EUMETSAT/ECMWF NWP-SAF Satellite data assimilation

Practical implementation of Radiative Transfer for operational NWP

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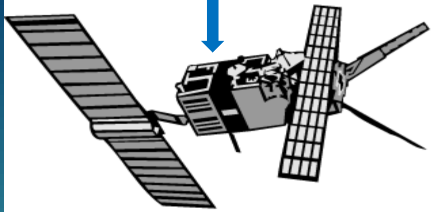
Why learn about radiative transfer

The exploitation of satellite data requires a radiative transfer model (also referred to as the "observation operator" in data assimilation) to predict a firs tguess observation from the NWP model fields corresponding to the observation

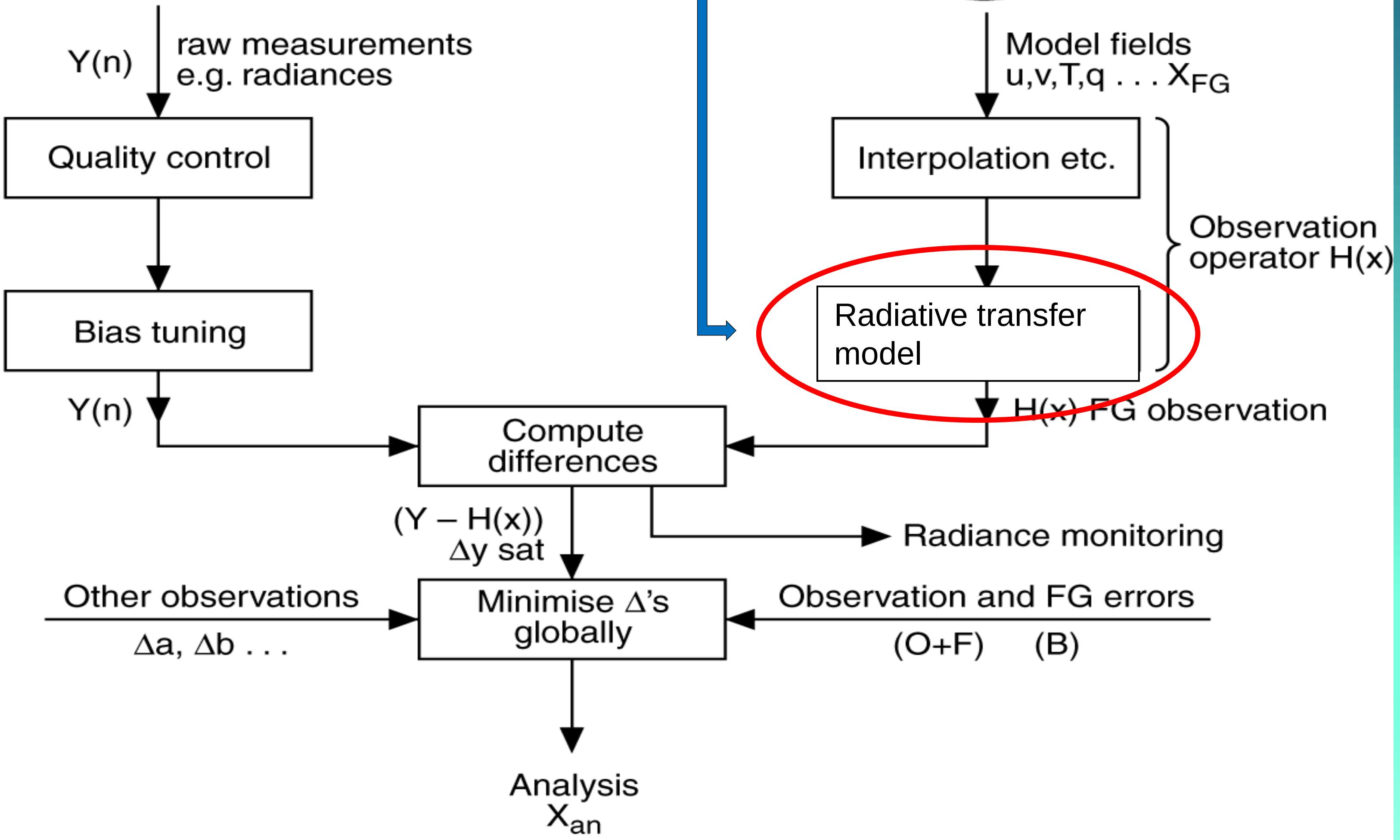
The radiative transfer model (and its adjoint) is
a key element in the assimilation of satellite data into a NWP system

Assimilation of satellite data

Satellite observations



The radiative transfer model simulates satellite observations using the equation of radiative transfer



Y(n) raw measurements e.g. radiances

Quality control

Bias tuning

Y(n)

Model fields $u,v,T,q \ldots X_{FG}$

Interpolation etc.

Radiative transfer model

Observation operator $H(x)$

$H(x)$ FG observation

Compute differences

$(Y - H(x))$
Δy sat

Radiance monitoring

Other observations
$\Delta a, \Delta b \ldots$

Minimise Δ's globally

Observation and FG errors
(O+F) (B)

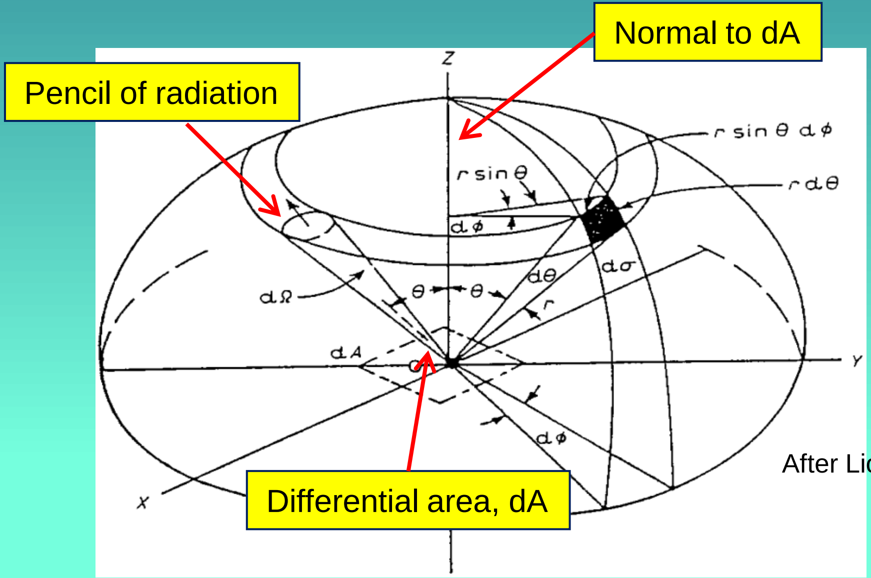
Analysis
X_{an}

Radiance

Satellite instruments measure the upwelling electromagnetic radiation at the top of the atmosphere. A fundamental quantity associated to a radiation field is the intensity of the radiation field or radiance.

The monochromatic radiance, L_ν, is defined as the amount of energy crossing, in a time interval *dt* and in the frequency interval ν to $\nu + d\nu$, a differential area *dA* at an angle *θ* to the normal to *dA*, the pencil of radiation being confined to a solid angle *dΩ*.

$$L_\nu = \frac{dE_\nu}{\cos(\theta)\, dA\, dt\, d\Omega\, d\nu} \quad [\frac{W}{m^2 sr\, s^{-1}}]$$



After Liou (2002)

The radiance can also be defined for a unit *wavelength*, *λ*, or *wave number*, $\tilde{\nu}$, interval. If, *c*, is the speed of light in vacuum, the relation between these quantities is:

$$\lambda = \frac{c}{\nu} = \frac{1}{\tilde{\nu}}$$

Wavelengths are usually expressed in units of *microns* (1µm=10^{-6} m) whereas wave numbers are expressed in units of *cm*$^{-1}$.

