Satellite meteorology

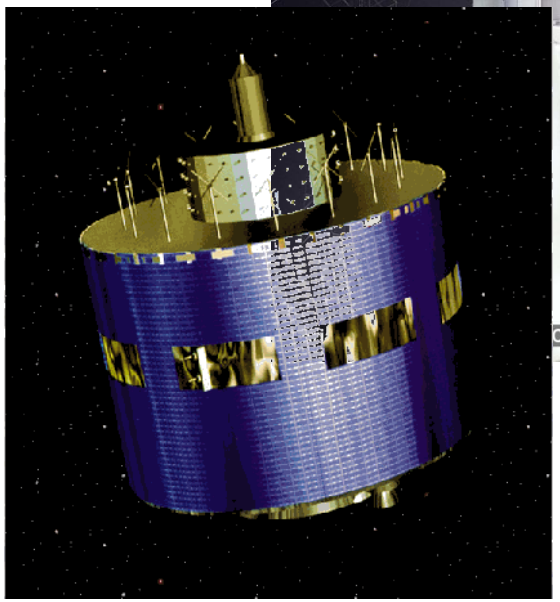
Part 1

Textbooks and web sites references for this lecture:

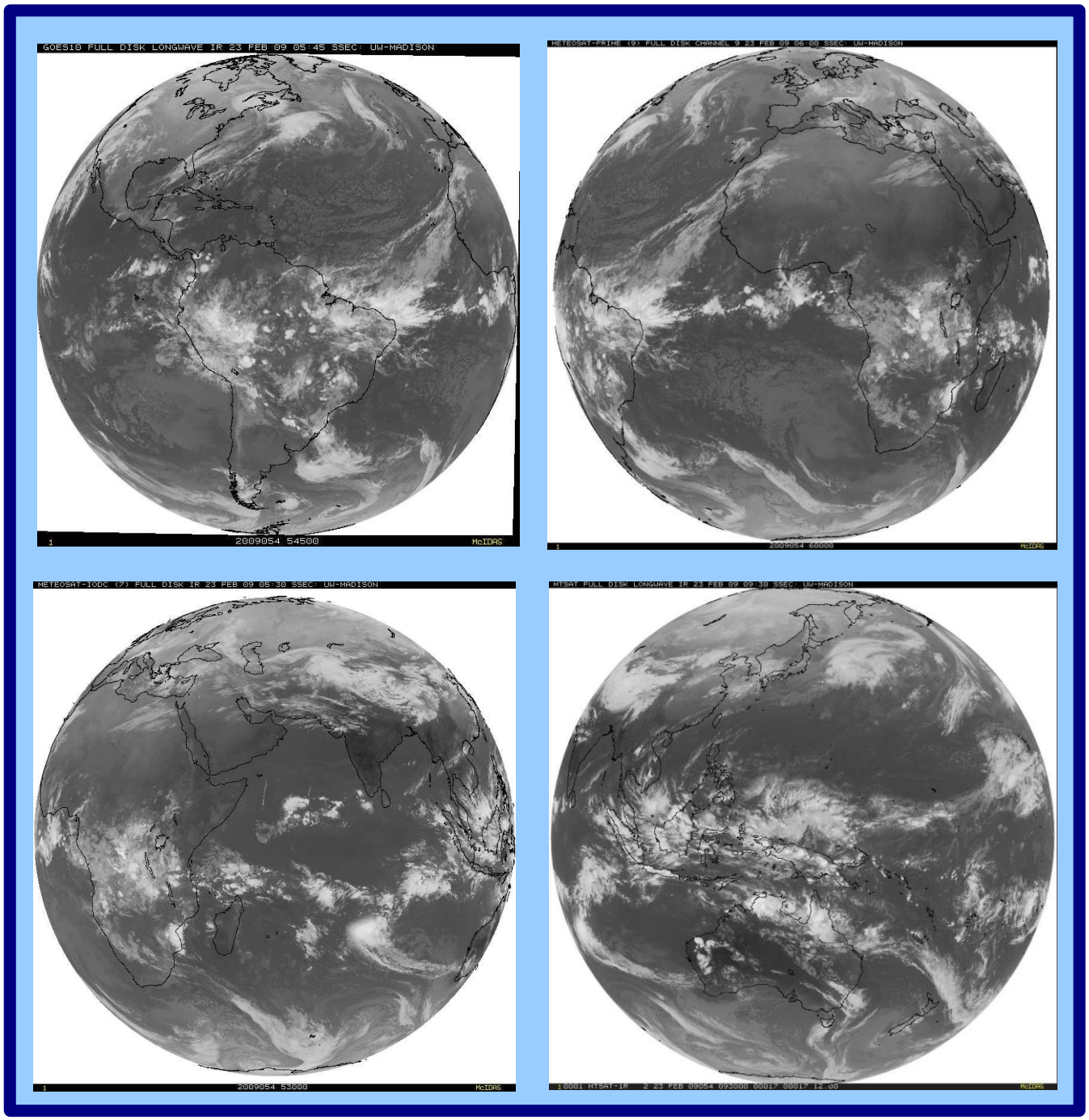
- Stanley Q. Kidder, Thomas H. Vonder Haar (Author) Satellite Meteorology: An Introduction, 1995, ISBN-13: 978-0124064300, Academic Press
- Manual of satellite meteorology (ZAMG): http://www.zamg.ac.at/docu/Manual/SatManu/main.htm

Definizioni

The Webster dictionary defines a satellite as a man-made object put into orbit around a celestial body, like the earth or the moon. Satellites serve a wide variety of purposes from transmission of television signals via communication satellites to guidance and tracking systems of defense satellites. For meteorologists, satellites provide a comprehensive view of the world's weather by observing weather and the environment on a scale not possible by other means.



I satelliti meteorologici permettono di sapere che tempo fa sull'intero globo terrestre. Inoltre si possono ricavare informazioni utili, ad esempio, sulla copertura nevosa del suolo, sulla temperatura del mare, sull'altezza e la temperatura delle nubi, sulla presenza di incendi, etc..



Campi di applicazione

- Atmospheric Vertical Moisture Profile
- Atmospheric Vertical Temp Profile
- Imagery
- Sea Surface Temperature
- Sea Surface Winds
- Soil Moisture
- Aerosol Optical Thickness
- Aerosol Particle Size
- Albedo (Surface)
- Auroral Boundary
- Auroral Imagery
- Cloud Base Height
- Cloud Cover/Layers
- Cloud Effective Particle Size
- Cloud Ice Water Path
- Cloud Liquid Water
- Cloud Optical Depth/Transmittance
- Cloud Top Height
- Cloud Top Pressure
- Cloud Top Temperature
- Currents (Ocean)
- Downward Longwave Radiance (Sfc)
- Electric Fields
- Electron Density Profile
- Fresh Water Ice
- Geomagnetic Field
- Ice Surface Temperature
- Energetic Ions
- In-situ Plasma Fluctuations
- In-situ Plasma Temperature
- Insolation
- Medium Energy Charged Particles
- Ionospheric Scintillation
- Land Surface Temperature
- Littoral Sediment Transport
- Net Heat Flux
- Net Short Wave Radiance (TOA)
- Neutral Density Profile
- Neutral Winds
- Normalized Difference Vegetation Index
- Ocean Color/Chlorophyll
- Ocean Wave Characteristics
- Ozone - Total Column/Profile
- Precipitable Water
- Precipitation Type/Rate
- Pressure (Surface/Profile)
- Sea Ice Age and Edge Motion
- Sea Surface Height/Topography
- Snow Cover/Depth
- Solar Irradiance
- Supra-Thermal - Auroral Particles
- Surface Wind Stress
- Suspended Matter
- Total Auroral Energy Deposition
- Total Longwave Radiance (TOA)
- Total Water Content
- Turbidity
- Vegetation Index/Surface Type

Atmospheric | Oceanic | Terrestrial | Space | Climate

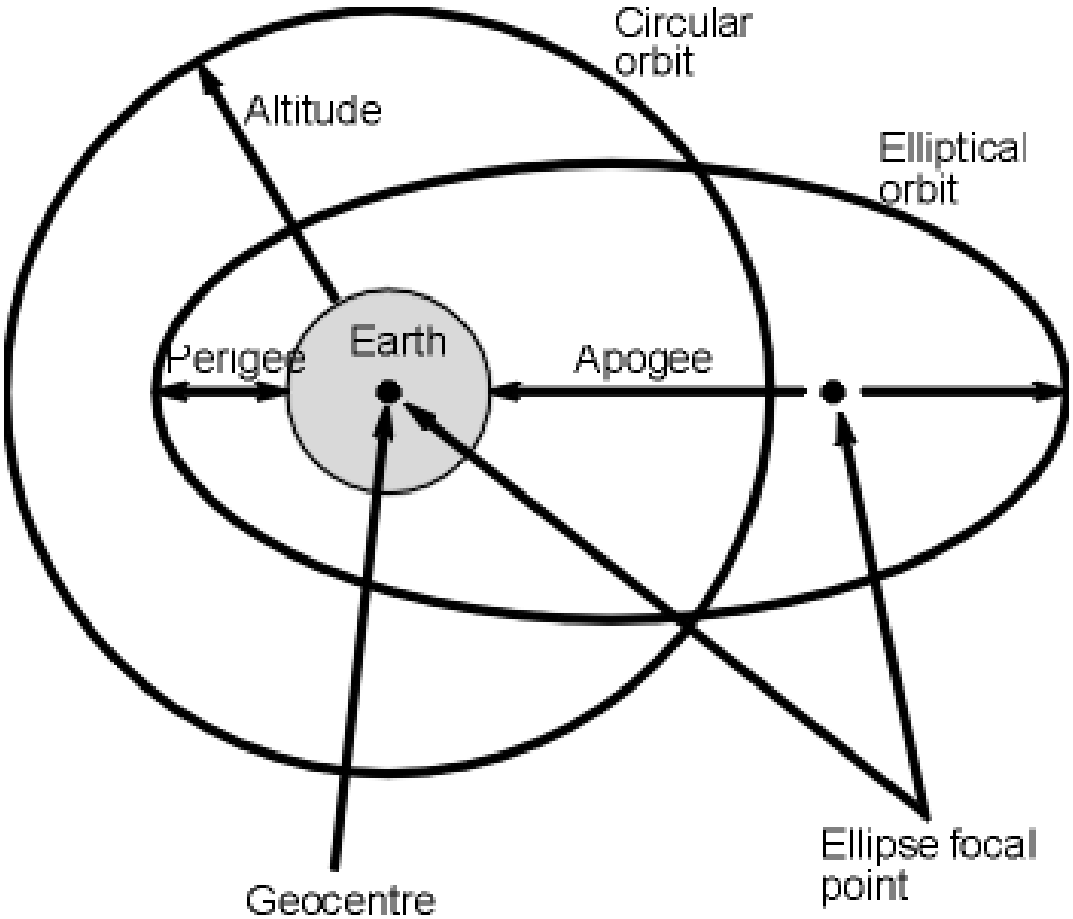
Geostationary satellites

$$\frac{mv^2}{r} = G\,m\frac{m_e}{r^2}$$

$$T^2 = 4\pi^2 / G m_e r^3$$

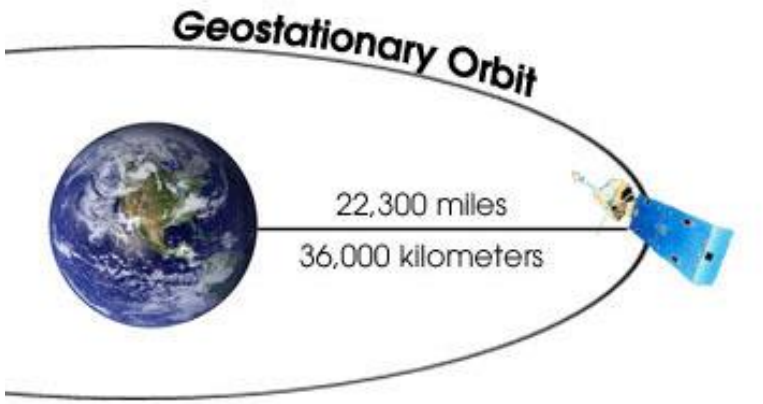
$$\xi = 2\pi / T^2$$

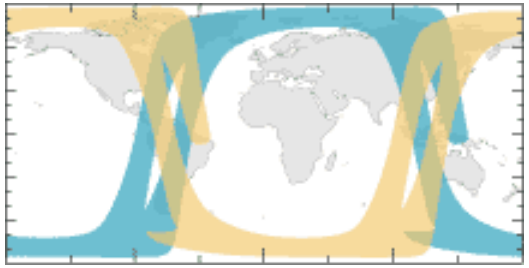
$$r = \sqrt[3]{G m_e / \xi^2} = 35{,}786\,km$$

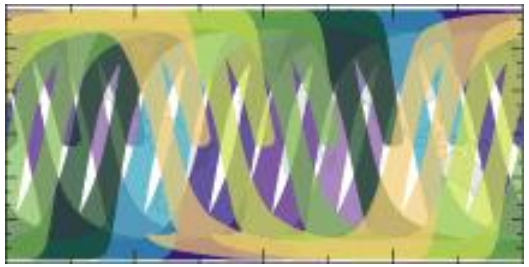


Le orbite

I satelliti possono essere **geostazionari**, fermi su un orbita a 36000 km. L'orbita "**polare"** è più bassa, ma il satellite per mantenerla deve avere una velocità non nulla: sono necessarie 12 ore per avere osservazioni su tutto il globo



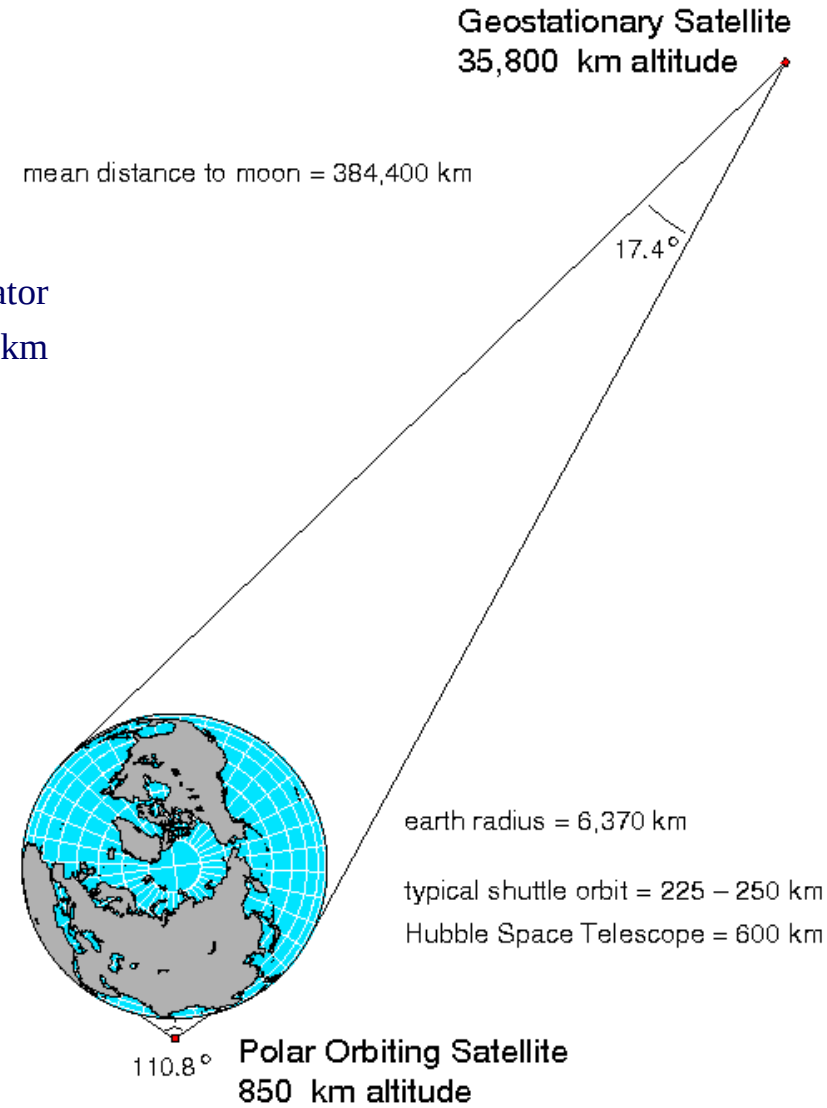




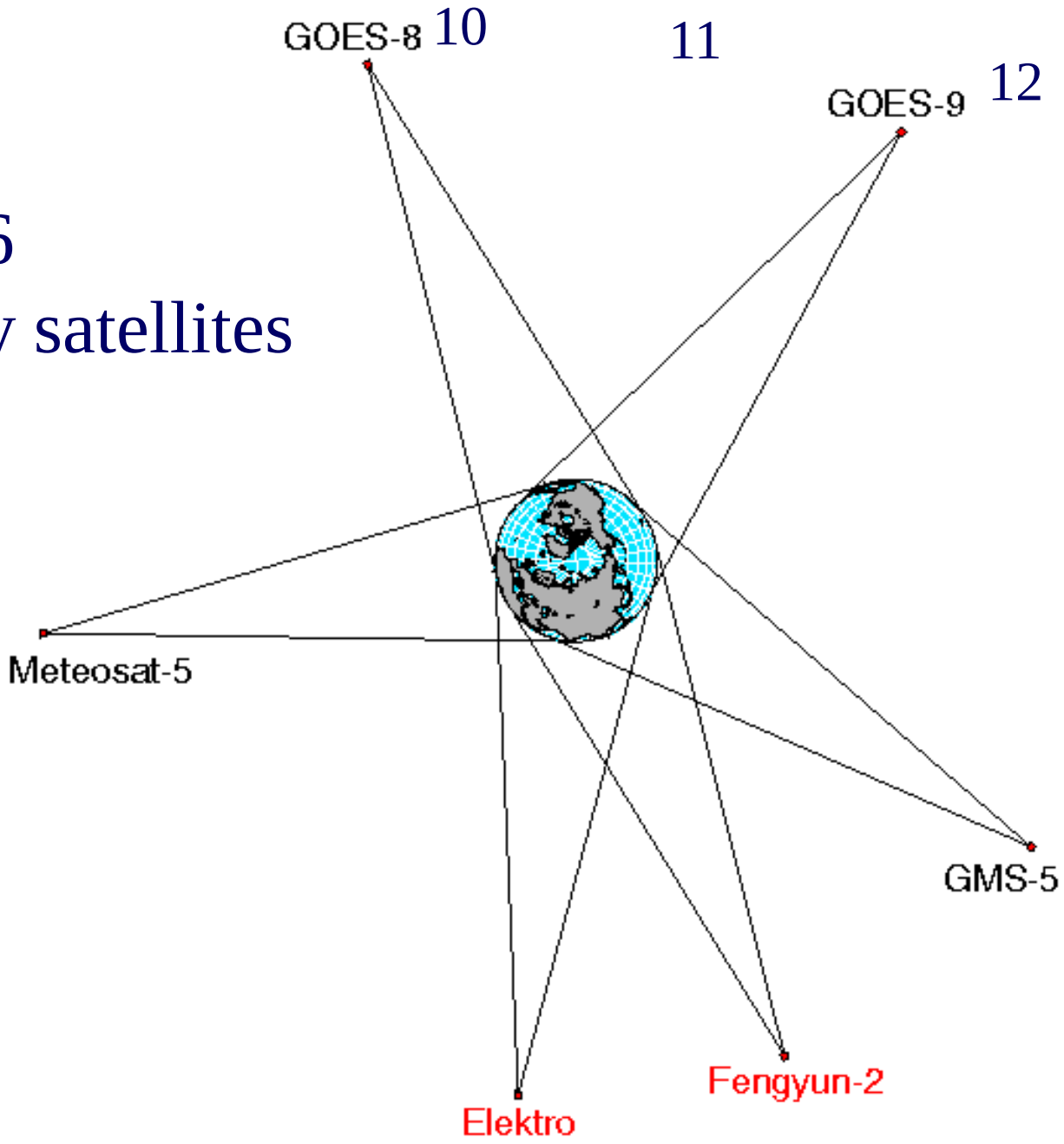
Geostationary vs polar-orbiting satellites

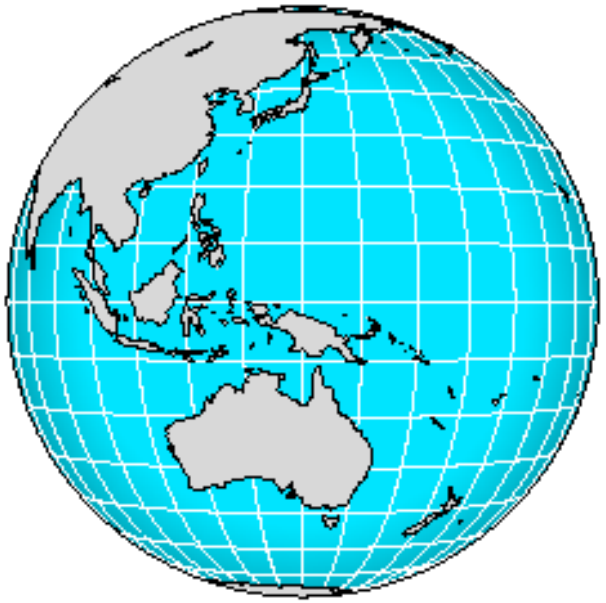
http://www.rap.ucar.edu/~djohnson/satellite/coverage.html

- Geostationary
  - same location wrt earth
  - rotation rate $\Omega = 2\pi/(24 \text{ hrs})$
  - axis of rotation identical as Earth's → positioned above equator
  - path radius R : $g(R_o/R)^2 = \Omega^2 R$ or R = 41,525 km, ie 35,150 km above the earth (almost 6 earth radii)
  - 1 km resolution = 0.00003°
  - 5-6 satellites monitor the globe continuously

