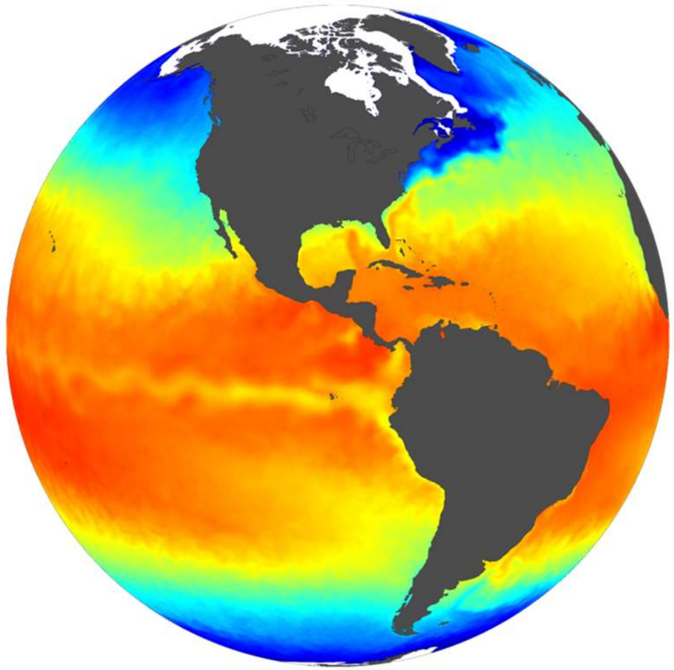

Atmospheric effects

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University of Miami
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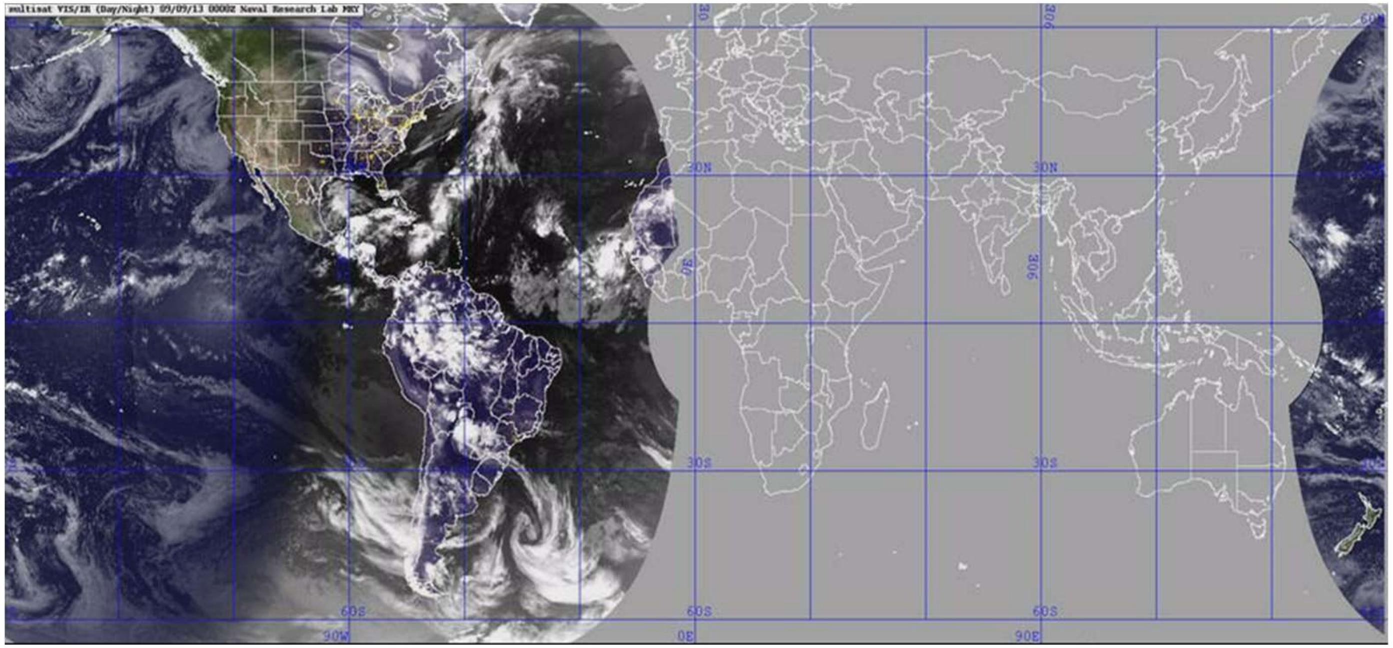
GHRSST SST Short Course
University of Cape Town
29-30 May 2014

To provide operational users and the science community with the SST measured by the satellite constellation

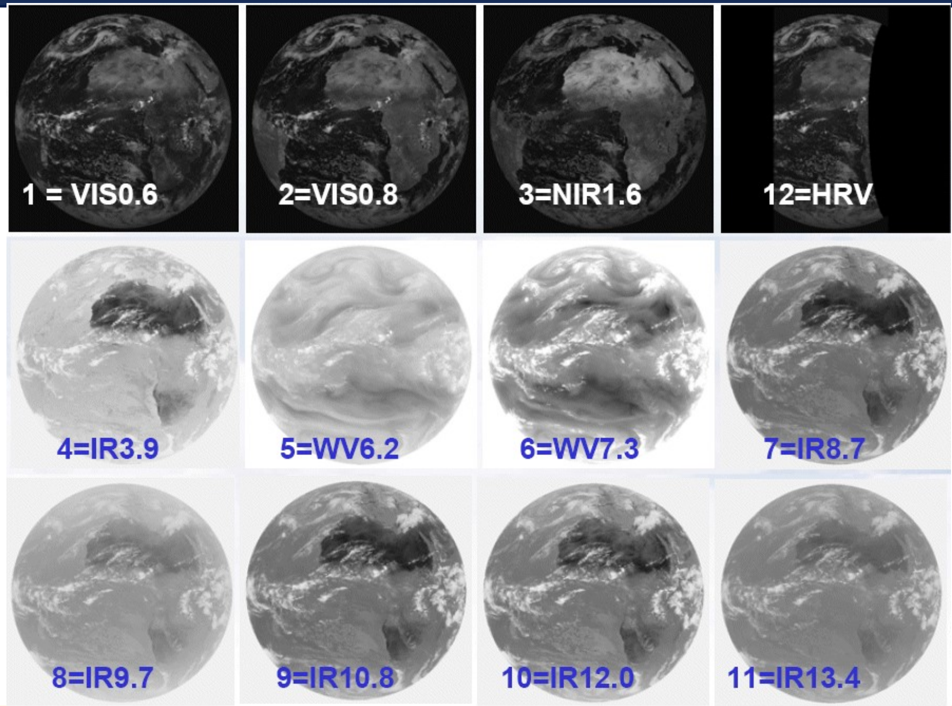
Overview

- Cloud screening
- Propagation through the atmosphere
- Aerosol scattering
- Quantum effects
- Atmospheric transmissivity
- Water vapor variability
- Infrared atmospheric correction algorithms

Clouds obscure in the visible and infrared



SEVIRI spectral images



Cloud Screening for SST

- Tests should be on a pixel-by-pixel basis.
- Spectral information can be a powerful means for cloud screening.
- Better to have false positives than false negatives.

Cloud screening

- Several layers of tests needed to identify all pixels contaminated by clouds

  e.g. temperature thresholds, reflected sunlight (during the day), "spatial coherence", channel differences (fog and cirrus).

- Problems remain with marine stratus, fog, cirrus, and partially cloud-filled pixels.

- Undetected aerosols remain a problem.

Cloud screening – spatial coherence

Many types of clouds tend to have more spatial variability than the sea-surface.

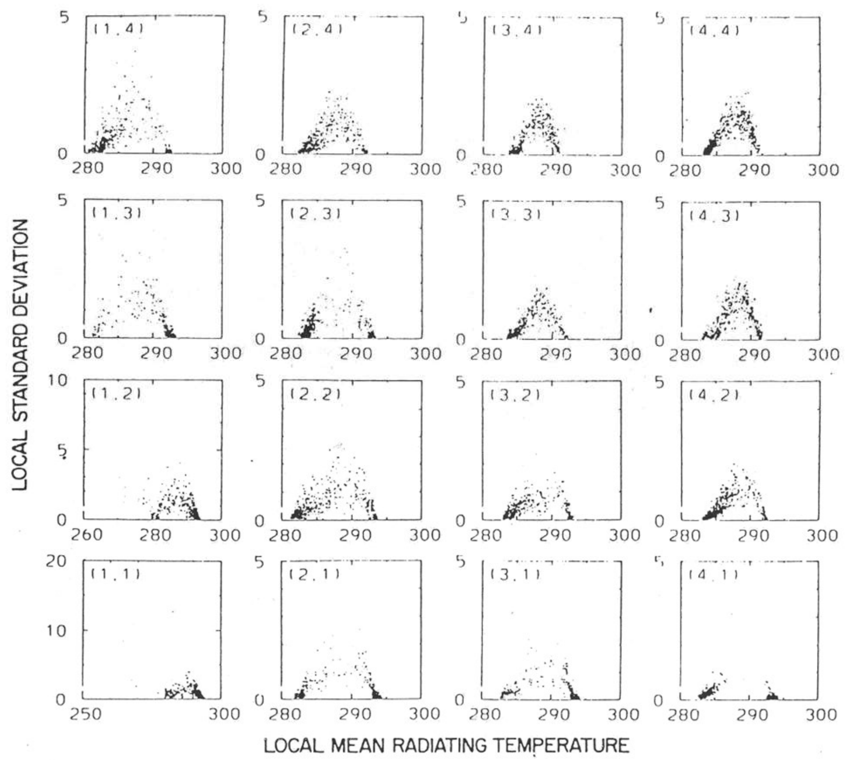
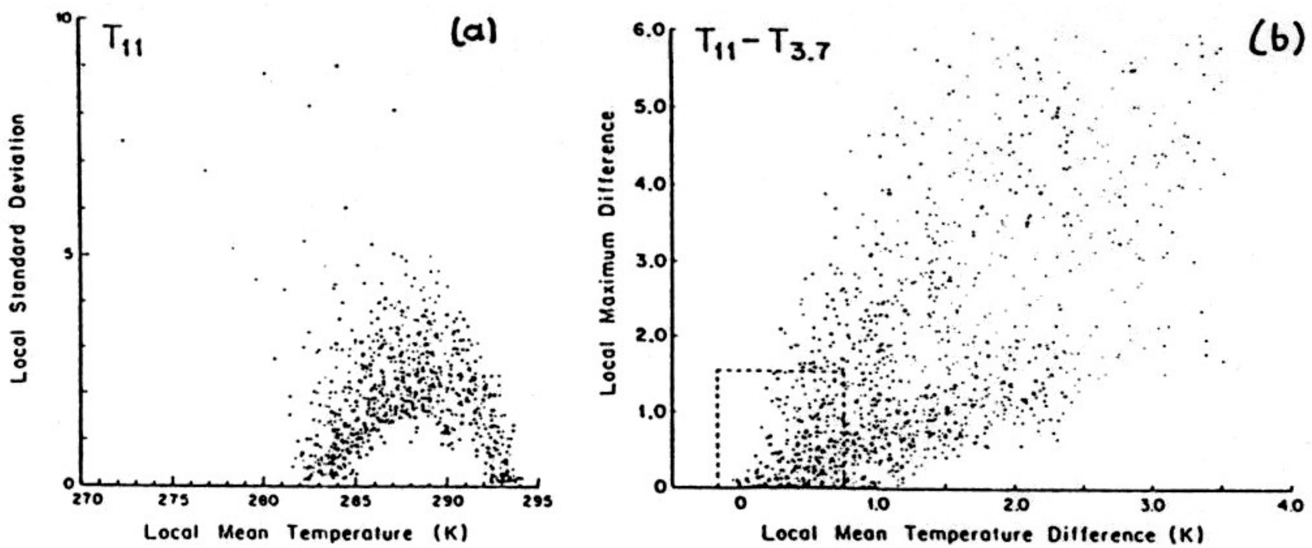


Fig. 3. The 11-μm local mean brightness temperatures and local standard deviations for 2 × 2 arrays of GAC data points for the scene shown in Figure 1. Each frame represents a (250 km)^2 portion of the scene. The location of the (250 km)^2 region is given by the (x, y) coordinates in the upper left corner of the frame. The origin of the coordinate system is (1, 1). The coordinate system coincides with the arrangement of the image in Figure 1. The positive x direction is perpendicular to the orbital track and toward the east. The positive y direction is parallel to the orbital track and toward the north.

