

Radiative Transfer for Data Assimilation

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With thanks to James Hocking, Marco Matricardi, Roger Saunders, Samuel Quesada Ruiz, Angela Benedetti, Alan Geer and many others..

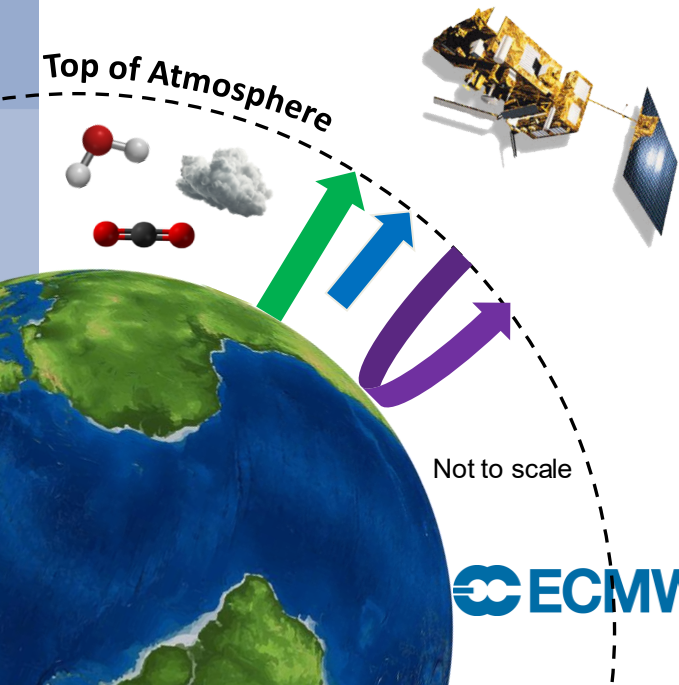
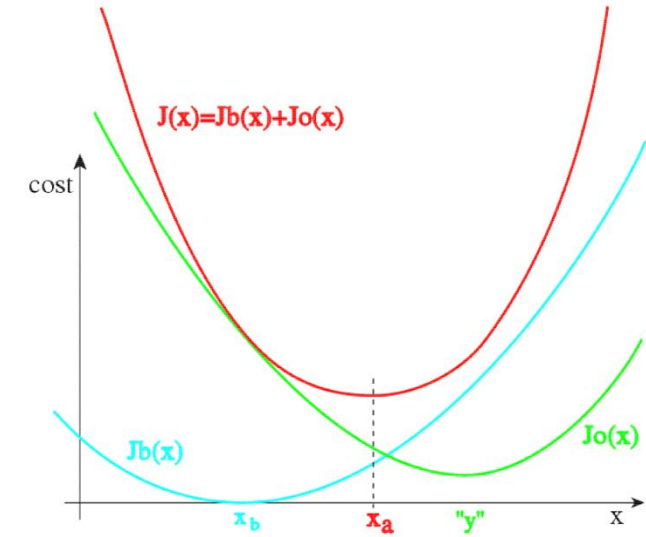
Topics covered

1. What is Radiative Transfer?
2. The Radiative Transfer Equation (clear-sky)
3. Spectroscopy and line-by-line models
4. Fast models (RTTOV)
5. Clouds and scattering
6. Surface
7. RTTOV Resources (moved to practical session)



What is Radiative Transfer?

Radiative transfer is the study of the propagation of electromagnetic **radiation** through the **atmosphere** which involves interactions with atmospheric constituents (gas molecules, aerosols, hydrometeors) and the surface.



Cost function \longrightarrow $J(x) = (x - x_B)^2 + (y - H[x])^2$

model background \swarrow (points to x_B)

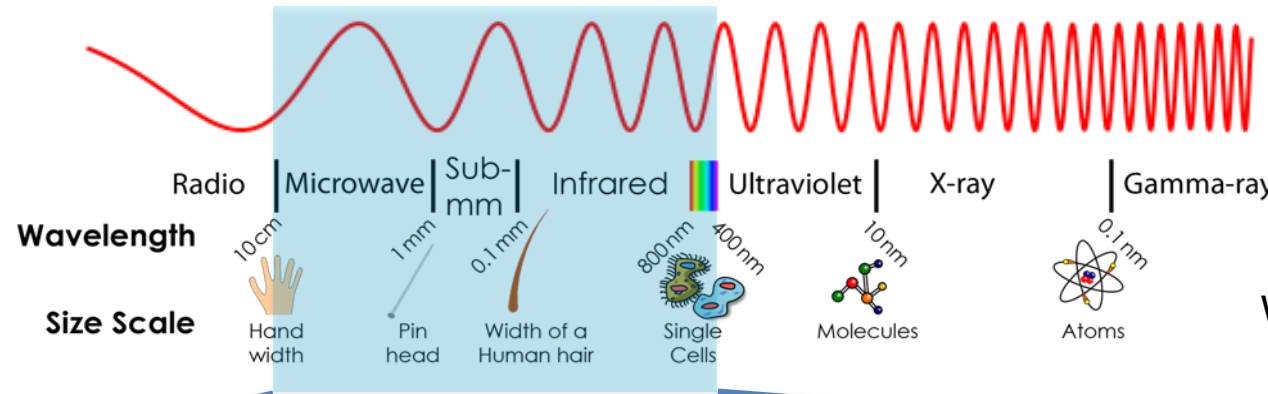
observations \swarrow (points to y)

model variable \swarrow (points to x)

observation operator \swarrow (points to $H[x]$)

From an NWP data assimilation perspective an RT model is the **observation operator** for assimilating visible/near-infrared, infrared and microwave satellite radiances into NWP models.

Electromagnetic Spectrum and spectral units



Wavenumber (ν) = Frequency / 30
 Wavelength (λ) = 1 / Wavenumber

	Microwave	Sub-mm	Far Infrared	Infrared	Near Infrared	Visible
Frequency	1 - 300 GHz	300 - 1000 GHz	1000 - 20000 GHz			
Wavenumber	0.03 - 10 cm ⁻¹	10 - 33 cm ⁻¹	33 - 667 cm ⁻¹	667 - 4000 cm ⁻¹	4000 - 12800 cm ⁻¹	
Wavelength	300 - 1 mm	1 - 0.3 mm	300 - 15 μm	15 - 2.5 μm	2500 - 780 nm	780 - 400 nm

Radar bands

	L	S	C	X	K _u	K	K _a
GHz	1-2	2-4	4-8	8-12	12-18	18-27	27-40

Infrared bands

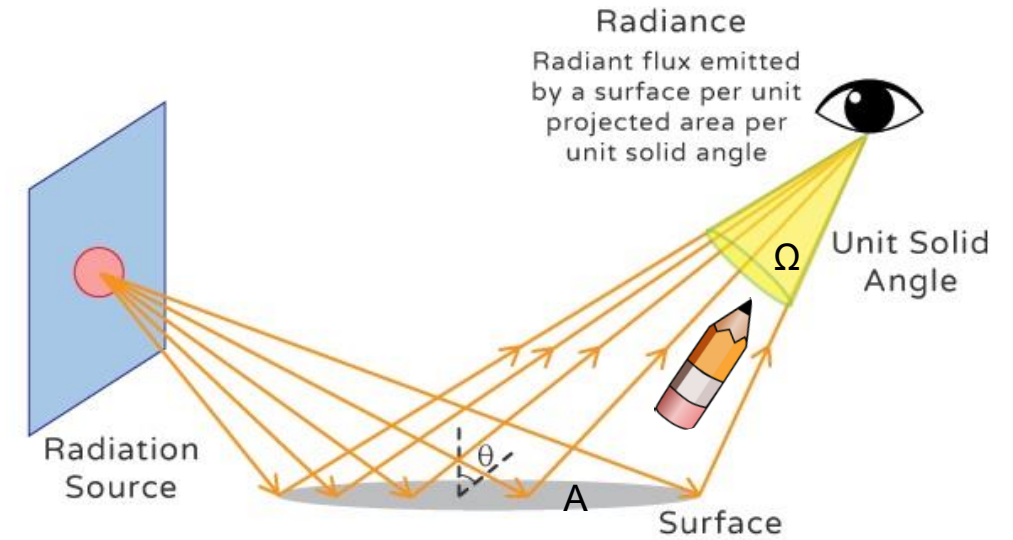
	Longwave	Midwave	Shortwave
Wavenumber	667 - 1250 cm ⁻¹	1250 - 2000 cm ⁻¹	2000 - 4000 cm ⁻¹
Wavelength	15 - 8 μm	8 - 5 μm	5 - 2.5 μm

→ to UV

Radiance and Planck's Law

Spectral Radiance

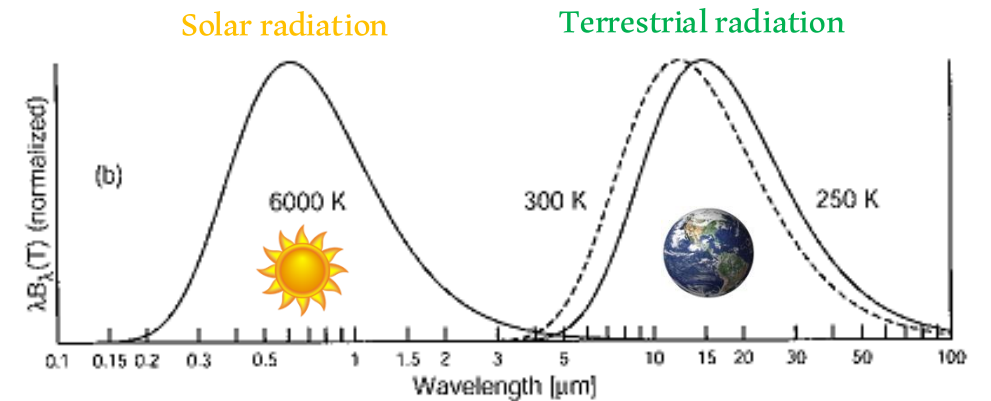
$$L_\nu = \frac{dE_\nu}{dA \cos \theta d\Omega d\nu} \quad \frac{W}{m^2 sr cm^{-1}}$$



All objects with a temperature greater than 0 kelvin radiate energy

Black-body radiance

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{k_B T}\right) - 1}$$



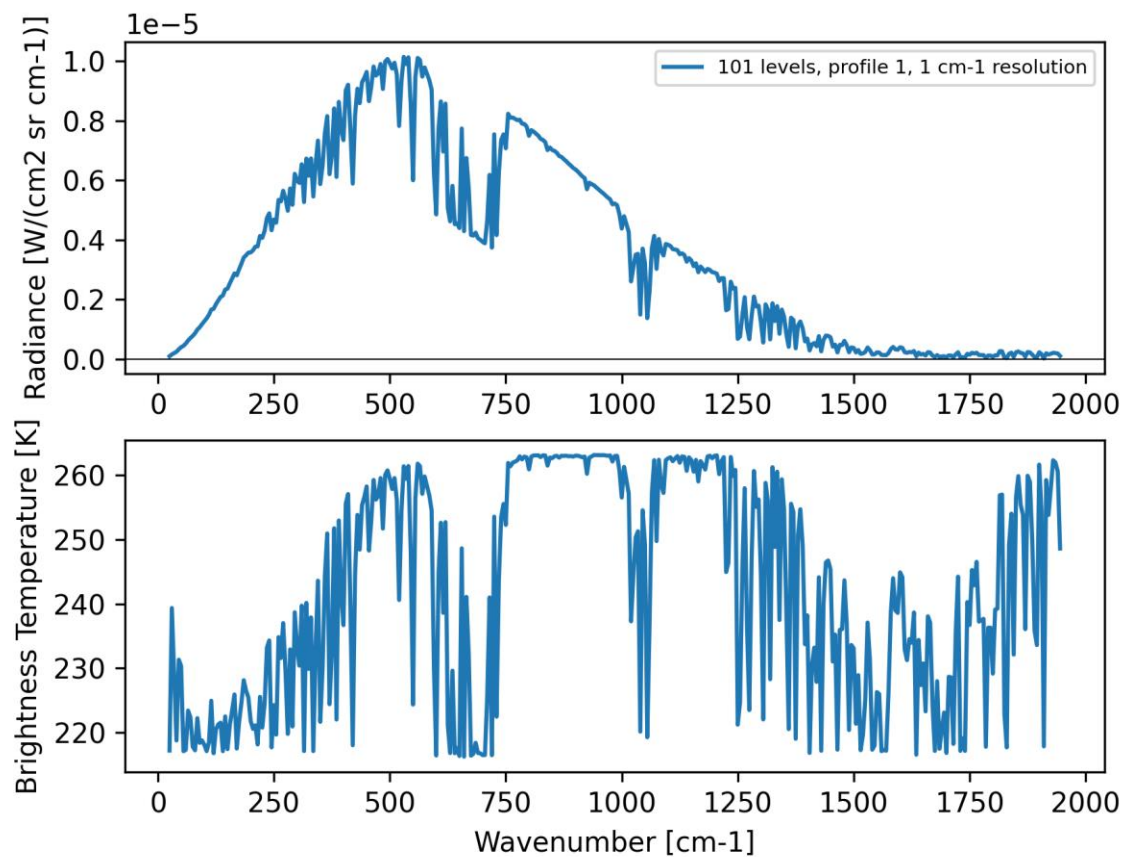
Radiance and Brightness Temperature

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{k_B T}\right) - 1}$$

Invert for temperature

$$T_B = \frac{h\nu}{k_B \ln\left(\frac{2h\nu^3}{c^2 L_\nu} + 1\right)}$$

TAPE11_0.1A: LBLRTM 12.15.1 / MT-CKD 4.2



Radiation vs. atmosphere

Attenuation =
Reduction in
intensity

Isotropic =
Equal in all
directions

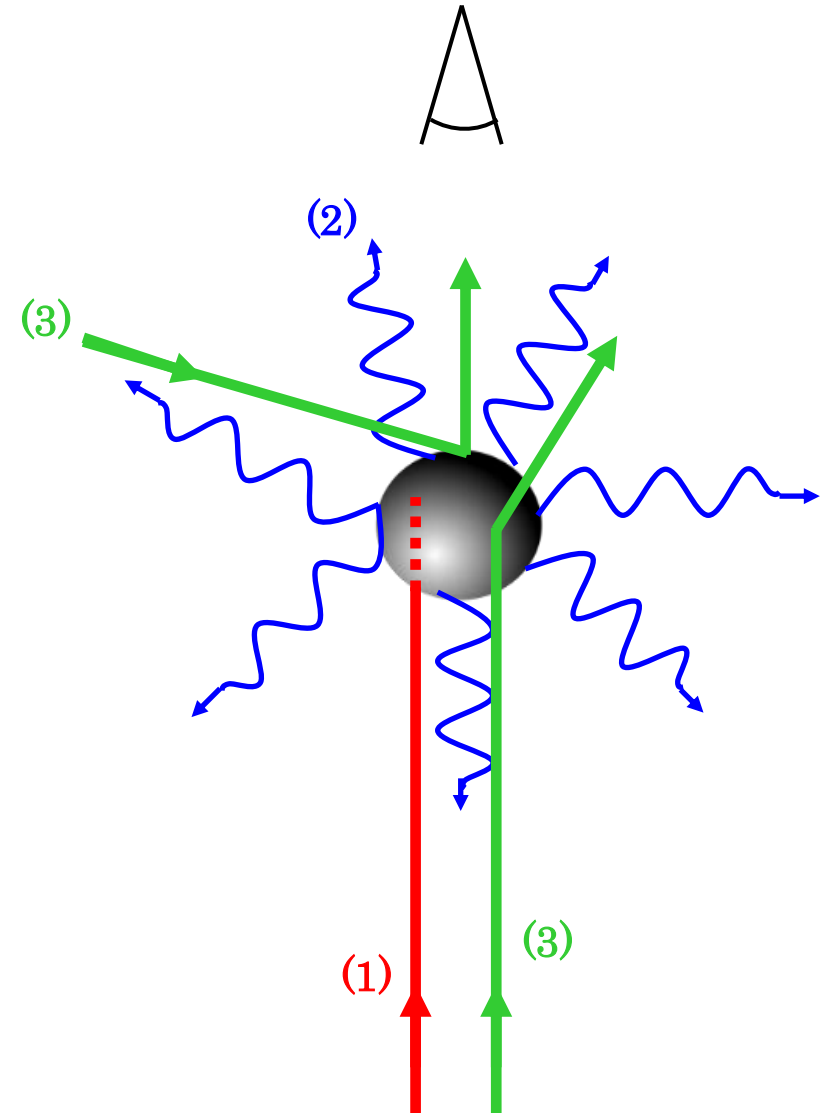
(1) **Absorption**: radiation is attenuated and converted to other forms of energy (i.e kinetic energy or chemical reaction)

(2) **Emission**: isotropic increase in radiation by molecular excitation due to absorption

(3) **Scattering**: radiation attenuation by deviation of radiation from original direction; also increase in radiation by deviation of radiation *into* direction under consideration

Extinction (Sink term) = Absorption + Scattering

Source term = Emission + Scattering



Radiation vs. atmosphere (no scattering)

Extinction (Sink term) = **Absorption**

Source term = **Emission**

Consider a slab of the atmosphere →

What is the change of radiation dL_ν at the top of the slab?