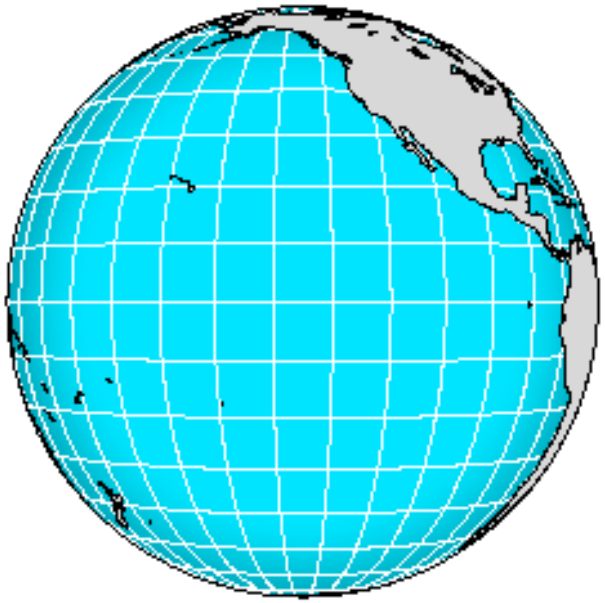


Location of 6 geostationary satellites





140° E GMS-5

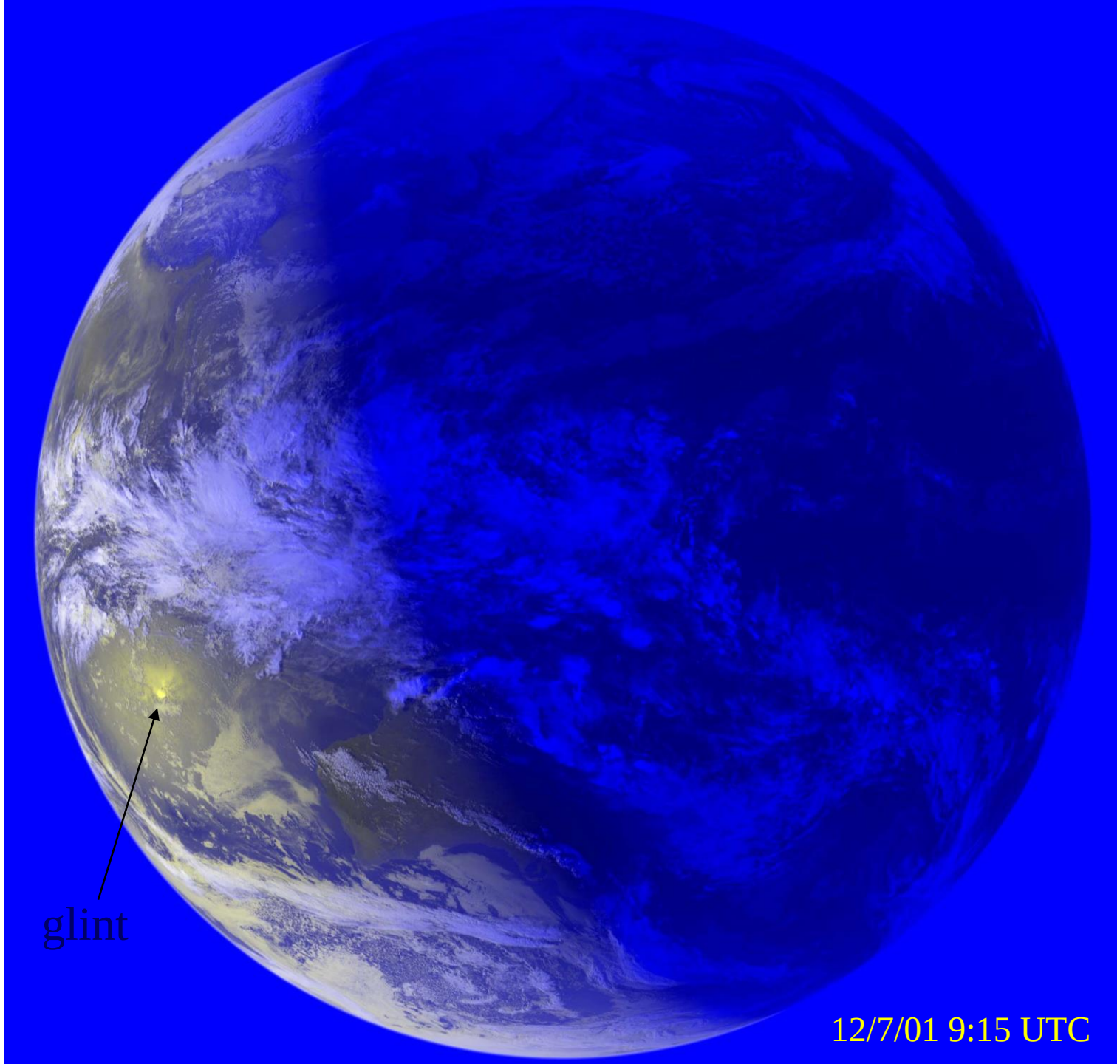


135° W GOES–9

75° W GOES-8

0° Meteosat-5

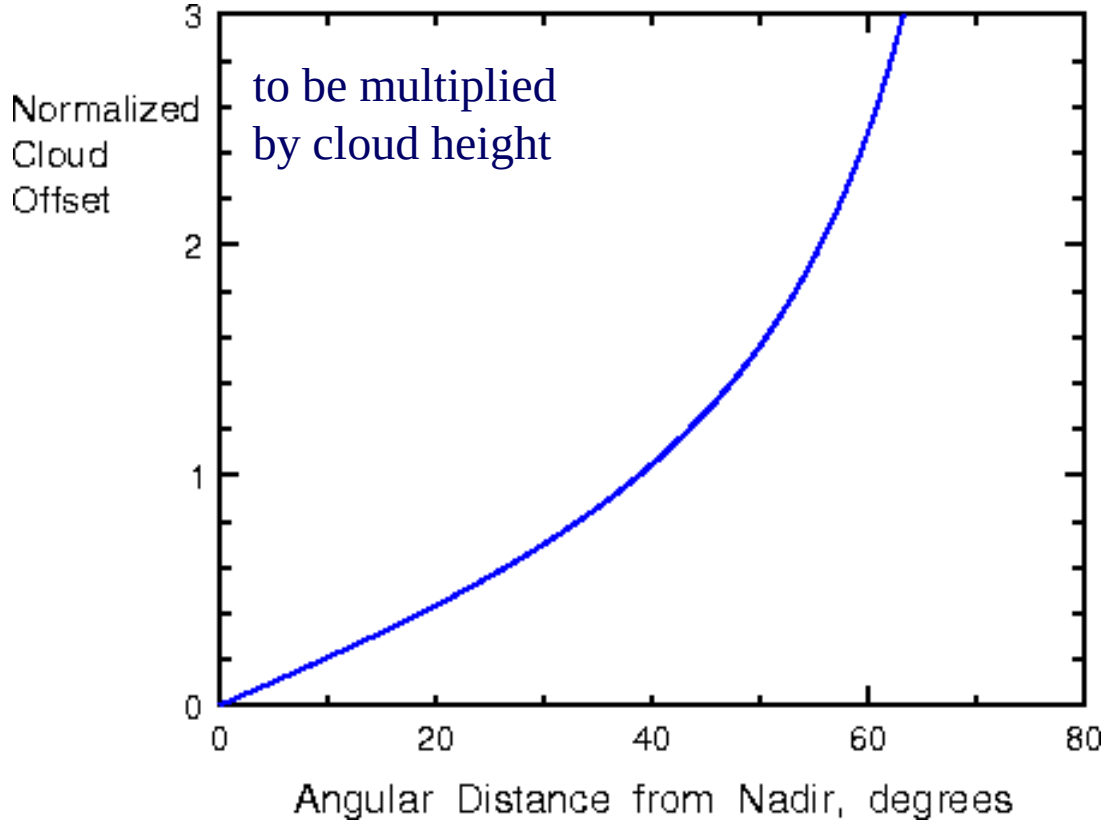
GMS



Geostationary satellites

- Advantage: continuous coverage
- Drawback: resolution decreases with cos(lat)

Cloud parallax displacement



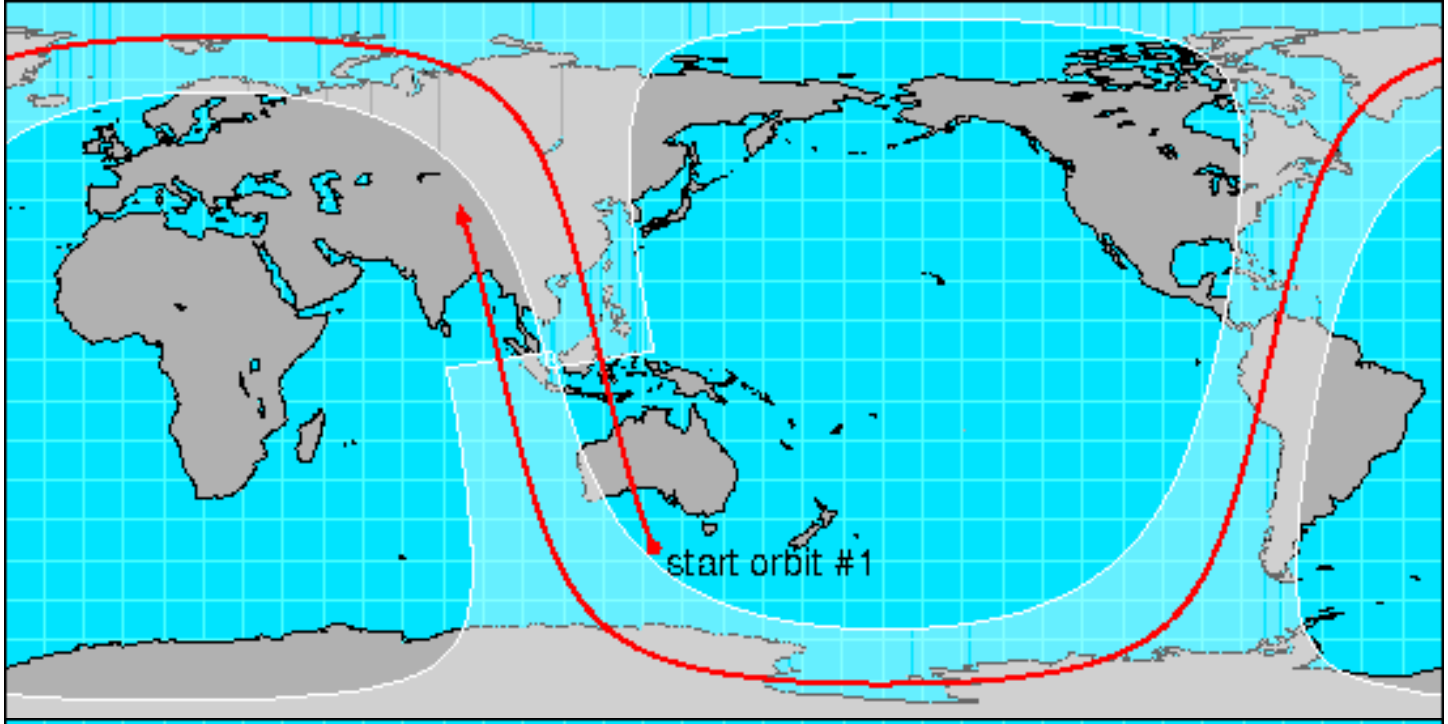
Polar-orbiting satellites

- Orbits can be either sun-synchronous (NOAA POES, DMSP, Aqua, Terra) or not (TRMM …)

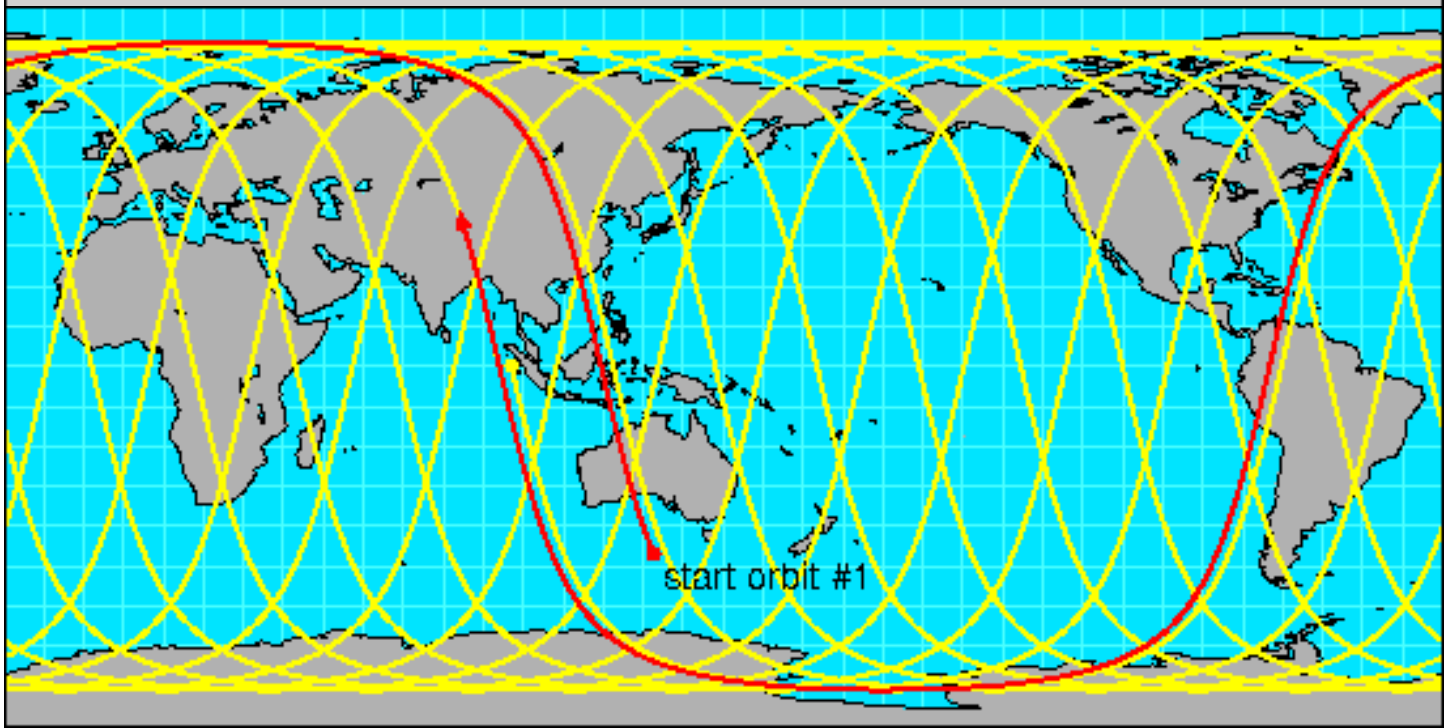
- Sun-synchronous POS altitudes usually range from 800 to 900 km, with orbital periods of 98 to 102 minutes.

