Consiglio Nazionale delle Ricerche
Istituto di Fisica Applicata
"Nello Carrara" - Firenze

Infrared technologies for remote-sensing of the atmosphere

Ugo Cortesi

Institute for Applied Physics «Nello Carrara»
of the National Research Council
Firenze, Italy

The Abdus Salam
International Centre
for Theoretical Physics

Winter College on Opticsm
Light:: a Bridge between Earth and Space
Trieste, February 2015

Outline

1. The Earth's atmosphere
2. Remote sensing of the atmosphere
3. Passive remote-sensing of the atmosphere in the IR region
4. The MIPAS-ENVISAT mission

Outline

1. The Earth's atmosphere

2. Remote sensing of the atmosphere
3. Passive remote-sensing of the atmosphere in the IR region
4. The MIPAS-ENVISAT mission

The Earth's Atmosphere

The atmosphere is an aggregate of gases and suspended matter held by gravity in a thin layer sorrounding the planet.

Total mean mass of the atmosphere = 5.15×10^{15} kg

An upper limit of the atmosphere is not defined.

The atmospheric structure

The atmospheric vertical structure is determined by three basic state variables Temperature, pressure and density and by the equation of state.

IDEAL GAS LAW

$$p\,V = m\,R\,T$$

$$p = \rho\,R\,T$$

p = pressure	[Pa]
V = volume	[m^3]
m = mass	[kg]
R = specific gas constant	[$J\ kg^{-1}\ K^{-1}$]
T = absolute temperature	[K]
ρ = density	[$kg\ m^{-3}$]

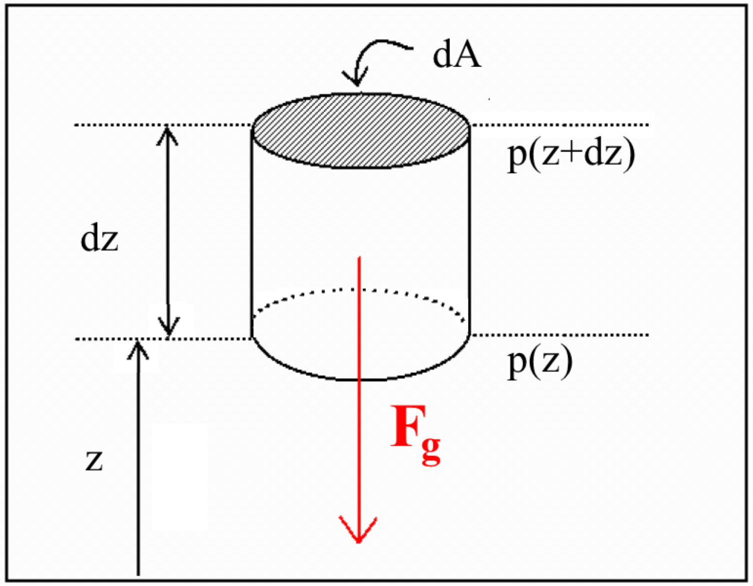
where $R = R^*/M$, with $R^* = 8.3143\ J\ K^{-1}\ mol^{-1}$ being the Universal Gas Constant and for dry air $R_d = R^*/M_d = 287\ J\ K^{-1}\ mol^{-1}$ ($/M_d = 28.97$ is the mean of the molar mass of the main components of dry air weighted with their molar fraction).

HYDROSTATIC BALANCE

In the absence of atmospheric motion, the force due to gravoty is exactly balanced by the vertical component of the pressure gradient

$$dp/dz = -\rho g$$

Hydrostatic Equation



where z is the altitude and g is the gravitational acceleration

If we combine the **Ideal Gas Law** and the **hydrostatic equation,** we obtain

$$dp/dz = -\, gp/RT$$

ISOTHERMAL ATMOSPHERE

If we assume that the Temperature is constant, i.e. $T = T_0$:

$$dp/dz = -\, gp/RT_0 = -\, p/H \quad \Rightarrow \quad p(z) = p_0 \exp(-z/H)$$

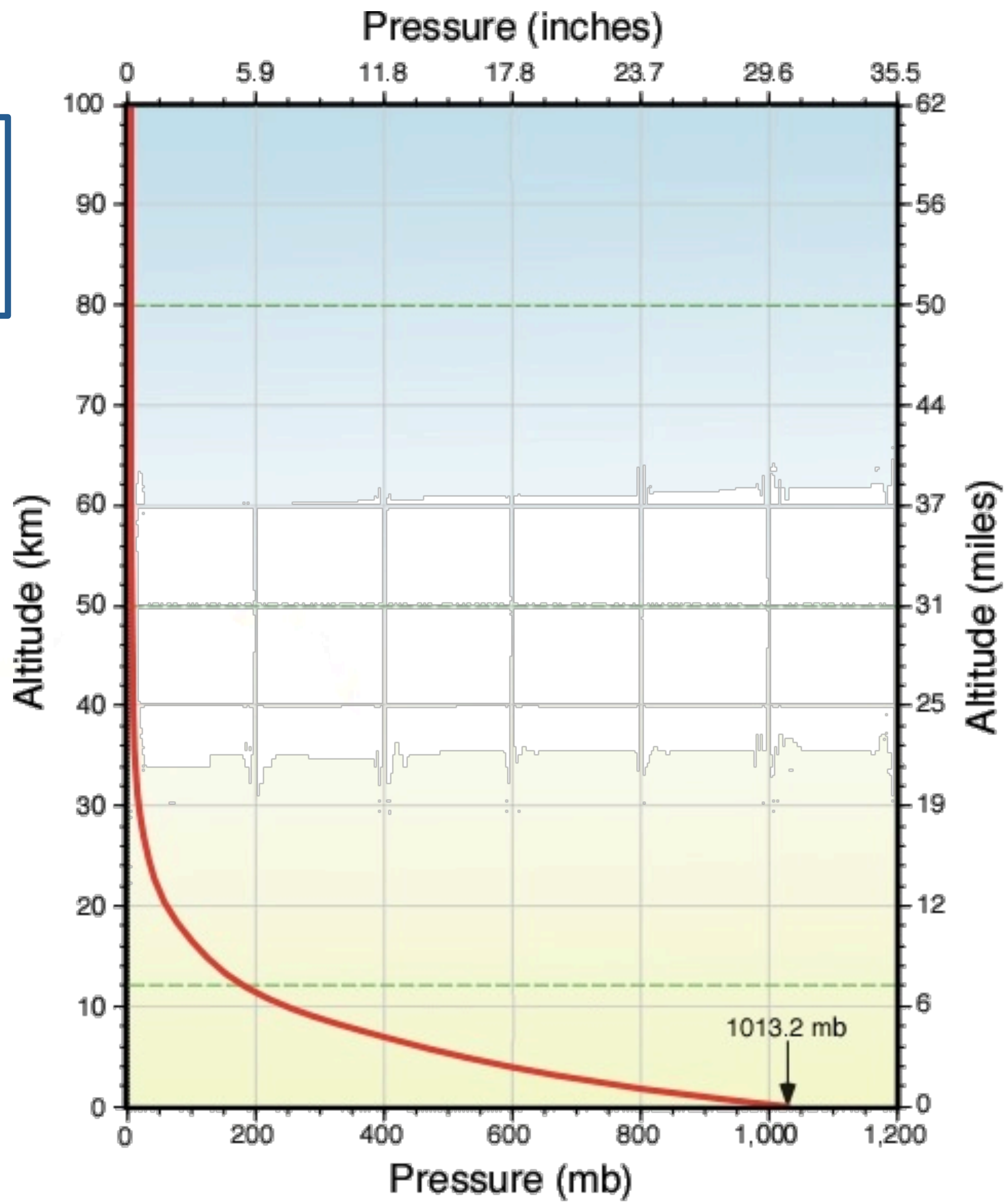
where $H = RT_0/g$ is the **SCALE HEIGHT** (constant if we neglect the variability of g with height) and p_0 is the pressure value at the surface..

NON-ISOTHERMAL ATMOSPHERE

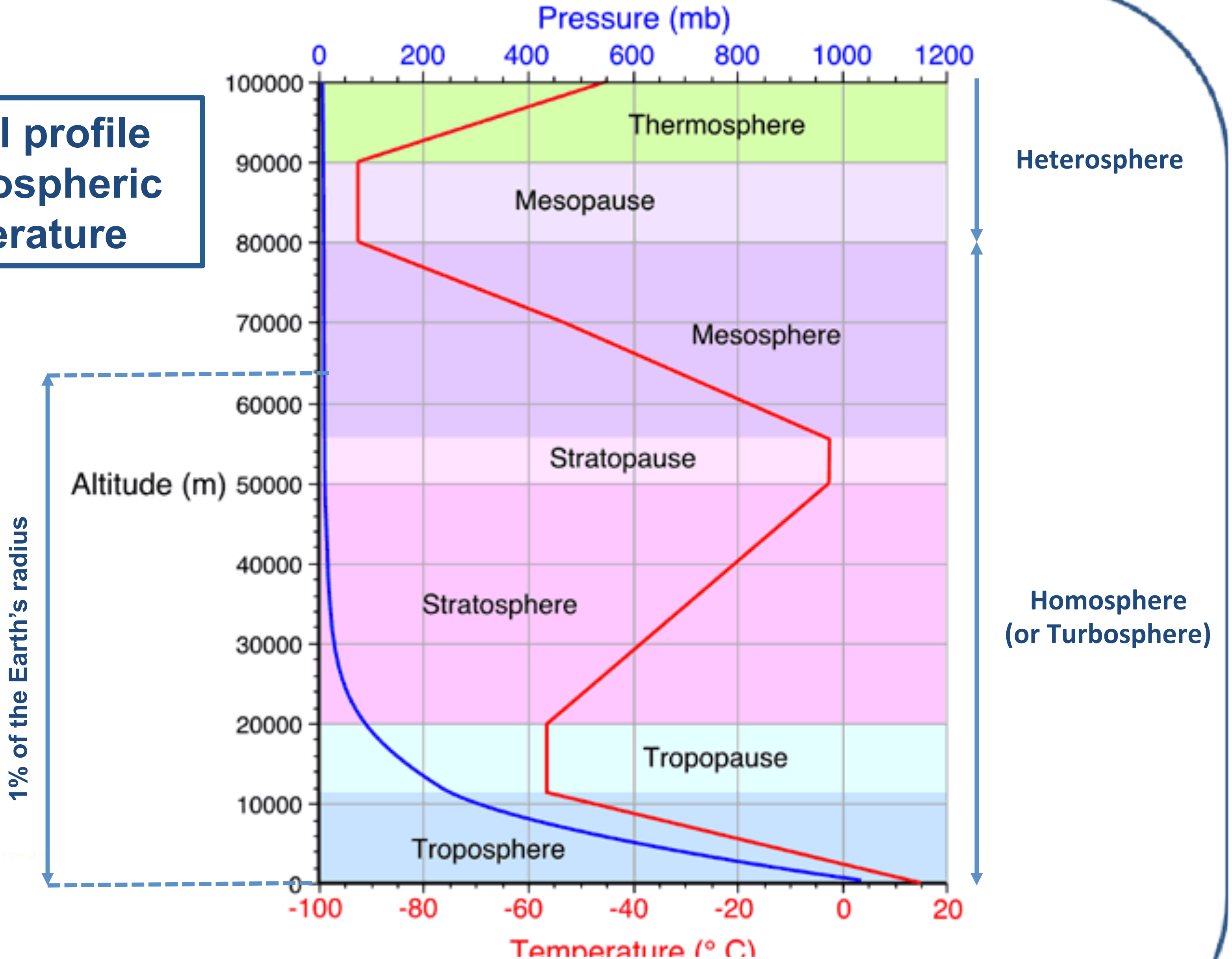
We define a **LOCAL SCALE HEIGHT** H(z) = RT(z)/g and we have:

$$dp/dz = -\, gp/RT(z) = -\, p/H(z) \quad \Rightarrow \quad p(z) = p_0 \exp\left(-\int_0^z dz'/H(z')\right)$$

Vertical profile of atmospheric pressure



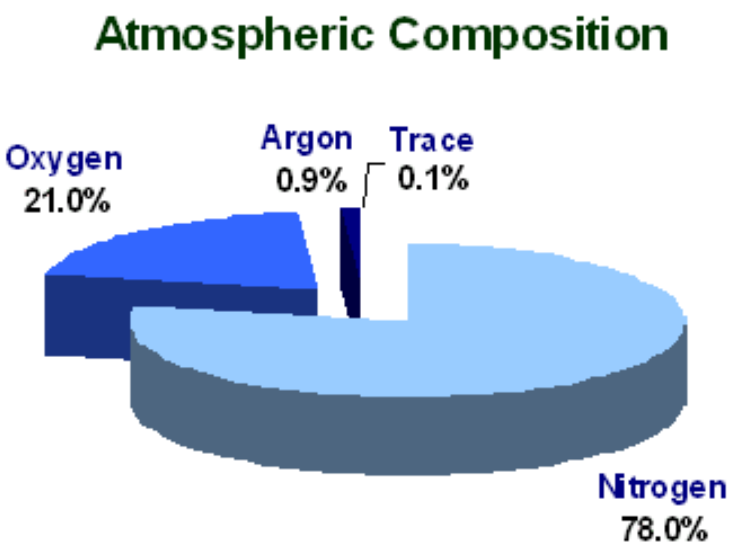
Vertical profile of atmospheric temperature

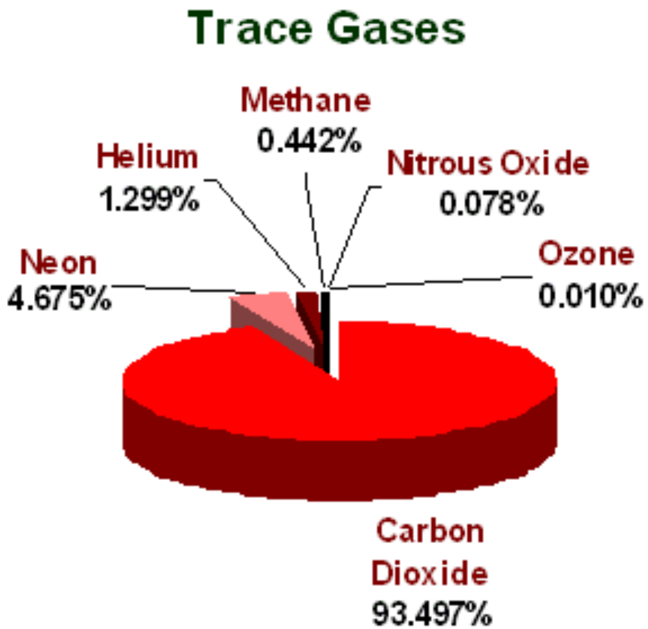


Lapse rate
Rate of decrease of Temperature with increasing height

$$\Gamma \equiv -\frac{\partial T}{\partial z}$$

Composition of the atmosphere





Composition of the atmosphere

PERMANENT GASES

NITROGEN	[N2]	78.08%
OXYGEN	[O2]	20.95.%
ARGON	[Ar]	0.93%

The relative percentages of the permament gases remain constant in the homosphere, up to the turbopause altitude (80-100 km)

VARIABLE GASES

WATER VAPOR	[H2O]	0-4%%
CARBON DIOXIDE	[CO2]	390 ppm
NEON	[Ne]	18 ppm
HELIUM	[He]	5 ppm
METHANE	[CH4]	1.8 ppm
KRYPTON	[Kr]	1 ppm
HYDROGEN	[H2]	0.5 ppm
NITROUS OXIDE	[N2O]	0.3 ppm
OZONE	[O3]	0.01-0.1 ppm

Dinamycs of the atmosphere

The **General Circulation of the Earth's atmosphere** is determined by the thermal contrast between the **equatorial** and the **polar regions**.