Brightness temperature

In many applications, the radiance, *L(v)*, is expressed in units of equivalent brightness temperature, *$T_b(v)$*

The brightness temperature is computed using the inverse Planck function.

$$B_\lambda(T) = \frac{c_1\lambda^{-5}}{\pi\left(e^{(\frac{c_2}{\lambda T})} - 1\right)}$$

The Planck function is used to compute the radiance emitted by a black body at temperature *T*

$$T_b(\lambda) = \frac{c_2}{\lambda \ln\left(\frac{c_1}{\pi\lambda^5 L(\lambda)} + 1\right)}$$

The brightness temperature

Spectrum of electromagnetic radiation

NWP data assimilation

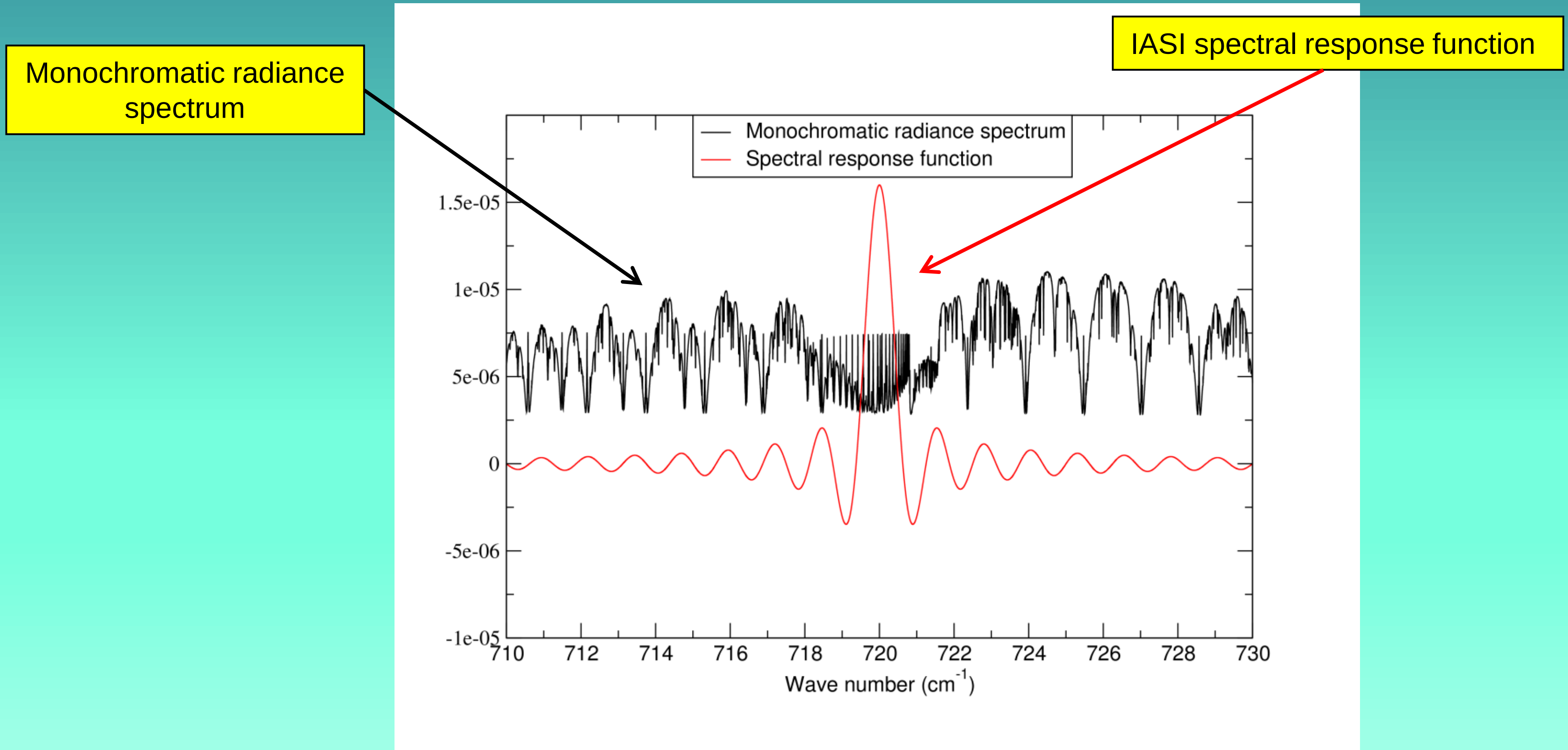
Name of region	Wavelength (cm)	Frequency (cps)
Gamma rays	10^{-9}	3×10^{19}
x-rays	10^{-6}	3×10^{16}
ultraviolet	3×10^{-5}	10^{15}
Visible		
Infrared	Near Infrared 10^{-4} Far infrared 10^{-1}	3×10^{11}
Microwaves	1	3×10^{10}
Spacecraft	10^{2}	3×10^{8}
Television & FM	10^{3}	3×10^{7}
Shortwave	10^{4}	3×10^{6}
AM Radiowaves	10^{5}	3×10^{5}

After Liou (2002)

Polychromatic (or channel) radiance

Satellite radiometers make measurements over a finite spectral interval. They respond to radiation in a non-uniform way as a function of frequency

To represent the outgoing radiance as viewed by a radiometer, the spectrum of monochromatic radiance must be convolved with the appropriate instrument response function. This yields *the polychromatic (or channel) radiance*.


Monochromatic radiance spectrum

IASI spectral response function

Transmittance and optical depth

Electromagnetic radiation interacts with atmospheric molecules and aerosol/cloud/hydrometeors particles through two main mechanisms

Mechanism 1: Extinction of radiation

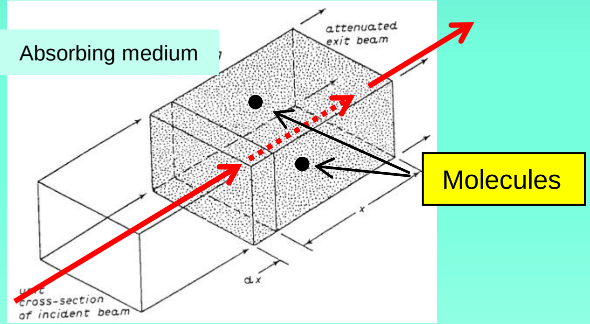
Extinction is the attenuation of the intensity of the radiation field. Extinction is the sum of absorption and scattering.

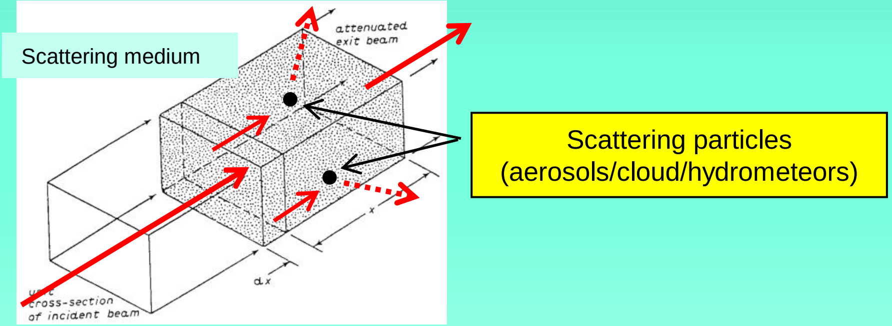
When we have *absorption*, radiant energy is converted into *other forms of energy* (e.g. kinetic energy of the medium).

When we have *scattering*, radiant energy is *redirected* from its original direction.

Mechanism 2: Emission of radiation

Emission is the conversion of molecular kinetic energy into electromagnetic energy.

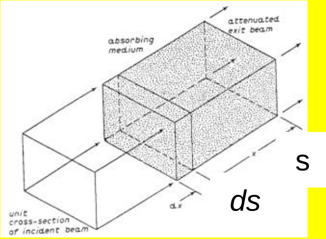




After McCartney (1983)

Transmittance and optical depth

The mechanism of extinction is governed by the Beer-Bouguer-Lambert law. It states that extinction is linear in the amount of matter and in the intensity of radiation



The attenuation of radiation intensity along a path *ds* is:

$$dL_\nu = -L_\nu k_\nu^e \rho(s) ds$$

Mass extinction coefficient [$m^2 Kg^{-1}$]

Density of the medium [$Kg\ m^{-3}$]

The extinction coefficient is the sum of the absorption coefficient, k_ν^a, and the scattering coefficient, k_ν^s.