- Sun-asynchronous POS altitudes are lower

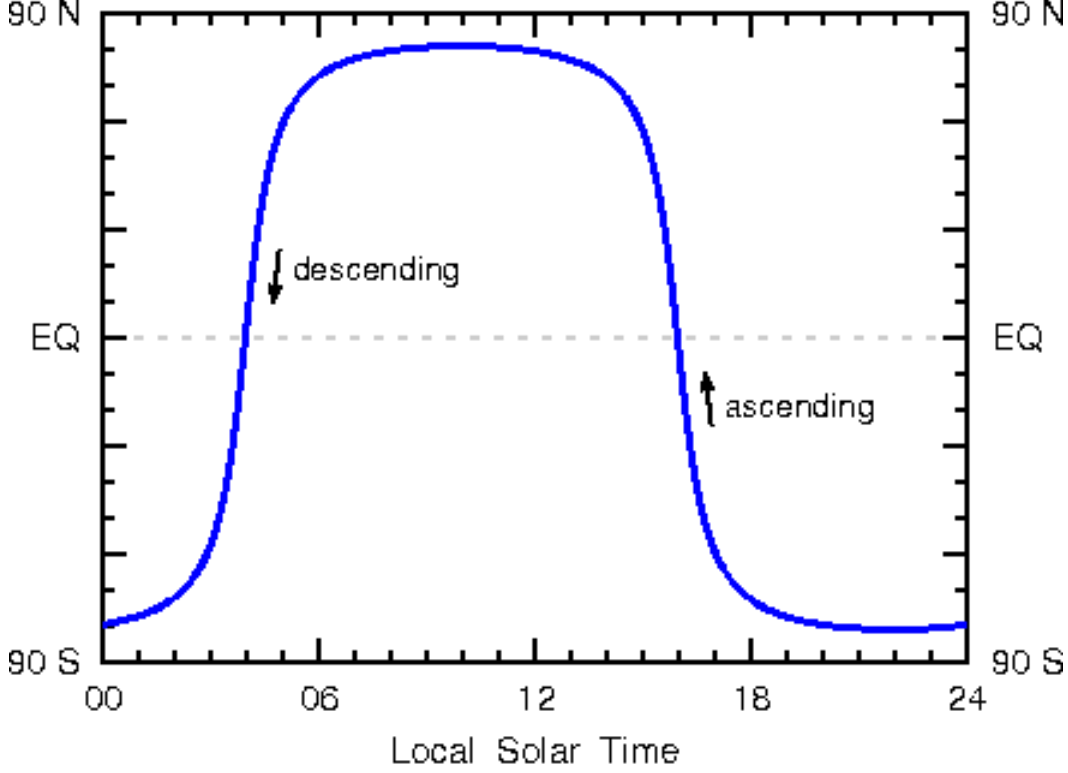
POES orbits



Swath width ~3000 km
displacement from one orbit to next: 24 degrees

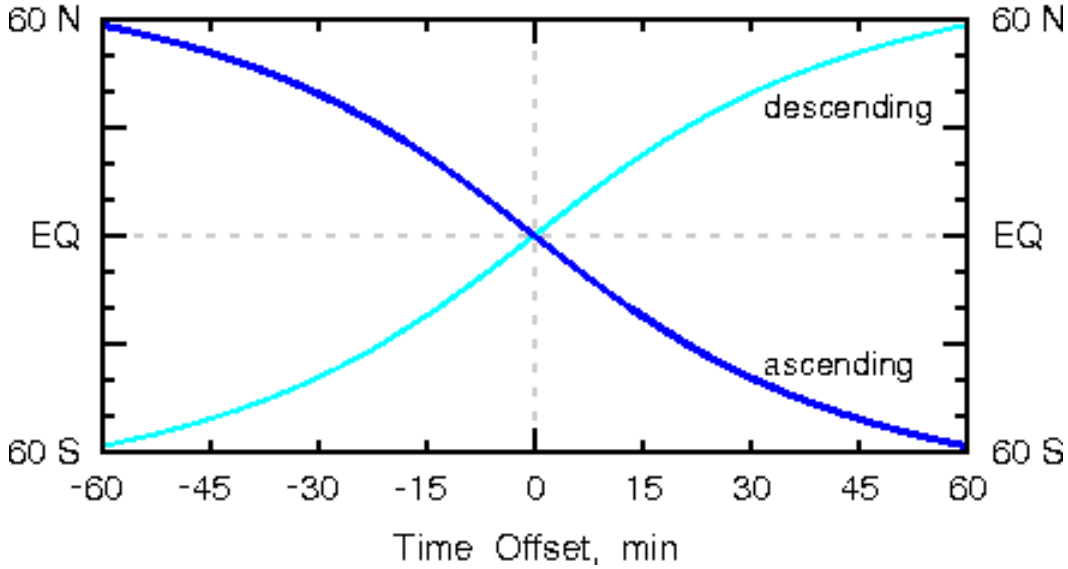


15 orbits
360/15 = 24 hrs!
→ two overpasses daily

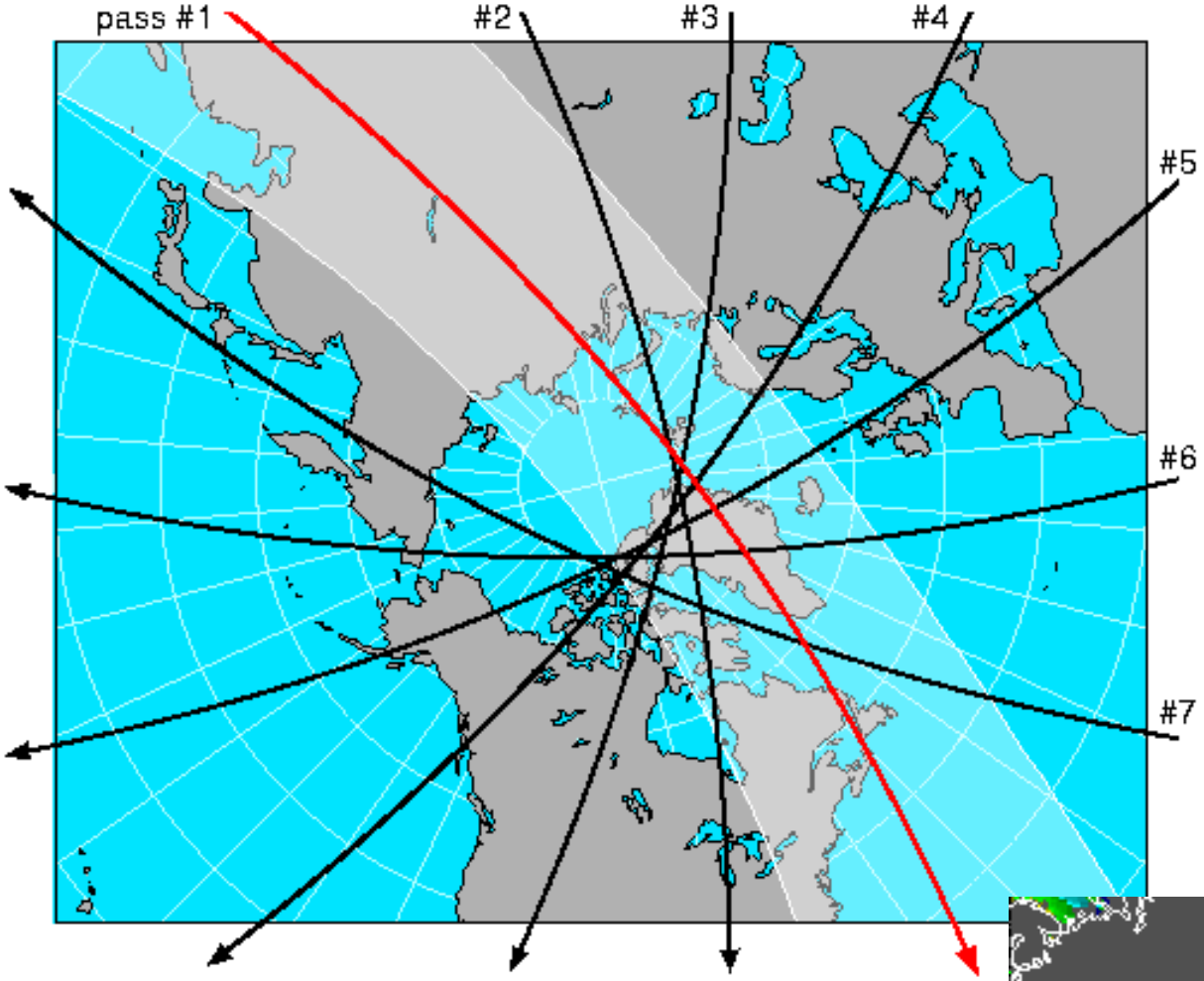


POES orbits

Sun-synchronous

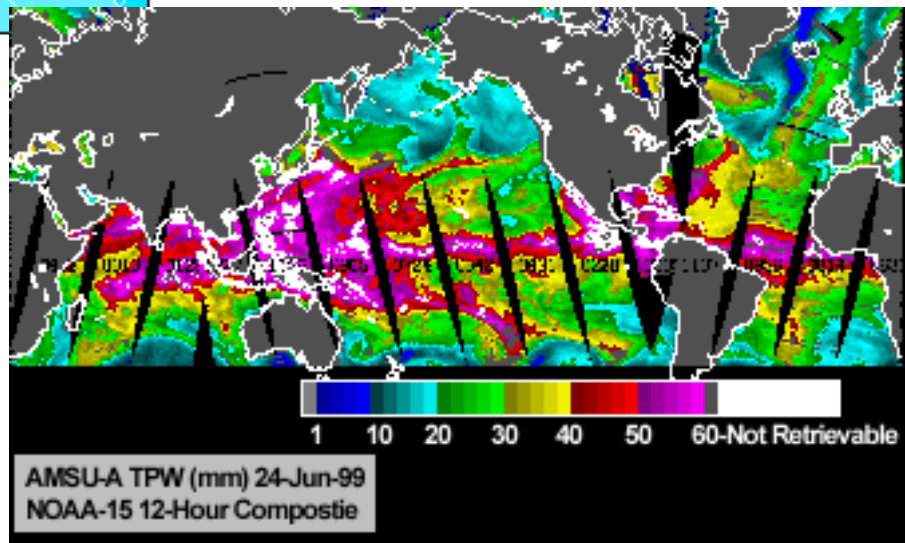


Time-offset from nominal time, which is fixed at the equator

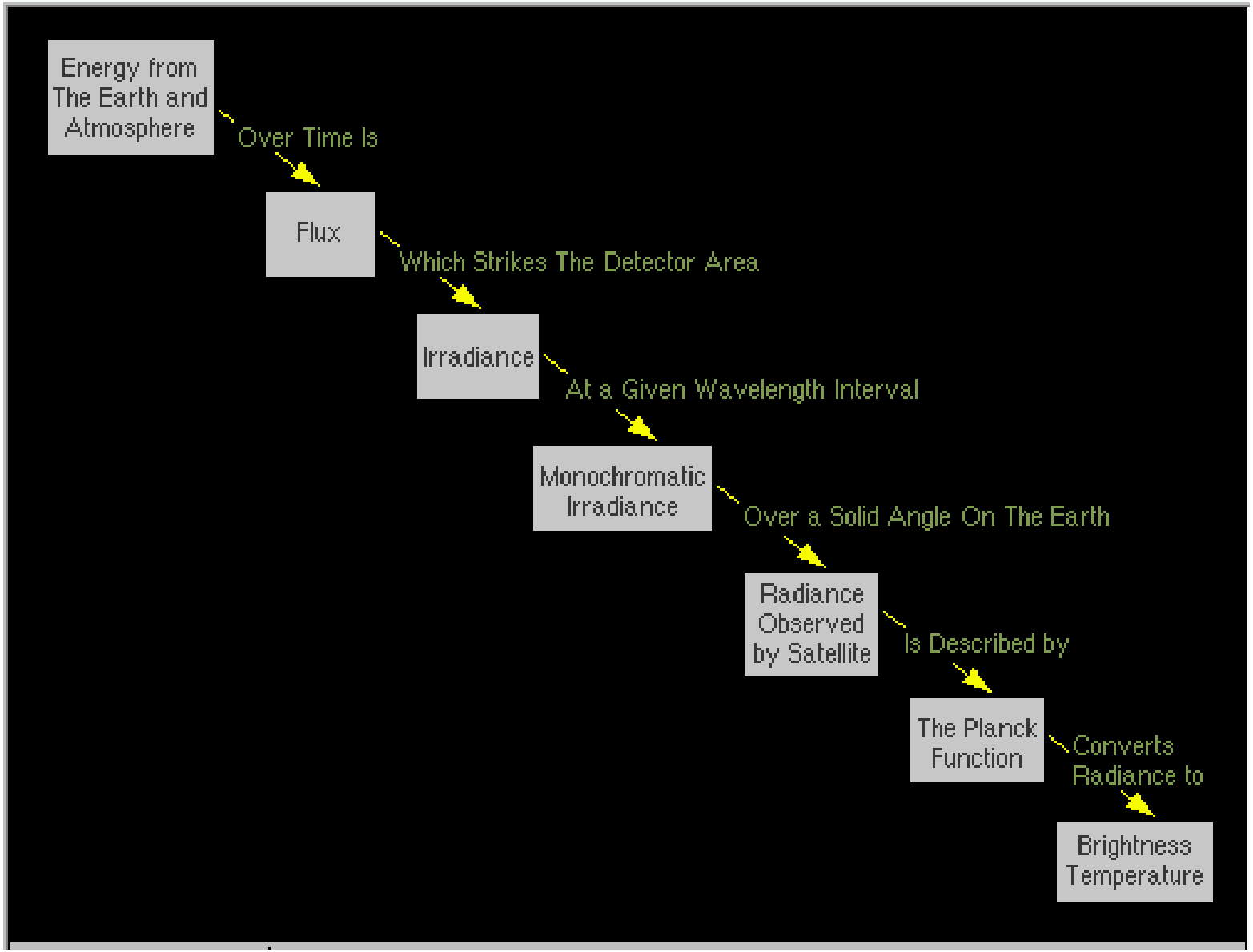


Best coverage near poles

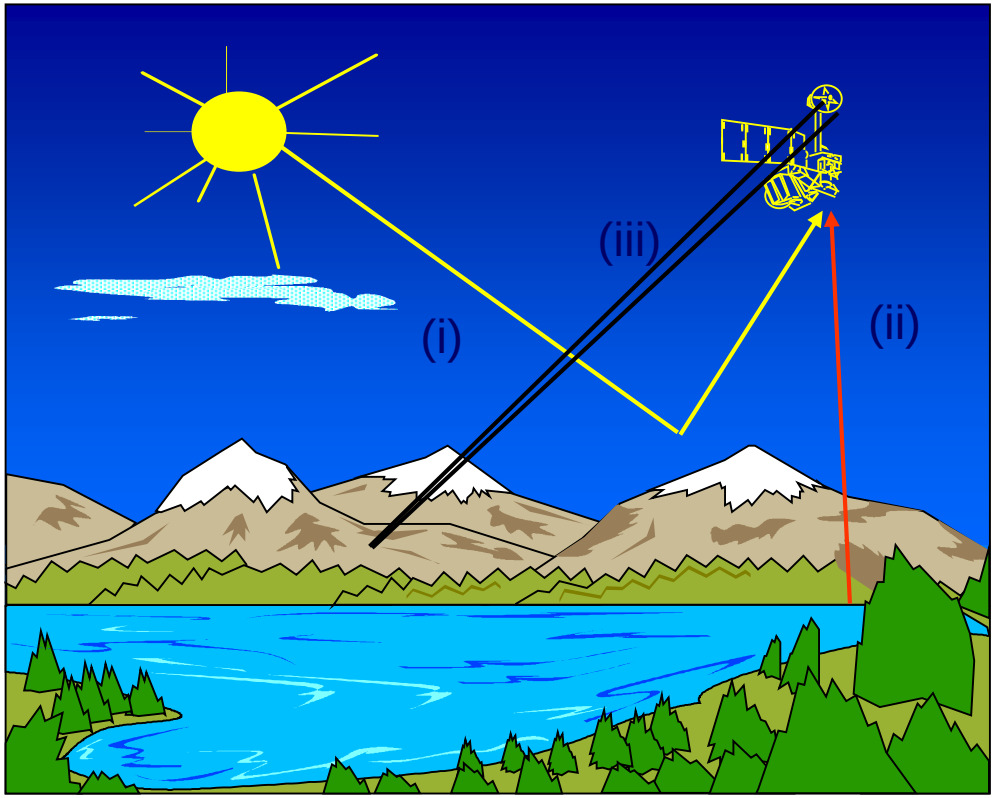
Worst coverage near equator



Dalla misura al dato meteorologico…



Processi radiativi



(i) reflection
(ii) emission
(iii) emission+reflection

Remote sensing uses the radiant energy that is reflected and emitted from Earth at various “wavelengths” of the electromagnetic spectrum

La radianza

La quantità di energia trasportata dalla radiazione EM si chiama **flusso radiante** [watt]:

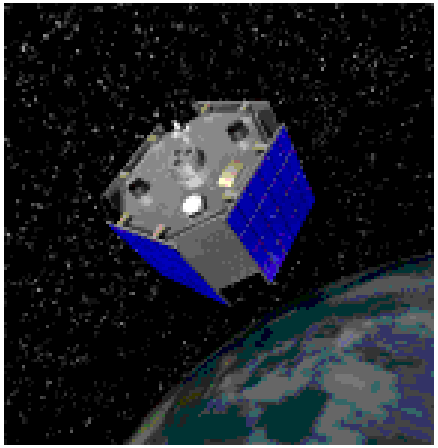
1. $$F = \frac{dQ}{dt}$$

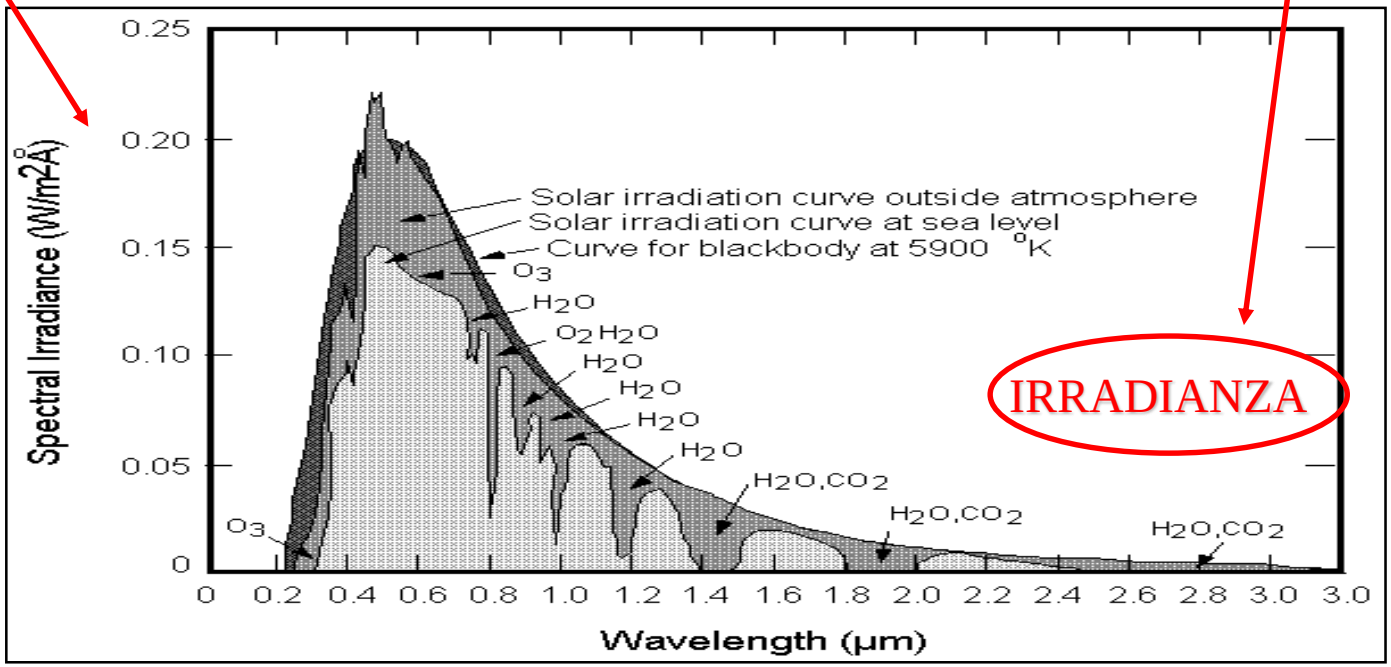
Il flusso radiante solare è di circa 3.90 x 10^{26} W.

Il flusso solare su unità di area è definito come **irradianza** (o densità di flusso radiante) [W/m^2]:

2.

$$E = \frac{dQ}{dt \cdot dA}$$




Spectral Irradiance (W/m2Å)
0.25
0.20
0.15
0.10
0.05
0
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.0
Wavelength (µm)
Solar irradiation curve outside atmosphere
Solar irradiation curve at sea level
Curve for blackbody at 5900 °K
O3
H2O
O2 H2O
H2O
H2O
H2O
H2O
H2O,CO2
H2O,CO2
H2O,CO2
O3
IRRADIANZA

La radianza

L'irradianza riferita all'angolo solido è definita **radianza** [W/(m^{2}sr m)]:

3.

$$I = dQ \,/\, dt \,/\, dA \,/\, d\lambda \,/\, d\Omega$$

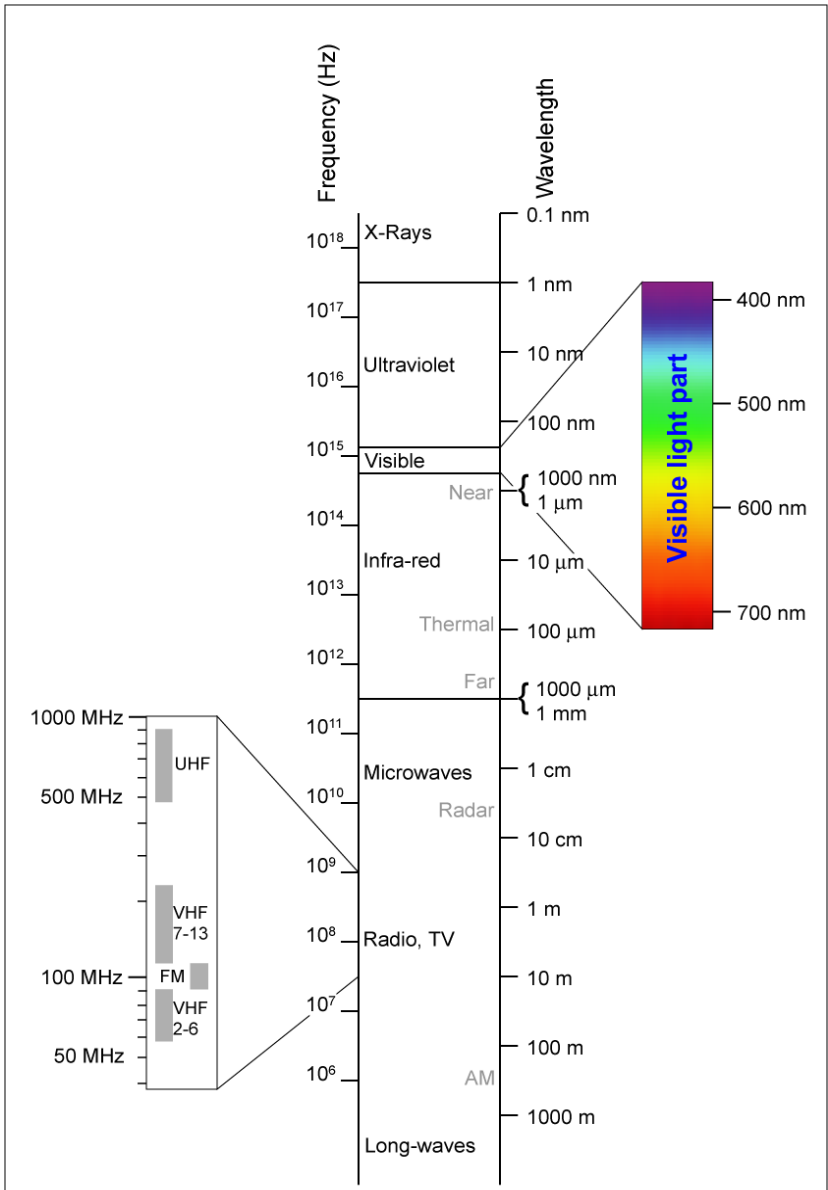
La radianza è spesso chiamata <u>intensità della radiazione</u> e associata alla lettera **B** quando si fa riferimento alla funzione di Planck.

Il trasferimento radiativo

$$B_t(T) = \frac{2hc^2 \lambda^{-5}}{\exp(hc/\lambda KT) - 1}$$

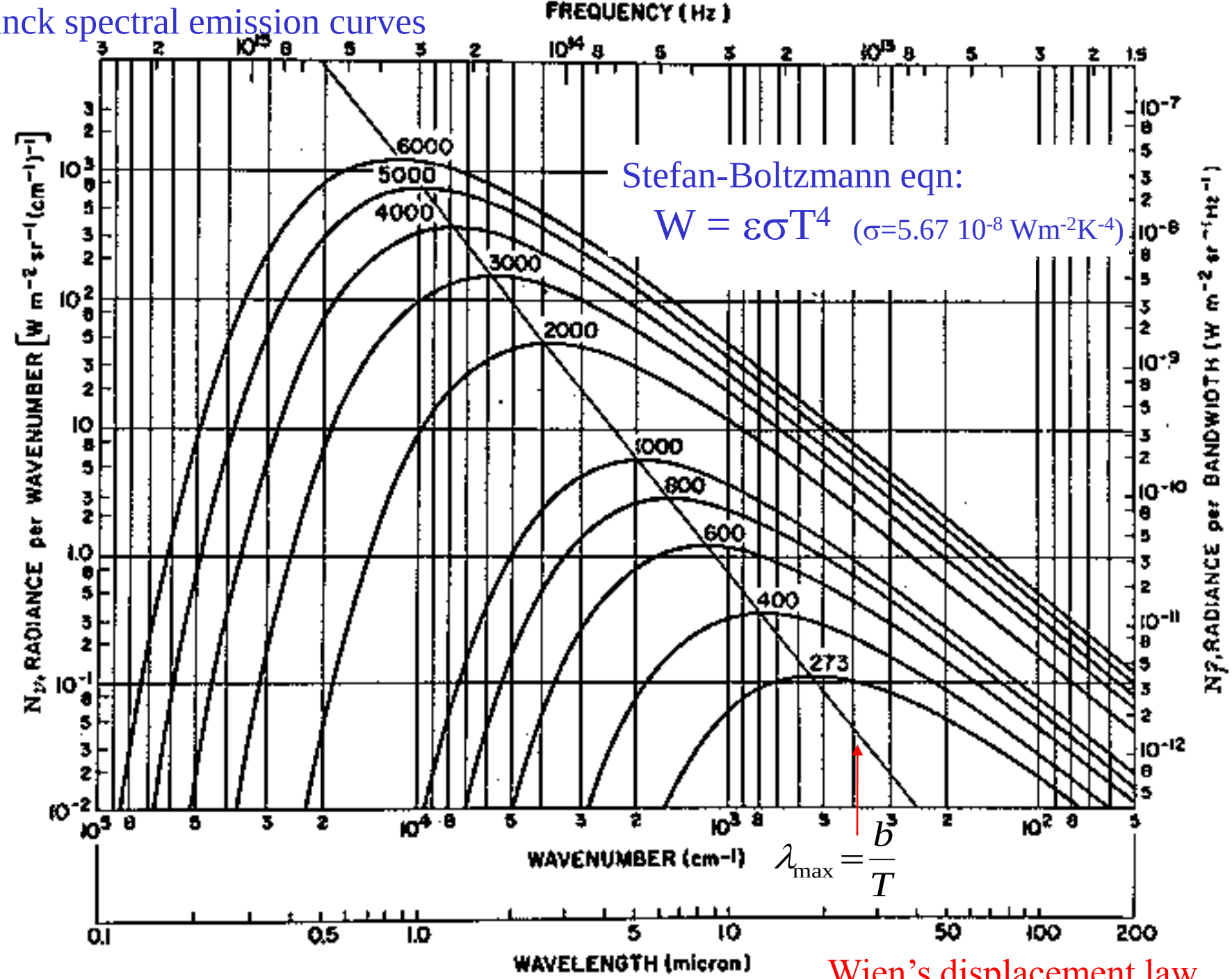
$$\lambda_m \cdot T = 2897.9 \mu m K$$

$$\tau_\lambda(a,b) = \exp\left(-\int_a^b \sigma_s(\lambda)\, ds\right)$$



The electromagnetic spectrum

Planck spectral emission curves



Stefan-Boltzmann eqn:

$$W = \varepsilon\sigma T^4 \quad (\sigma = 5.67\ 10^{-8}\ \mathrm{Wm^{-2}K^{-4}})$$