Cloud screening –
spatial coherence and ΔBT

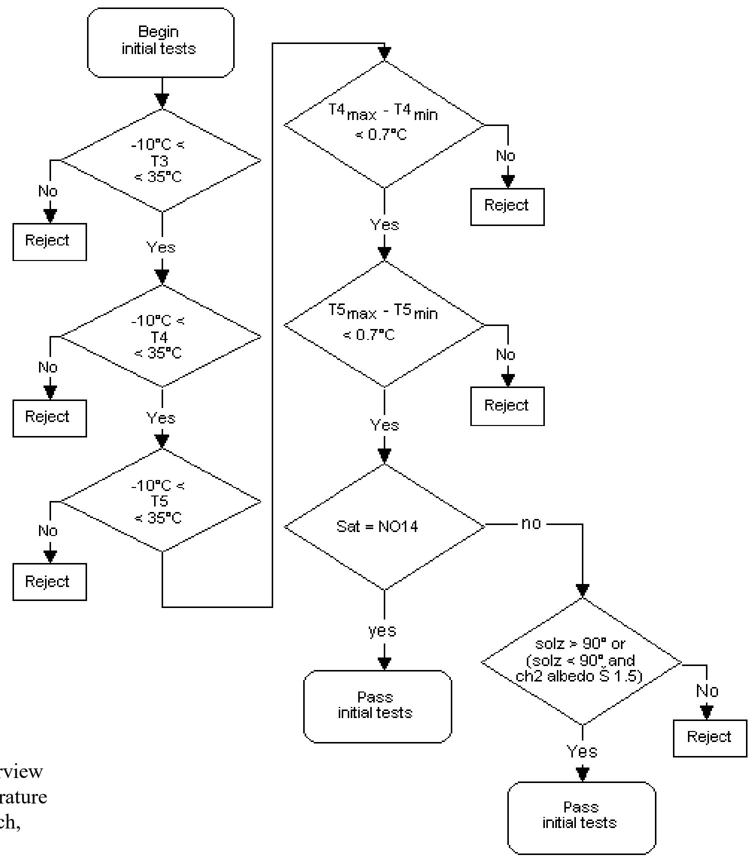


AVHRR Pathfinder SST cloud screening (1)

AVHRR 3 ≅ MODIS 20

AVHRR 4 ≅ MODIS 31

AVHRR 5 ≅ MODIS 32

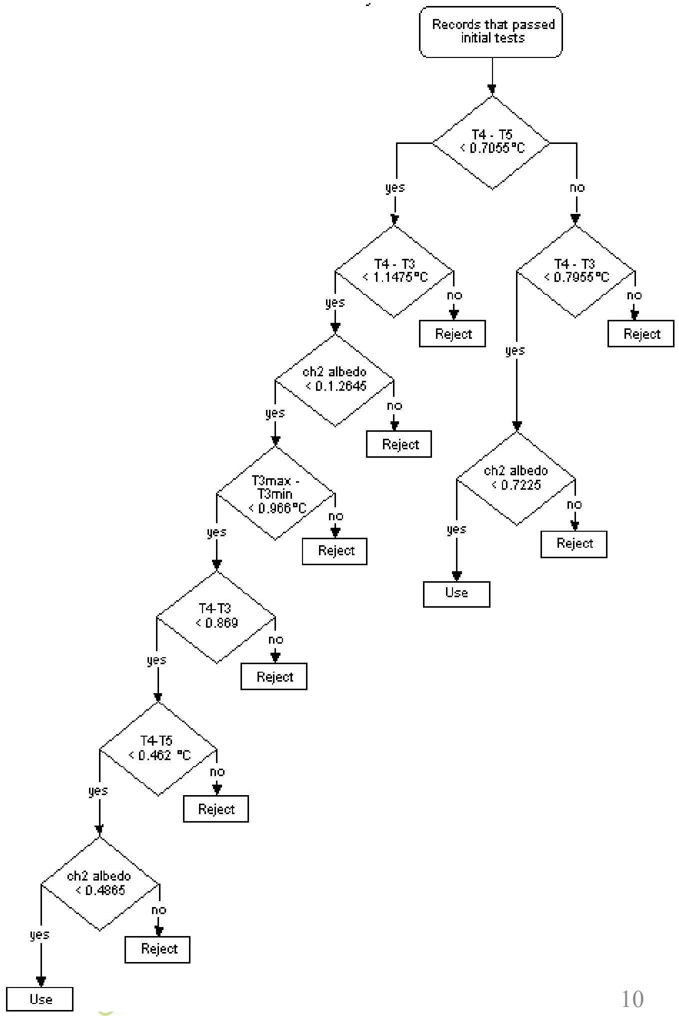


From: Kilpatrick, K. A., G.P.Podesta and R. H. Evans, 2001. Overview of the NOAA/NASA Pathfinder algorithm for Sea Surface Temperature and associated Matchup Database, Journal of Geophysical Research, 106, 9179-9198

AVHRR Pathfinder SST cloud screening (2)

Thresholds tuned
to NOAA-14 AVHRR

From: Kilpatrick, K. A., G.P.Podesta and R. H. Evans, 2001. Overview of the NOAA/NASA Pathfinder algorithm for Sea Surface Temperature and associated Matchup Database, Journal of Geophysical Research, 106, 9179-9198



GHRSST GROUP FOR HIGH RESOLUTION SEA SURFACE TEMPERATURE http://www.ghrsst.org

What happens to a beam of radiation as it passes through the atmosphere ?

There are four processes that can alter the radiation as it passes through an elemental slab of the atmosphere:

- Radiation from the beam can be absorbed by the atmosphere; the photon is destroyed, and its energy is converted to heat
- Radiation can be emitted by the atmosphere; a photon is created and its energy is removed from the emitter
- Radiation can be scattered out of the beam into other directions; the photon survives the encounter - if its energy remains the same, it is an elastic scattering event, if the energy changes, it is inelastic.
- Radiation can scattered into the beam from other directions

Absorption

Beer's Law (a.k.a. Bouguer's Law, a.k.a. Lambert's Law)

The rate of decrease of the intensity of the radiation is proportional to the intensity of the radiation:

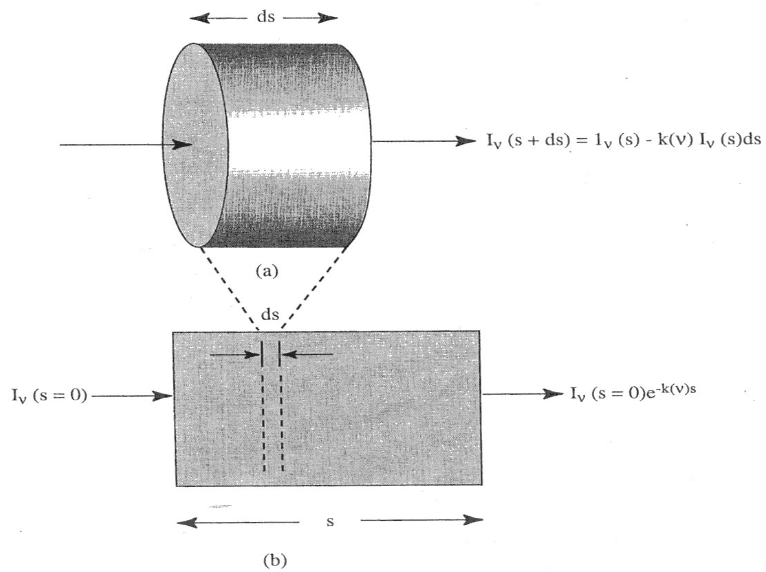
$$dL_\lambda / dz = -\kappa_\lambda^{abs} L_\lambda$$

κ_λ^{abs} is the volume absorption coefficient. It is a function of the state of the atmosphere, i.e. $\kappa_\lambda^{abs} = \kappa_\lambda^{abs}(t,T(z),c_i(z))$, where c_i is the concentration of the i^{th} component of the atmosphere (e.g. water vapor, CO_2, O_3, aerosols,........)

Integrate over finite depth, from a to b:

$$L_\lambda = L_o \exp(-\int_a^b \kappa_\lambda^{abs} dz)$$

Beer's Law



(a) Intensity passing through a thin slab suffers extinction proportional to the path length ds. (b) Intensity passing through a finite path length s suffers exponential extinction.

Scattering out of the beam

Beer's Law:

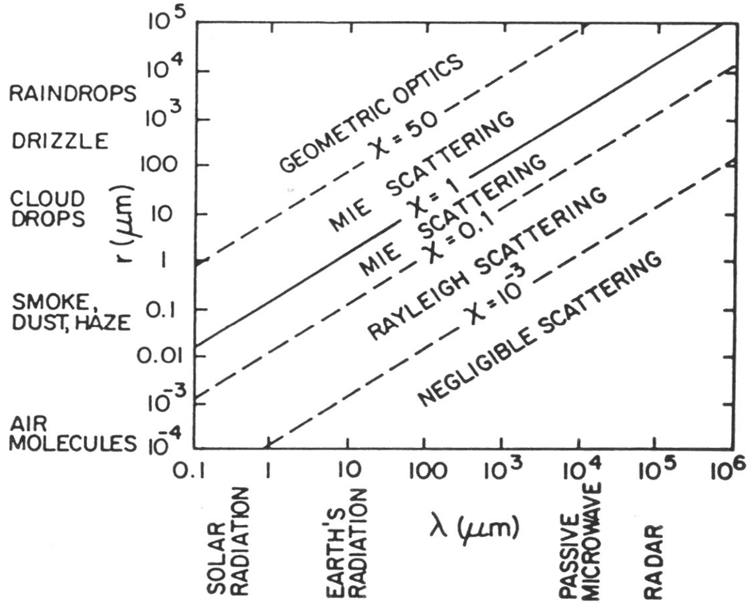
$$dL_\lambda / dz = -\kappa_\lambda^{scat} L_\lambda$$

κ_λ^{scat} is the volume scattering coefficient.