The *optical depth* of the medium between points s_1 and s_2 is defined as:

$$\tau_\nu = \int_{s_1}^{s_2} k_\nu^e \rho(s) ds$$

The *transmittance* of the medium between points s_1 and s_2 is defined as:

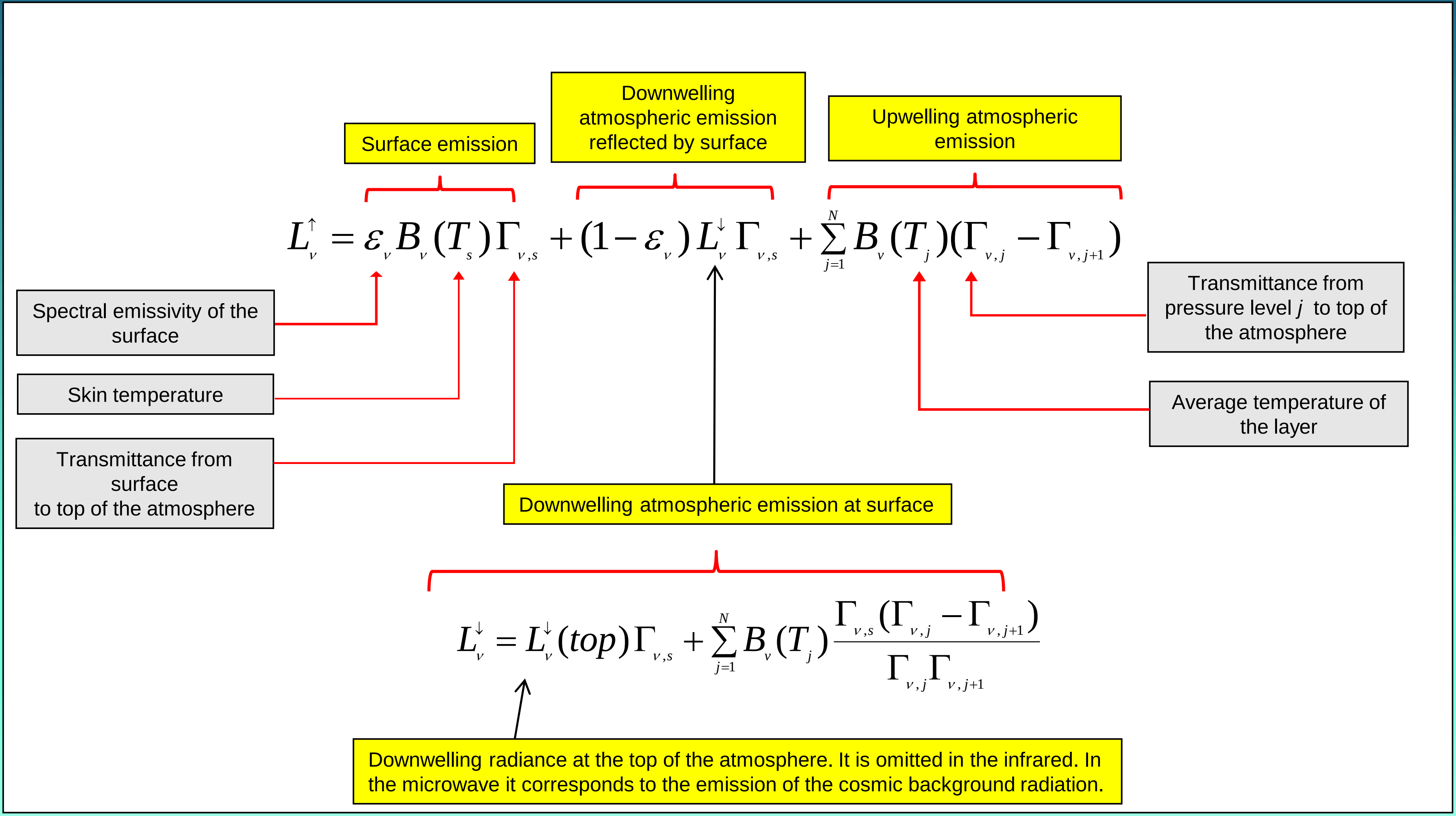
$$\Gamma_\nu = \exp(-\tau_\nu)$$

A completely transparent medium has a transmittance of 1

A completely opaque medium has a transmittance of 0

The equation of radiative transfer in clear sky (i.e. no scattering)

To compute the upwelling monochromatic radiance at the top of the atmosphere we divide the atmosphere into *N* homogeneous layers bounded by N+1 pressure levels



$$L_\nu^\uparrow = \overbrace{\varepsilon_\nu B_\nu(T_s)\Gamma_{\nu,s}}^{\text{Surface emission}} + \overbrace{(1-\varepsilon_\nu)L_\nu^\downarrow\Gamma_{\nu,s}}^{\text{Downwelling atmospheric emission reflected by surface}} + \overbrace{\sum_{j=1}^{N} B_\nu(T_j)(\Gamma_{\nu,j}-\Gamma_{\nu,j+1})}^{\text{Upwelling atmospheric emission}}$$

Spectral emissivity of the surface

Skin temperature

Transmittance from surface to top of the atmosphere

Transmittance from pressure level *j* to top of the atmosphere

Average temperature of the layer

Downwelling atmospheric emission at surface

$$L_\nu^\downarrow = L_\nu^\downarrow(top)\Gamma_{\nu,s} + \sum_{j=1}^{N} B_\nu(T_j)\frac{\Gamma_{\nu,s}(\Gamma_{\nu,j}-\Gamma_{\nu,j+1})}{\Gamma_{\nu,j}\Gamma_{\nu,j+1}}$$

Downwelling radiance at the top of the atmosphere. It is omitted in the infrared. In the microwave it corresponds to the emission of the cosmic background radiation.

Weighting function

The upwelling atmospheric emission term can be rewritten as:

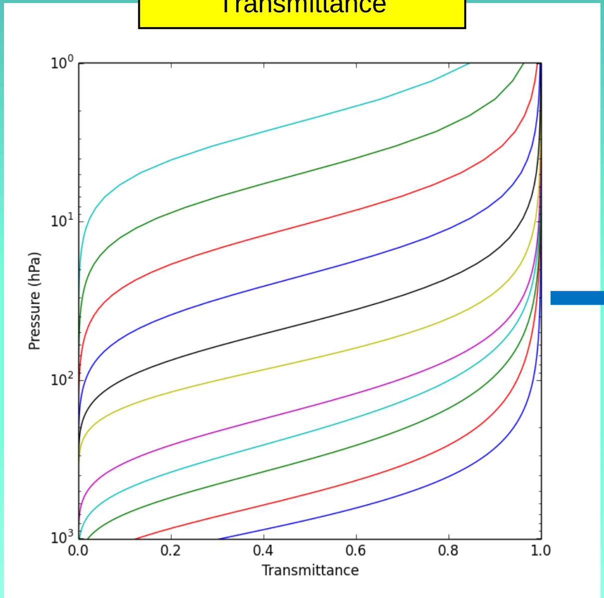
$$\sum_{j=1}^{N} B_{\nu}(T_j)\underbrace{\left(-\frac{\Gamma_{\nu,j}-\Gamma_{\nu,j+1}}{\ln(p_j)-\ln(p_{j+1})}\right)}_{}(\ln(p_{j+1})-\ln(p_j))$$

Weighting function: *w(p)*

The contribution of the Planck function to the upwelling atmospheric emission is weighted by *w(p)*

AMSU-A channels

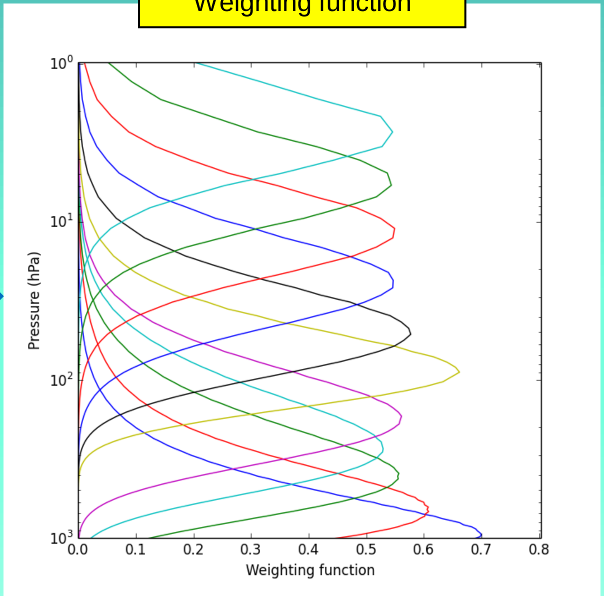
Transmittance



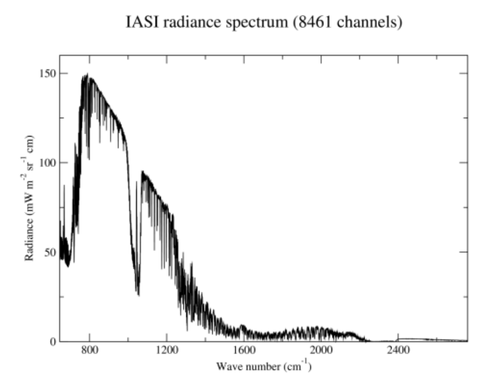
The weighting function has a peak in the region where the transmittance varies most rapidly with height.