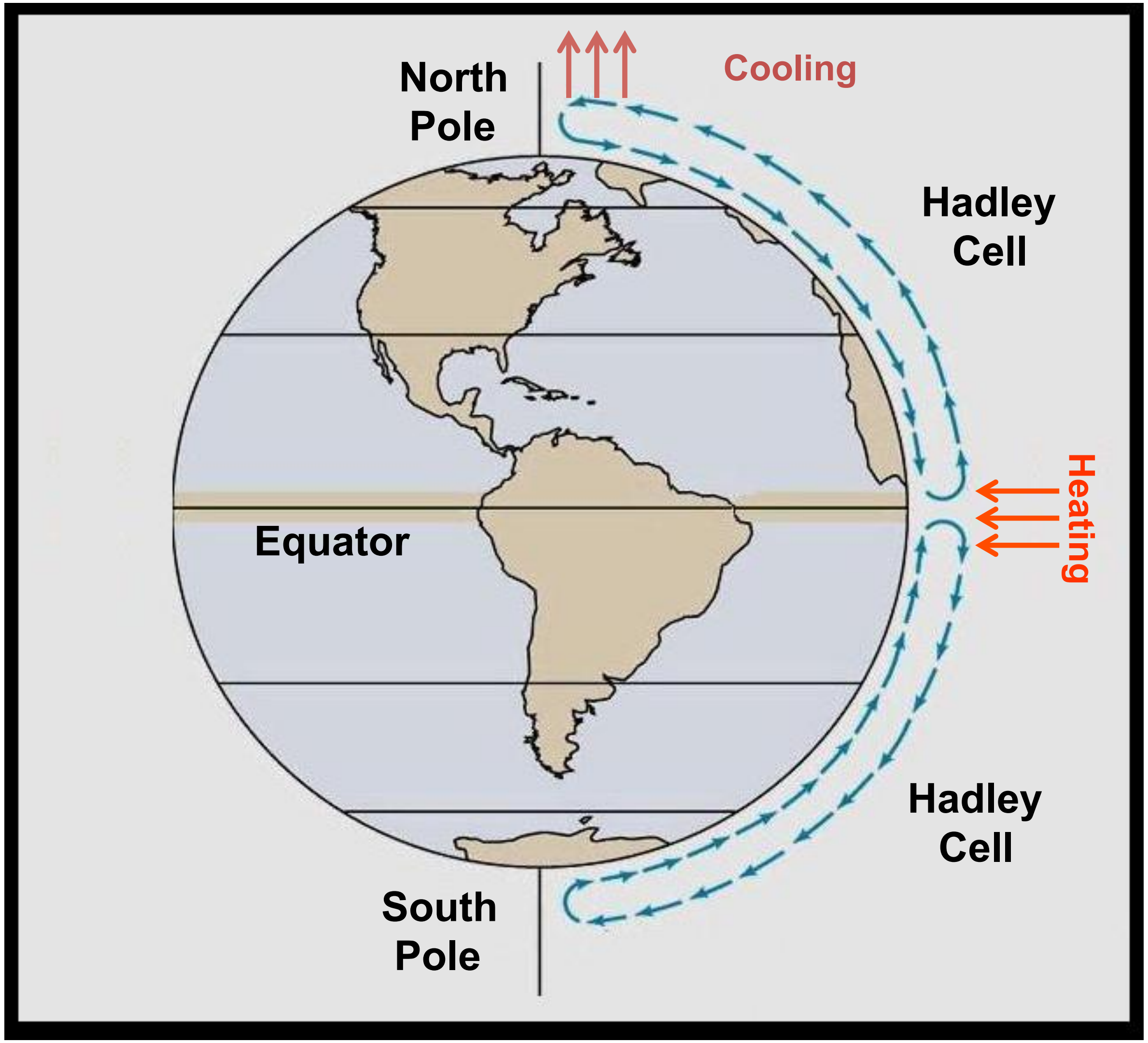
In absence of the Earth's rotation, differential heating of the surface at the Equator and at the Poles would generate a single convective cell for each hemisphere (**Hadley Cell**).

Because of terrestrial rotation, **Coriolis force** deflects the winds from the equator to the poles at the higher altitudes and generates a system of **three cells** for each hemisphere:

In the Northern Hemisphere:

- Air masses moving SOUTHWARD turn EASTWARD.
- Air masses moving NORTHWARD turn WESTWARD

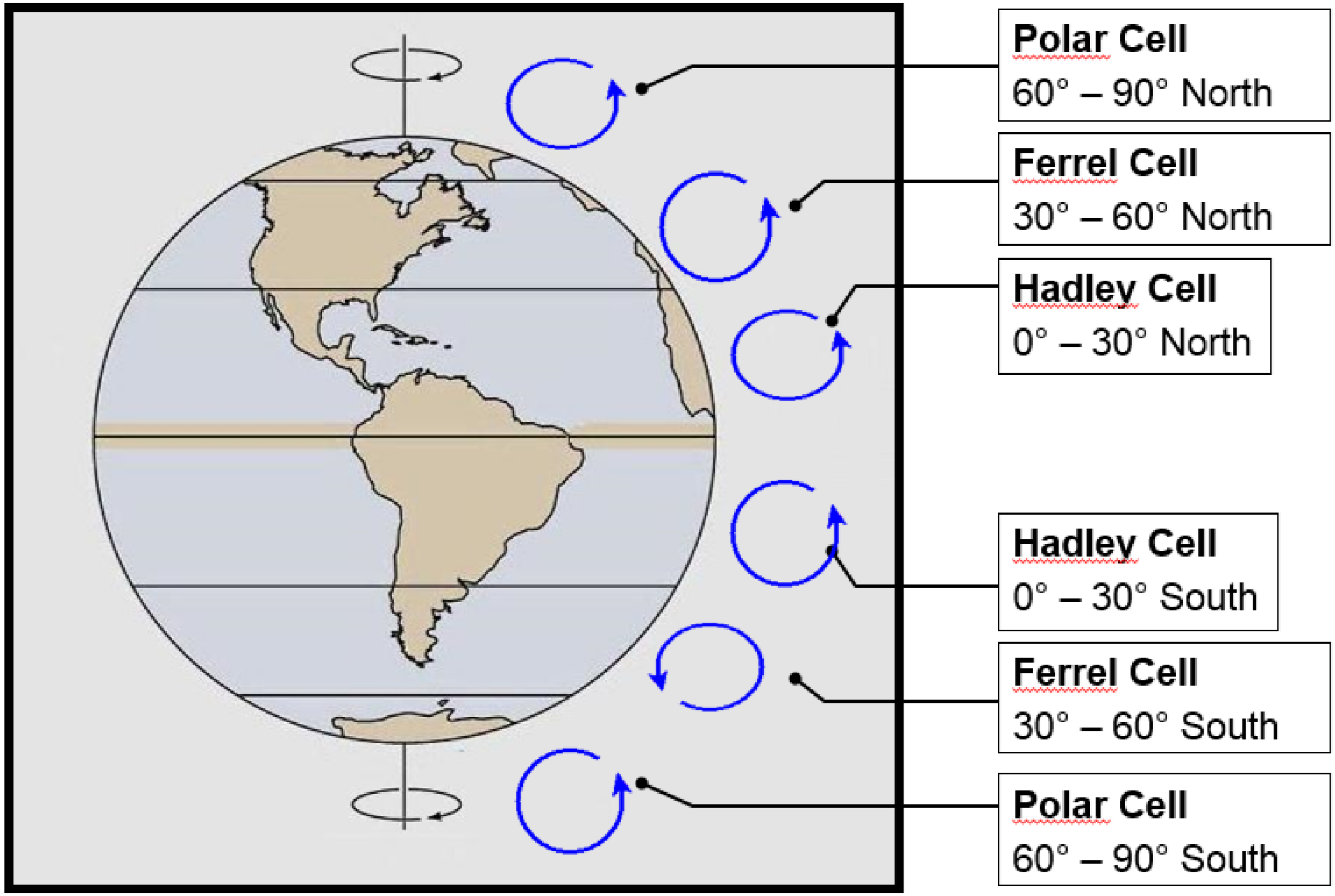
and viceversa in the Southern Hemisphere.



Factors controlling global circulation of air masses:

(1) **uneven solar heating at different latitudes**

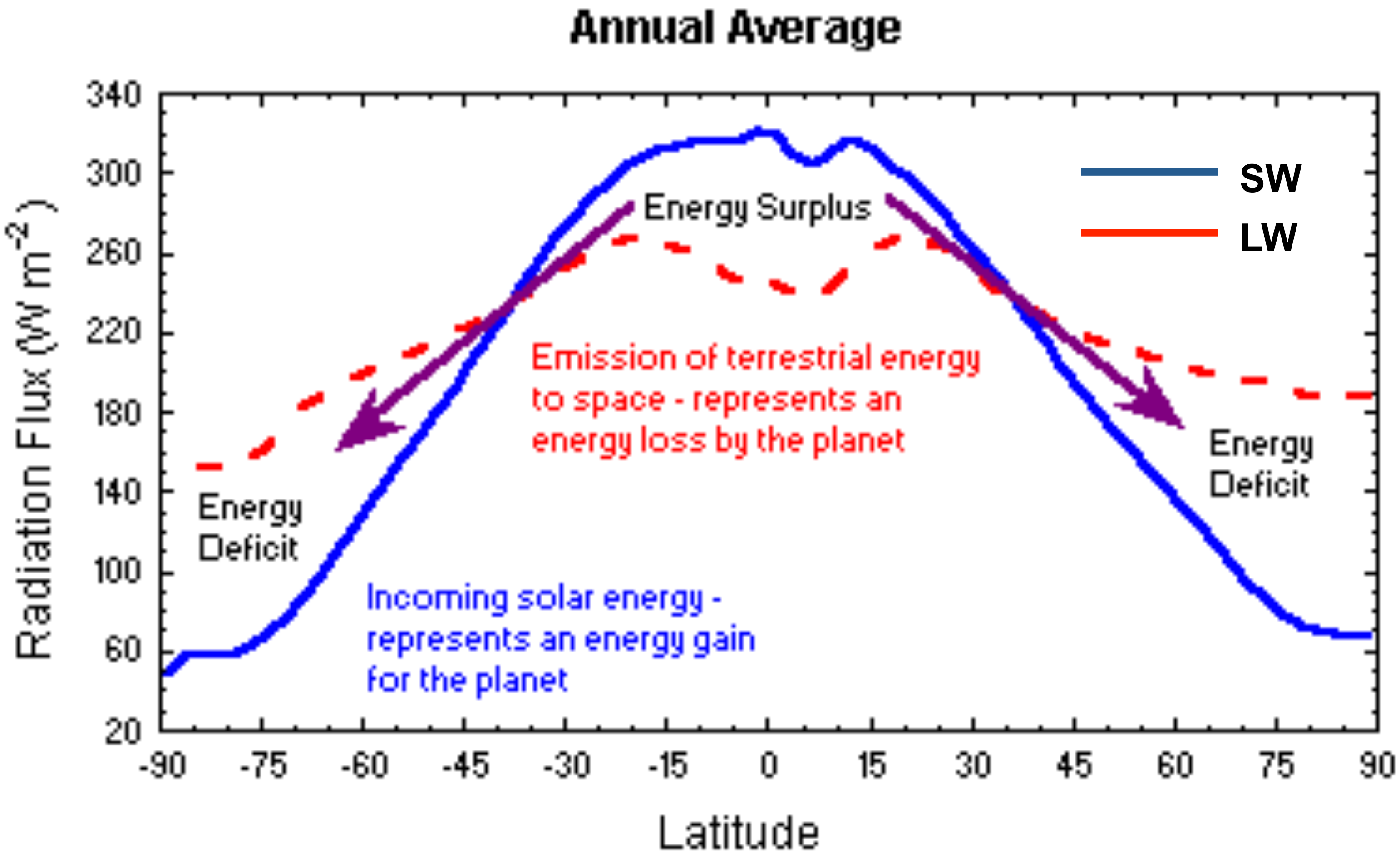
(2) [the Coriolis effect]



Factors controlling global circulation of air masses:

(1) **uneven solar heating at different latitudes**

(2) **the Coriolis effect**



Energy surplus from extra solar heating
with respect to terrestrial emission cooling at low latitudes
is transferred by atmosphere and ocean circulation
to higher lattiudes.

Outline

1. The Earth's atmosphere
2. **Remote sensing of the atmosphere**
3. Passive remote-sensing of the atmosphere in the IR region
4. The MIPAS-ENVISAT mission

Observation of the Earth's atmosphere

WHY?