Wien's displacement law

Solar Spectrum, Top of the Atmosphere and at the Surface

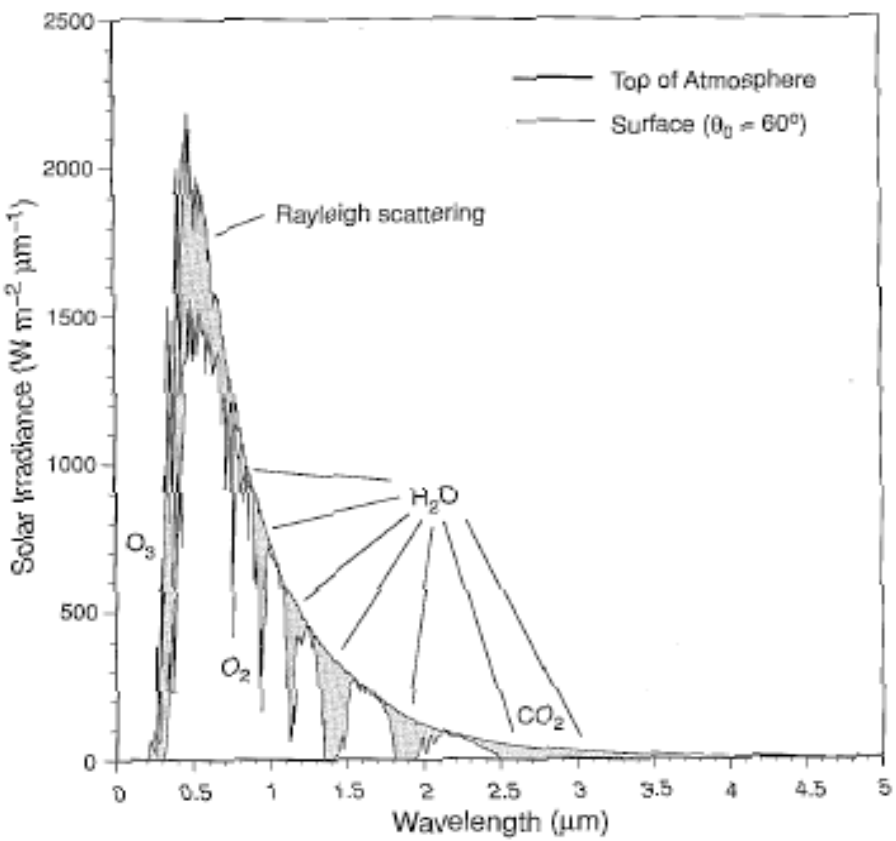


Figure 3.9 Solar irradiance curve for a 50 cm^{-1} spectral interval at the top of the atmosphere (see Fig. 2.9) and at the surface for a solar zenith angle of 60° in an atmosphere without aerosols or clouds. Absorption and scattering regions are indicated. See also Table 3.3 for the absorption of N_2O, CH_4, CO, and NO_2.

Shaded region is solar irradiance removed by Rayleigh scattering and absorption by gases as indicated. (from Liou).

L'emissività

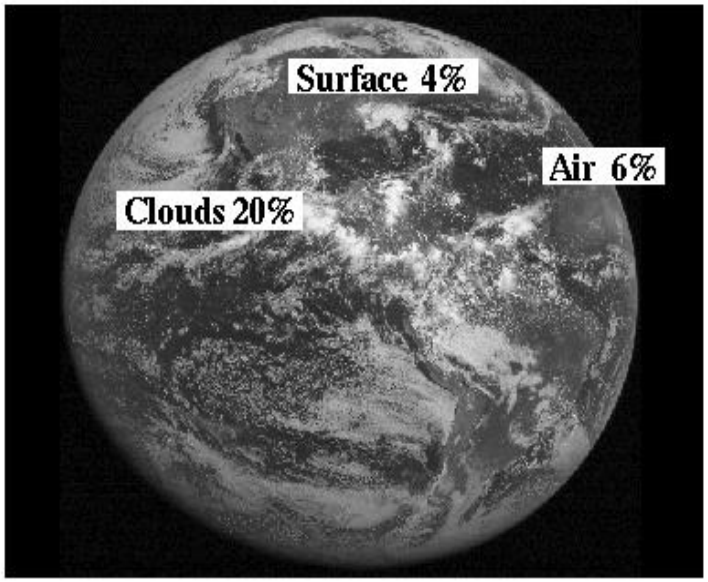
L'emissività ε_λ è la frazione di energia irraggiata rispetto a quella emessa da un corpo nero alla medesima temperatura.

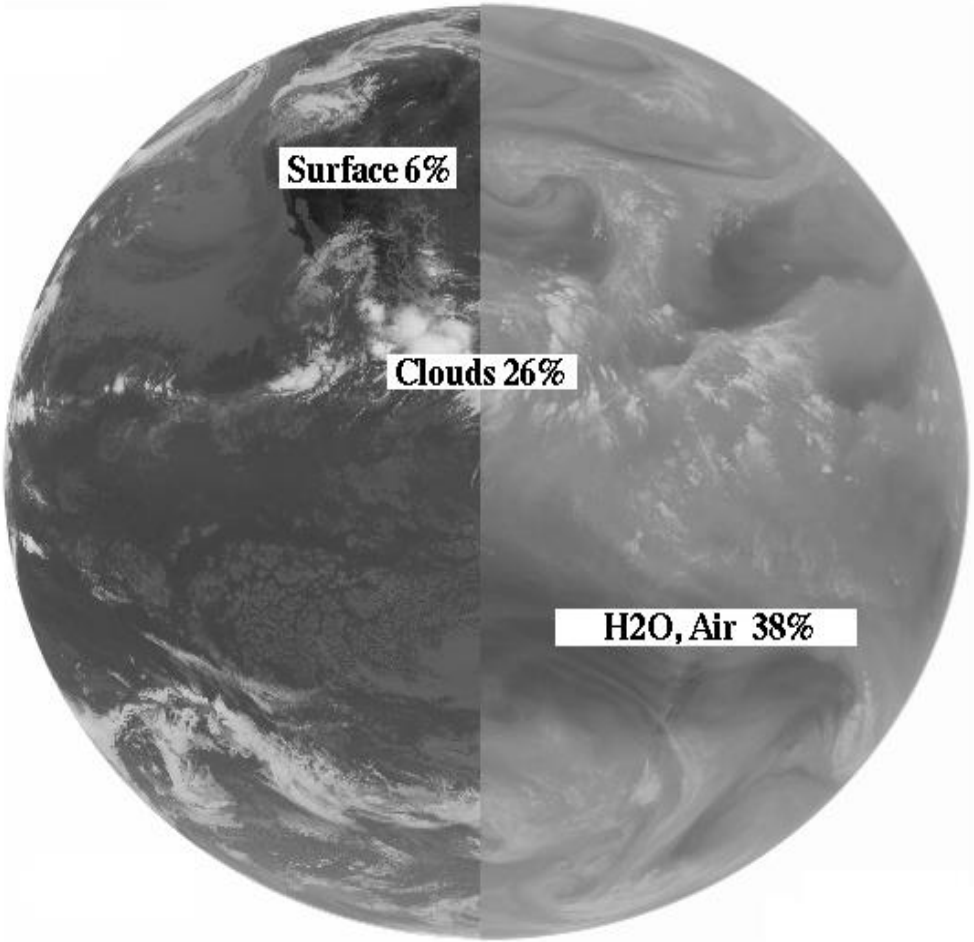
$$\epsilon_\lambda = \frac{R_\lambda}{B_\lambda} \qquad 0 \leqslant \epsilon_\lambda \leqslant 1$$

Energy emitted into space

Global Mean Energy Balance

Top of the Atmosphere





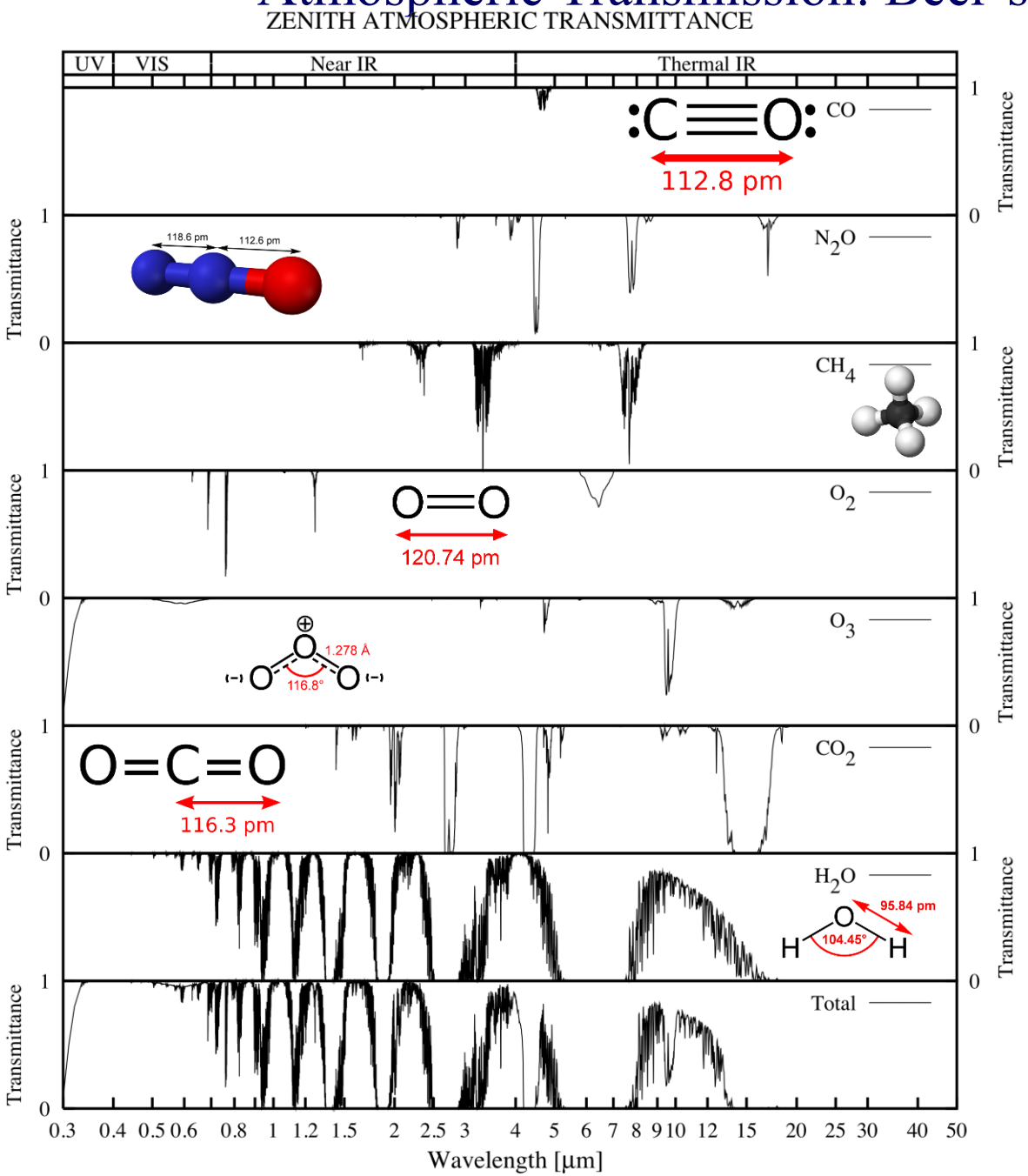
Reflected Solar Radiation (30%)

Outgoing Infrared Radiation (70%)

NOAA/NESDIS/ORA/ARAD/ASPT

…as a fraction of the total incoming solar radiation = S/4 (S=1373 Wm^{-2})

Atmospheric Transmission: Beer's Law: $I(x)=I_0 e^{(-\beta_{abs} x)}$



What are the main sources for each gas?

Which gases are infrared active and contribute to greenhouse warming?

Which gases significantly absorb solar radiation?

Gas concentrations from 'typical' midlatitude summer atmosphere.

Nitrous oxide is emitted by bacteria in soils and oceans, and thus has been a part of Earth's atmosphere for eons. Agriculture is the main source of human-produced nitrous oxide: cultivating soil, the use of nitrogen fertilizers, and animal waste handling can all stimulate naturally occurring bacteria to produce more nitrous oxide. The livestock sector (primarily cows, chickens, and pigs) produces 65% of human-related nitrous oxide. [1] Industrial sources make up only about 20% of all anthropogenic sources, and include the production of nylon and nitric acid, and the burning of fossil fuel in internal combustion engines. Human activity is thought to account for somewhat less than 2 teragrams of nitrogen oxides per year, nature for over 15 teragrams.

THE SCHWARZSCHILD EQUATION

$$dL_\lambda / ds = rad.\,absorbed\,(A) + rad.\,emitted\,(B)$$
$$+ rad.\,scattered\,(C) + rad.\,scattered\,into\,the\,beam\,(D)$$

$$A = -\sigma_a(\lambda) L_\lambda(\theta, \phi) \qquad Beer's\,law$$

$$B = +\sigma_a(\lambda) B_\lambda(T) \qquad Kirchhoff's\,law$$

$$C = -\sigma_s(\lambda) L_\lambda(\theta, \phi) \qquad Beer's\,law$$

$$D = +\sigma_s(\lambda)/4\pi \iint L_\lambda(\theta', \phi')\, p(\psi_s) \sin(\theta')\, d\theta'\, d\phi'$$
$$= \sigma_s(\lambda) \langle L'_\lambda \rangle$$

$$\boxed{dL_\lambda / ds = \sigma_a(\lambda)[B_\lambda(T) - L_\lambda(\theta, \phi)] + \sigma_s[\langle L'_\lambda(\theta, \phi) \rangle - L_\lambda(\theta, \phi)]}$$

PRACTICAL CONSEQUENCES OF THE SCHWARZSCHILD EQUATION FOR RADIATION TRANSFER WHEN SCATTERING IS NEGLIGIBLE

$$\boxed{\frac{dI}{ds} = \beta_a (B - I)\,.} \qquad (8.4)$$

$$\tau_\lambda(a,b) = \exp\left(\int_a^b \beta_a(\lambda)\,ds\right)$$

$$\boxed{I(0) = I(\tau')e^{-\tau'} + \int_0^{\tau'} Be^{-\tau}\,d\tau\,.} \qquad (8.13)$$

Key Point: *Almost all common radiative transfer problems involving emission and absorption in the atmosphere (without scattering) can be understood in terms of (8.13)!*[2]

From Grant Petty's Book, A first course in Atmospheric Radiation.

Atmosphere Emission Measurements, Downwelling Radiance

Notes:

- Wavelength range for CO2, H20, O3, CH4.
- Envelope blackbody curves.
- Monster inversion in Barrow.
- Water vapor makes the tropical window dirty.

$$I^{\downarrow}(0) = \int_0^{\infty} B(z)W^{\downarrow}(z)dz$$

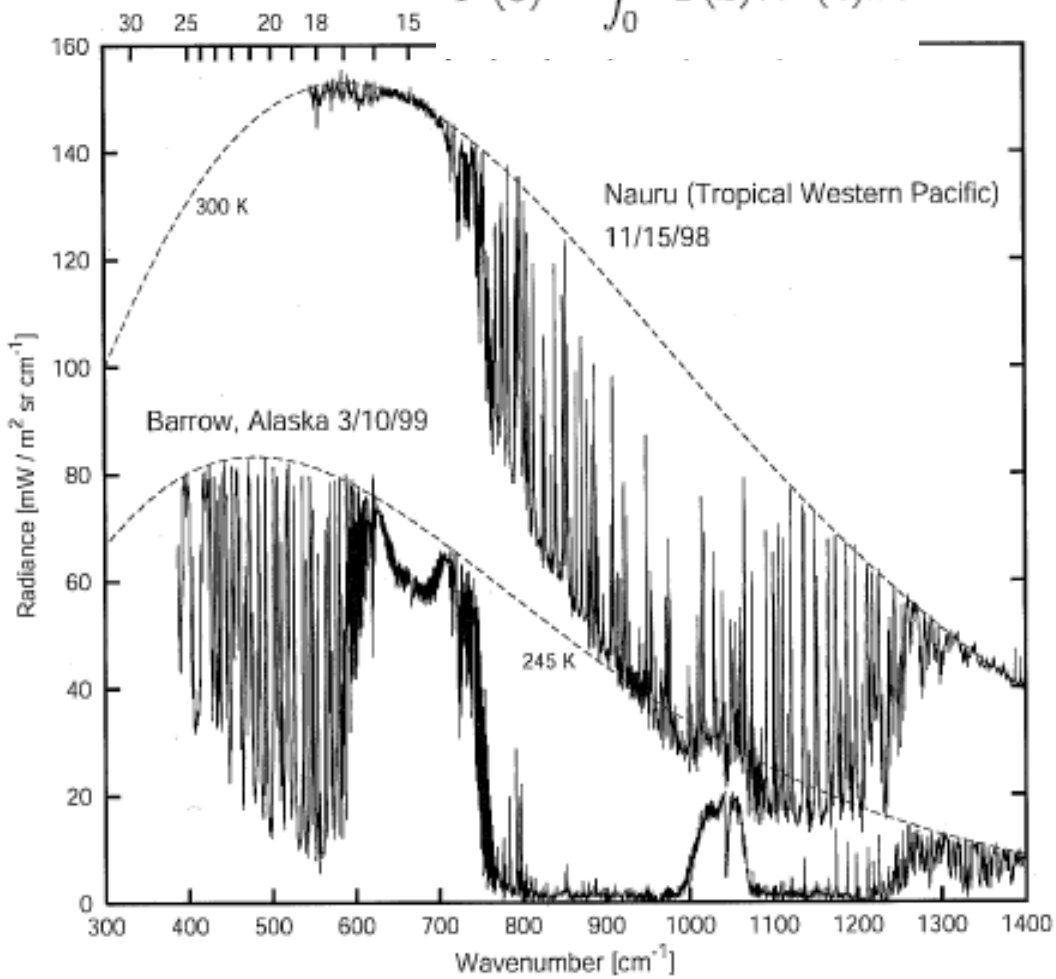
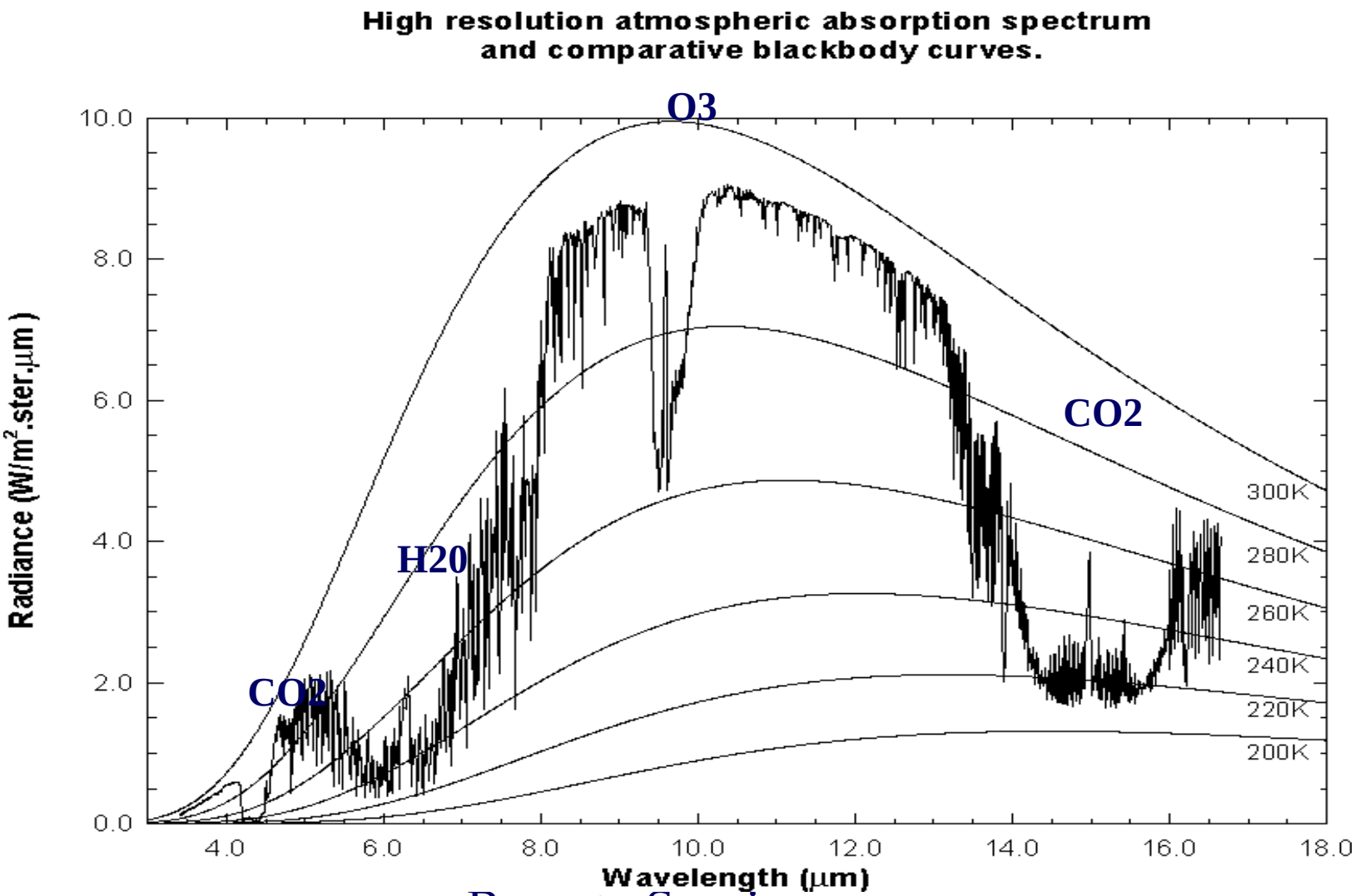


