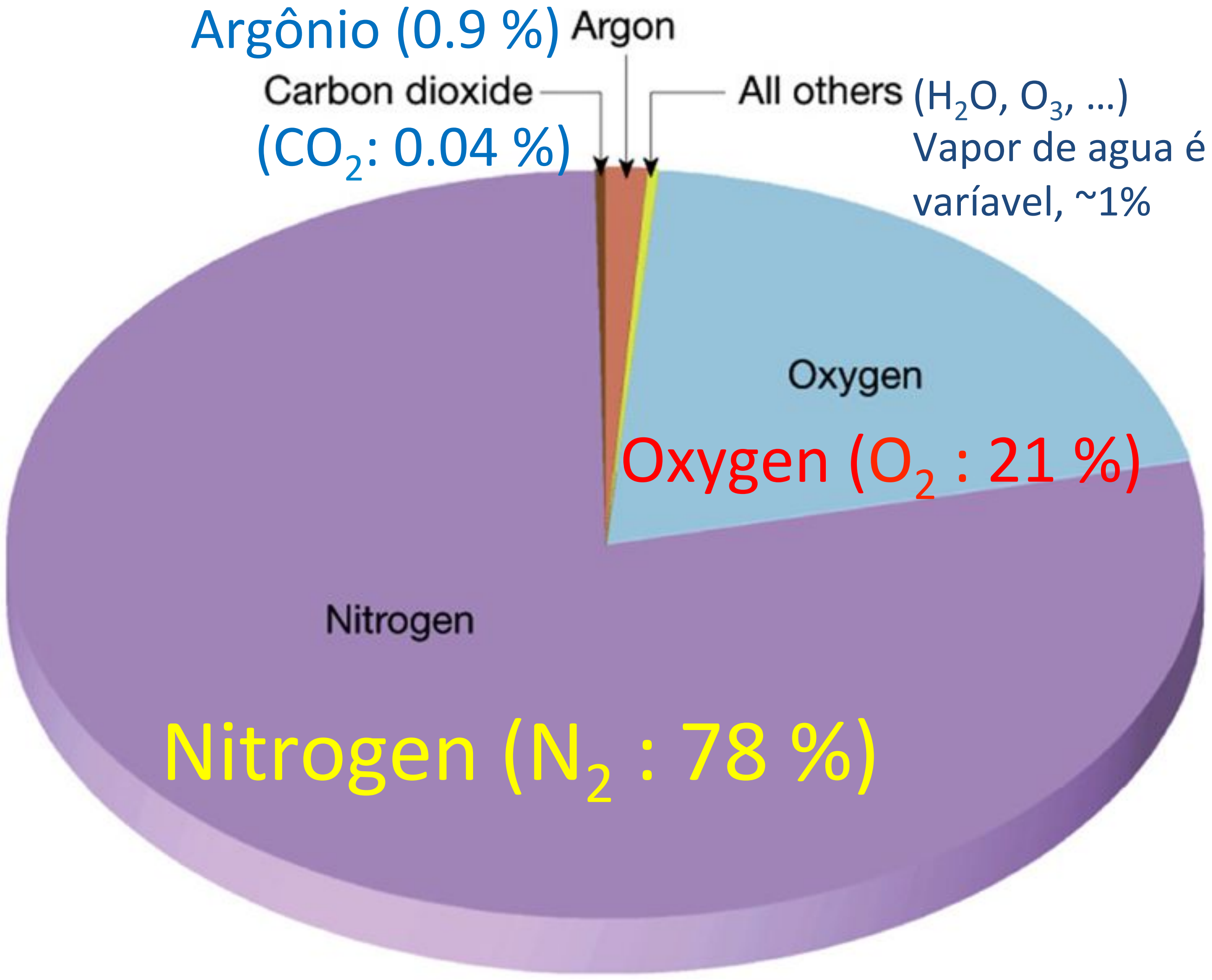
g: gravity

H = 8km



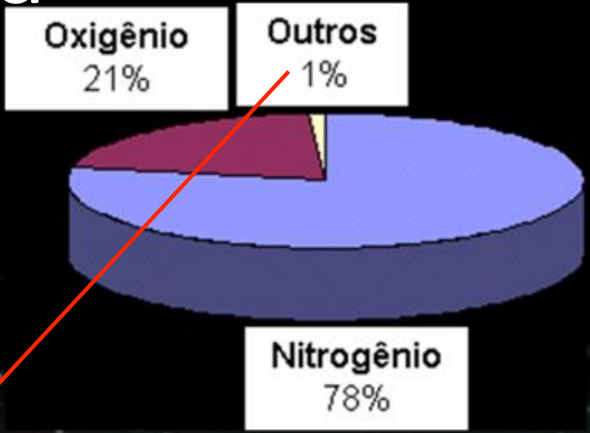
Which are the main constituents of the atmosphere?

Constituents of the atmosphere

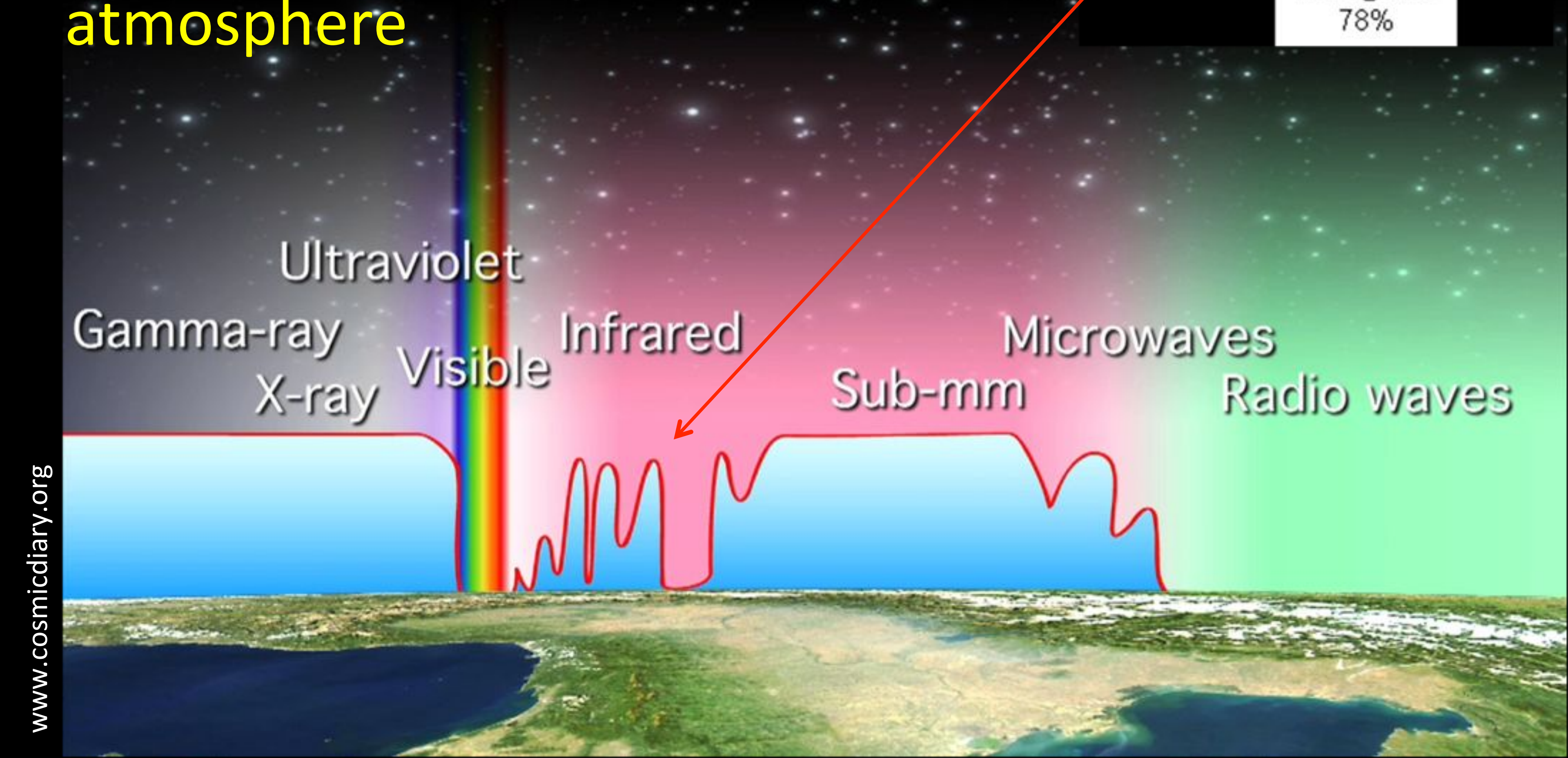


N & O are the main constituents and its proportion is relatively constant between 0-90 km

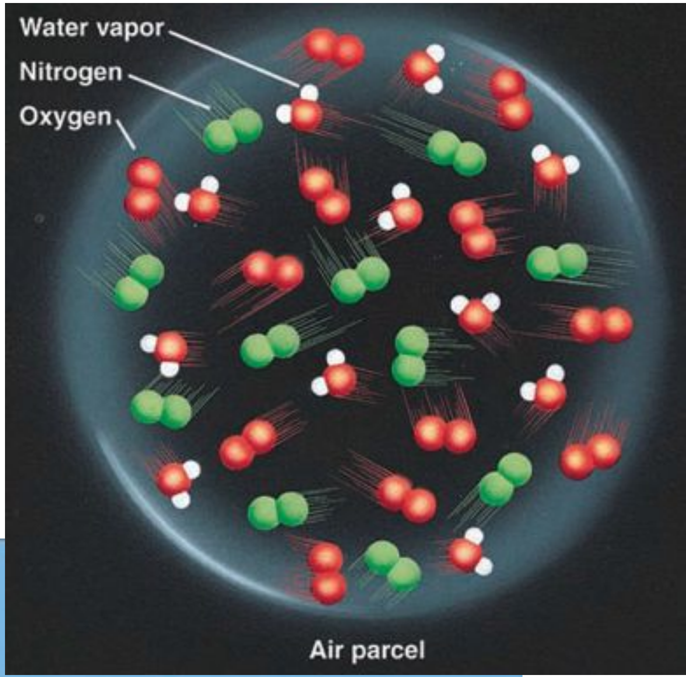
Constituents of the atmosfera (CO$_2$, H$_2$O, O$_3$,…)

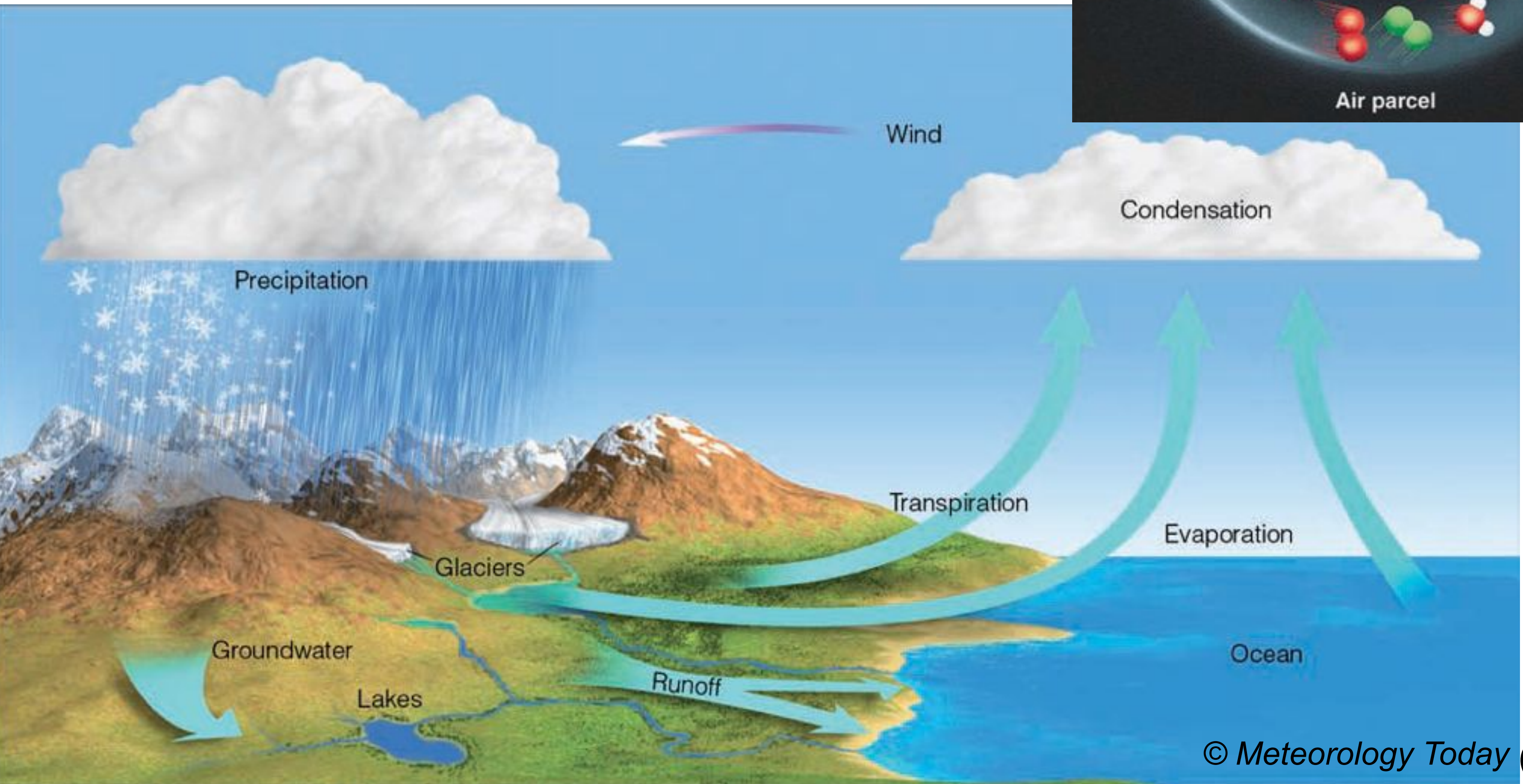


The minor (and variable) constituents are important sources of opacity in the atmosphere



Water vapor: one of the most important sources of opacity





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Measurement of the water vapor content

The *fractional content*, *mixing ratio*, or *specific humidity* is:

$$r = \frac{\text{mass of } H_2O \text{ per m}^3}{\text{mass of air per m}^3}$$

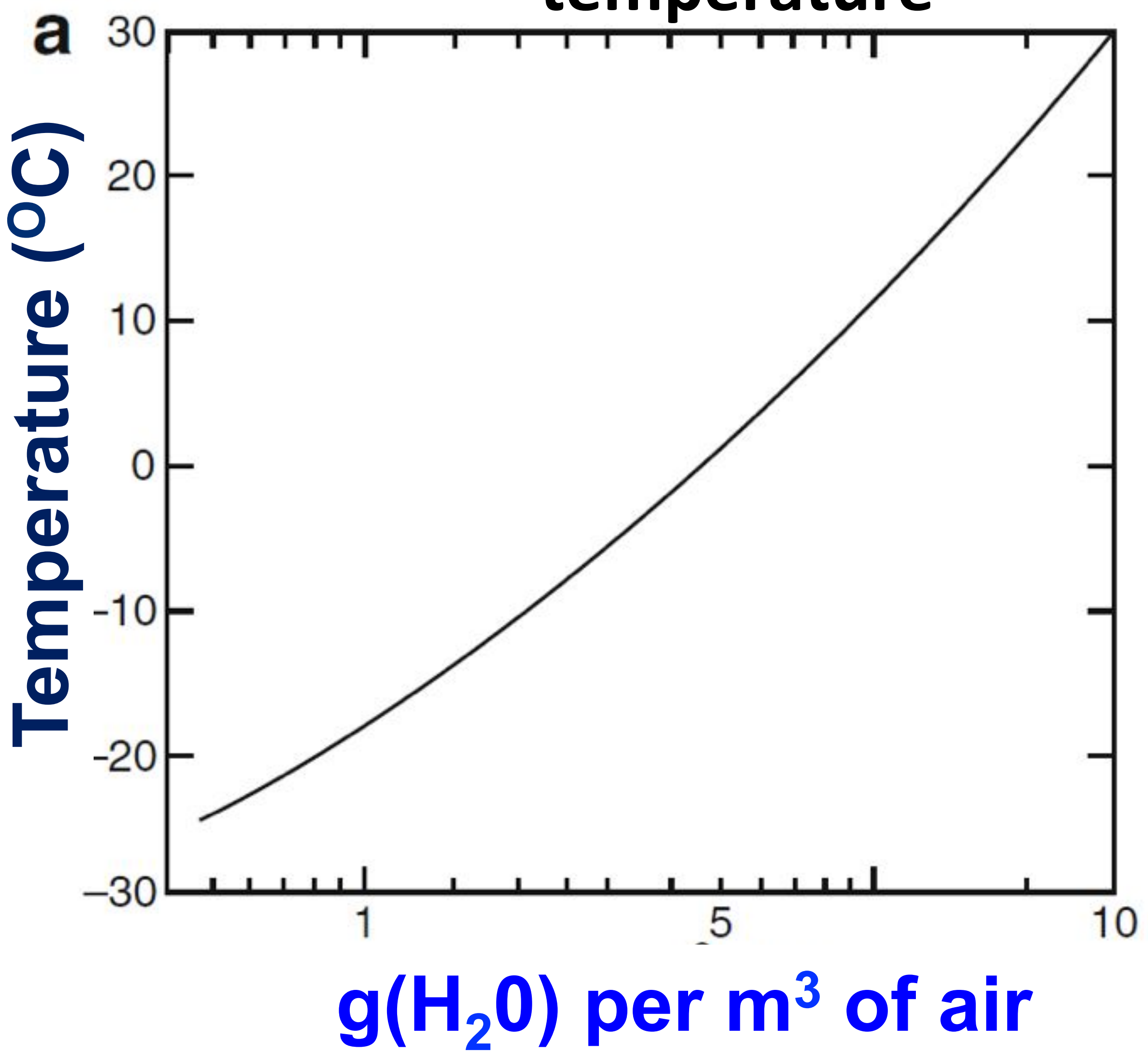
•$0 < r \leq r_s(T)$ (saturation)

$[r]$ = g/Kg

Very sensitive to:

- Temperature
- z (altitude)
- Latitude
- time

Mass concentration of water vapor per volume of saturated air at normal pressure as a function of temperature



Mixing ratio as a function of latitude

$$r = \frac{\text{mass of } H_2O \text{ per m}^3}{\text{mass of air per m}^3}$$

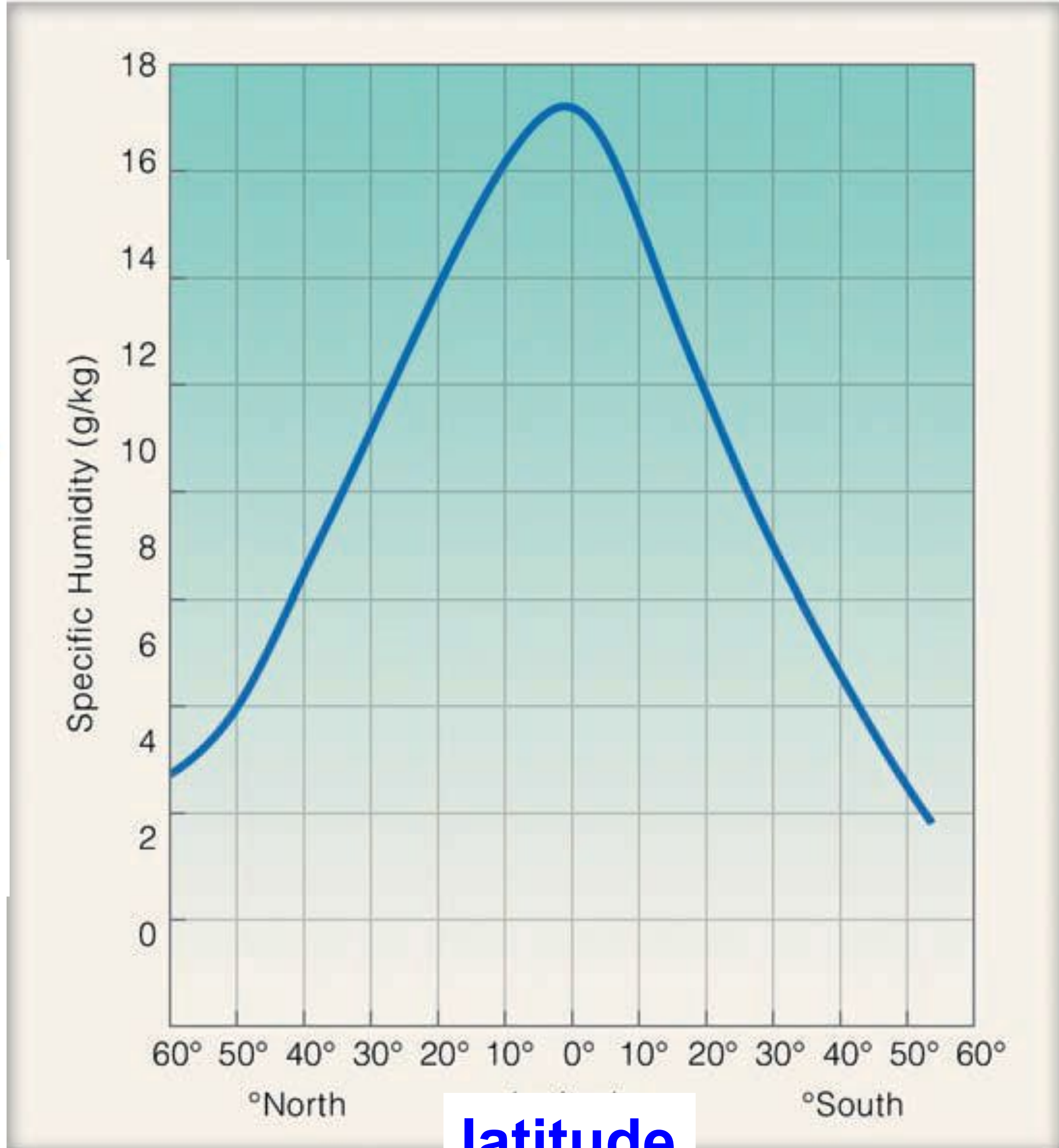
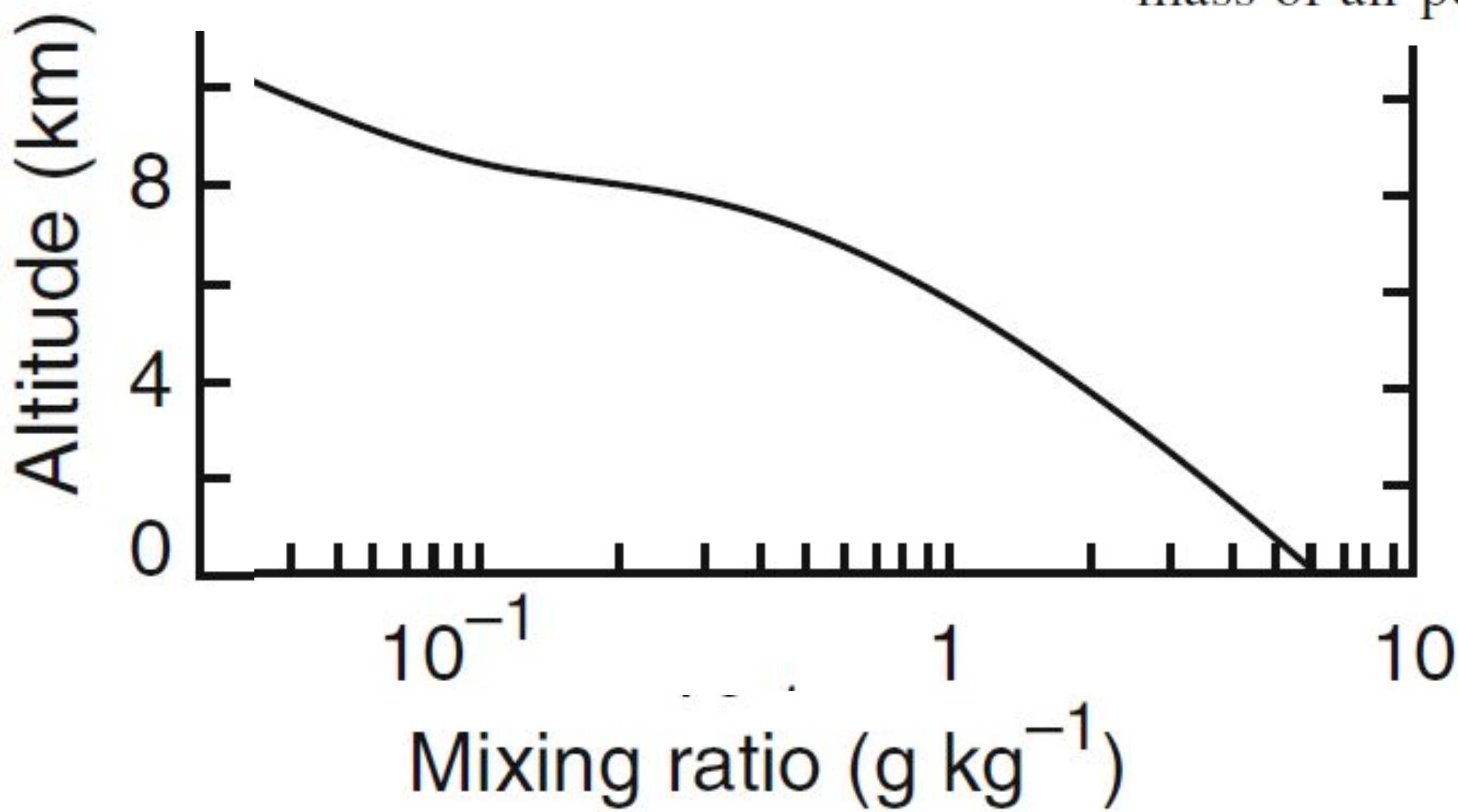


FIGURE 4.9 The average specific humidity for each latitude.

Concentration of water vapor as a funtion of altitude

$$r = \frac{\text{mass of } H_2O \text{ per m}^3}{\text{mass of air per m}^3}$$



Precipitable water

Precipitable water above altitude z_0:

$$w(z_0) = \int_{z_0}^{\infty} N_{H_2O} \, dz$$

where $N_{H_2O}(z)$ is the number of molecules/volume

For normal pressure and temperature P_0 and T_0, respectively,

$$N_{H_2O}\,[m^{-3}] = 4.3 \times 10^{25} \frac{P}{P_0} \frac{T}{T_0} r(z).$$

Column of precipitable wapor vapor

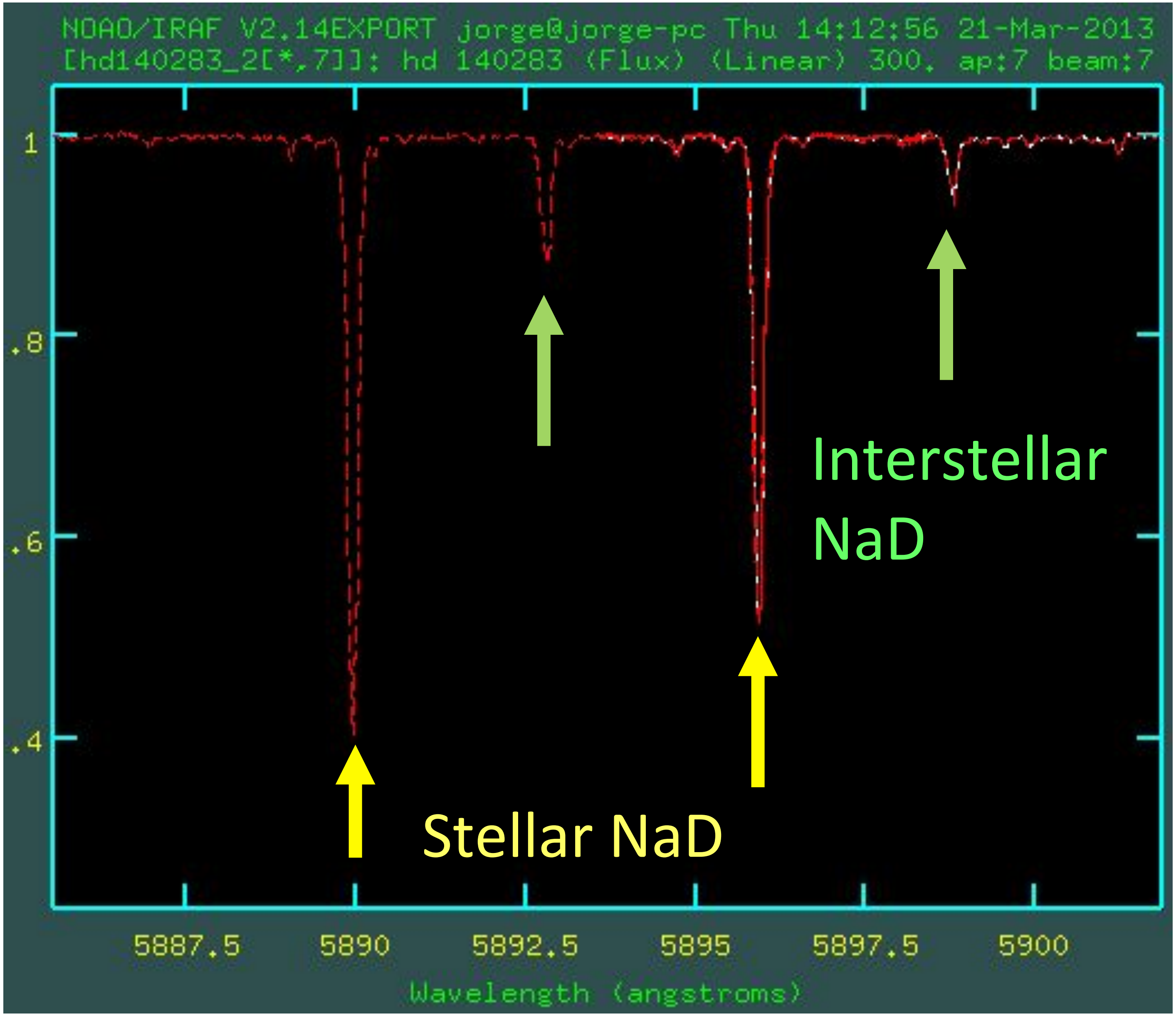
$$h_{H_2O}\ [\mathrm{cm}] = \rho_0\ [\mathrm{g\,cm^{-3}}] \int_{z_0}^{\infty} r(z) e^{-z/H}\, \mathrm{d}z,$$

where ρ_0 is air density at z_0

r(z) changes rapidly: scale height of water vapor is (3km) << dry air (8 km)