AMSU-A channels

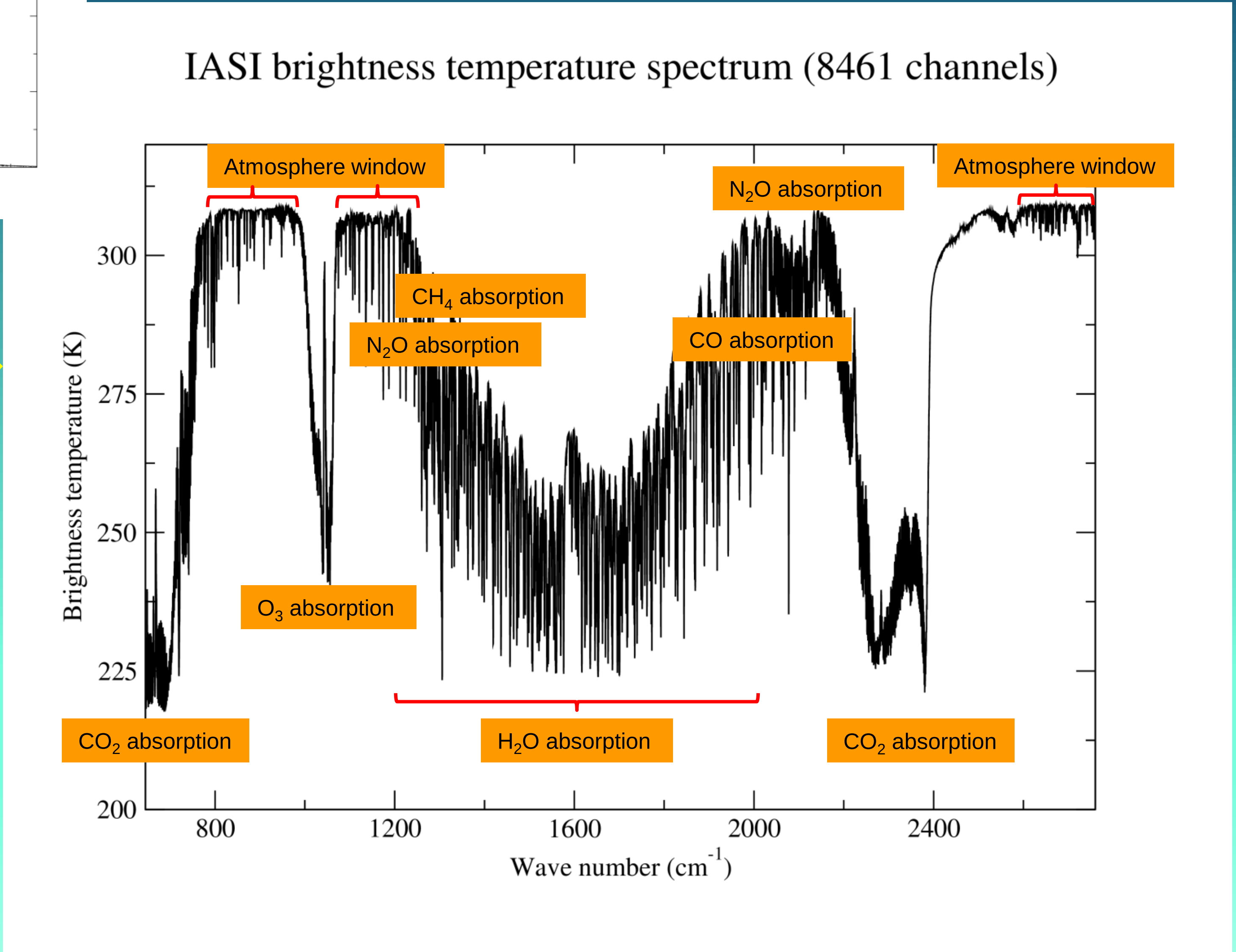
Weighting function



Example of radiance/brightness temperature spectrum



Equivalent brightness temperature spectrum



Fast radiative transfer model for use in NWP

The accurate computation of atmospheric transmittances/radiances is carried out using physical models based on first principles. These models are called *line-by-line models* (e.g. LBLRTM).

Line-by-line models, however, are too slow to be used operationally in NWP.

The near real-time simulation of satellite data is carried out using *fast radiative transfer models*. These models are very computationally efficient and are able to reproduce line-by-line “exact” calculations very closely.

The RTTOV fast radiative transfer model

Operational satellite data assimilation at ECMWF (and many other NWP centres) is carried out using the RTTOV fast radiative transfer model.

RTTOV is an acronym for Radiative Transfer for TOVS

TOVS = TIROS Operational Vertical Sounder

RTTOV was originally developed ~25 years ago and is funded by EUMETSAT through the NWP SAF, developed by ECMWF, Met Office, Météo-France, and DWD

The RTTOV suite comprises direct, tangent linear (TL), adjoint (AD) and K routines

RTTOV has >1000 users worldwide

The RTTOV fast radiative transfer model

RTTOV solves the radiative transfer equation using the so-called polychromatic approximation

Ideally, one should solve the radiative transfer equation at many monochromatic frequencies and convolve the resulting radiances with the instrument spectral response function to obtain the channel radiance

Too computationally expensive

In RTTOV, the channel radiance is computed solving the radiative transfer equation for polychromatic transmittances

The RTTOV fast radiative transfer model: optical depth simulation

How does RTTOV compute the polychromatic transmittances?

RTTOV is a *regression based* fast model where channel optical depths are parameterised using profile dependent predictors. This allows the very fast calculation of optical depths for each channel.

In RTTOV, the atmosphere is divided into *N* homogeneous layers bounded by *N+1* fixed pressure levels. The total channel optical depth for layer *j* is written as:

$$\hat{\tau}_{j,\nu^*} = \sum_{k=1}^{M} a_{j,k,\nu^*} X_{k,j}$$

here *M* is the number of predictors, a_{j,k,ν^*} are *expansion coefficients* and $X_{k,j}$ are *profile-dependent predictors*.