Integrate over finite depth, from a to b:

$$L_\lambda = L_o \exp(-\int_a^b \kappa_\lambda^{scat} dz)$$

Scattering regimes



Scattering regimes. [Adapted from Wallace and Hobbs (1977).

$$\chi = 2\pi a / \lambda$$

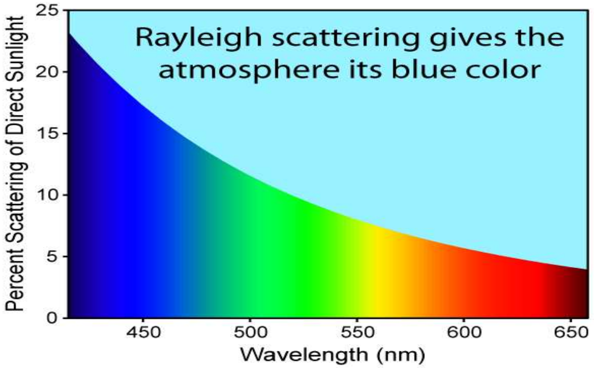
$$= q$$

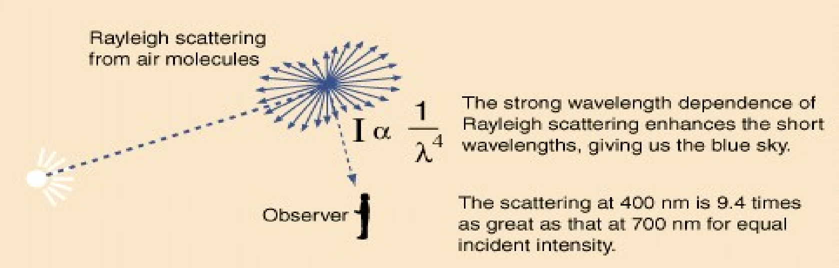
Rayleigh Scattering

Scattering by molecules:

$$I = I_0 \frac{8\pi^4\alpha^2}{\lambda^4 R^2}(1+\cos^2\theta).$$

Where R is distance from the scatterer, λ is wavelength, α is the polarizability (related to the refractive index of a material, but for individual molecules). θ is the scattering angle.

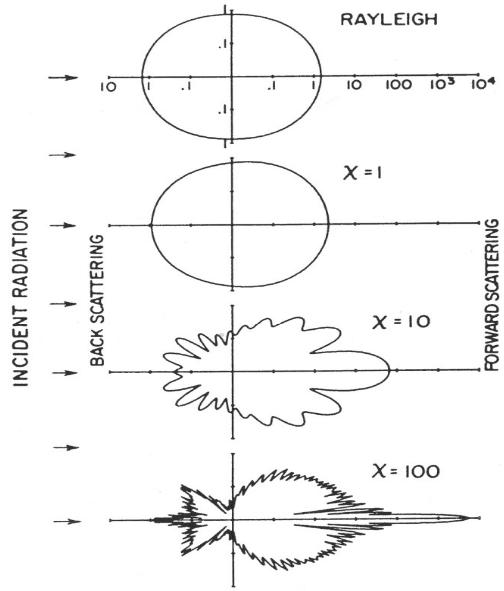




http://en.wikipedia.org/wiki/Rayleigh_scattering

Mie scattering

The glory



Polar plots (note the logarithmic scales) of the scattering phase function of water drops for several size parameters.

Good examples of web-pages for scattering

See

- http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html
- http://www.philiplaven.com/p2.html (*)
- http://www.severewx.com/Radiation/scattering.html

For interactive calculations, see http://omlc.ogi.edu/software/mie/

Emission into the beam

This is Planckian emission at the temperature of the slab of the atmosphere.

By Kirchhoff's Law, absorptance = emittance, so

$$dL_\lambda /dz = \varepsilon_\lambda B_\lambda(T(z,t)) = \kappa_\lambda^{abs} B_\lambda(T(z,t))$$

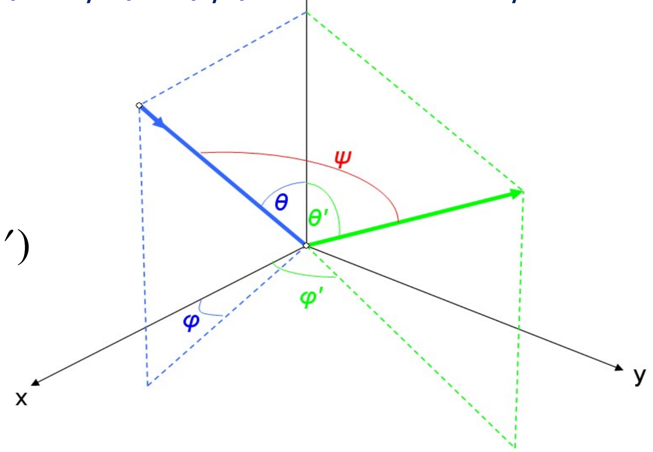
Scattering into the beam

This is the most difficult to deal with, as it requires consideration of scattering from all directions:

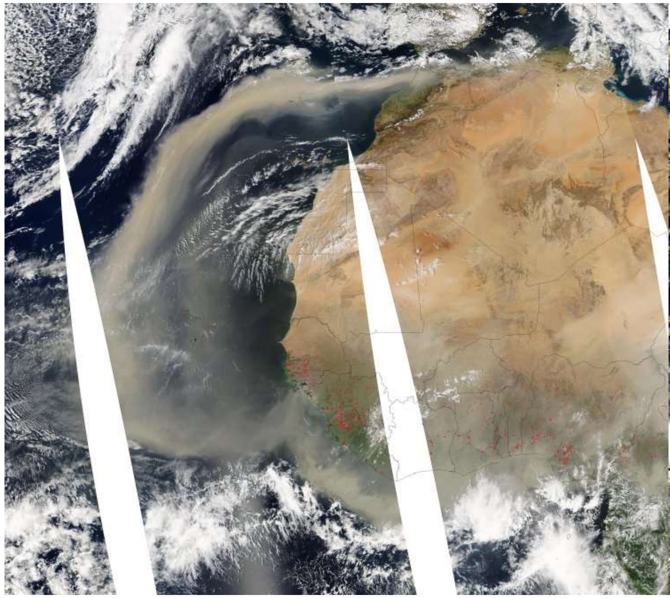
$$dL_\lambda / dz = \kappa_\lambda^{scat} / (4\pi) \int_0^{2\pi} \int_0^{\pi} L_\lambda(\theta', \varphi') \, P(\psi) \sin \theta' \, d\theta' d\varphi'$$

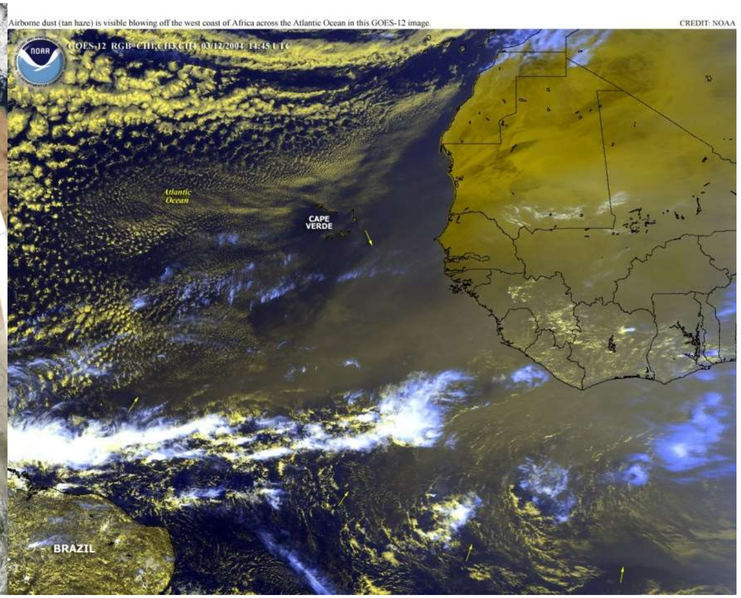
$P(\psi)$ is the scattering phase function
ψ is the scattering angle:

$$\cos \psi = \cos \theta \cos \theta' + \sin \theta \sin \theta' \cos(\varphi - \varphi')$$



Aerosol Scattering





Radiative Transfer Equation

$dL_\lambda / dz =$

$- \kappa_\lambda^{abs} L_\lambda$

$- \kappa_\lambda^{scat} L_\lambda$

$+ \kappa_\lambda^{abs} B_\lambda(T(z,t))$

$+ \kappa_\lambda^{scat}/(4\pi) \int_0^{2\pi} \int_0^{\pi} L_\lambda (\theta',\varphi') P(\psi_s) \sin\theta' \, d\theta' d\varphi'$

Extinction coefficient

The radiation losses due to scattering and absorption can be expressed by a single parameter - the extinction coefficient:

$$\kappa_\lambda^E = \kappa_\lambda^{scat} + \kappa_\lambda^{abs}$$

Optical depth

Optical depth is defined as

$$\tau_\lambda^i(0,h) = \int_0^h \kappa_\lambda^i(z)\, dz$$

where i = E or (abs, scat).

For the entire atmosphere (h=∞):

$$I = I_0 e^{-\tau}$$

for propagation along the vertical.

The optical depth is the number of "mean free paths" in the medium.

Atmospheric slant path

The slant path through the atmosphere, s, sometimes called the airmass (not to be mistaken for the meteorological term), is related to the vertical by simple geometry:

$$s = z / \cos(\theta) = z/\mu$$

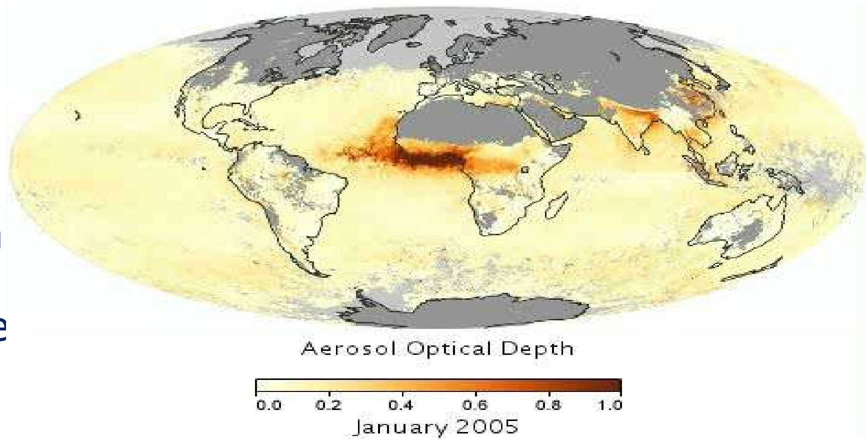
where θ is the zenith angle of the beam.