Motivation for continuous and global monitoring of the state of the atmosphere (structure and chemical composItion, transport of air masses and radiatio budget) and investigation of chemical, dynamical and radiative processes at different spatial and temporal scales..

Copernicus/ Program – Sentinel 4 and 5 (ref. Mission Requirements Document)

Environmental Theme Information	**Ozone Layer & Surface UV radiation** **A**	**Air Quality** **B**	**Climate** **C**
Protocols **1**	UNEP Vienna Convention; Montreal and subs. Protocols CFC emission verification Stratospheric ozone, halogen and surface UV distribution and trend monitoring	UN/ECE CLRTAP; EMEP / Göteborg Protocol; EC directives EAP / CAFE AQ emission verification AQ distribution and trend monitoring	UNFCCC Rio Convention; Kyoto Protocol; Climate policy EU GHG and aerosol emission verification GHG/aerosol distribution and trend monitoring
Services **2**	Stratospheric composition and surface UV forecast NWP assimilation and (re-) analysis	Local Air Quality (BL); Health warnings (BL) Chemical Weather (BL/FT) Aviation routing (UT)	NWP assimilation and (re-) analysis Climate monitoring Climate model validation
Assessments **3**	Long-term global data records WMO Ozone assessments Stratospheric chemistry and transport processes; UV radiative transport processes Halogen source attribution UV health & biological effects	Long-term global, regional, and local data records UNEP, EEA assessments Regional & local PBL AQ processes; Tropospheric chemistry and long-range transport processes AQ source attribution AQ Health and safety effects	Long-term global data records IPCC assessments Earth System, climate, rad. forcing processes; UTLS transport-chemistry processes Forcing agents source attribution Socio-economic climate effects

Application per environment theme and user information

Observation of the Earth's atmosphere

HOW?

Identification of the most suitable observation strategies and measurement techniques to meet the increasingly demanding requirements on atmospheric targets

Observation of the Earth's atmosphere

- **IN-SITU** and **REMOTE-SENSING** measurements
- **DIRECT** and **INDIRECT** measurements
- **ACTIVE** and **PASSIVE** measurements

Observation Geometry

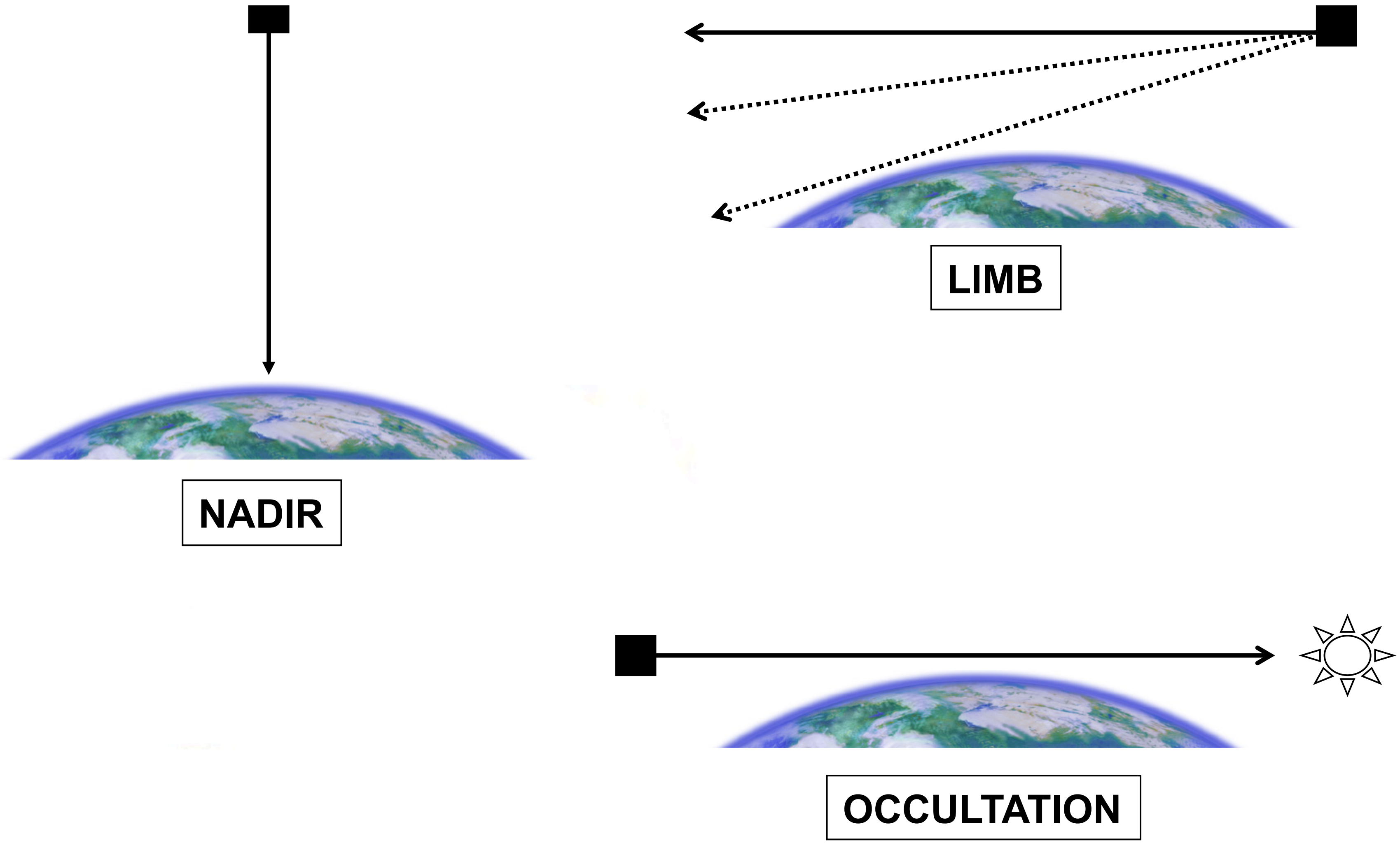
Observation platfrom

- Space platform (satellites, ISS)
- Airborne platform (aircraft, balloon, LTA platform)
- Ground station

Viewing Geometry

- Limb
- Occultation
- Nadir
- Zenith

Viewing geometry



Forward modeling of the observation

A **radiative transfer model** in the atmosphere calculates the spectral radiance at any point in space, as a function of frequency and of the direction of propagation determined by the observation geometry.

SPECTRAL RADIANCE (or **MONOCHROMATIC INTENSITY**) is the energy transferred by electromagnetic radiation in one direction, per unit area normal to the direction of propagatio , per unit time and per unit frequency.

$$I(\sigma,\theta)=\frac{\mathrm{dE}_{\sigma}}{\cos(\theta)\cdot dA\cdot dt\cdot d\Omega\cdot d\sigma}\qquad\left[\frac{\mathrm{W}}{\mathrm{m}^{2}\cdot sterad\cdot cm^{-1}}\right]$$

A **FORWARD MODEL** calculates the spectral radiance measured by an instrument by convolving the atmospheric spectral radiance obtained from the radiative transfer model with instrumental effects.

ILS = INSTRUMENT LINE SHAPE

$$\mathrm{S}(\sigma,\theta)=\int\!\!\int\left[\mathrm{I}(\sigma,\theta)\cdot\mathrm{ILS}(\sigma-\sigma')\cdot\mathrm{d}\sigma'\right]\cdot\mathrm{IFOV}(\theta-\theta')\,\mathrm{d}\theta'$$

IFOV = INSTANTANEOUS FIELD OF VIEW

Radiative transfer in the Earth's atmosphere

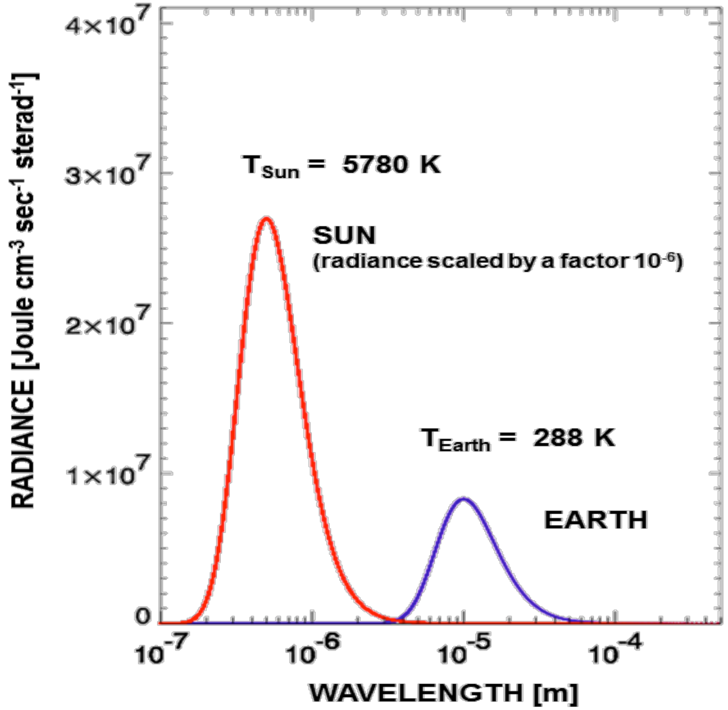
The **RADIATIVE TRANSFER THEORY** describes the interaction of electromagnetic energy (solar radiation and terrestrial radiation) and atmospheric matter (gas, aerosol and clouds).

Radiation propagating through the atmosphere consists of two main components:

- Radiation coming from the Sun (SW, short-wavelength, $\lambda < 4.0\ \mu m$)
- Radiation emitted from atmosphere/surface (LW, long-wavelength, $\lambda > 4.0\ \mu m$)

The two contributions can be described in first approximation as radiation emitted from blackbodies at temperature Tsun and Tearth and are significant in different spectral regions.

Therefore, solar radiation and terrestrial radiation can be treated in a separate manner.



Extinction and Emission of e.m. radiation

The interactions between an electromagnetic radiation field and a medium can occur as two classes of processes: **EXTINCTION** and **EMISSION**.

EXTINCTION decreases the intensity of radiation through processes of **absorption** and **scattering**.

EXTINCTION = ABSORPTION + SCATTERING

ABSORPTION is a process that removes radiant energy from the e.m. field and transfer it to another form of energy

SCATTERING is a process that does not remove energy from the radiation field, but can change its direction.

EMISSION increases the iradiant energy of the e.m. field through the mechanisms of **THERMAL EMISSION** and **SCATTERING**.

EMISSION = THERMAL EMISSION + SCATTERING

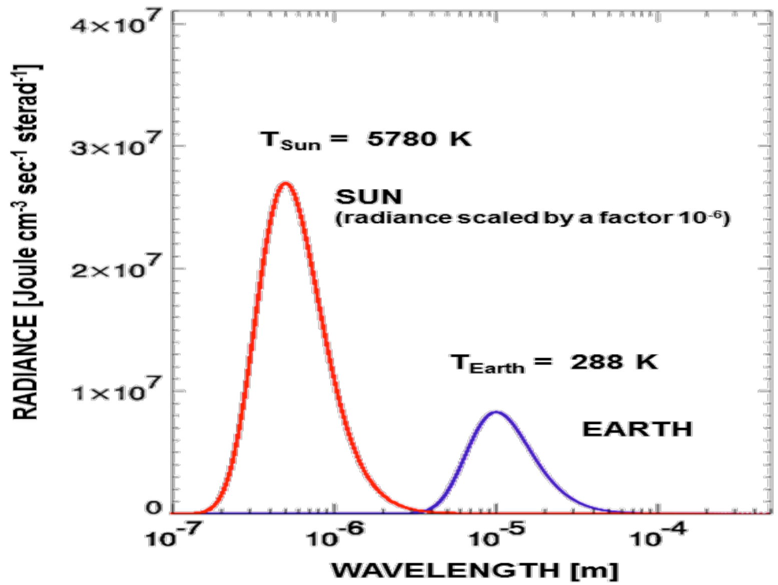
THERMAL EMISSION is the process by which any material at temperature larger than 0°K emits radiation by spontaneous transitions between energy levels of atoms and molecules.

Extinction and Emission in the Earth's atmosphere

INTERACTIONS RADIATION-MATTER
IN THE EARTH'S MATTERE

Solar radiation
Terrestrial radiation

Gas
Aerosol
Clouds



	Solar Radiation		Terrestrial Radiation	
Atmospheric Components	Absorption	Scattering	Absorption and Emission	Scattering
Gas	A	B	A	C
Aerosol	B	B	B	C
Clouds	B	A	A	C

RADIATIVE TRANSFER &
EARTH RADIATION BUDGET

A = first priority processes
B = second priority processes
C = processes with negligible effects

Atmospheric Radiative Transfer Equation

The **RADIATIVE TRANSFER EQUATION** is a differential equation to calculate the variation in the spectral intensity of the radiation propagating in the terrestrial atmosphere.

The full form of the equation describes the general case of loss and gain in intensity due to to the interaction of radiation with gas molecules and particles of aerosol and clouds and associated to the different processes of absorption, emission and scattering.