Absorption coefficient [m^{-1}]

$$(dL_\nu)_{ext} = -k_{abs} L_\nu dz$$

$$(dL_\nu)_{src} = k_{abs} B_\nu(T) dz$$

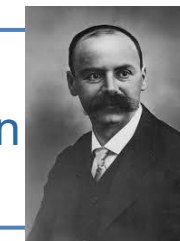
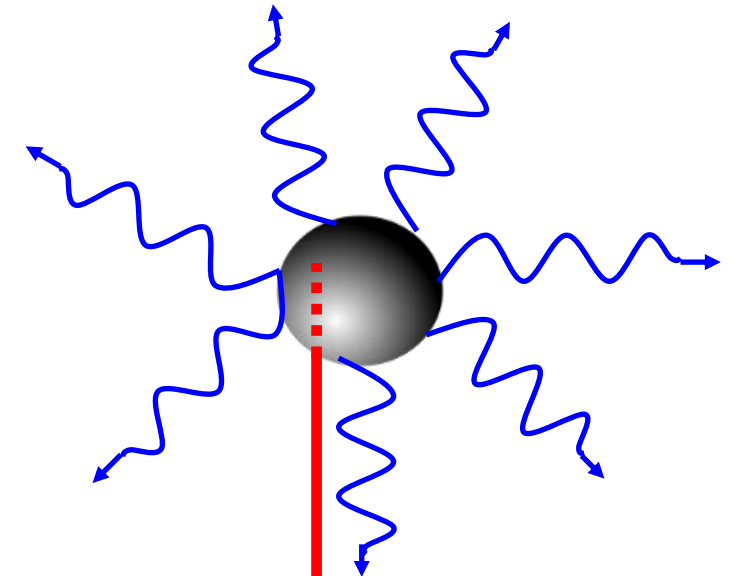
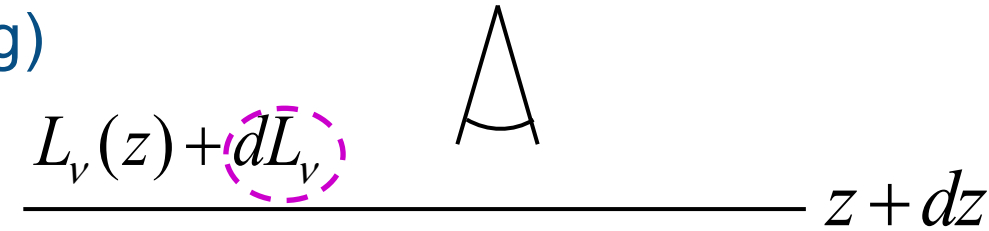
$$d\tau = -k_{abs} dz$$

Optical depth [no units]

$$dL_\nu = (dL_\nu)_{ext} + (dL_\nu)_{src}$$

$$dL_\nu = -k_{abs} (L_\nu - B_\nu(T)) dz$$

$$\frac{dL_\nu}{d\tau} = L_\nu - B_\nu(T) \quad \text{Schwarzschild's Equation}$$



Optical Depth (τ) and Transmittance (t)

$$d\tau = -k_{abs} dz$$

↑
tau

Optical depth is unitless (and frequency dependent)

A large OD means lots of attenuation by the atmosphere.

A small OD means radiation gets through easier.

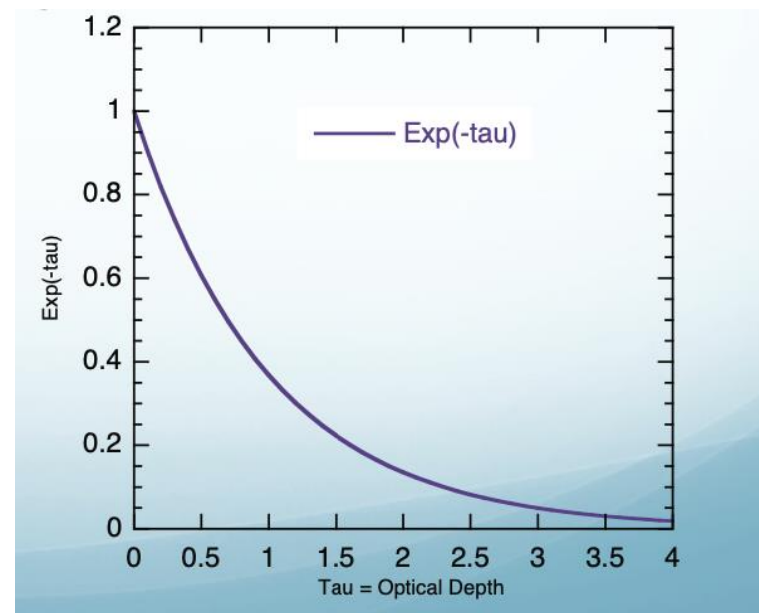


Transmittance
[no units]

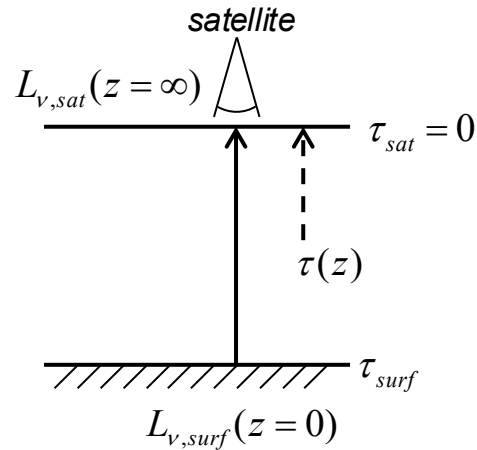
$$t = e^{-\tau} \quad 0 \leq t \leq 1$$

A completely transparent medium has a transmittance of 1

A completely opaque medium has a transmittance of 0



Radiative Transfer Equation (clear-sky, no scattering)



$$\frac{dL_v}{d\tau} = L_v - B_v(T) \quad \text{Schwarzschild's Equation}$$

$$\frac{d}{d\tau}(L_v e^{-\tau}) = -B_v(T) e^{-\tau}$$

Emissivity
[0-1]

$$L_{v,surf} = \varepsilon_{v,surf} B_v(T_{surf})$$

$$L_{v,sat} = L_{v,surf} e^{-\tau_{surf}} - \int_{\tau_{surf}}^0 B_v(T) e^{-\tau} d\tau$$

$$L_{v,sat} = \boxed{\varepsilon_{v,surf} B_v(T_{surf}) t_{surf}} + \boxed{\int_{t_{surf}}^1 B_v(T) dt} + \boxed{(1 - \varepsilon_{v,surf}) t_{surf}^2 \int_{t_{surf}}^1 \frac{B_v(T)}{t^2} dt}$$

Surface emission

Upwelling
atmospheric emission

Downwelling surface-reflected
atmospheric emission

Weighting Functions

≠

(but they can look the same)

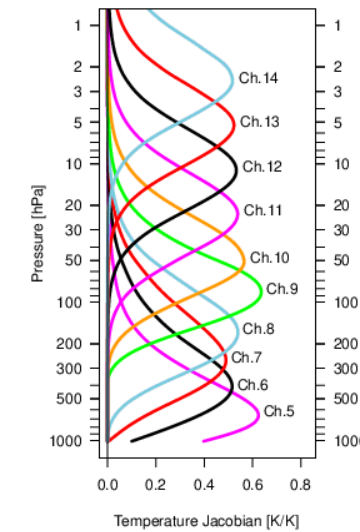
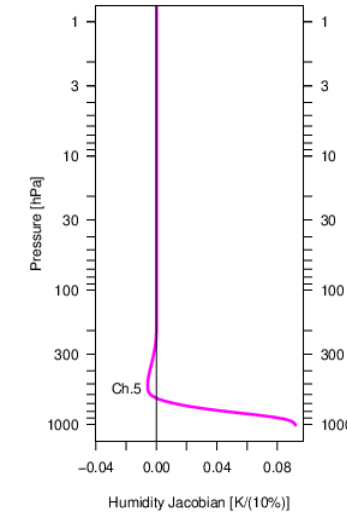
$$L_{v,sat} = \int_{t_{surf}}^1 B_v(T) dt = \int_{p_{surf}}^0 B_v(T) \frac{\partial t}{\partial p} dp$$

Weighting function

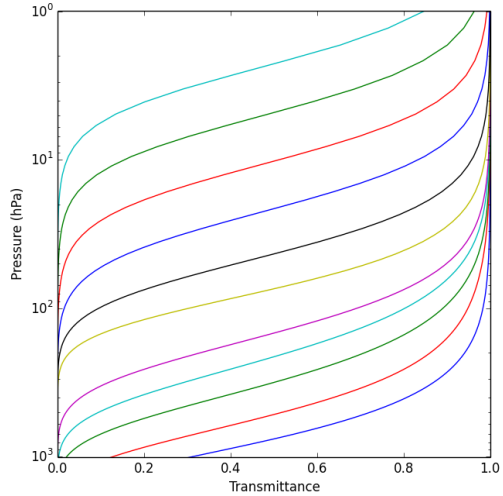
Upwelling atmospheric emission

$$J_Q = \frac{\partial L_v}{\partial Q}$$

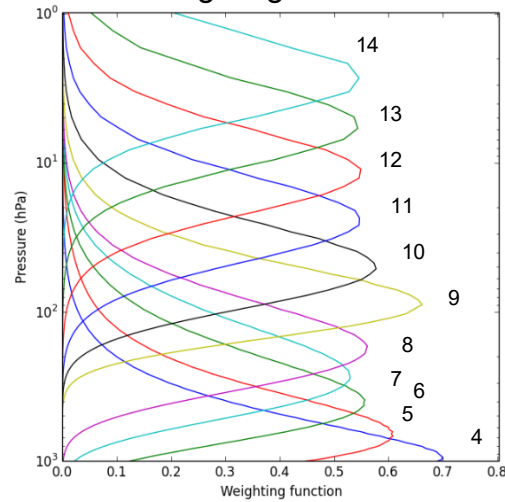
$$J_T = \frac{\partial L_v}{\partial T}$$



AMSU-A: 50-57 GHz channels

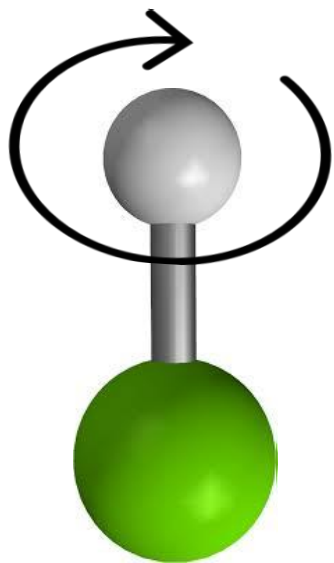


Weighting functions

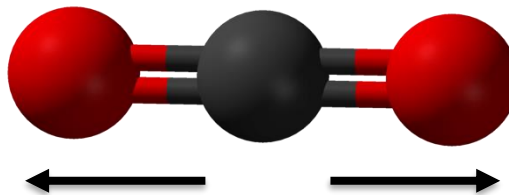


Molecular transitions

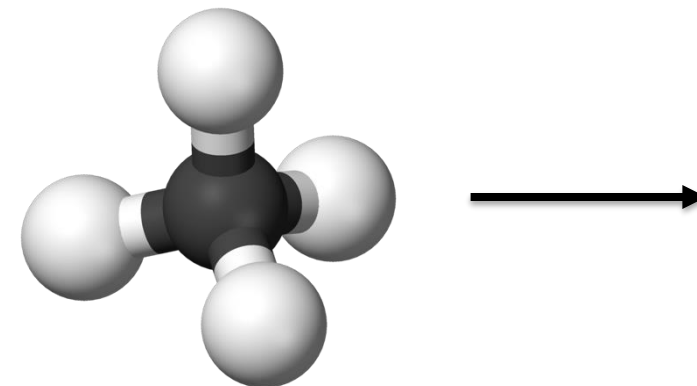
Rotational



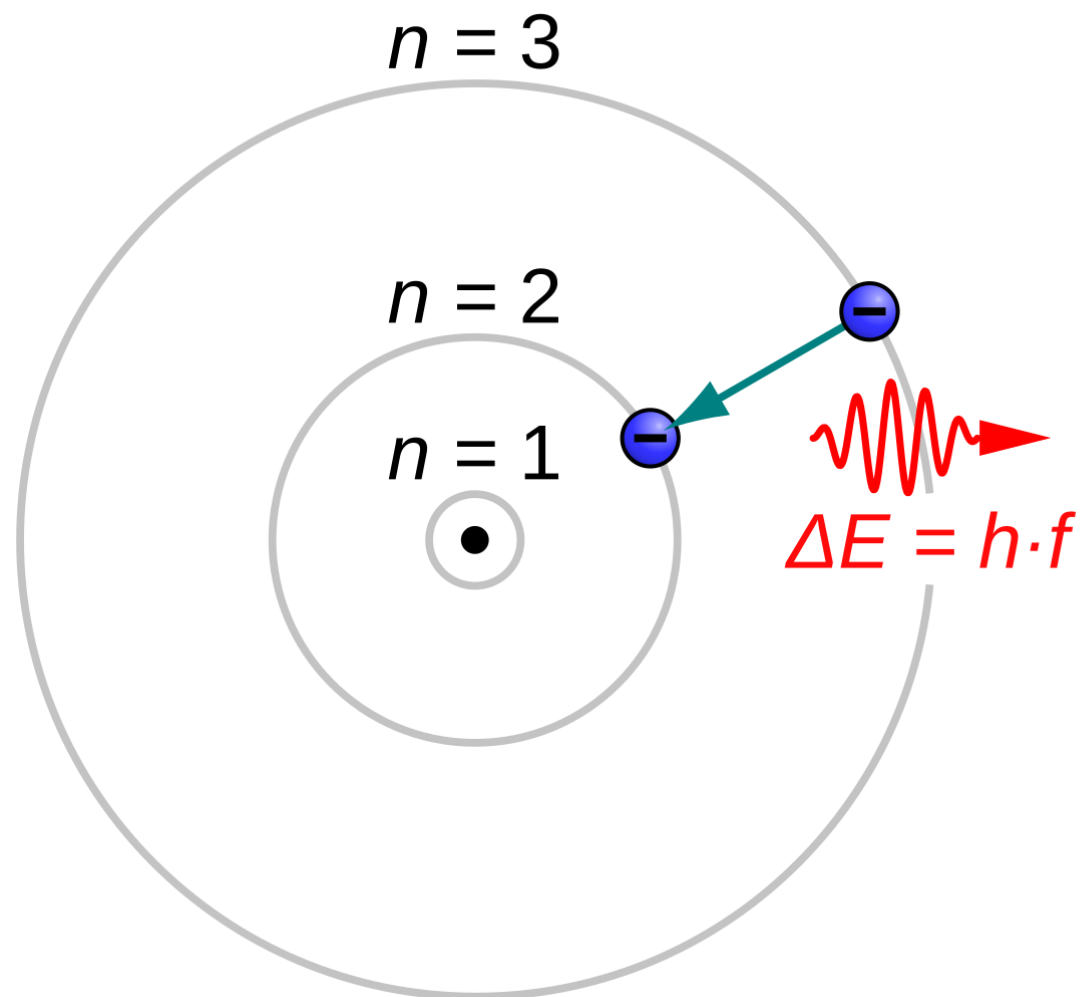
Vibrational



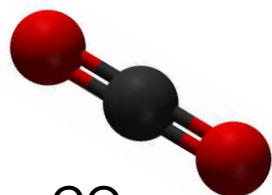
Translational / Electronic



Electronic transitions



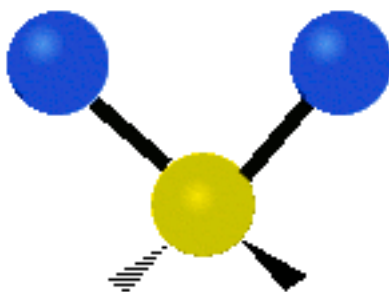
Vibrational normal modes

CO₂

$$\nu^1: 3657 \text{ cm}^{-1}$$

$$\nu^1: 1388 \text{ cm}^{-1}$$

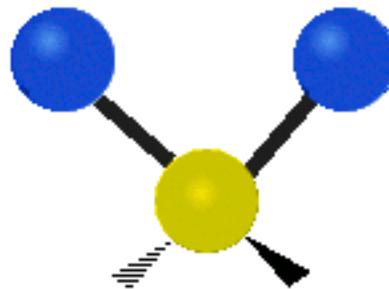
Symmetric stretching



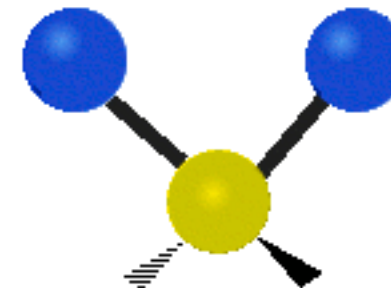
$$\nu^3: 3756 \text{ cm}^{-1}$$

$$\nu^3: 2349 \text{ cm}^{-1}$$

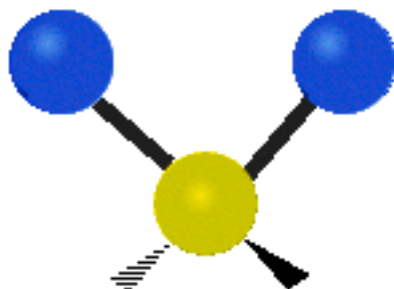
Asymmetric stretching



Wagging



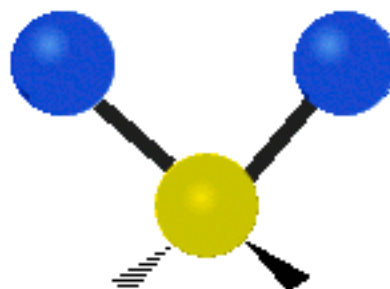
Twisting



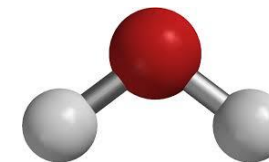
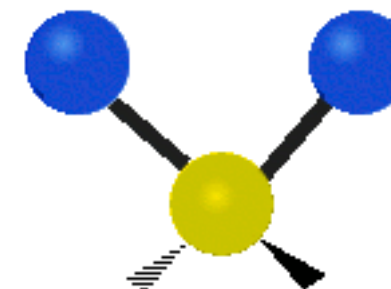
$$\nu^2: 1595 \text{ cm}^{-1}$$

$$\nu^2: 2 \times 667 \text{ cm}^{-1} \text{ (degenerate)}$$

Bending

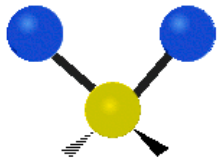


Rocking

H₂O

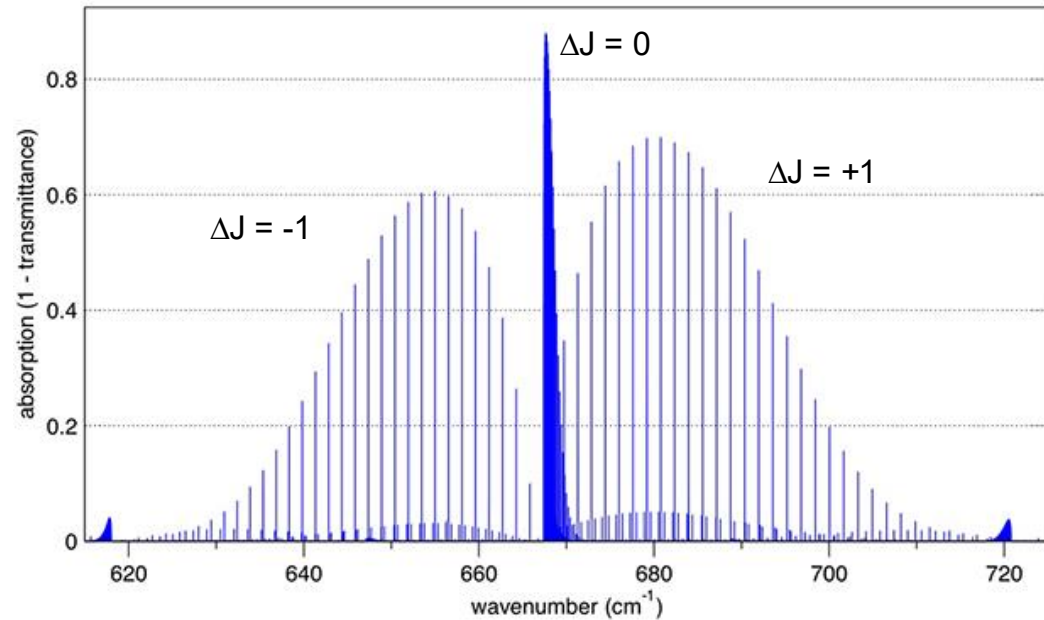
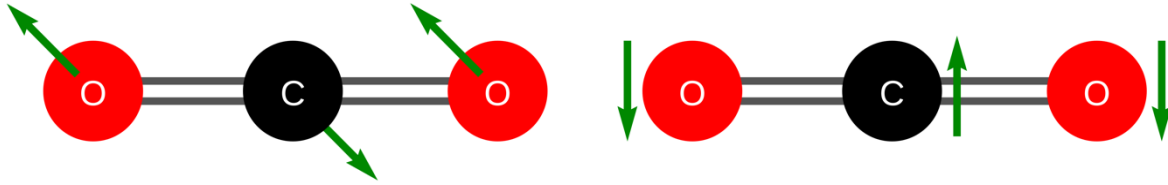
Courtesy Tiago Becerra Paolini on Wikipedia for CH₂