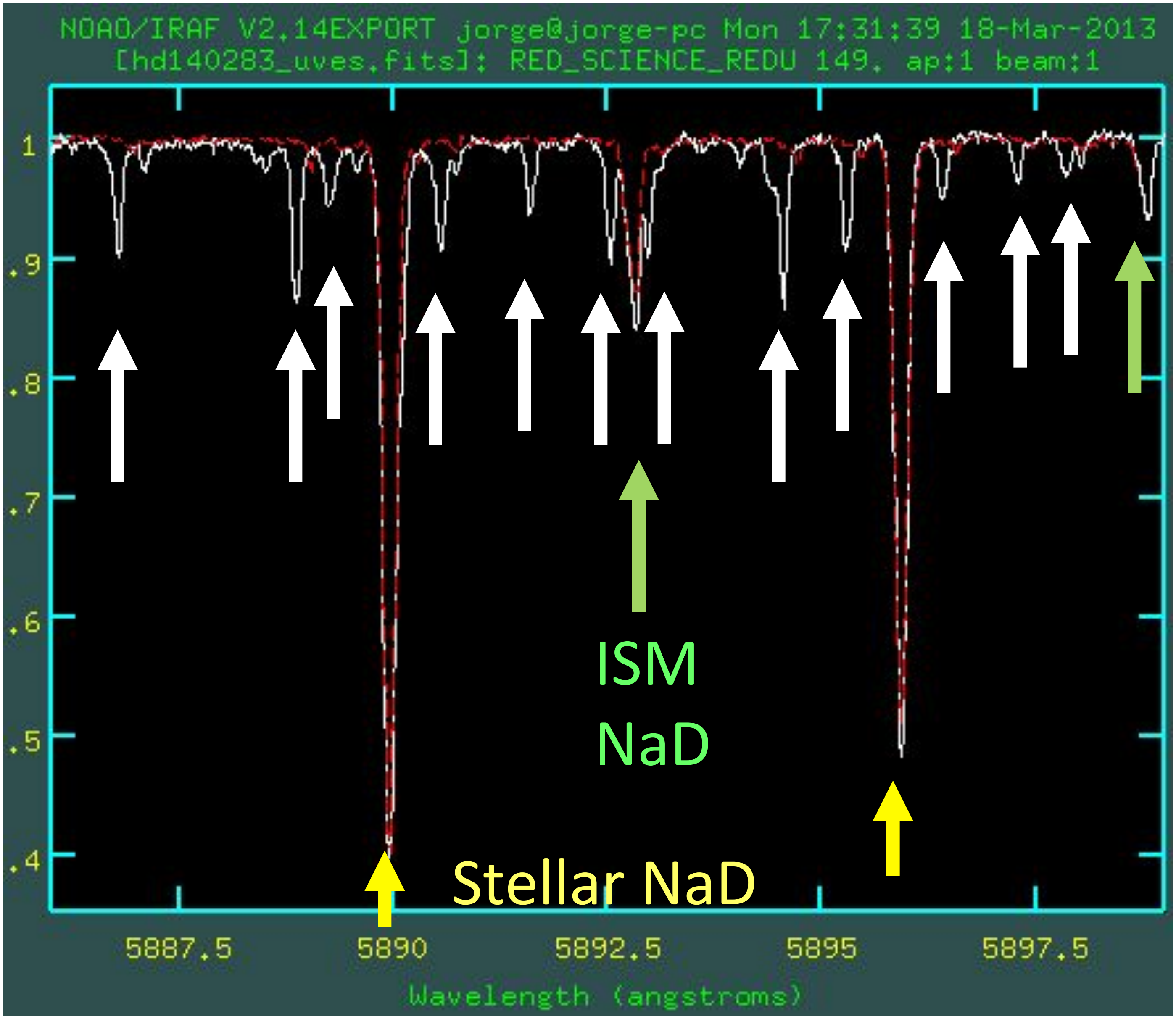
Comparison of water vapor at 2 diferent observatories

Keck (4.2km) spectrum of HD140283

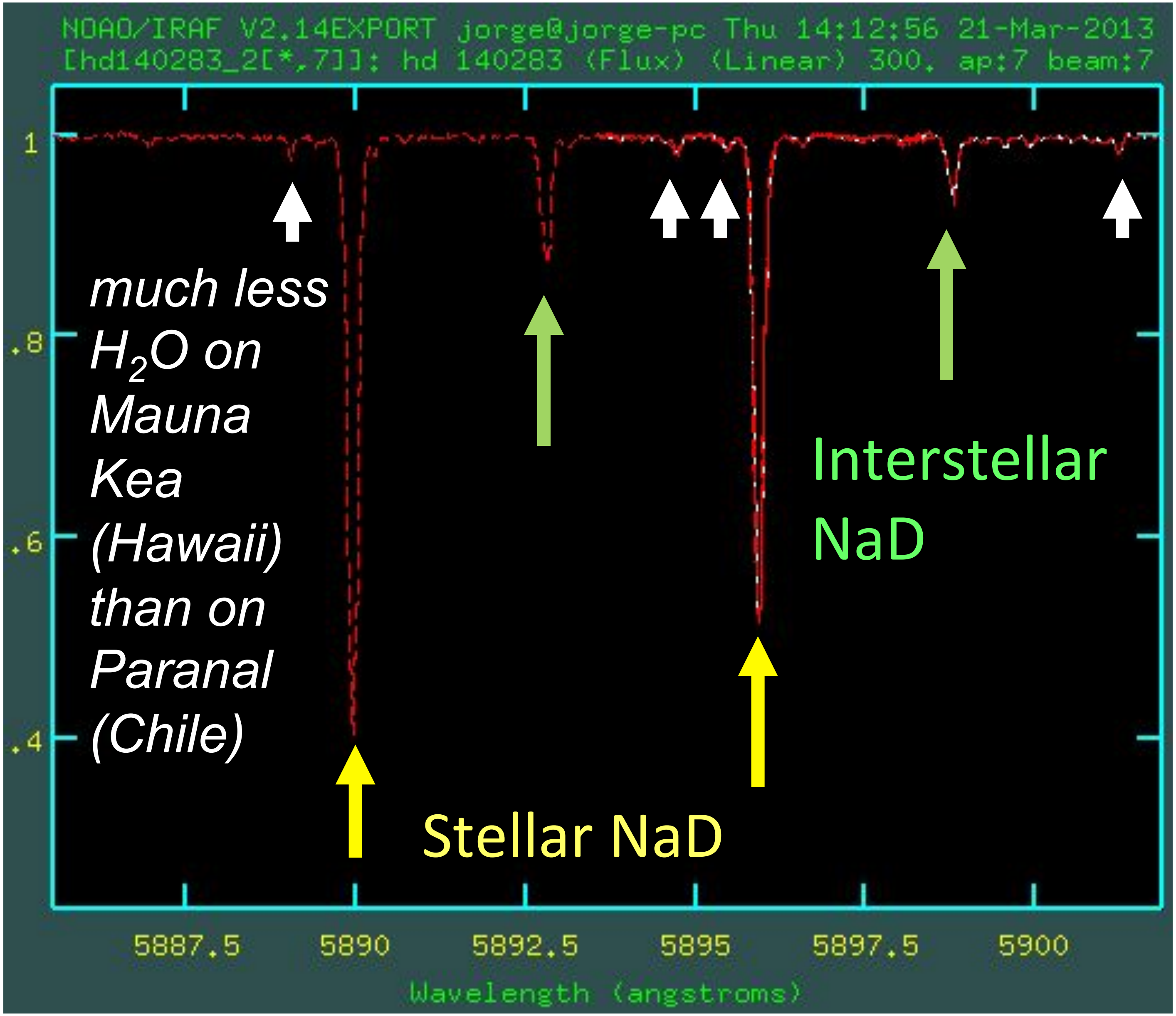


Keck (4.2km) vs. VLT (2.7km)

Water vapor clearly present on Paranal (VLT)



Keck (4.2km) spectrum of HD140283

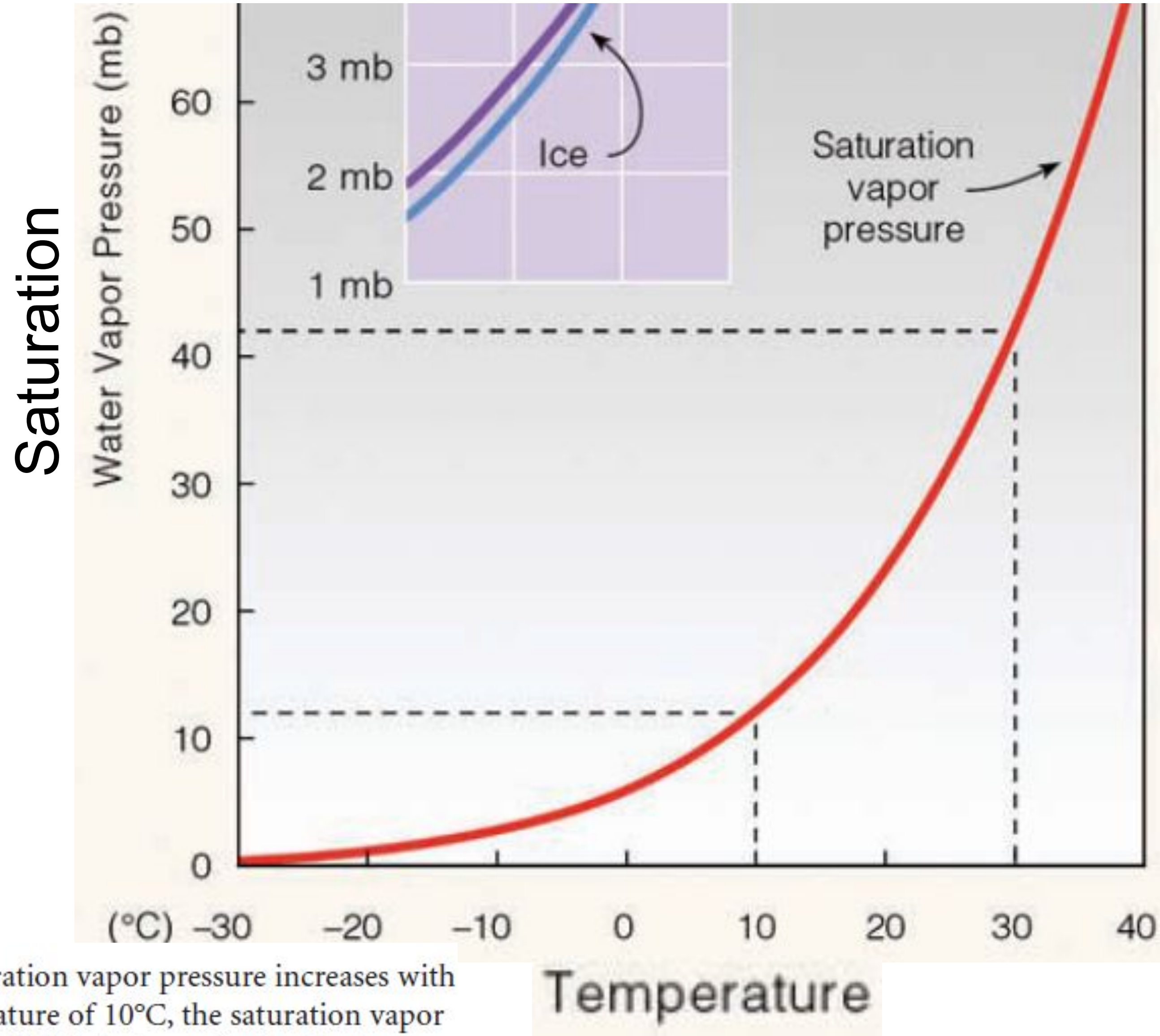


Umidade relativa
(Relative humidity: RH)

$$\text{RH} = \frac{\text{water vapor content}}{\text{water vapor capacity}}$$

$$\textbf{RH} = \frac{\textbf{water vapor content}}{\textbf{Maximum water vapor content for saturation at a given T}}$$

$$RH = \frac{\text{Water vapor content}}{\text{Maximum water vapor content for saturation}}$$



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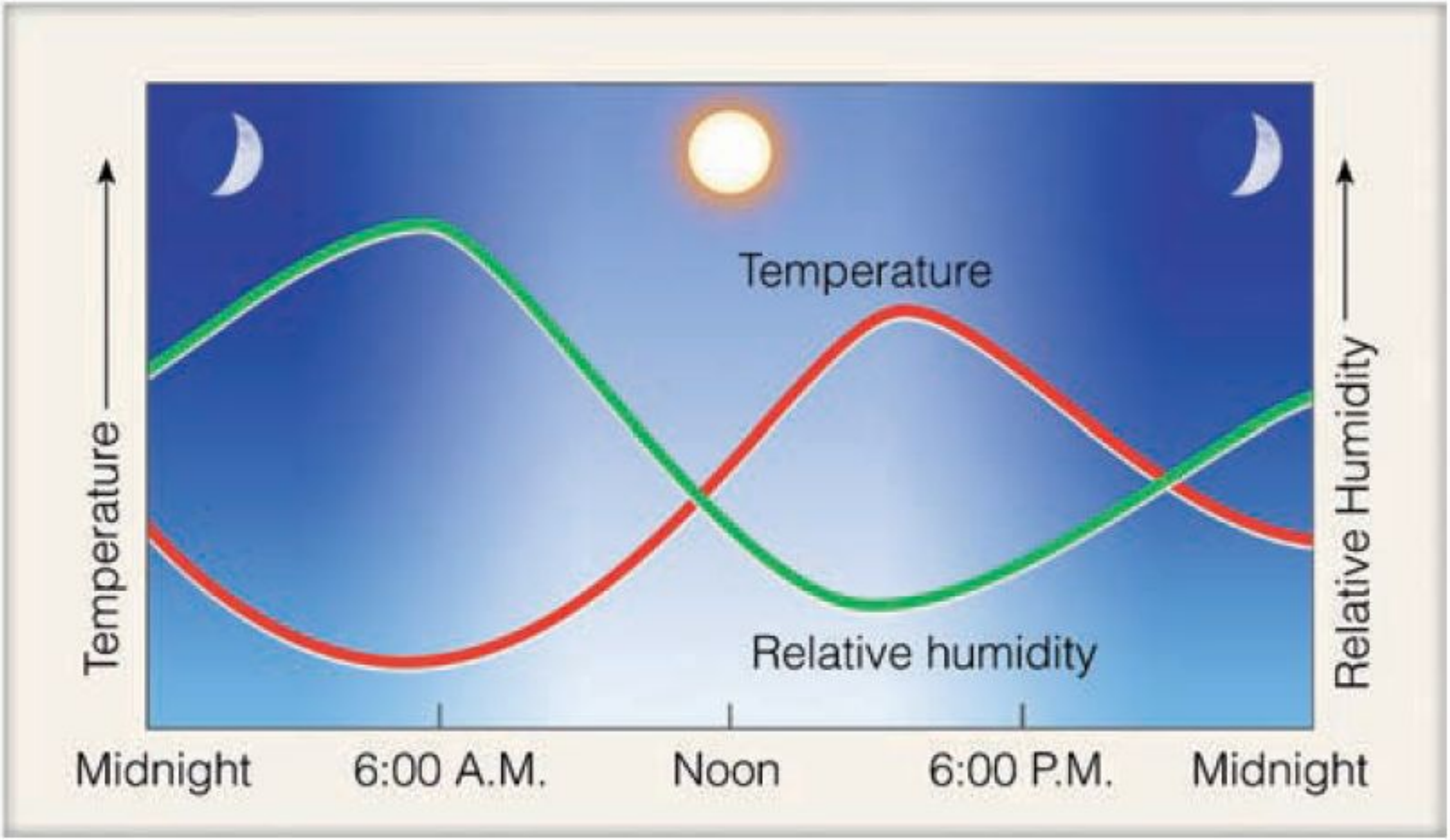
ACTIVE FIGURE 4.10 Saturation vapor pressure increases with increasing temperature. At a temperature of 10°C, the saturation vapor pressure is about 12 mb, whereas at 30°C it is about 42 mb. The insert

Variation of relative humidity during the day



• FIGURE 4.12 When the air is cool (morning), the relative humidity is high. When the air is warm (afternoon), the relative humidity is low. These conditions exist in clear weather when the air is calm or of constant wind speed.

Change in RH on 5/mar/2014
OPD observatory

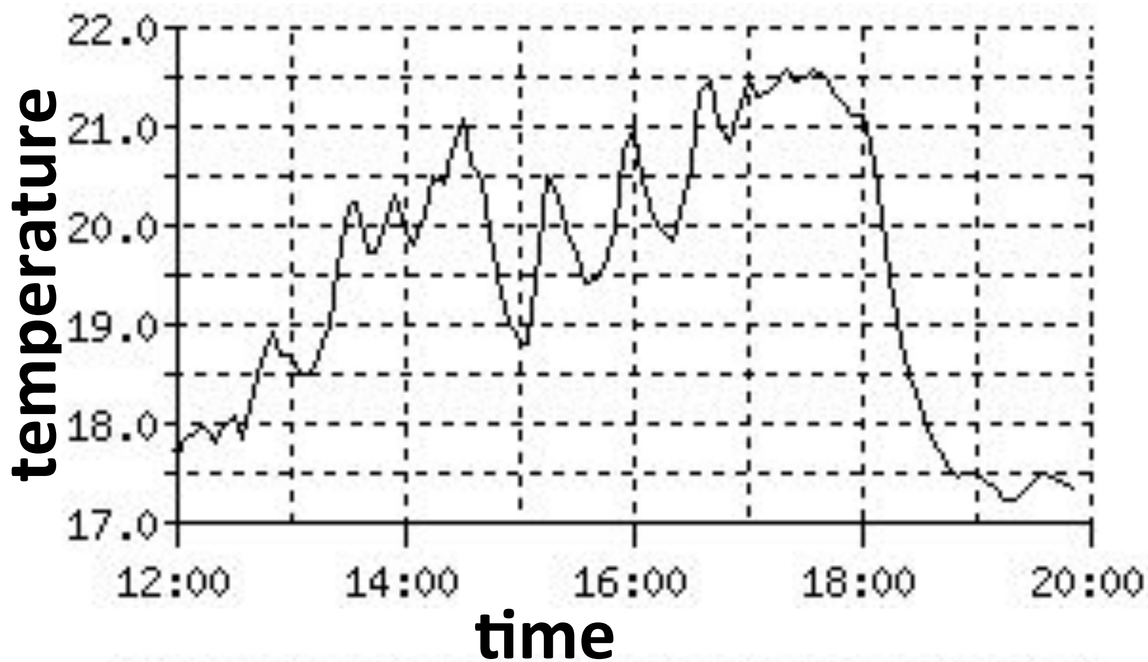
18h: 70%

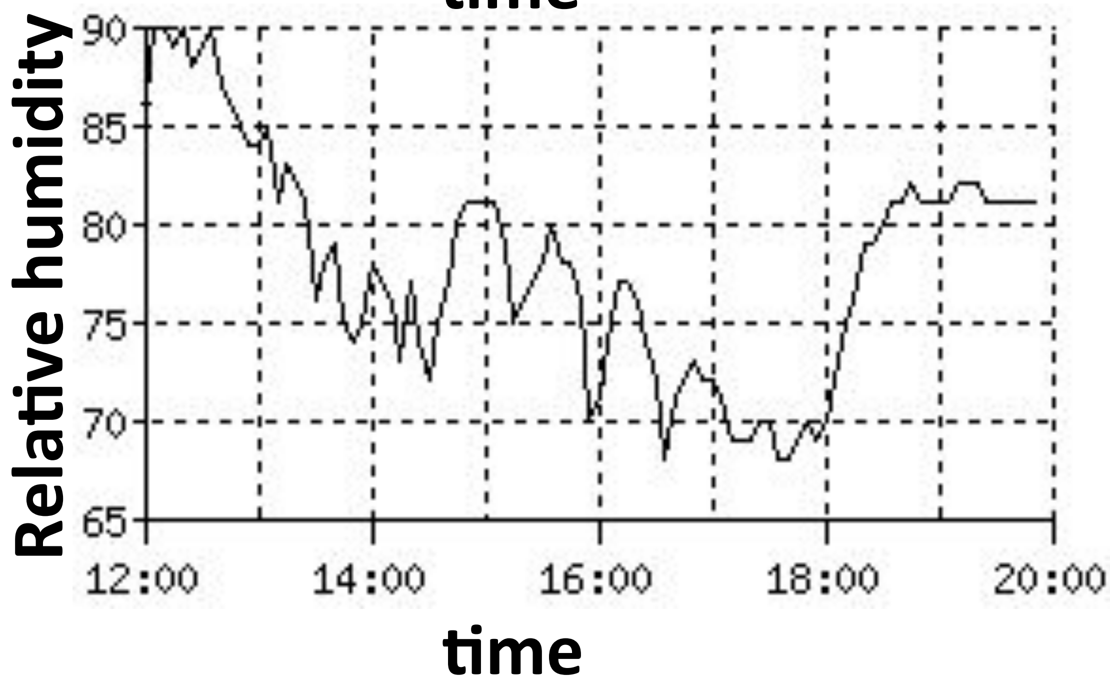
20h: 80%

22h: 90%

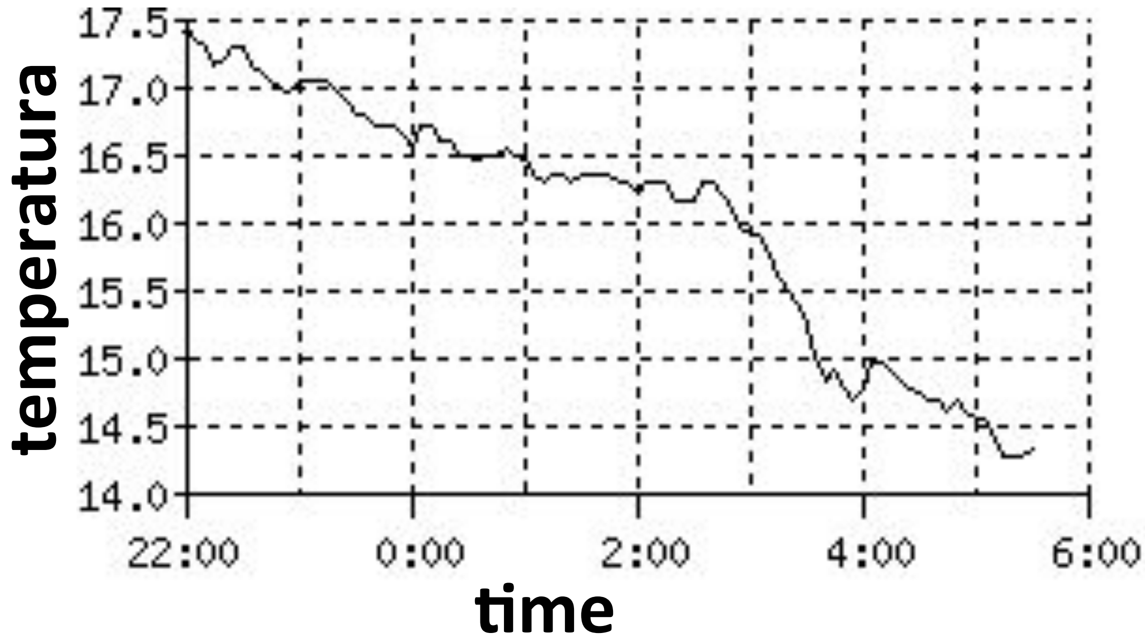
0h: 100%

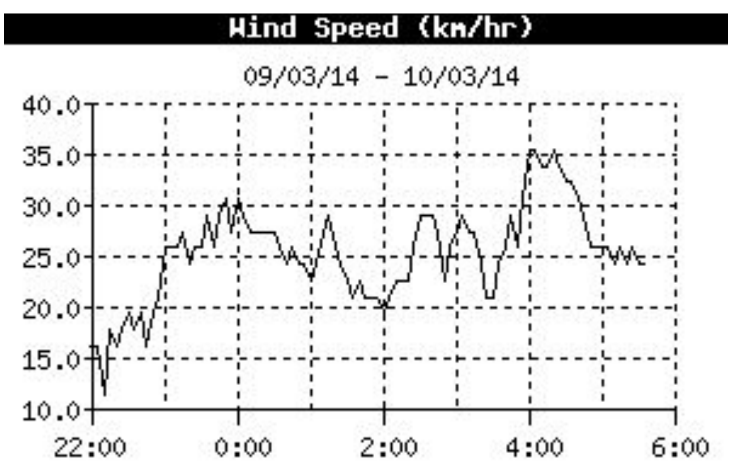
Change in temperature and RH on 9/3/2014