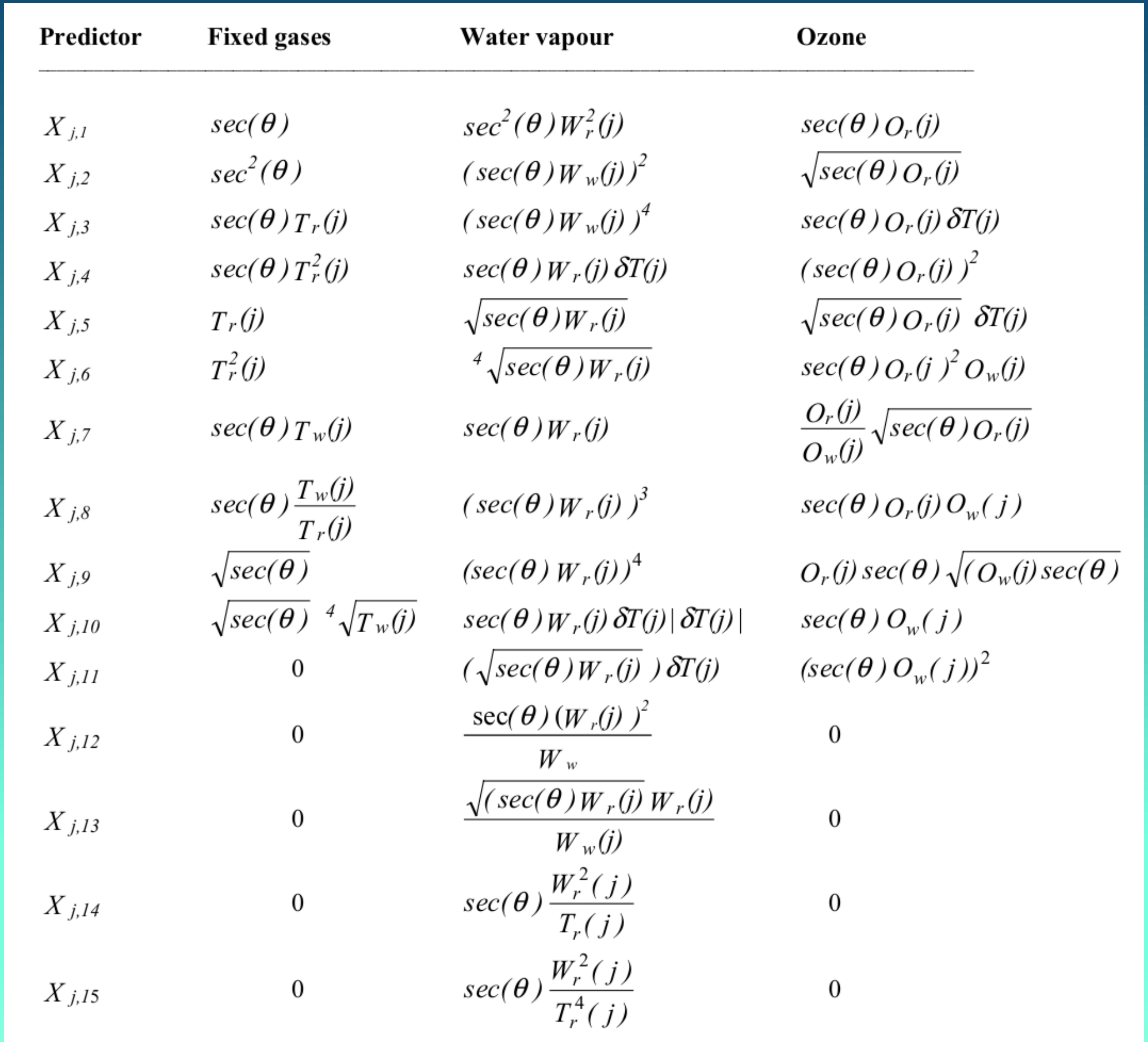
The RTTOV fast radiative transfer model: optical depth simulation

The total channel optical depth is the sum of different terms

$$\hat{\tau}_{j,v^*} = \sum_{k=1}^{M_{Mixed}} \overbrace{a^{Mixed}_{j,k,v^*} X^{Mixed}_{k,j}}^{\text{Optical depth due to fixed gases}} + \sum_{k=1}^{M_{WV}} \overbrace{a^{WV}_{j,k,v^*} X^{WV}_{k,j}}^{\text{Optical depth due to water vapour}} + \sum_{k=1}^{M_{OZ}} \overbrace{a^{OZ}_{j,k,v^*} X^{OZ}_{k,j}}^{\text{Optical depth due to ozone}}$$

In general, the predictors are functions of temperature, gas absorber amount, pressure and viewing angle

The RTTOV fast radiative transfer model: optical depth simulation



Predictor	**Fixed gases**	**Water vapour**	**Ozone**
$X_{j,1}$	$\sec(\theta)$	$\sec^2(\theta)W_r^2(j)$	$\sec(\theta)O_r(j)$
$X_{j,2}$	$\sec^2(\theta)$	$(\sec(\theta)W_w(j))^2$	$\sqrt{\sec(\theta)O_r(j)}$
$X_{j,3}$	$\sec(\theta)T_r(j)$	$(\sec(\theta)W_w(j))^4$	$\sec(\theta)O_r(j)\,\delta T(j)$
$X_{j,4}$	$\sec(\theta)T_r^2(j)$	$\sec(\theta)W_r(j)\,\delta T(j)$	$(\sec(\theta)O_r(j))^2$
$X_{j,5}$	$T_r(j)$	$\sqrt{\sec(\theta)W_r(j)}$	$\sqrt{\sec(\theta)O_r(j)}\;\delta T(j)$
$X_{j,6}$	$T_r^2(j)$	$\sqrt[4]{\sec(\theta)W_r(j)}$	$\sec(\theta)O_r(j)^2\,O_w(j)$
$X_{j,7}$	$\sec(\theta)T_w(j)$	$\sec(\theta)W_r(j)$	$\dfrac{O_r(j)}{O_w(j)}\sqrt{\sec(\theta)O_r(j)}$
$X_{j,8}$	$\sec(\theta)\dfrac{T_w(j)}{T_r(j)}$	$(\sec(\theta)W_r(j))^3$	$\sec(\theta)O_r(j)O_w(j)$
$X_{j,9}$	$\sqrt{\sec(\theta)}$	$(\sec(\theta)W_r(j))^4$	$O_r(j)\sec(\theta)\sqrt{(O_w(j)\sec(\theta)}$
$X_{j,10}$	$\sqrt{\sec(\theta)}\;\sqrt[4]{T_w(j)}$	$\sec(\theta)W_r(j)\,\delta T(j)\lvert\delta T(j)\rvert$	$\sec(\theta)O_w(j)$
$X_{j,11}$	0	$(\sqrt{\sec(\theta)W_r(j)}\,)\,\delta T(j)$	$(\sec(\theta)O_w(j))^2$
$X_{j,12}$	0	$\dfrac{\sec(\theta)(W_r(j))^2}{W_w}$	0
$X_{j,13}$	0	$\dfrac{\sqrt{(\sec(\theta)W_r(j)W_r(j)}}{W_w(j)}$	0
$X_{j,14}$	0	$\sec(\theta)\dfrac{W_r^2(j)}{T_r(j)}$	0
$X_{j,15}$	0	$\sec(\theta)\dfrac{W_r^2(j)}{T_r^4(j)}$	0

RTTOV predictors for fixed gases, water vapour and ozone

The RTTOV fast radiative transfer model: optical depth simulation

To compute the expansion coefficients, a line-by-line model is used to compute accurate channel optical depths for a diverse set of temperature and atmospheric constituent (typically water vapour and ozone) profiles.

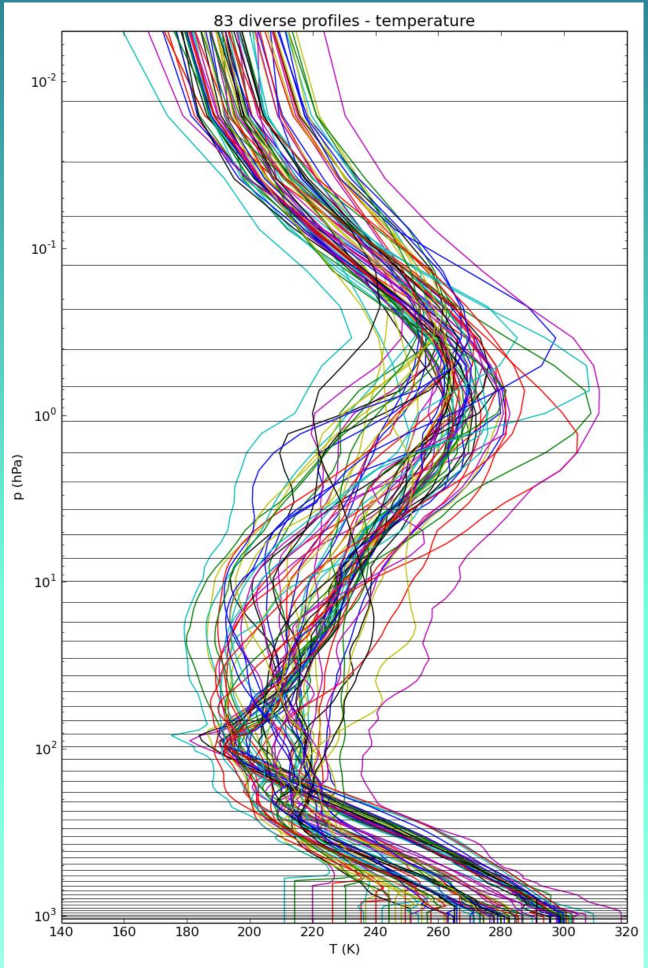
The training profiles are chosen to be representative of widely differing atmospheric situations.