Bending

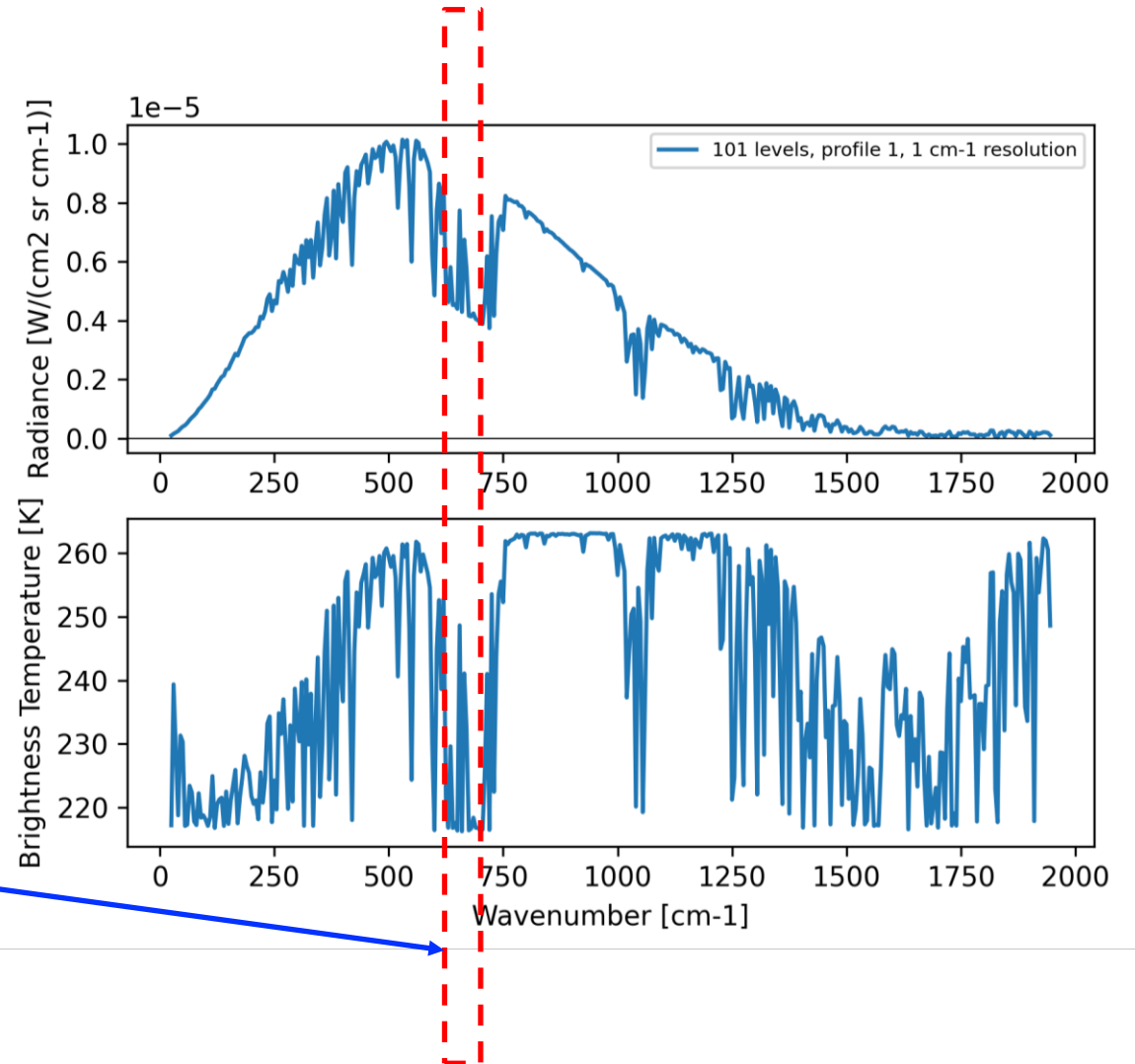


CO₂ Vibrational bending → Rotational-vibrational spectrum

ν^2 : 2 x 667 cm⁻¹ (degenerate)



P branch **Q branch** **R branch**



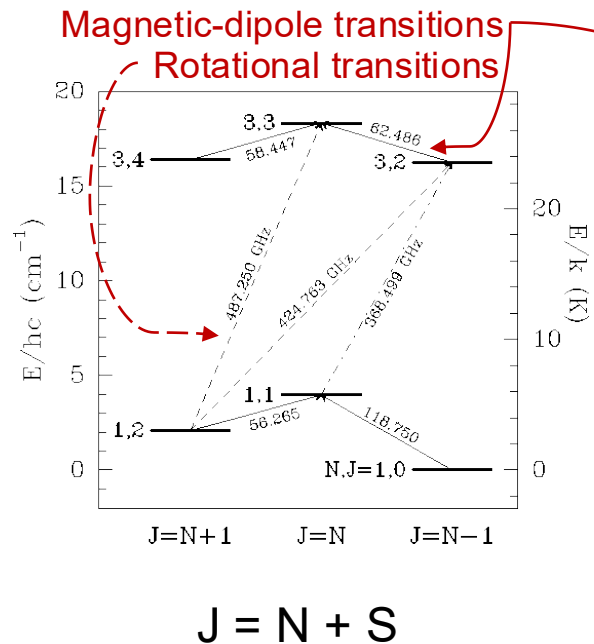
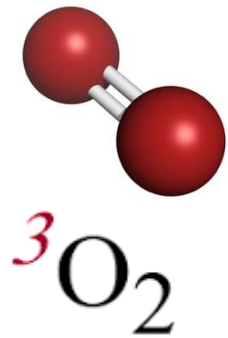
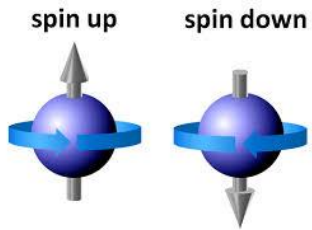
Fine structure transitions

E = electronic

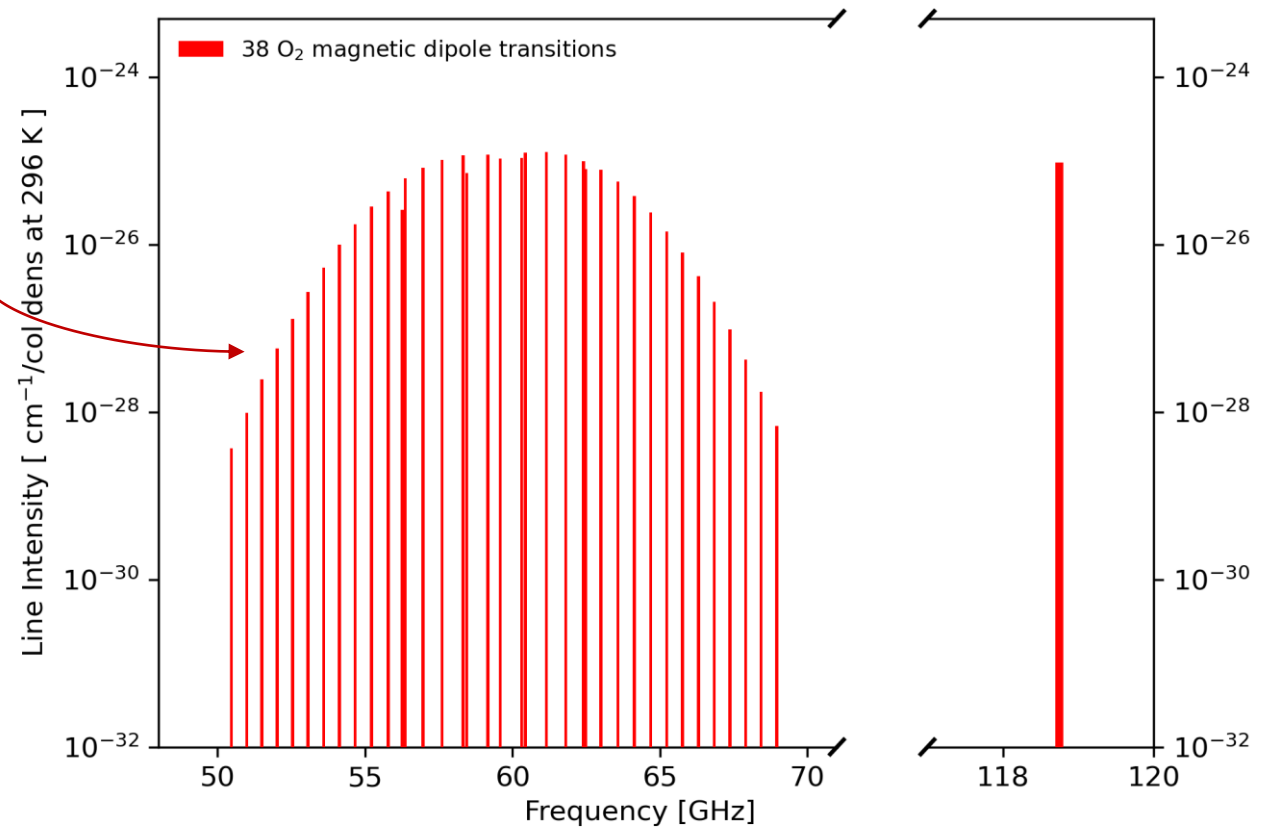
ν = vibrational

J = rotational

S = spin



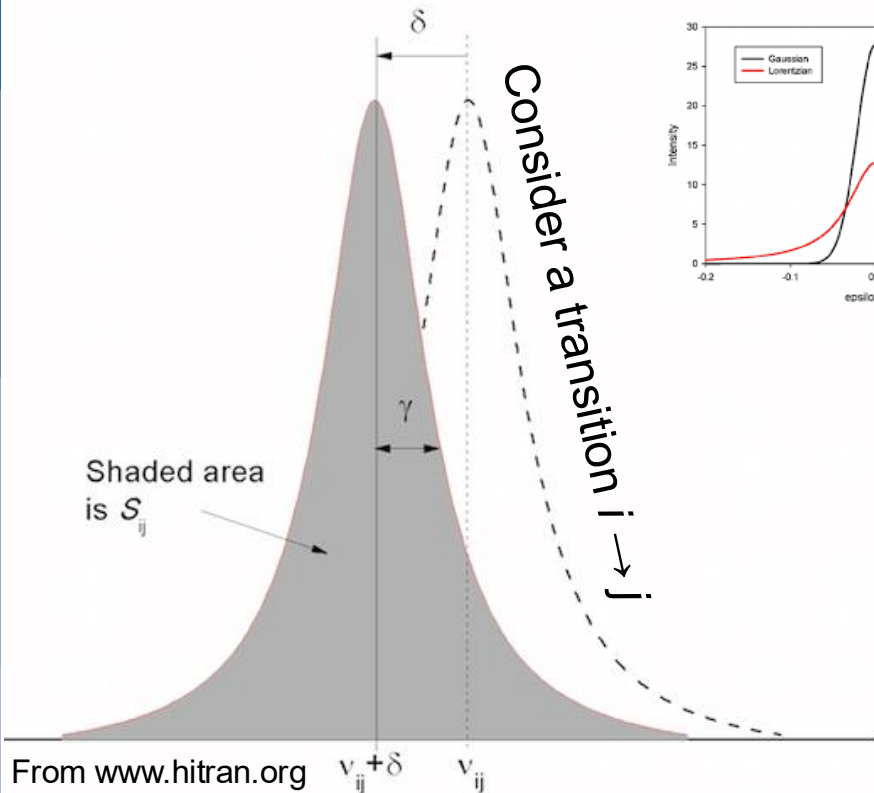
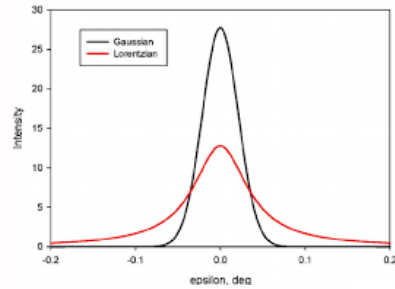
The oxygen molecule has non-zero spin, which interacts with rotational transitions creating further transitions *within* rotational energy levels, these new transitions we rely on for temperature sounding



Spectroscopy: Lines

Region	Broadening mechanism	Dominant shape
Lower atmosphere	Pressure	Lorentzian
Upper atmosphere	Doppler	Gaussian

Region	Lineshape
Microwave	Van-Vleck Weisskopf
Infrared	Voigt



Absorption coefficient

Line Shape (function of halfwidth γ_{ij})

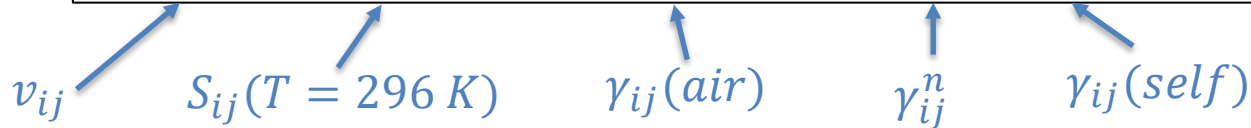
$$k_{ij}(\nu) = S_{ij}(T) f(\nu - \nu_{ij})$$

Line Intensity

Wavenumber of transition

Line parameters for CO₂ vibrational line at 667.4 cm⁻¹ from HITRAN 2024

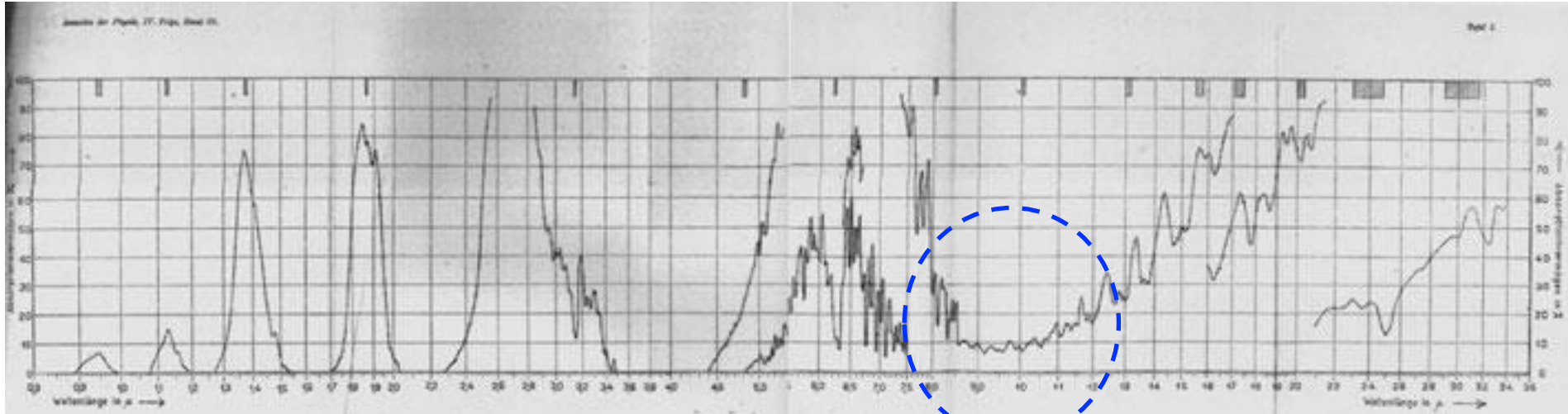
21	667.400621	1.303E-19	1.527E+00	0.08620	0.118	7.80430	0.69	-0.000431	0	1	1	0	1	0	0	0	0	1	Q	4e	3766632429	9	9	711	9.0	9.0
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Other line databases from AER, GEISA, JPL, (Microwave specific: MPM, Rosenkranz..) or stand-alone studies ¹⁷

Spectroscopy: Continuum

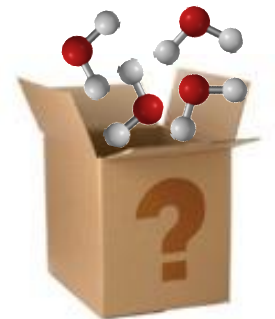
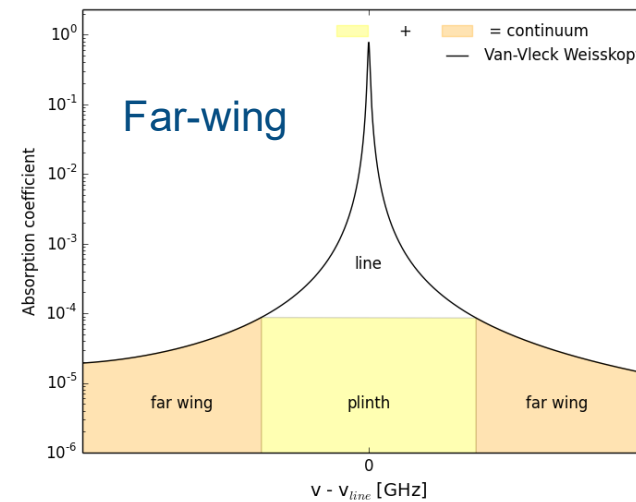
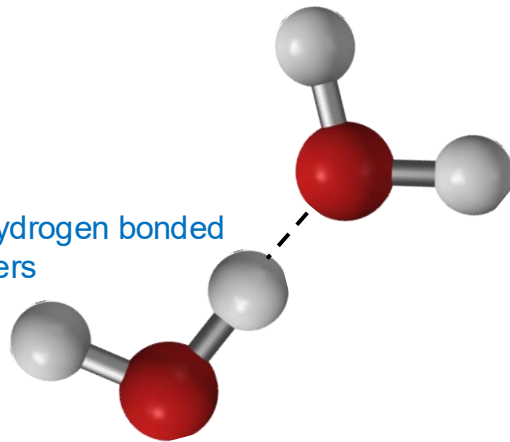
From Shine et al. (2012)



Absorption spectrum of water vapour obtained by laboratory observations by Hettner (1918), which displays the characteristic 'band' and 'window' structure of that absorption. To obtain measurable absorption in the 8–12 μ m region, Hettner had to use increased concentrations of water vapour, and hence two curves are plotted in the vicinity of this window.