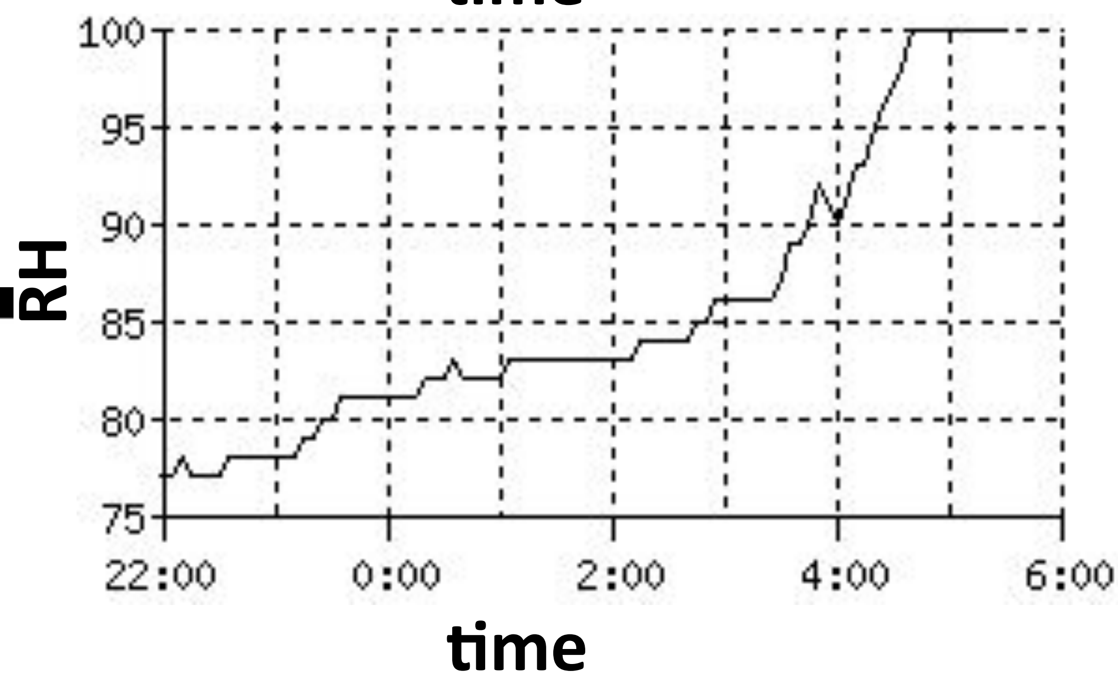




Change in temperature and RH on 9/3/2014

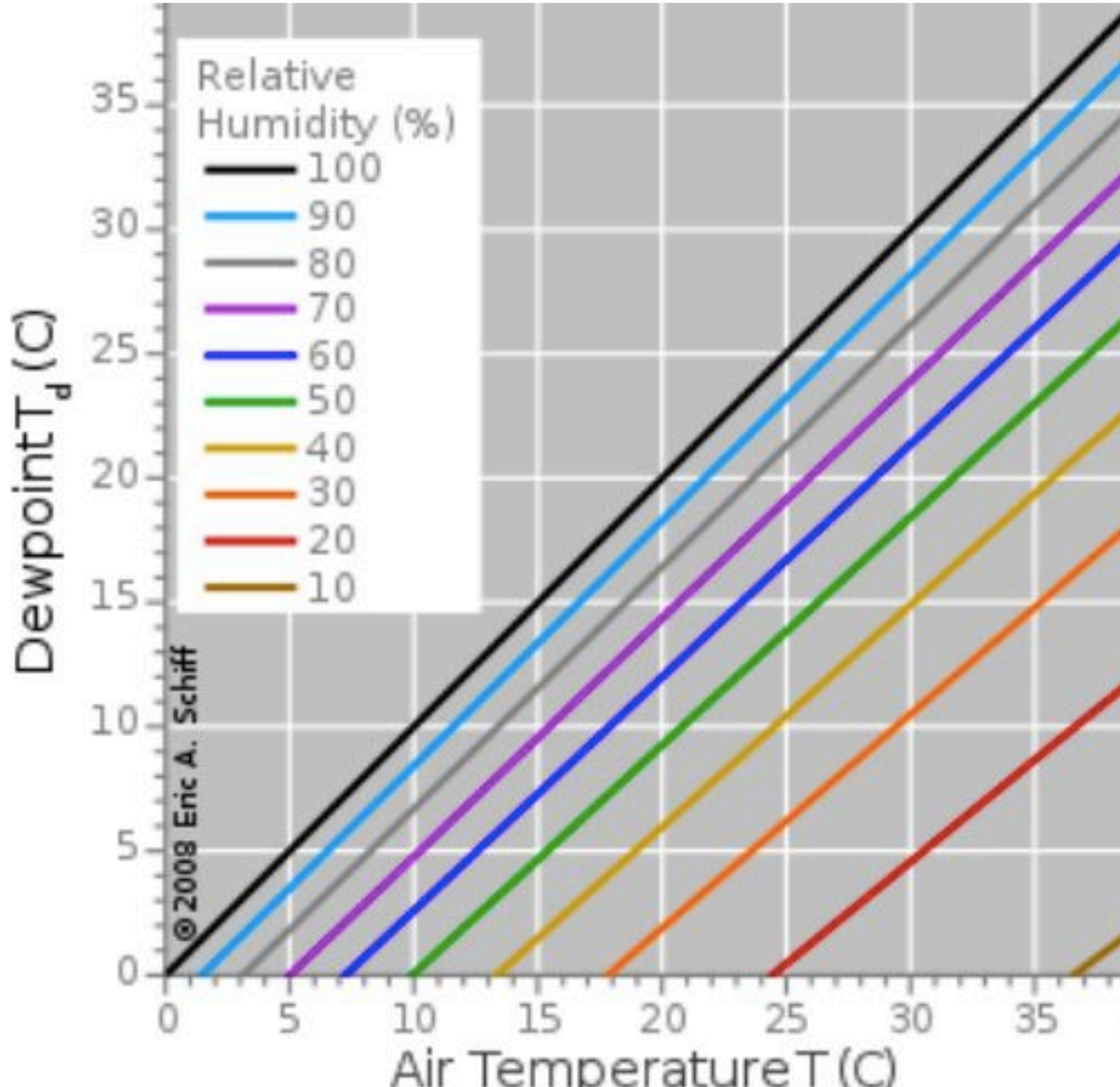




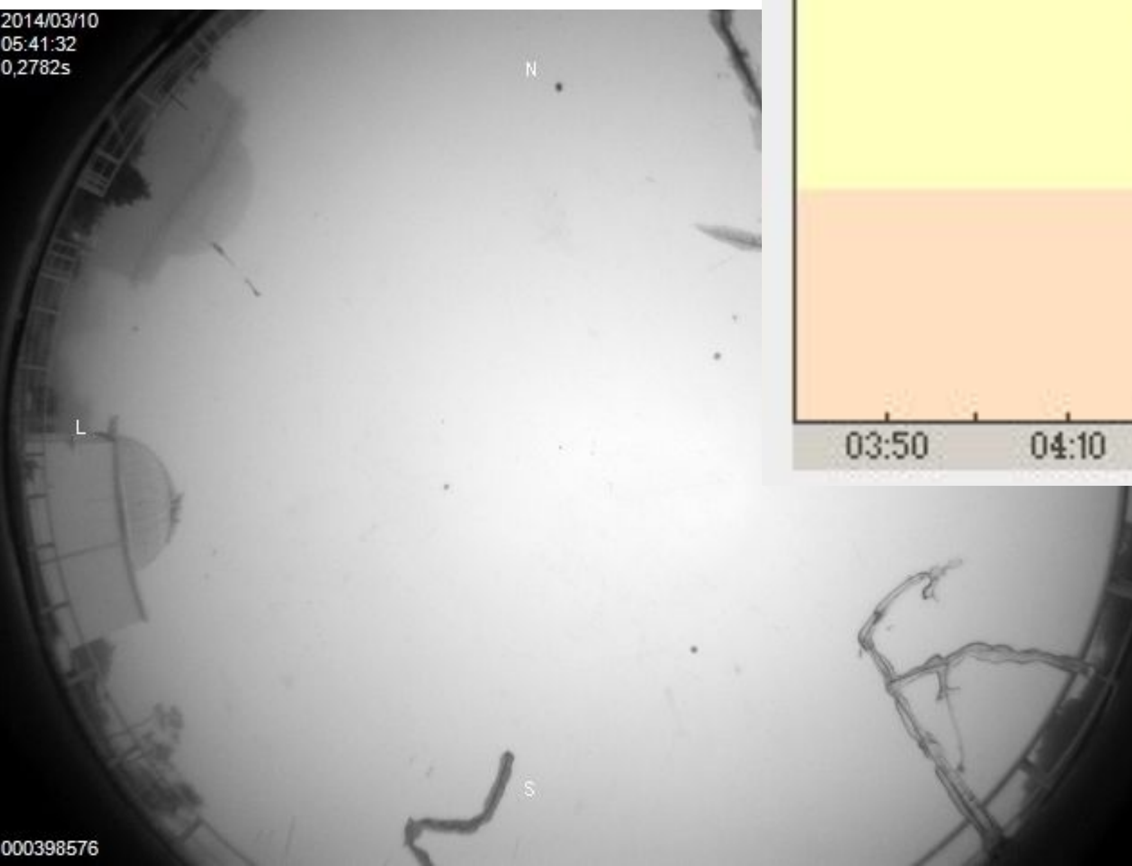


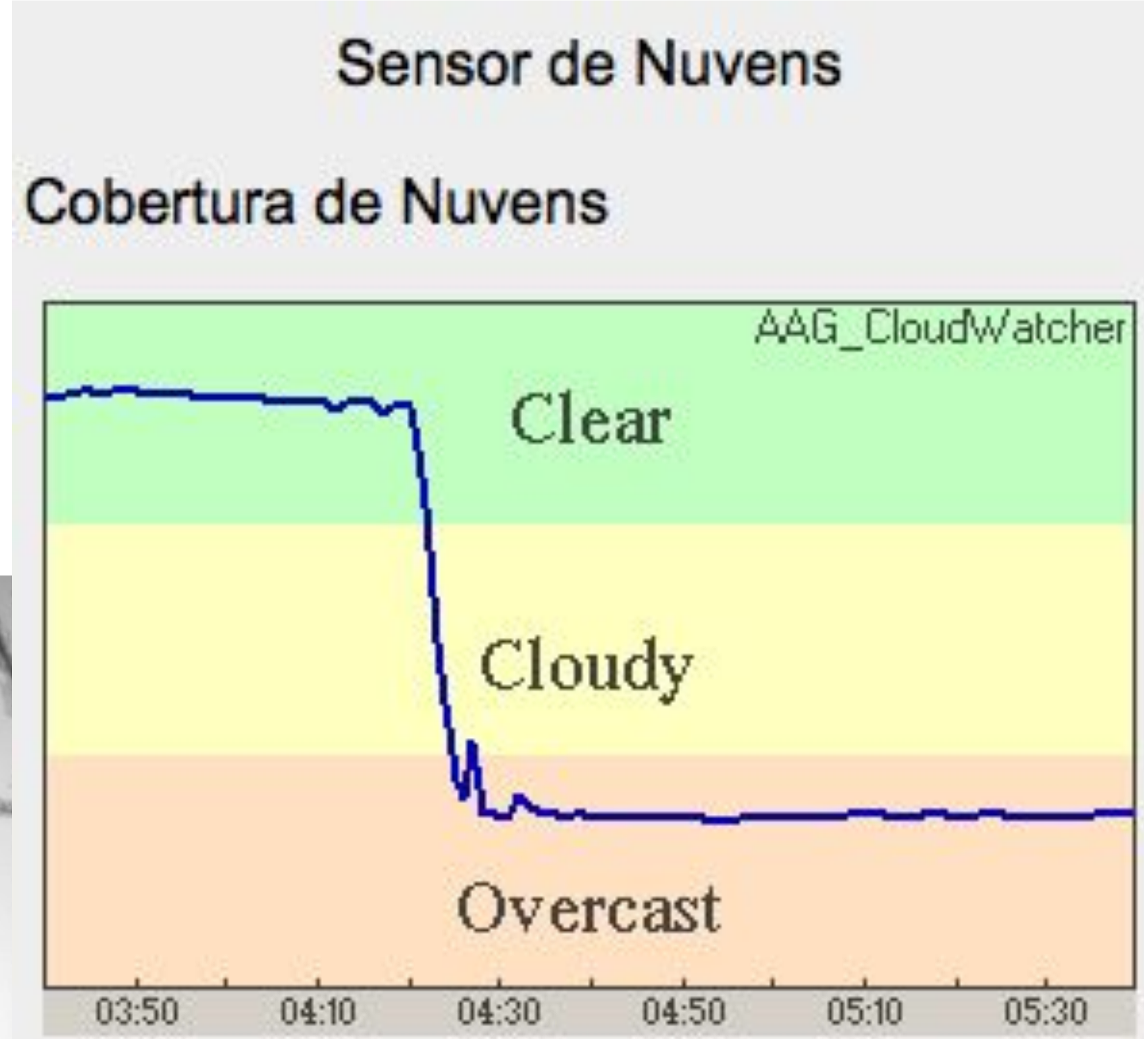
Dew point

Temperature to which the air must be cooled to become saturated with water vapor



Cloud coverage 9-10/3/2014

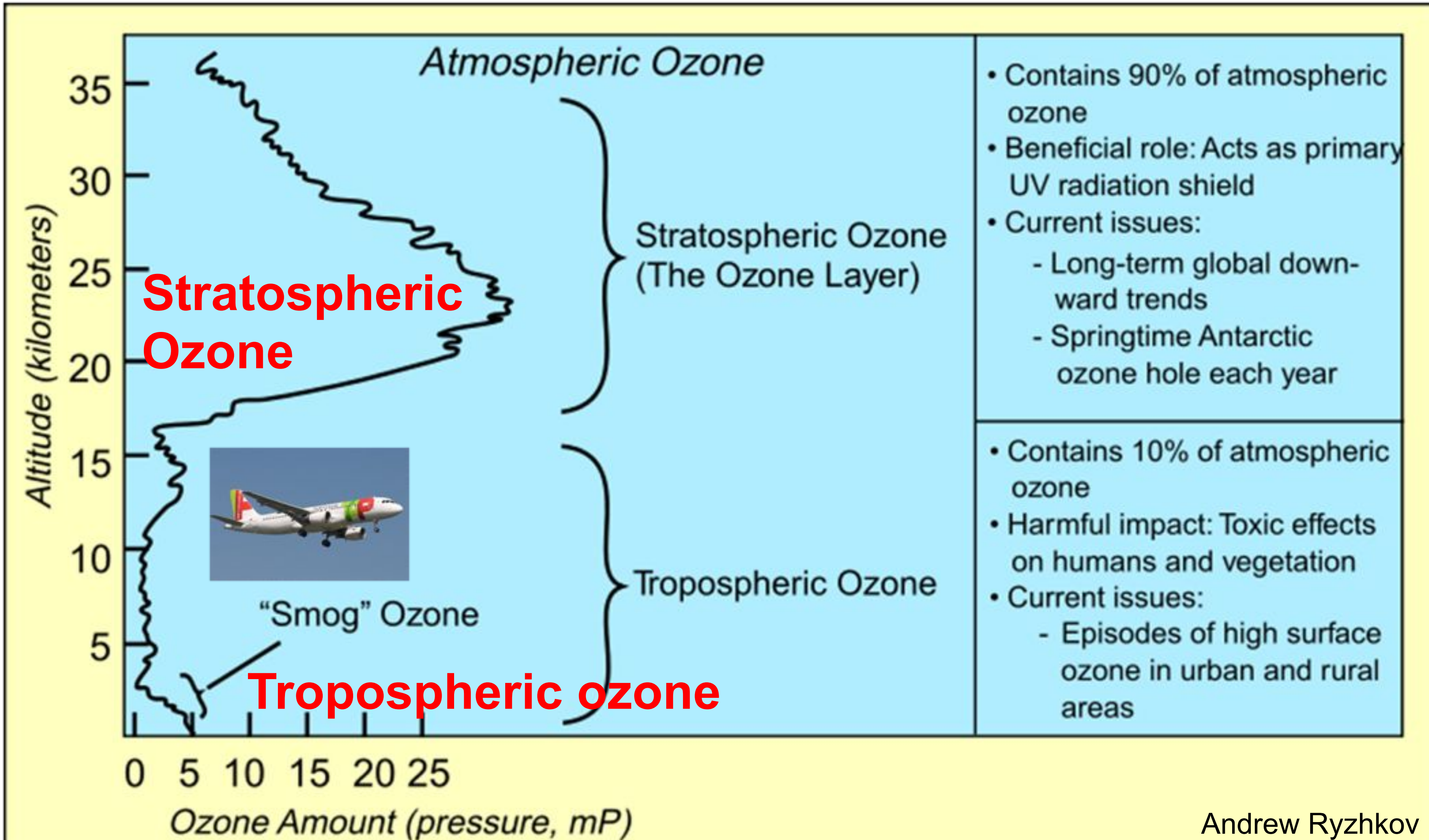




time

Ozone (O_3)

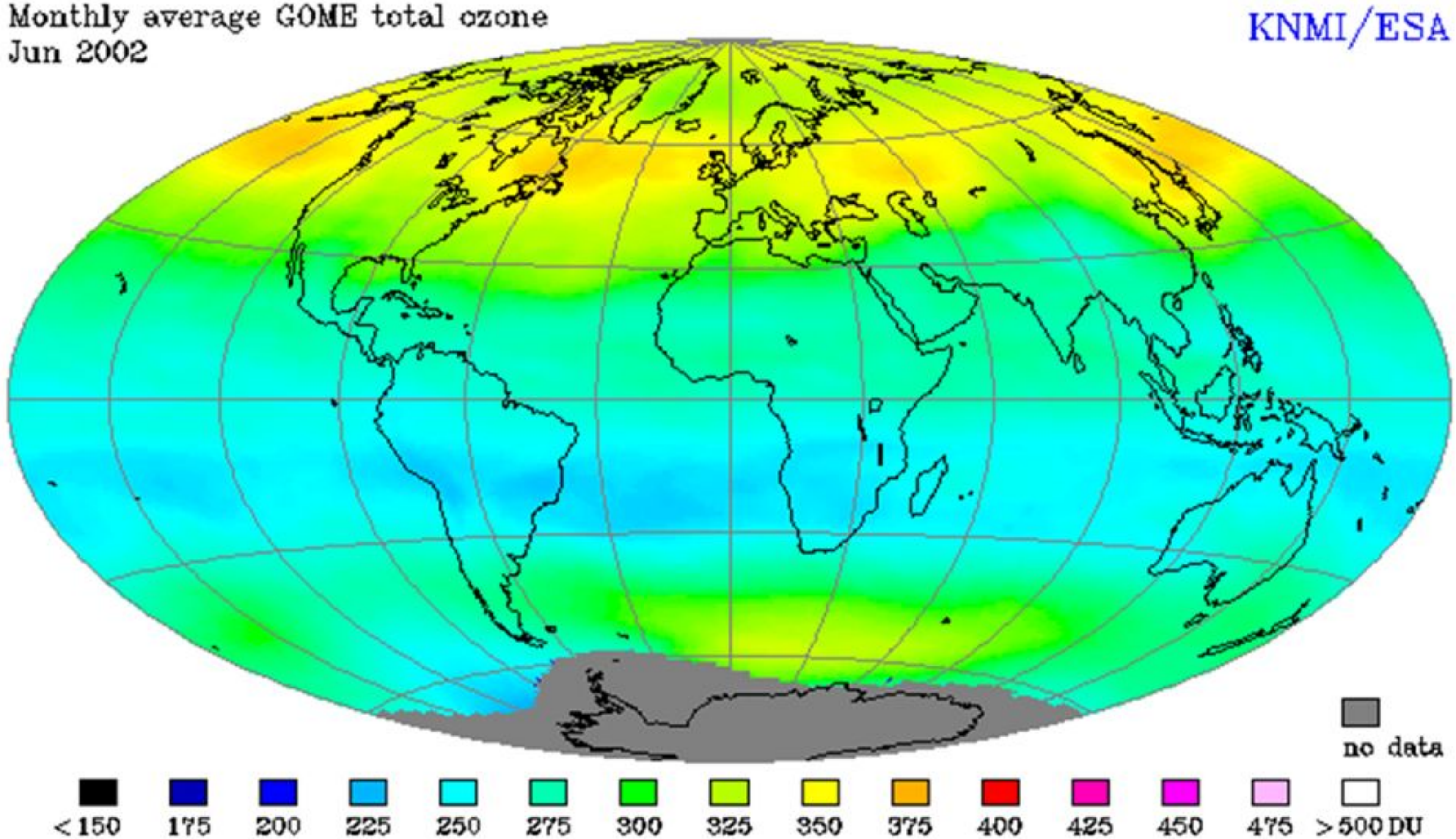
Vertical structure of O_3 changes a lot (latitude, season of the year), but maximum ~20km



Andrew Ryzhkov

Ozone (O_3)

Northern hemisphere has larger concentration of ozone



Ozone (O_3)

Zone O_3 has an annual cycle

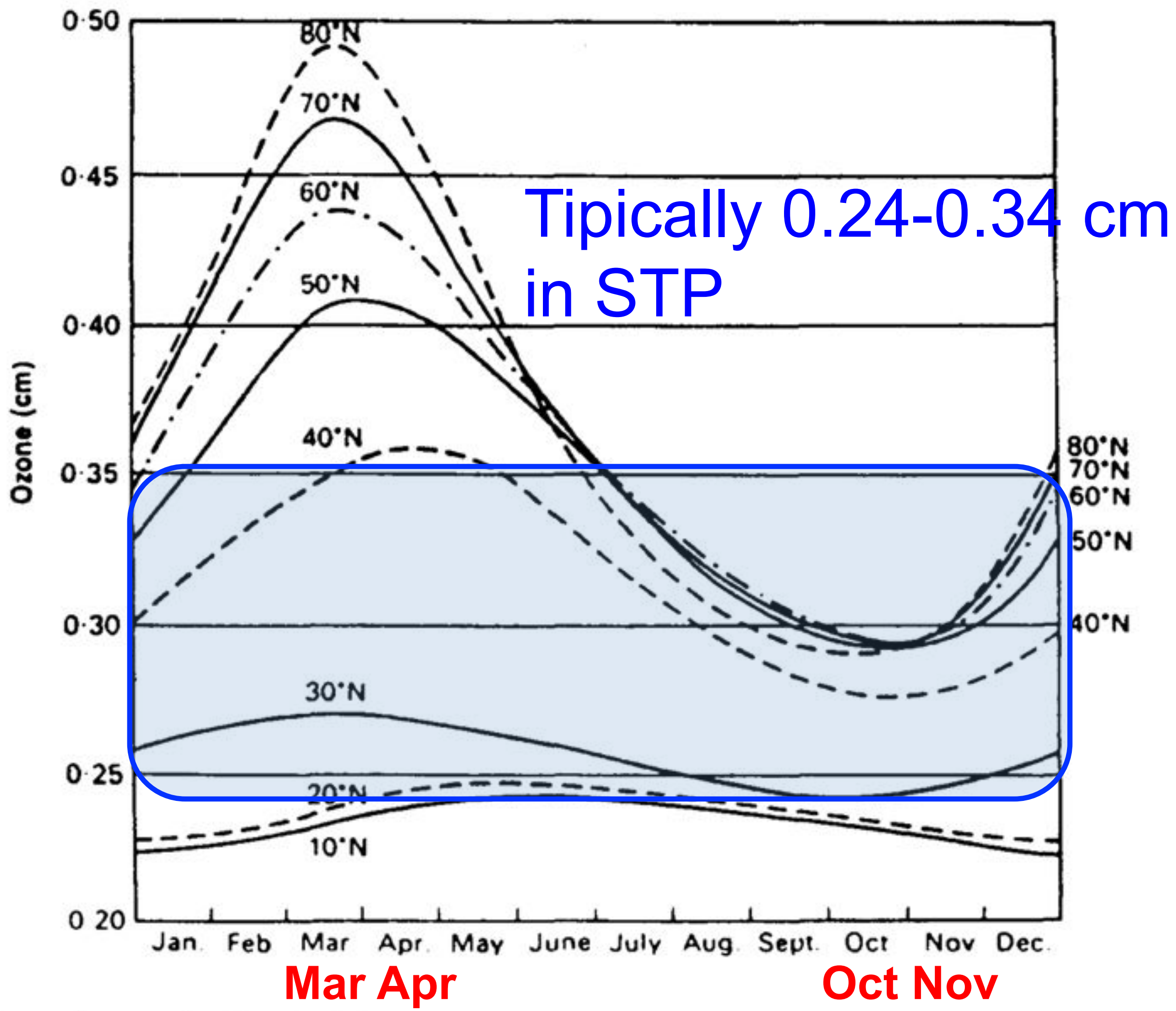
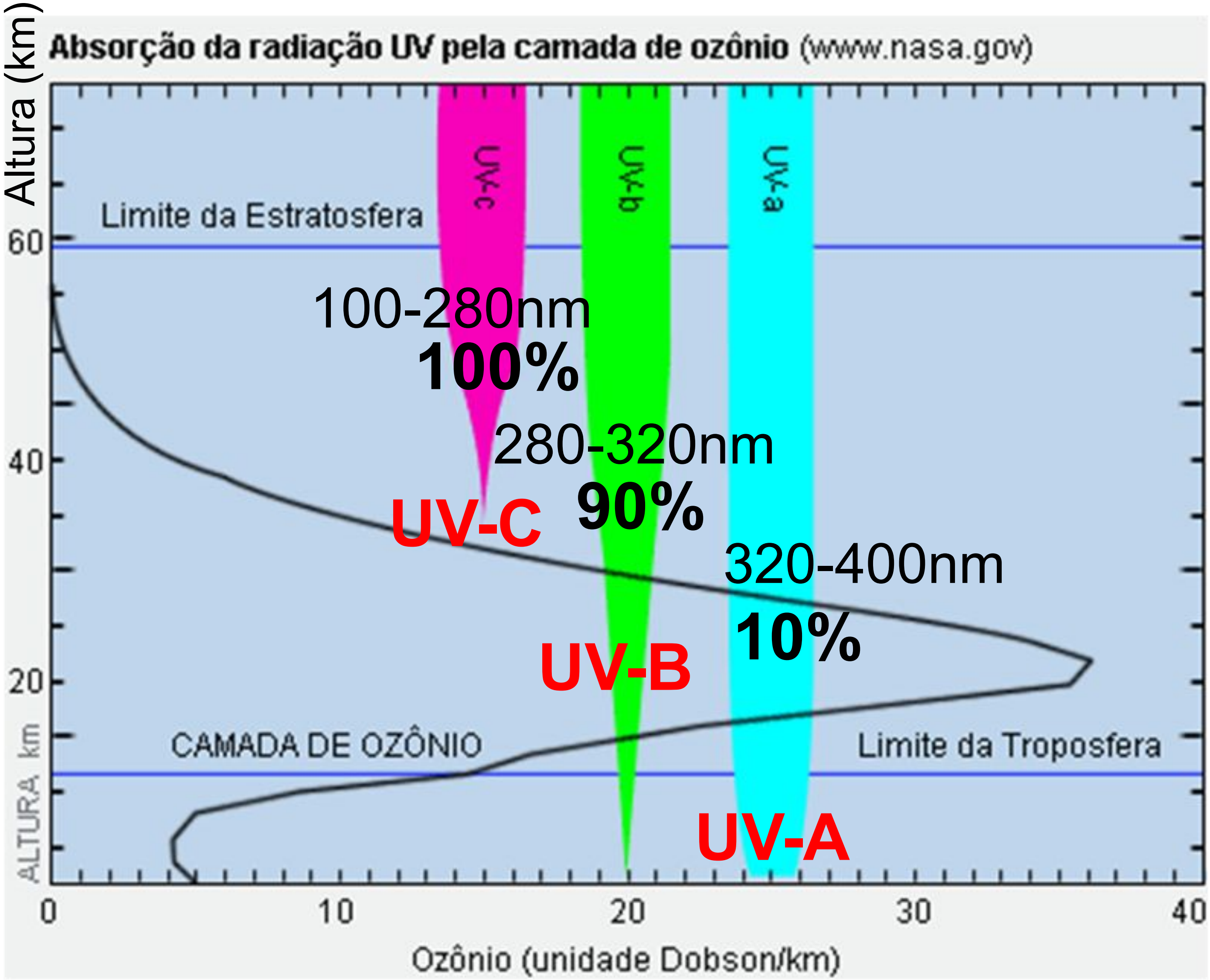
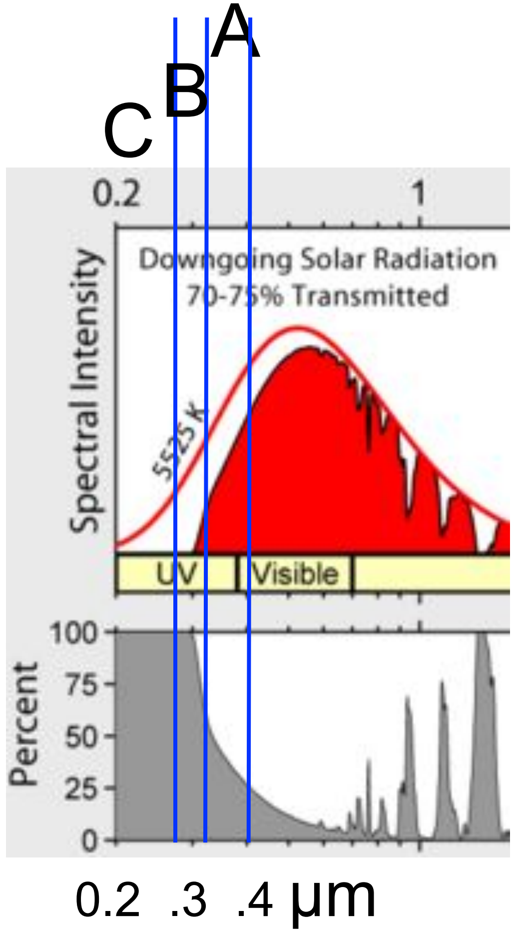


Figure 1. Annual Variation of Total Ozone for Each 10° of N Latitude

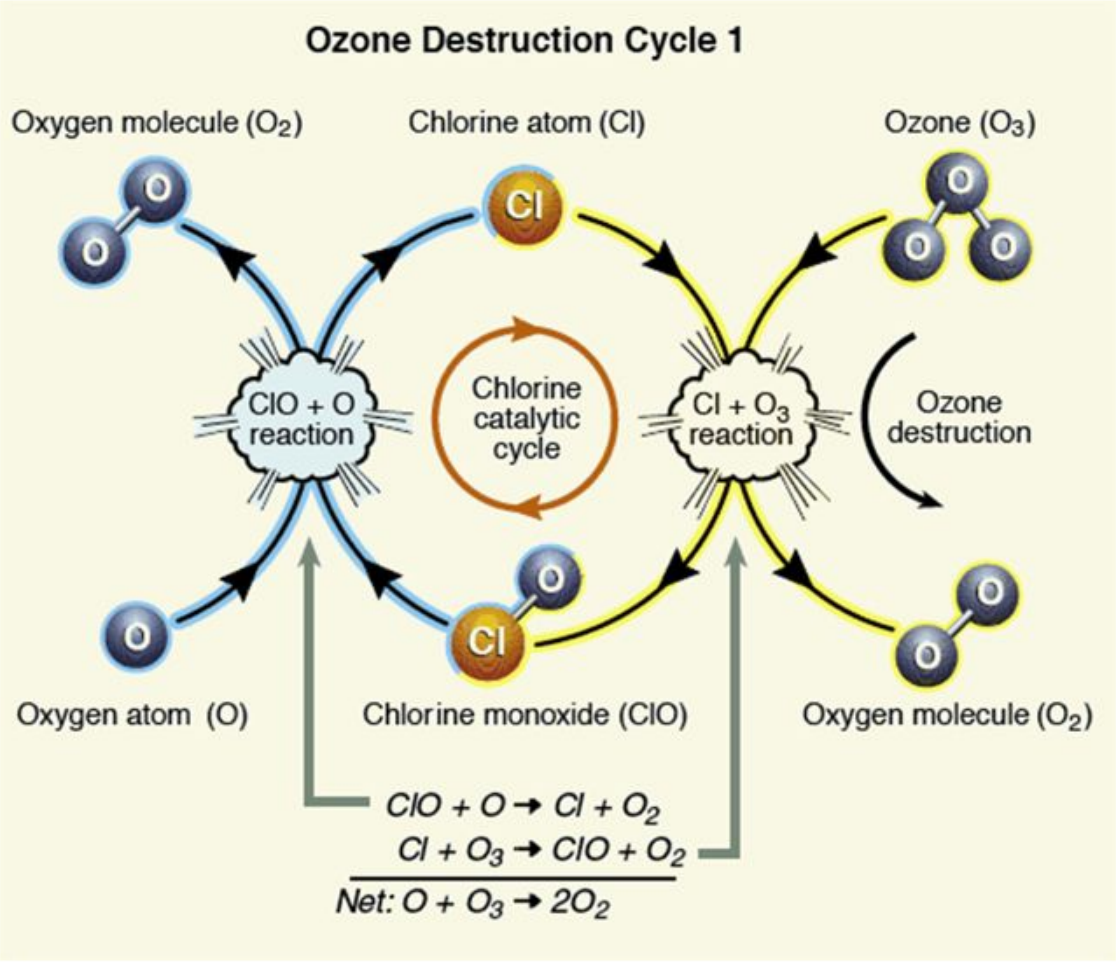
Ozone: principal protection for UV solar radiation





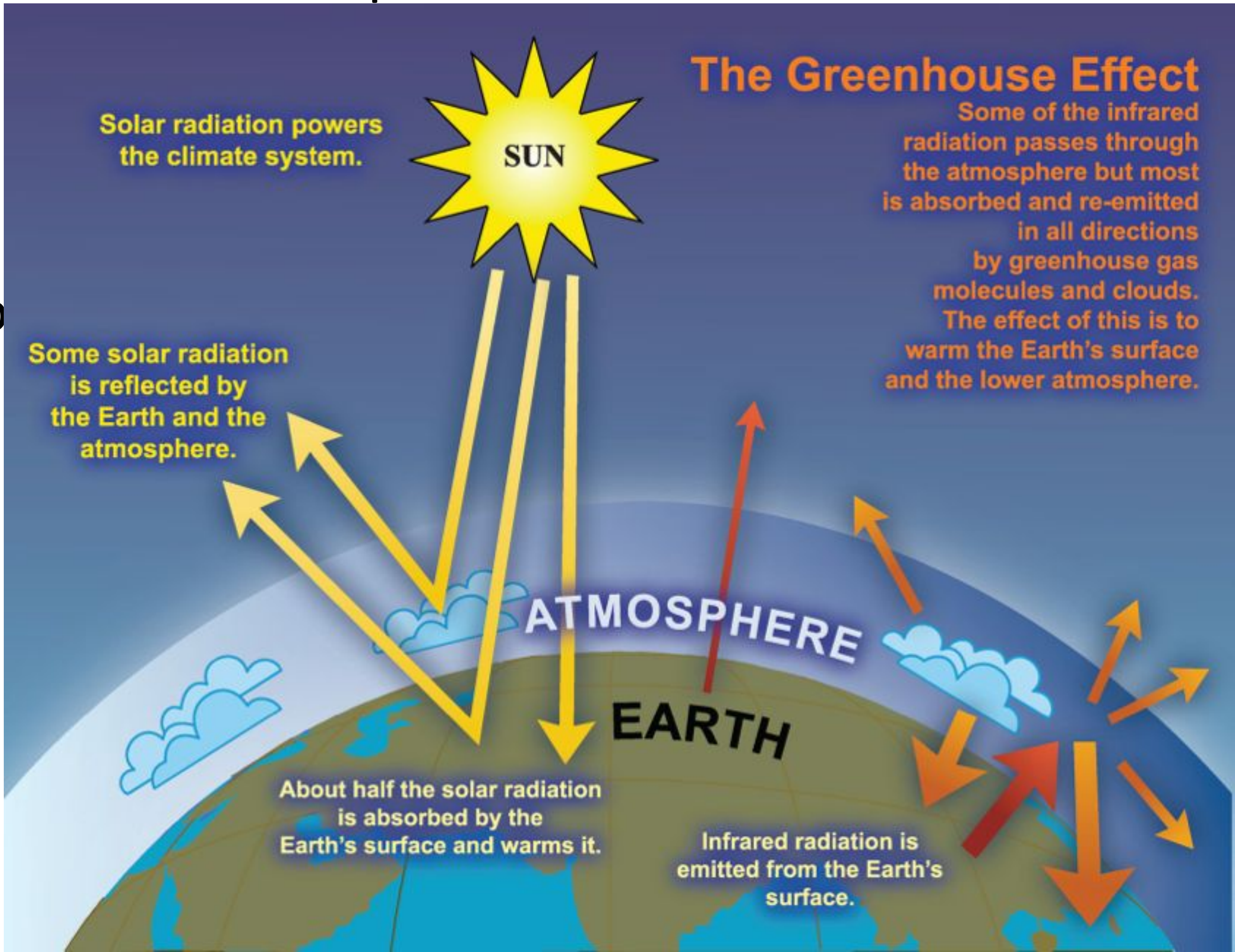
Ozone destruction

- Minor constituents (Cl, NO) destroy O_3
- Cloroflour-carbonates, CFCs, can reach the stratosphere and destroy ozone



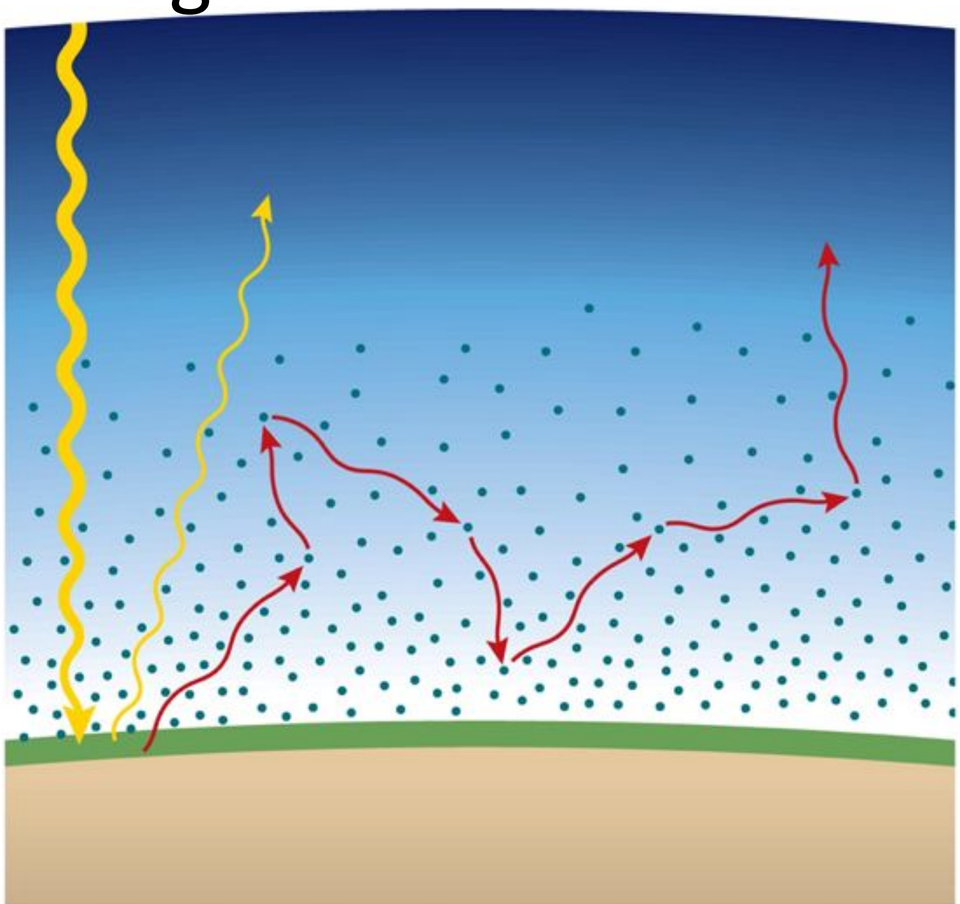
Carbon dioxide CO_2

- Important source of absorption in the infrared
- Similar distribution to O_2 e N_2
- Mixing ratio does not depend on altitude