For radiation propagating through an atmospheric path of length dx the radiative transfer equation is:

$$\frac{dI_\sigma}{dx} = -\gamma_\sigma \cdot I_\sigma + S_\sigma$$

RADIATIVE TRANSFER EQUATION

LOSS (extinction): $-\gamma_\sigma \cdot I_\sigma$

GAIN (sources): S_σ

γ_σ = extinction coefficient per unit volume

$$\gamma_\sigma = \alpha_\sigma + s_\sigma$$

α_σ = absorption coefficient

s_σ = scattering coefficient

S_σ = Total Source Function

$$S_\sigma = \gamma_\sigma \cdot J_\sigma = j_\sigma^{therm} + j_\sigma^{scat}$$

j_σ^{therm} = contribution of thermal emission

j_σ^{scat} = contribution of scattering

The **RADIATIVE TRANSFER EQUATION** can also be written in the form:

$$\frac{dI_\sigma}{dx} = -[\alpha_\sigma + s_\sigma] \cdot I_\sigma + j_\sigma^{therm} + j_\sigma^{scat}$$

Or in the equivalent form:

$$\frac{dI_\sigma}{d\tau} = -I_\sigma + J_\sigma$$

Schwarzchild Equation

where **τ** is the **OPTICAL DEPTH** of the atmospheric path travelled by the radiation, which determines the opacity of the medium and which is defined by:

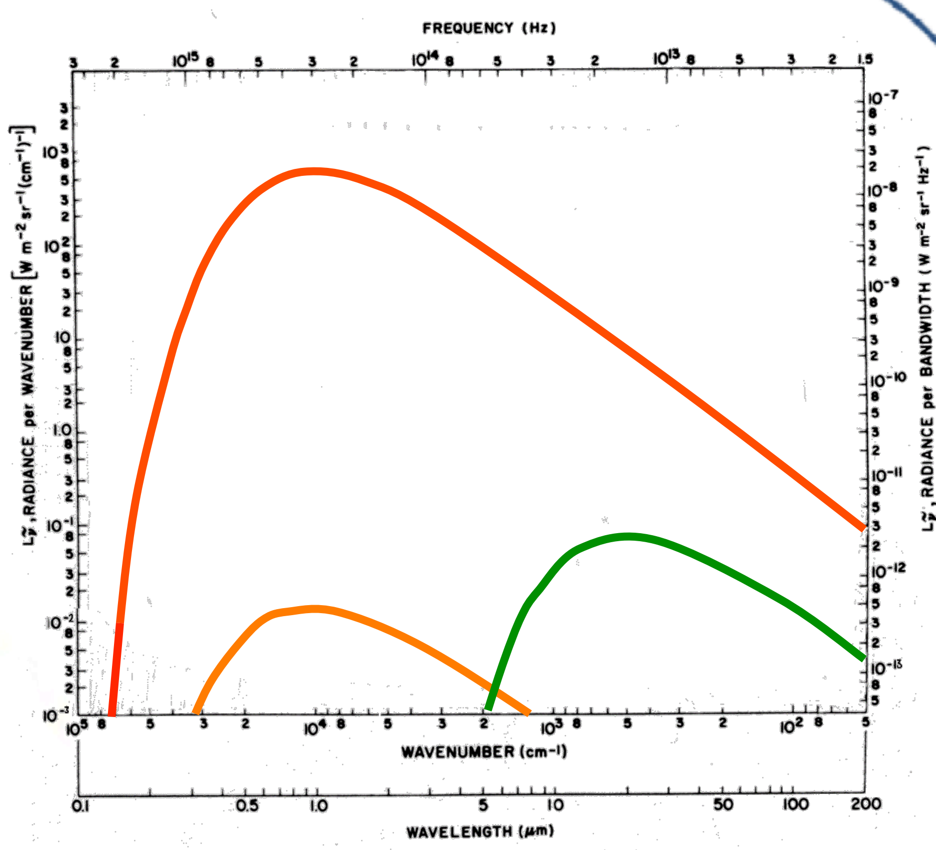
$$d\tau = [\alpha_\sigma + s_\sigma] \cdot dx$$

The Sources

Sun/Star
Moon
Earth/planet

Atmosphere

Sun
Earth/atmosphere

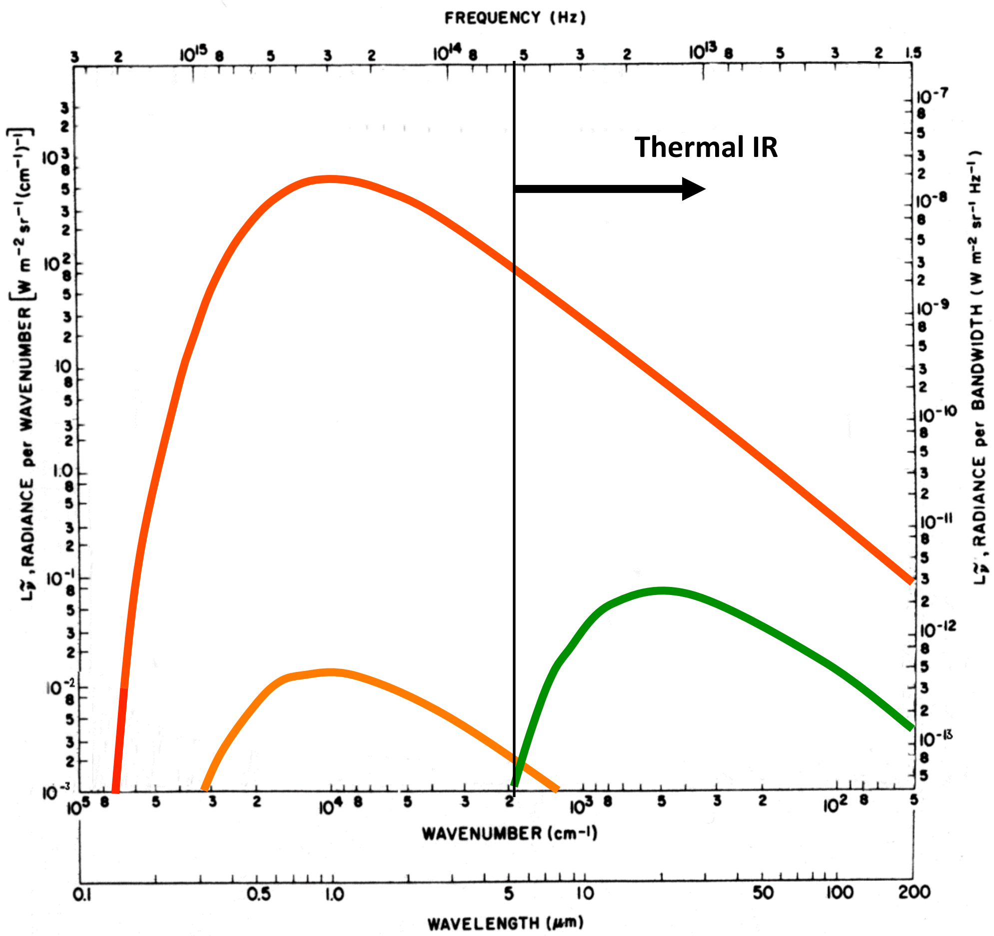


$$\frac{dI_\sigma}{dx} = -\left[\alpha_\sigma + s_\sigma\right]\cdot I_\sigma + j_\sigma^{therm} + j_\sigma^{scat}$$

RADIATIVE TRANSFER EQUATION

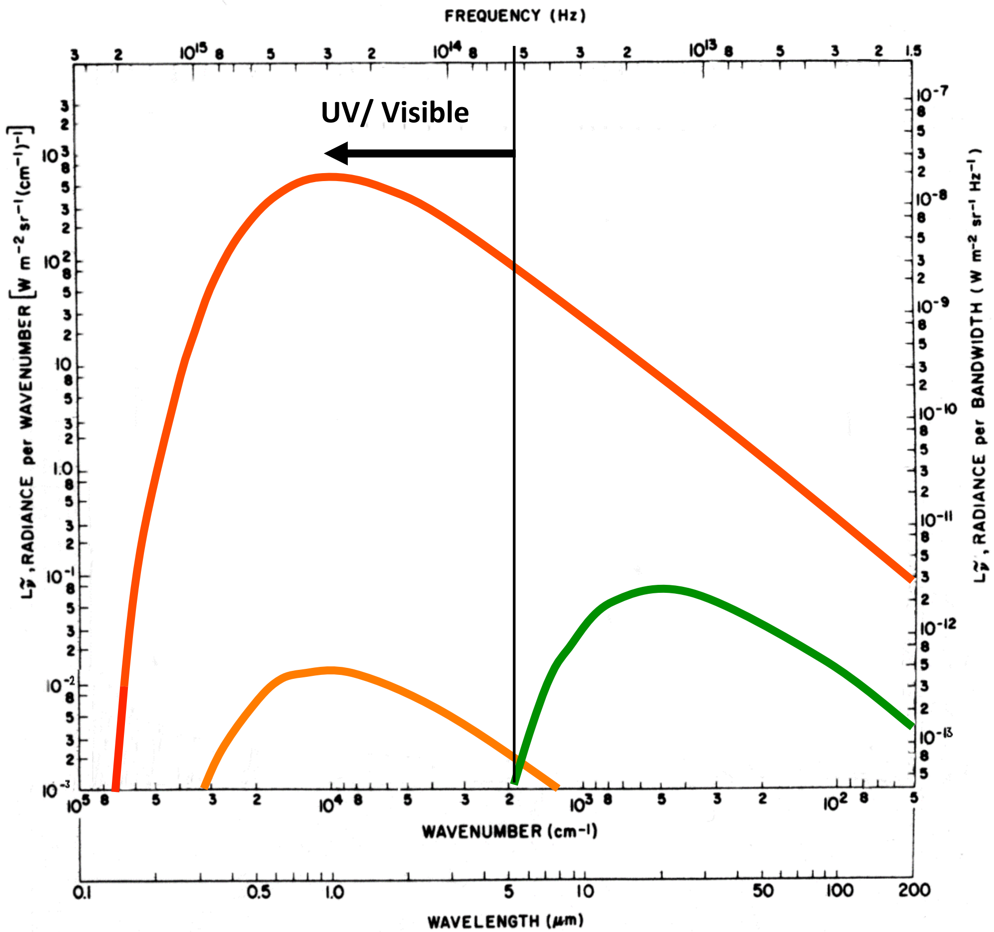
Thermal Infrared
Sources

- SUN: solar occulation
- ATMOSPHERE: emission sounding

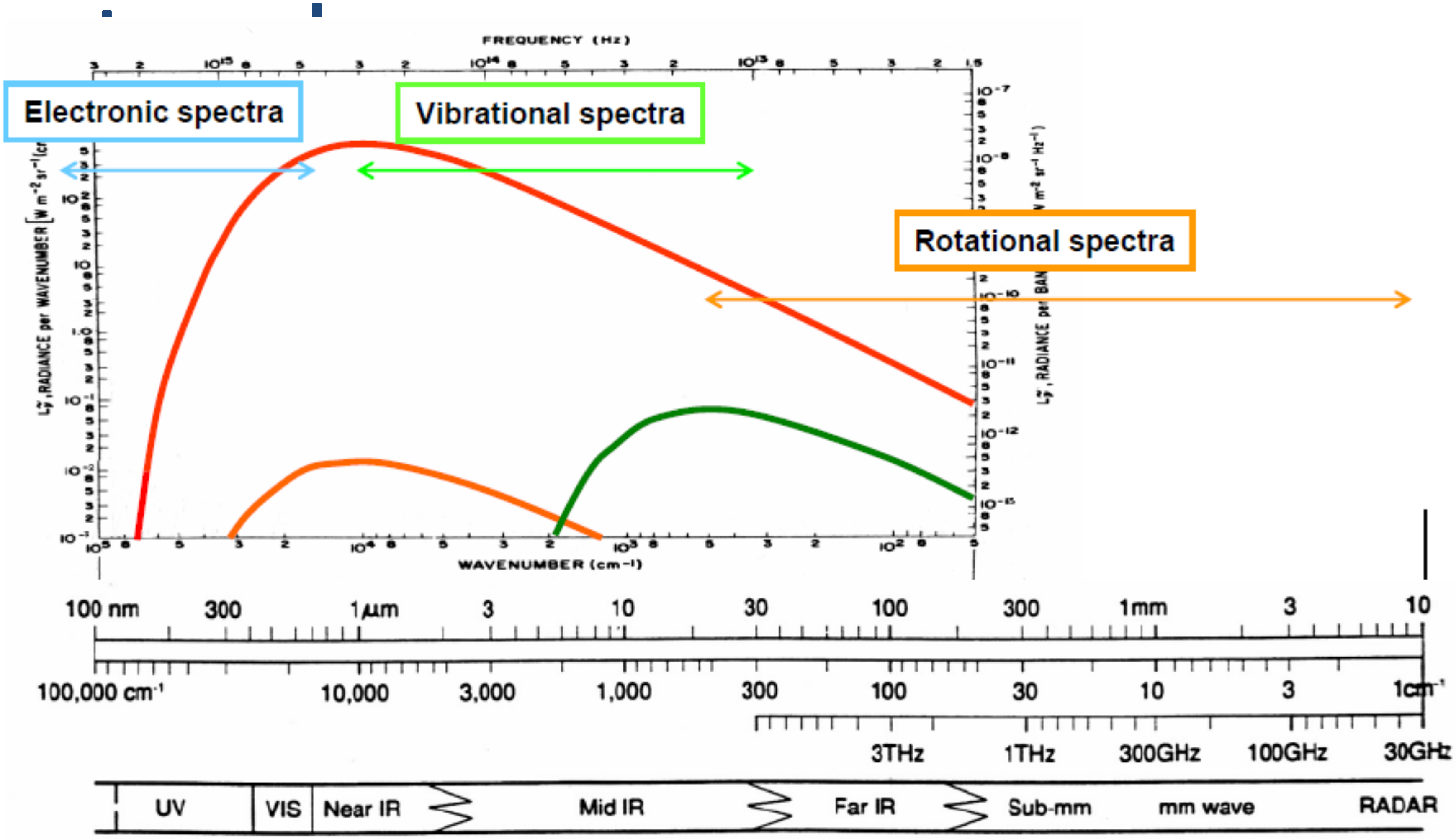


Near-IR & VIS/UV
Sources

- SUN: solar occulation e scattering
- MOON: moon occultation
- STARS: star occultation



Spectroscopy of the Earth's



Spectroscopy of the Earth's

Main spectroscopic constituents of the Earth's atmosphere:

- water vapor (●●)
- ozone (●●●)
- carbon dioxide (●)
- methane (●)
- nitrous oxide (●●)
- nitric acid (●●)