The line-by-line optical depths are regressed into the predictors $X_{k,j}$ for each channel. The resulting expansion coefficients are used by RTTOV to compute optical depths for any other input profile.

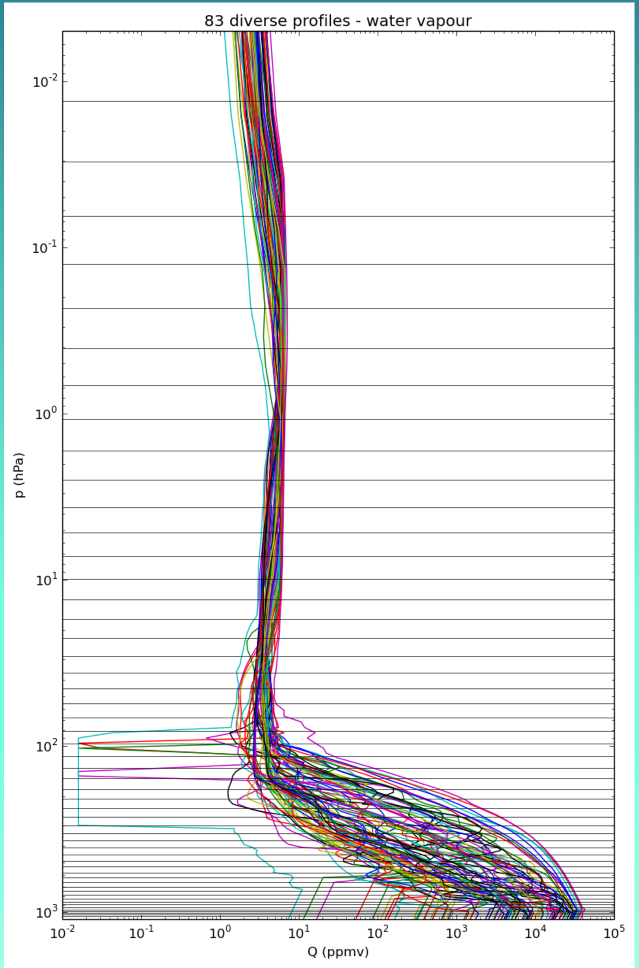
The RTTOV fast radiative transfer model: training profiles

The training of RTTOV is carried out using 498 profiles, i.e. 83 diverse atmospheric profiles each at 6 zenith angles.

Temperature training profiles



Water vapour training profiles



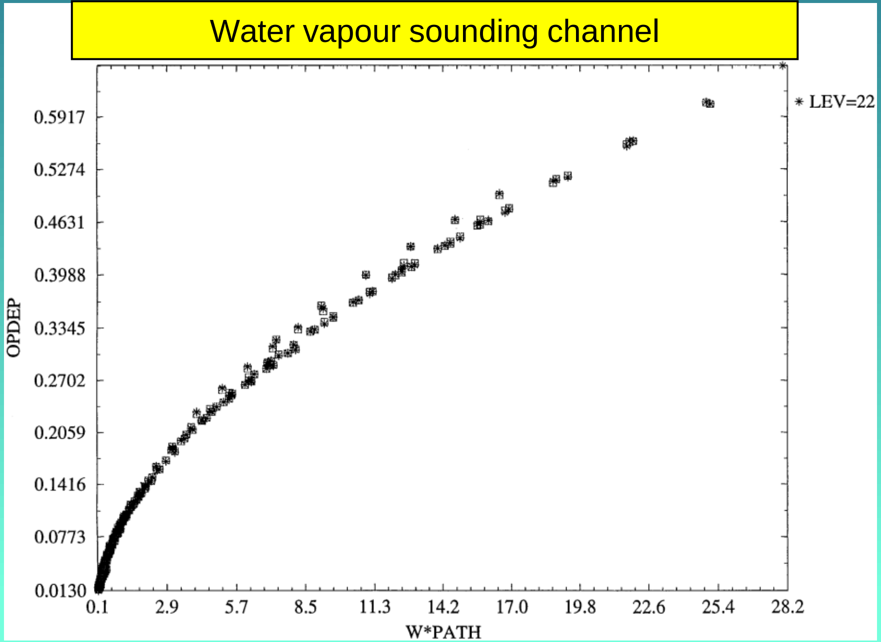
The RTTOV fast radiative transfer model: optical depth simulation

The ability of RTTOV to reproduce line-by-line optical depths

HIRS: High resolution Infrared Radiation Sounder
(wheel radiometer with broad channels)

Water vapour sounding channel

Optical depth of the path

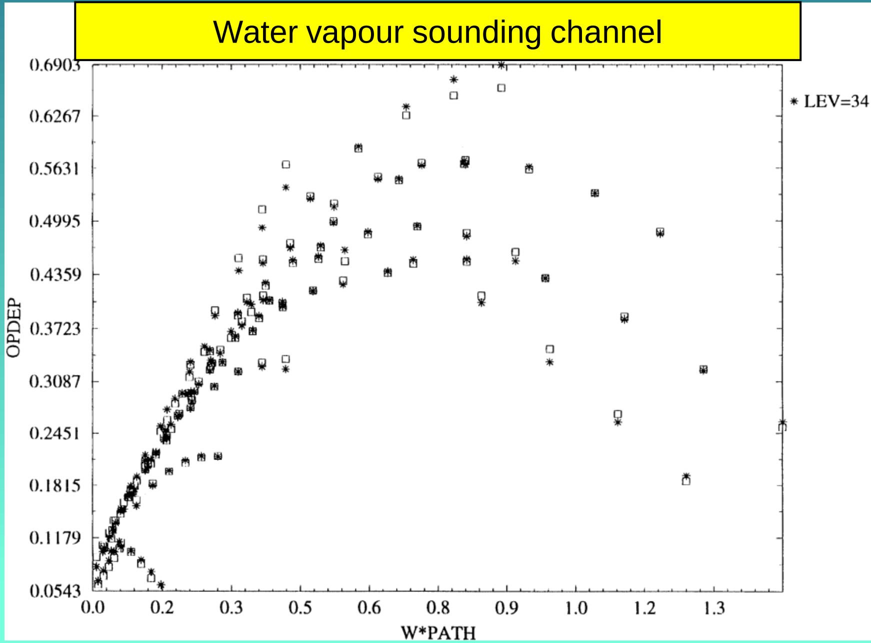


Water vapour amount in the path

IASI: Infrared Atmospheric Sounding Interferometer
(hyperspectral sensor with very narrow channels)

Water vapour sounding channel

Optical depth of the path



Water vapour amount in the path

Stars indicate the fast model optical depths

Squares indicate the line-by-line optical depths

The RTTOV fast radiative transfer model: inputs

Inputs to RTTOV

Vertical atmospheric profiles

Mandatory

Pressure, temperature and water vapour

Optional

Trace gases: O_3, CO_2, CO, N_2O, CH_4, SO_2

Viewing geometry

Zenith and azimuthal angles

Surface variables

Mandatory

Skin temperature, surface pressure, 10m u/v wind

Optional

Surface emissivity

The RTTOV fast radiative transfer model: accuracy

Main sources of RTTOV errors

1) Use of polychromatic optical depths

2) Optical depth parameterisation

3) Discretisation of the atmosphere into homogeneous layers and associated interpolation