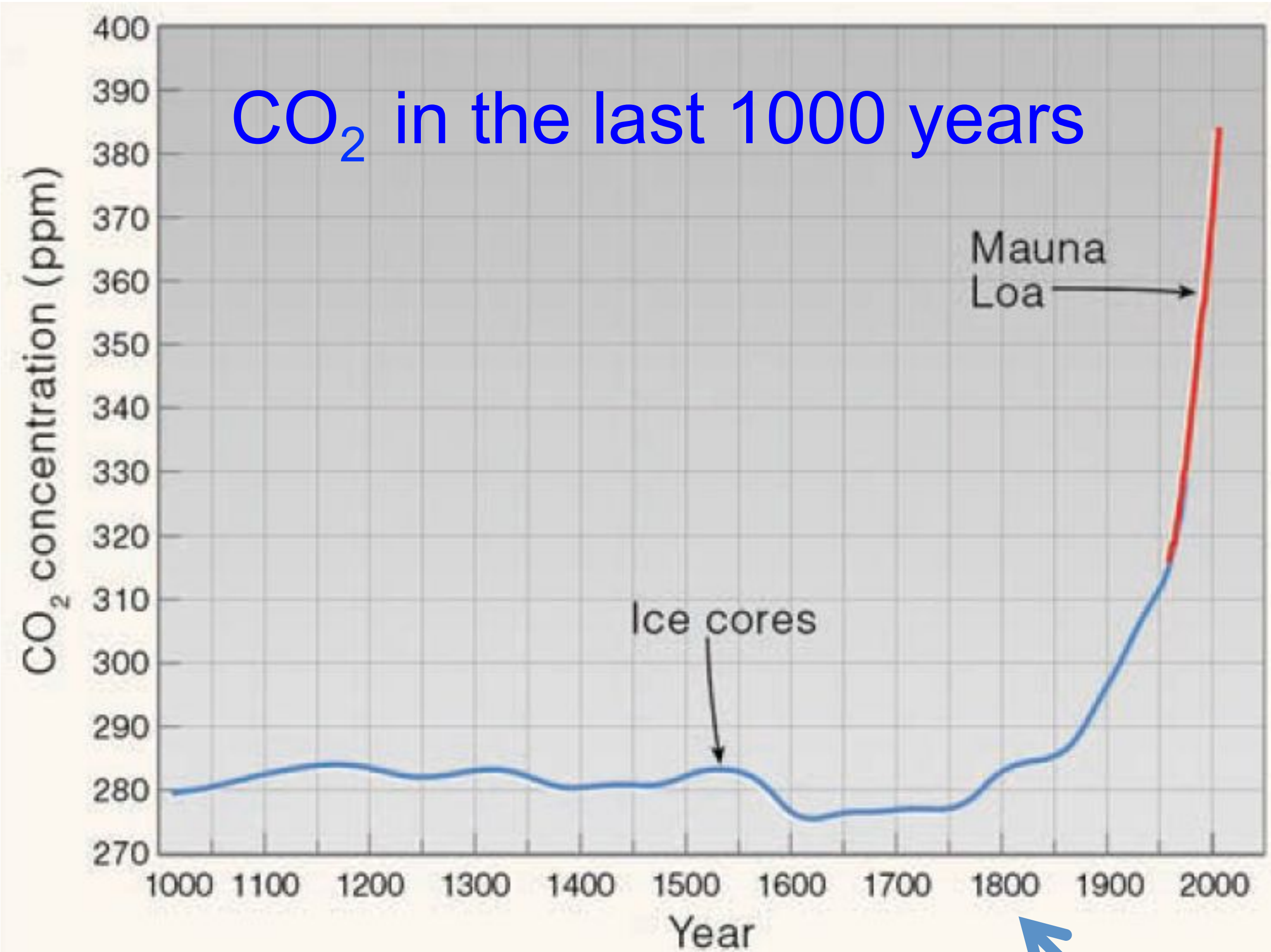
CO_2 and global warming

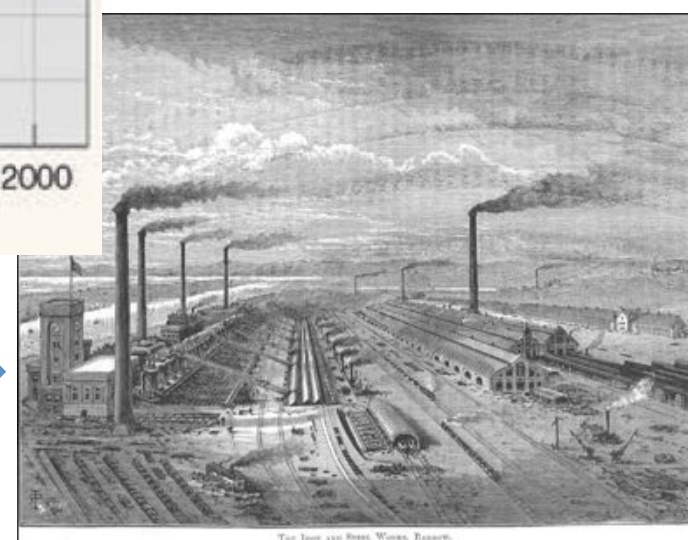
Visible light pass through atmosphere and heats the surface. Gases (CO_2, H_2O & CH_4) in atmosphere absorb the reflected IR light, re-emitting in random directions



CO_2 is the second source of global warming (after H_2O)

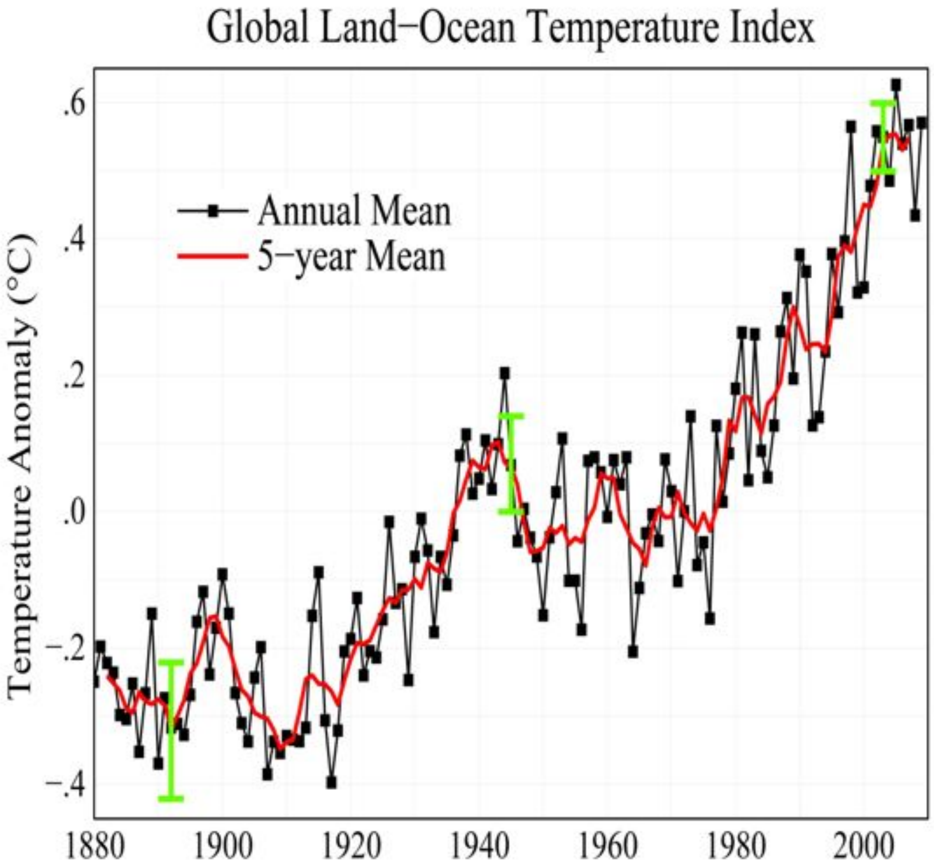
CO_2 and global warming

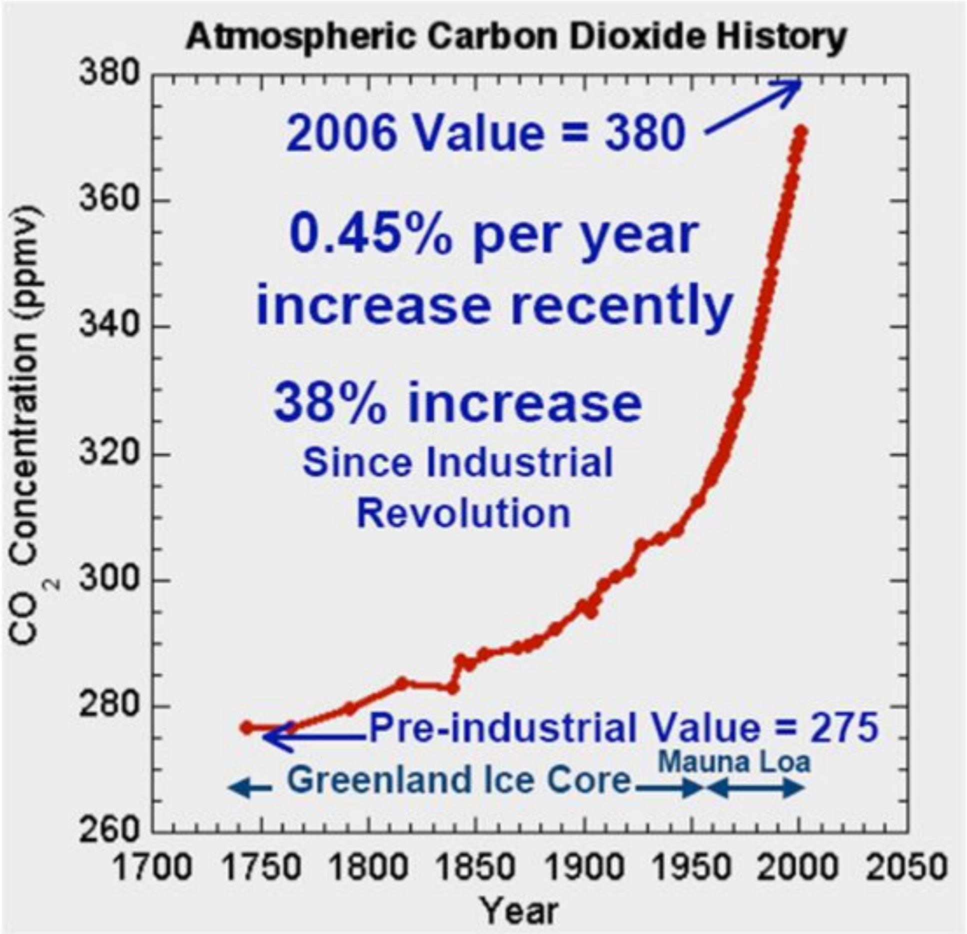




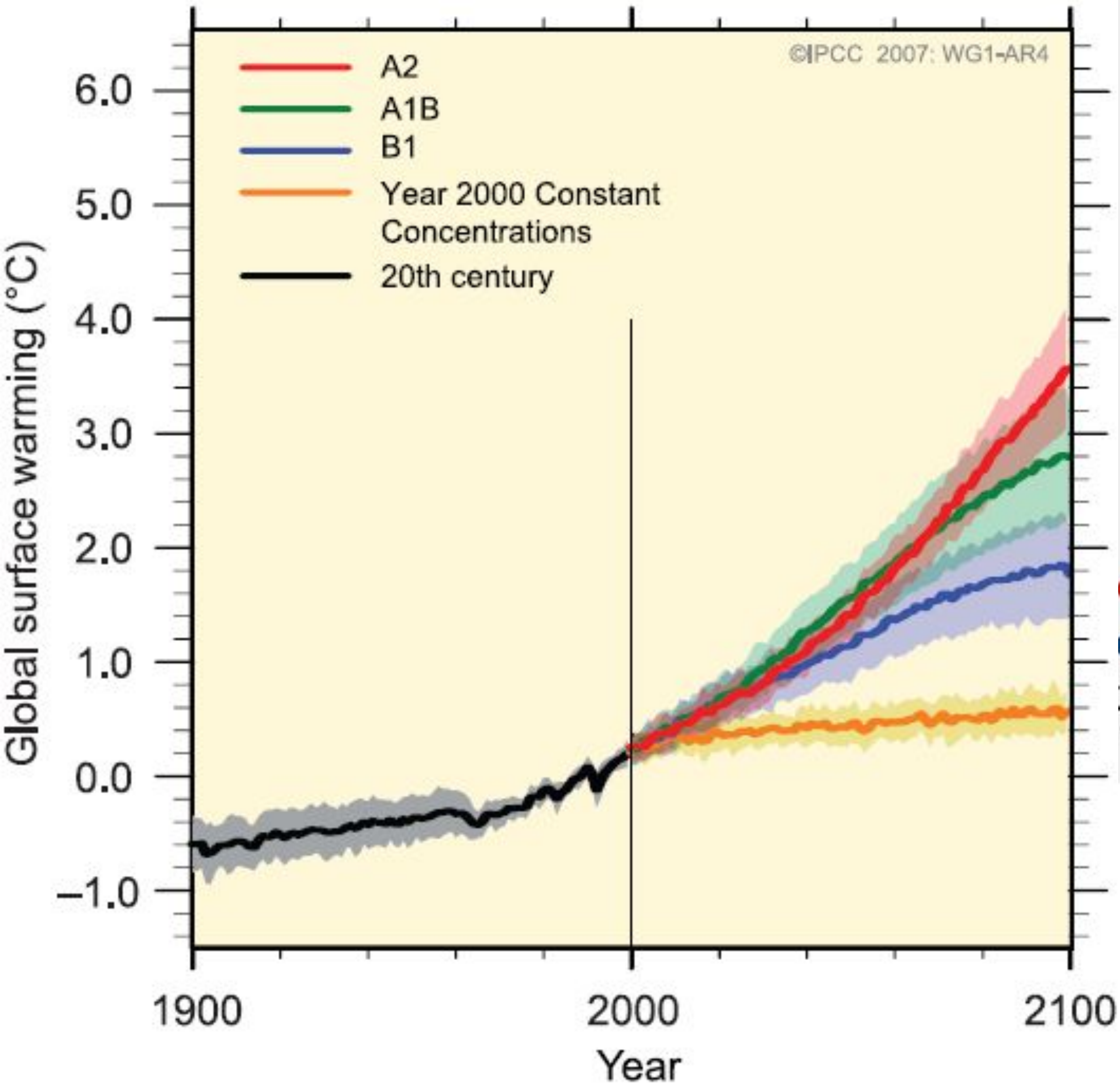
● FIGURE 1.6 Carbon dioxide values in parts per million during the past 1000 years from ice cores in Antarctica (blue line) and from Mauna Loa Observatory in Hawaii (red line). (Data courtesy of Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory.)

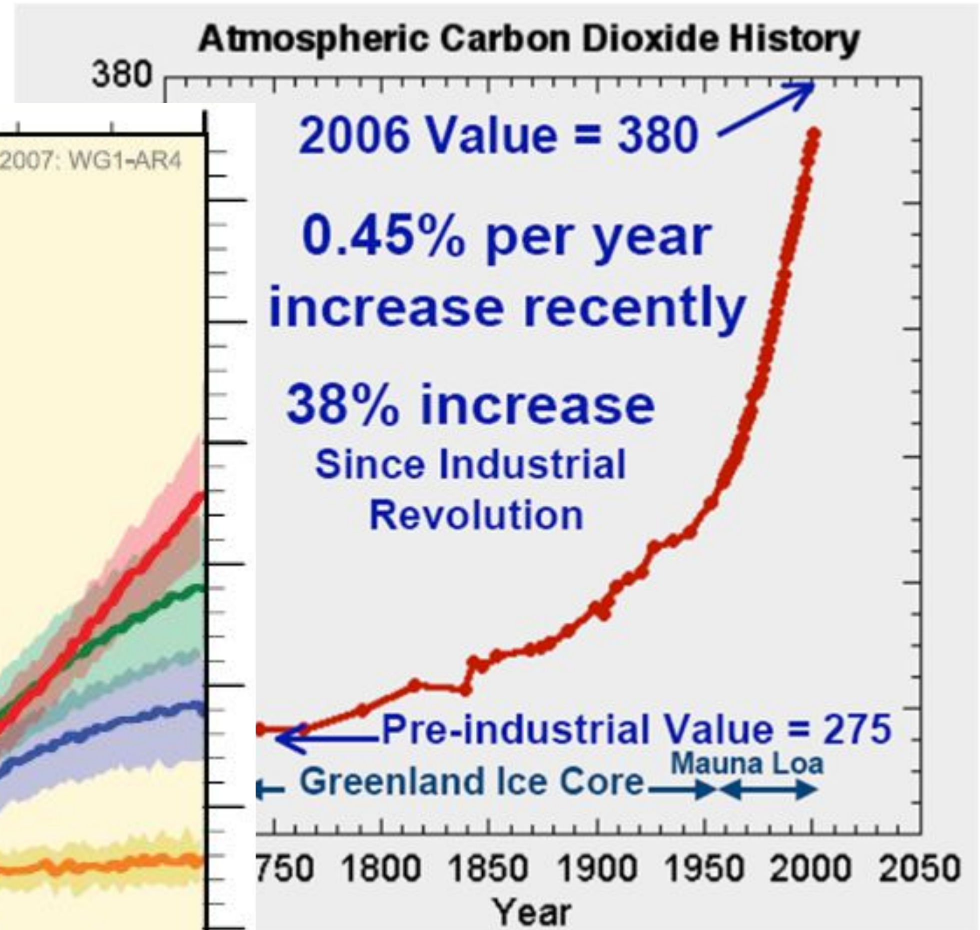
CO_2 and global warming





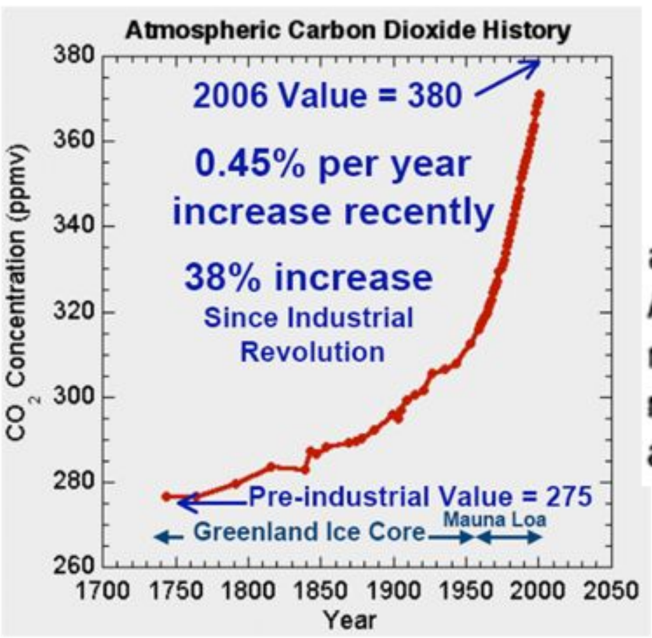
CO_2 and global warming

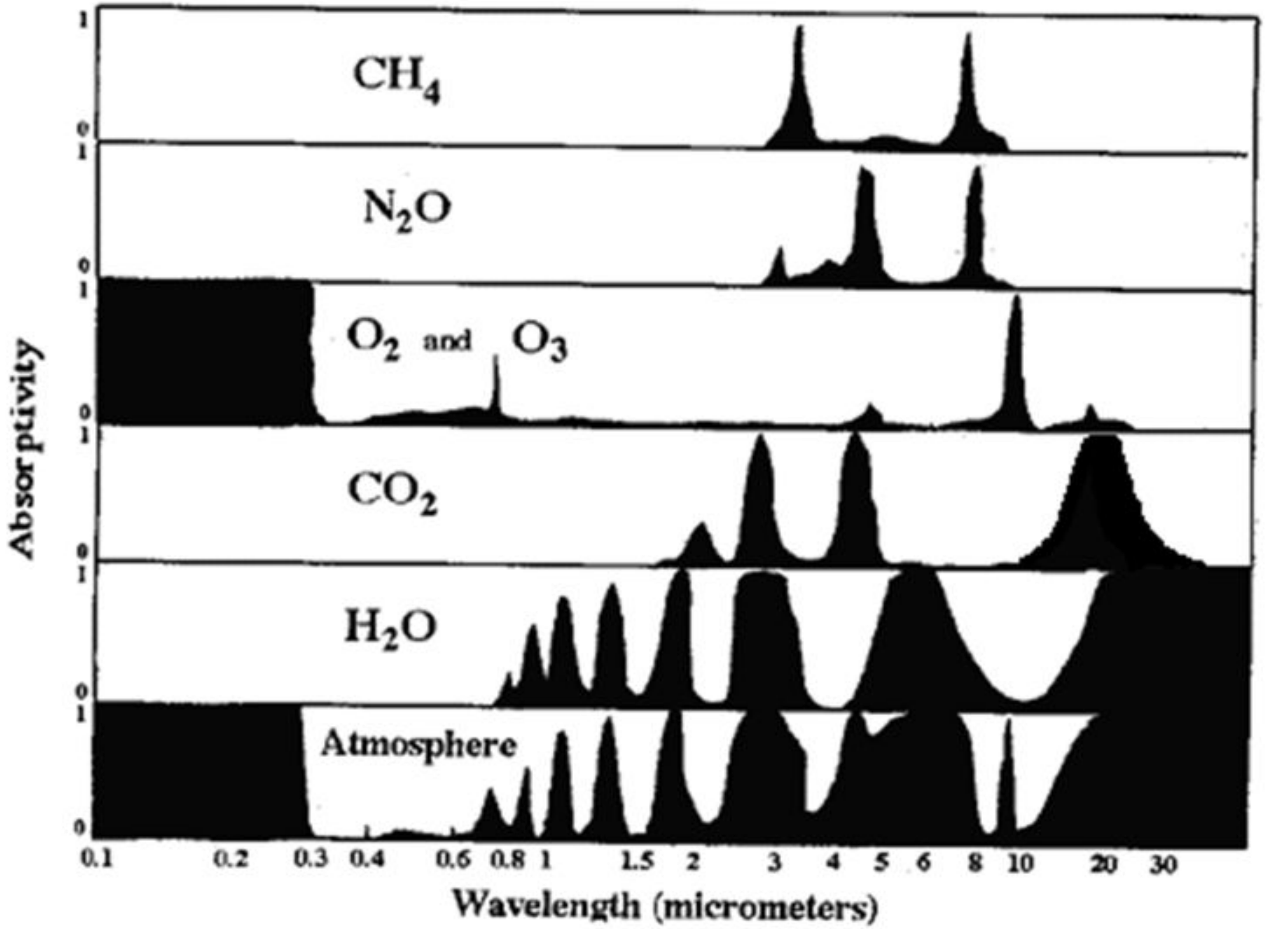




Impact on Astronomy

Rise of CO_2: deeper absorption bands in the atmosphere





Absorptivity of various gases of the atmosphere and the atmosphere as a whole as a function of the wavelength of radiation. An absorptivity of zero means no absorption while a value of one means complete absorption. The dominant absorbers of infrared radiation are water vapor (H_2O) and carbon dioxide (CO_2). Oxygen (O_2) and ozone (O_3) absorb much of the sun's ultraviolet radiation.

Atmospheric absorption bands (telluric bands)

Impact on Astronomy?

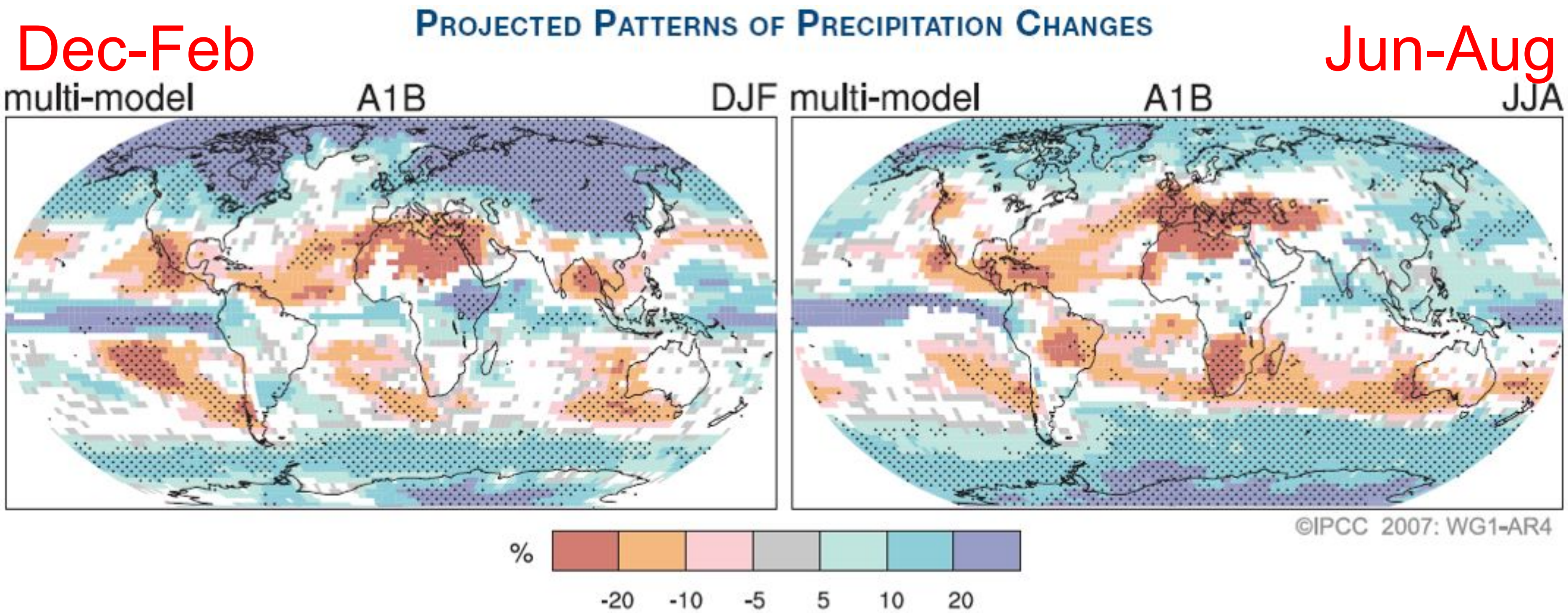
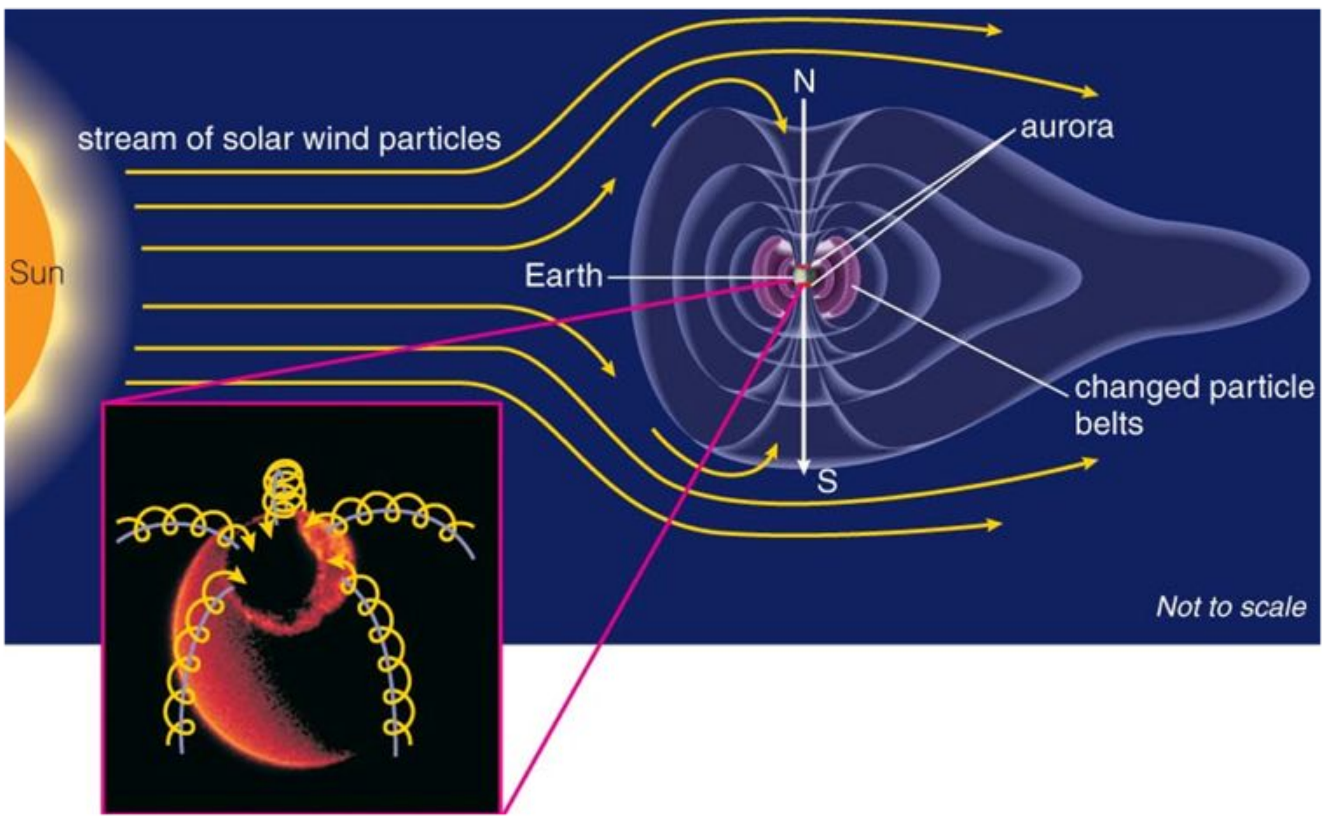


Figure SPM.7. *Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. {Figure 10.9}*

Ions

- Above 60km, solar UV radiation ionizes the atmosphere
- Ionization changes with altitude, solar illumination, solar activity
- At high latitudes, electron cascades enter magnetic poles, causing auroras



Ions : Auroras

Ions

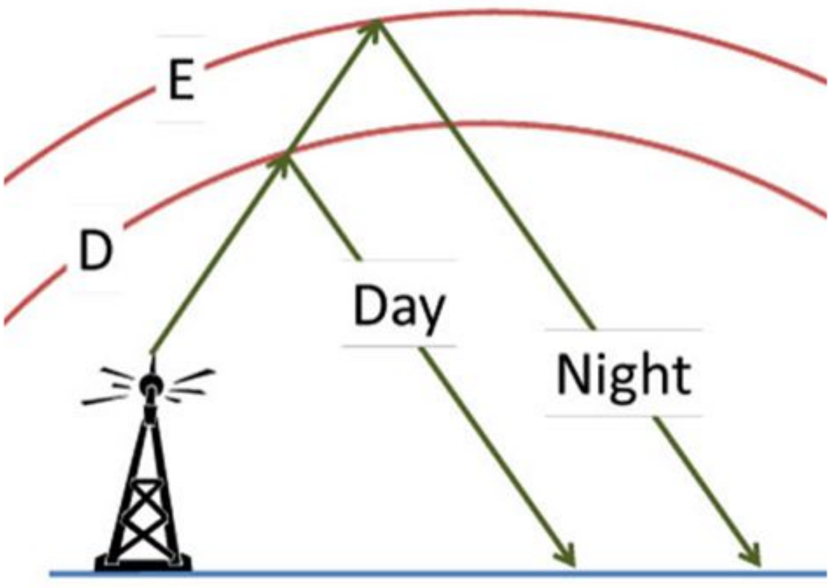
•Typical reactions:

$$O_2 + h\nu \rightarrow O_2^+ + e^-$$

$$O_2 + h\nu \rightarrow O^+ + O + e^-$$

• Variation of eletronic densities:

Layer	z(km)	$N_e[cm^{-3}]$
D	60	10^3
E	100	10^5
F	150-300	$2x10^6$
	> 2000	10^4

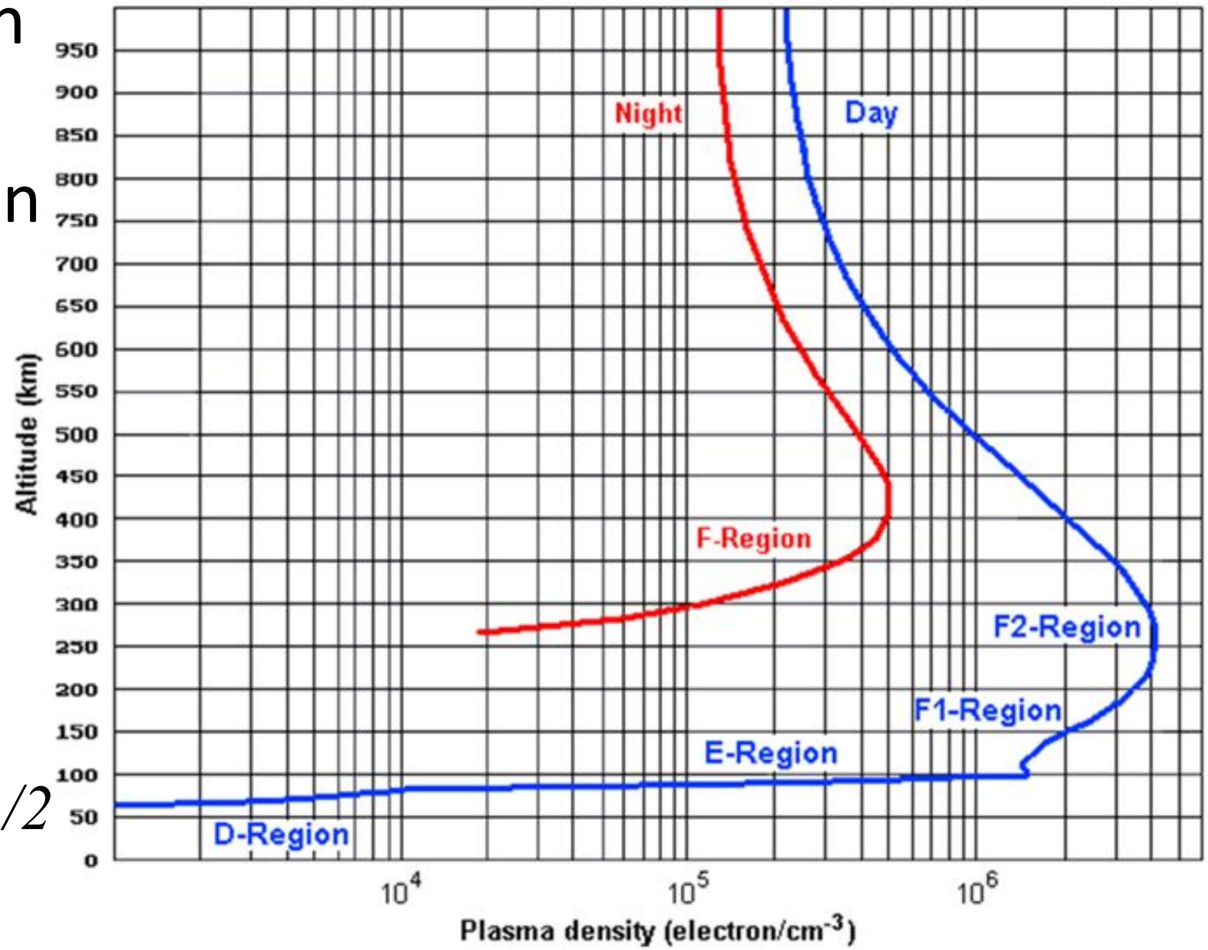


•D almost dissapears at night
•Interference in radio waves

Ionospheric plasma

Ionized layers have an index of refraction *n* related to the electron density *Ne*

- $n^2 = 1 - \omega_p^2/\omega$
  $= 1 - (\lambda/\lambda_p)^2$
- $\nu_p[Hz] = \omega_p/2\pi$
  $= 9 \times 10^3 N_e^{1/2}$

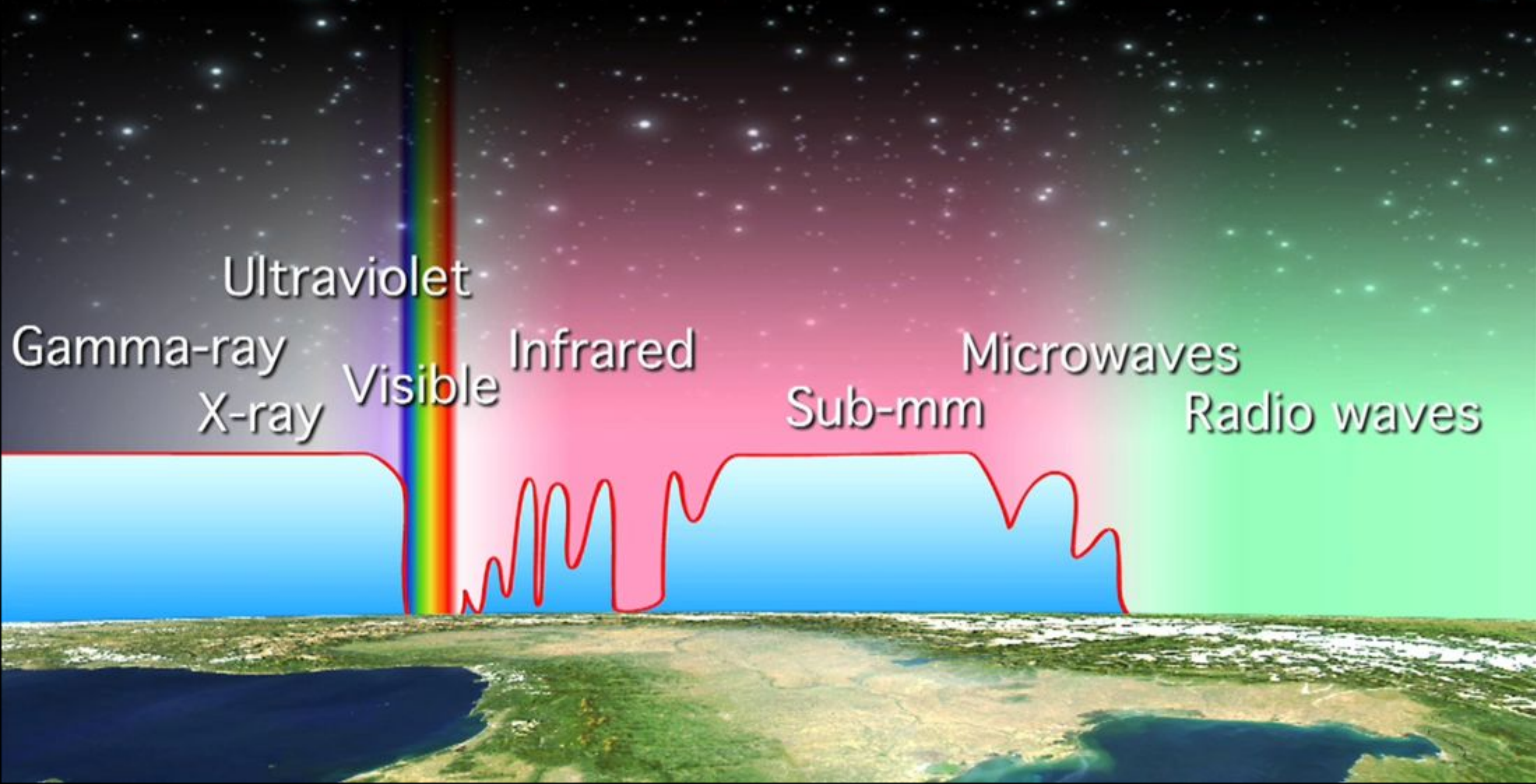


Total internal reflection

For *F* layer (N_e = 2x10^6 cm^{-3}), $\lambda_p = 23.5m$ ($\nu_p = 12$ MHz)

Absorption of Radiation

The absorption by the atmosphere could be total or partial



Atomic and Molecular absorption

Atomic: O, N

Molecular:

- Electronic

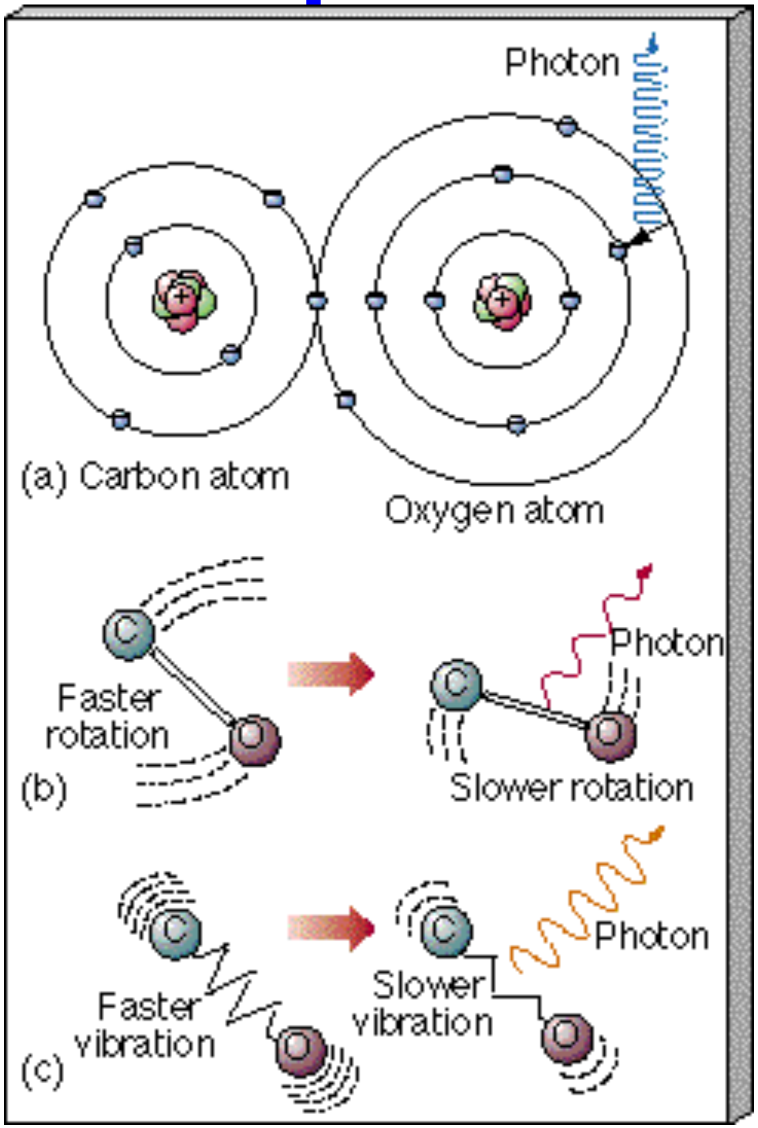
  CH_4, CO, H_2O, O_2, O_3, …

- Rotacional:

  H_2O, CO_2, O_3, …

- Vibrational-Rotational:

  CO_2, NO, CO …

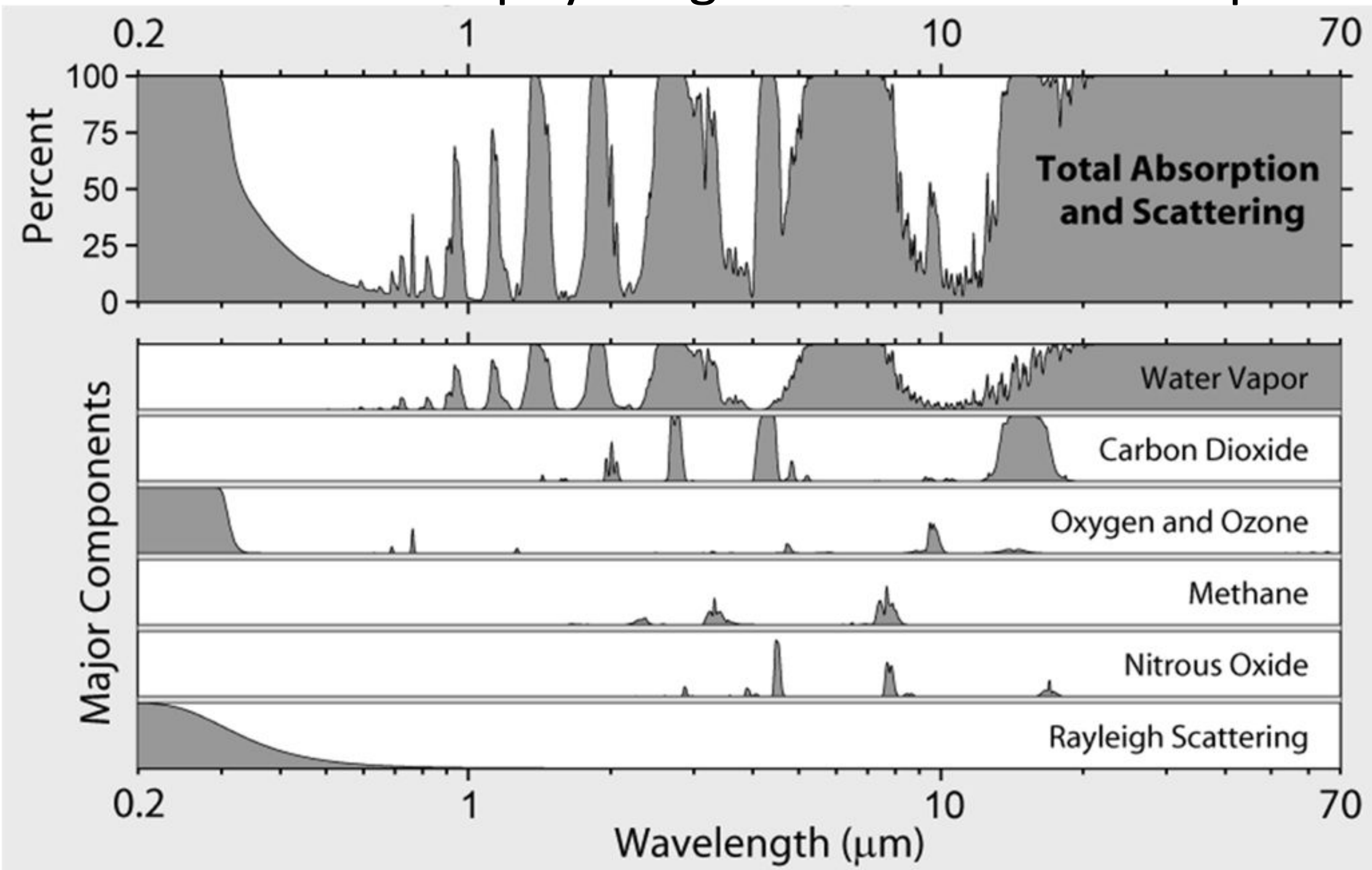


$$E_{el,v'',J''} = [T_e + G_v + F_v(J)]\, hc$$

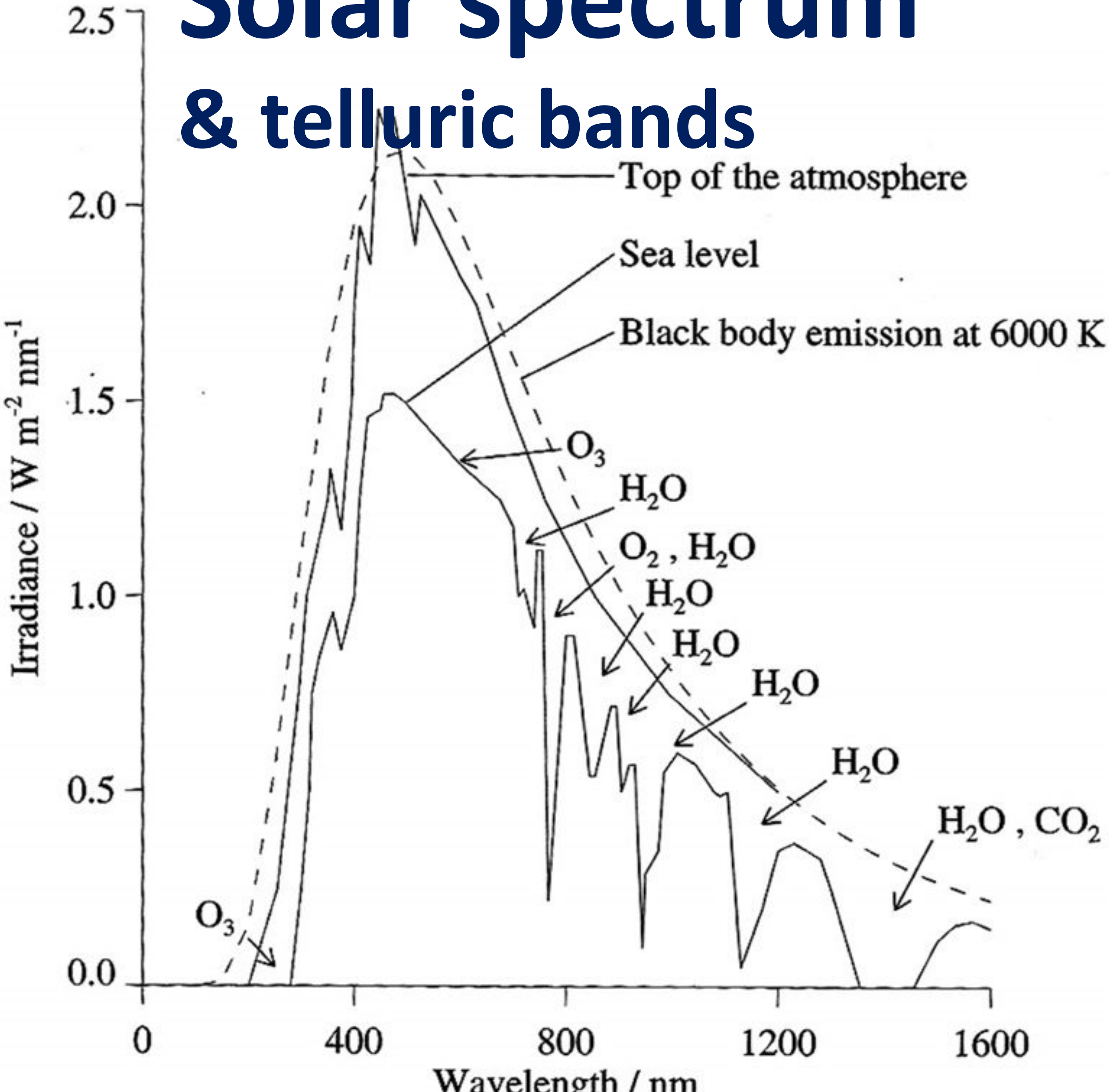
Atmospheric absorption bands

Telluric bands

Atomic & molecular physics gives κ or σ for each species



Solar spectrum
& telluric bands



In the optical and near infrared, O_3, H_2O & CO_2 cause strong absorption bands in Earth's atmosphere

γ **Cas** and telluric bands

At the near infrared, H_2O cause strong absorption bands in Earth's atmosphere

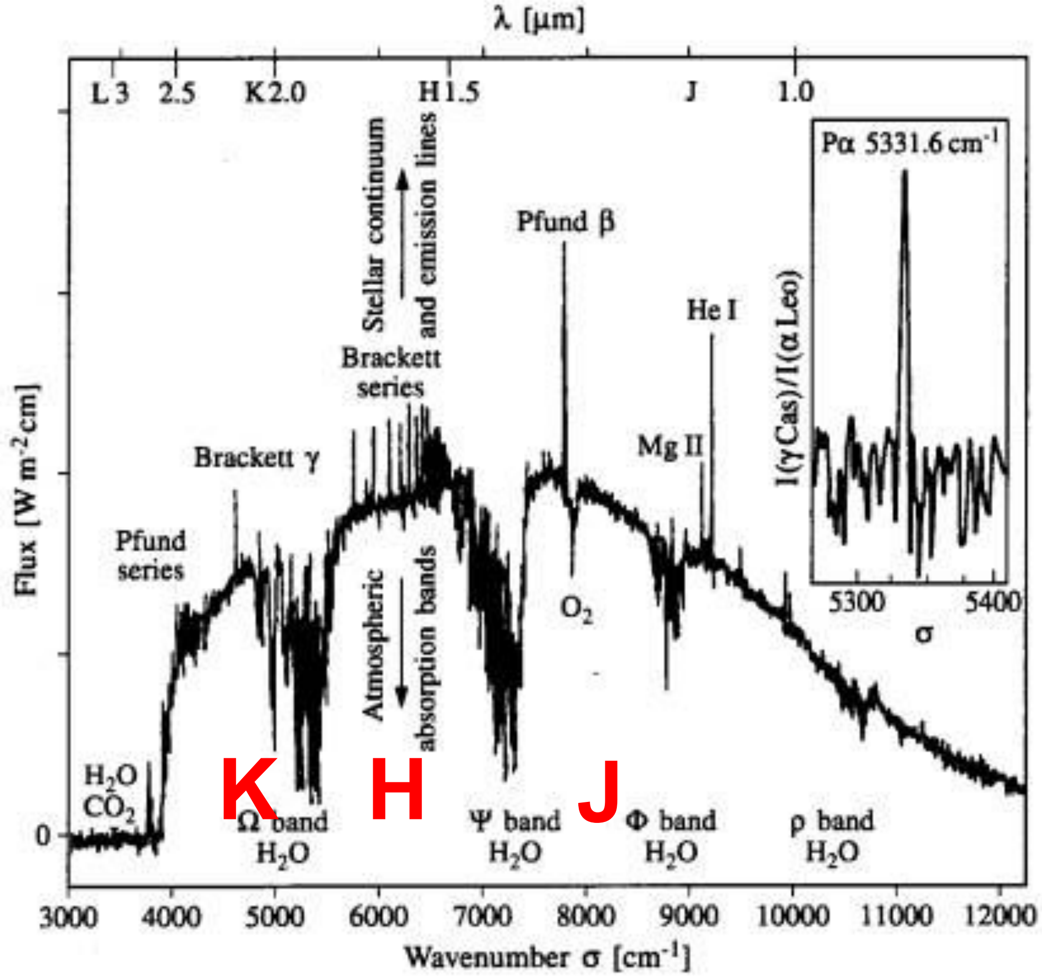
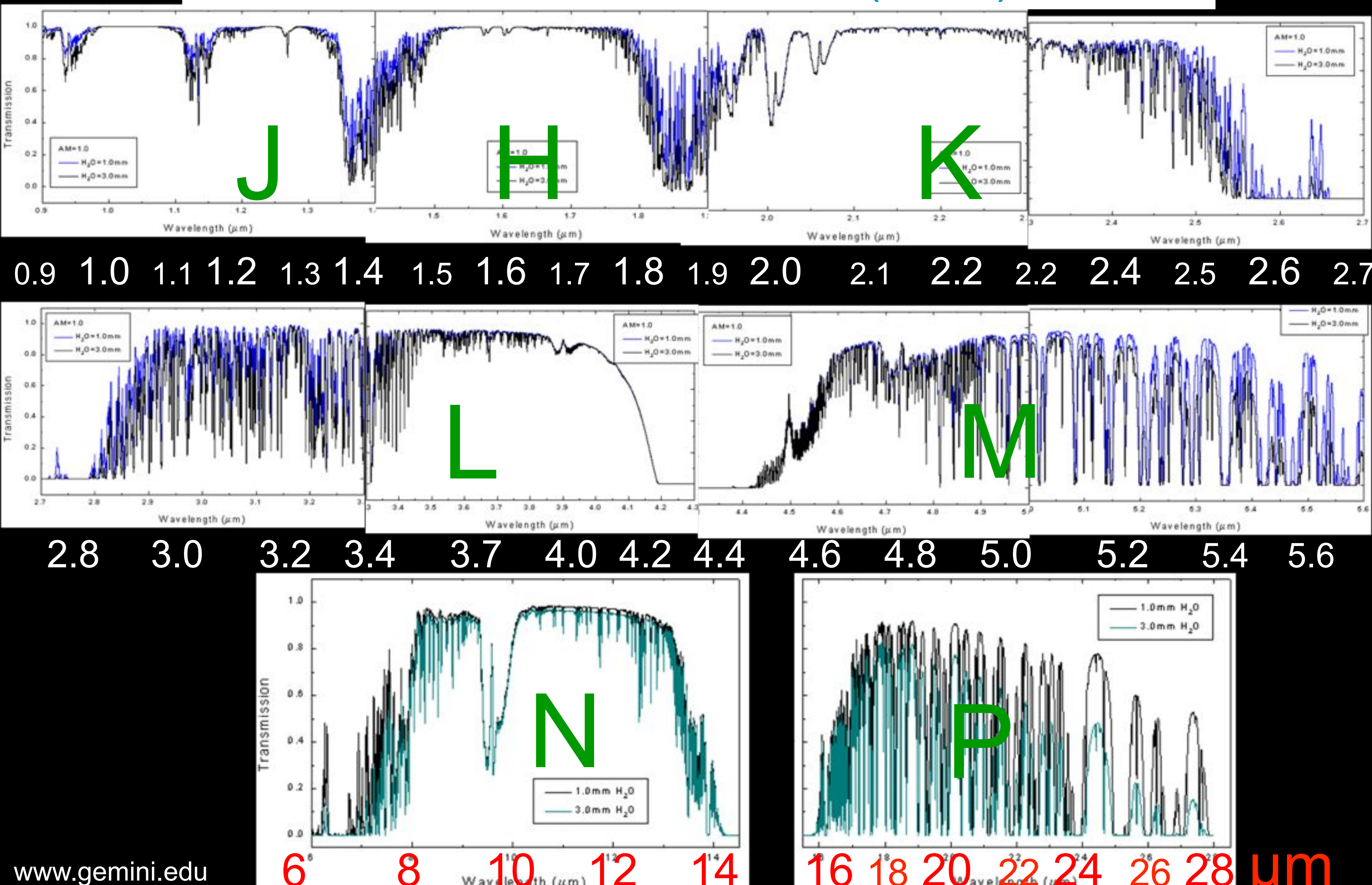


Fig. 2.5. Telluric absorption and spectroscopy: the spectrum of the star γ Cas. The spectrum was obtained using the 3.6 m Canada-France-Hawaii telescope at the summit of Mauna Kea, Hawaii, USA. (4 200 m), with a Fourier transform interferometer (cf. Sect. 5.3.4), in the near infrared atmospheric transmission window, with a resolution of $\Delta\sigma = 0.5\,\mathrm{cm}^{-1}$. (Chalabaev A., Maillard J.-P., Ap. J. **294**, 640, 1984.) Atmospheric absorption bands are indicated, together with photometric windows I,J and K (cf. Sect. 3.3). The star has both a continuum and emission lines (mainly H recombination lines). The inset shows the 3–4 Paschen α line (5331.6 cm^{-1}) extracted from a heavily absorbed part of the spectrum: the spectrum of γ Cas was divided by that of a reference star (α Leo) to eliminate atmospheric bands. As α Leo (spectral type B7) also has hydrogen lines, the absolute value of Pα is not significant. Observation of Pα would be impossible at lower altitude. (With the kind

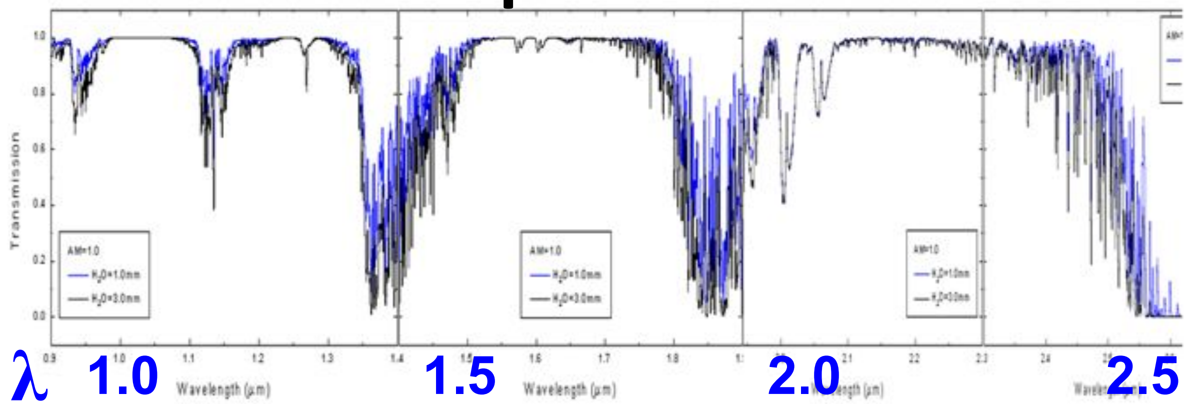
Atmospheric transmission

Mauna Kea com H2O = 1mm(1mm) & 3mm

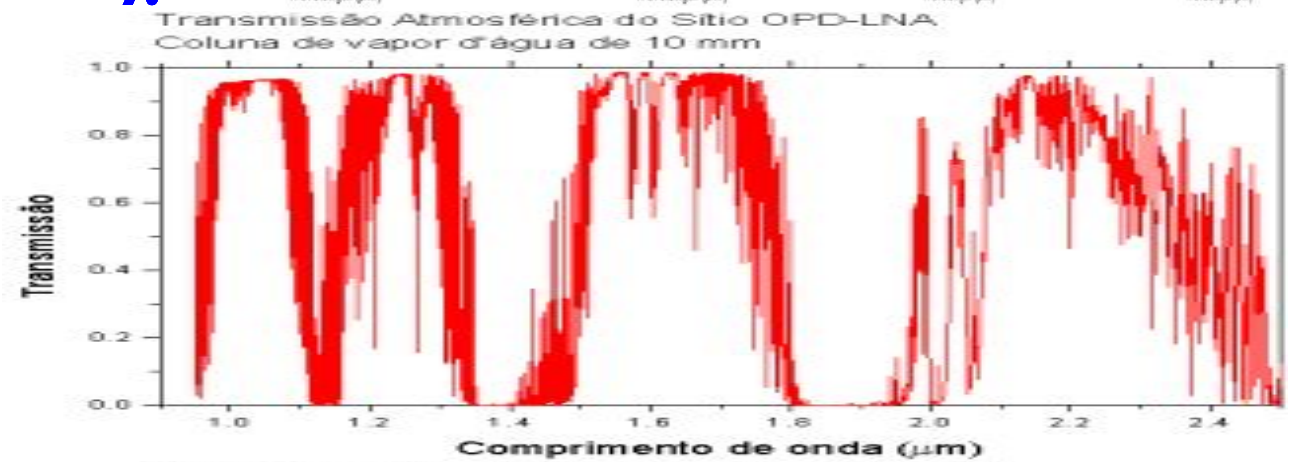


www.gemini.edu

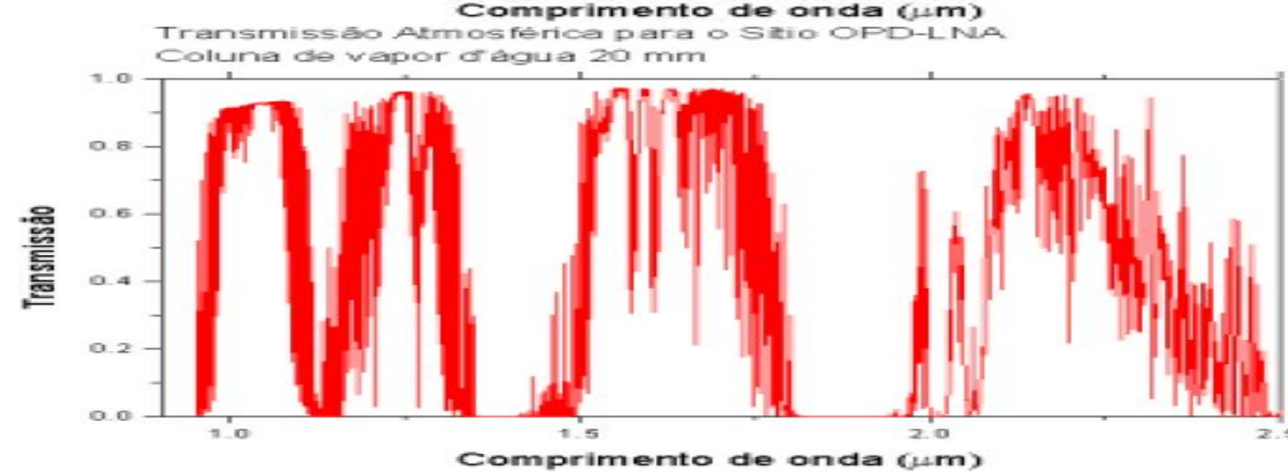
Water Vapor: Mauna Kea vs OPD



Mauna Kea
h(1mm ,3mm)