Rotational spectra

Vibrational spectra

Electronic spectra

ICTP

Spectroscopy of the Earth's

LINE WIDTH

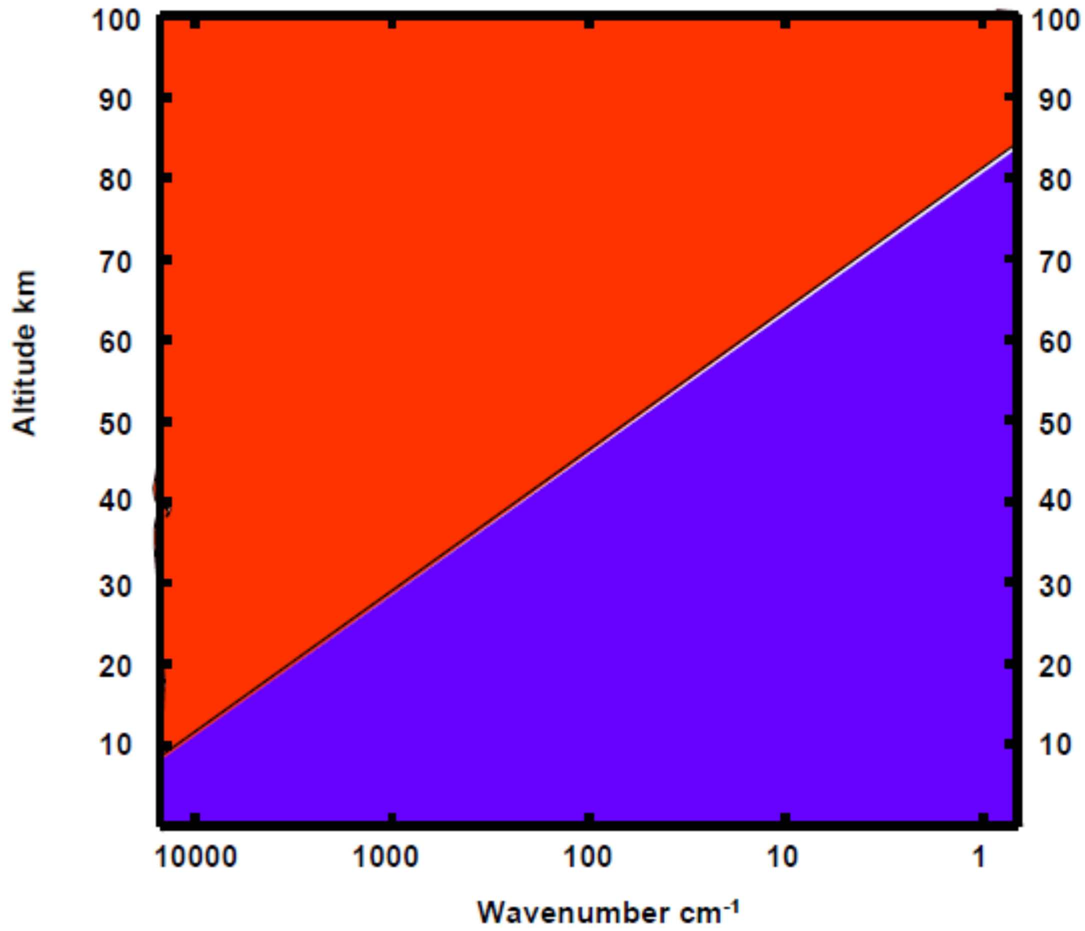
Temperature broadening:
Gaussian line shape

$$\Delta\sigma \propto \sigma \cdot \sqrt{T}$$

Pressure broadening:
Lorentzian line shape

$$\Delta\sigma \propto P$$

Voight line shape equal convolution between Gaussian and Lorentzian distributions.

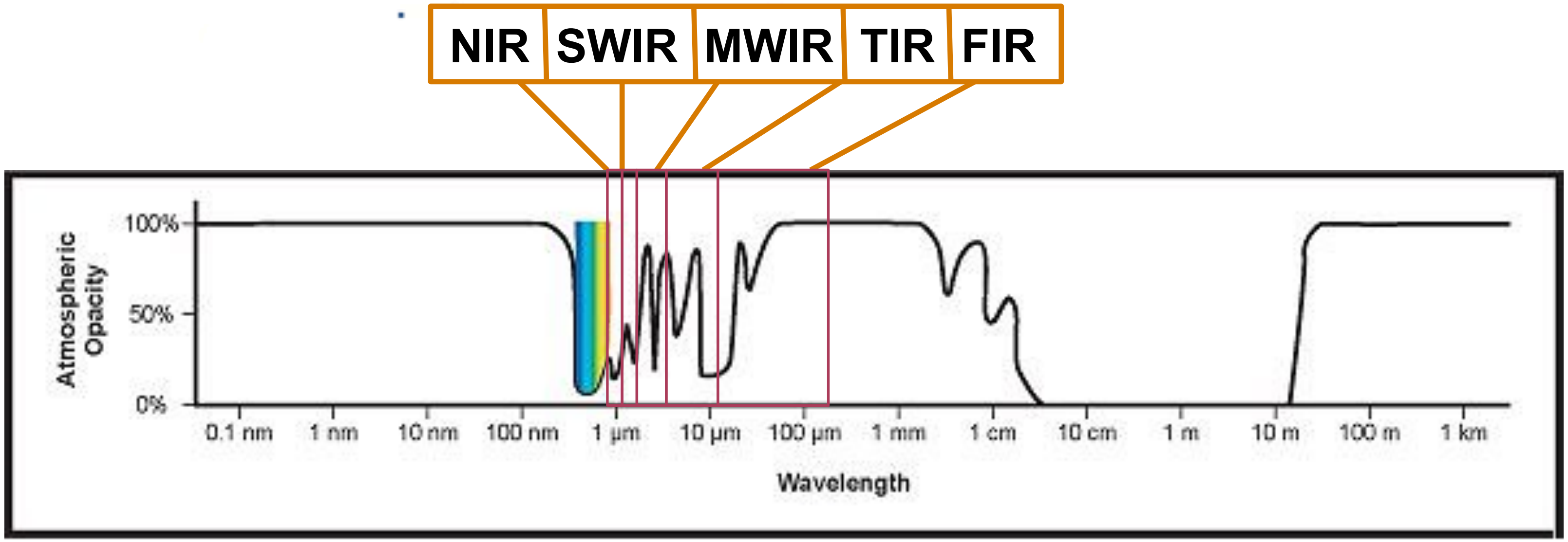


Outline

1. The Earth's atmosphere
2. Remote sensing of the atmosphere
3. **Passive remote-sensing of the atmosphere in the infrared region**
4. The MIPAS-ENVISAT mission

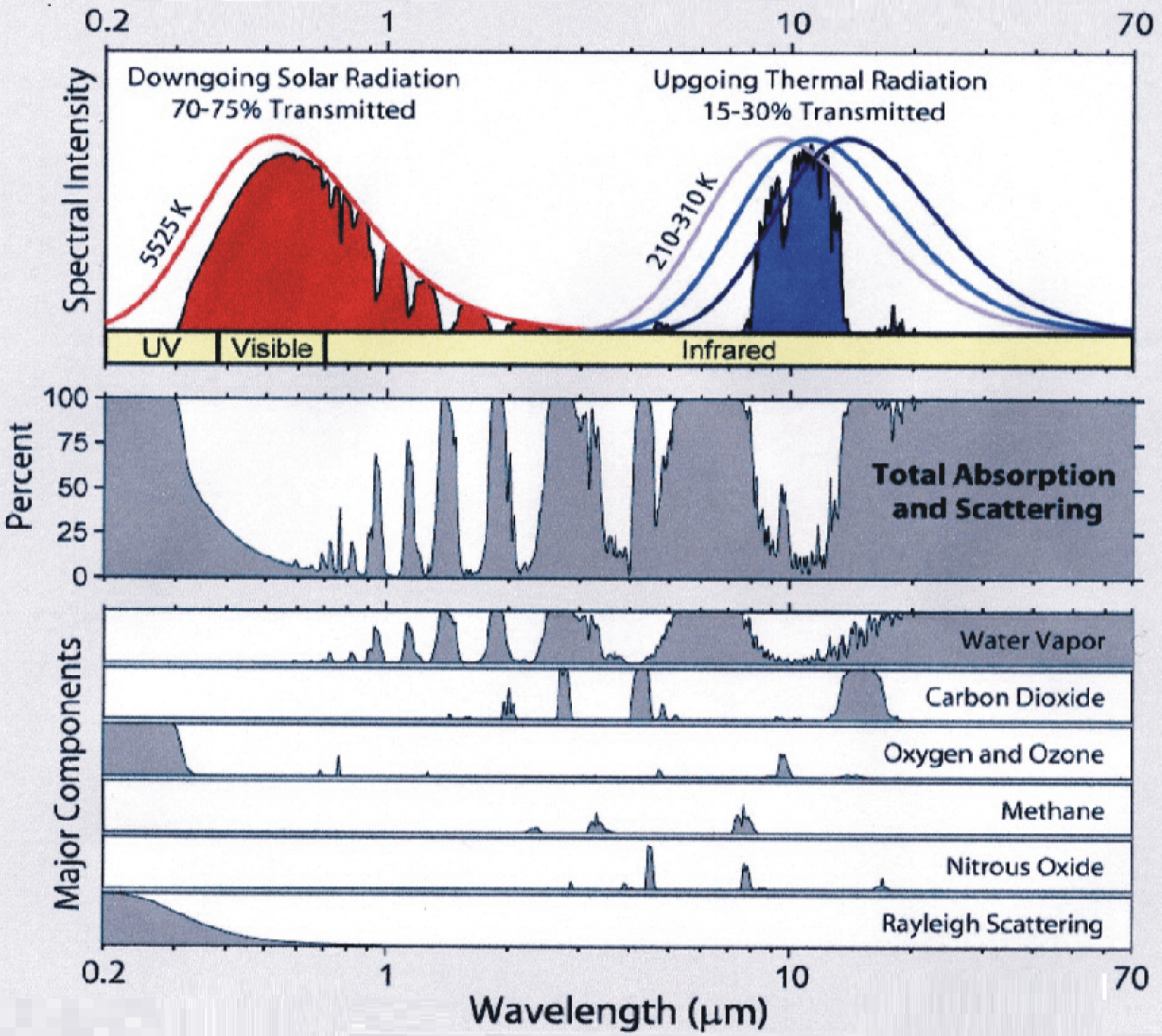
The Infrared spectral region

Near Infrared	**NIR**	0.7 – 1.5 μm
Short-wavelength Infrared	**SWIR**	1.5 – 3.0 μm
Mid-wavelength Infrared	**MWIR**	3.0 – 8.0 μm
Long-wavenght Infrared	**LWIR**	8.0 – 15 μm
or Thermal Infrared	**TIR**	
Far Infrared	**FIR**	longer than15 μm



Atmospheric Opacity

Radiation transmitted by the atmosphere

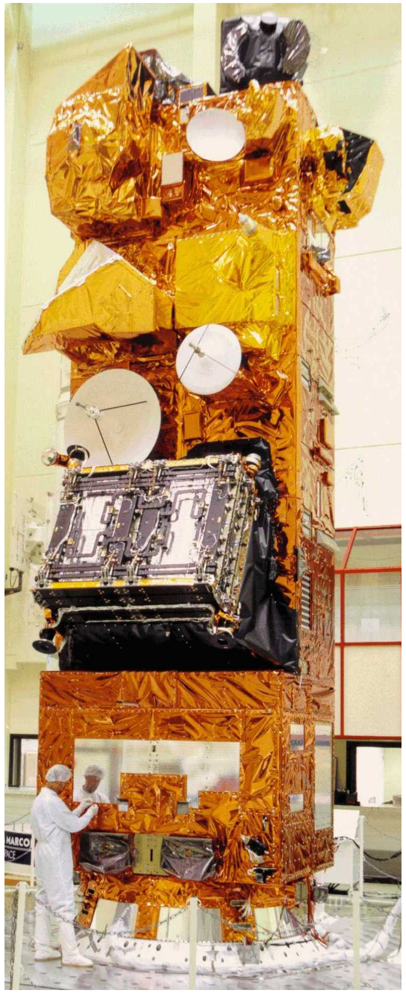


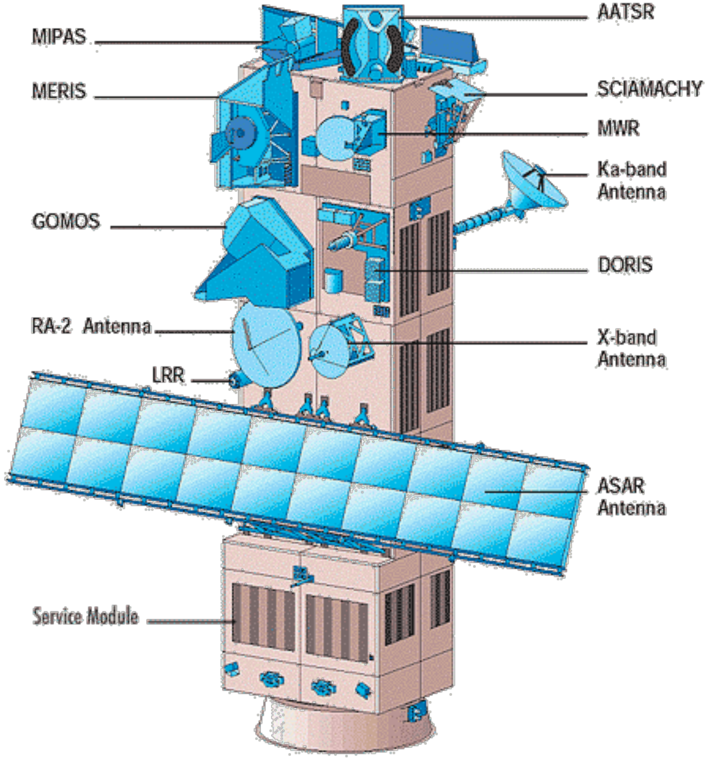
Outline

1. The Earth's atmosphere
2. Remote sensing of the atmosphere
3. Passive remote-sensing of the atmosphere in the IR region
4. **The MIPAS-ENVISAT mission**

The global picture of atmospheric composition by MIPAS-ENVISAT

The ENVISAT Mission





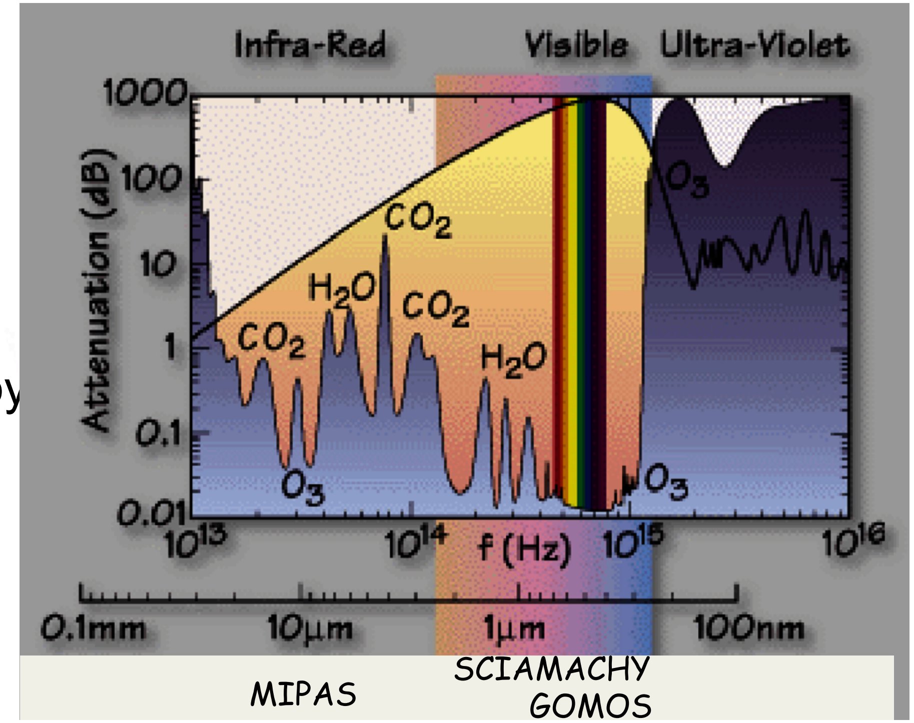
The **ENVironment SATellite** was launched by ESA on March 1°, 2002, carrying onboard a scientific payload of 10 multi-disciplinary instruments for Earth observation.