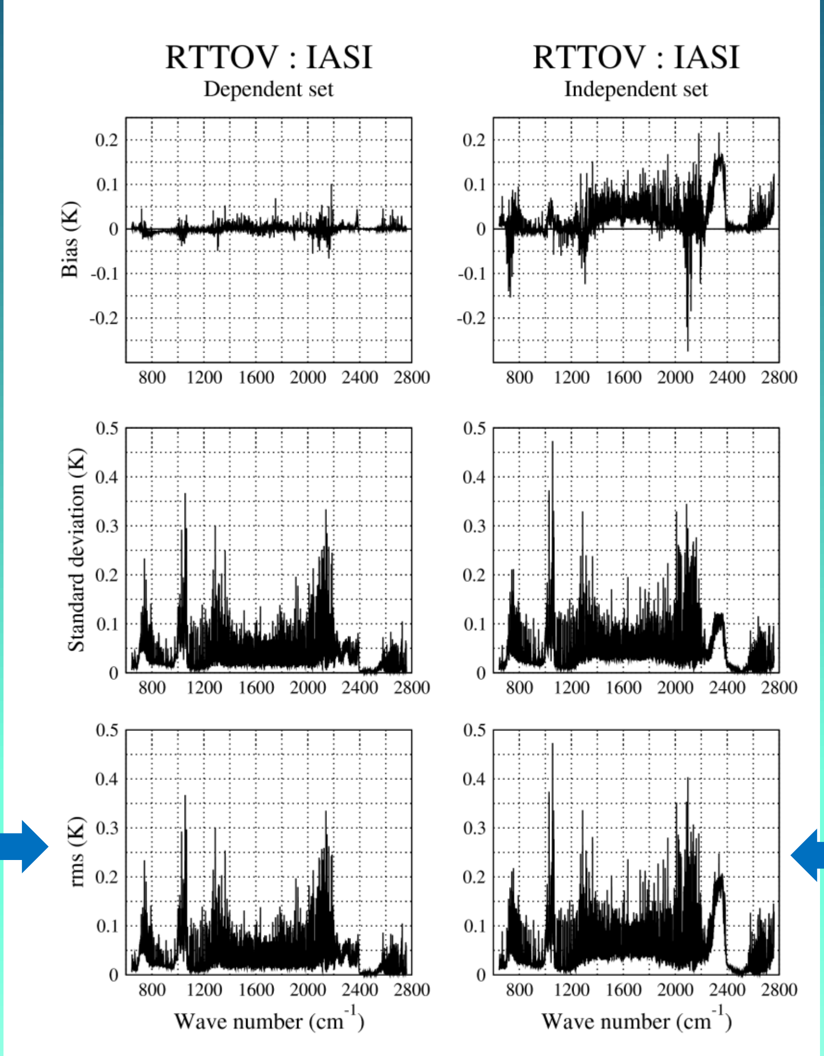
4) Input profiles values (including zenith angle) lying beyond the limits of the training set

The RTTOV fast radiative transfer model: optical depth parameterisation errors

The error introduced by the parameterisation of the optical depths can be assessed by comparing fast model and line-by-line computed radiances

In general, RTTOV can reproduce the line-by-line radiances to an accuracy typically below the instrument noise

The ability of RTTOV to reproduce line-by-line radiances



Statistics of the difference between RTTOV and line-by-line radiances for the 498 training profiles

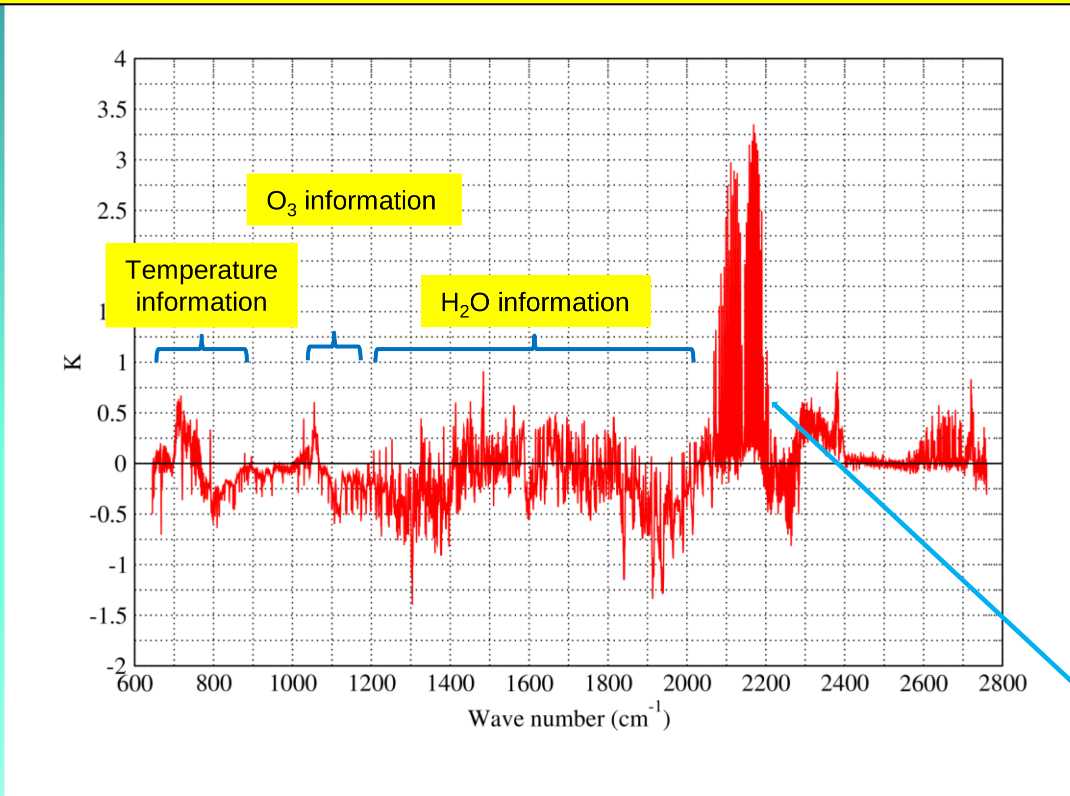
Statistics of the difference between RTTOV and line-by-line radiances for 3000 profiles independent of the regression coefficients

The RTTOV fast radiative transfer model: optical depth parameterisation errors

The ability of RTTOV to reproduce line-by-line radiances

Note that to characterize the total RTTOV error we must include the error contribution from the underlying line-by-line model.

The average difference between IASI observations and RTTOV simulations using ECMWF temperature and water vapour forecast fields as inputs



Differences include the effects of:

1) Errors in the RTTOV parameterisation
2) Errors in the underlying LBL calculations
3) Errors in the NWP fields
4) Mismatch between real and assumed trace gas concentrations

The fixed CO profile used in the simulations does not represent the variability seen in the real atmosphere

The RTTOV fast radiative transfer model: capabilities

RTTOV capabilities

- Clear-sky visible/near-infrared, infrared and microwave radiances
- Internal sea surface emissivity and reflectance models
- Land surface emissivity and reflectance atlases
- Aerosol- and cloud-affected infrared radiances
- Cloud- and precipitation-affected microwave radiances
- Cloud affected visible radiances/reflectances
- Simulated Principal Components for high resolution infrared sounders
- *and more...*

It should be stressed that the RTTOV suite comprises *direct* and *gradient routines (TL, AD, K).* This is a prerequisite for a fast model to be used in NWP assimilation.

The RTTOV fast radiative transfer model: the Jacobian capability

The Jacobian (K) model calculates the derivatives of the simulated radiances or brightness temperatures with respect to each profile variable.

profile variables: $$\frac{\partial L}{\partial T_i}, \frac{\partial L}{\partial q_i}, \frac{\partial L}{\partial O_{3i}}, \ldots$$ for 1 <= *i* <= *nlevels*

and surface parameters: $$\frac{\partial L}{\partial T_s}, \frac{\partial L}{\partial \varepsilon_s}, \ldots$$

It tells us how sensitive the satellite-seen radiance is to each individual profile variable.