Optical depth along a slant path:

$$I = I_0 e^{-\tau/\mu}$$

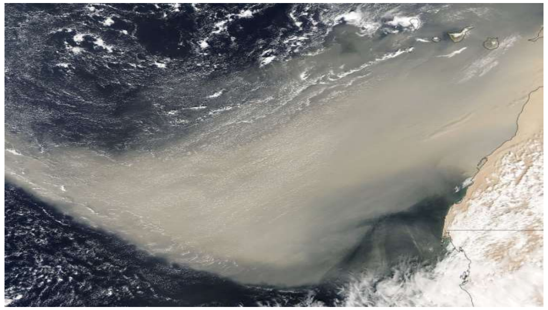
Aerosol Optical Depth

- Derived from *Terra* MODIS visible and near infrared data
- An optical thickness of less than 0.1 (pale yellow) indicates a crysta clear sky with maximum visibility, whereas a value of 1 (brown) indicates very hazy conditions.



http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=MODAL2_M_AER_OD#

Aerosol Scattering



Single scatter albedo

The single scatter albedo, ϖ_λ, is defined as

$$\varpi_\lambda = \kappa_\lambda^{scat} / \kappa_\lambda^{E}$$

Absorption number

The absorption number, α_λ, is defined as

$$\alpha_\lambda = \kappa_\lambda^{abs} / \kappa_\lambda^{E}$$

Planck Function

The Planck Function

In se: derivation of blackbody radiation, Planck made the revolutionary assumption that an oscillating atom in the wall of a cavity can exchange energy with the radiation field inside a cavity only in discrete bundles called *quanta* given by $\Delta E = h\nu$, where h is known as *Planck's constant*.

With this assumption, he showed that the radiance being emitted by a blackbody is given by

$$B_\lambda(T) = \frac{2hc^2\lambda^{-5}}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}, \qquad (3.7)$$

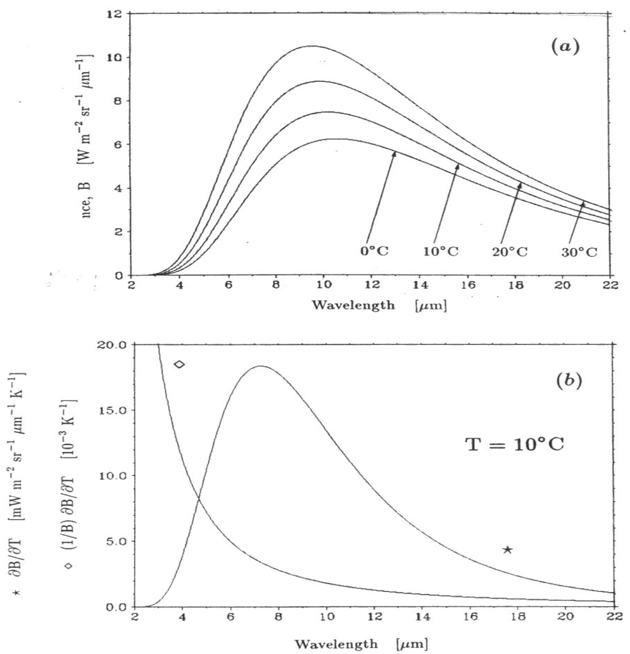
where k is Boltzmann's constant, and T is the absolute temperature.

This is the *Planck function*; it earned him the Nobel Prize in 1918. The Planck function is more conveniently written as

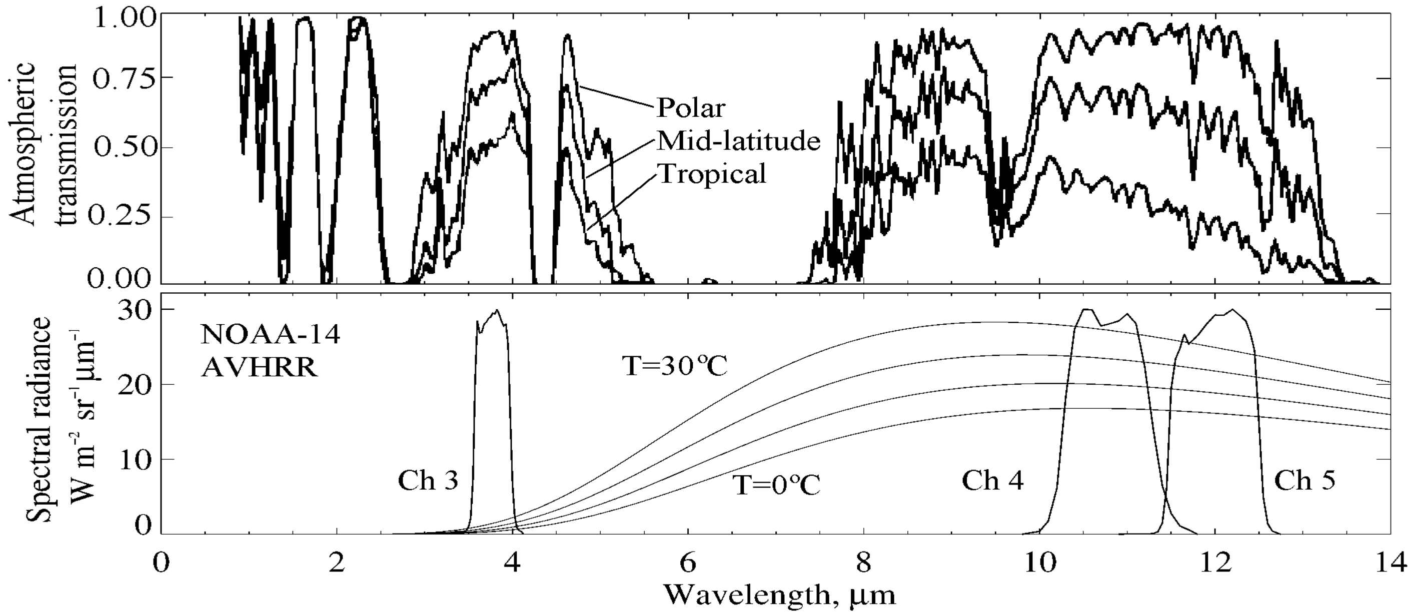
$$B_\lambda(T) = \frac{c_1\lambda^{-5}}{\exp\left(\frac{c_2}{\lambda T}\right) - 1}, \qquad (3.8)$$

where c_1 and c_2 are the first and second radiation constants.

Since the radiance from a blackbody is independent of direction, the radiant exitance from a blackbody is simply πB_λ.



Variability of atmospheric transmission



Review of Quantum Physics

Energy can only be exchanged in discrete units call quanta. For radiation absorption and emission the quanta are related to the frequency of the radiation, ν, by:

$$\Delta E = h\nu$$

h is Planck's constant

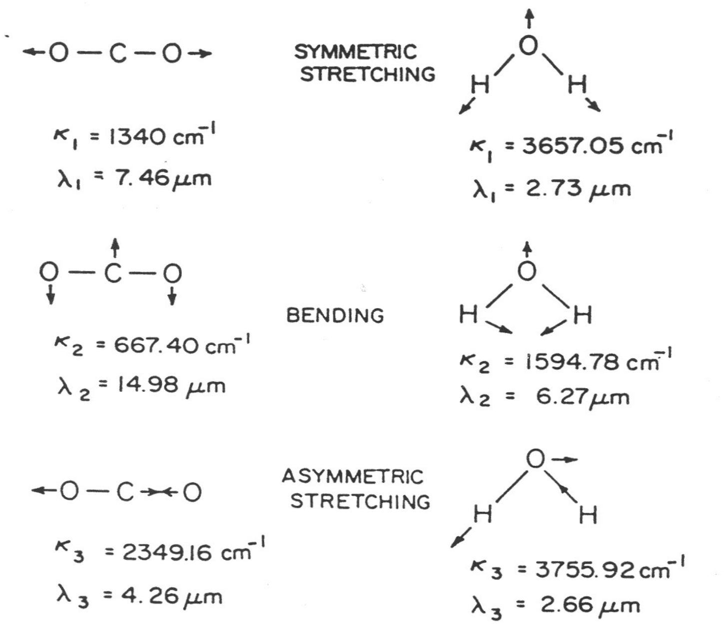
Review of Quantum Physics (II)

Thus exchange between the radiation field and atoms and molecules in the atmosphere can only take place if the frequency of the radiation coincides with a possible energy transition of the atom or molecule. When energy is absorbed the atom or molecule becomes *excited*. When the atom or molecule returns to a lower energy level radiation is emitted.

Review of Quantum Physics (III)

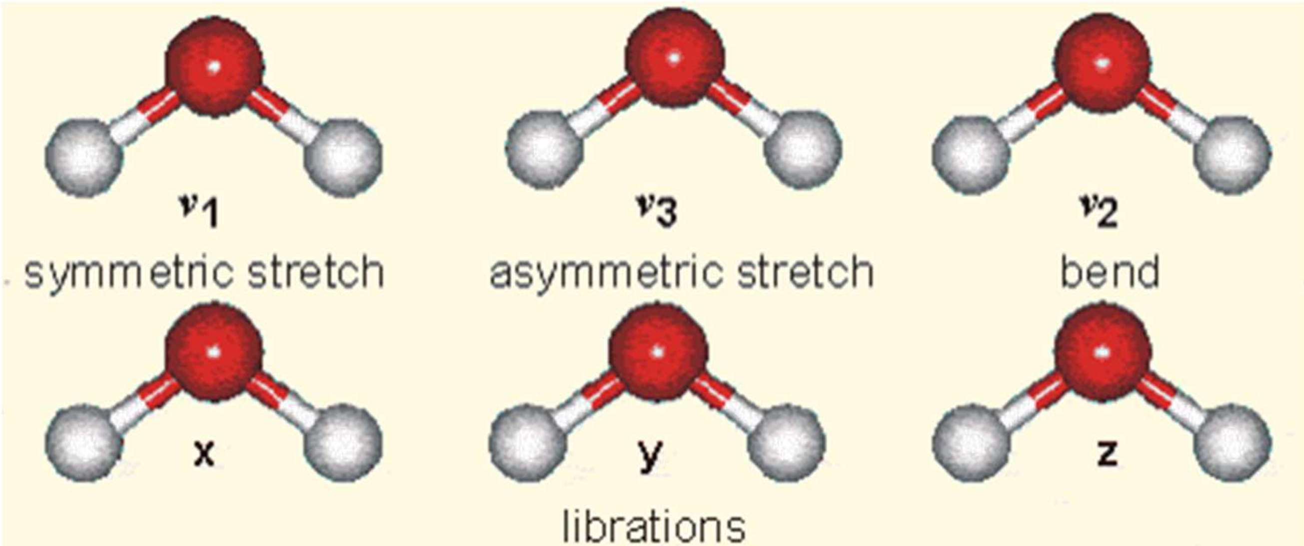
For small ν (microwaves), molecules rotate, as ν increases the molecules vibrate (infrared), then electronic transitions occur (uv, vis, ir), then for high ν electrons be stripped from the atoms or molecules (uv and higher).