Dimers

Weak hydrogen bonded monomers



Water vapour continuum is mysterious

Line-by-line models

$$k(\nu) = \sum_{ij=0}^{H_2O} S_{ij}(T) f(\nu - \nu_{ij})$$

$$+ C_{H_2O}(\nu)$$

$$+ \sum_{ij=0}^{O_2} S_{ij}(T) f(\nu - \nu_{ij})$$

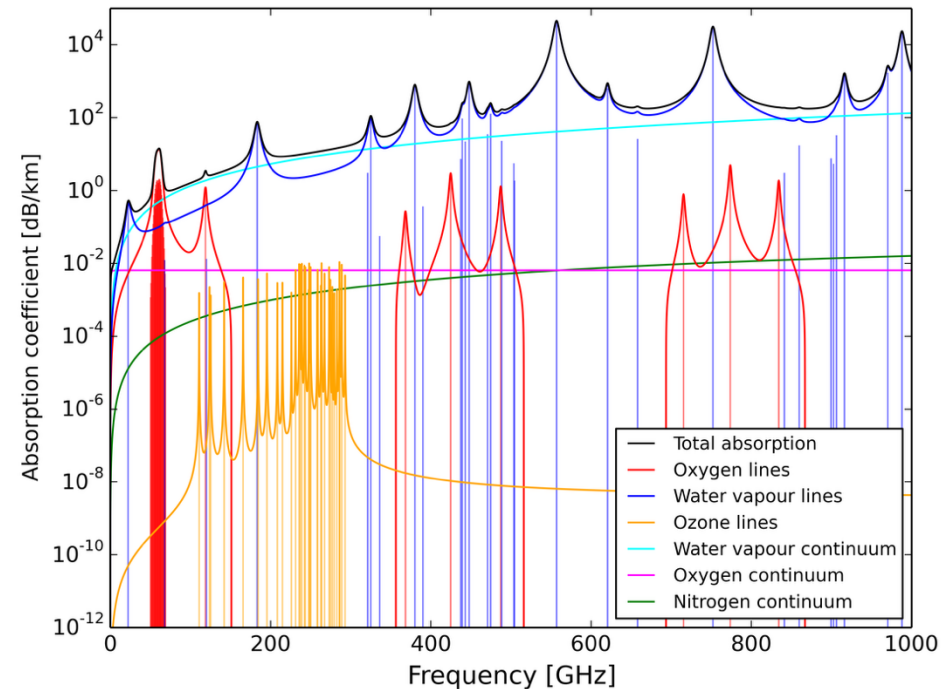
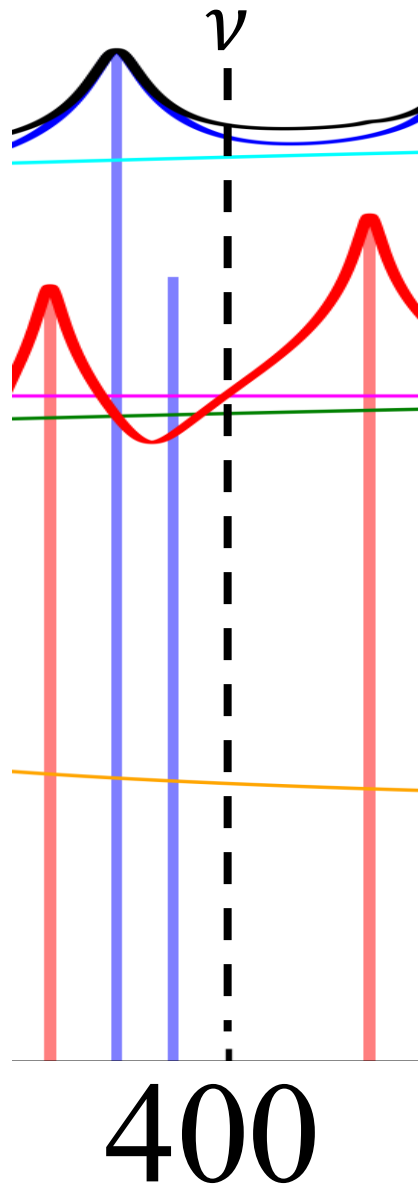
$$+ C_{O_2}(\nu) + C_{N_2}(\nu)$$

$$+ \sum_{ij=0}^{O_3} S_{ij}(T) f(\nu - \nu_{ij})$$

Transmittance

$$t(\nu) = e^{-k(\nu) dz}$$

Spectral line



From Turner et al. (2019)

Line-by-line models include:
 LBLRTM, MonoRTM,
 ARTS, MODTRAN (MPM,
 Rosenkranz) ..

Fast models: RTTOV



TIROS-N launched 1978

- **RTTOV** is the **R**adiative **T**ransfer (model) for **TOVS** (TIROS **O**perational **V**ertical **S**ounder)
- A *fast* satellite simulator code
- It is the observation operator in the ECMWF assimilation system and many other NWP centres and is used in reanalysis, retrieval applications and simulated satellite imagery. It is also used as a stand-alone code for research applications
- First developed in the early 1990's (at ECMWF)
- Developed under the NWP SAF since 1998
- International collaboration between Météo-France, ECMWF, DWD and lead by the Met Office
- Over 2000 people are registered to use it worldwide
- Currently at version 14.1, released in February 2026.
- Find it on the NWP SAF website <https://nwp-saf.eumetsat.int/site/software/rttov/>

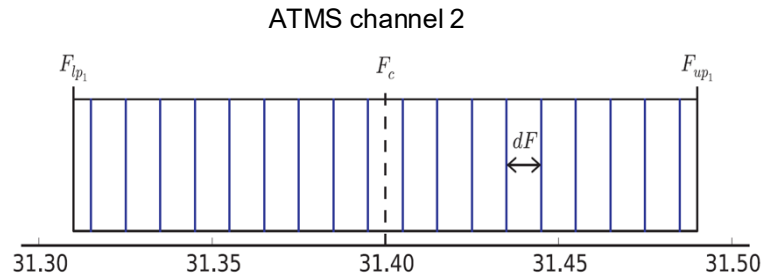
The EUMETSAT
Network of
Satellite
Application
Facilities



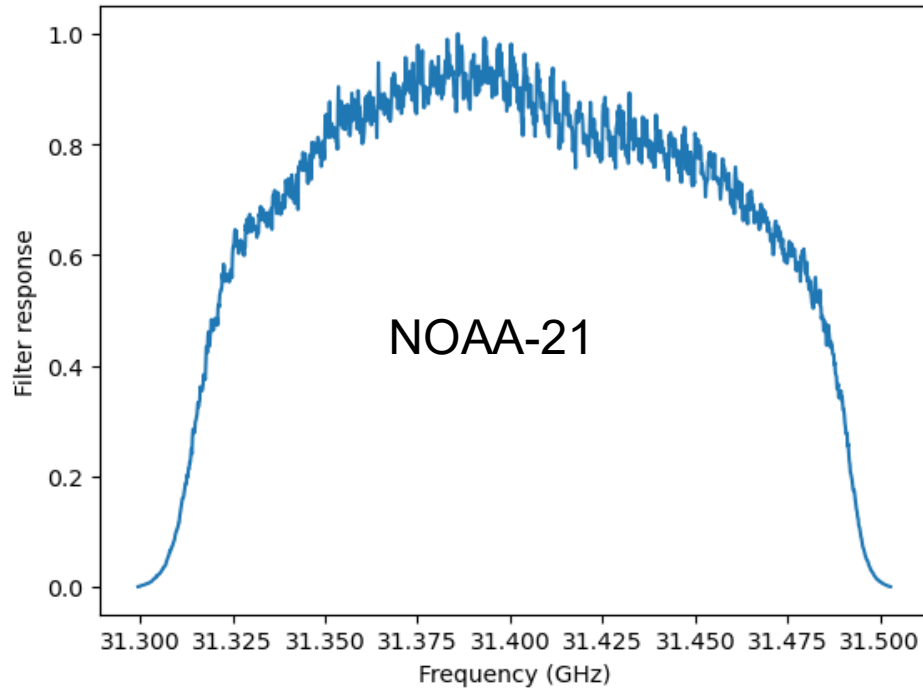
There are other fast satellite simulators: CRTM (JSCDA, U.S) and ARMS (CMA, China)

Spectral Response Functions: Multi-spectral

Channel transmittance



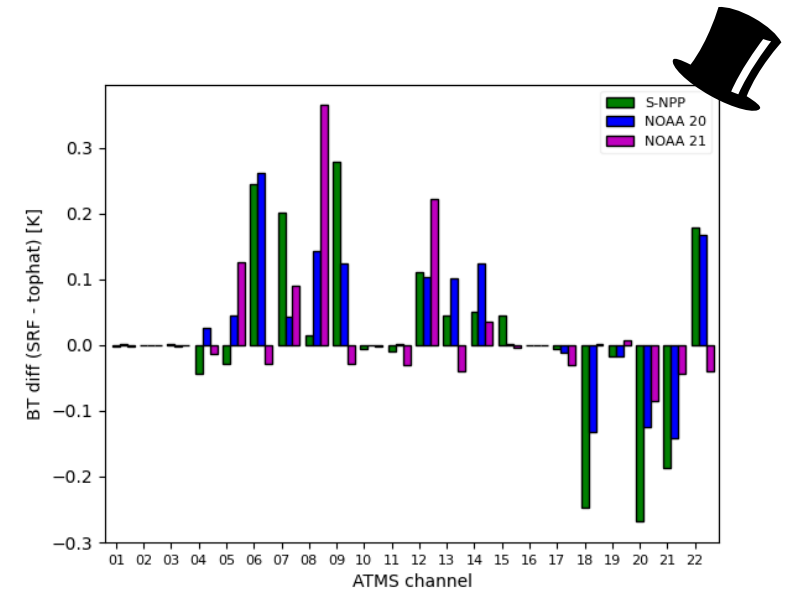
$$\bar{t} = \sum_{v=1}^{n_v} \frac{t(v)}{n_v}$$



$$\bar{t} = \frac{\sum n_v SRF(v)t(v)}{\sum n_v SRF(v)}$$

Region	Line-by-line model
MW	AMSUTRAN*
IR/VIS	LBLRTM

*Developed at Met Office



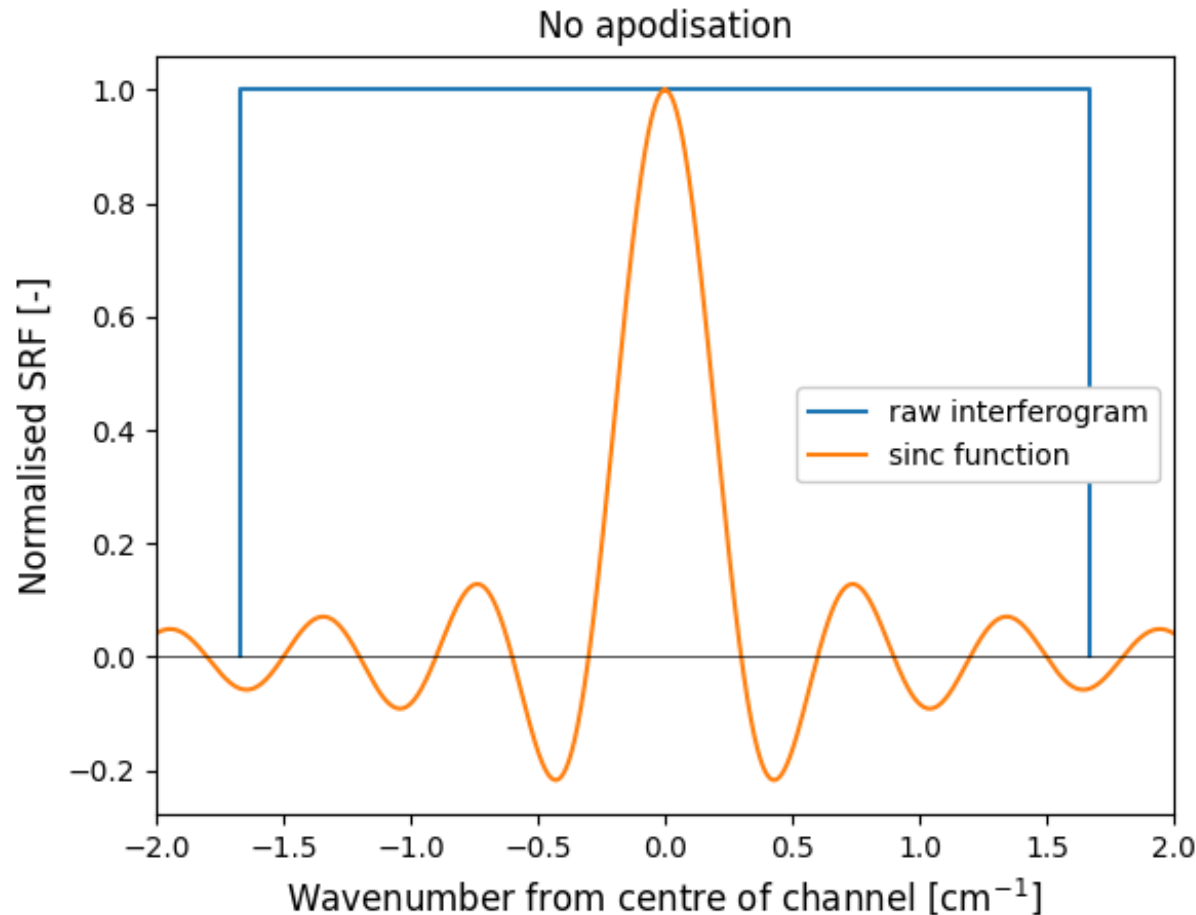
Spectral Response Functions: Hyperspectral

Also known as instrument line shapes (ILS)

$$\bar{t} = \frac{\sum_{n_\nu} SRF(\nu)t(\nu)}{\sum_{n_\nu} SRF(\nu)}$$

Region	Line-by-line model
MW	AMSUTRAN
IR/VIS	LBLRTM*

*Developed at AER (U.S.)