OPD/LNA
h(10mm)
Barbosa(2000)



OPD/LNA
h(20mm)
Barbosa(2000)

Optical depth

The optical depth along a vertical line, of a constituent *i* with mixing ratio $r_i(z)$ is:

$$\tau(\lambda, z_0) = \int_{z_0}^{\infty} r_i(z)\rho_0(z)k_i(\lambda)dz$$

The attenuation of an incident ray of intensity I_0 (top of the atmosphere) received at altitude z_0 and at an angle θ from the zenith, is:

$$\frac{I(z_0)}{I_0(\infty)} = exp\left\{-\frac{1}{cos\theta}\sum_i \tau_i(\lambda, z_0)\right\}$$

The sum is over all species that absorb

Atenuation of radiation with altitude

Atmosphere totally opaque for $\tau = 10$

Ideally observatories are feasible for $\tau < 0.5$ (transmission > 61%)

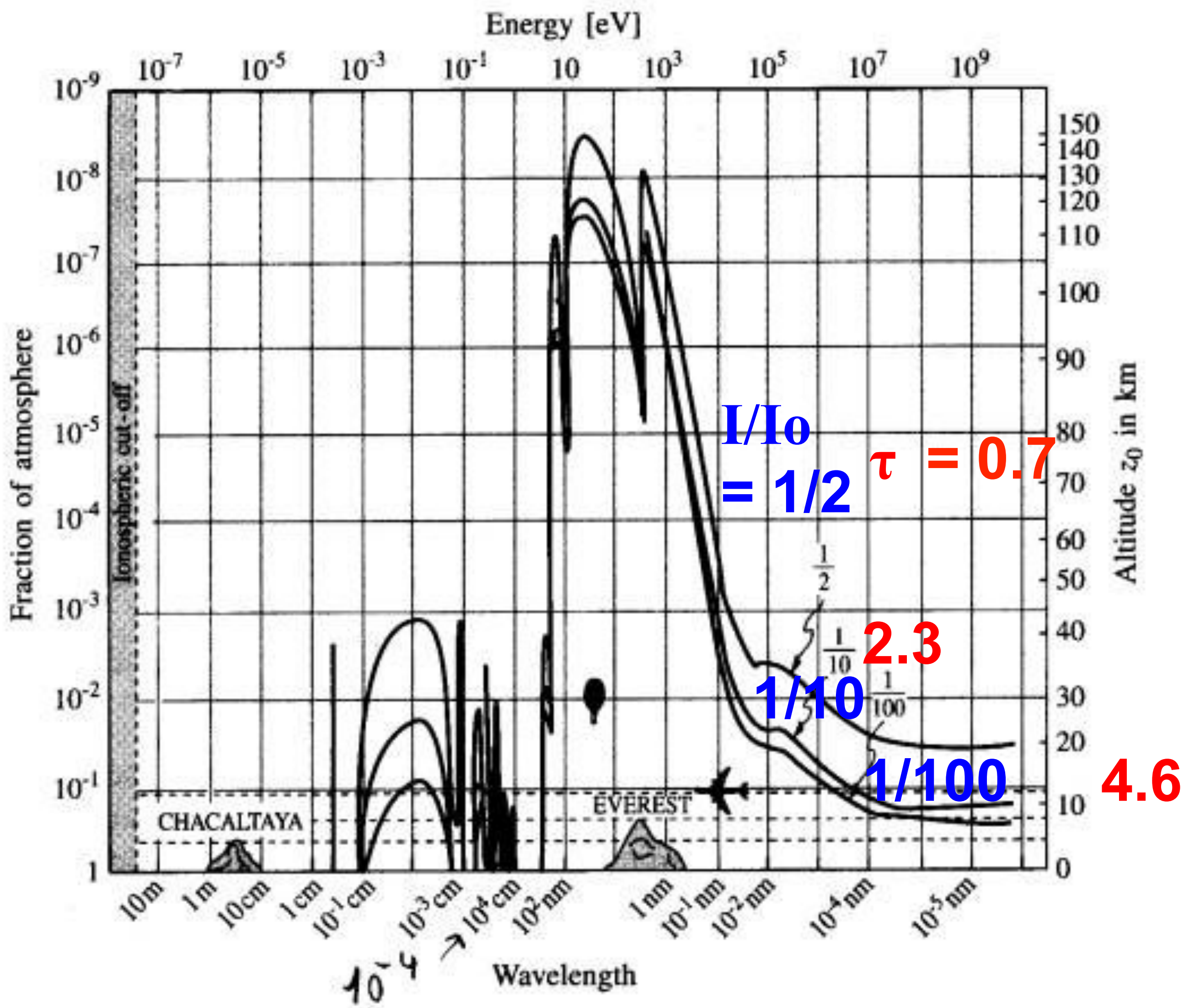
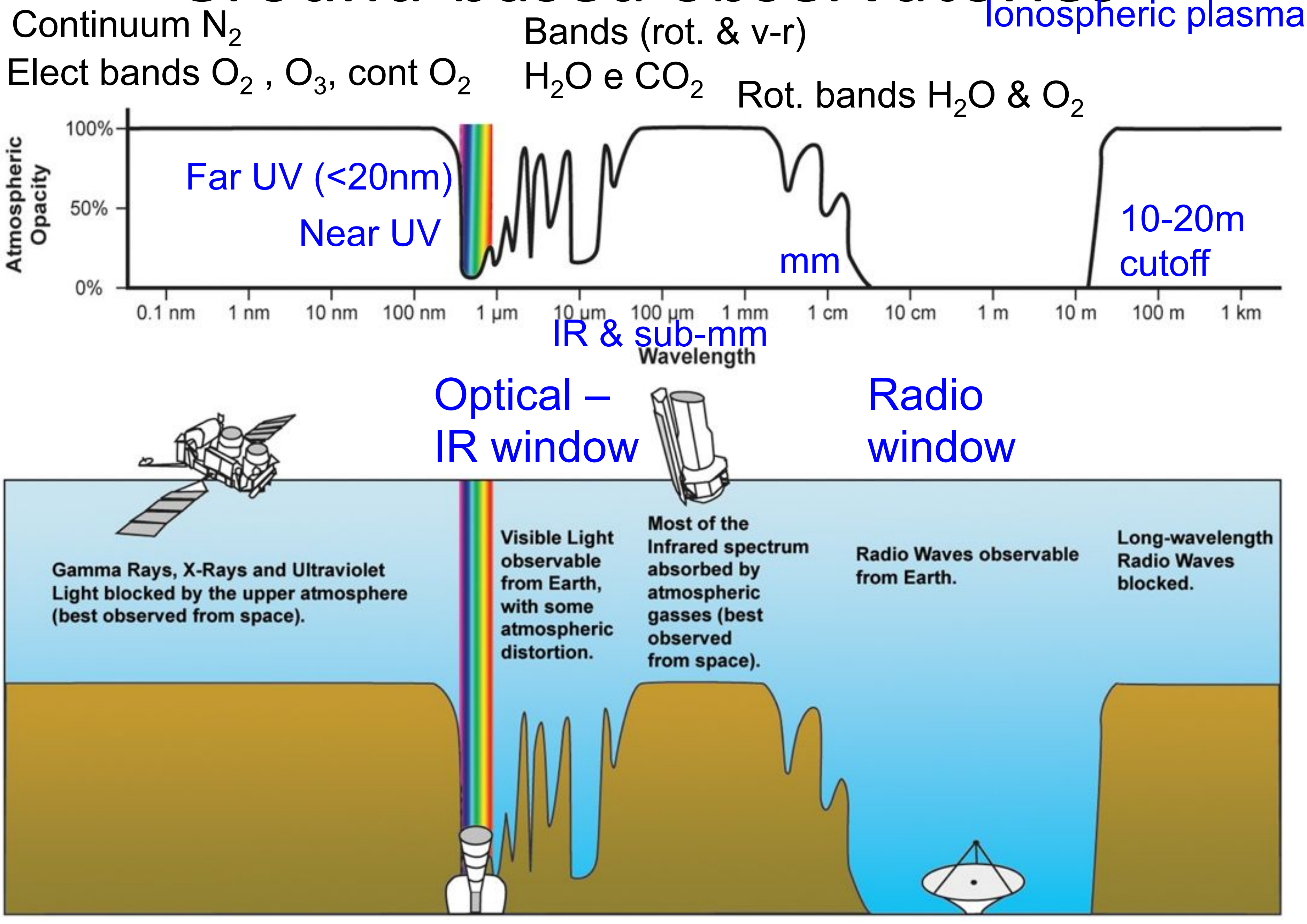


Fig. 2.4. Attenuation of electromagnetic radiation by the atmosphere. Curves give the altitude z_0 (*right-hand scale*) or the residual fraction of the atmosphere, in mass, above z_0 (*left-hand scale*), for three values of the ratio $I(z_0, \lambda, \theta = 0°)/I_0(\infty, \lambda)$. Chacaltaya is a site in the Andes (altitude ~6 000 m)

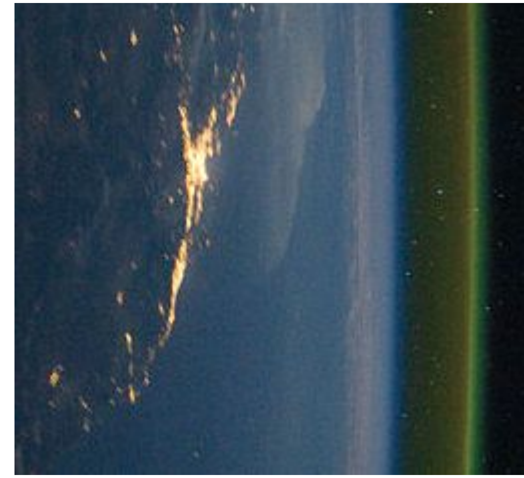
Ground-based observatories



ALMA:

66 antennas working together at mm and submm

Atmospheric emission



- The atmosphere emits by florescence (*airglow*) & termically

FLUORESCENCE: recombination of e- & ions from diurnal dissociation; ex.:

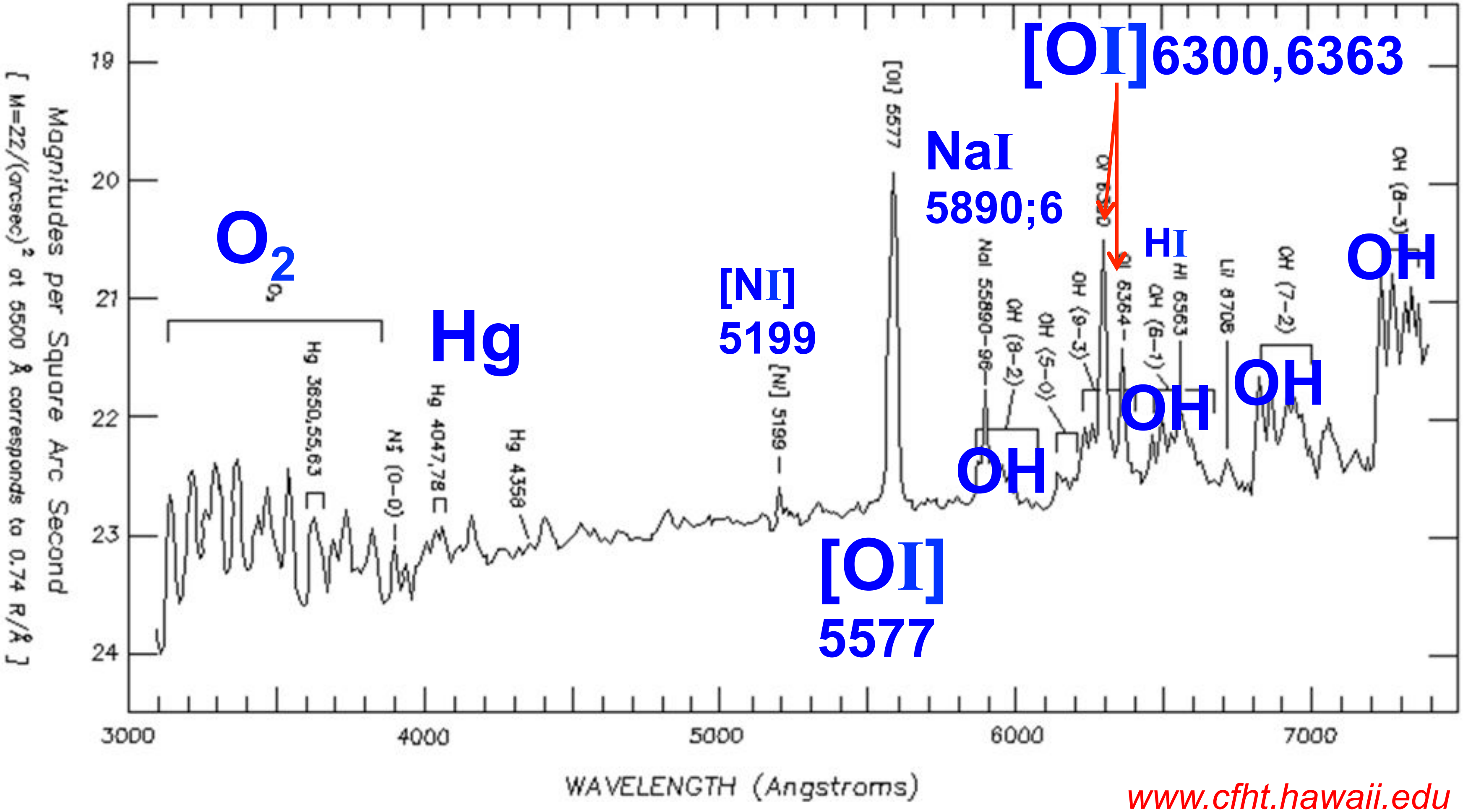
$$O_2 + h\nu \rightarrow O_2^+ + e^-$$

- Continuum: 1-3 Rayleigh $Å^{-1}$
- Lines: 500 R

  1 Rayleigh (R) = 10^6 photons cm^{-2} s^{-1} str^{-1}

  = $6.8x10^{-17}$ $Wm^{-2}um^{-1}arcsec^{-2}$(em =550nm) = 22 mag $arcsec^{-2}$
- Main emitters: OI, NaI, O_2, OH, H

Spectrum of the night sky (optical)
Mauna Kea (Hawaii)

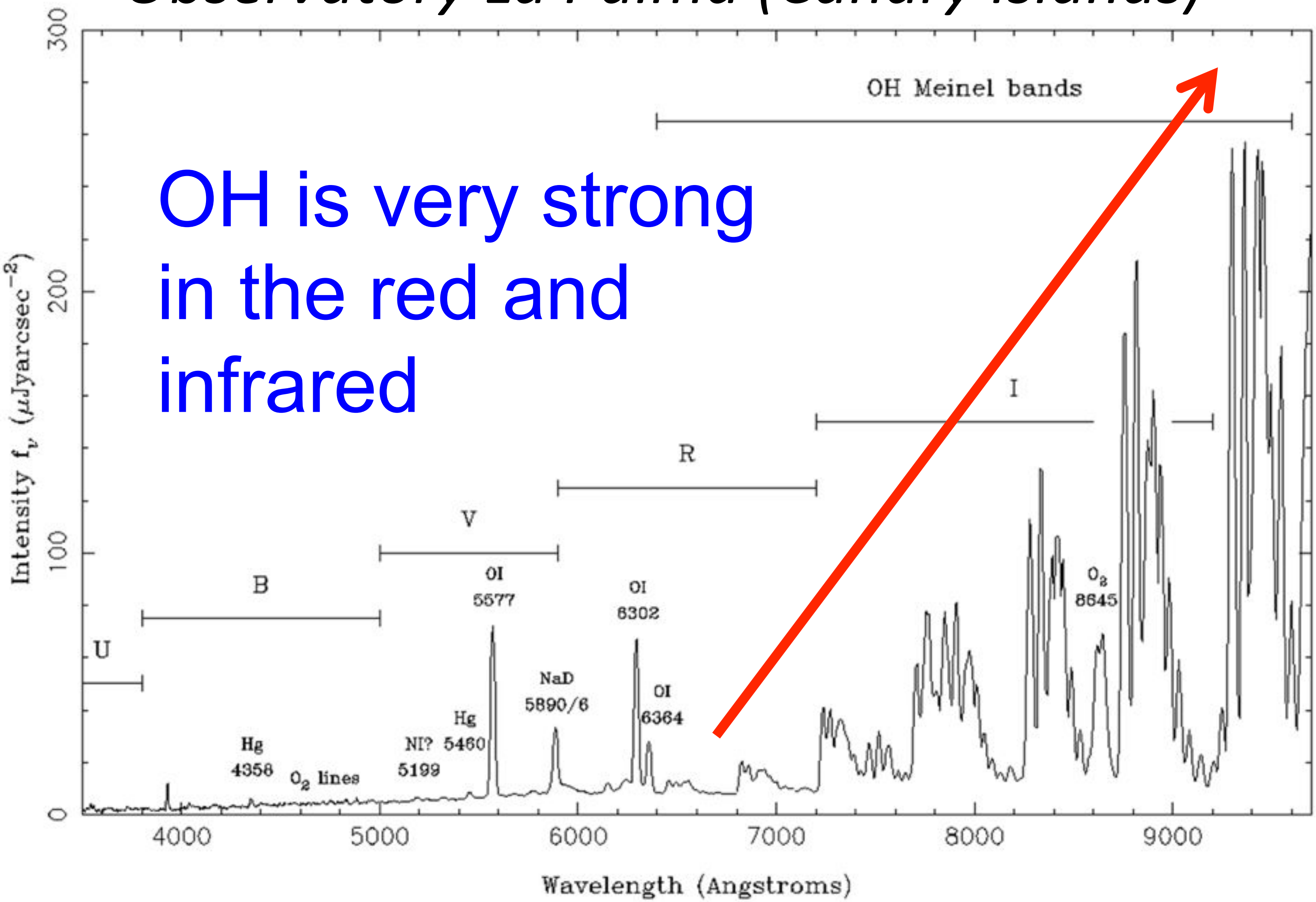


www.cfht.hawaii.edu

Spectrum of the sky at night (optical & infrared)

Observatory La Palma (Canary Islands)

OH is very strong in the red and infrared



Sky background for observations on ground and space near Earth

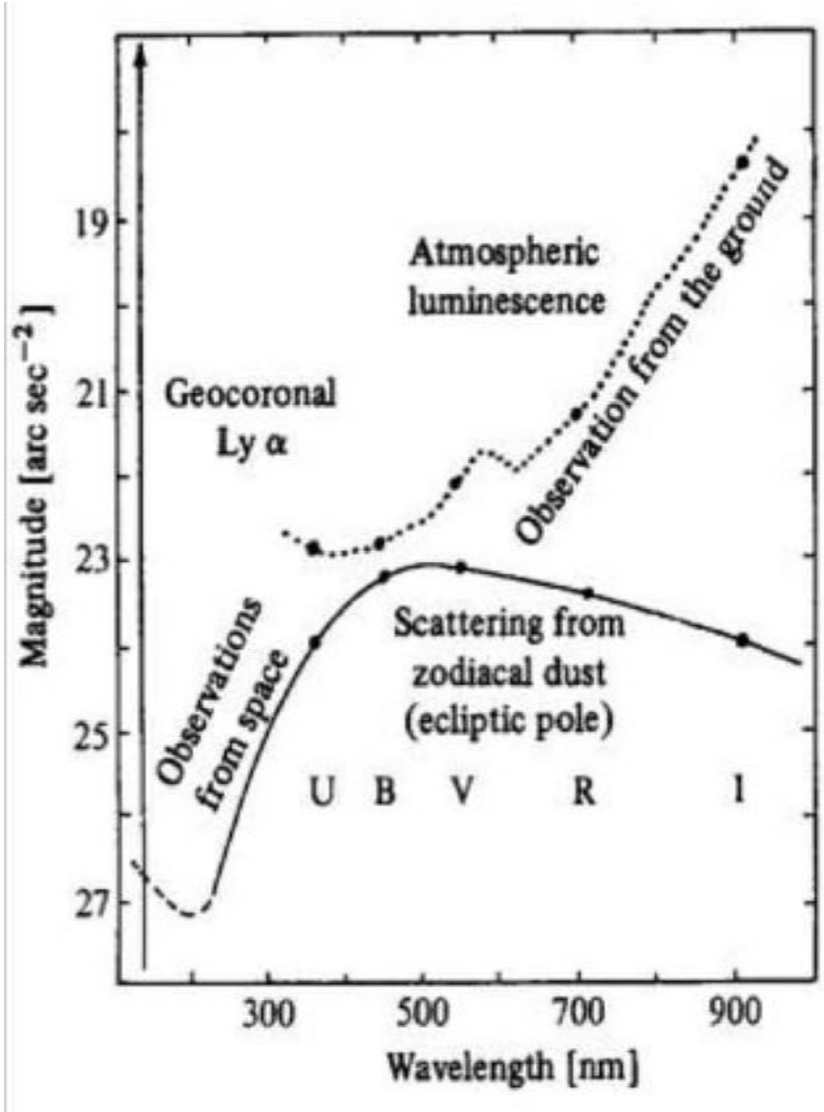
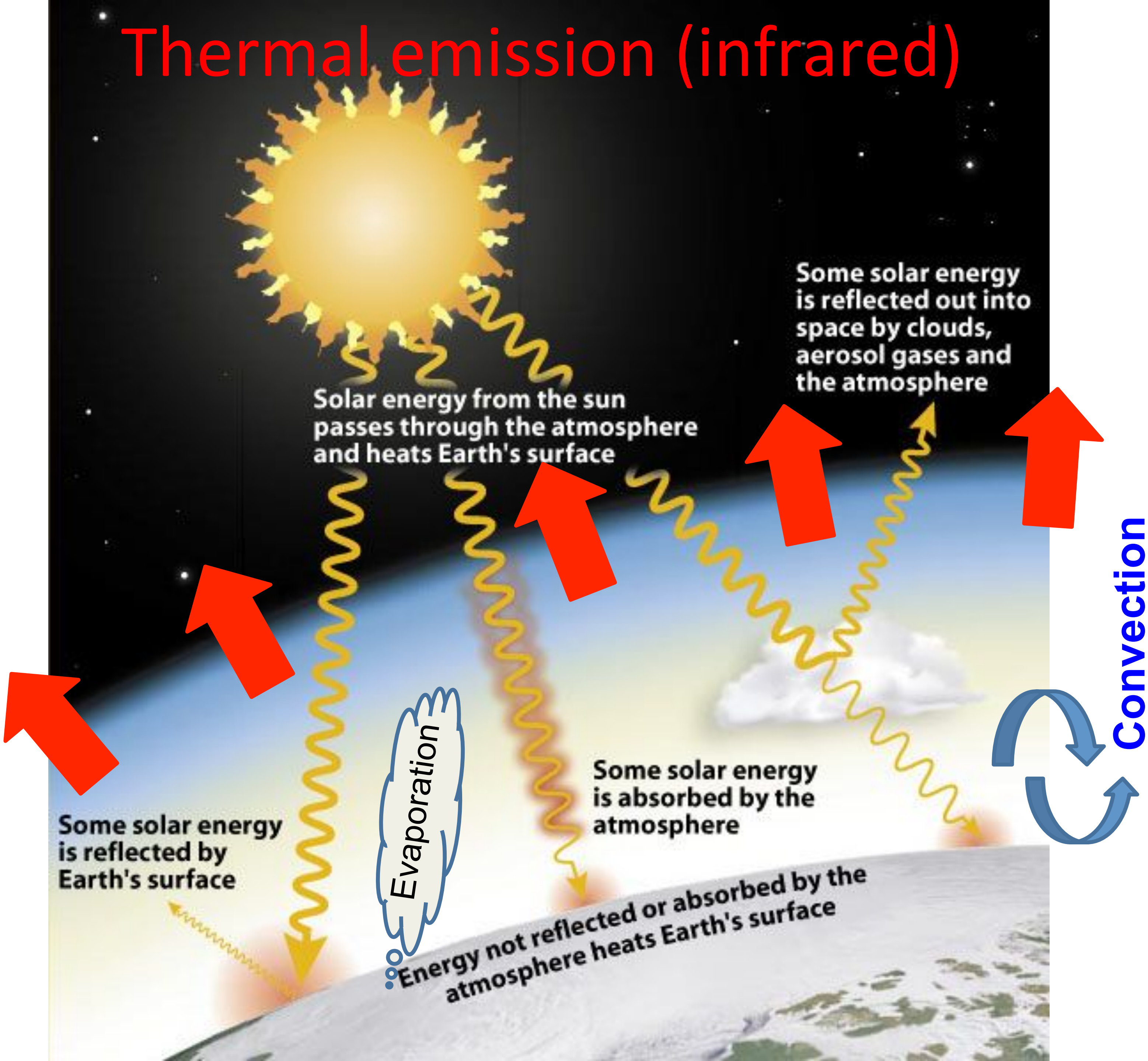


Fig. 2.8. Visible and ultraviolet magnitudes of the sky background per square arc second, for observations from the ground and from space near the Earth. Letters denote the spectral bands of the photometric system (cf. 3.3), corresponding to the points (•). [After Courtès G., personal communication; Smith H.E., Burbridge E.M., Ap. J. **210**, 629, 1979; Leinert C., Sp. Sci. Rev. **18**, 281, 1975; Machetto F. et al, ESA-SP **1028**, 1980, European Space Agency]



Thermal emission (infrared)
Some solar energy is reflected out into space by clouds, aerosol gases and the atmosphere
Solar energy from the sun passes through the atmosphere and heats Earth's surface
Convection
Evaporation
Some solar energy is absorbed by the atmosphere
Some solar energy is reflected by Earth's surface
Energy not reflected or absorbed by the atmosphere heats Earth's surface

Thermal emission

- Atmosphere could be considered a gas in LTE until 40-60km
- For $\tau << 1$ (shallow optical depth), the intensity of radiation at altitude z and zenithal distance θ, is:

$$I_\lambda(z) \approx \tau_\lambda B_\lambda(\bar{T}) \frac{1}{\cos\theta}$$

B_λ : Planck function at mean temperature $\bar{T}$ of the atmosphere

$\tau << 1$ and B_λ non-negligible, satisfied for:

- Infrared window: 1 - 20 μm
- Milimeter window: 0.5 – 2 mm

Thermal emission

$$I_\lambda(z) \approx \tau_\lambda B_\lambda(\bar{T}) \frac{1}{\cos\theta}$$

Using a mean temperature 250K:

Astronomical sources could be several orders of magnitude weaker than sky thermal emission (also could be problematic for sky fluorescent emission).

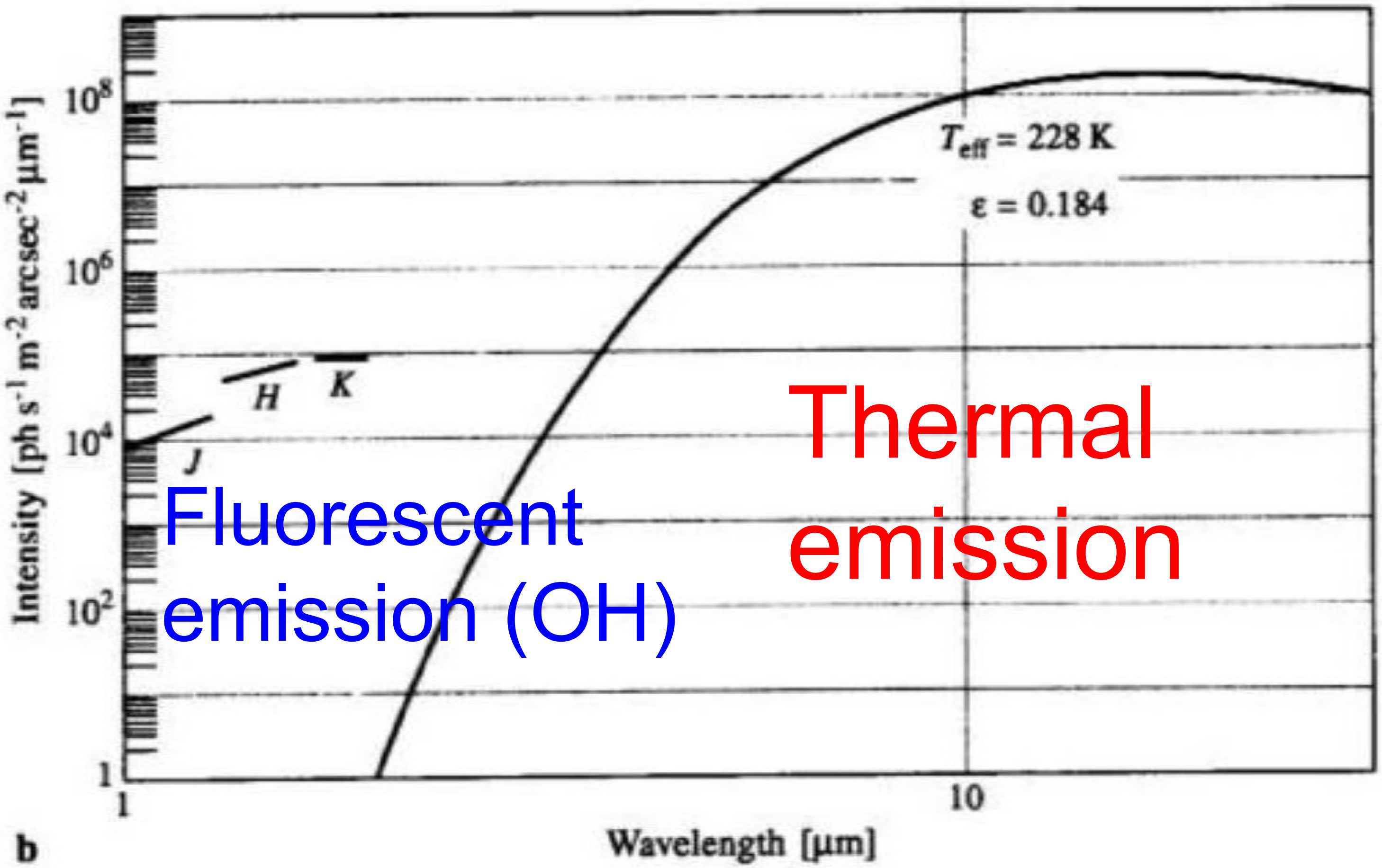
Table 2.3. Mean thermal emission of the atmosphere

Spectral band (cf. Sect. 3.3)	L	M	N	Q
Mean wavelength [μm]	3.4	5.0	10.2	21.0
Mean optical depth τ	0.15	0.3	0.08	0.3
Magnitude [arcsec^{-2}]	8.1	2.0	−2.1	−5.8
Intensity [Jy arcsec^{-2}][a]	0.16	22.5	250	2 100

[a] 1 Jansky = 10^{-26} W m^{-2} Hz^{-1}.