The ENVISAT mission ended on 8 April 2012 after 10 years of operation

The atmospheric chemistry payload onboard the ENVISAT mission

Three instruments of the ENVISAT mission aimed at the study of atmospheric chemistry

- **MIPAS** Michelson Interferometric Passive Atmospheric Sounder
- **GOMOS** Global Ozone Monitoring by Occultation of Stars
- **SCIAMACHY** Scanning Imaging Absorption spectrometer for Atmospheric Cartography



MIPAS-ENVISAT scientific objectives

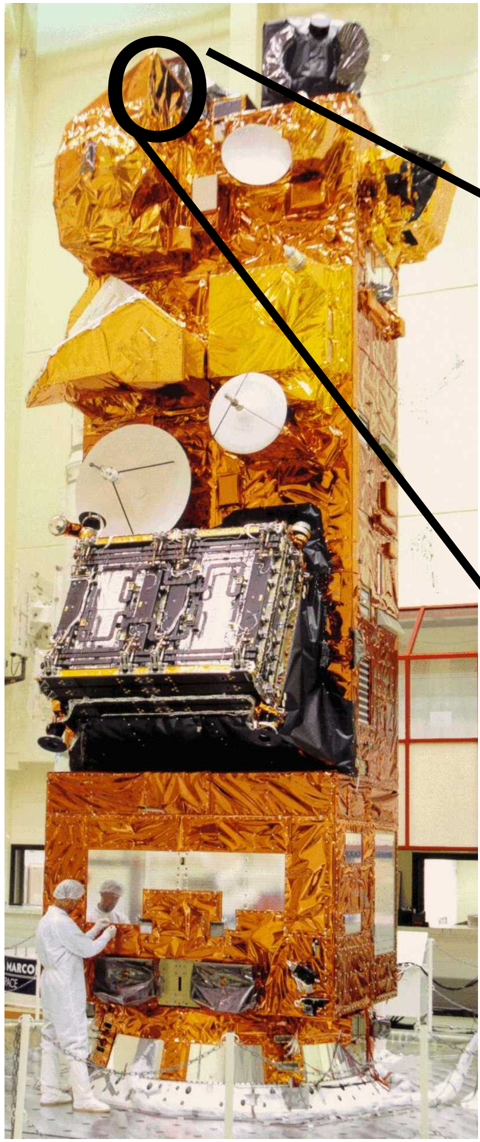
The original objectives for the MIPAS instrument were:

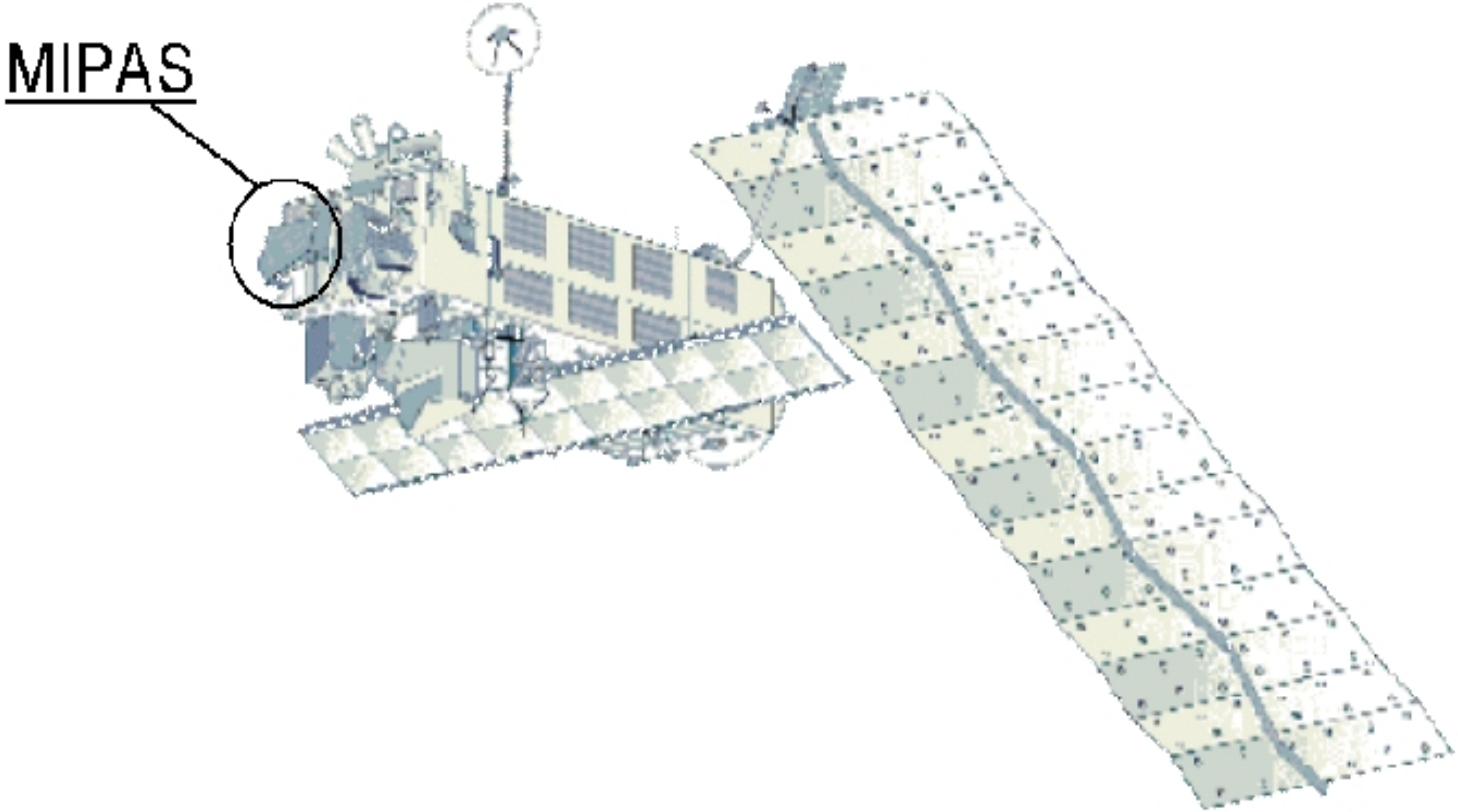
- Real time, simultaneous, global geophysical measurements of the middle atmosphere.
- Study of chemical composition, dynamics, and radiation budget of the middle atmosphere.
- Monitoring of stratospheric O_3 and CFC's.

MIPAS-ENVISAT

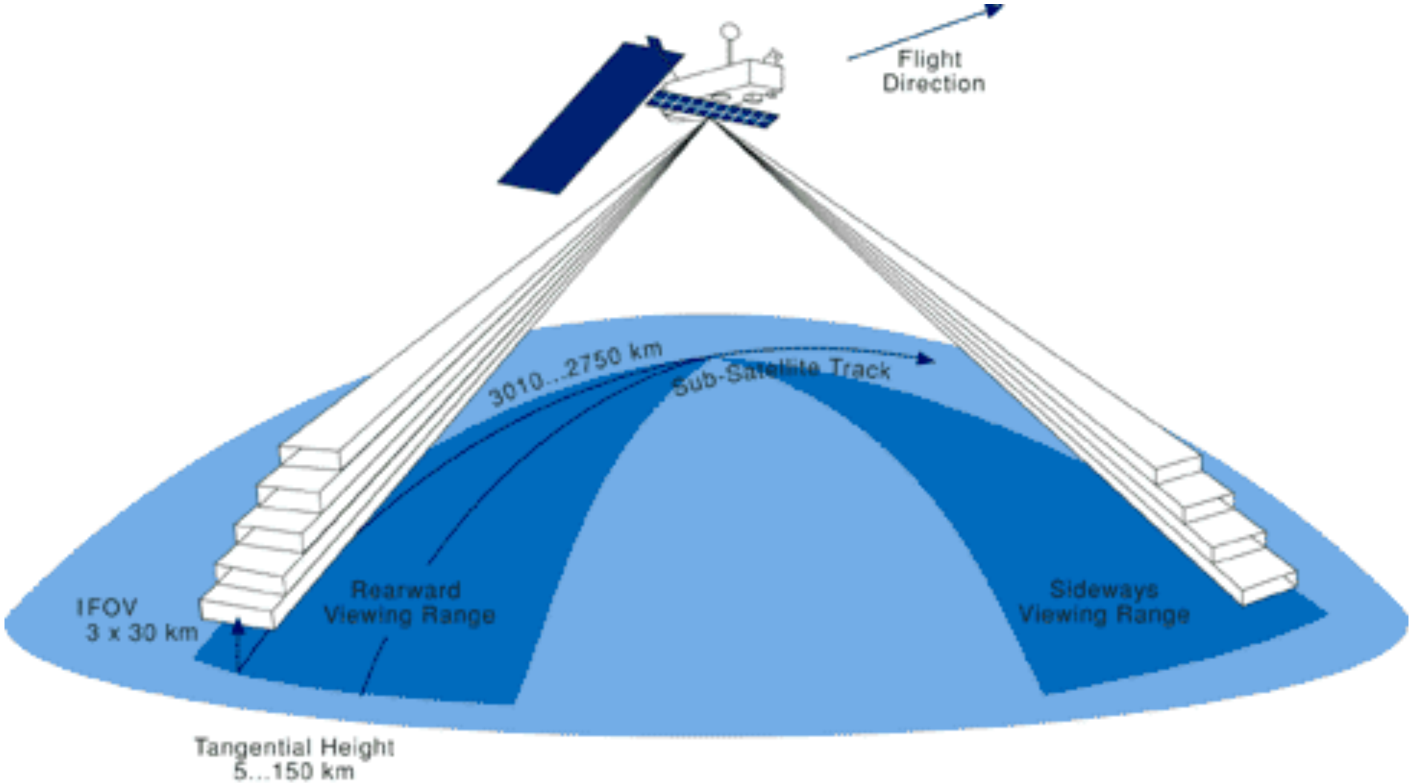
A Fourier Transorm Spectrometer for broadband and high resolution measurements of atmospheric emission in the middle infrared region.

	Full Spectral Resolution June 2002 - Mar 2004	Optimised Spectral Resolution Jan 2005 – Apr 2012
Spectral coverage	685-2410 cm^{-1} **(14.6 μm-4.15 μm)**	
Spectral resolution	0.025 cm^{-1}	0.0625 cm^{-1}
IFOV	3 x 30 km^2	
Vertical coverage	6-68 km	
Time / spectrum	4.6 sec.	1.8 sec.
# spectra / scan	17	27