Fig. 8.1: Two examples of measured atmospheric emission spectra as seen from ground level looking up. Planck function curves corresponding to the approximate surface temperature in each case are superimposed (dashed lines). *(Data courtesy of Robert Knuteson, Space Science and Engineering Center, University of Wisconsin-Madison.)*

Earth emitted spectra overlaid on Planck function envelopes



Coincident FTIR Measurements, Down and Up.

$$I^{\uparrow}(\infty) = B(T_S)t^* + \int_0^{\infty} B(z)W^{\uparrow}(z)dz$$

$$I^{\downarrow}(0) = \int_0^{\infty} B(z)W^{\downarrow}(z)dz$$

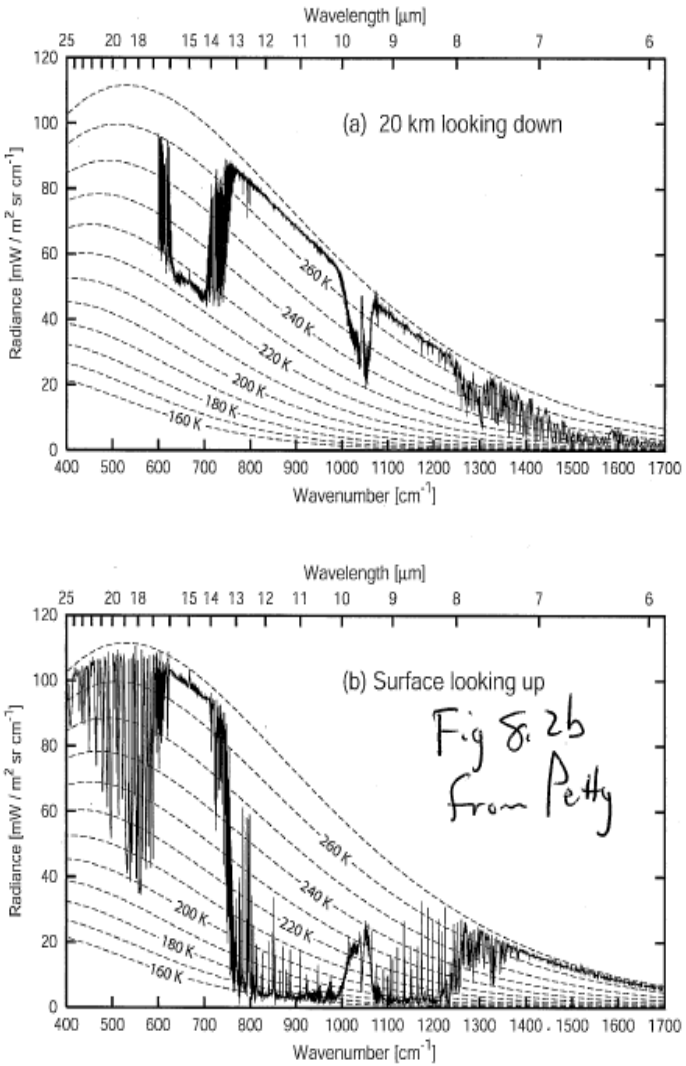
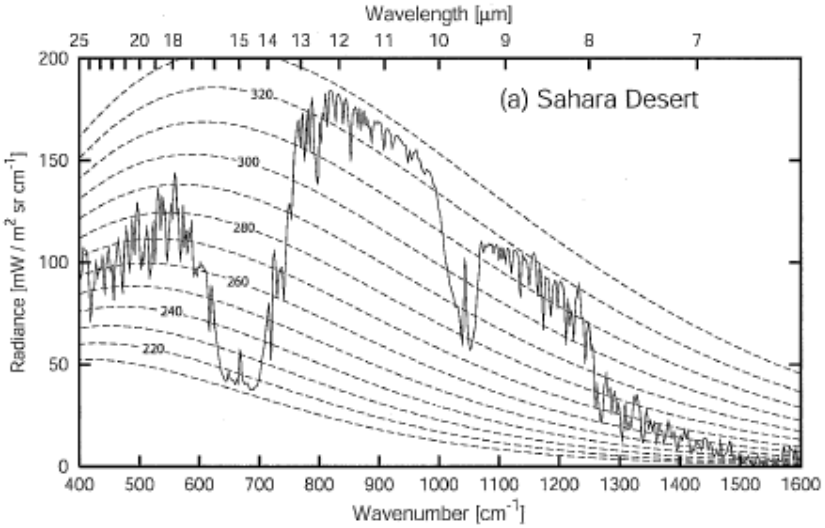
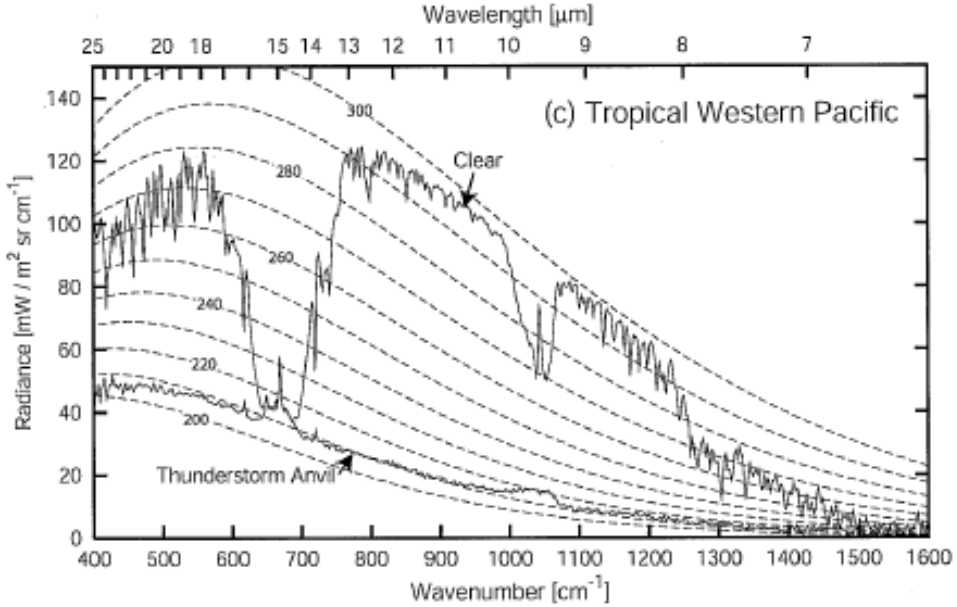
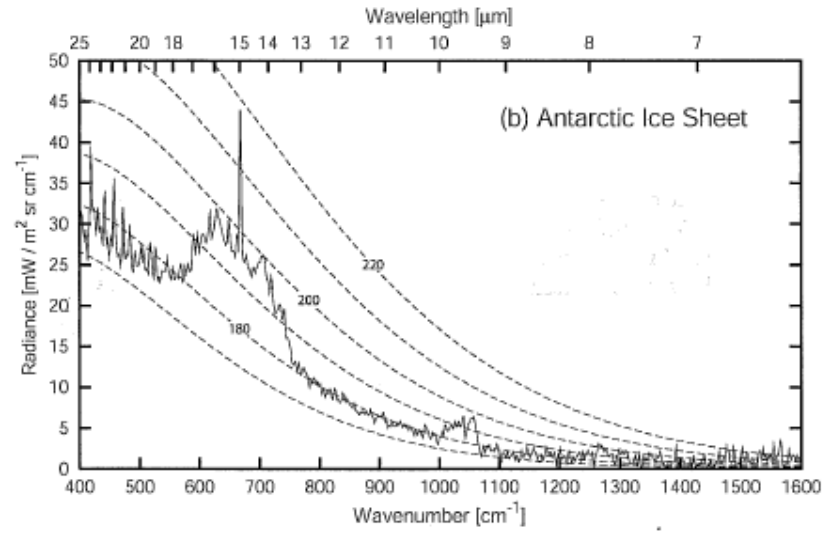


Fig. 8.2: Coincident measurements of the infrared emission spectrum of the cloud-free atmosphere at (a) 20 km looking downward over the polar ice sheet and (b) at the surface looking upward. *(Data courtesy of David Tobin, Space Science and Engineering Center, University of Wisconsin-Madison.)*







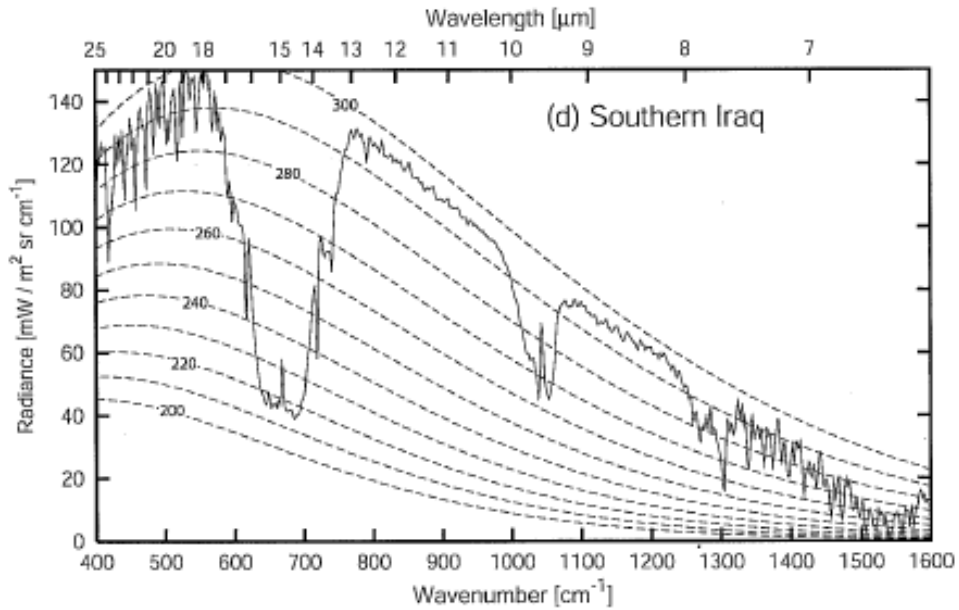


Fig. 8.3: Examples of moderate resolution IR spectra observed by a satellite spectrometer. Except for the curve labeled "thunderstorm anvil" in panel (c), all spectra were obtained under cloud-free conditions. *(Nimbus-4 IRIS data courtesy of the Goddard EOS Distributed Active Archive Center (DAAC) and instrument team leader Dr. Rudolf A. Hanel.)*

FTIR Data from the NASA ER2 with Responsible Gases labeled.

IR Window 8-13 microns. IR radiation from the Earth's surface escapes to space (cooling the Earth). Absorption by O_3 near 9 microns 'dirties' the window.

(From Liou, pg 120).

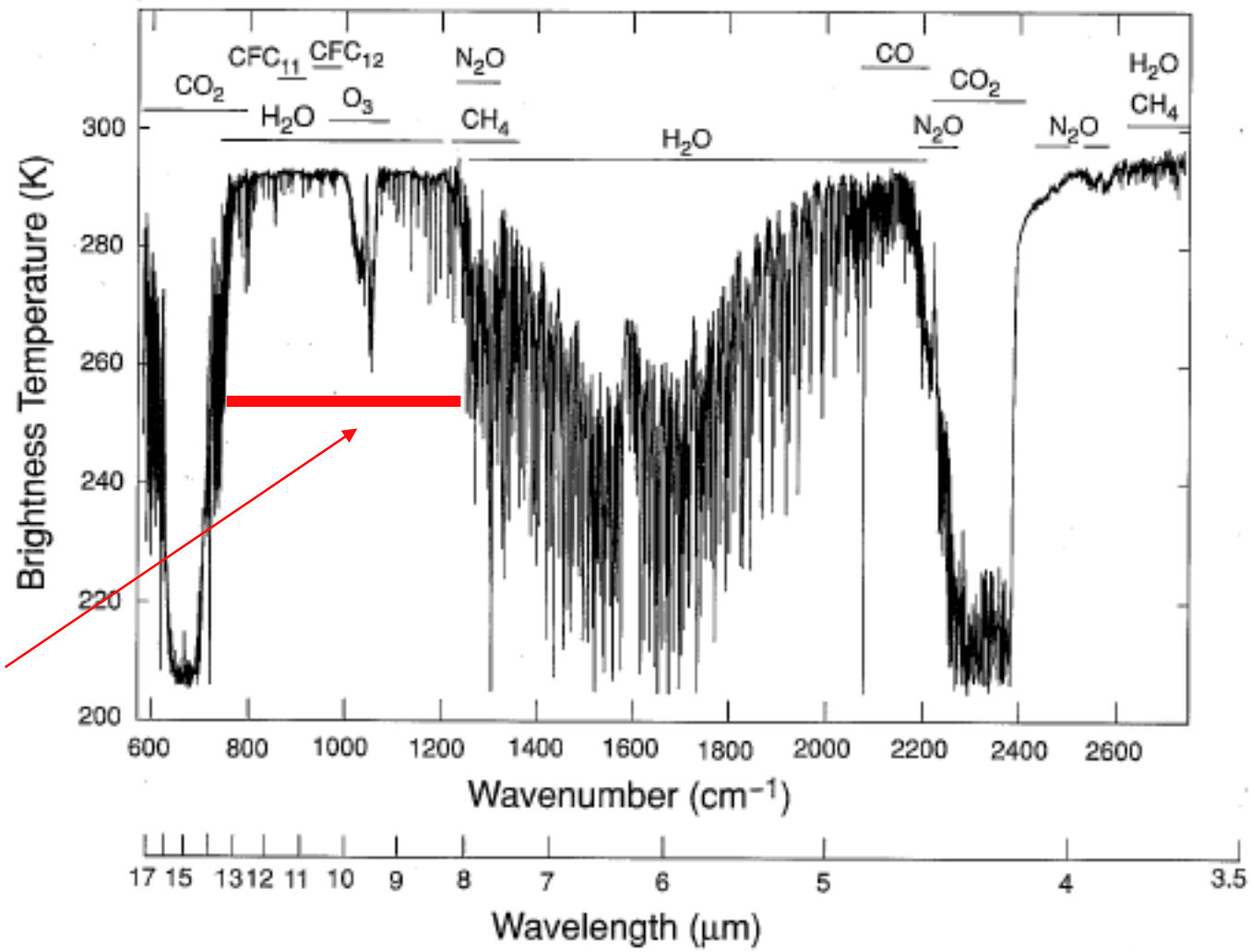
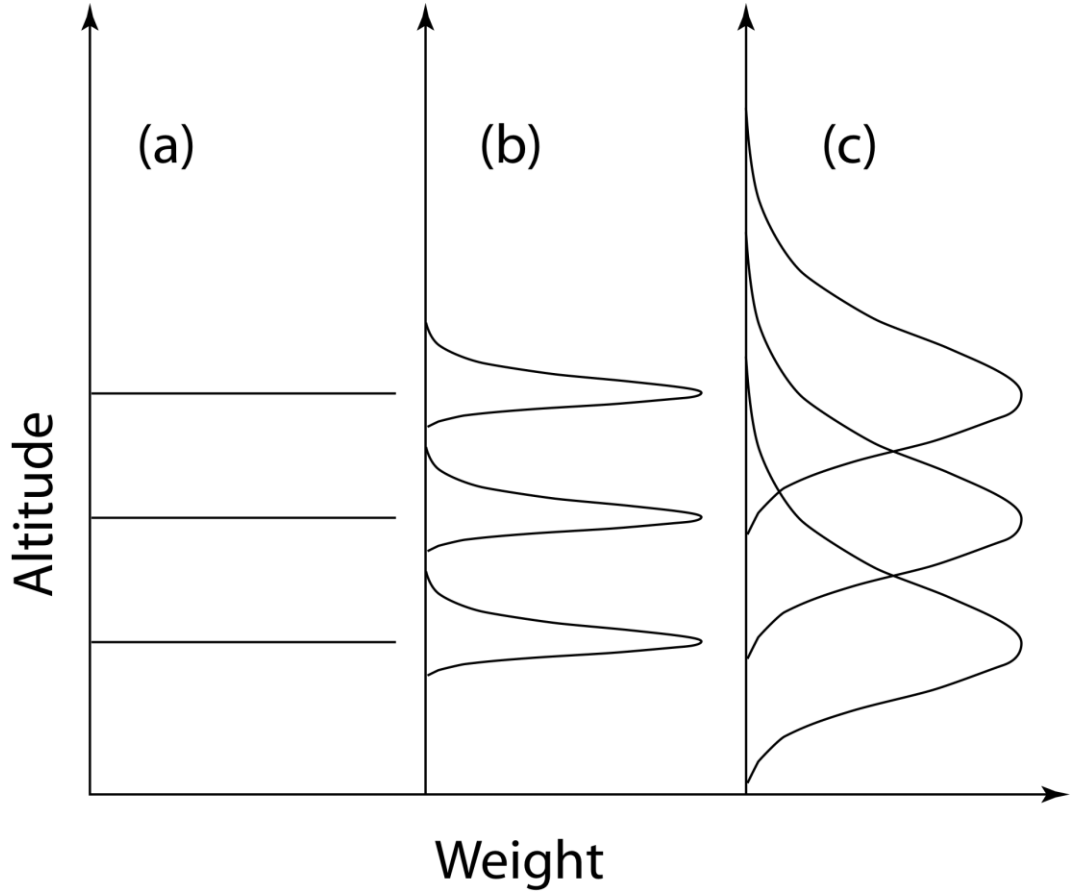


Figure 4.3 Observed infrared spectrum displaying all the absorption gases and their spectral location. This spectrum was obtained from the scanning high-resolution interferometer sounder (S-HIS), which measured the emitted thermal radiation between 3.3 and 18 μm, onboard the NASA ER-2 aircraft over the Gulf of Mexico southeast of Louisiana on April 1, 2001 (courtesy of Allen Huang and Dave Tobin of the University of Wisconsin).

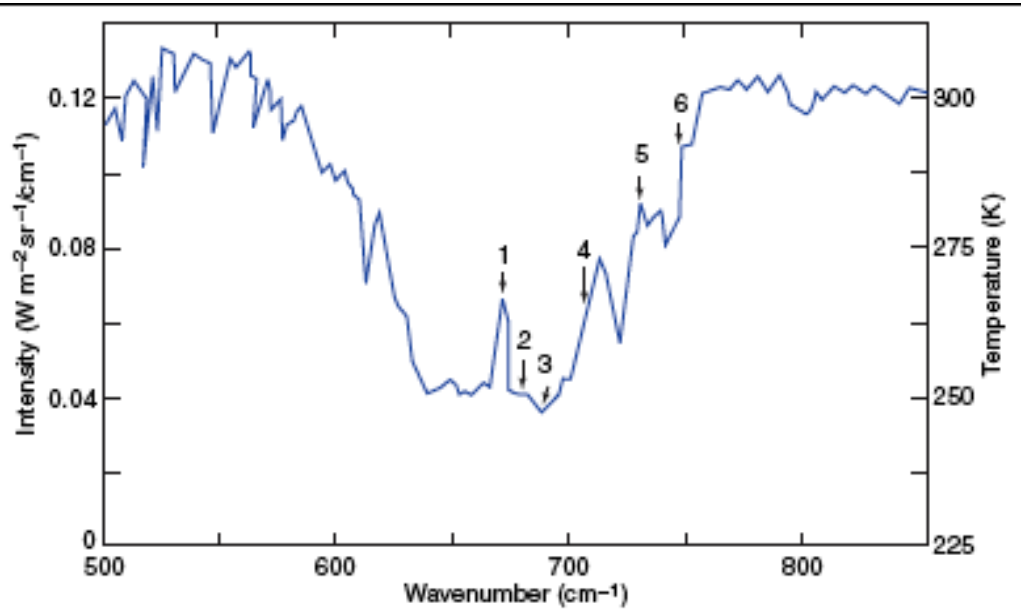
Ideal Weighting Function W_i: Where in the atmosphere the main contribution to the radiation at wavenumber ν_i comes from.