Fourier Transform Spectrometers measure an **interferogram**, not radiances

Apply Fourier Transform to obtain the spectral response function / instrument line shape

Raw interferogram can be considered a **tophat**

FT on a **tophat** produces a **sinc** function with negative lobes – not good for fast RT models

Apply **apodisation** function to reduce the lobes, but the spectral resolution will reduce

Hyperspectral SRFs are *applied* rather than measured

RTTOV Training: Linear regression

For 1 to >16,921 channels:

For 53 or 100 vertical layers:

For 2 to 9 atmospheric species:

For 83 diverse atmospheric profiles:

For 6 or 14 satellite viewing angles:

Predictand
(channel
optical depth
from line-by-
line code)

$$Y = \sum_{p=1}^{n_X} \beta X_p$$

Predictor

Coefficient

498 or 1162 samples
per regression

Solve for coefficient, β

$$t = e^{-\tau}$$

RTTOV 13 Predictors

Predictor	Mixed gases	H ₂ O lines	H ₂ O continuum
1	$\sec(\theta)$	$(\sec(\theta)W_r)^2$	$\sec(\theta)W_r^2/T_r$
2	$\sec^2(\theta)$	$\sec(\theta)W_w$	$\sec(\theta)W_r/T_r$
3	$\sec(\theta)T_r$	$(\sec(\theta)W_w)^2$	$\sec(\theta)W_r^2/T_r^4$
4	$\sec(\theta)T_r^2$	$\sec(\theta)W_r\delta T$	$\sec(\theta)W_r/T_r^2$
5	T_r	$\sqrt{\sec(\theta)W_r}$	-
6	T_r^2	$\sqrt[4]{\sec(\theta)W_r}$	-
7	$\sec(\theta)T_w$	$\sec(\theta)W_r$	-
8	$\sec(\theta)T_r^3$	$(\sec(\theta)W_w)^{1.5}$	-
9	$\sec(\theta)\sqrt{\sec(\theta)T_r}$	$(\sec(\theta)W_r)^{1.5}$	-
10	1	$(\sec(\theta)W_r)^{1.5}\delta T$	-
11	-	$\sqrt{\sec(\theta)W_r}\delta T$	-
12	-	$(\sec(\theta)W_w)^{1.25}$	-
13	-	$\sec(\theta)W_r^2/W_w$	-
14	-	$\sqrt{\sec(\theta)W_r}W_r/W_{wt}$	-
15	-	$\sec(\theta)\sqrt{W_w}$	-

Predictor	O ₃	CO ₂	N ₂ O
1	$\sec(\theta)O3_r$	$\sec(\theta)CO2_r$	$\sec(\theta)N2O_r$
2	$\sqrt{\sec(\theta)O3_r}$	T_r^2	$\sqrt{\sec(\theta)N2O_r}$
3	$\sec(\theta)O3_r\delta T$	$\sec(\theta)T_r$	$\sec(\theta)N2O_r\delta T$
4	$\sec(\theta)O3_r/O3_w$	$\sec(\theta)T_r^2$	$(\sec(\theta)N2O_r)^2$
5	$(\sec(\theta)O3_r)^2$	T_r	$N2O_r\delta T$
6	$\sec(\theta)O3_r^2O3_w$	$\sec(\theta)T_w$	$\sqrt[4]{\sec(\theta)N2O_r}$
7	$\sqrt{\sec(\theta)O3_r}O3_r/O3_w$	$(\sec(\theta)CO2_w)^2$	$\sec(\theta)N2O_w$
8	$\sec(\theta)O3_rO3_w$	$\sec(\theta)T_w\sqrt{T_r}$	$\sec(\theta)N2O_{wt}$
9	$(\sec(\theta)O3_w)^{1.75}$	$\sqrt{\sec(\theta)CO2_r}$	$\sqrt{\sec(\theta)N2O_r}N2O_r/N2O_w$
10	$\sec(\theta)O3_r\sqrt{\sec(\theta)O3_w}$	T_r^3	$(\sec(\theta)N2O_{wt})^2$
11	$(\sec(\theta)O3_w)^2$	$\sec(\theta)T_r^3$	$(\sec(\theta)N2O_{wt})^3$
12	$\sqrt{\sec(\theta)O3_w}\delta T$	$\sqrt{\sec(\theta)T_r}T_w^3$	$\sec^2(\theta)N2O_{wt}\delta T$
13	$\sec(\theta)O3_w$	$T_r^2T_w^2$	-
14	-	$\sec(\theta)CO2_w$	-

RTTOV Coefficients

```

...
!-----
FAST_COEFFICIENTS
!
! Transmission coefficients
! Order of the gases:
!   Mixed_gases
!   Water_vapour
!   Ozone
!   WV_Continuum
Mixed_gases
-0.13135869E-06 0.48995257E-09 0.19724040E-06 -0.36634932E-06 0.74546791E-09
-0.38929794E-08 0.19723021E-06 0.11465163E-06 -0.30824225E-08 0.45302731E-07
-0.13112305E-08 -0.79572053E-08 -0.17484502E-07 0.53306483E-08 0.90602692E-08
0.71347700E-09 0.78482579E-08 0.10247346E-07 -0.38541175E-06 0.12161134E-08
0.14401361E-05 -0.14147359E-05 -0.12858648E-07 -0.43142057E-08 -0.47165153E-08
0.46885341E-06 -0.94970740E-08 -0.46412499E-06 -0.48107716E-09 0.18413717E-05
-0.18357248E-05 0.23009660E-07 -0.66434826E-08 -0.59766331E-09 0.60639639E-06
0.42707095E-08 -0.55263556E-06 0.72994413E-09 0.25386925E-05 -0.24945027E-05
-0.16552690E-07 0.16253866E-08 -0.16609641E-09 0.81842601E-06 -0.58709793E-08
-0.10765046E-06 -0.58184846E-09 0.20550260E-05 -0.20485494E-05 0.46979408E-09
0.34782669E-08 -0.72918115E-09 0.67665254E-06 0.33446040E-08 0.67137408E-06
-0.23846540E-09 0.10335868E-05 -0.10592216E-05 -0.95191067E-09 0.23686162E-08
0.22471725E-07 0.35233611E-06 0.15537349E-08 0.20618702E-05 0.11747395E-09
0.63489120E-06 -0.75190853E-06 0.86582386E-09 -0.13060708E-08 0.15965748E-06
0.24321330E-06 -0.59003882E-09 0.69807462E-05 0.56319716E-10 -0.32160817E-05
0.29670936E-05 -0.84365280E-09 0.22973727E-09 0.44325174E-06 -0.10201491E-05
-0.41858826E-09 0.19646290E-04 -0.24435544E-10 0.92614060E-06 -0.10947721E-05
0.34832423E-09 -0.18698992E-09 0.70815168E-06 0.25378657E-06 0.16573909E-10
0.48170017E-04 -0.19021405E-09 0.76466131E-05 -0.74162922E-05 -0.21431299E-09
0.19951088E-09 0.84590556E-06 0.22272364E-05 -0.18882673E-11 0.84836930E-04
-0.85206192E-09 0.39263937E-04 -0.38174553E-04 -0.34289616E-09 0.33460479E-09
...

```

RTTOV Radiative Transfer Equation

For a channel:

For a vertical layer:

For a satellite viewing angle:

Optical depth \rightarrow

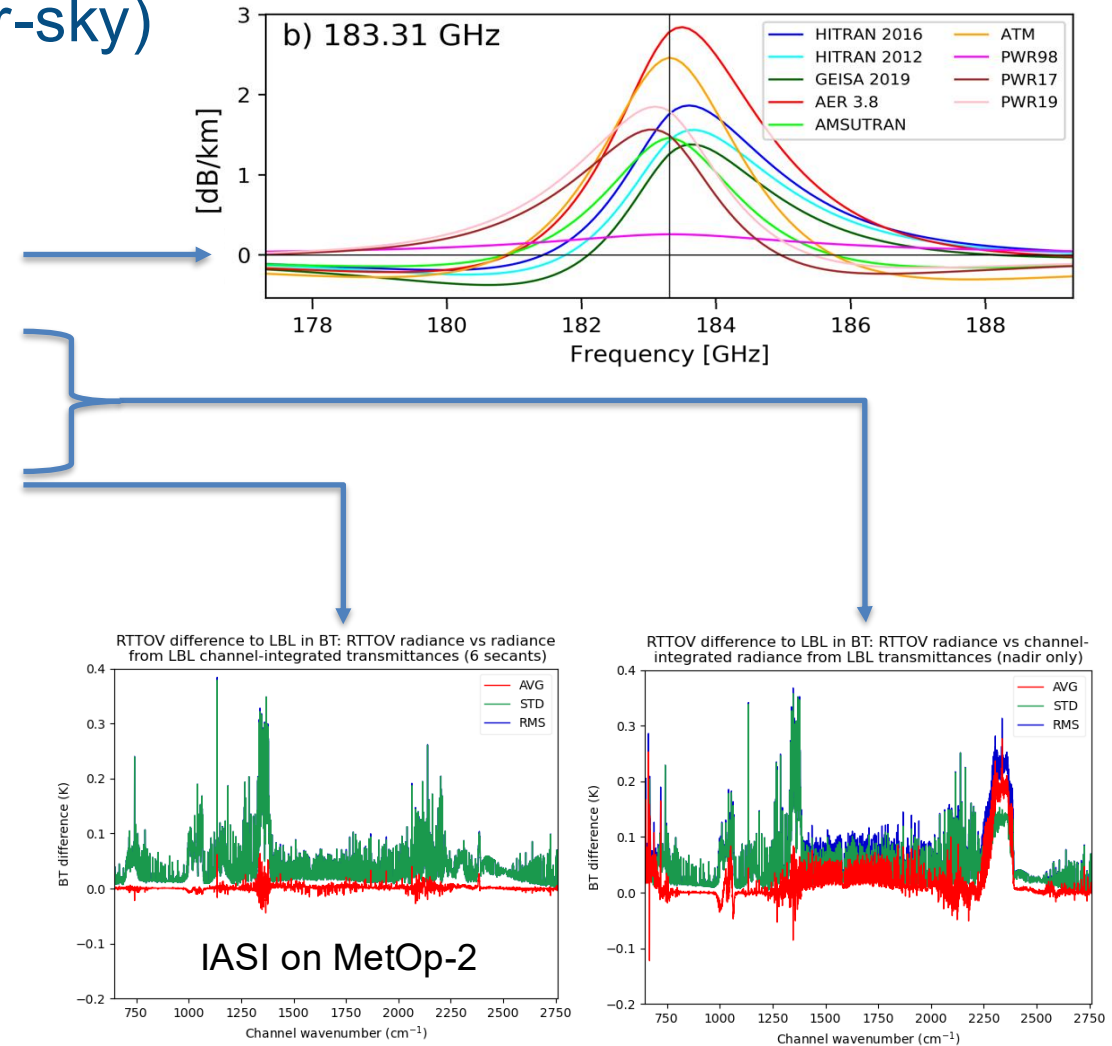
$$Y = \sum_{p=1}^{10} \beta_p^{mg} X_p^{mg} + \sum_{p=1}^{15} \beta_p^{H_2O_l} X_p^{H_2O_l} + \sum_{p=1}^4 \beta_p^{H_2O_c} X_p^{H_2O_c} + \sum_{p=1}^{13} \beta_p^{O_3} X_p^{O_3} + \dots$$

Mixed gases
 Water vapour lines
 Water vapour continuum
 Ozone

$$t = e^{-\tau}$$

How accurate is RTTOV? (clear-sky)

- Errors in the line-by-line (LBL) code
- Polychromatic channels reduced to monochromatic
- Skill of predictors in reproducing the LBL
- Discretization of the atmosphere into homogeneous layers (and interpolation)
- Input profiles lying outside bounds of training dataset



Scattering / Clouds



Heavy rain can attenuate microwave radiation

What kind of (and even if) scattering is important depends on spectral domain and particle size

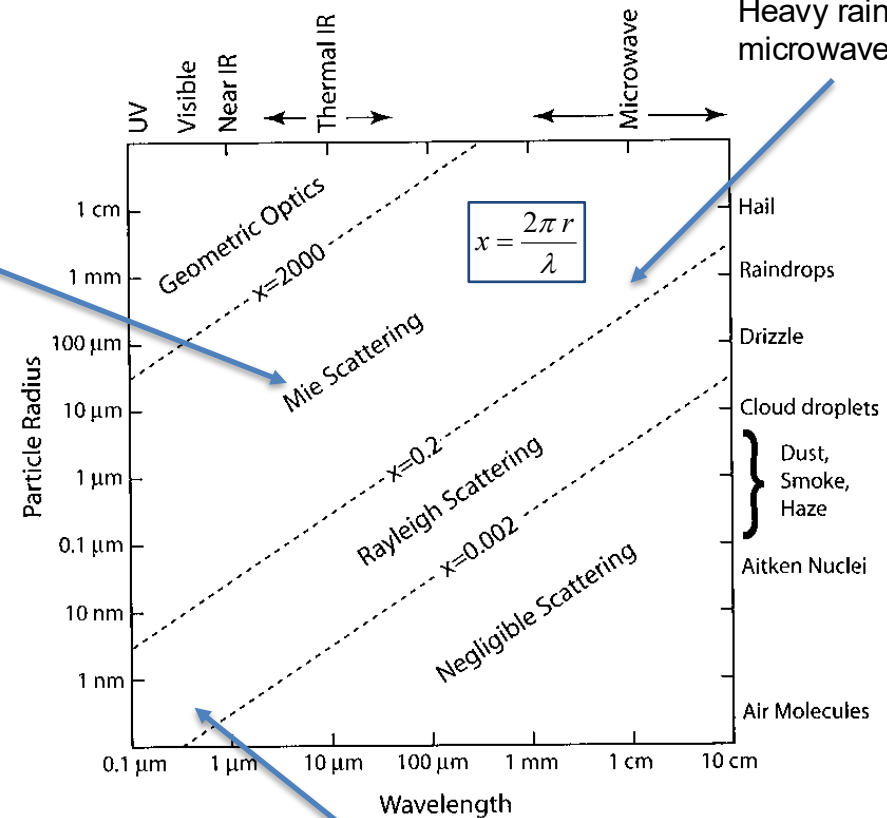


Infrared and visible radiation strongly scattered by clouds

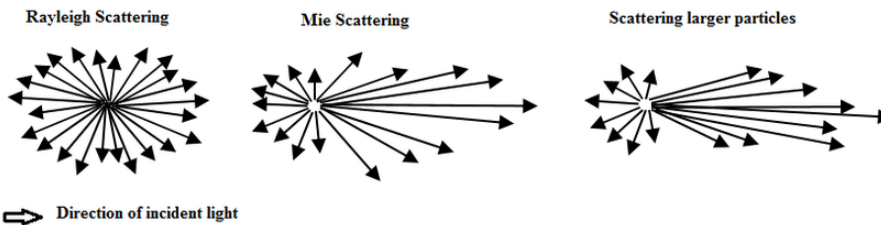
MW: scattering from molecules and aerosols is negligible, but not heavy precipitation

IR: scattering from molecules is negligible, but not aerosols

VIS/NIR: must account for molecular and aerosol scattering



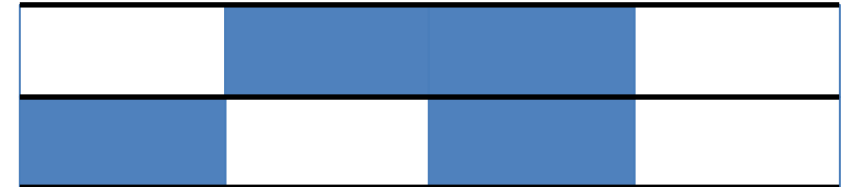
From Petty (2006)



More Rayleigh scattering of air at blue wavelengths

What do you need to calculate cloudy radiances?

- **Profiles** of cloud fraction, cloud liquid and ice water content on layers
- **Overlap** assumption
 - how to place the clouds horizontally in each gridbox →
- **Partition** clouds into different types



```

if (present(pcape)) ll_convective = (pcape(j) > minCAPE_convection) ! CAPE larger than 250 J.kg^-1
  ll_maritime = (ksurf(j) == 1)
  if ( ll_convective .and. ll_maritime ) icld_type(j) = opac_cuma_index ! 5 Maritime cumulus
  if ( ll_convective .and. (.not. ll_maritime) ) icld_type(j) = opac_cucc_index ! 3 Continental cumulus
  if ((.not.ll_convective).and. ll_maritime ) icld_type(j) = opac_stma_index ! 2 Maritime stratus
  if ((.not.ll_convective).and.(.not. ll_maritime) ) icld_type(j) = opac_stco_index ! 1 Continental stratus

```

- **Optical Properties**
 - **bulk** optical properties for each satellite channel (stored in coefficients called *hydrotables*)
- **Solver**
 - solves the equations

$$\beta_{ext} = \int_{D_{min}}^{D_{max}}$$

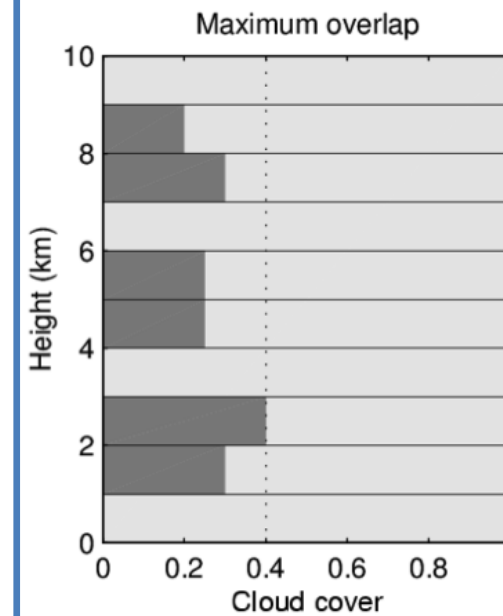
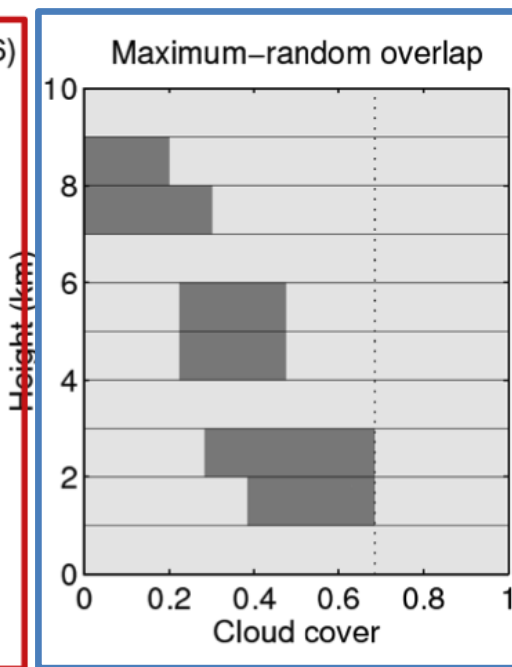
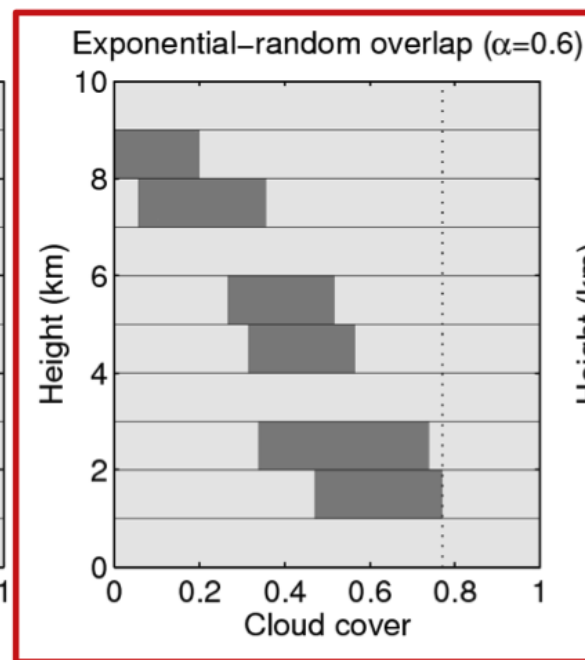
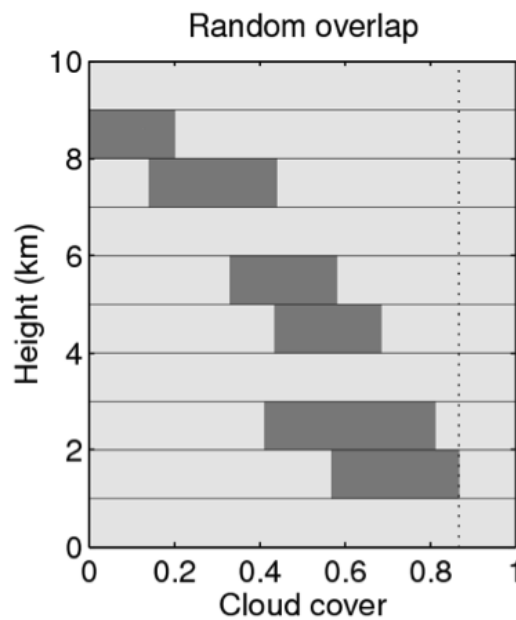
Cloud overlap