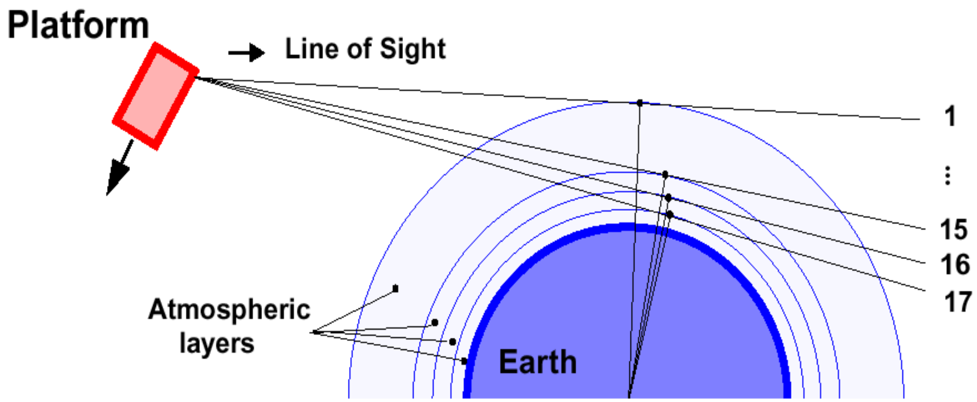


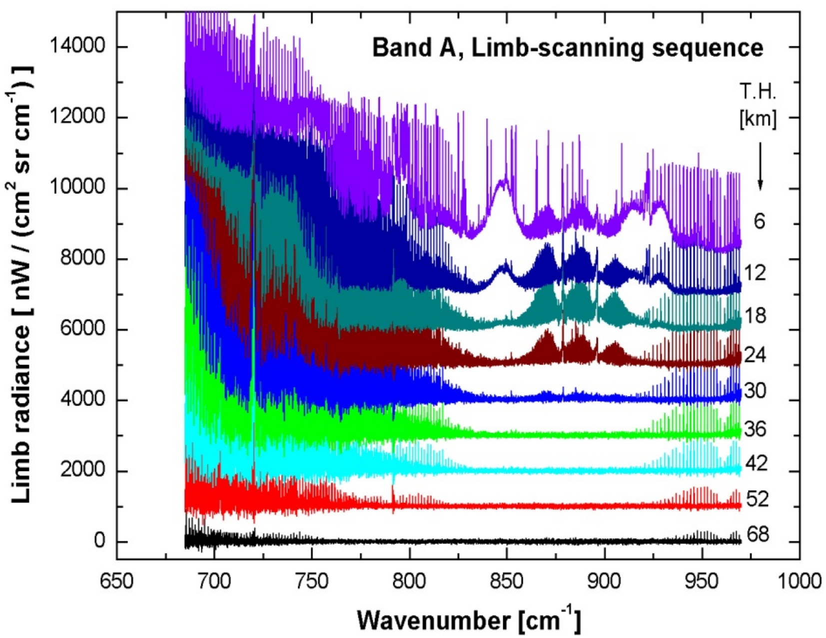

MIPAS

Limb sounding observation geometry



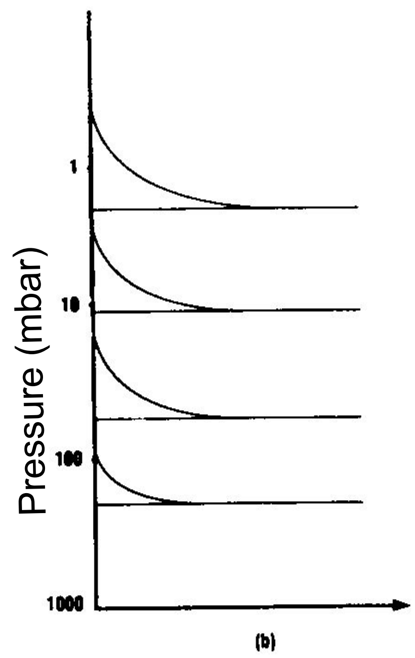
Limb sounding measurements





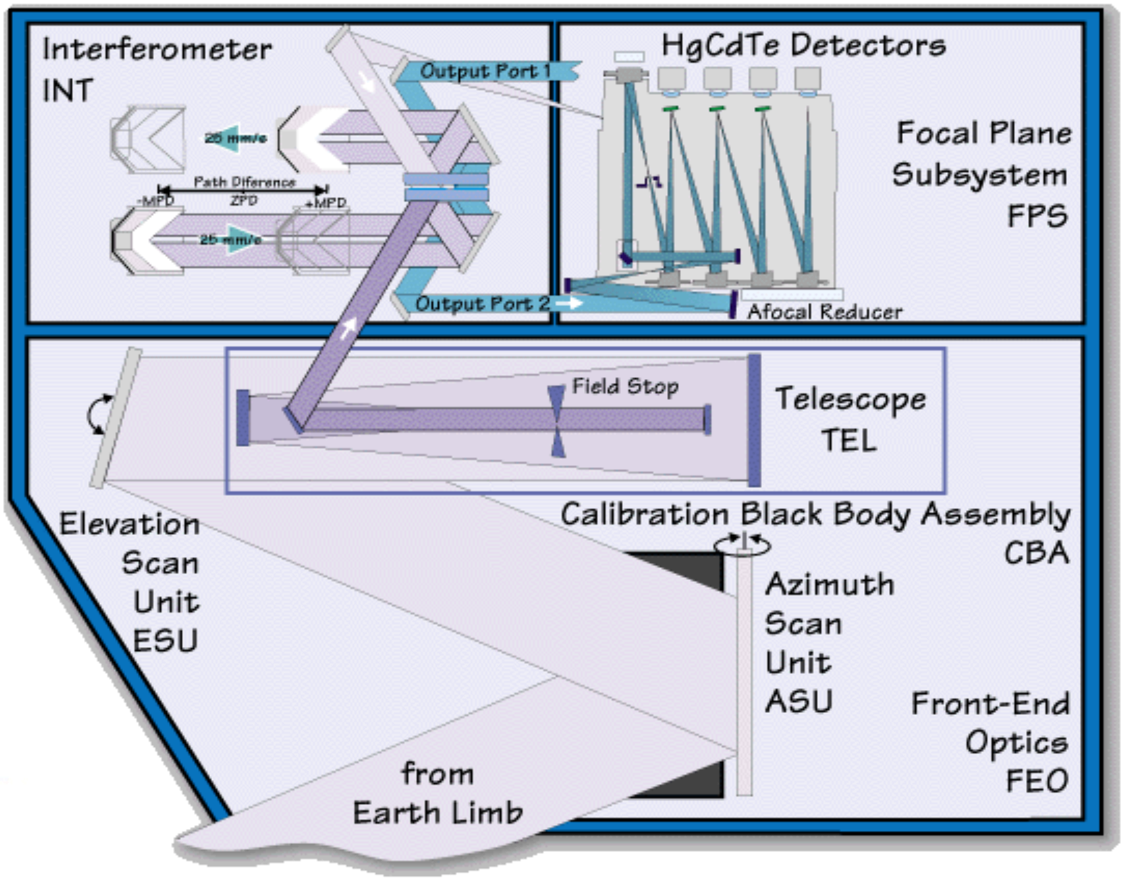
Limb sounding measurements

- Limb sounding technique provides a selective information of the atmospheric composition at the tangent altitudes
- Combining information coming from all the spectra of the scan it is possible to retrieve profiles characterised by a high vertical resolution.
- Limb scanning measurements are characterised by a great sensibility due to the long path in the atmosphere, but poor horizontal resolution. Furthermore, they have a strong impact from clouds that prevent the possibility of retrieval at low altitudes.

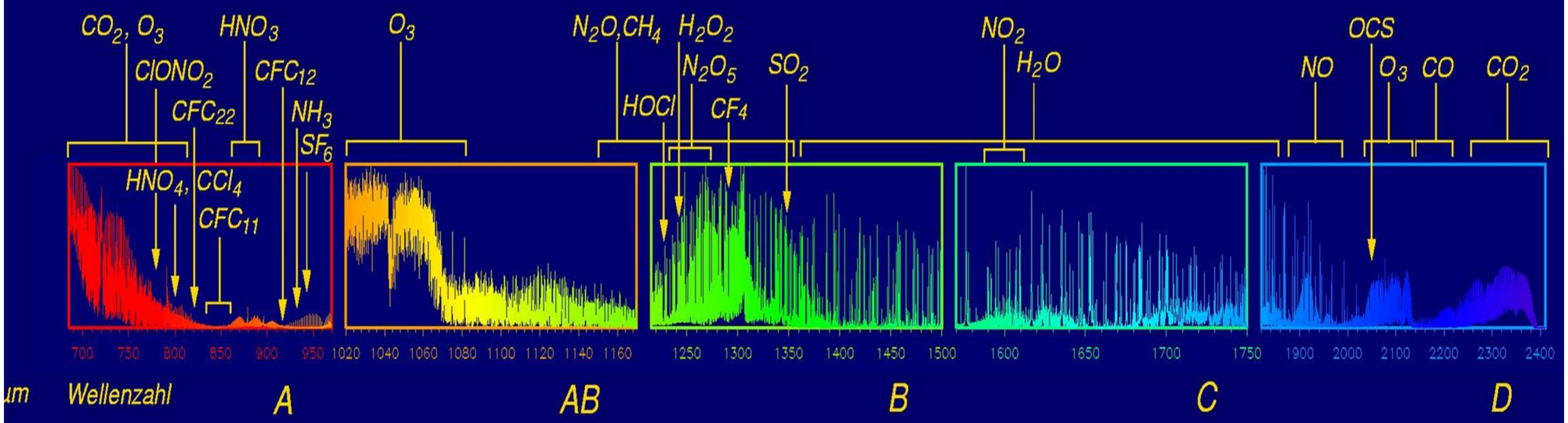


Typical Weighting functions

MIPAS-ENVISAT: instrument layout



MIPAS spectral bands



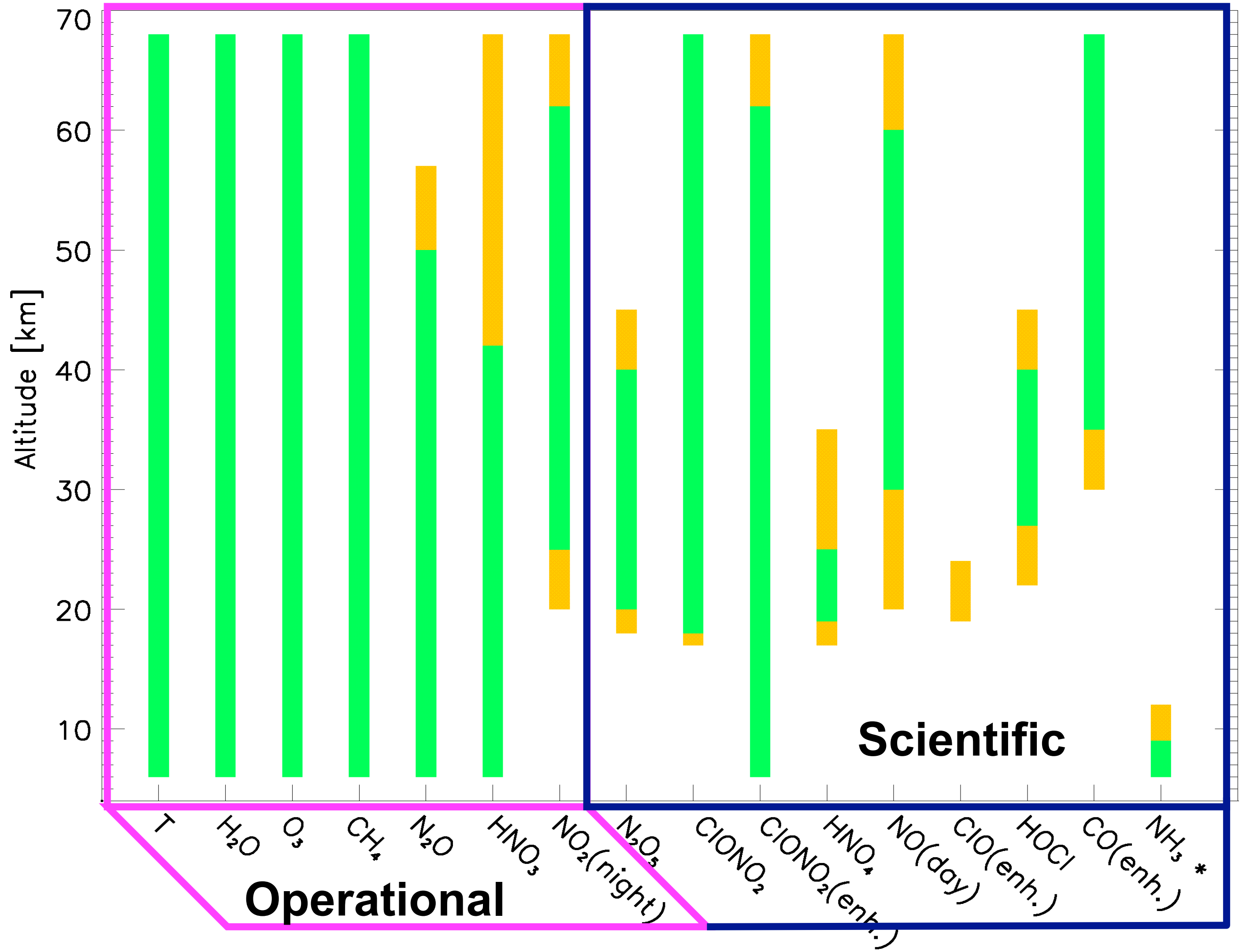
685 cm^{-1}
14.6 µm

Spectrum at 28 km tangent altitude

2410 cm^{-1}
4.15 µm

broadband and high resolution measurements

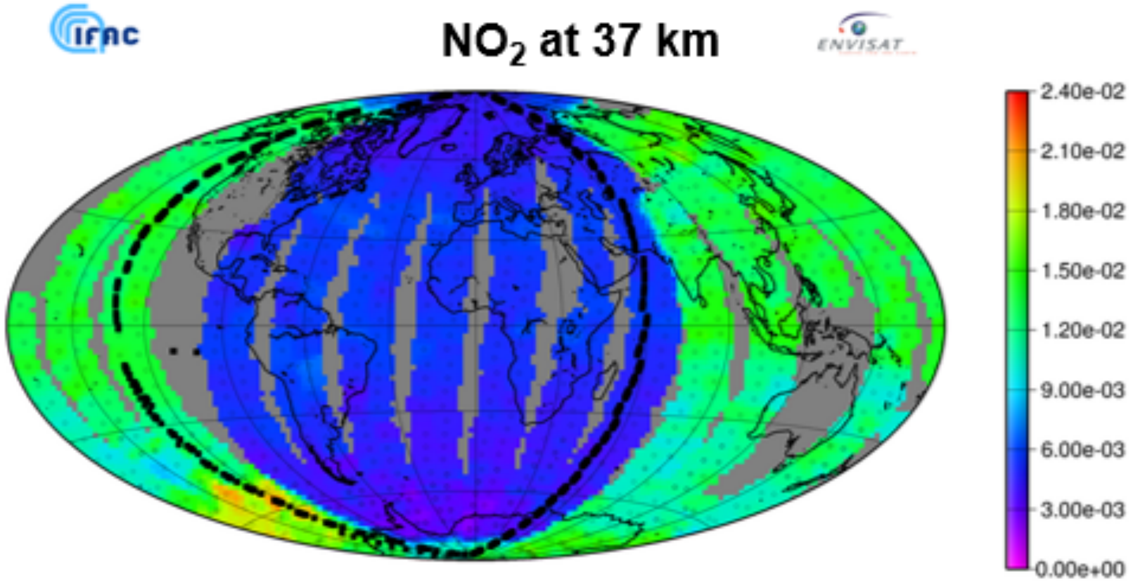
MIPAS retrieved atmospheric constituents