Molecular vibrations



Vibration modes of carbon dioxide and water vapor.

Water vapor molecule vibrations



Molecular vibrations

For animations see:

http://en.wikipedia.org/wiki/Infrared_spectroscopy

http://www.chemtube3d.com/vibrationsH2O.htm

http://www.lsbu.ac.uk/water/vibrat.html

Line broadening

The observed lines in the atmosphere are not infinitesimally thin. Three physical phenomena occur to broaden lines:

1. Natural broadening
2. Collision broadening
3. Doppler broadening

Natural broadening

- Spreading of the energy levels involved in the transition.
- Due to the Heisenberg uncertainty principle resulting from the finite duration of each transition ($\sigma(E)\ \sigma(t) > \hbar/2$).
- Natural broadening gives the Lorentz line shape:

$$k_a^M = \frac{S}{\pi} \frac{\alpha_n}{(\nu - \nu_o)^2 + \alpha_n^2} \quad , \quad S = \int_{-\infty}^{+\infty} k(\nu) d\nu$$

where S is the line strength and α_n is the line half width.

The line half width is independent of frequency and its value is of the order of 10^{-5} nm.

Collision broadening

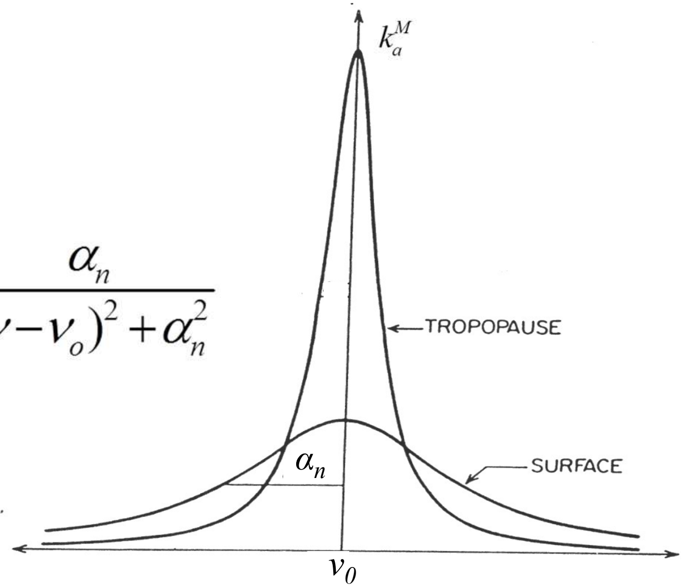
- Changes in energy levels involved in absorption and emission transitions caused by collisions between molecules
- Results in Lorentzian line shape (cf natural broadening), but the half width is orders of magnitudes greater; inversely proportional to the mean free path between collisions, i.e. a function of pressure *p* and temperature *T* of the gas.
- If the partial pressure of the absorbing gas is a small fraction of the total gas pressure:

$$\alpha_c = \alpha_{c,s} \frac{p}{p_s} \sqrt{\frac{T_s}{T}}$$

where p_s and T_s are reference values.

Lorentz line shape

$$k_a^M = \frac{S}{\pi} \frac{\alpha_n}{(\nu - \nu_o)^2 + \alpha_n^2}$$



Doppler broadening

- Molecules have a temperature-dependent Maxwell velocity distribution
- Leads to Doppler effect, causing a shift in frequency in emitted and absorbed radiance.
- The absorption coefficient is a Gaussian:

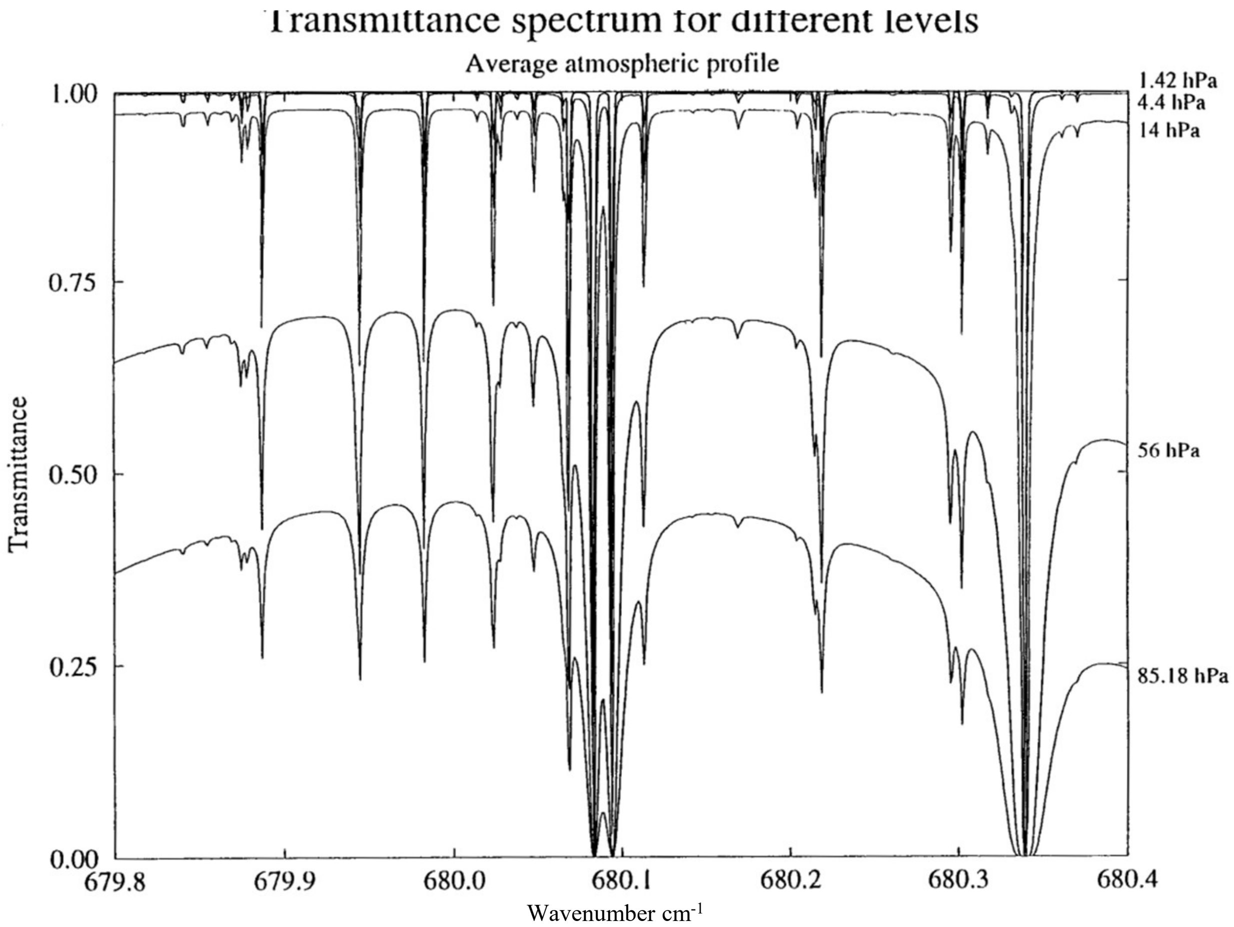
$$k_a^M = \frac{S}{\alpha_d \sqrt{\pi}} \exp\left[\frac{-(\nu - \nu_o)^2}{\alpha_d^2}\right]$$

$$\alpha_d = 3.58 \cdot 10^{-7} \nu_o \sqrt{\frac{T}{M_a}}$$

where M_a is the molecular mass.

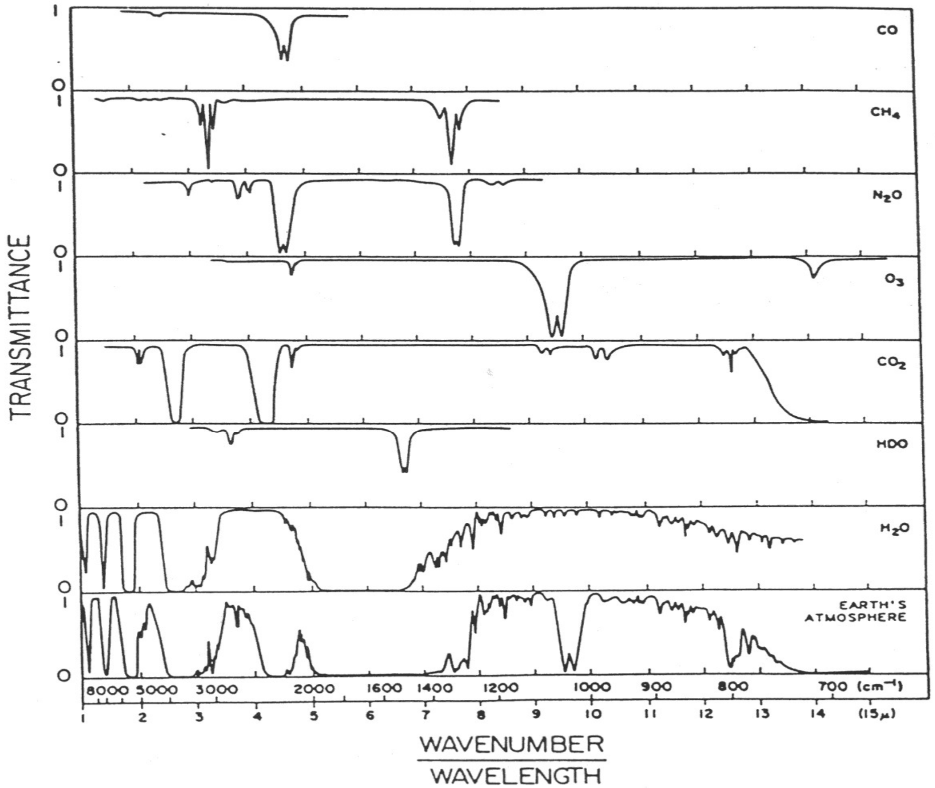
Broadening in the atmosphere

- **Collision** broadening is dominant in the **troposphere**.
- **Doppler** broadening is dominant in the **stratosphere**.
- At intermediate conditions, neither dominate. Assuming the collision and Doppler broadening are independent, the collision broadened line shape can be shifted by the Doppler effect, weighted by the Maxwell distribution, gives the Voigt line shape.
- The Voigt line shape is then a convolution of a Lorentz line shape and a Gaussian line shape.