Broadband radiation scheme in the IFS (ECMWF NWP model)

ecRad

Default for infrared/visible currently

RTTOV



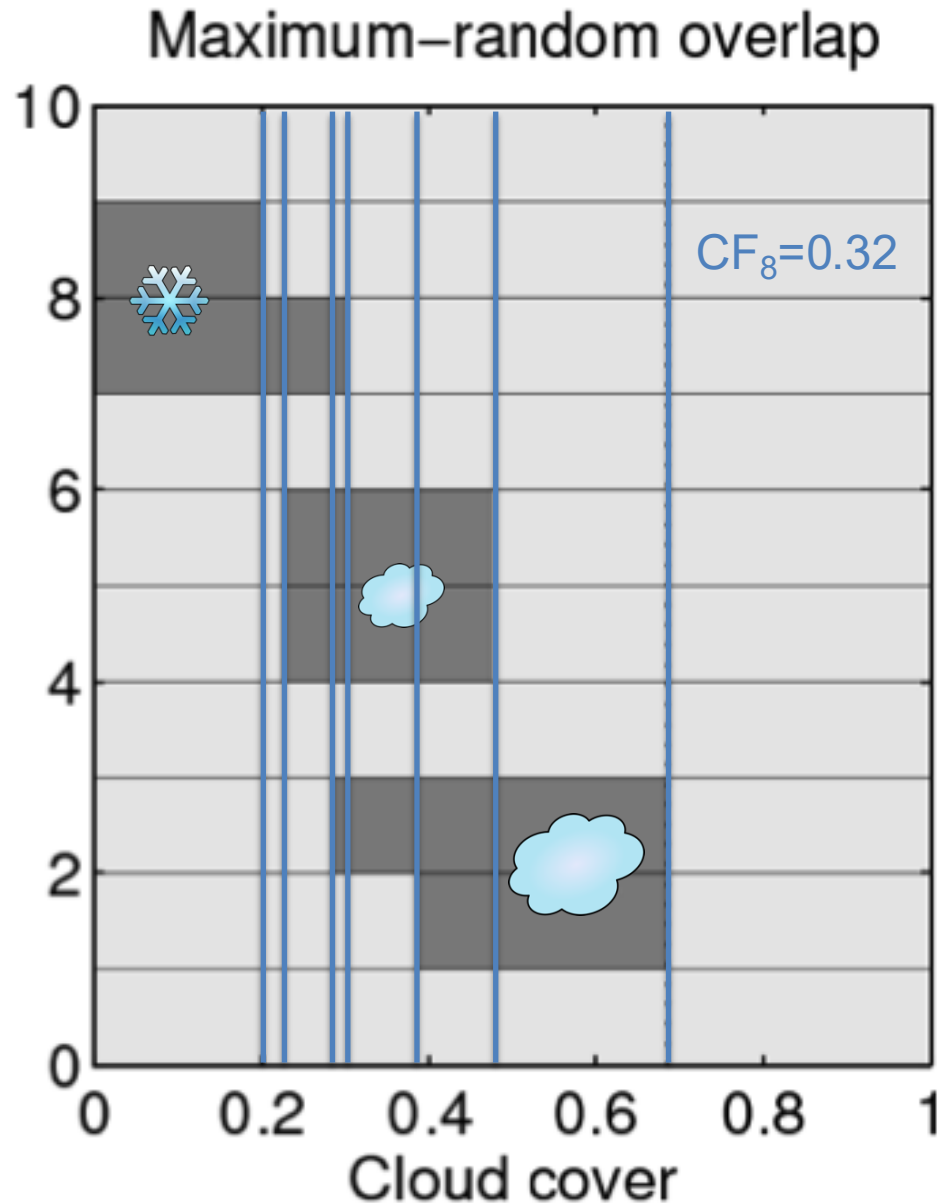
Exponential random overlap has been implemented as of RTTOV v14.1

RTTOV 'column' method for IR

Where vertically adjacent cloud exists, overlap is maximum

Horizontal placement is *calculated*, not random. Needed for TL and AD

Form horizontally homogeneous columns cloud either 0 % or 100 %



7 cloudy columns (c)
1 clear column

$$L_{all} = \sum_{c=1}^{n_c} CF_c L_c$$

n_c can be up to the number of layers (137 for IFS) ..

coming soon ..

2-column scheme for MW.
*5-column scheme for IR
*4-column scheme for VIS

RTTOV scattering solvers

Spectral Domain	Solver
Microwave	Delta-Eddington
Infrared	Chou-scaling (with Tang) Discrete Ordinates (DOM) Delta-Eddington
Visible	MFASIS-NN (Cloud) Discrete Ordinates (DOM)

Radiative Transfer Equation (with scattering)

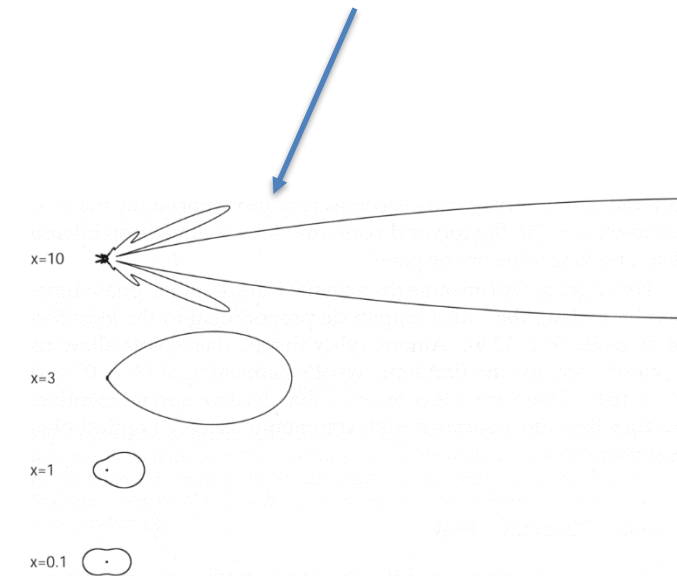
$$\frac{dL}{d\tau} = L - (1 - \omega)B(T) - \frac{\omega}{4\pi} \int_{4\pi} p(\hat{\Omega}', \hat{\Omega}) I(\hat{\Omega}') d\hat{\Omega}'$$

$$\omega = \frac{k_{sca}}{k_{ext}}$$

Single scattering albedo

$p(\hat{\Omega}', \hat{\Omega})$

Phase function



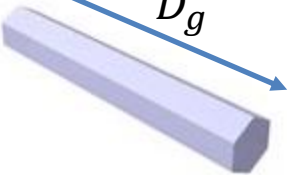
Microwave – sub-mm scattering (formerly RTTOV-SCATT)

RTTOV-SCATT has been implemented since RTTOV version 8

Optical properties are from external databases, like ARTS

Instrument specific **bulk** hydrometeor optical properties are stored in *hydrotables* (Look-up table for five hydrometeor types)

Bulk extinction coefficient

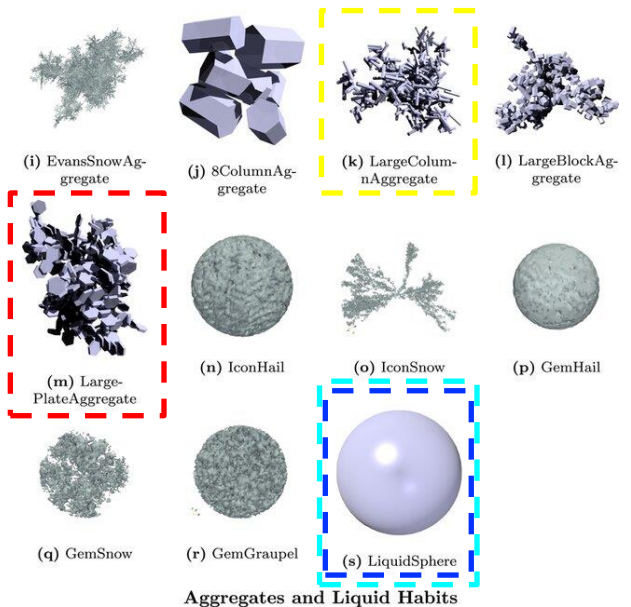
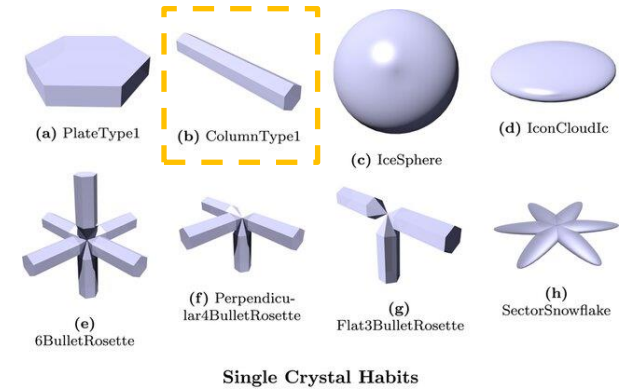
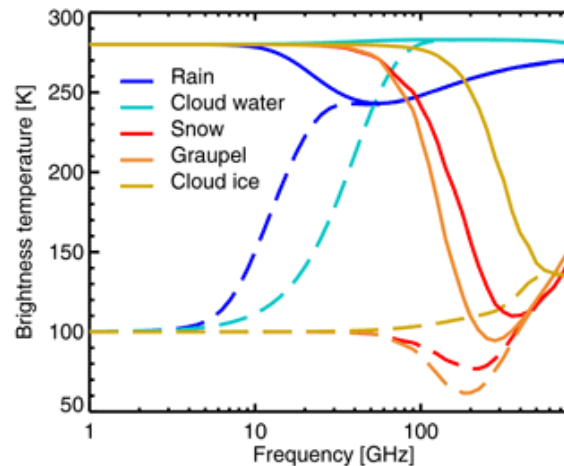
$$\beta_{ext} = \int_{D_{min}}^{D_{max}} \dots$$


$\omega = \frac{\beta_{sca}}{\beta_{ext}}$ (Bulk single scattering albedo) g (Asymmetry parameter)

Graupel



Five default hydrometeor types
Figure from Geer et al. (2021)



Habits in the ARTS scattering database
Figure from Eriksson et al. (2018)

Microwave solver is the delta-Eddington (also in IR in RTTOV v14)

Infrared optical properties

Bulk extinction coefficient

Asymmetry parameter

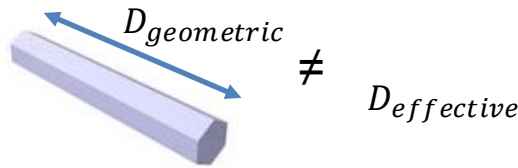
$$\beta_{ext} \quad \omega = \frac{\beta_{sca}}{\beta_{ext}} \quad g \quad b$$

Backscattering Fraction

Bulk single scattering albedo

Properties from OPAC

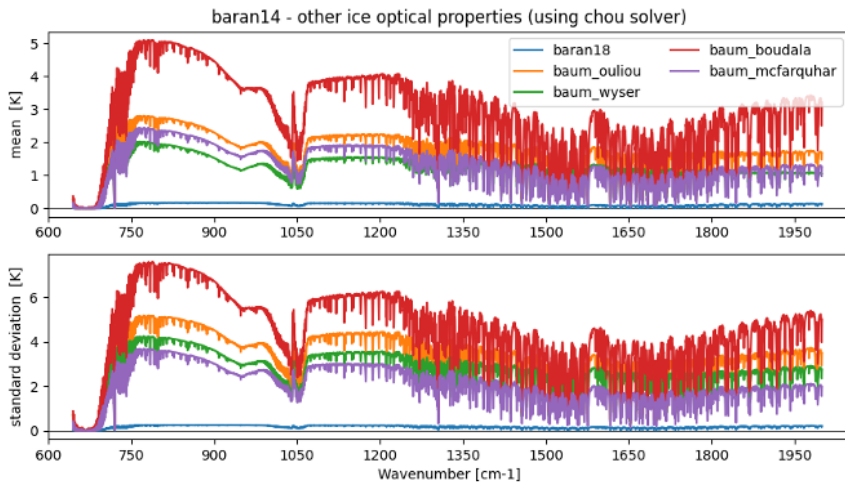
6 and 7 require the effective diameter D_{eff} be specified via a parameterization or *supply your own values in μm*



	Hydrometeor
1	Stratus Continental
2	Stratus Maritime
3	Cumulus Continental Clean
4	Cumulus Continental Polluted
5	Cumulus Maritime
6	Cloud liquid water
7	Ice cloud (Baum 2011)
8	Baran ice scheme

Liquid cloud scheme	D_{eff} a function of:
Martin (1994)	LWC

Ice cloud scheme	D_{eff} a function of:
Ou & Liou (1995)	Temp
Wyser (1998)	Temp, IWC
Boudala (2002)	Temp, IWC
McFarquhar (2003)	IWC



Different process. No D_{eff} needed. Optical properties are calculated directly from temperature and IWC.

Chou scaling (Infrared)

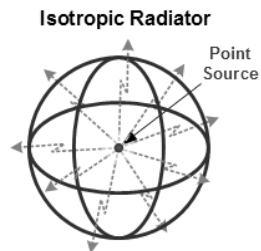
Chou et al. (1999) has been implemented since RTTOV version 9. It is 1.5 times faster than the delta-Eddington:

$$\tau_{effective} = \tau_{absorption} + b\tau_{scattering}$$

b is the backscattering fraction [0-1] computed from aerosol, cloud or ice.

$$\beta_{ext} \quad \omega = \frac{\beta_{sca}}{\beta_{ext}} \quad g \quad b$$

Chou assumption:
Diffuse radiation
field is isotropic
equal to Planck
function of layer.



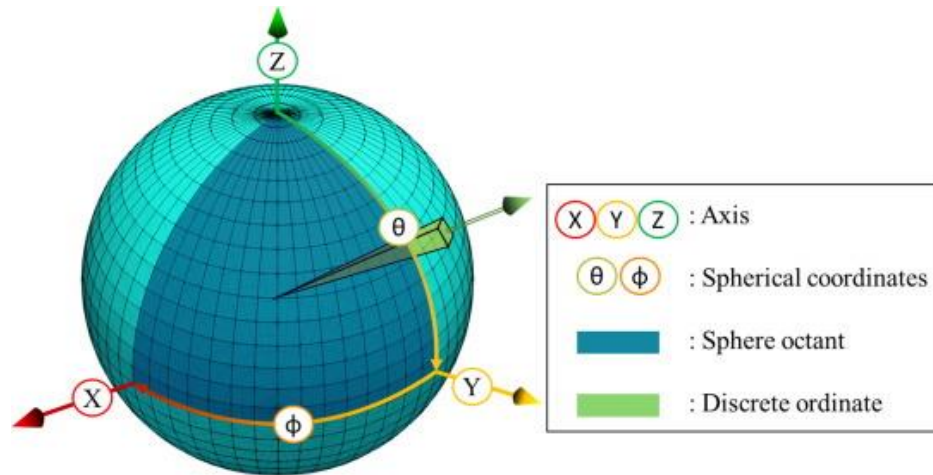
Tang et al. (2018) correction has been implemented since RTTOV version 14 and does not set radiation equal to the Planck function. Intended to improve ice clouds in the far-infrared. Still quite experimental.

Hydrometeor	
1	Stratus Continental
2	Stratus Maritime
3	Cumulus Continental Clean
4	Cumulus Continental Polluted
5	Cumulus Maritime
6	Cloud liquid water
7	Ice cloud
8	Baran ice scheme



RTTOV_DOM (Discrete Ordinates Method) for infrared and visible

A version of DOM (Chandrasekhar, 1960) has been implemented since RTTOV version 12



DOM involves dividing all angles in a sphere into a discrete number (ordinates), which turns the scattering integral in the RTE into a sum, where different directions are weighted.