Léna, Lebrun & Mignard 1998
Observational astrophysics, 2nd Ed

Sky background in the infrared: thermal emission vs. OH



Sky background emission in the infrared, at the altitude of Mauna Kea (4200m).

Scattering of radiation: Rayleigh & Mie

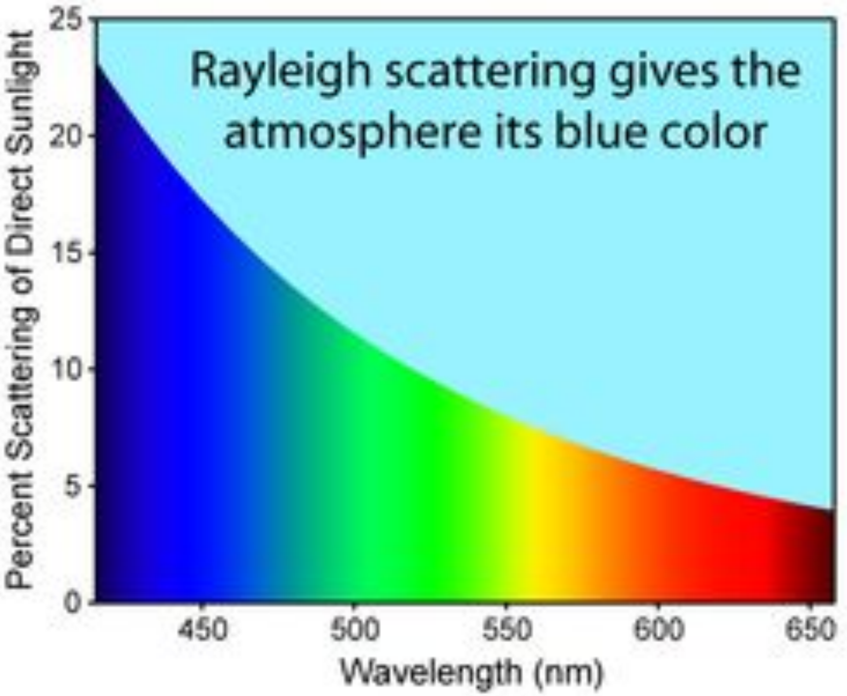
- Caused by molecules and aerosols in suspension
- Influence of ar molecules depends on altitude, *but aerosols depend on winds, weather, season, volcanic activity, industrial pollution*

Rayleigh scattering

- For particles smaller than the light wavelength λ:

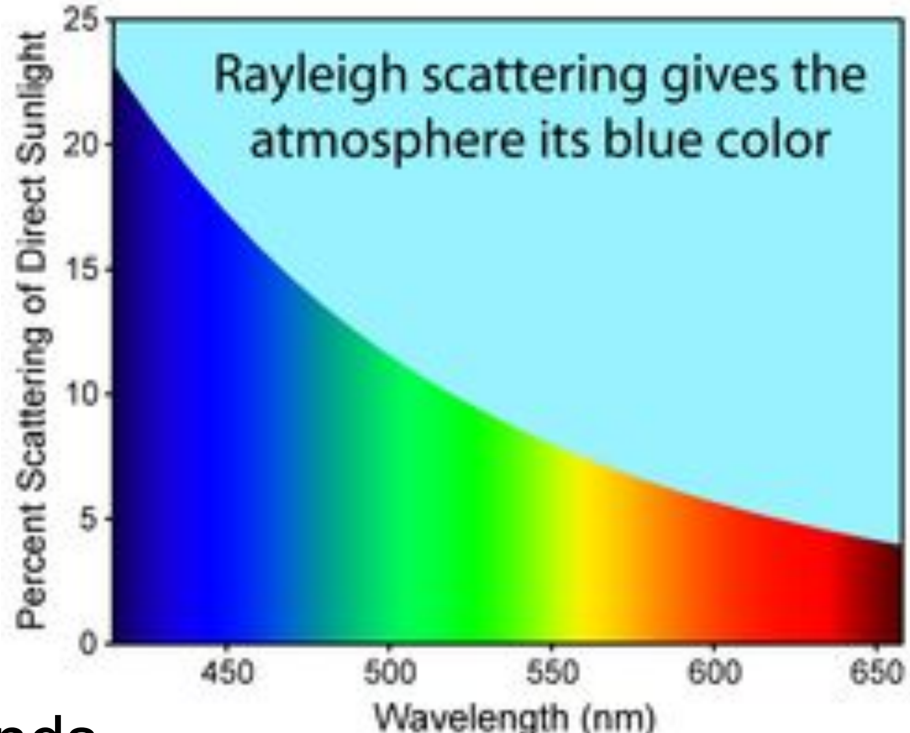
$$\sigma_R(\lambda) = \frac{8\pi^3}{3}\frac{(n^2-1)^2}{N^2\lambda^4}$$

- n: refraction index;
- N: density of molecules



This is why the sky is blue

$$\sigma_R(\lambda) = \frac{8\pi^3}{3}\frac{(n^2-1)^2}{N^2\lambda^4}$$



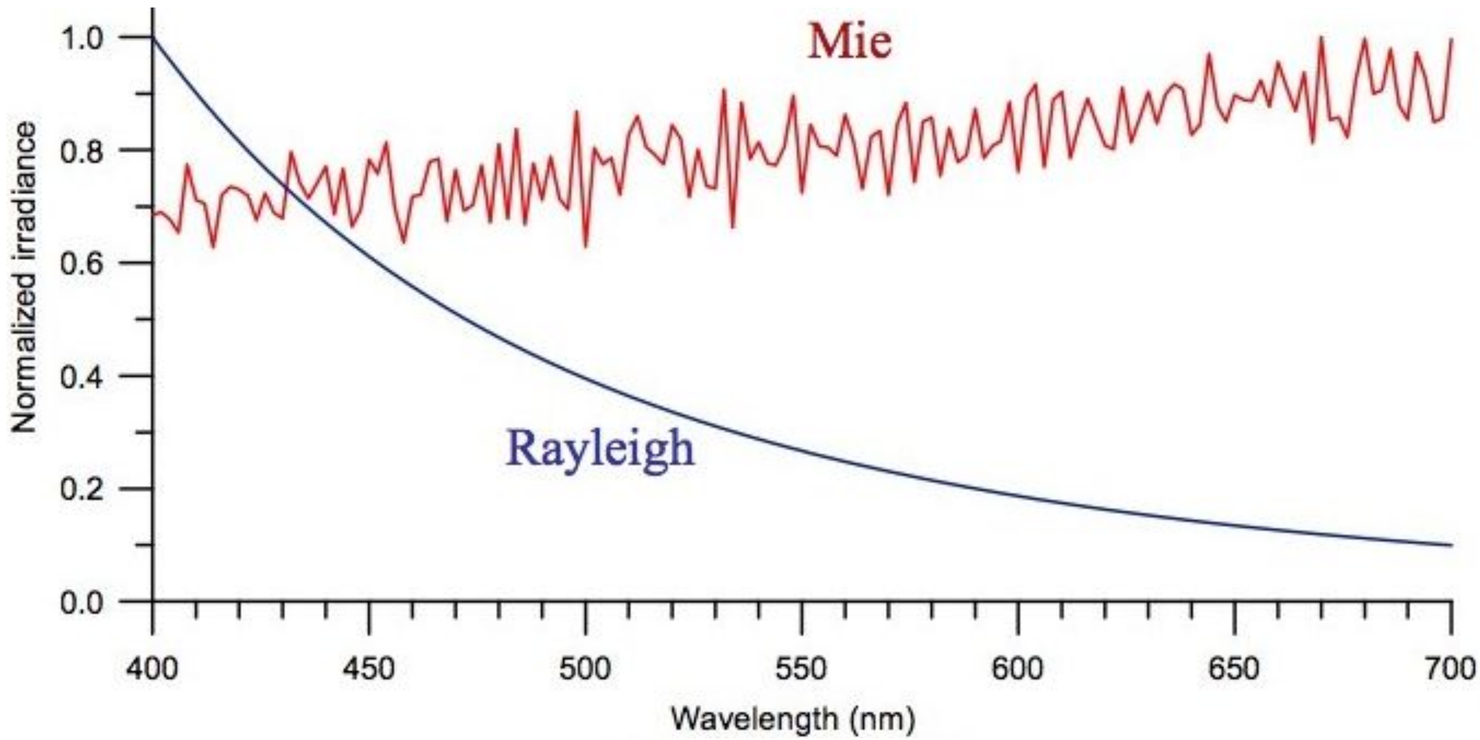
Rayleigh scattering also depends on the incident angle θ:

$$j = \sigma_R \frac{3}{4}(1+\cos^2\theta)\frac{d\omega}{4\pi} I$$

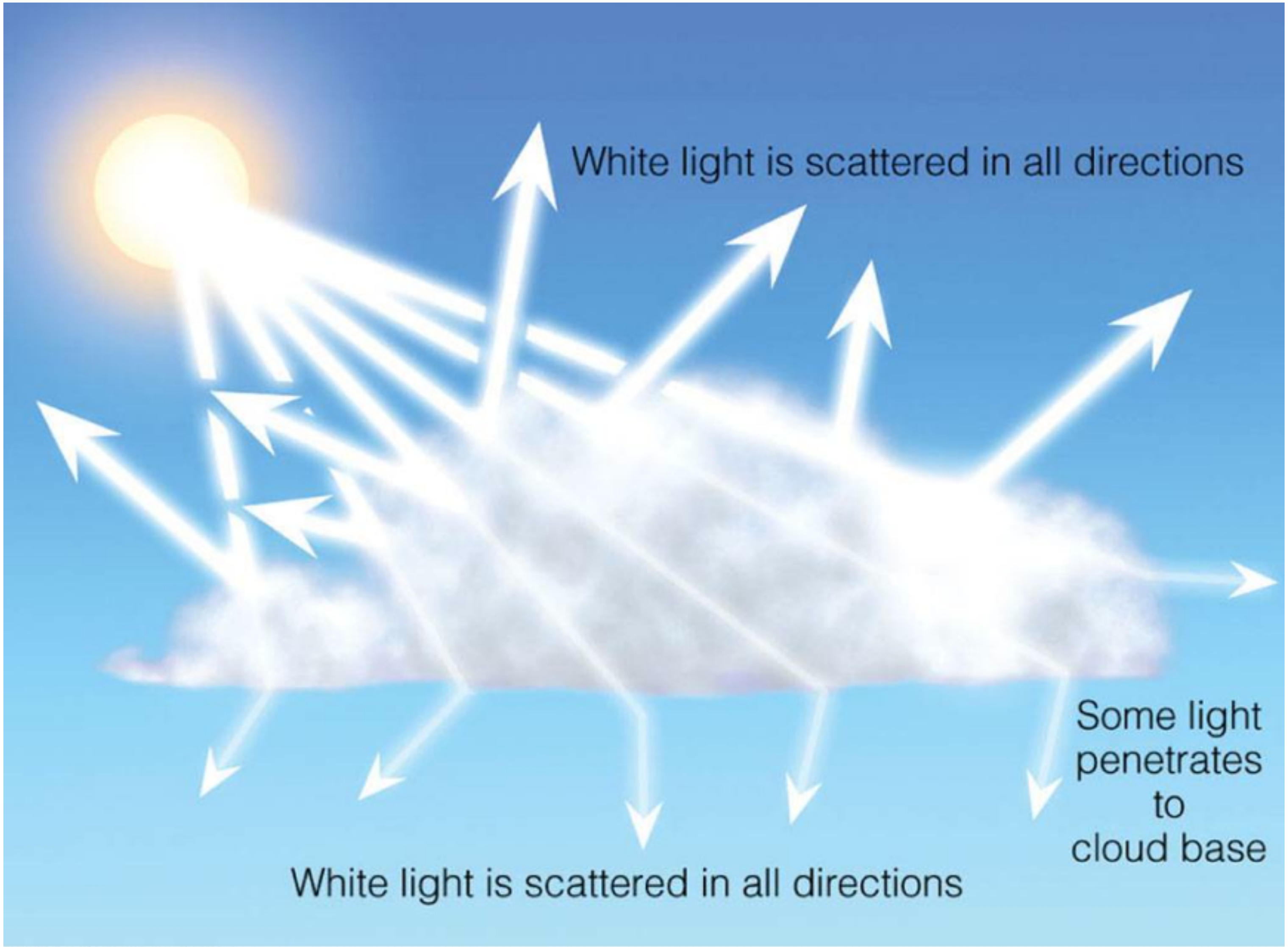
At z=2km: at 90^0 from the Sun, λ=7000A, sky brightness is 10^{-7} of the Sun's disk

Mie scattering

- Scattering by particles larger than λ of light
- Does not depend much on wavelength



Mie scattering



Sky brightness during the day in the optical and infrared

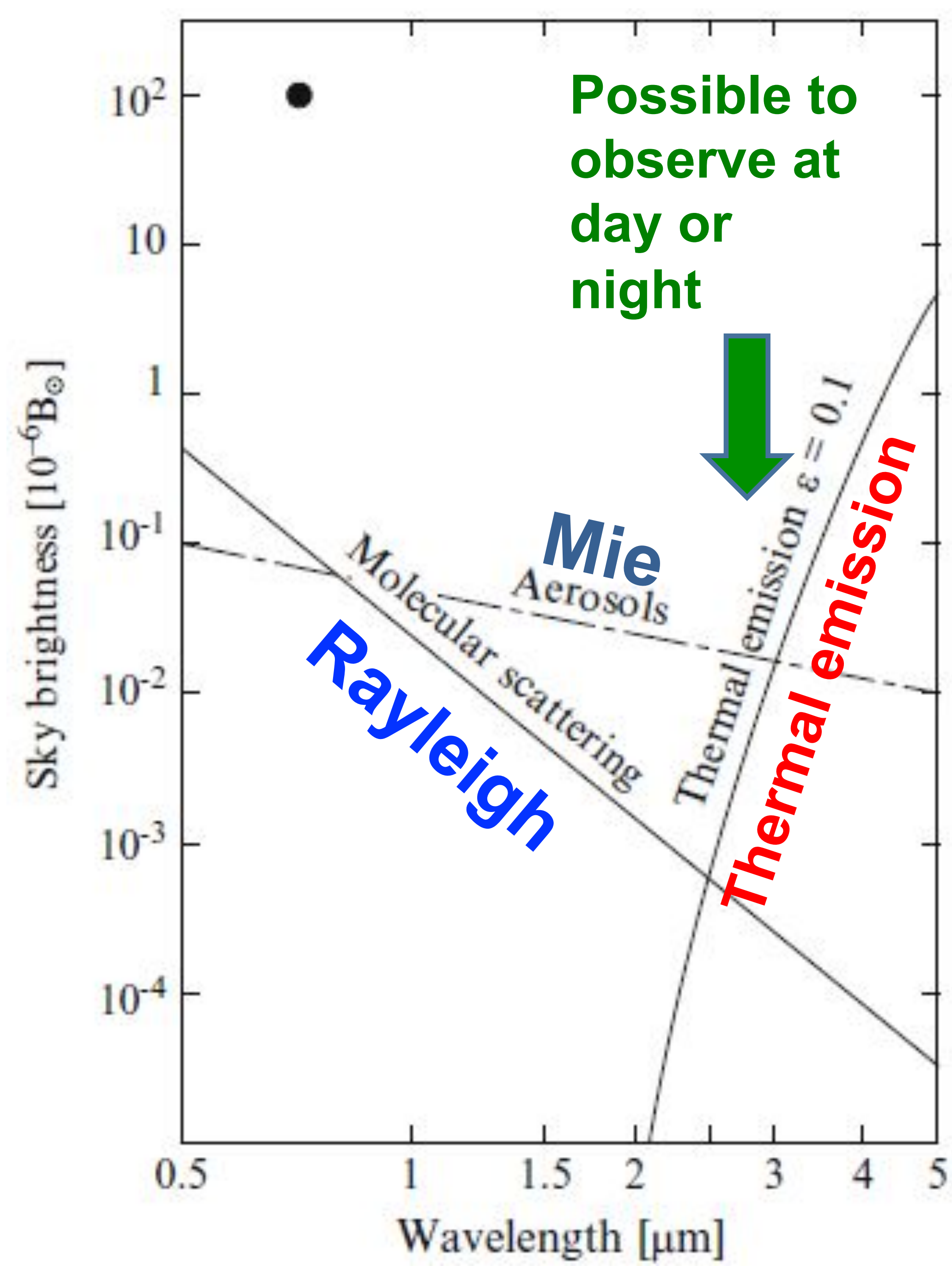


Fig. 2.11 (Lena, Observational Astrophysics). Molecular scattering is given for the altitude z = 2000m, at 90^0 from the Sun. The wavelength dependence is λ^{-4}. Thermal emission is also shown, assuming uniform mean emissivity of 0.1.

The dashed line shows the possible additional contribution due to aerosols, varying as λ^{-1}. For comparison, (•) marks the sky brightness measured at 0.5 arcmin from the Sun's limb at Kitt Peak (Arizona)

Other atmospheric factors: Atmospheric turbulence

Vincent ***van Gogh***

Sources of turbulence by different obstacles

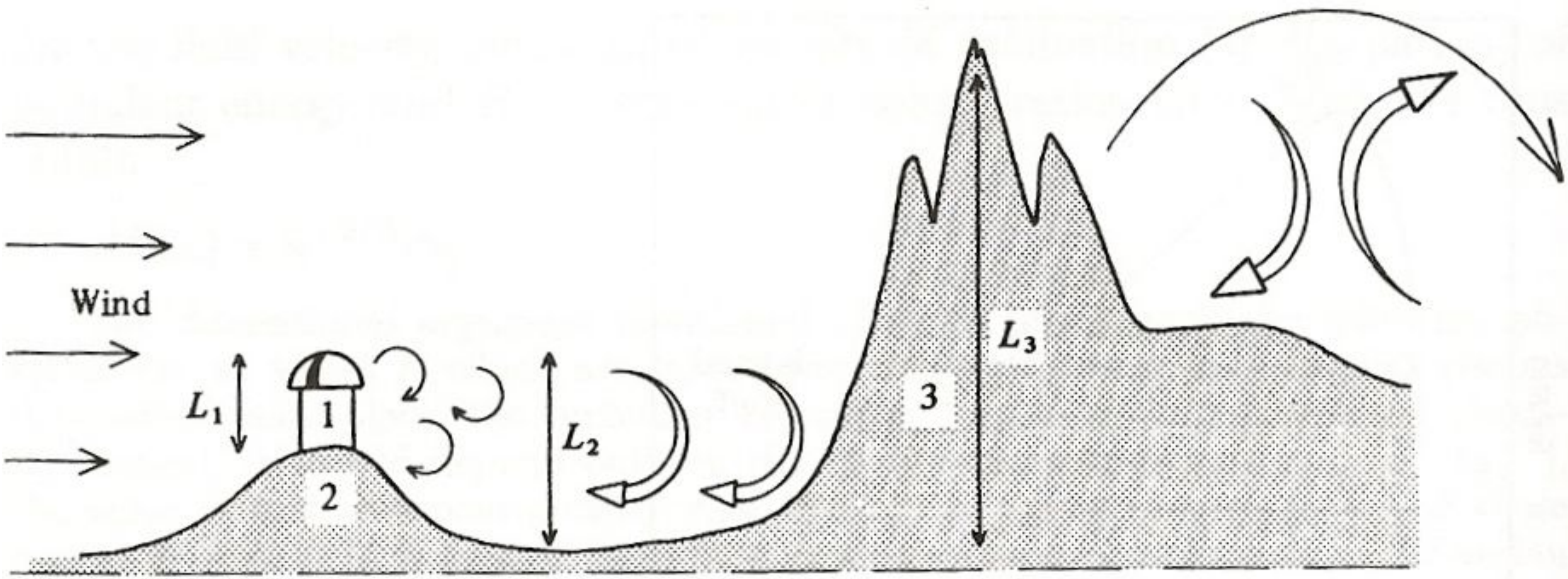
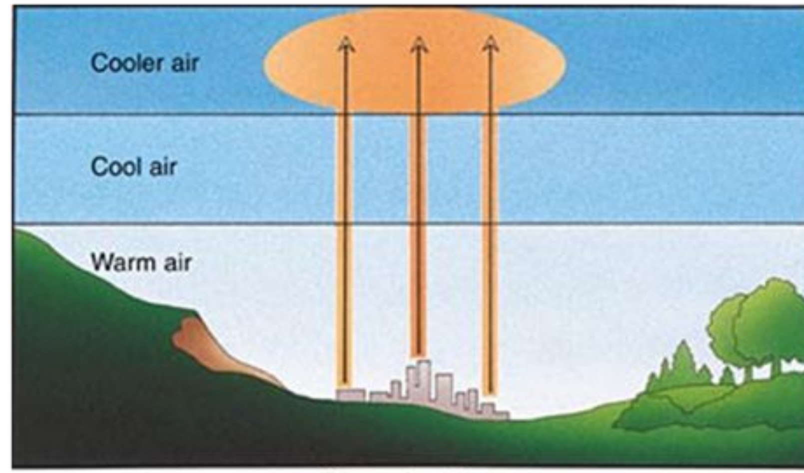


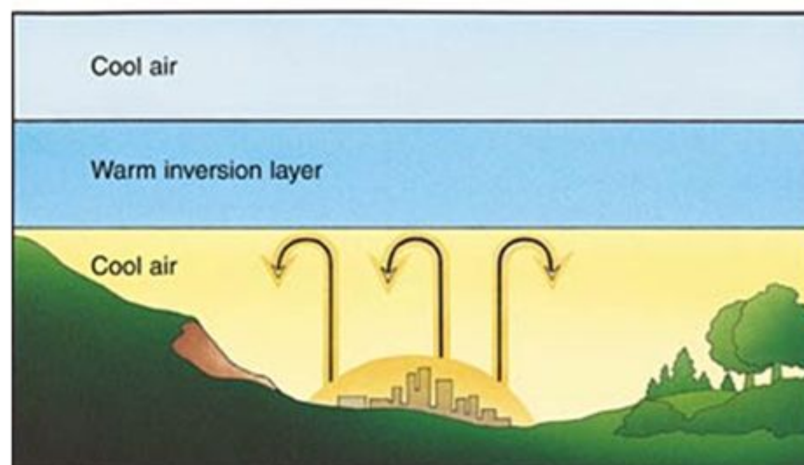
Fig. 2.13. Schematic representation of the generation of turbulence in the atmosphere by different obstacles. The amplitude of the temperature fluctuations depends on the amplitude of the turbulence and on the deviation of the actual temperature gradient from the adiabatic gradient. The scales L_1, L_2, L_3 are characteristic of the external scales of turbulence caused by wind around the obstacles 1, 2 and 3

Other atmospheric factors: **inversion layer**

- Important factor to choose an astronomical site
- Inversion layer ~ 2km, but could occur at lower *z*



Normal pattern

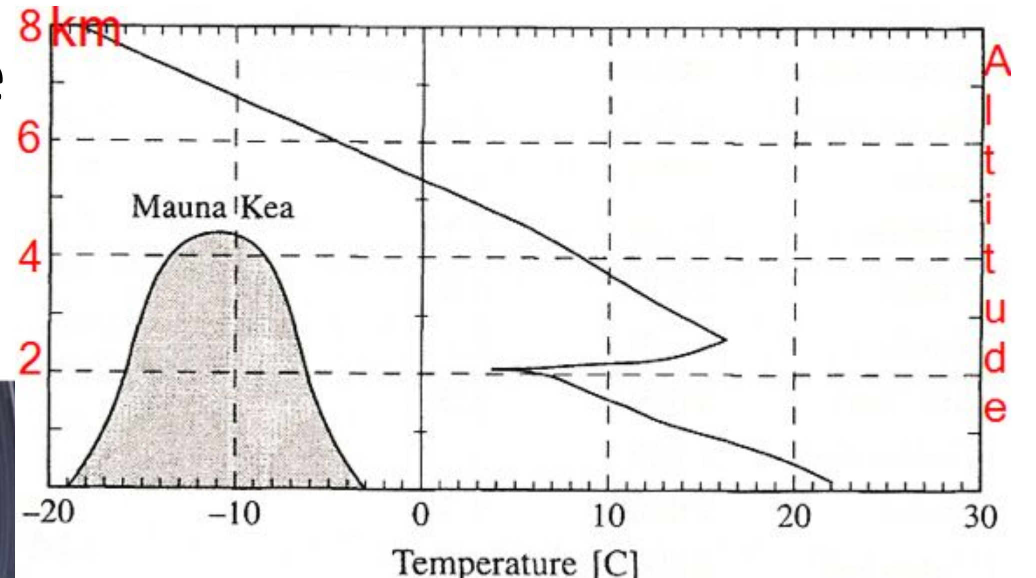


Thermal inversion

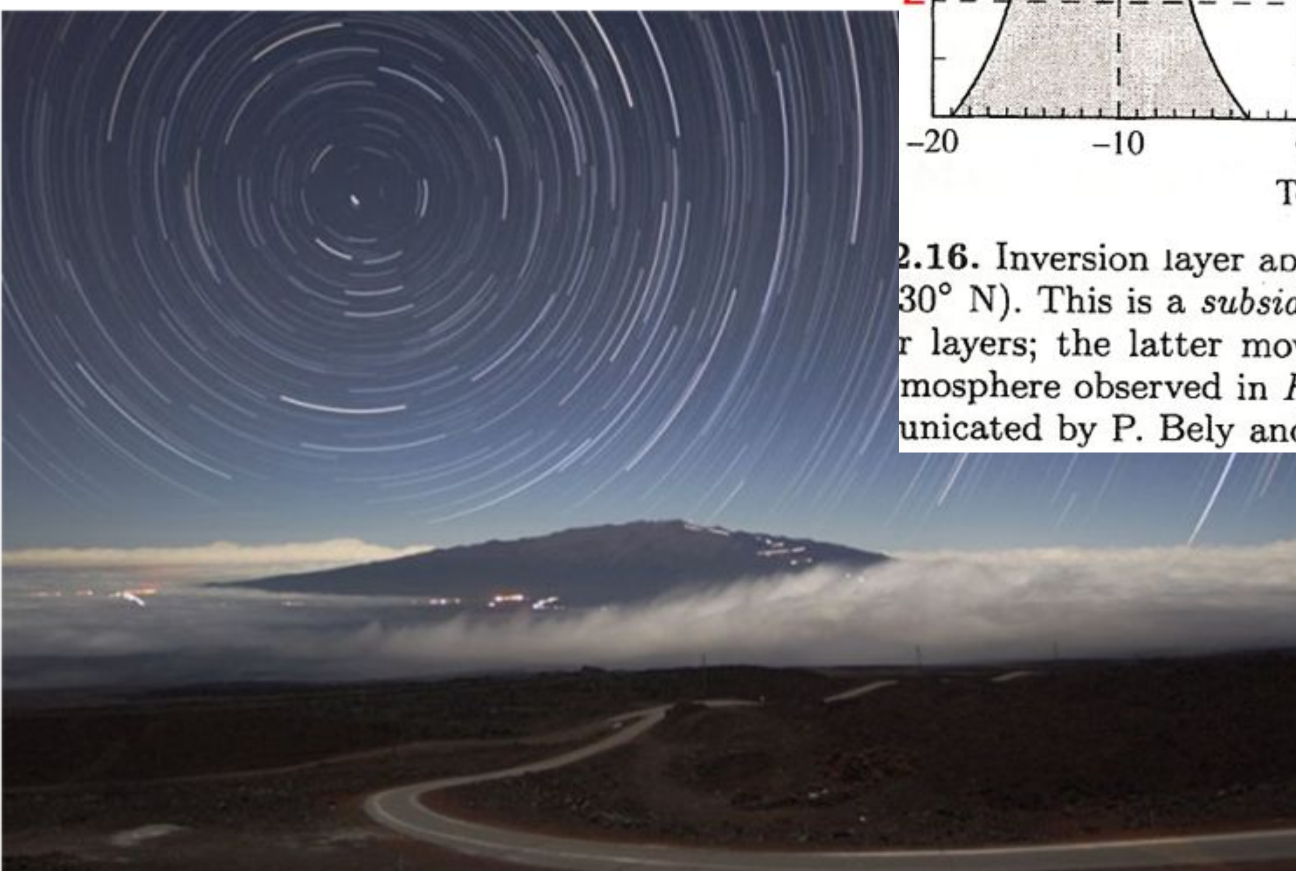
São Paulo, 6af, 23 maio 2008, 08h30m *www.estadao.com.br*