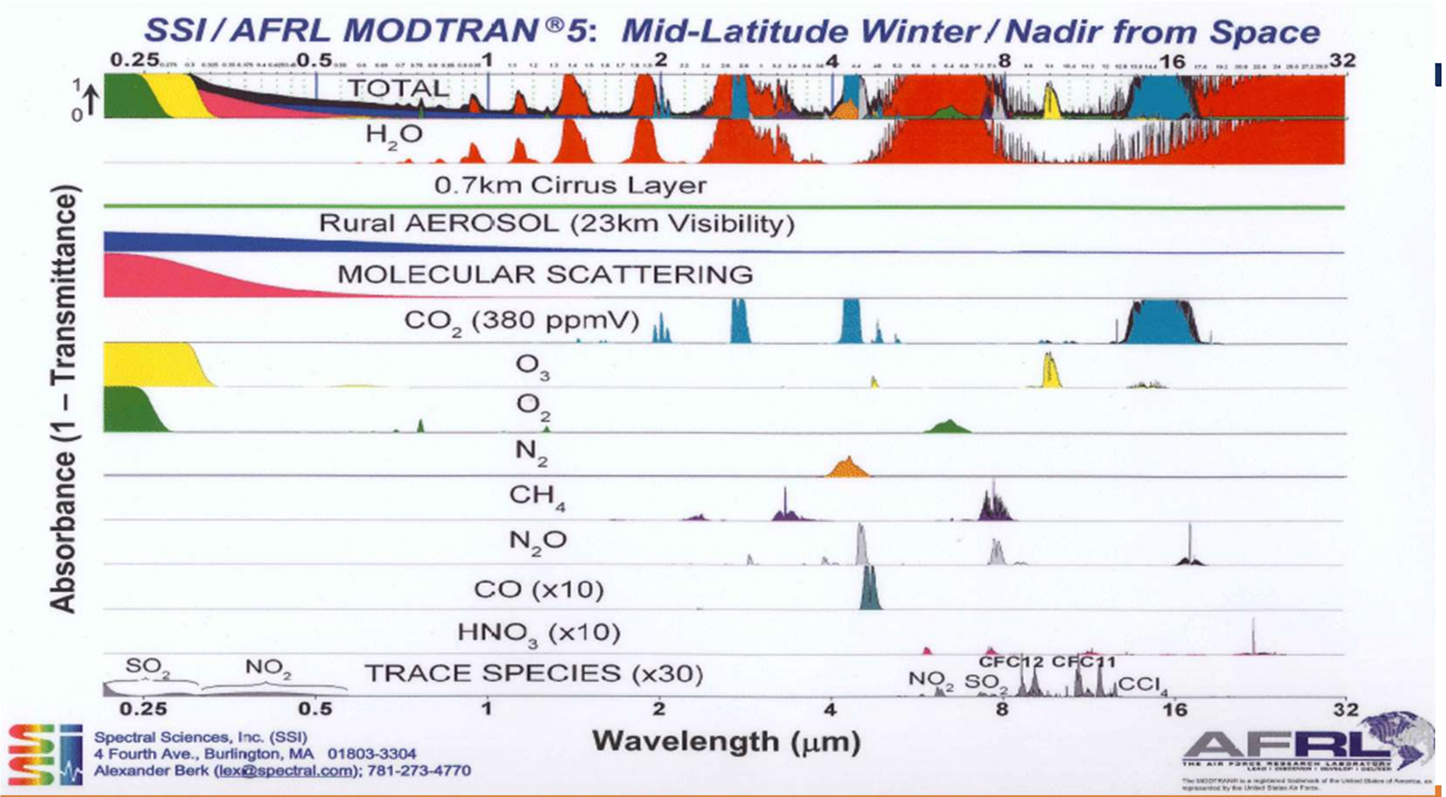
From Marco Matricardi, ECMWF

Atmospheric transmission



Infrared transmittance of several gases in the Earth's atmosphere [After Valley (1965).]

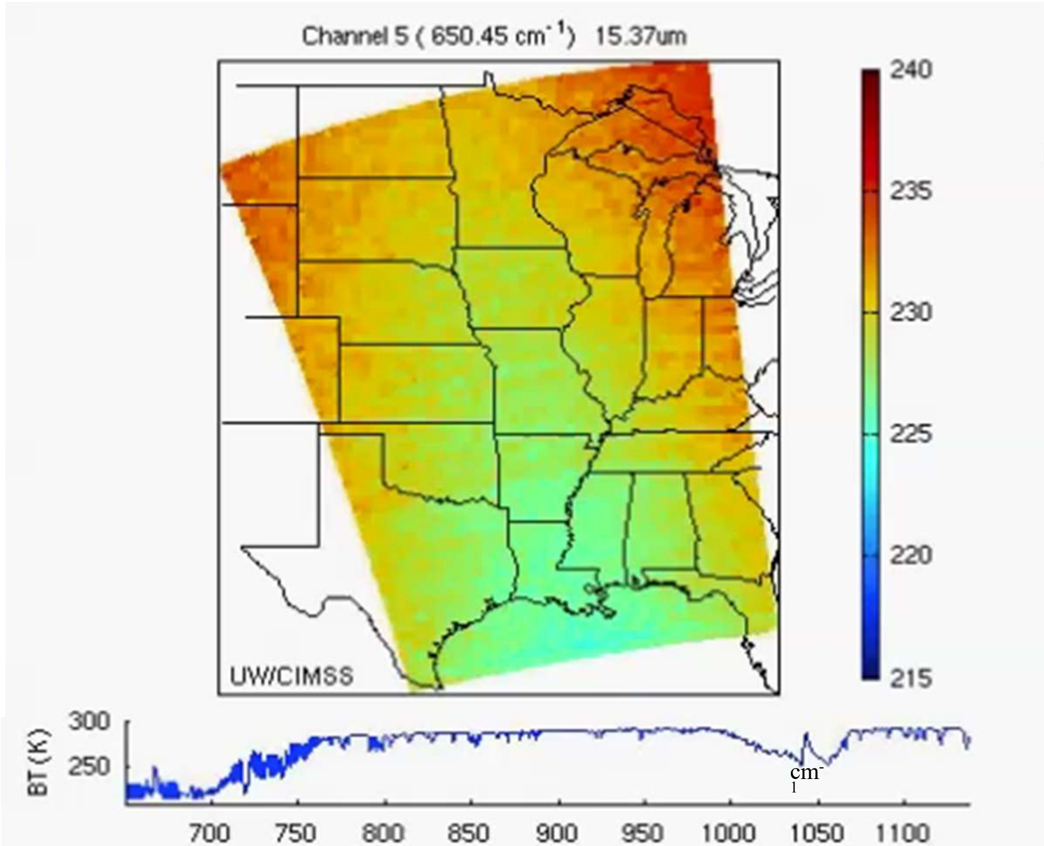
Atmospheric transmission



Infrared spectral imagery

AIRS
λ = 8.80 to 15.37µm

20 July 2002

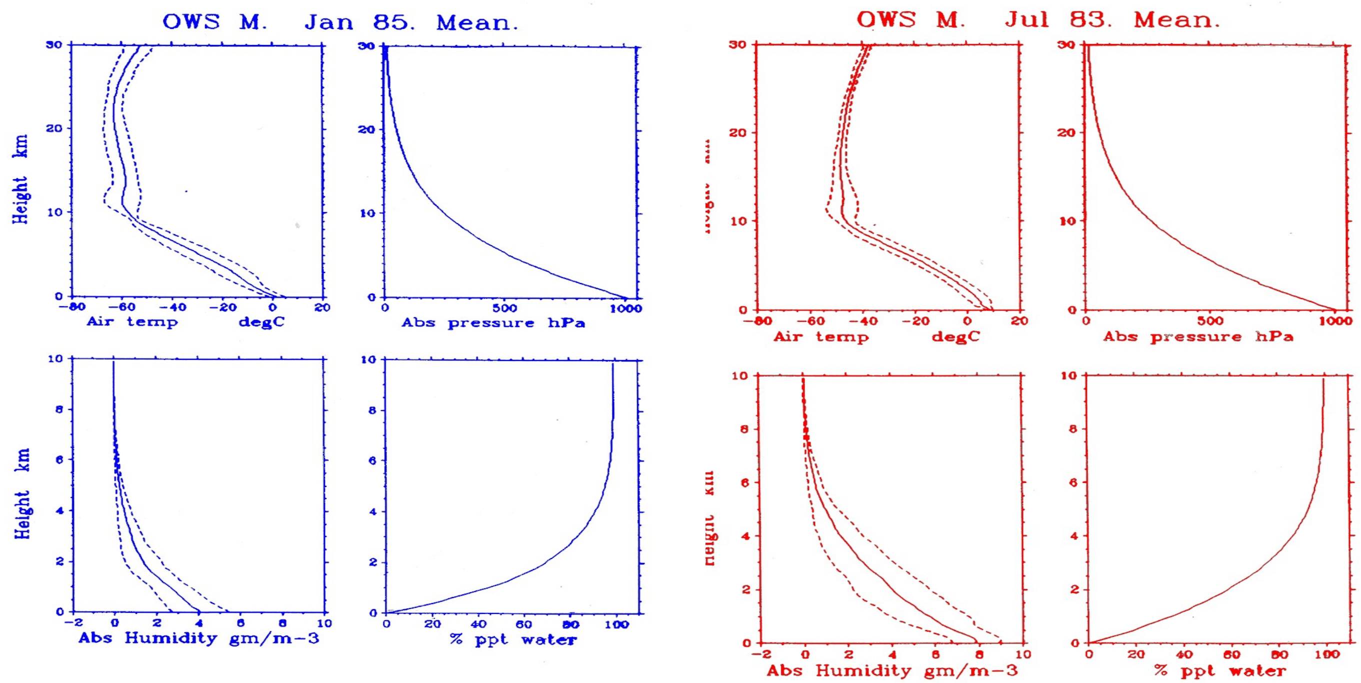


AVHRR Temperature Deficits

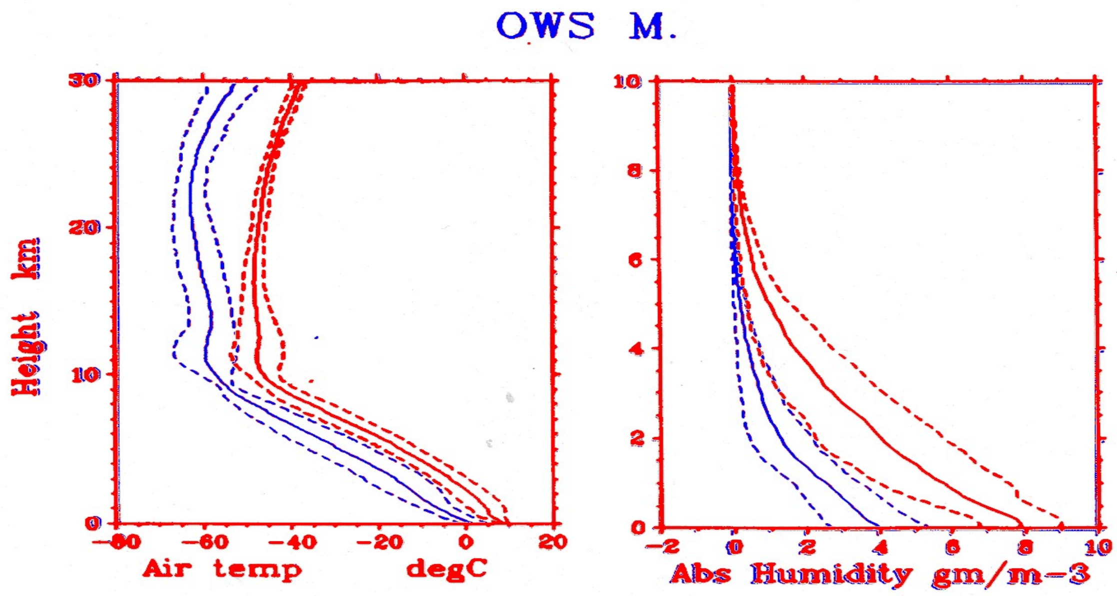
Species	Brightness Temperature Deficits 3	4	5
H_2O	0.79	0.83	1.51
CO_2	0.02	0.25	0.07
O_3	0.01	0.01	0.01
CH_4	0.28	–	–
N_2O	0.45	–	–
HNO_3	–	0.06	0.05
N_2	0.13	–	–
F11	–	–	0.15
F12	–	0.18	0.03

Table 5. Calculated AVHRR top of atmosphere brightness temperature deficits (deg K) due to various atmospheric gases for the three infrared channels viewing a black body surface at 287.2K through a U.S. standard atmosphere for a nadir view.