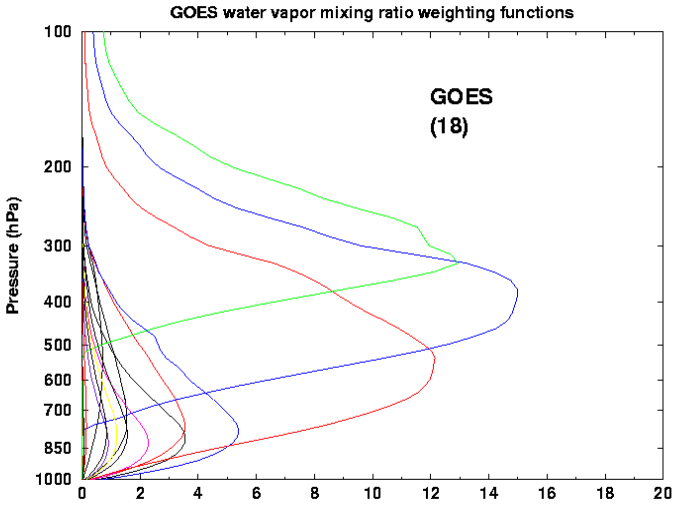
$$I_\lambda = I_0 \tau_0^{1/\mu} + \int_{h0}^{ht} B_\lambda(T) W_\lambda(h,\mu)\, dh$$

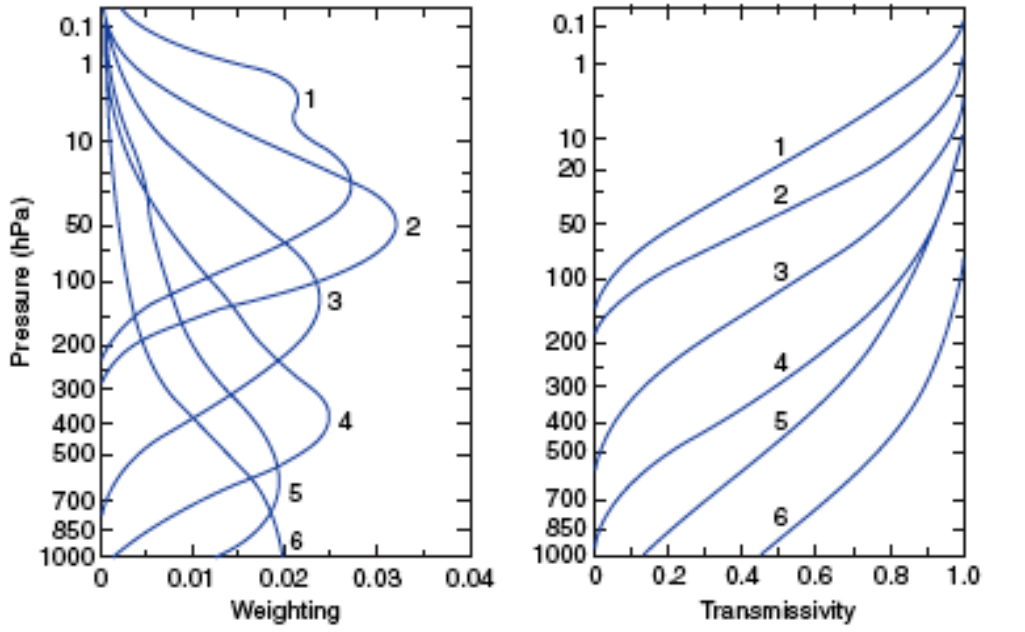
$$W_\lambda(h,\mu) = \frac{d}{dh}\left(\tau_\lambda^{1/\mu}\right)$$



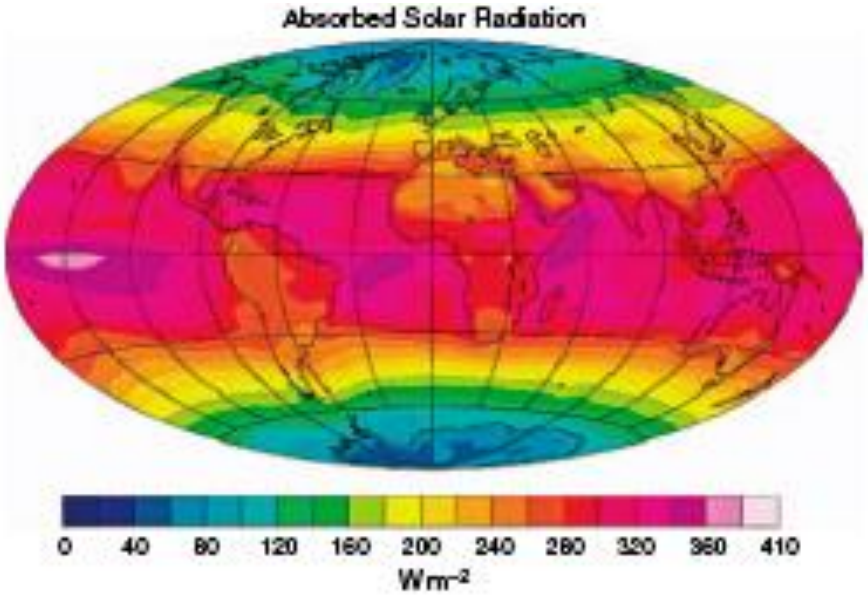
Weighting functions

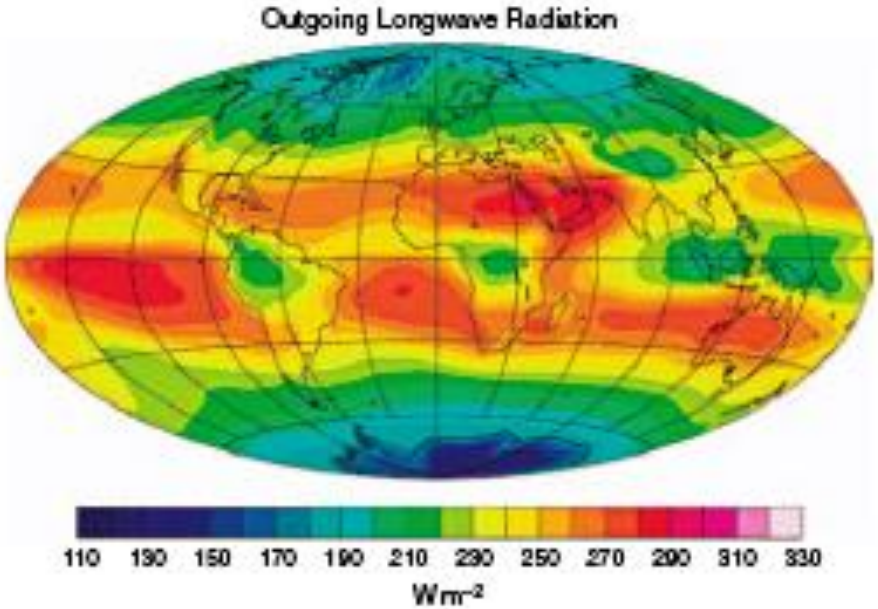






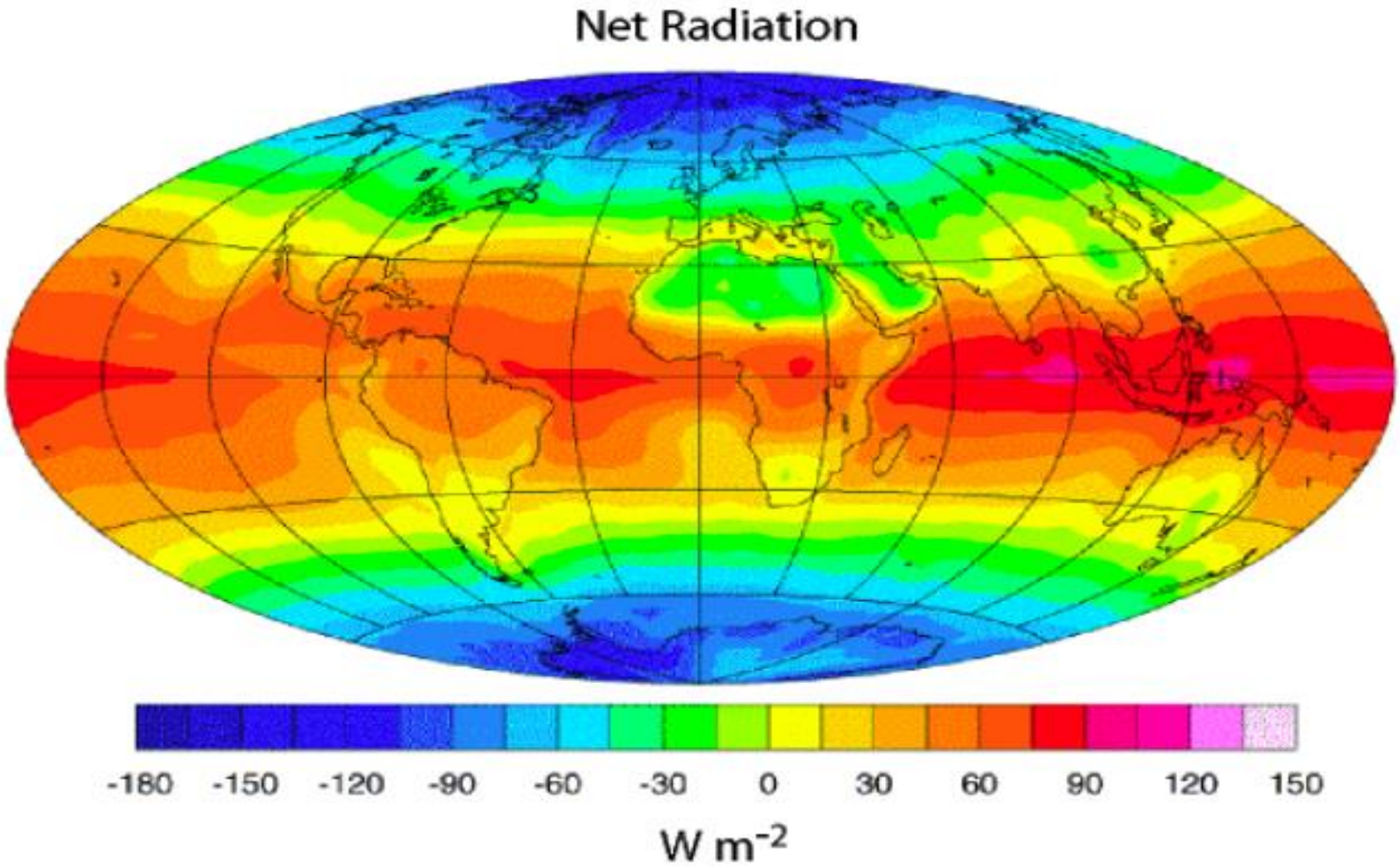
ERBE View of the radiation story (Wallace and Hobbs CH4)

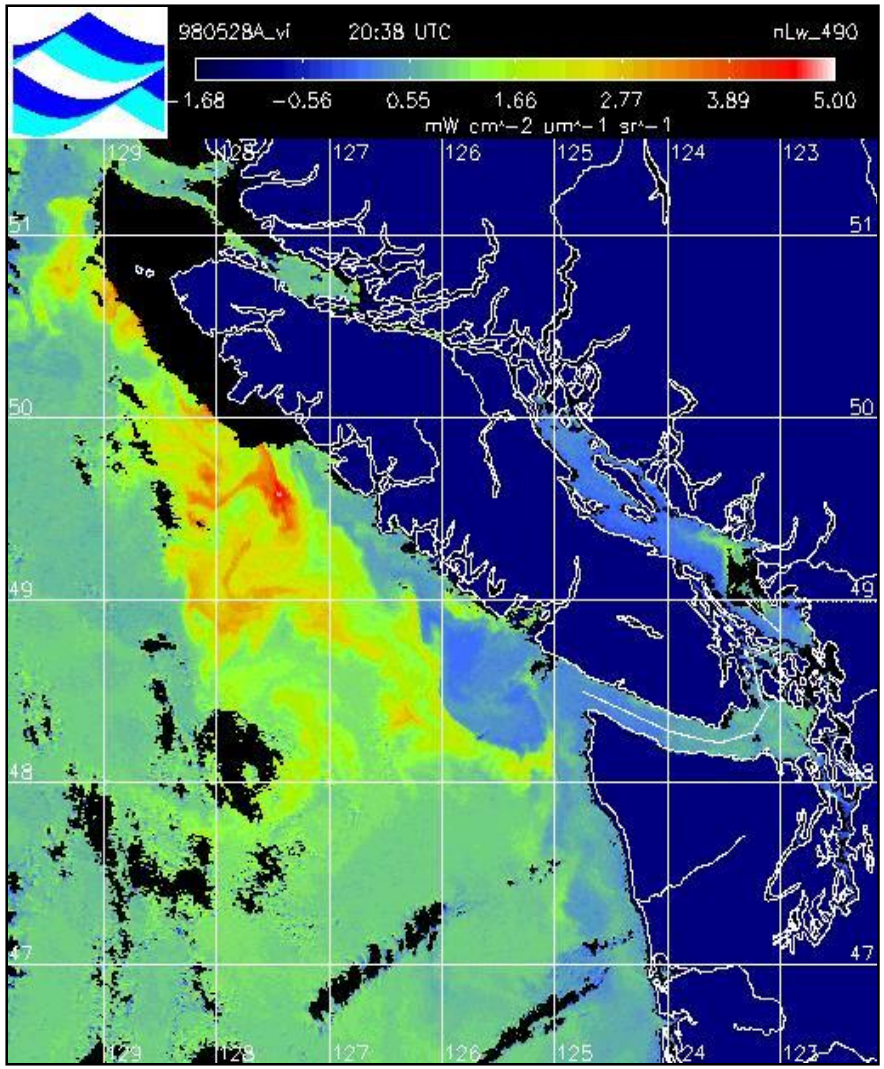




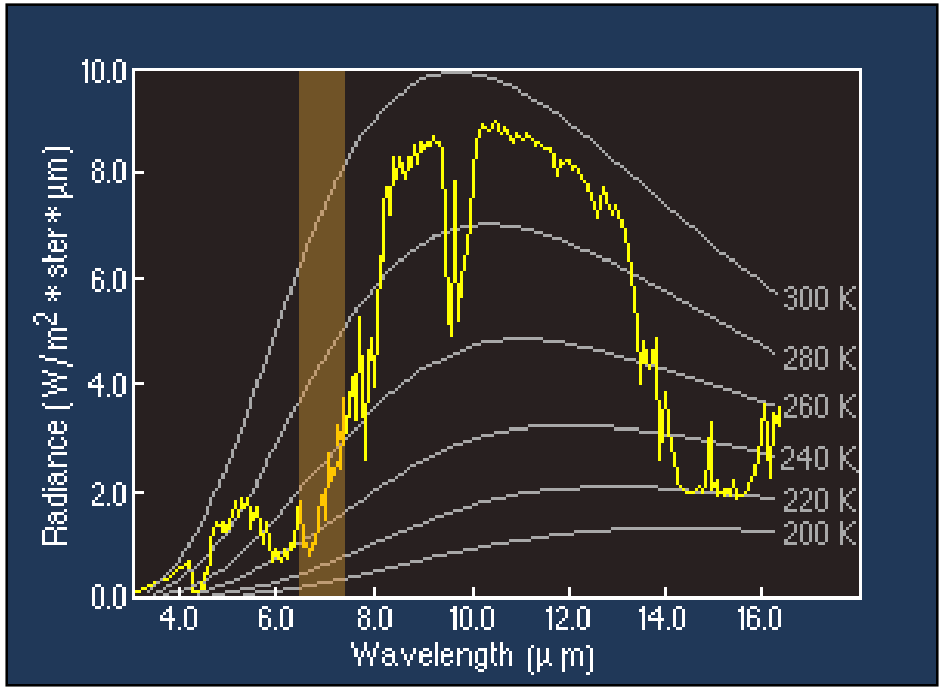
Note the IR cold spots near the Equator and the cold poles.

ERBE View of the radiation story (Wallace and Hobbs CH4)

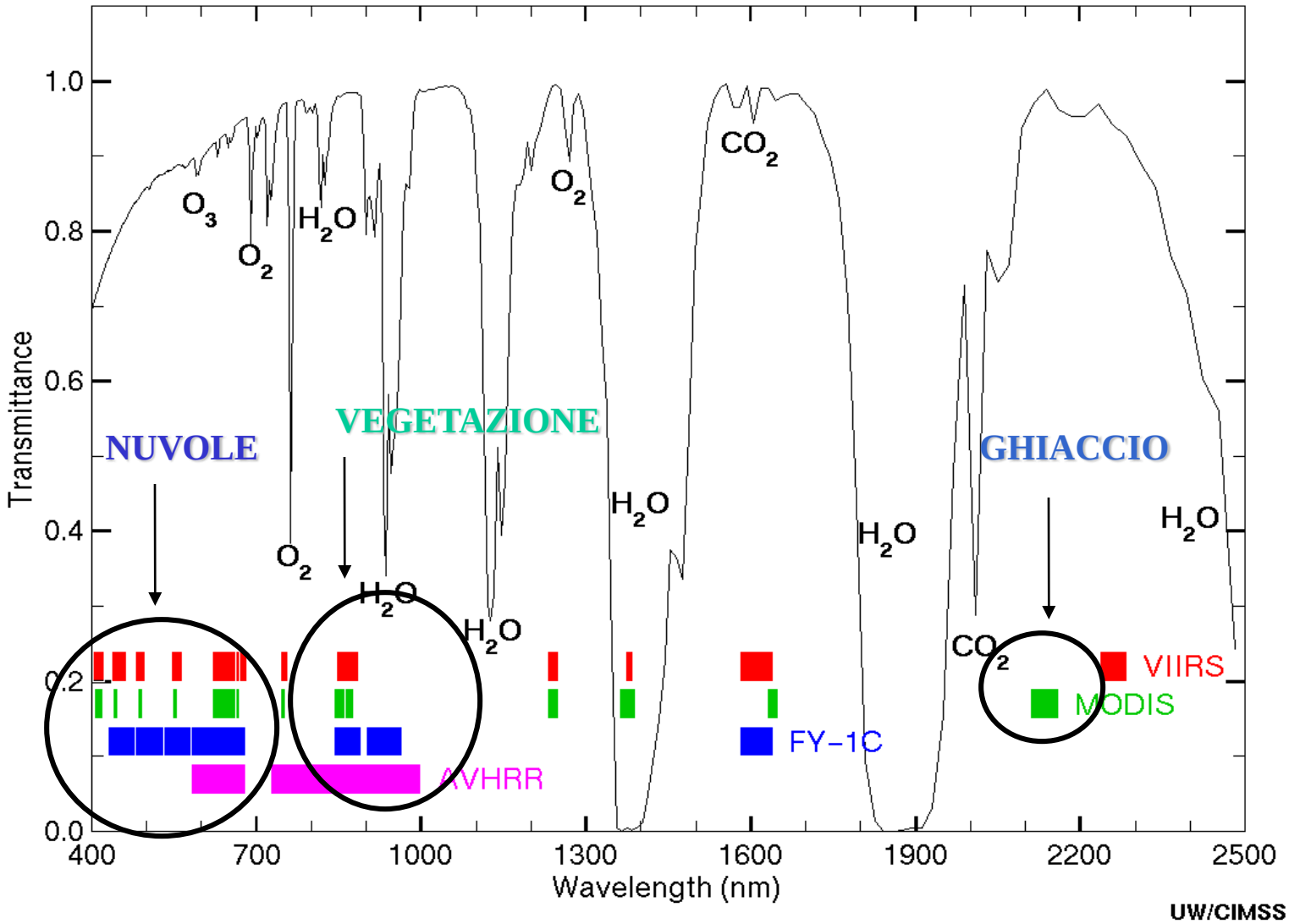



980528A_vi
20:38 UTC
nLw_490
-1.68
-0.56
0.55
1.66
2.77
3.89
5.00
mW cm^-2 um^-1 sr^-1
129
128
127
126
125
124
123
51
50
49
48
47