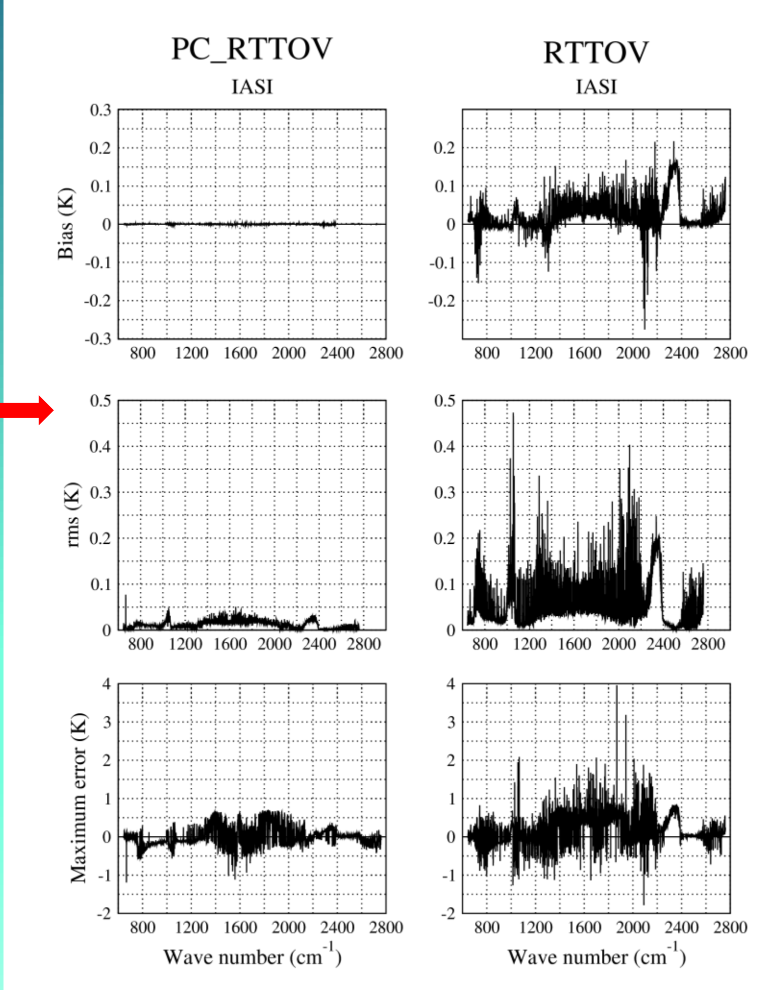
The RTTOV fast radiative transfer model: Principal Components capability

A Principal component (PC) based version of RTTOV (PC_RTTOV) has been developed for hyperspectral (i.e. for sensors with many thousand channels) remote sensing applications

PC based fast models parameterise the PC scores of the radiance spectrum

The PC scores have much smaller dimensions as compared to the number of channels. This optimizations results in significant computational savings and more accurate results.

Statistics of the difference between fast model and line-by-line radiances for 3000 profiles independent of the regression coefficients



The RTTOV fast radiative transfer model: scattering capability

In presence of scattering, the radiative transfer equation cannot be solved analytically

An “exact” solution for the scattering radiative transfer equation can only be obtained using numerical techniques (e.g. discrete-ordinate, doubling-adding, Monte-Carlo).

In RTTOV we have Implemented a Discrete Ordinate Model (DOM). **Too slow to be used operationally**

An analytical solution, however, can still be sought if approximate methods are used (e.g. two/four-stream approximation, Eddington/Delta-Eddington approximation, single scattering approximation, etc.)

For microwave scattering simulations we use the Delta-Eddington approximation

We can parameterise scattering

For infrared scattering simulations we use the optical depth scaling approach

For visible scattering simulations we use the look-up table approach (MFASIS model)

The RTTOV fast radiative transfer model: infrared scattering capability

The infrared scattering parameterisation introduced in RTTOV enables to write the radiative transfer equation in a form that is identical to that in clear sky conditions.

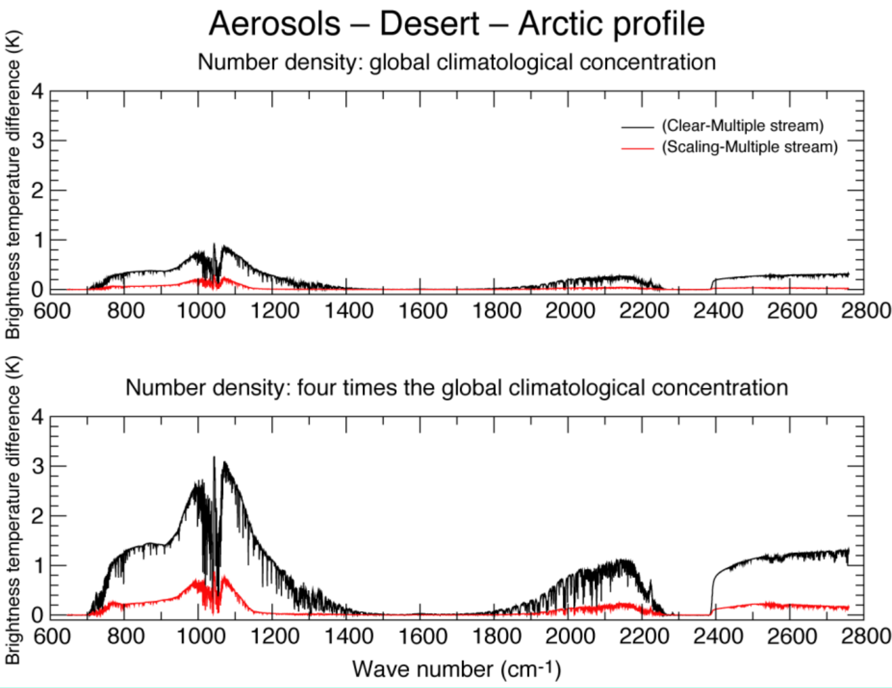
In the optical depth scaling approach, the absorption optical depth, τ_a , is replaced by an effective extinction optical depth, $\tilde{\tau}_e$, defined as: $\tilde{\tau}_e = \tau_a + b\tau_s$,
here τ_s is the scattering optical depth.

The RTTOV fast radiative transfer model: infrared scattering capability

The accuracy of the scattering parameterisation

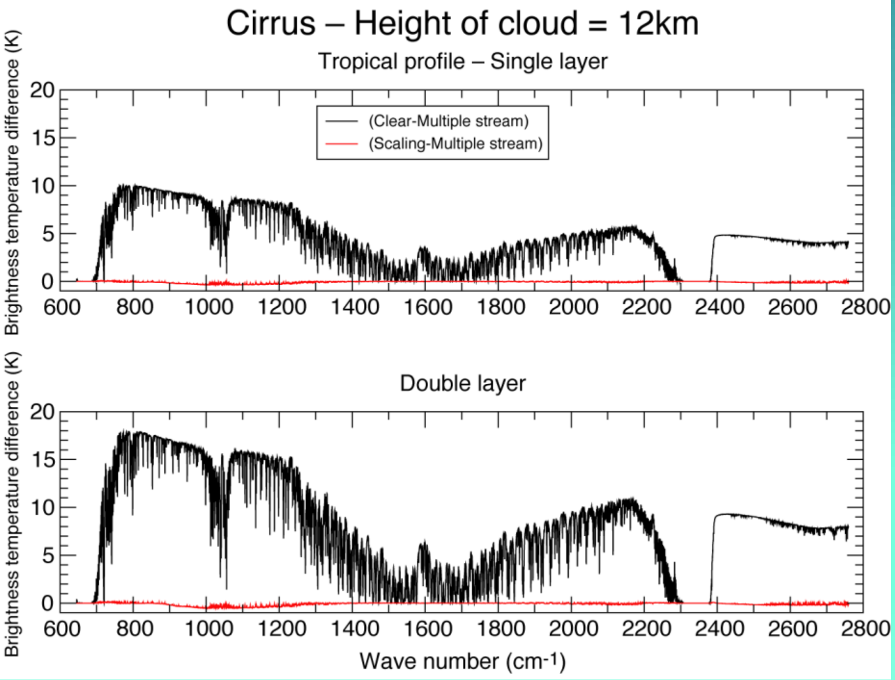
The **red line** denotes the difference between approximate (RTTOV) and exact scattering computations

The **black line** denotes the difference between clear sky and exact scattering computations performed introducing either aerosol or ice crystal particles.


Aerosols – Desert – Arctic profile

Number density: global climatological concentration

Number density: four times the global climatological concentration


Cirrus – Height of cloud = 12km

Tropical profile – Single layer

Double layer

How to get RTTOV

RTTOV is freely available. You can register here:
https://nwpsaf.eu/site/register

Coefficients are available here:
https://nwpsaf.eu/site/software/rttov/download/coefficients/

RTTOV forum:
https://nwpsaf.eu/site/forums/forum/rttov/