User selects the number of 'streams' (Legendre coefficients), 8 is usually sufficient

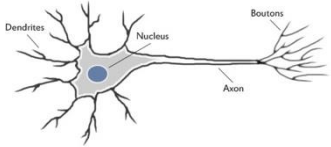
More efficient implementation than DISORT (faster)

Radiances are simulated at a single channel wavelength, errors of 1-2%

Too slow for NWP, but treated as truth

$$\omega = \frac{\beta_{sca}}{\beta_{ext}} \quad \beta_{ext}$$

$$\beta_{legendre} \quad p(\hat{\Omega}', \hat{\Omega})$$



MFASIS-Cloud (Method for Fast Satellite Image Synthesis) VIS/NIR

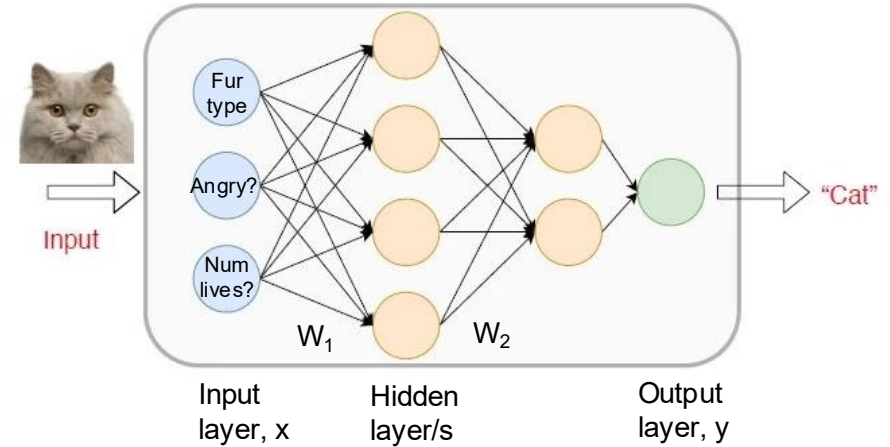
MFASIS-NN (Scheck et al. 2021) has been implemented since RTTOV version 13.2

It is a fast approximation for RTTOV-DOM, a Neural Network (NN) trained on DOM

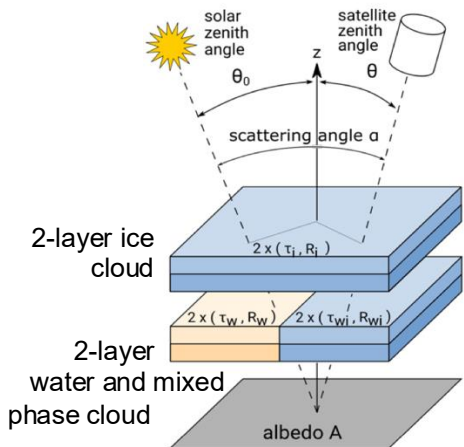
Initially it was a LUT (discontinued in RTTOV version 14)

Used for channels between 0.4 to 2.25 μm

What is a Neural Network?



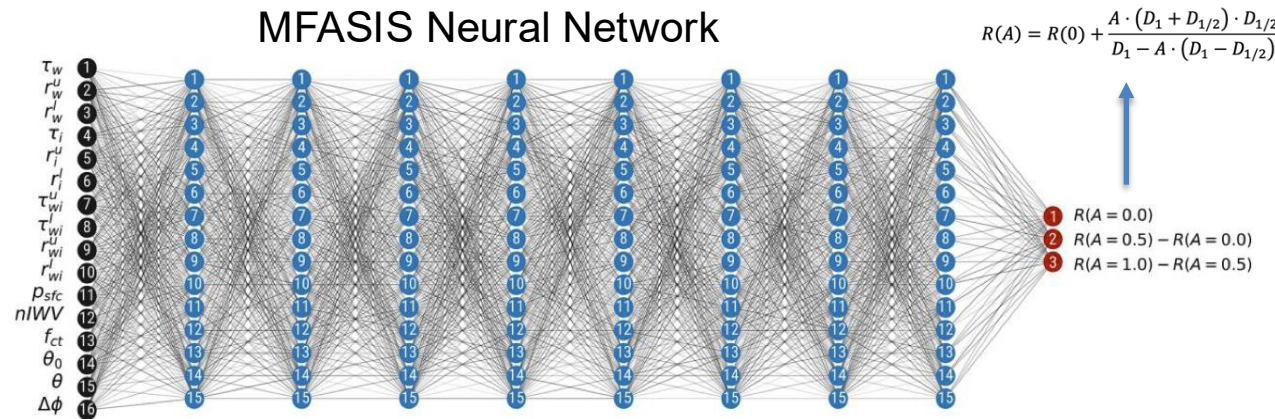
Profile simplified to a 2-layer model



16 input parameters:

- Liquid, ice, mixed optical depth (x2)
- Liquid, ice, mixed x2 effective particle radii
- Integrated water content
- Surface and cloud top pressure
- Solar, satellite and scattering angle

MFASIS Neural Network

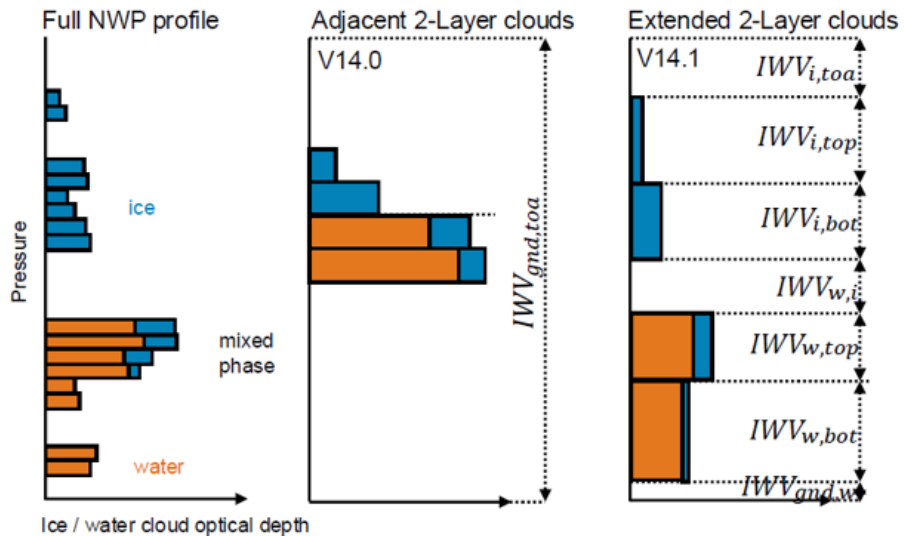


MFASIS



for RTTOV v14.1

V14.0 Profiles: Not enough information on WV distribution



with thanks to Leonhard Scheck / DWD team

- WV absorption depends on photon path length and WV concentration
 - Clouds: Path length increased by multiple scattering, depends on geometric thickness of cloud
- We need additional input parameters describing WV content in / between clouds + cloud geometry
- **27 NN input parameters**

New channels can be simulated around:

- 0.9 μm water vapour band (MODIS, FCI, MetImage, SEVIRI @ 0.8 μm)
- 1.4 μm water vapour band (MODIS, FCI, MetImage, VIIRS, ABI)
- 0.76 μm O₂ A-band (MODIS, MetImage, VIIRS)



plus... there is now an MFASIS-Aerosol* compatible with CAMS!

* can't be used simultaneously with MFASIS-Cloud

Surface emissivity and reflectivity

$$L_{\nu,sat} = \underbrace{\epsilon_{\nu,surf} B_{\nu}(T_{surf}) t_{surf}}_{\text{Surface emission}} + \underbrace{\int_{t_{surf}}^1 B_{\nu}(T) dt}_{\text{Upwelling atmospheric emission}} + \underbrace{(1 - \epsilon_{\nu,surf}) t_{surf}^2 \int_{t_{surf}}^1 \frac{B_{\nu}(T)}{t^2} dt}_{\text{Downwelling surface-reflected atmospheric emission}}$$



Emissivity ($\epsilon_{\nu,surf}$) is a property of a material in how efficient it is at emitting radiation.

1 = perfect emitter (black-body)

0 = totally reflective

$$\text{Reflectivity} = 1 - \epsilon_{\nu,surf}$$

Model Atlas


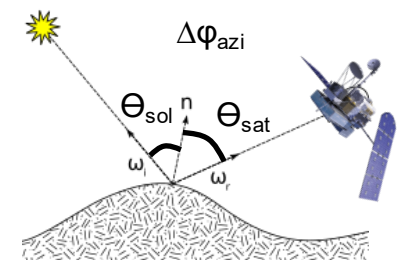
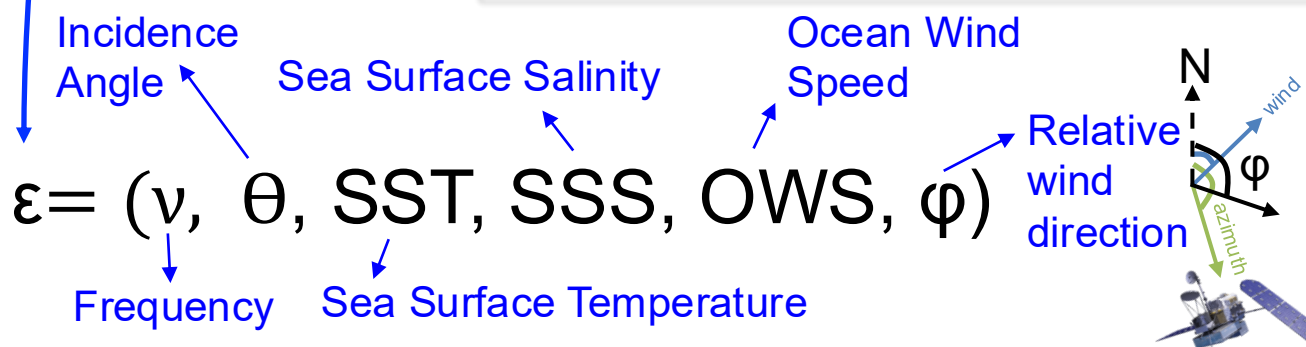
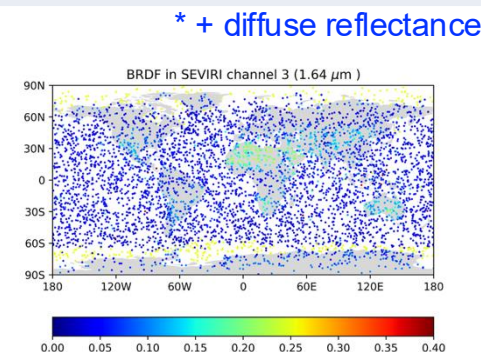
Emissivity / BRDF in RTTOV

$$\epsilon = (\theta, SST, OWS, \text{coefficients})$$

Surface type	MW (0.5/10 - 700 GHz)	IR (3.6 – 14.3 μm)	VIS/NIR (0.4 – 2.5 μm)
Ocean	SURFEM-OCEAN (v13.2)	IREMIS (v12.0)	Elfouhaily (1997)* (v12.2)
Land	TELSEM2 (v12.1)	CAMEL v3 (v14.0)	CMS BRDF (v11.0)
Snow	TELSEM2	CAMEL v3 weighted	CMS BRDF (v11.3)
Sea-Ice	TELSEM2	Fixed spectrum	0.8 / π

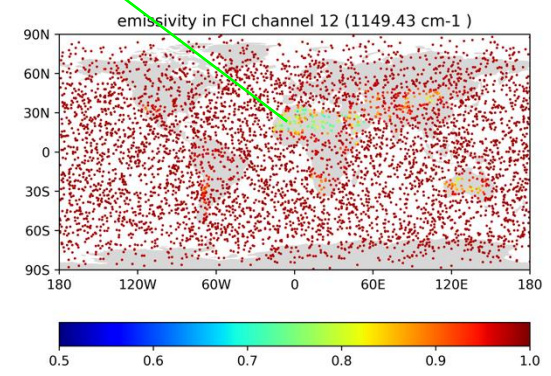
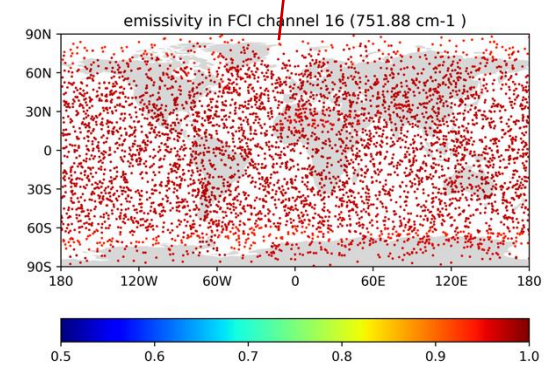
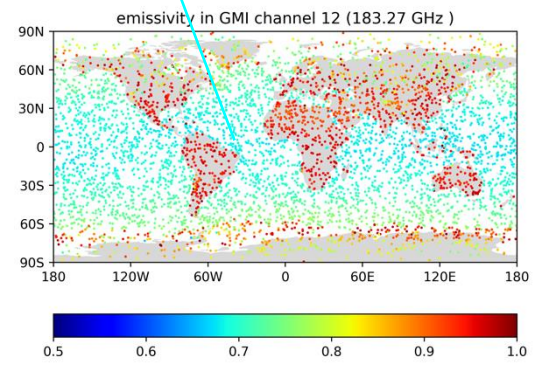
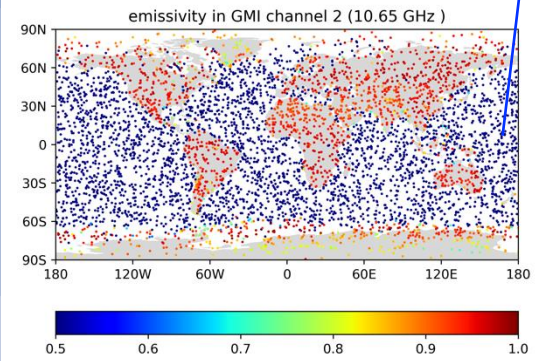
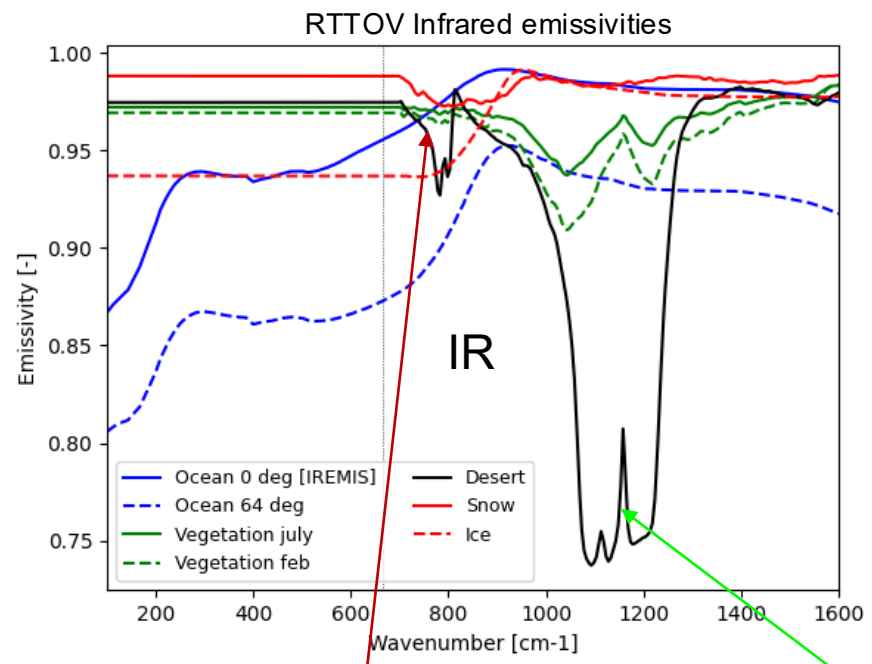
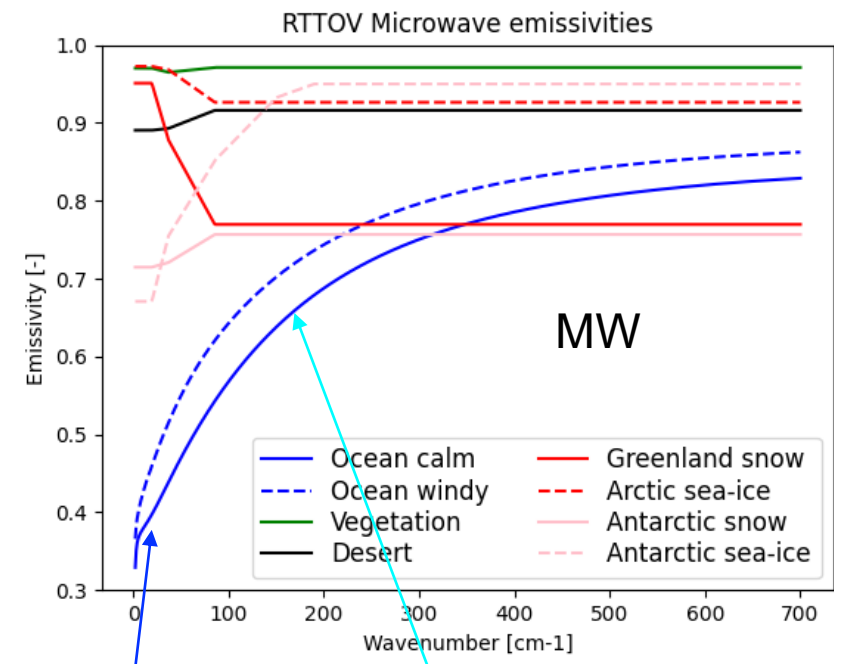
Heterogeneous surfaces (v14.0)

Multiple surface types can be included within a satellite footprint, each with its own area fraction and surface properties.