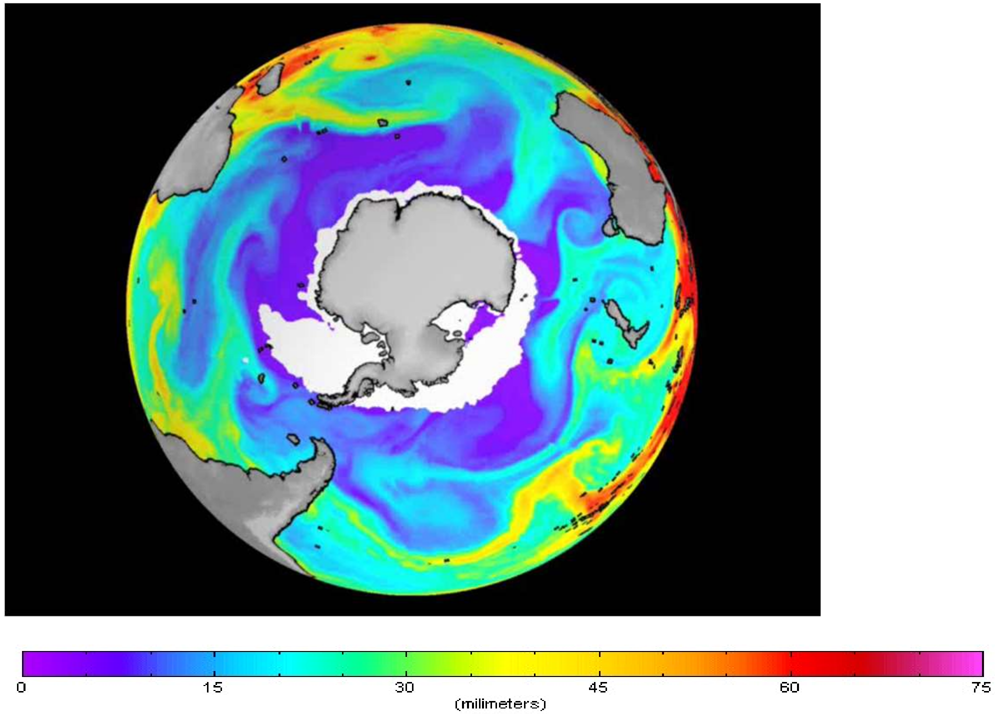
Atmospheric variability



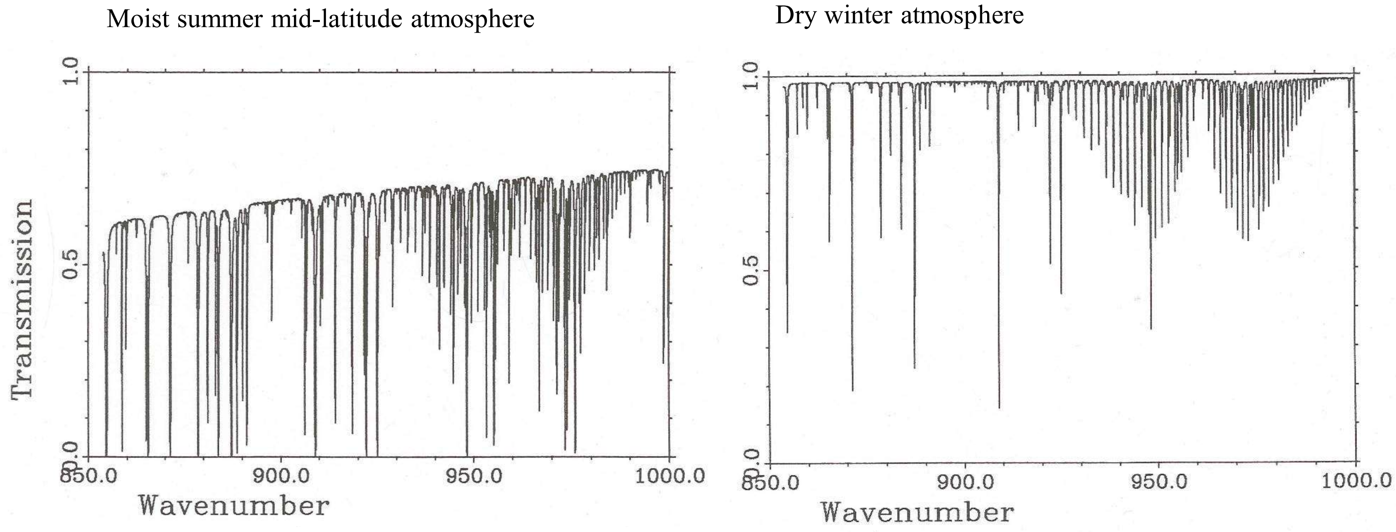
Seasonal variability



Satellite-derived water vapor

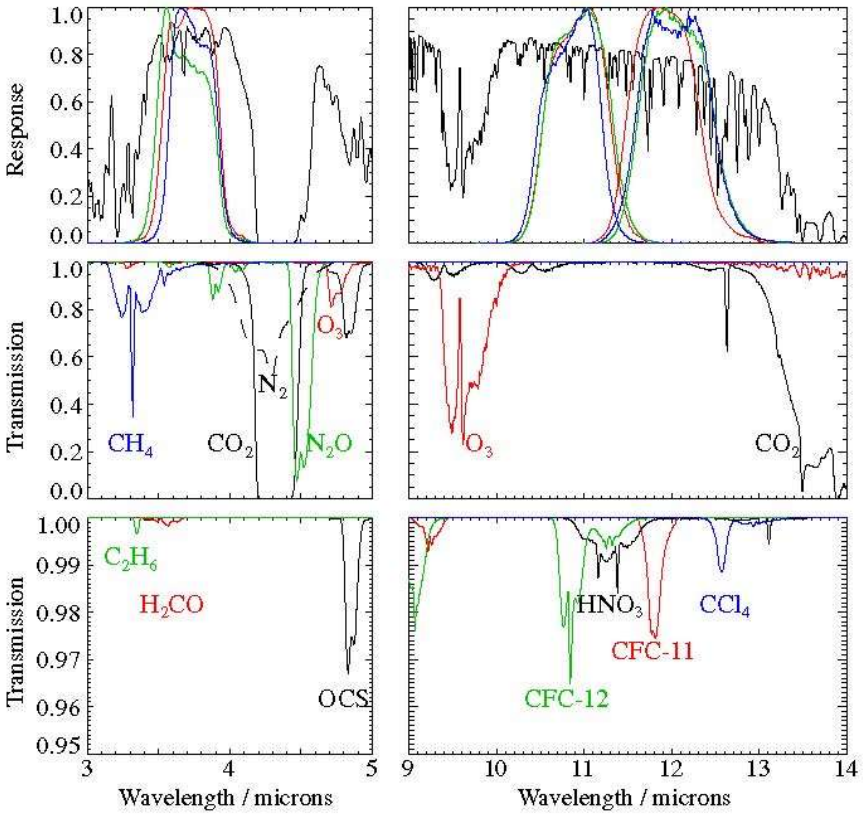


Atmospheric Transmissivity



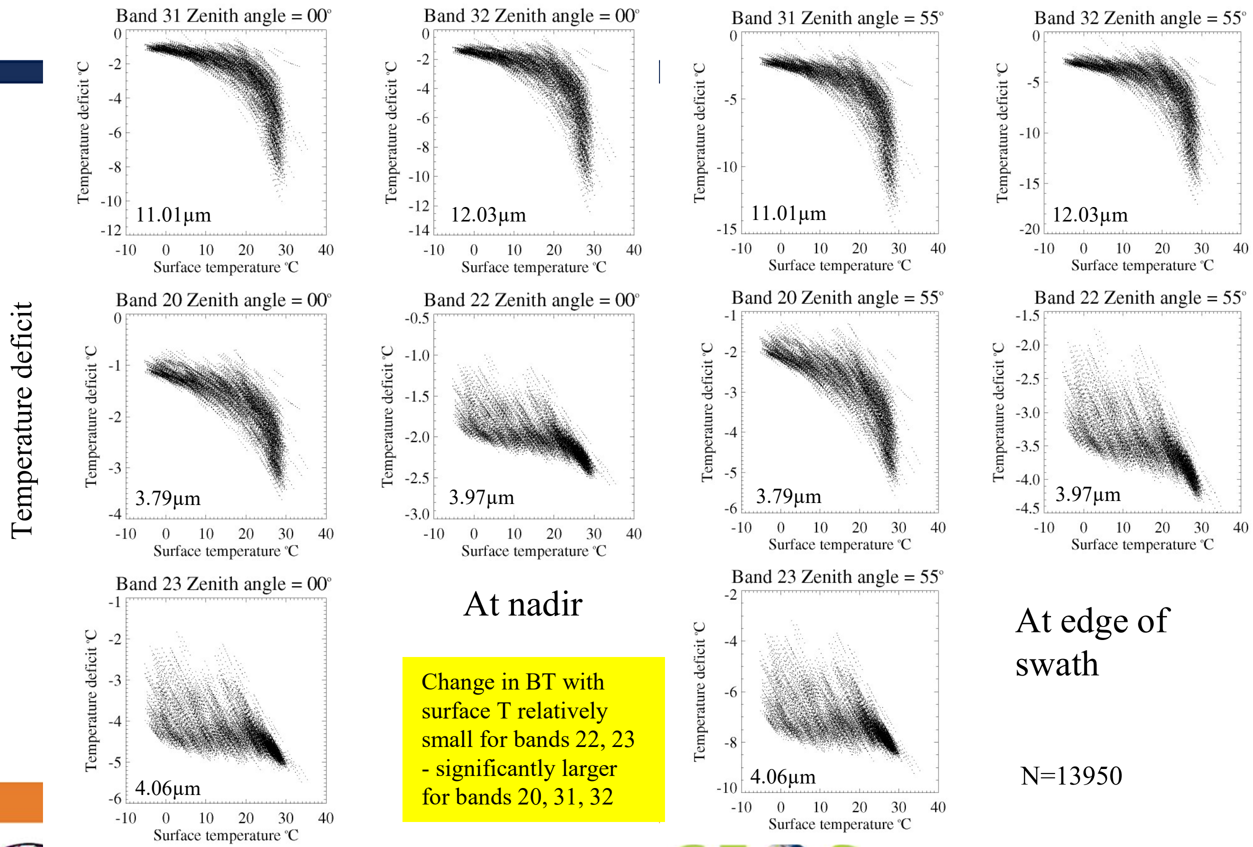
Transmission spectra calculated for a moist summer mid-latitude atmosphere, and a very dry winter atmosphere.