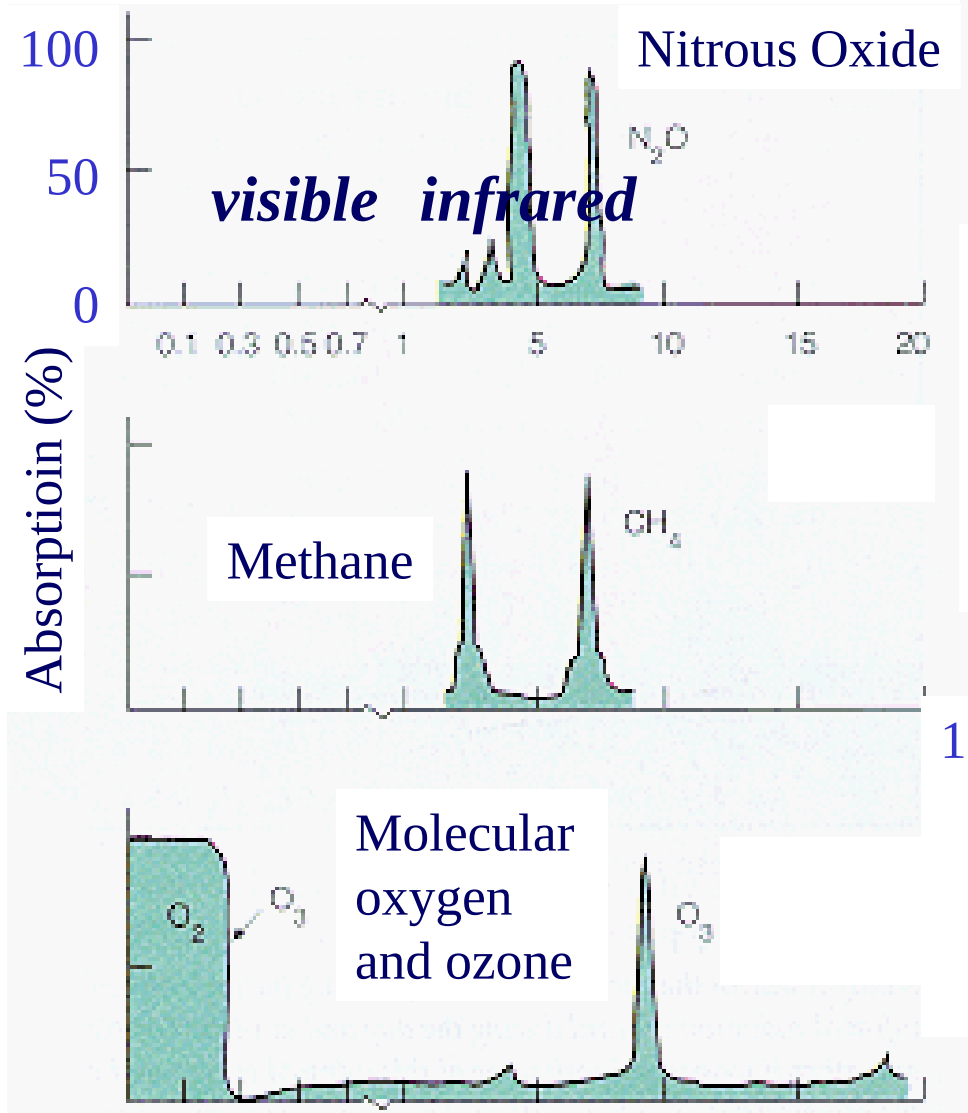
RADIANZA

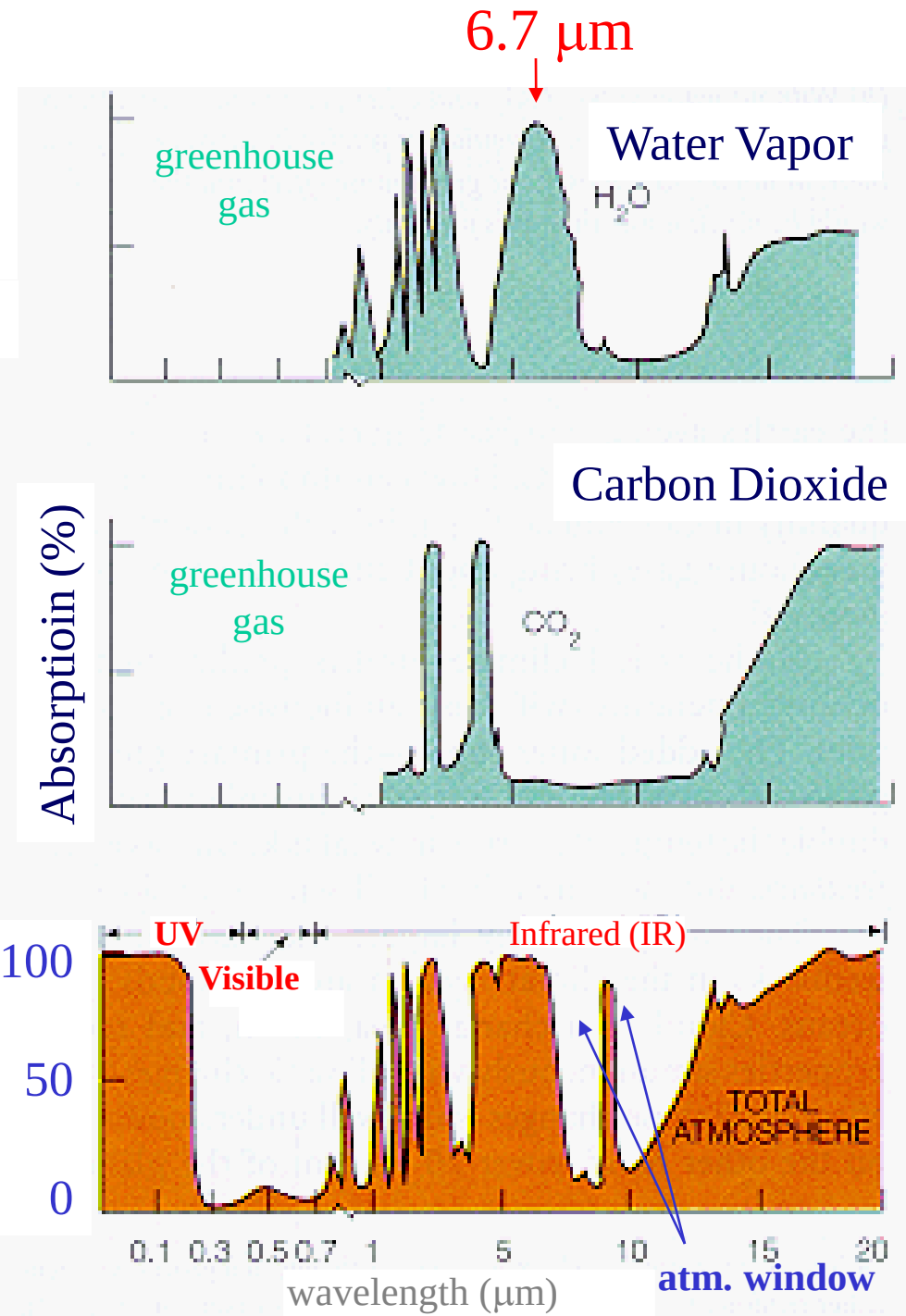

Radiance [W/m2 * ster * µm]
10.0
8.0
6.0
4.0
2.0
0.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Wavelength (µ m)
300 K
280 K
260 K
240 K
220 K
200 K

Osservazioni multispettrali

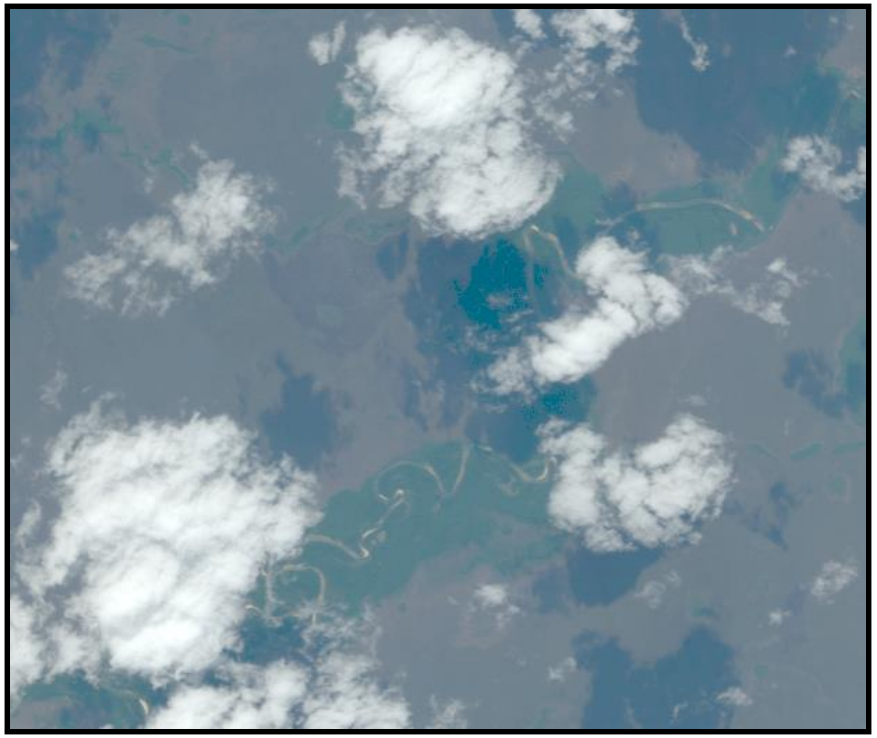


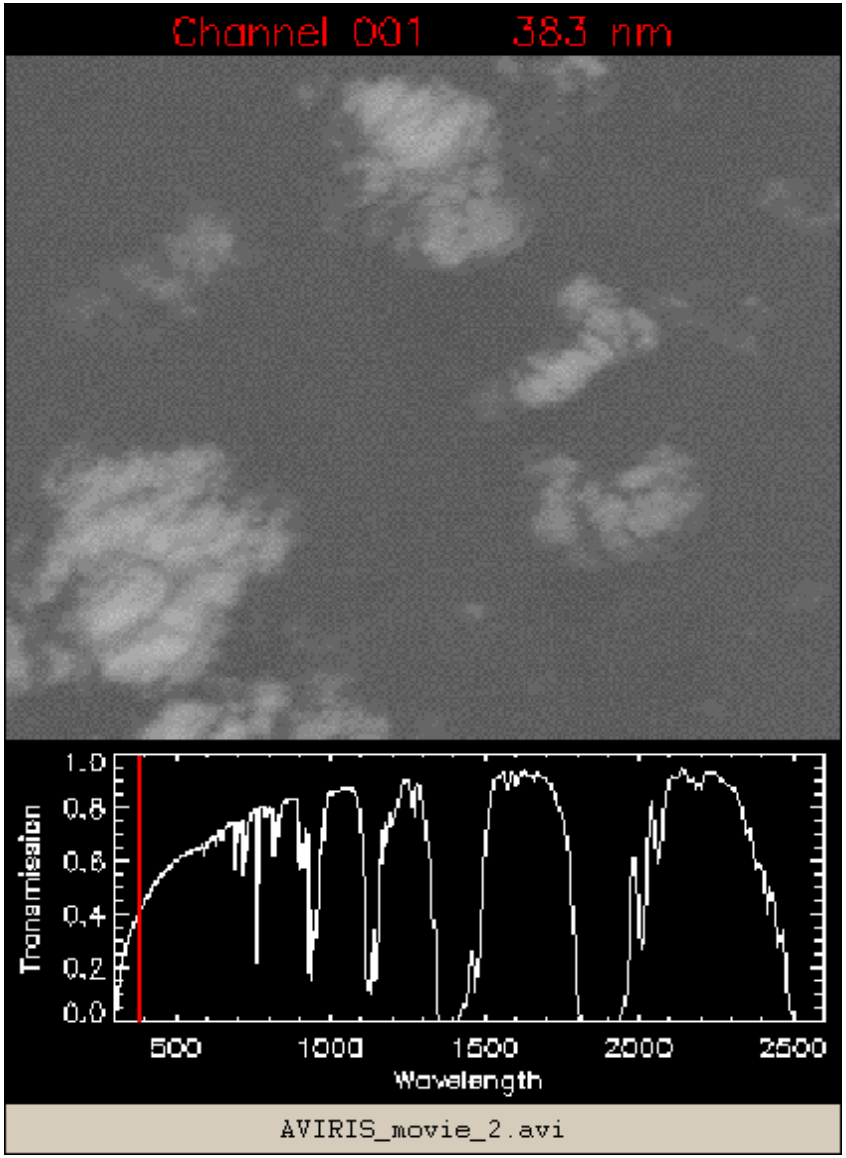
absorption of radiation



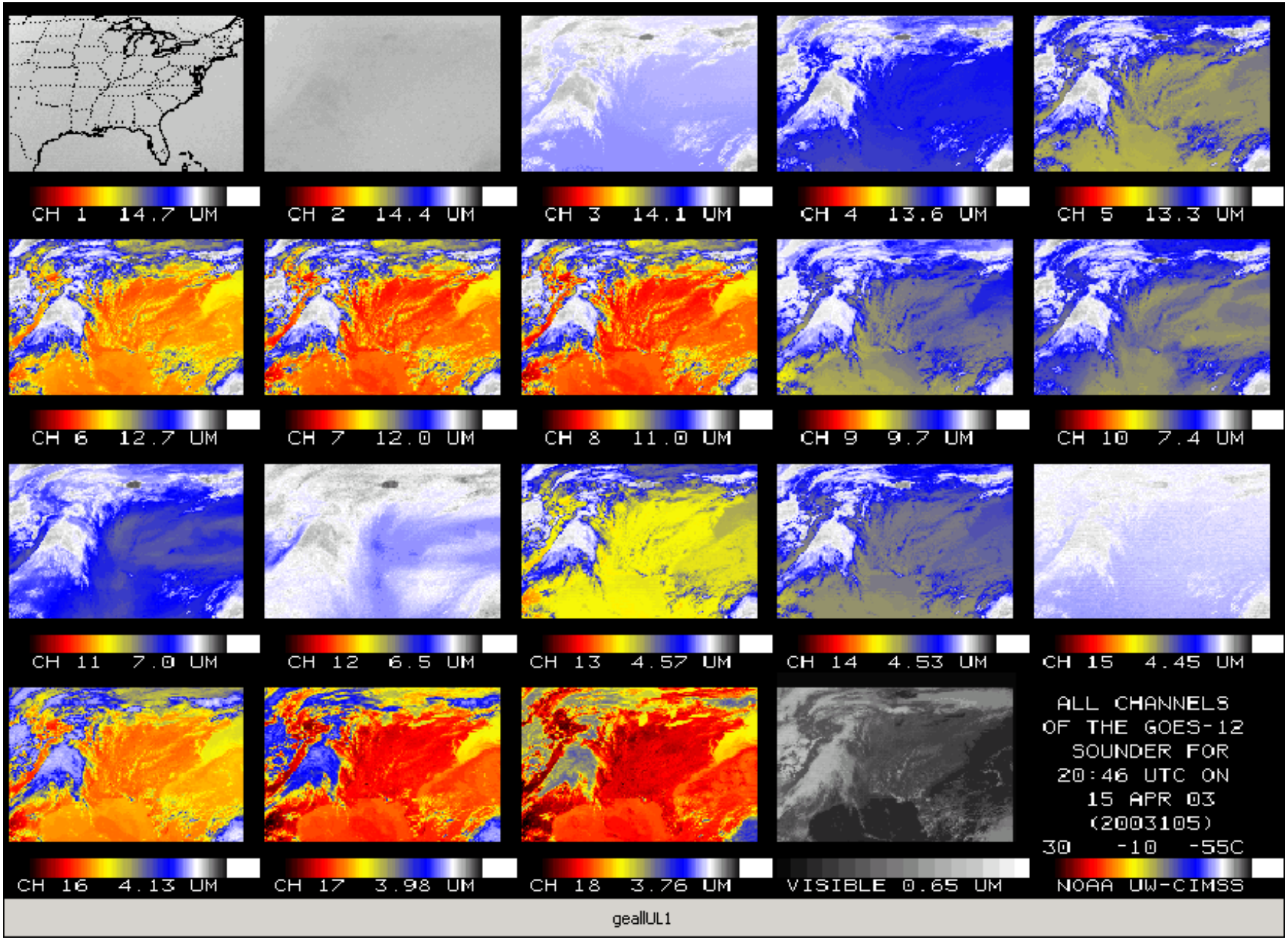


AVIRIS Immagini - Porto Nacional, Brazil
20-Aug-1995
224 Spectral Bands: 0.4 - 2.5 mm
Pixel: 20m x 20m Scene: 10km x 10km

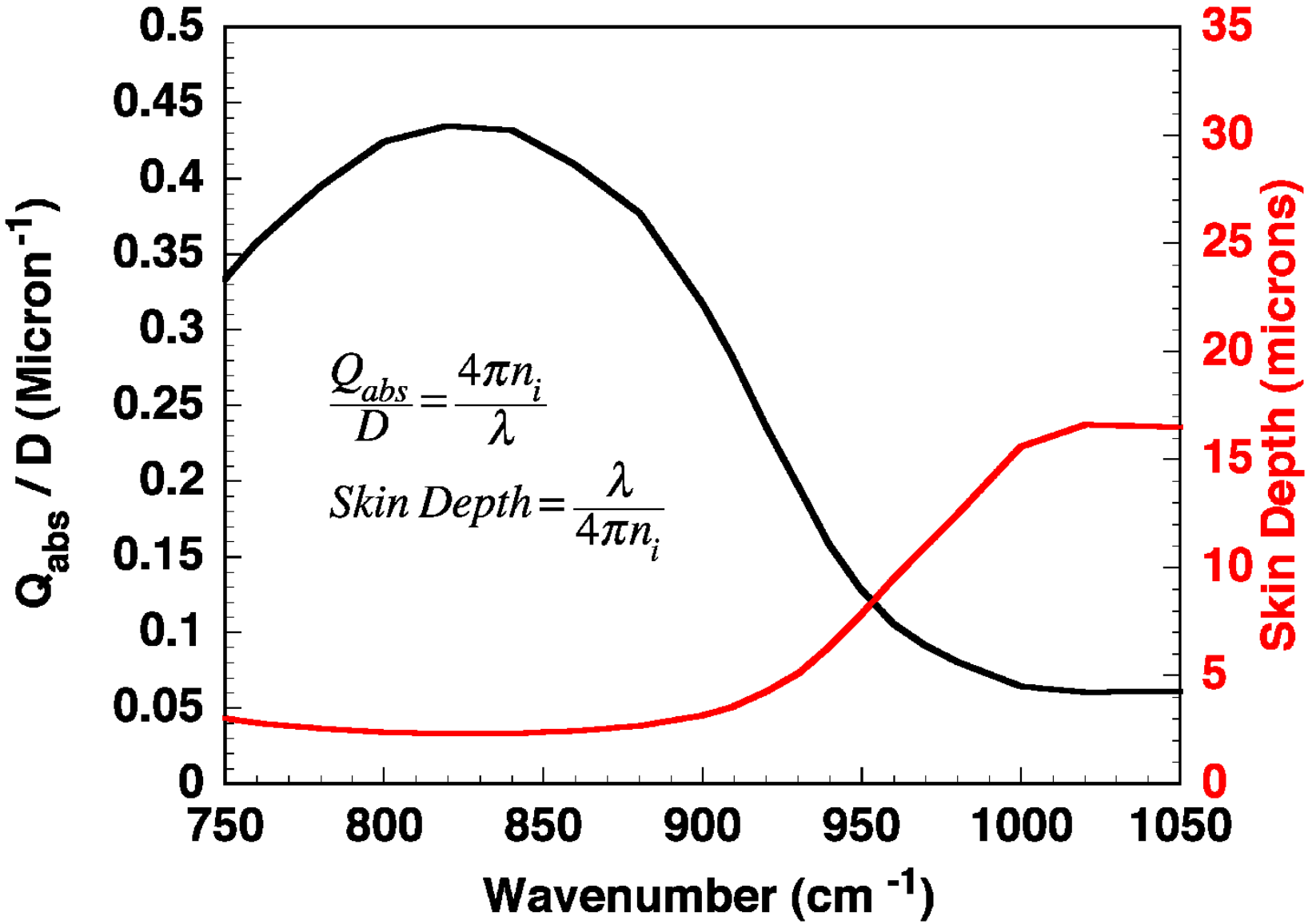




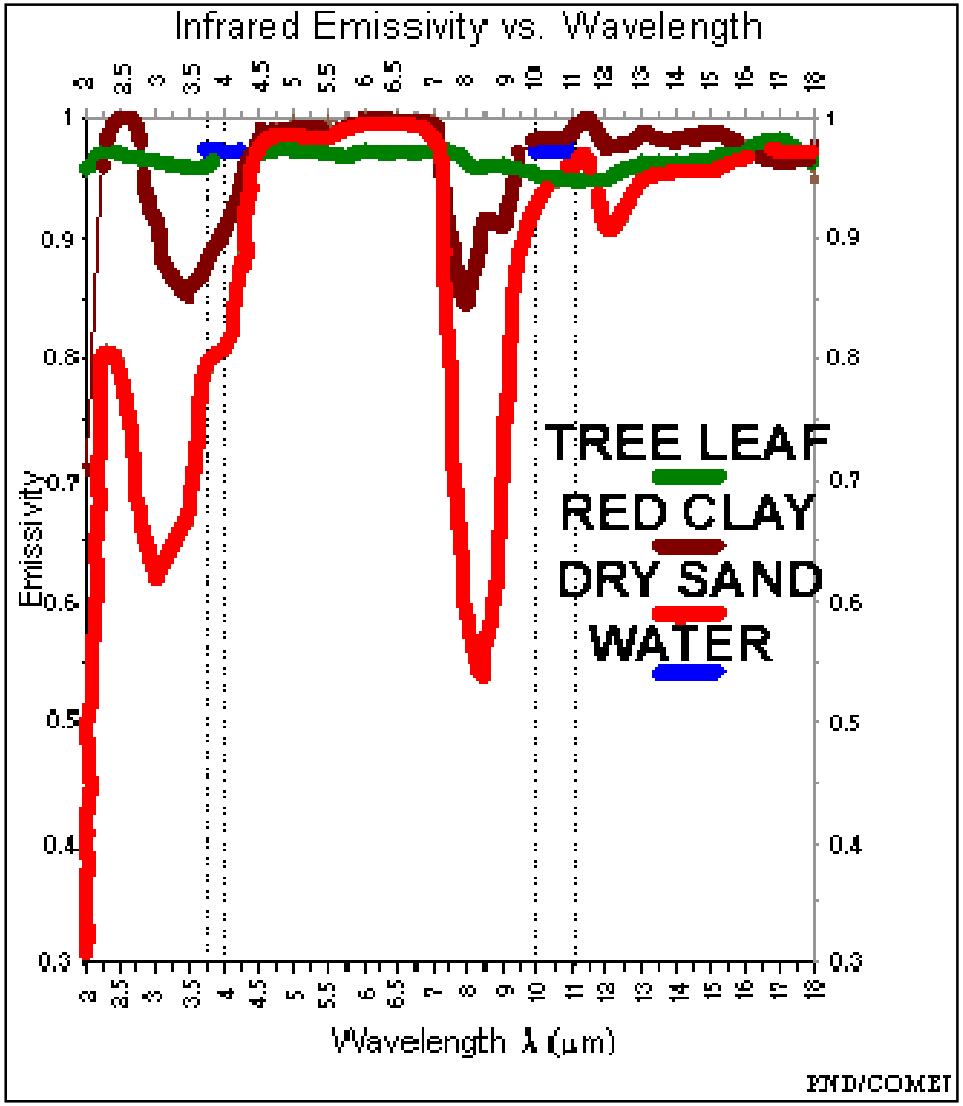
GOES-12 SOUNDER – RADIANCES – ALL BANDS FROM 14.7 TO 3.7 µm