ICTP

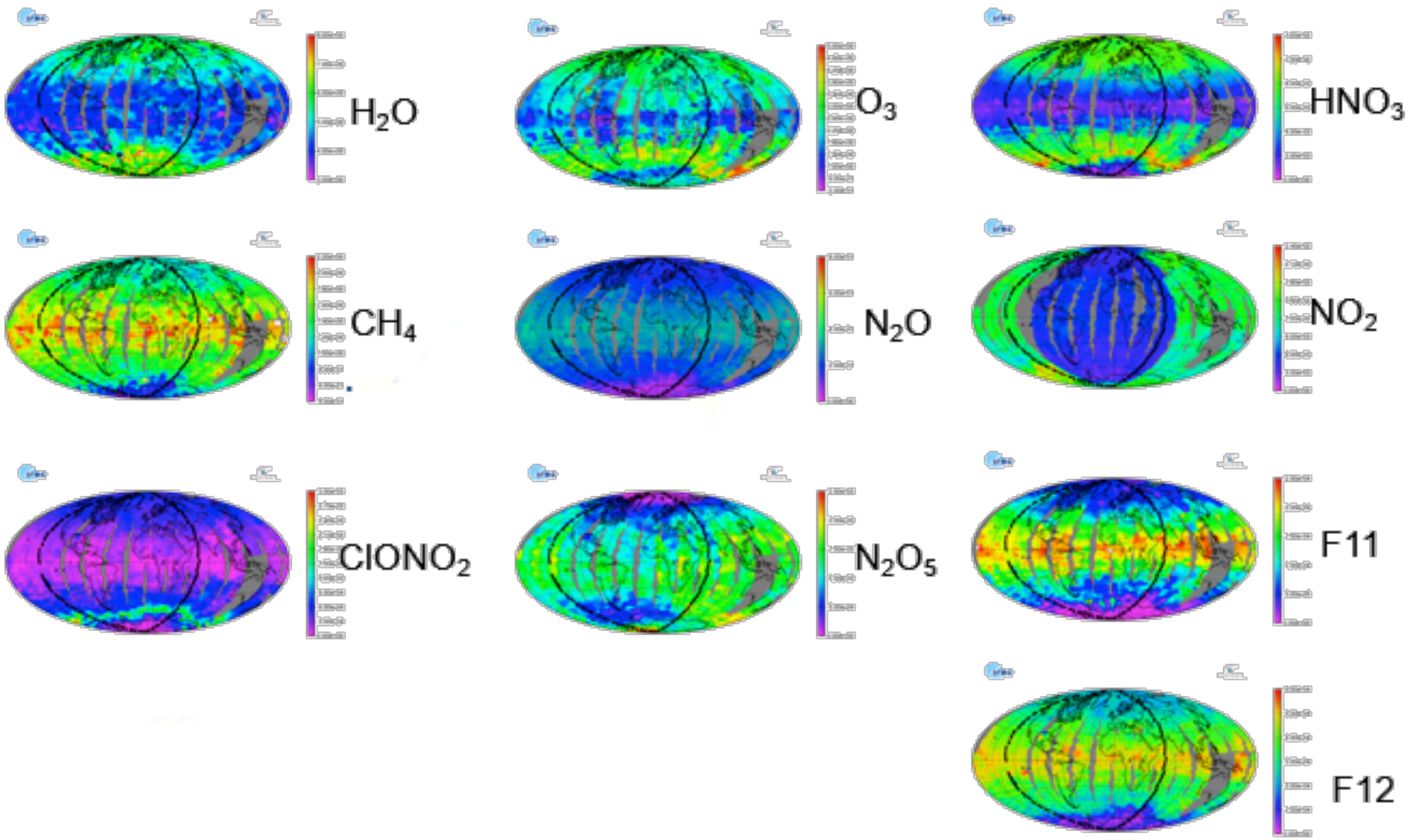
Measurement of emission

- Continuous measurements are possible, both during day and night
- Diurnal variability of compounds can be detected



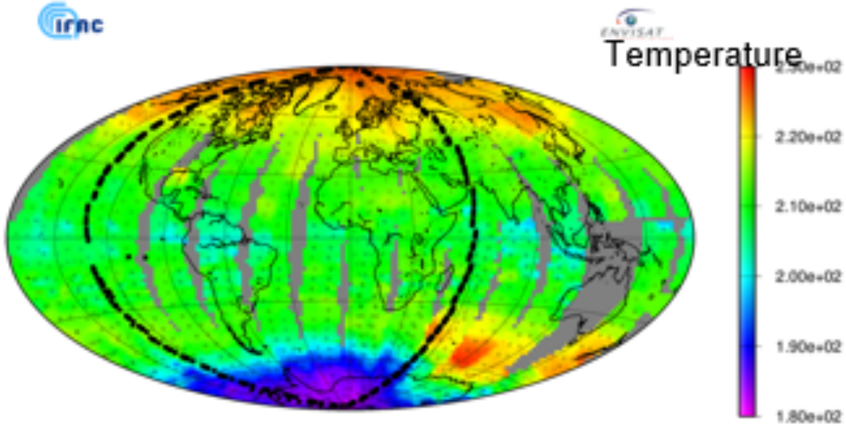
Simultaneous and global measurements …

TARGET SPECIES

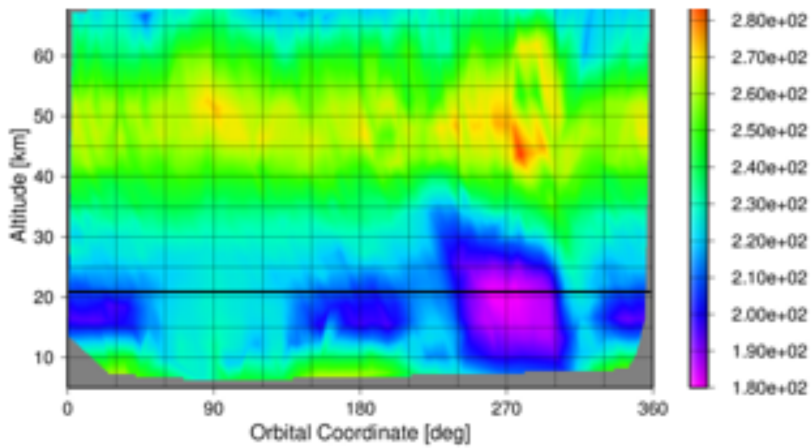


… of vertically resolved composition

3D GEOMETRICAL COVERAGE

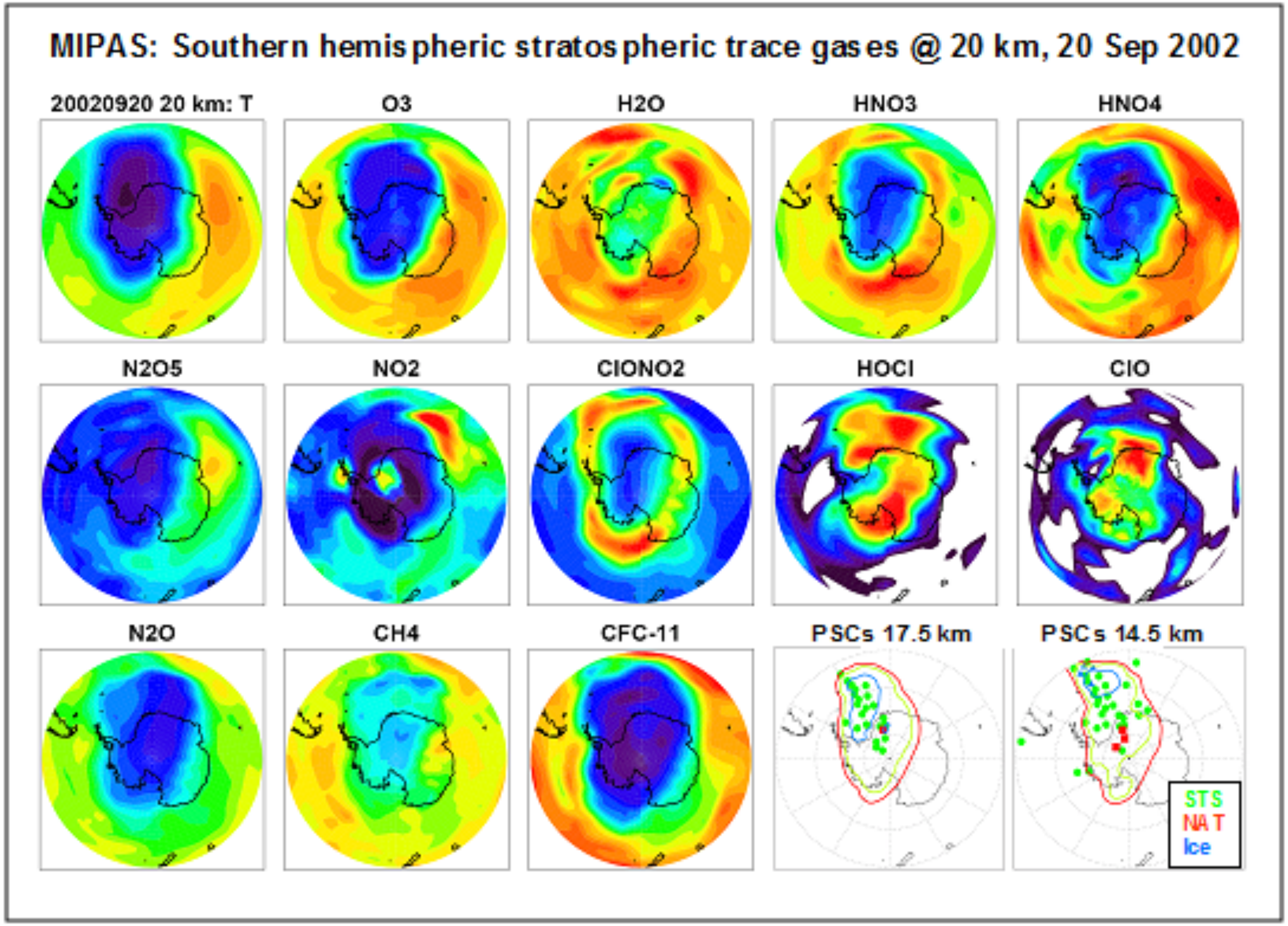


Horizontal section



Vertical section

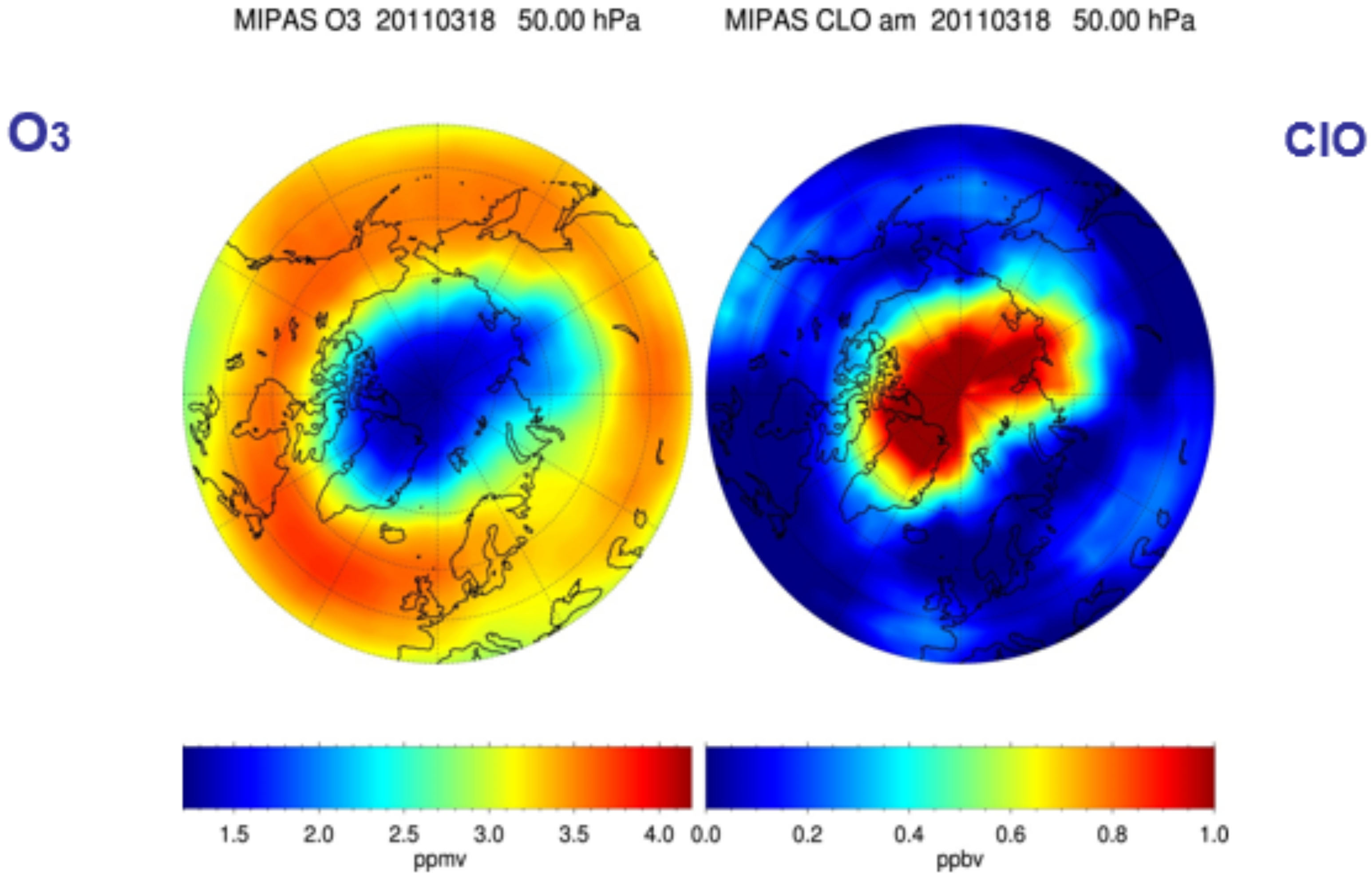
Ozone chemistry



(courtesy of KIT)

Ozone chemistry

Arctic ozone hole 2011



(courtesy of KIT)