Gaseous effects in AATSR bands



From: Embury, O., Merchant, C.J., & Filipiak, M.J. (2012). A reprocessing for climate of sea surface temperature from the along-track scanning radiometers: Basis in radiative transfer. *Remote Sensing of Environment, 116*, 32-46

Simulated MODIS brightness temperatures at satellite height



At nadir

Change in BT with surface T relatively small for bands 22, 23 - significantly larger for bands 20, 31, 32

At edge of swath

N=13950

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CEOS

Surface temperature range, -10 to 40°C

Split window SST equation

$$(SST - T_{11}) = m\left(T_{11} - T_{12}\right) + c$$

$$SST = T_{11} + m(T_{11} - T_{12}) + c$$

Anding and Kauth, 1970

A procedure is derived for obtaining improved estimates of water surface temperature by … simultaneous radiometric measurements in two wavelength intervals … to approximately ±0.15°C.

MODIS SST atmospheric correction algorithms

The form of the daytime and night-time algorithm for measurements in the long wave atmospheric window is:

$$SST = c_1 + c_2 * T_{11} + c_3 * (T_{11}-T_{12}) * T_{sfc} + c_4 * (\sec(\vartheta)-1) * (T_{11}-T_{12})$$

where T_n are brightness temperatures measured in the channels at n μm wavelength, T_{sfc} is a 'climatological' estimate of the SST in the area, and ϑ is the satellite zenith angle. This is based on the Non-Linear SST algorithm.

[Walton, C. C., W. G. Pichel, J. F. Sapper and D. A. May (1998). "The development and operational application of nonlinear algorithms for the measurement of sea surface temperatures with the NOAA polar-orbiting environmental satellites." Journal of Geophysical Research **103** 27,999-28,012.]

The MODIS night-time algorithm, using two bands in the 4μm atmospheric window is:

$$SST4 = c_1 + c_2 * T_{3.9} + c_3 * (T_{3.9}-T_{4.0}) + c_4 * (\sec(\vartheta)-1)$$

Note, the coefficients in each expression are different. They can be derived in three ways:

- empirically by regression against SST values derived from another validated satellite instrument
- empirically by regression against SST values derived surface measurements from ships and buoys
- theoretically by numerical simulations of the infrared radiative transfer through the atmosphere.

(A)ATSR SST atmospheric correction algorithms

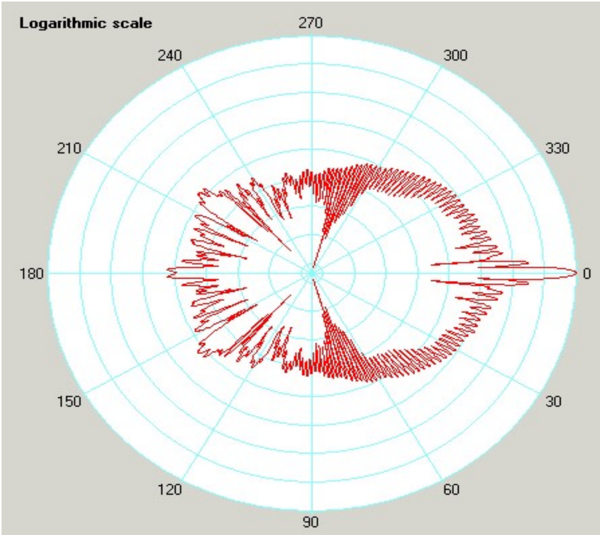
$$SST = a_o + \Sigma\, a_i\, T_i$$

Where *i* indicates spectral bands, geometrical views or both.

For example, N2 means nadir view only, 2 spectral bands; D3 means dual view, 3 spectral bands (i.e. 6 brightness temperature measurements).

Mie scattering by a water droplet

Polar diagram of scattering of red light (wavelength 0.65 µm, perpendicular polarization) from a water droplet of r = 10 µm



Alternative form of the radiative transfer equation

$$\mu \, dL_\lambda/d\tau_\lambda = - L_\lambda(\theta,\varphi) + \alpha_\lambda B_\lambda(T)$$

$$+ (\varpi_\lambda/4\pi)\int_0^{2\pi} \int_{-1}^{1} L_\lambda(\mu',\varphi') p(\psi_s) \, d\mu' \, d\varphi'$$

This is difficult to solve or use, but there are some important simplifications.

Non-scattering atmospheres

Non-scattering atmospheres (an approximation used in the infrared for cloud- and aerosol-free conditions)

$$\mu \, dL_\lambda / d\tau_\lambda = - L_\lambda(\theta,\varphi) + \alpha_\lambda B_\lambda(T)$$

Schwarzschild Equation

Non-emissive atmospheres

Non-emissive atmospheres (an approximation used in the visible):

$$\mu \, dL_\lambda/d\tau_\lambda = - L_\lambda(\theta,\varphi) + (\varpi_\lambda/4\pi)\int_0^{2\pi} \int_{-1}^{1} L_\lambda(\mu',\varphi') \, p(\psi_s) \, d\mu' \, d\varphi'$$

It is often acceptable to assume that clouds and aerosols are non-absorbing, so $\varpi_\lambda = 1$. This is called the *conservative scattering* assumption, because radiant energy is conserved.

Vertical atmospheric transmittances – all contributions. AVHRR

Mechanism	Contributor	AVHRR Channel Numbers 1	2	3	4	5
Gaseous Absorption	H_2O lines	1.0	0.96	0.92	0.97	0.94
	H_2O continuum	1.0	1.0	0.98	0.93	0.90
	Mixed Gases	1.0	0.98	0.95	0.98	0.99
	O_3	0.97*	1.0	1.0	1.0	1.0
	CFCs	1.0	1.0	1.0	0.99	0.99
Scattering	Rayleigh	0.94†	0.98†	1.0	1.0	1.0
	Aerosol maritime	0.93	0.94	0.97	0.99	0.99
	urban	0.42	0.56	0.93	0.97	0.97
Total	maritime	0.85	0.86	0.83	0.87	0.82
	urban	0.38	0.52	0.80	0.85	0.80

* computed from LOWTRAN 5 † taken from Saunders (1988)[2]

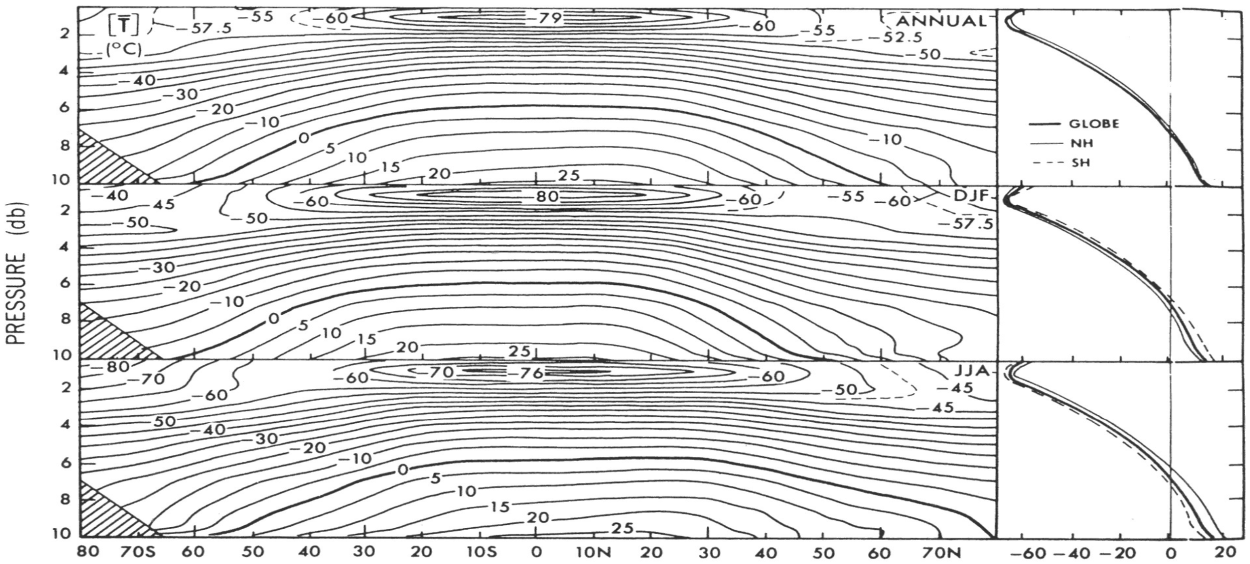
Table 4. Ground to space vertical path transmittances integrated over the AVHRR channels for all known contributions to the atmospheric attenuation.

Vertical atmospheric transmittances for gaseous absorbers - AVHRR

Absorber	AVHRR Channel Numbers 2	3	4	5	Atmosphere
	0.9562	0.9009	0.9057	0.8436	U.S. Standard
	0.9120	0.7773	0.5828	0.4308	Tropical
H_2O	0.9277	0.8255	0.7293	0.6047	Mid-lat summer
	0.9689	0.9348	0.9504	0.9129	Mid-lat winter
	0.9826	0.9658	0.9820	0.9663	Sub-arctic winter
CO_2	1.0	0.9990	0.9854	0.9960	U.S. Standard
O_3	1.0	0.9990	0.9997	0.9998	U.S. Standard
N_2O	1.0	0.9794	1.0	1.0	U.S. Standard
CH_4	1.0	0.9770	1.0	1.0	U.S. Standard
O_2	0.9790	1.0	1.0	1.0	U.S. Standard
NH_3	1.0	1.0	0.9995	0.9998	U.S. Standard
HNO_3	1.0	1.0	0.9987	0.9988	U.S. Standard
OCS	1.0	1.0	1.0	0.9998	U.S. Standard
C_2H_6	1.0	1.0	1.0	0.9996	U.S. Standard
HCl	1.0	0.9999	1.0	1.0	U.S. Standard
H_2CO	1.0	0.9996	1.0	1.0	U.S. Standard
N_2	1.0	0.9927	1.0	1.0	U.S. Standard
$CFCl_3$	1.0	1.0	1.0	0.9948	U.S. Standard
CF_2Cl_2	1.0	1.0	0.9936	0.9994	U.S. Standard
Total	0.9361	0.8536	0.8849	0.8335	U.S. Standard

Table 3. Ground to space vertical path transmittances due to gaseous absorption (line and continuum) integrated over four of the AVHRR channels

Global variability



Zonal-mean cross sections of the temperature for annual-mean, DJF, and JJA con ditions in °C. Vertical profiles of the hemispheric and global mean temperatures are shown on the right.

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