Skin Depth and Absorption Efficiency

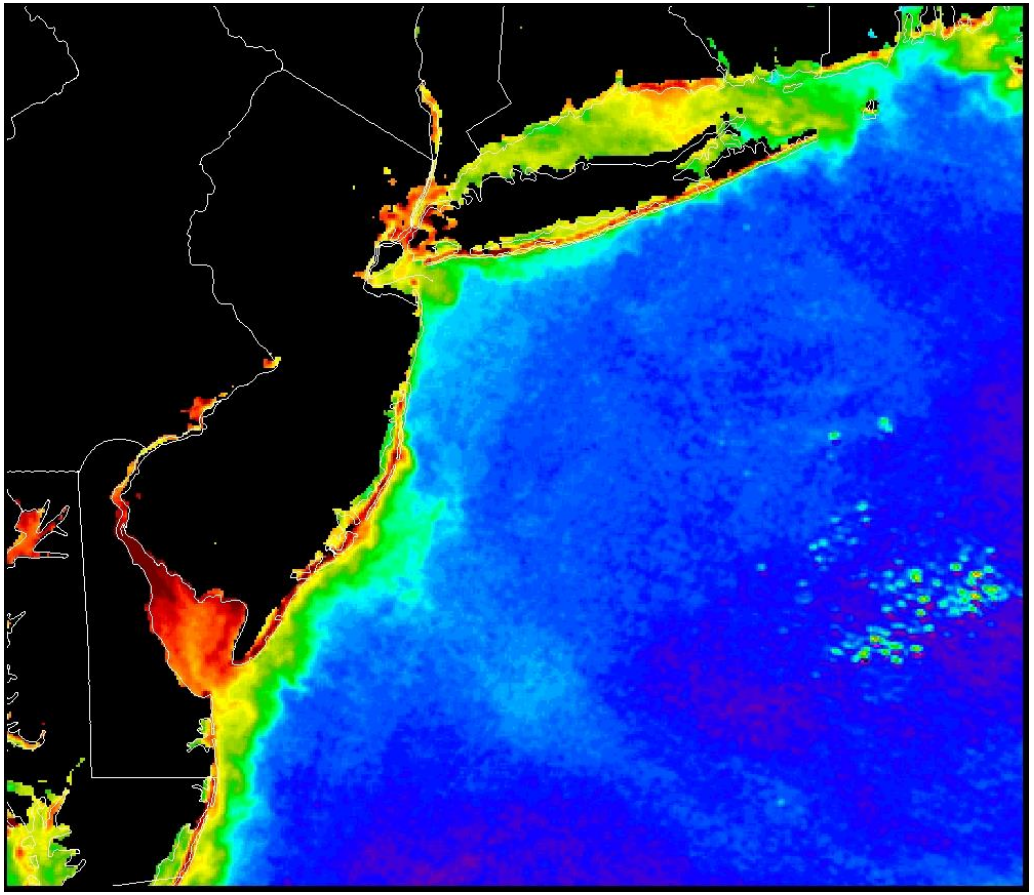


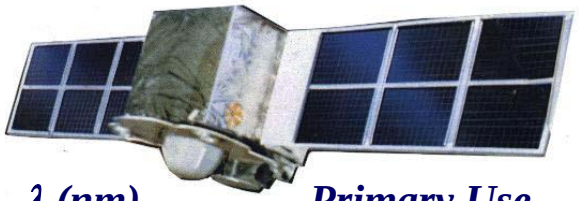
L'EMISSIVITÀ COME FUNZIONE DI λ E DEL TIPO DI SUOLO



- Emissività più variabile attorno ai 3.9 µm
- Le aree desertiche sembrano più fredde di 5-10 K nel canale IR3.9 che nel IR10.8 (di notte, atmosfera secca)
- Durante il giorno la superficie appare diversa, dipende dal tipo di suolo

Relative chlorophyll concentration. The FY1-D satellite has 10 channels in the visible and infrared spectrum and provides 1km resolution data. Red areas are indicative of murky green water, while blue areas represent clearer, bluer water. The raw satellite data is processed by ratioing channel 9:channel 7





Ch	*λ (nm)*	*Primary Use*
1	580-680	Daytime cloud, ice and snow vegetation
1	840-890	Daytime cloud, vegetation, water
3	3550-3930	Heat source, night cloud
4	10300-11300	SST, day/night cloud
5	11500-12500	SST, day/night cloud
1	1580-1640	Soil humidity, ice/snow distinguishing
7	430-480	Ocean color
8	480-530	Ocean color
9	530-580	Ocean color
10	900-965	Water vapor

Atmospheric Temperature Profile: US "Standard" Atmosphere.

Cirrus cloud level.
High cold clouds, visible optical depth range 0.001 to 10, emits IR to surface in the IR window.

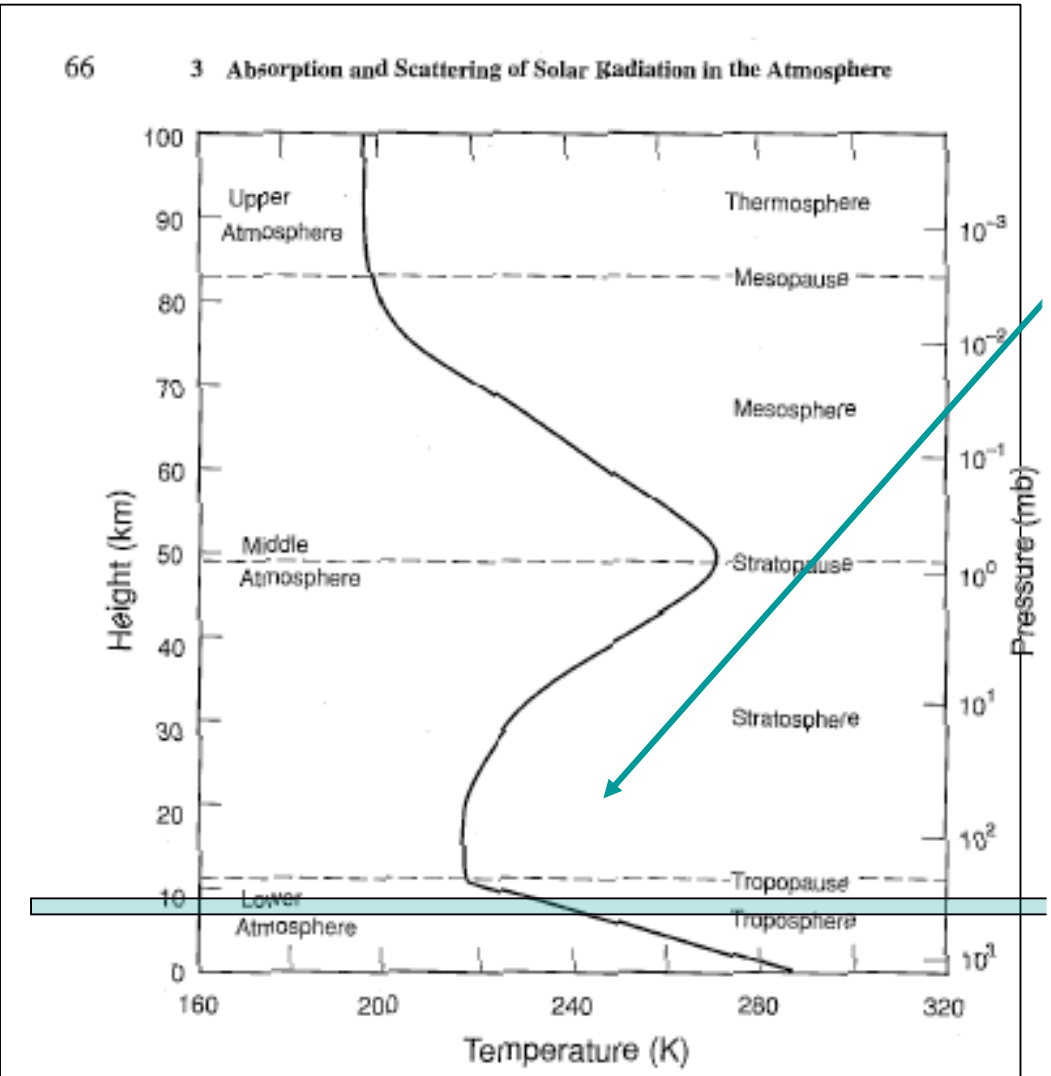
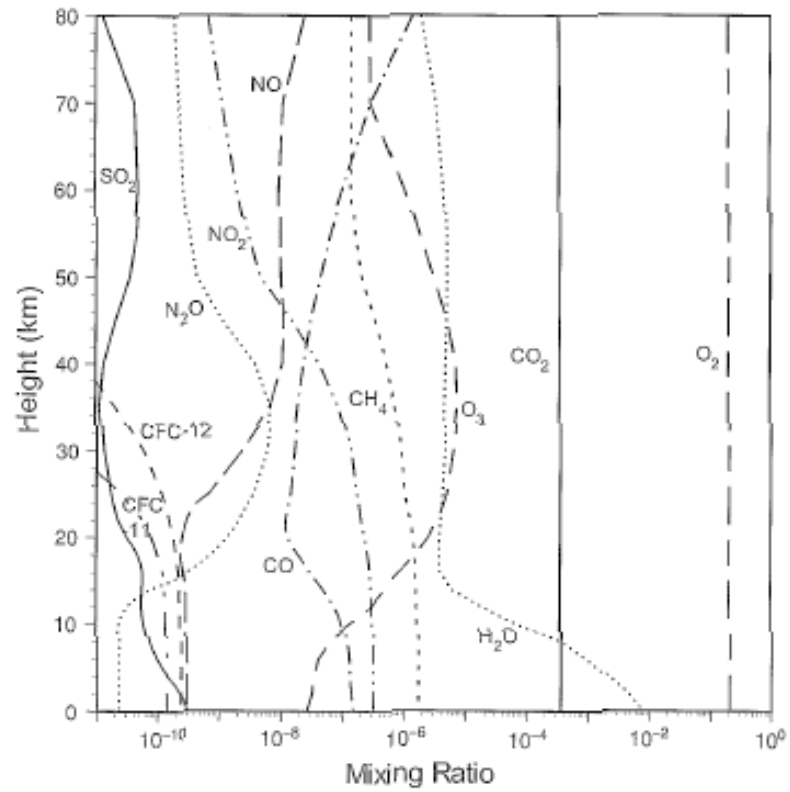


Figure 3.1 Vertical temperature profile after the U.S. Standard Atmosphere and definitions of at spheric nomenclature.



From Liou

Cirrus Clouds: Small Crystals at Top, -40 C to -60 C

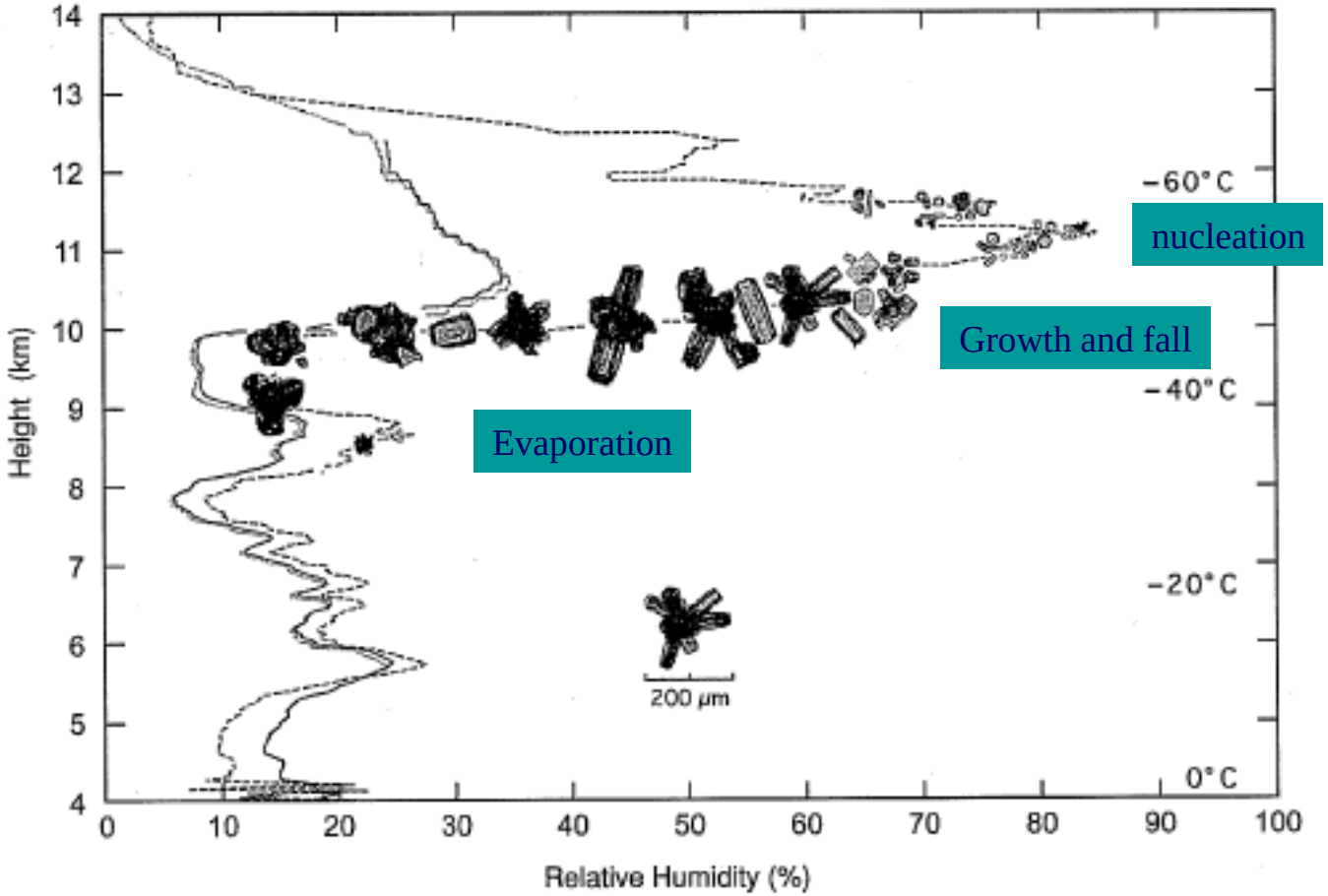


Figure 5.3 Ice crystal size and shape as a function of height and relative humidity captured by a replicator balloon sounding system in Marshall, Colorado, on November 10, 1994. The relative humidity was measured by cryogenic hygrometer (dashed line) and Vaisala RS80 instruments (solid line and dots). Also shown is temperature as a function of height (courtesy of Andrew Heymsfield of the National Center for Atmospheric Research).

IR Atmospheric window region

FTIR Data from the NASA ER2, Clear and Cloudy Sky. (From Liou's book). The ice cloud with small ice crystals has emissivity << 1, so the ground below is partially seen. Clouds reduce the IR making it to space in the atmospheric window region.

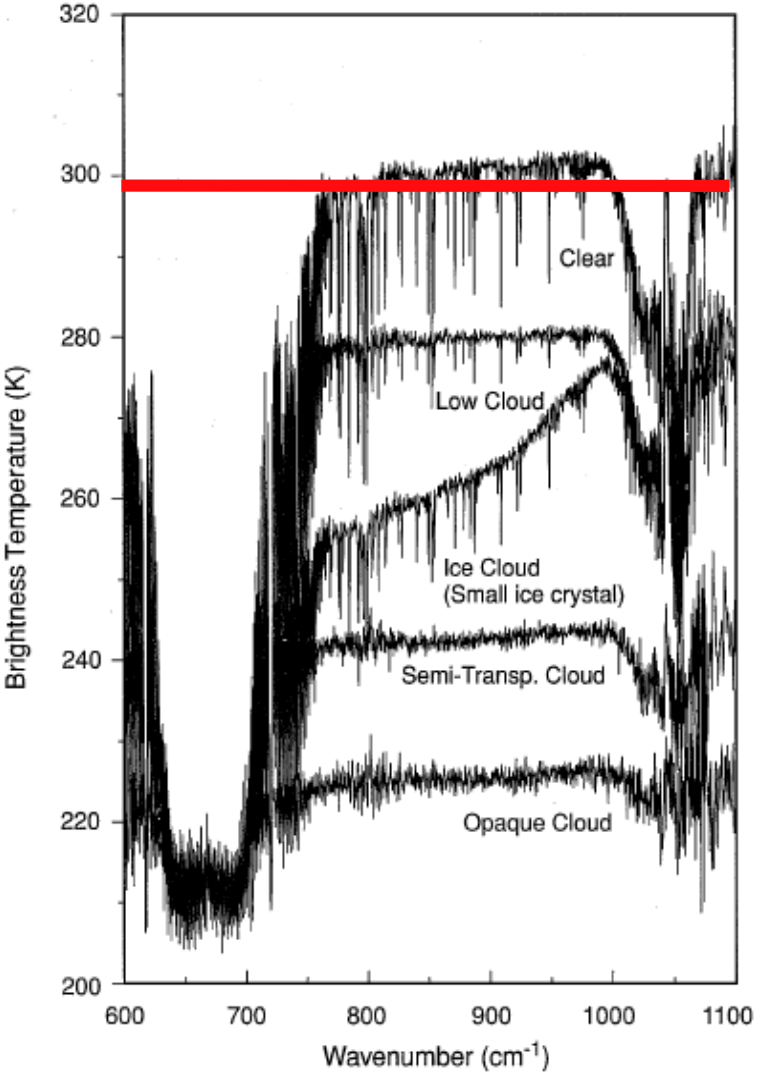
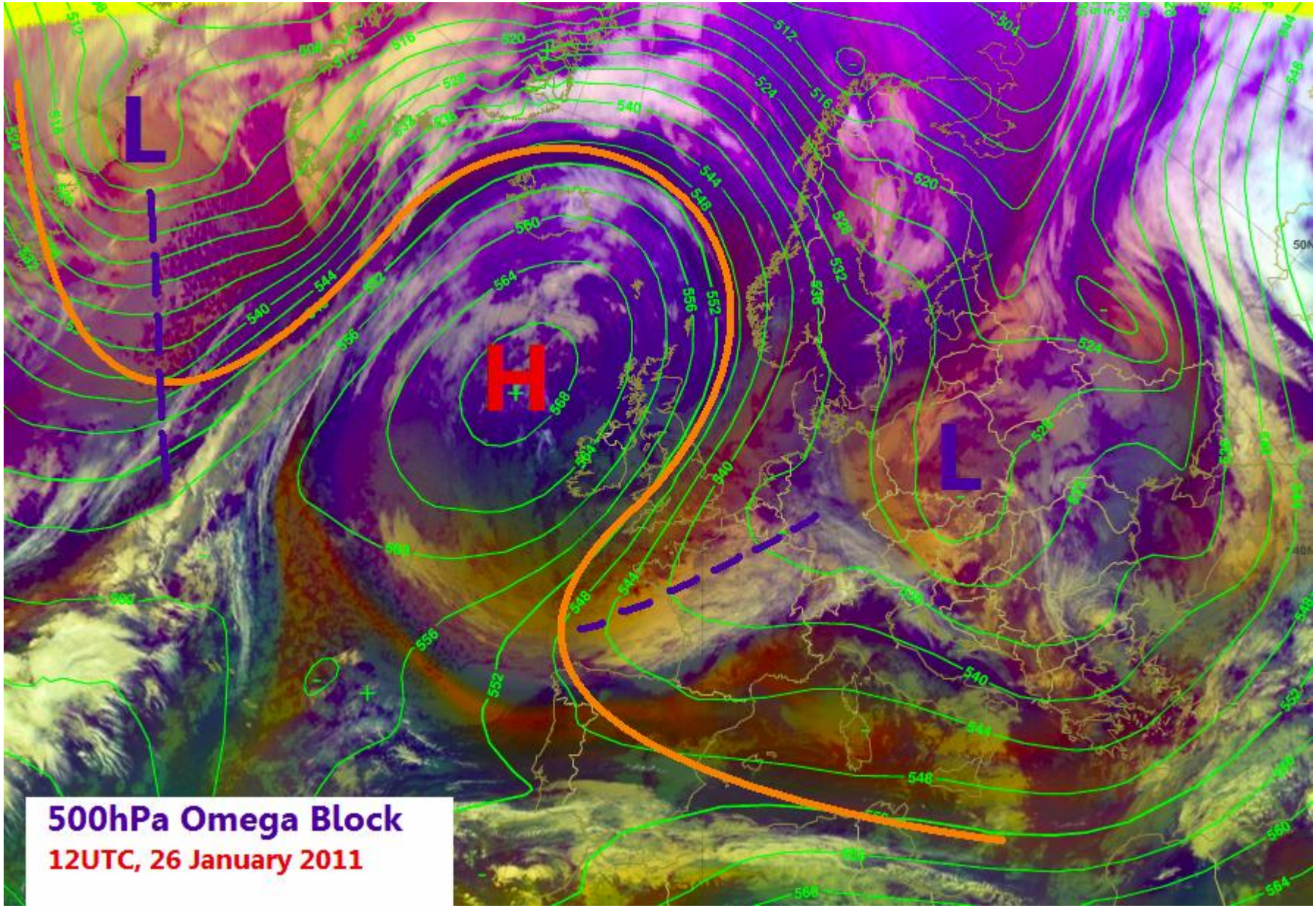


Figure 4.12 Spectra of brightness temperature observed from a high spectral resolution infrared spectrometer from the high-flying ER-2 aircraft over a domain, 37.1°–37.4° N, 95.0°–95.3° W, on April 21, 1996, indicating wavelength-dependent window brightness temperature changes according to various cloud types. The type of cloud indicated for each spectrum is identified from the Cloud Lidar System aboard the ER-2 (data taken from Smith *et al.*, 1998).

Satellite imagery interpretation: summary of theory

- EM energy is emitted by all surfaces, in proportion to T^4 (Stefan-Boltzmann).
- The wavelength at which the spectral EM emission peaks is inversely proportional to T (Wien).
- Solar energy at the top of the atmosphere is 44% visible and 48% IR.
- The 'shortwave' radiation (VIS) in the atmosphere is only from the Sun, while the 'longwave' radiation (IR) is both solar and terrestrial.
- The atmosphere *scatters* shortwave radiation, mainly the shorter wavelengths, yet most of the planetary albedo (30%) is due to clouds (two thirds).
- Clouds, even thin clouds, and most Earth surfaces behave as *blackbodies* (emissivity = 1 so absorptivity = 1 at any wavelength… Kirchoff)
- The albedo of clouds and Earth surfaces is highly variable.
- Specific frequencies, mainly in the IR band, are absorbed by gases in the atmosphere. The main window (other than the visible) is between 7-11 mm. There is a water vapor absorption band at 6.7 mm.
- Most satellite imagery is *passive* and *narrow-band*.


L
H
L
500hPa Omega Block
12UTC, 26 January 2011