Inversion layer

Inversion layer above the pacific ocean around the Big Island of Hawaii



2.16. Inversion layer above the Pacific Ocean, near the isla
30° N). This is a *subsidence inversion*, caused by reheatin
r layers; the latter movement itself is caused by the gen
mosphere observed in *Hadley cells*. (Sounding balloon mea
unicated by P. Bely and the Hilo Weather Bureau, Hawaii



www.gemini.edu

High altitude → less clouds

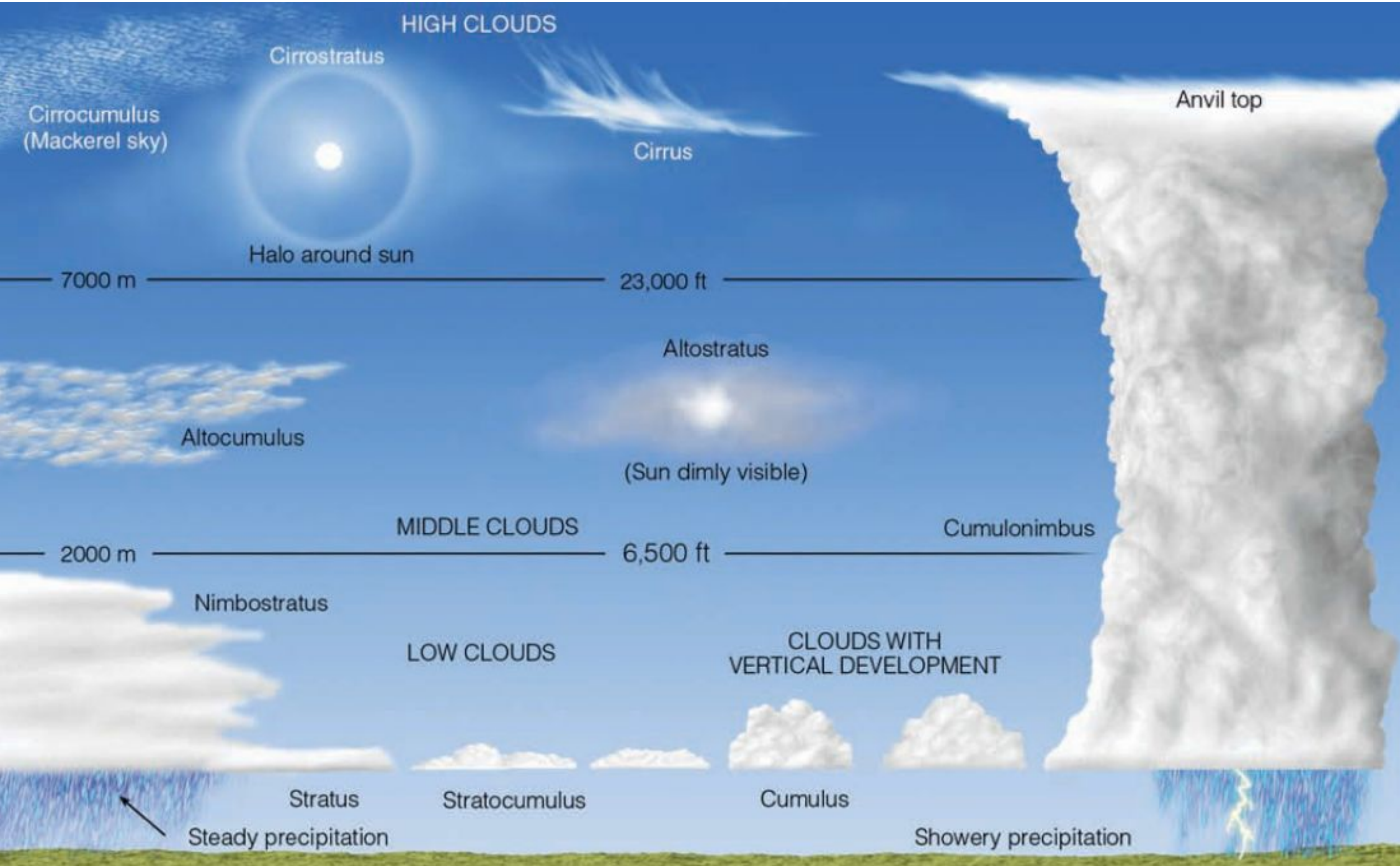
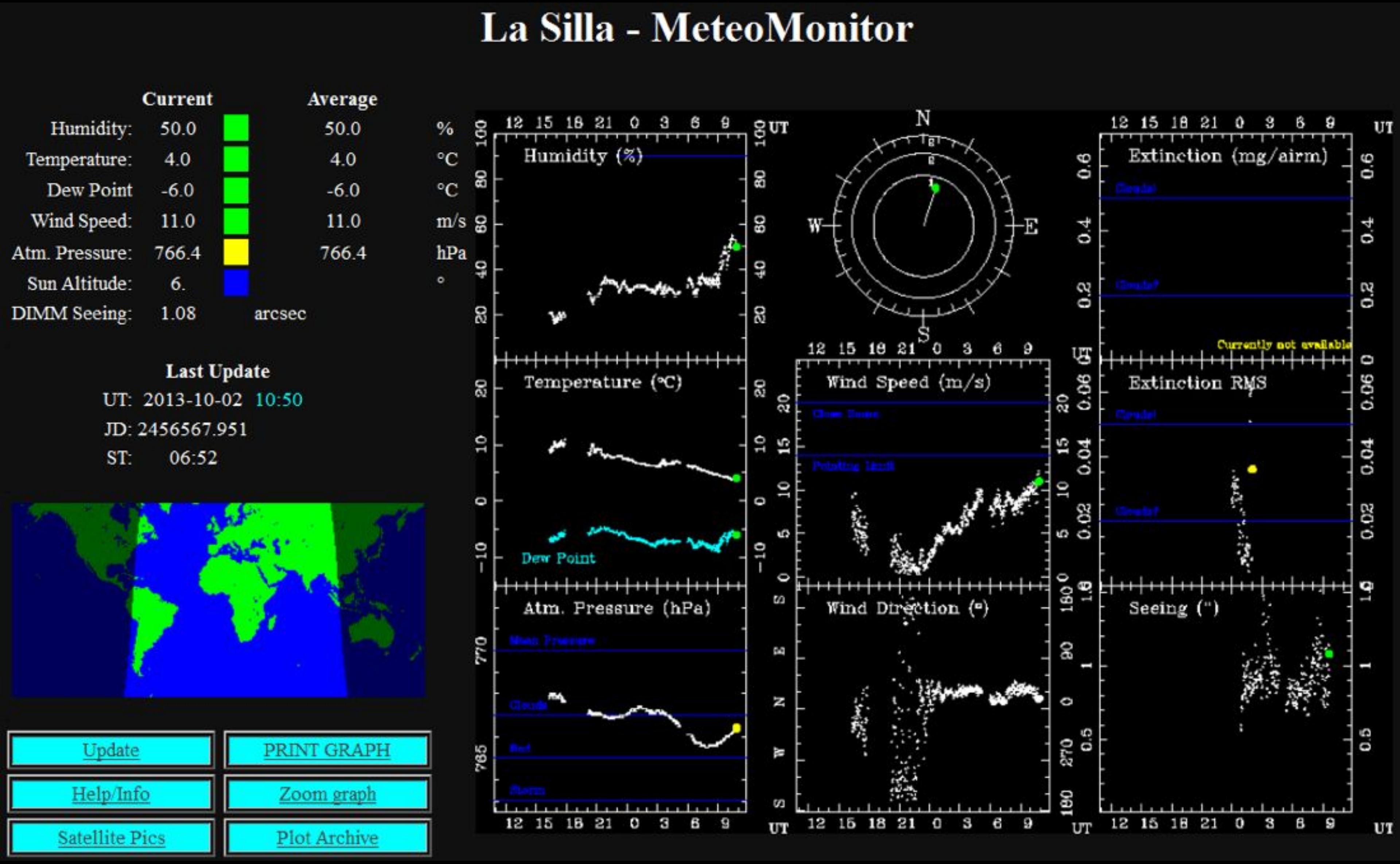


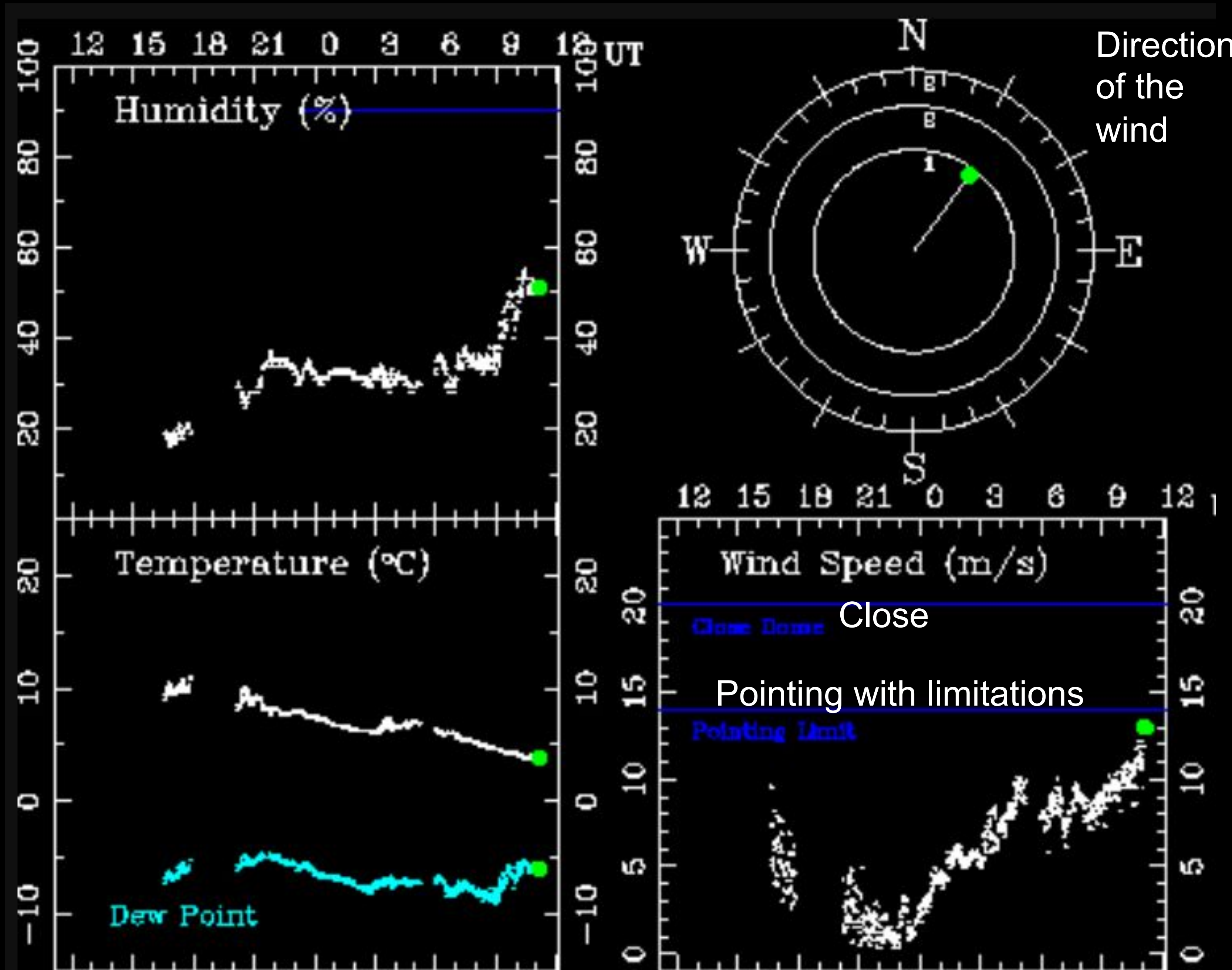
FIGURE 5.24 A generalized illustration of basic cloud types based on height above the surface and vertical development

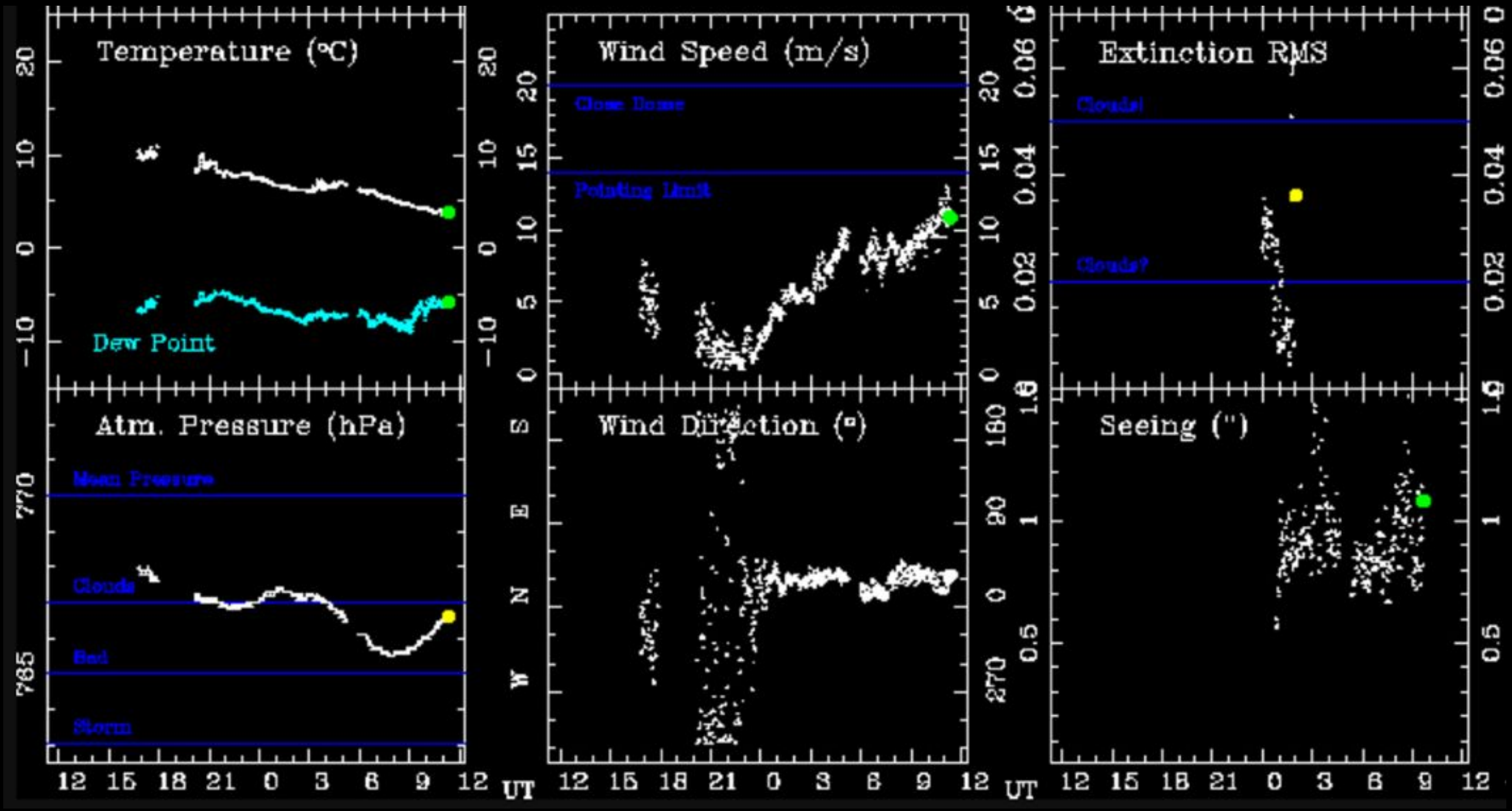
Meteorological conditions at La Silla (Chile)

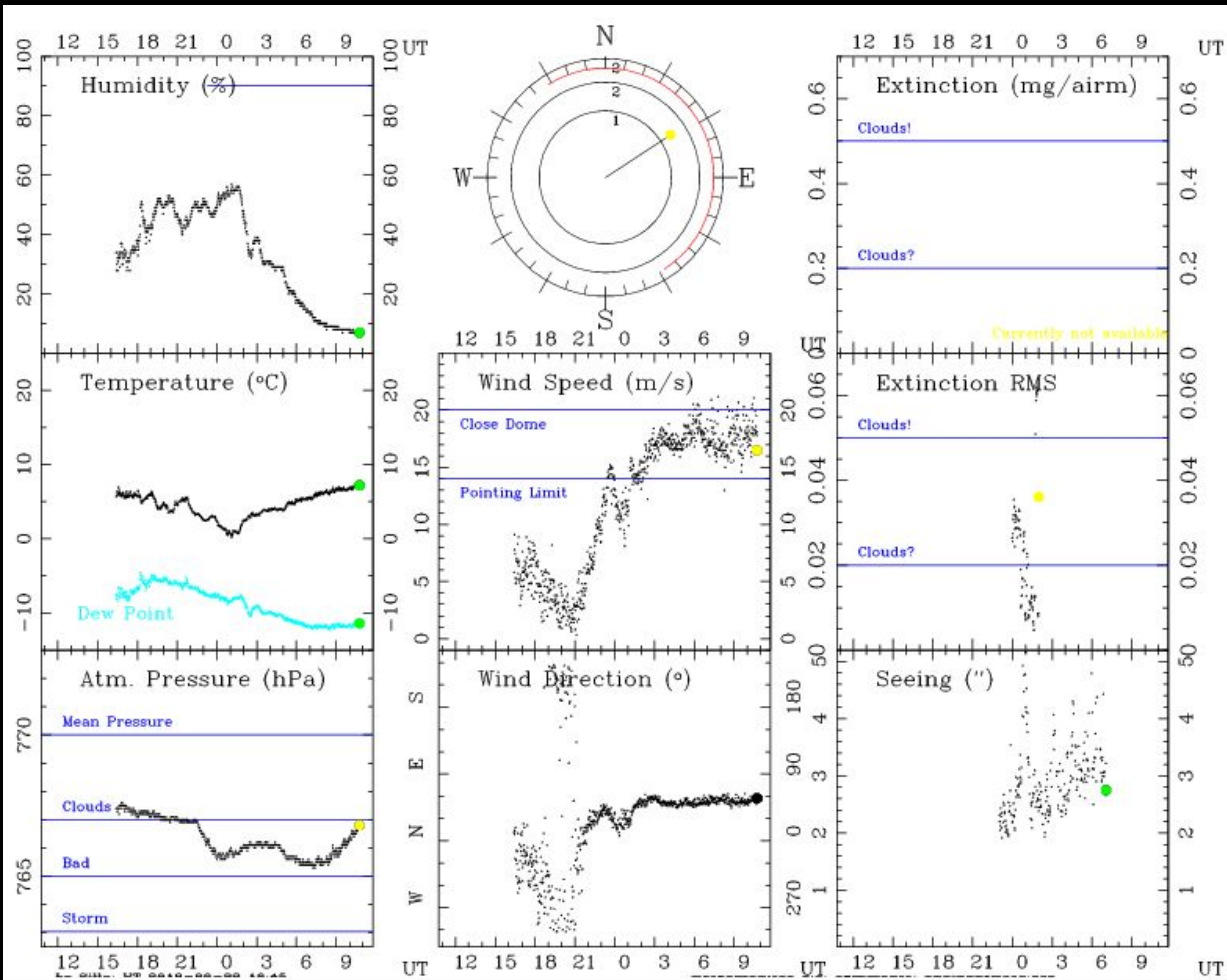
1/10/2013



La Silla - MeteoMonitor
Current
Average
Humidity: 50.0 50.0 %
Temperature: 4.0 4.0 °C
Dew Point -6.0 -6.0 °C
Wind Speed: 11.0 11.0 m/s
Atm. Pressure: 766.4 766.4 hPa
Sun Altitude: 6. °
DIMM Seeing: 1.08 arcsec
Last Update
UT: 2013-10-02 10:50
JD: 2456567.951
ST: 06:52
Update
PRINT GRAPH
Help/Info
Zoom graph
Satellite Pics
Plot Archive
Humidity (%)
Temperature (°C)
Dew Point
Atm. Pressure (hPa)
Wind Speed (m/s)
Wind Direction (°)
Extinction (mg/airm)
Extinction RMS
Seeing (")
Currently not available
N
S
E
W
UT


Direction of the wind
Close
Pointing with limitations
Humidity (%)
Temperature (°C)
Dew Point
Wind Speed (m/s)
Close Dome
Pointing Limit
UT
N
W
E
S
12 15 18 21 0 3 6 9 12


Temperature (°C)
Dew Point
Wind Speed (m/s)
Close Dome
Pointing Limit
Extinction RMS
Clouds!
Clouds?
Atm. Pressure (hPa)
Mean Pressure
Clouds
Bad
Storm
Wind Direction (°)
Seeing (")
UT



Humidity (%)
Temperature (°C)
Dew Point
Atm. Pressure (hPa)
Mean Pressure
Clouds
Bad
Storm
N
E
S
W
Wind Speed (m/s)
Close Dome
Pointing Limit
Wind Direction (°)
Extinction (mg/airm)
Clouds!
Clouds?
Currently not available
Extinction RMS
Clouds!
Clouds?
Seeing (")
UT

Dome-Closing Conditions at ESO LaSilla

Wind Speed Monitor Light Codes

Lights	Speed (m/sec)	Action By Observer
	< 14 m/s	
	< 14-20 m/s	Don't observe into the wind
	> 20 m/s (18 m/s for 3,6m)	: DOME: Don'wait to be told!

Humidity. General humidity sensors are installed on the weather tower; their readings are relayed on the MeteoMonitor . Domes have to be closed when the relative humidity exceeds 80% (was 90%), and can be re-opened when it remains below 70% for 30min. Similarly, the domes must be closed when the temperature difference between the coldest part of the telescope and the dew point drops below 2 degress.

https://www.eso.org/sci/facilities/lasilla/sciops/At_Telescope.html

Hawaii

Hawaii, 18/8/2013

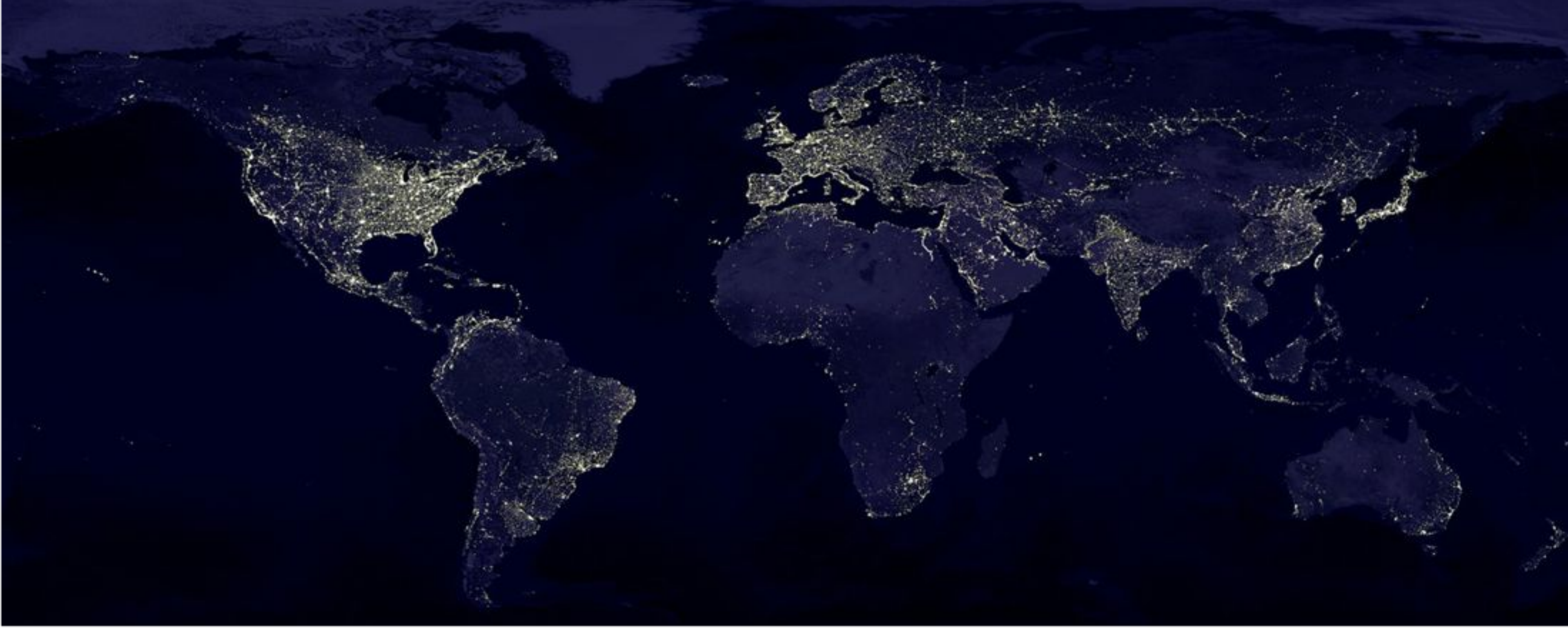
Mauna Kea Weather conditions

Current Conditions

Temp	1.9 C
RH	60 %
Wind	W 7 mph
Road	Open

Observations

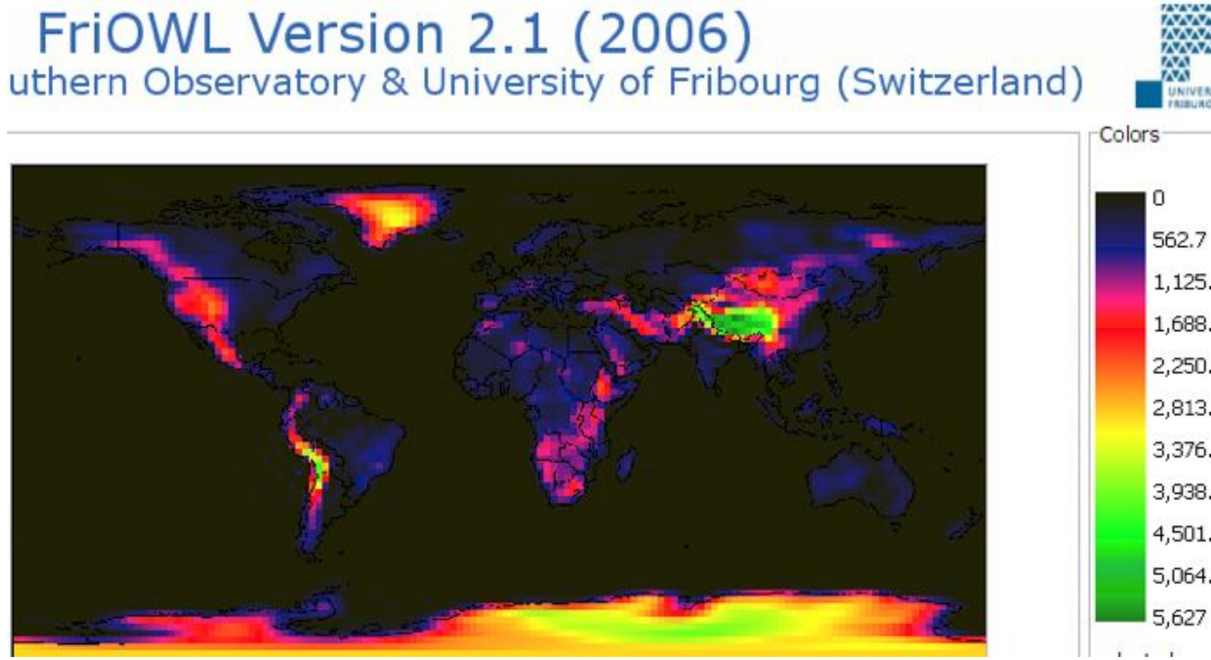
STN	DATE HST	TIME HST	TEMP °C	DPNT °C	RH %	WSPD mph	PK WSPD mph	WDIR dir	PRES mb	RAIN mm	PW mm	Seeing arcsec	Trends
CFHT/GEM	10/02/13	01:31	1.9	-5.1	60	7	11	W	617	0.00		0.50	Meteogram
UKIRT	10/02/13	01:27	1.9	-5.8	57	5		NW	615				Meteogram
IRTF	10/02/13	01:28	0.0	-5.4	57	6	7	NW					Meteogram
SUBARU	10/02/13	01:28	0.8	-4.9	66	2	4	WNW	621	0			Meteogram
KECK	10/02/13	01:30	2.1	-5.9	56				620				
JCMT	10/02/13	01:26	2.5	-5.5	56	4		N	625		3.16		Meteogram
CSO	10/02/13	01:30	9.3	-3.6	40	0	0	N	626		3.45		Tau
SMA	10/02/13	01:17	3.4	-3.6	60	3		ENE	624	0.0			Trend
VLBA	10/02/13	01:26	5.2	-8.9	36	4	7	NNW	654	0			Meteogram
HP	10/02/13	01:30	9.3	1.3	57	7	8	WNW	727	0			Meteogram
UNITS	UTC | HST		°C | K | F		%	mph | Kts | mps		dir	mb	mm	Tau | mm	arcsec	



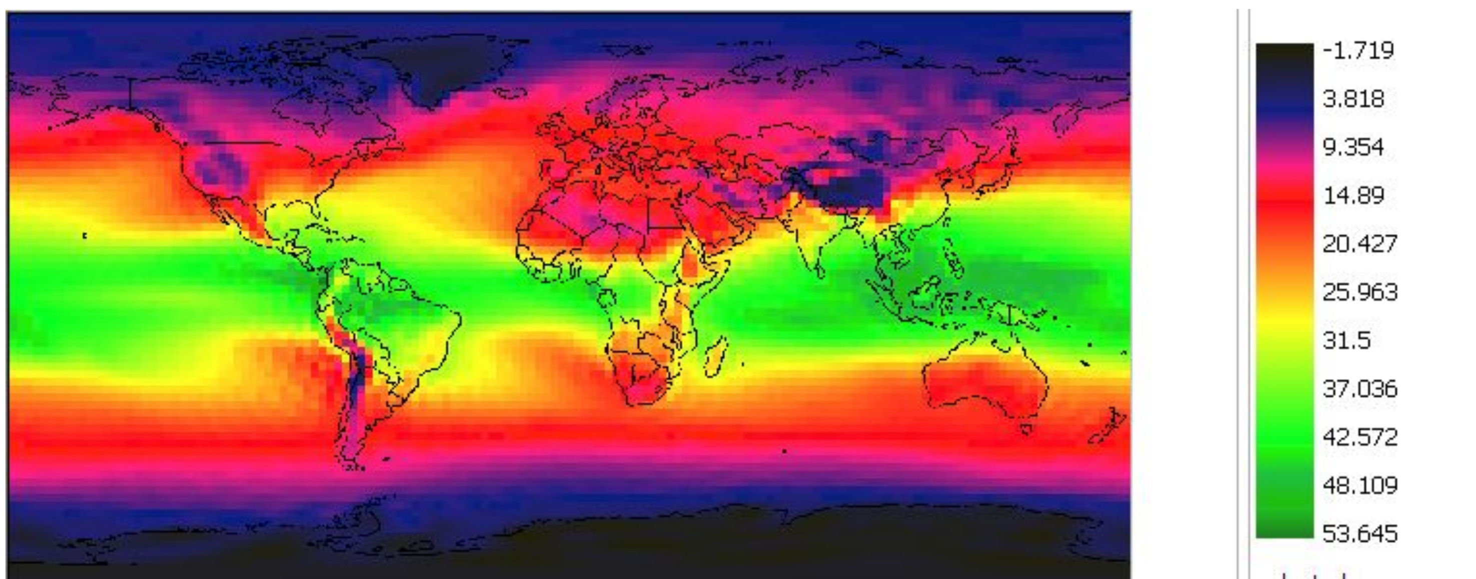
Choosing an astronomical site

- No clouds (related to inversion layer)
- Photometric quality (atmospheric transparence)
- Transparence in the infrared & mm (atmospheric H_2O)
- Image quality (related to variations in temperature and the air refraction index)

Choosing an astronomical site



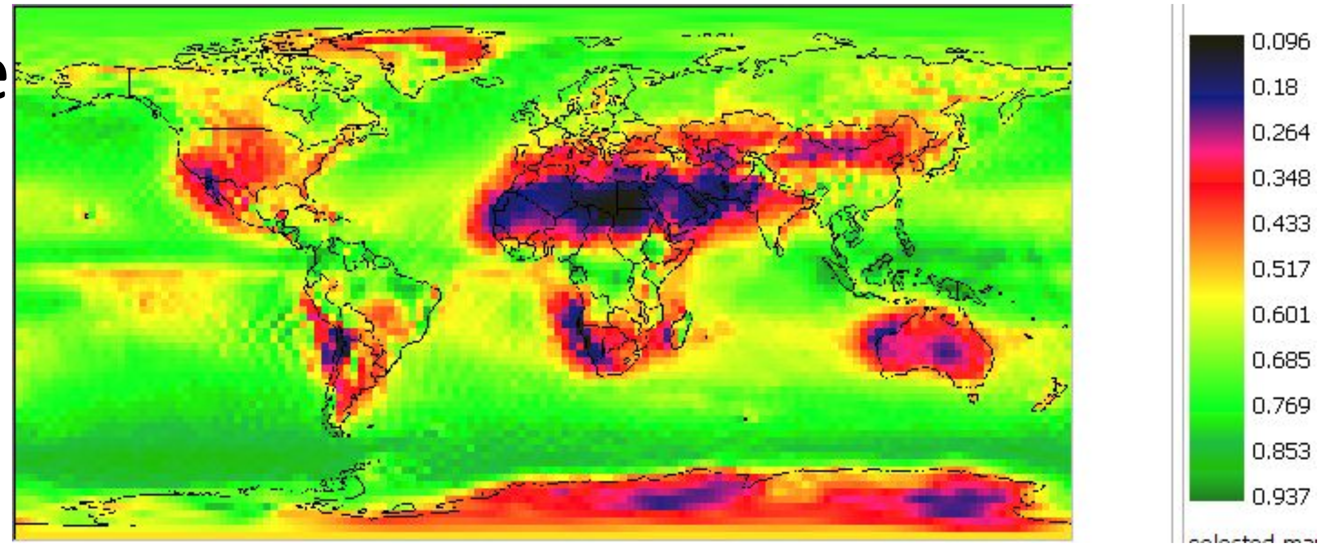
Altitude



precipitable H_2O

Choosing an astronomical site

Cloud coverage



BEST SITES

High summits + low cloudiness + low precipitable water vapor