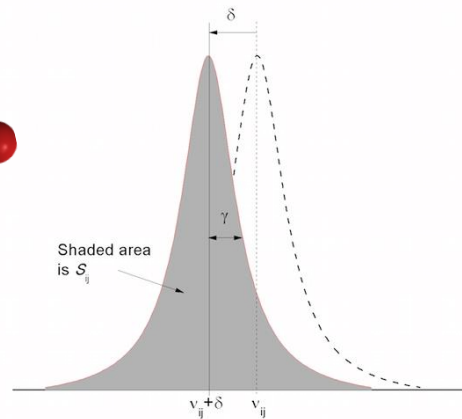
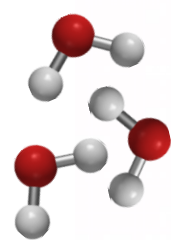



Bidirectional Reflectivity Distribution Function (BRDF)

RTTOV emissivity



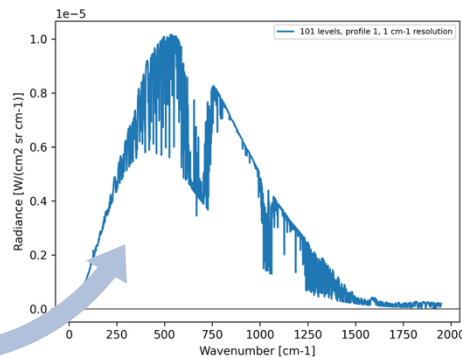
Quick recap



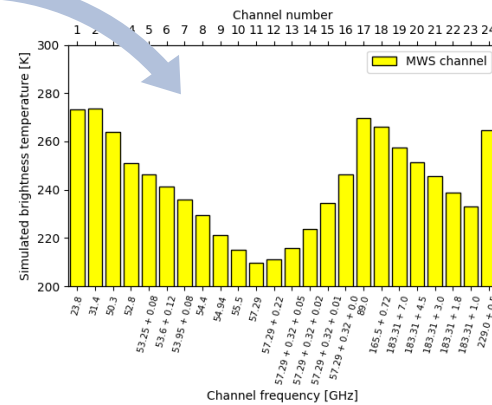
Spectroscopy

Line-by-line (LBLRTM)

TAPE11: LBLRTM 12.15.1 / MT-CKD 4.2



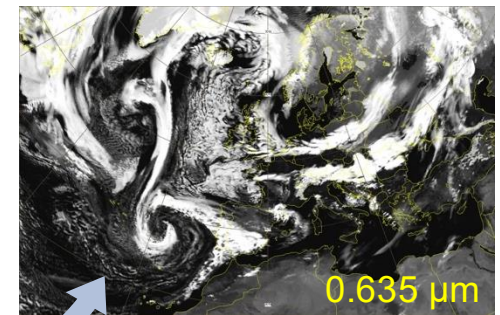
coefficients



Fast code (RTTOV)

scattering surface

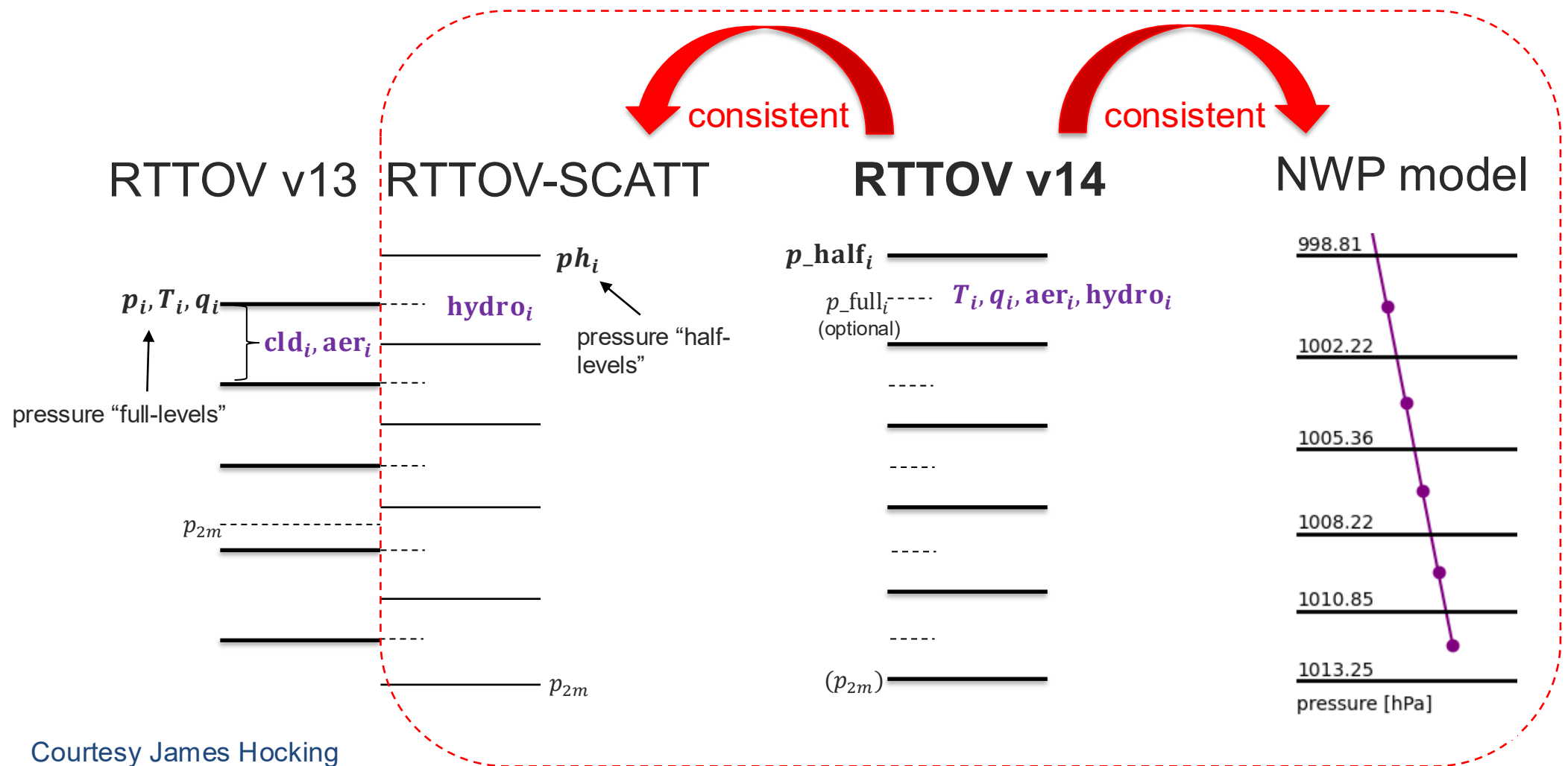
Satellite simulated BT's



End of lecture

See the accompanying practical session for RTTOV Resources and WESS4T

Implementing RTTOV 14 in the IFS (candidate for CY50R1)

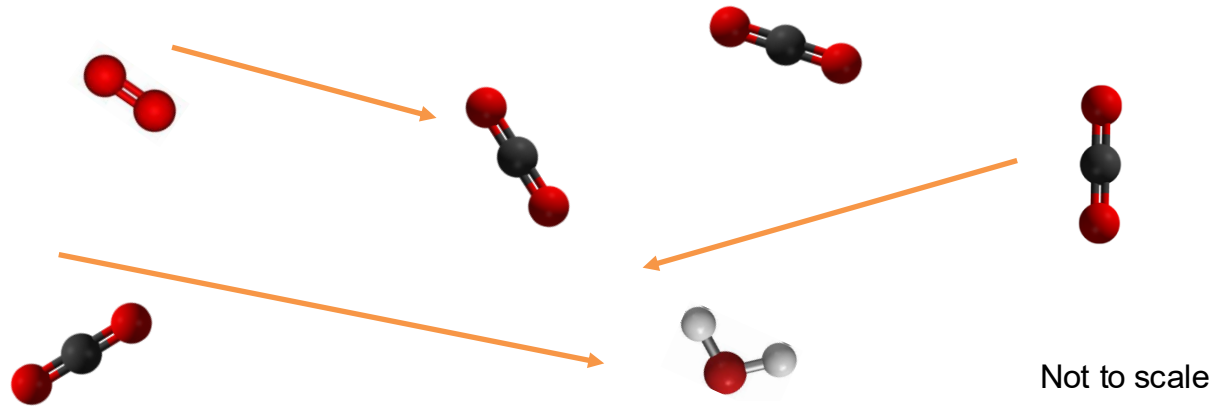


Courtesy James Hocking

What is NLTE?

Non-Local Thermodynamic Equilibrium

Collisions sparse, radiation/other processes dominate



$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\frac{\Delta E}{kT_k}}$$

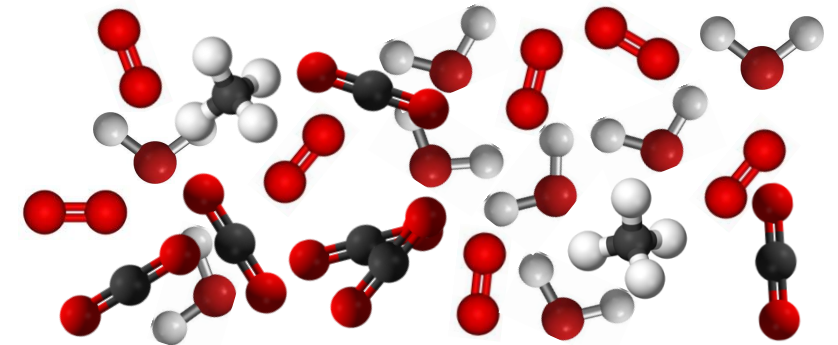
Internal molecular temperature \neq local kinetic temperature

A large system as a collection of local regions each described by a single temperature

Atmosphere has a well-defined temperature on a scale much greater than the free mean path of a photon

Local thermodynamic equilibrium

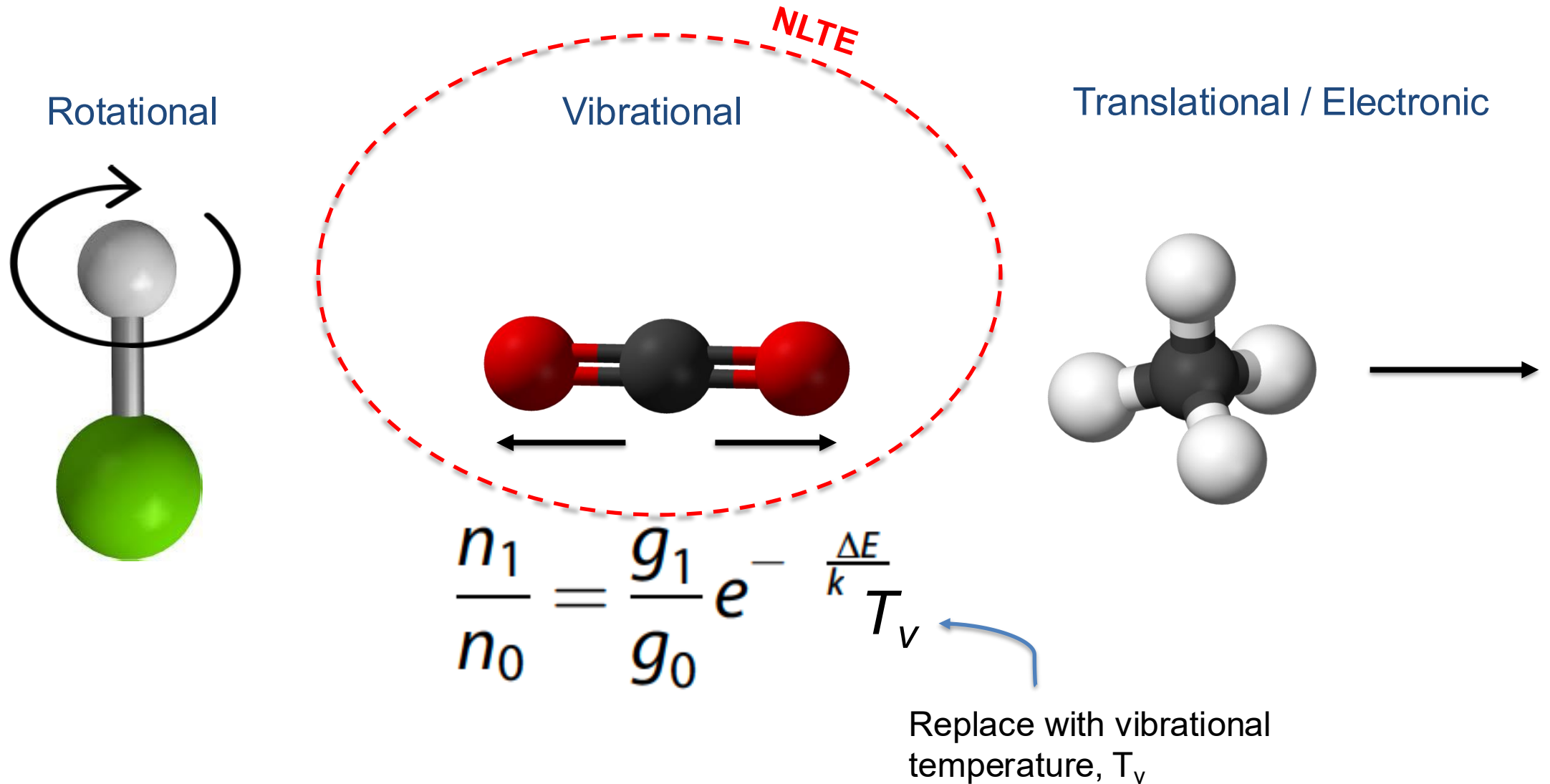
Collisions dominate, radiation neglected



$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\frac{\Delta E}{kT_k}}$$

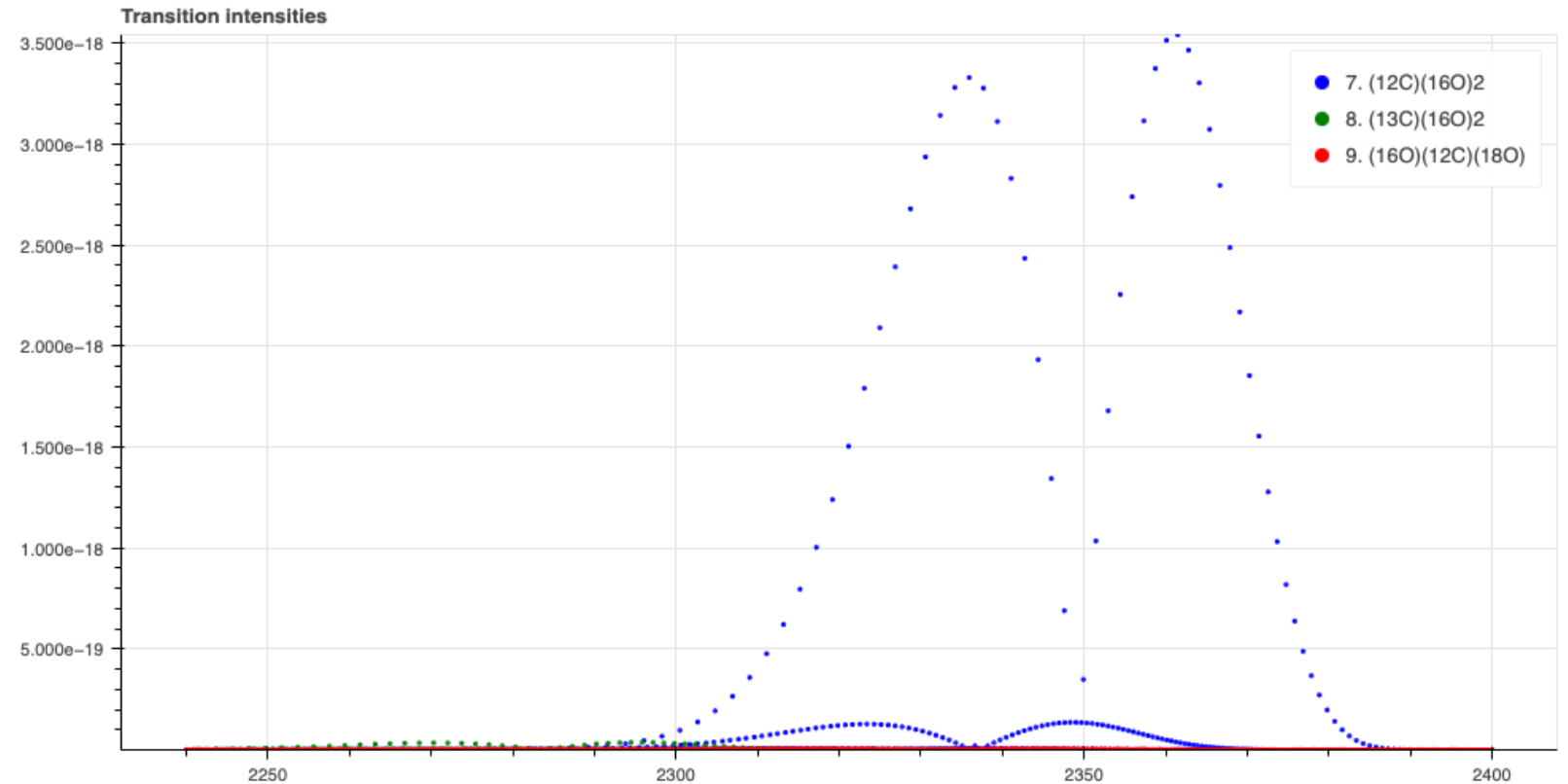
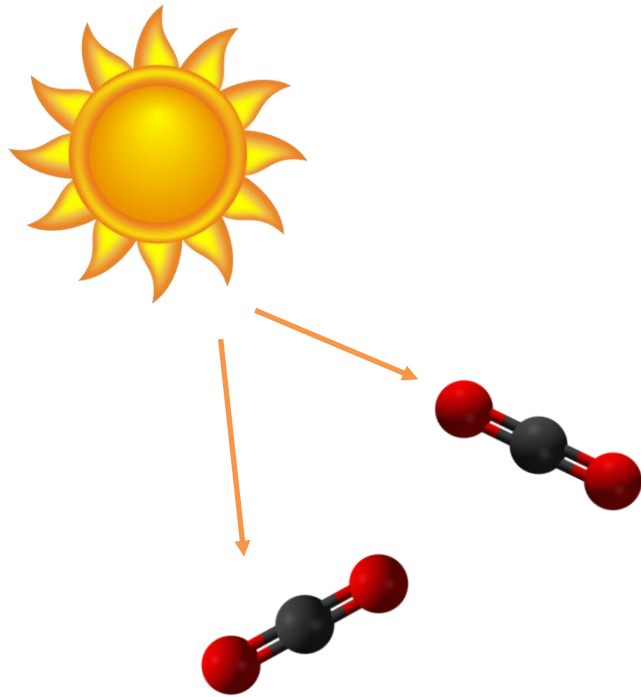
Boltzmann equation describes the distribution of molecules between two states, which depends mainly on the local kinetic energy, T_k

NLTE molecular states



NLTE affects CO₂ at 4.3 μm (ν_3 asymmetric stretching vibrational mode)

Above ~ 40 km LTE breaks down due to the strong solar radiation field and lower molecular densities



From www.hitran.org