- Seminar on the Use of Satellite Observations in Numerical Weather Prediction -

Overview of the status of radiative transfer models for satellite data assimilation

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9 September 2014

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Objectives of the talk

⇒ 1. Provide key concepts of the physics for atmospheric RT

⇒ 2. Describe the current satellite radiance operators

⇒ 3. Point out new and future developments

Outline

- Introduction on atmospheric RT for satellite radiance assimilation
- Atmospheric RT physical principles
- Satellite radiance operators
- New improvements
- Conclusion

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General introduction on atmospheric RT

- Atmospheric radiative transfer is the physical phenomenon of energy transfer in the form of electromagnetic radiation. It describes the propagation of radiation through the Earth's atmosphere affected by interaction processes between radiation and atmospheric consituents (gas, clouds and aerosols) and surface.

- The purpose of atmospheric RT is to solve the radiative transfer equation (RTE) that describes these interaction processes in a mathematical way and to develop numerical radiative transfer models (RTM).

Atmospheric RTMs for satellite radiances assimilation

- They link **atmospheric variables of NWP models** (T,p,q,…) to satellite observations during the assimilation process (satellites do NOT measure temperature, moisture, cloud properties, etc…)

- They must be **fast and accurate** (at least below the instrument noises in clear-sky condition)

- They are called **Fast RTMs**.

- For satellite radiances assimilation, there are two main fast RTMs :
  - **CRTM** (2005 NOAA) op. used at NCEP
  - **RTTOV** (90's J. Eyre and now NWPSAF) op. used at ECMWF, UKMO, Météo-France, JMA, DWD, CMC

  ⇨ Both fast RTMs share ideas, improvements and developments through the Radiative Transfer and Surface Properties sub group of the International TOVS WG

  (https://groups.ssec.wisc.edu/groups/itwg/rtsp)

Fast RTM distinctive features

- **Fast simulation of many satellite instruments**
  - Passive IR sounders / imagers (3-20 µm or 500-3000 cm^{-1})
  - Passive MW sounders 10-200 GHz
  - Ex: > 50 instruments assimilated in IFS

- **To provide required information for assimilation process**
  - Forward (TOA radiances or BTs) + Tangent Linear, Adjoint, Jacobian models

- **Use ONLY NWP model variables as input**
  - Need parametrization to relate NWP model variables to optical properties and to facilitate derivative calculations

- **Take into account many interactions**
  - IR+MW : Land/ocean surface emissions, cloud scattering and overlapping
  - IR only: NLTE effect, Solar contribution
  - MW only: Zeeman effect, SSU pressure cell

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Interactions radiation - particles

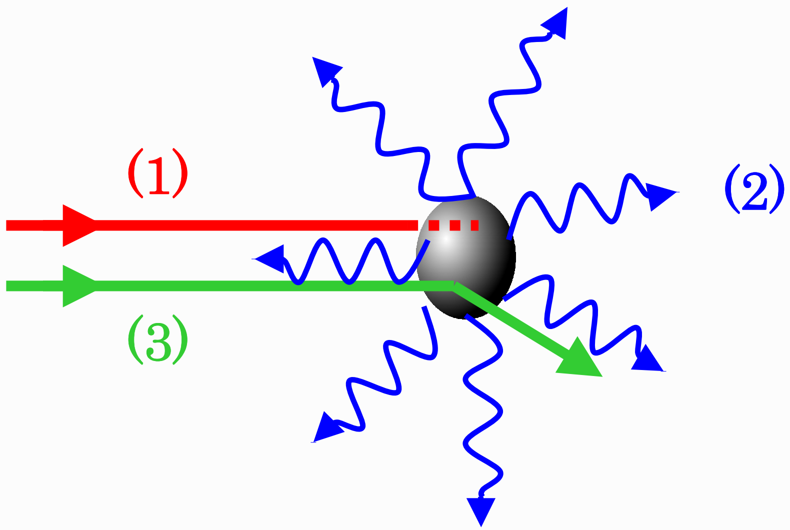
- Physical interactions in atmosphere

  (1) Absorption = Radiation attenuation by energetic modification (heat or chemical reaction)

  (2) Emission = Isotropic radiation increase by molecular excitation due to **absorption** (Kirchhoff's law)

  (3) Scattering = Radiation attenuation by deviation in other directions than the original radiation trajectory

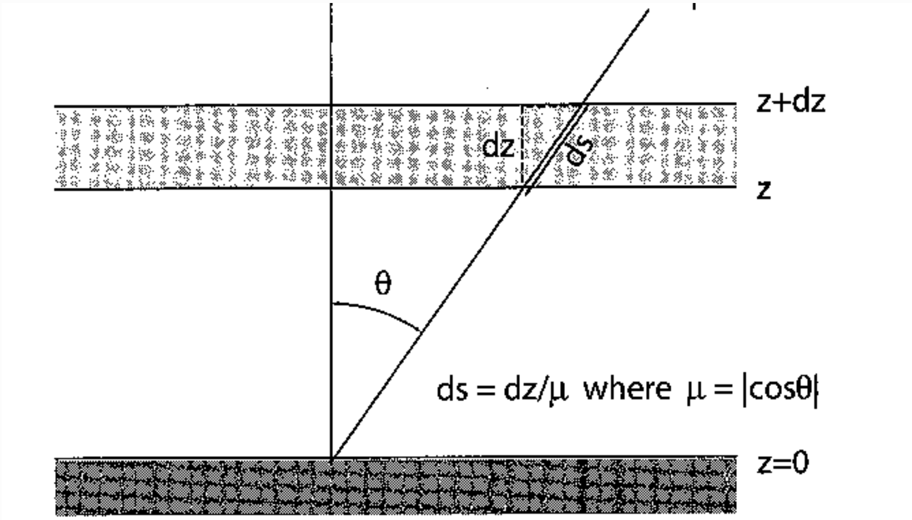
⇨**Extinction = Absorption + Scattering**



- Absorption, scattering and extinction are represented by coefficients k (units of inverse length) that depend on the particles' properties (refractive index, size and shape)

General form of RTE

- Assumptions:
  - Plane-parallel atmosphere
  - Homogeneous layers
  - LTE
  - 3D effects ignored
  - Polarization is ignored



From Petty, 2006

- The differential change of monochromatic radiance **dR** (at wavenumber ν) along path **ds** in the direction **(μ,ϕ)**

$$\mu \frac{dR(\nu;\mu,\phi)}{dz} = -k_e R(\nu;\mu,\phi) + k_e J(\nu;\mu,\phi)$$

- 1st term represents the lost by extinction
- 2nd term represents the gain from the source function

Emission component of the source term J

- Thermal emissions from the Sun and from terrestrial environment
- Planck's Fonction

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

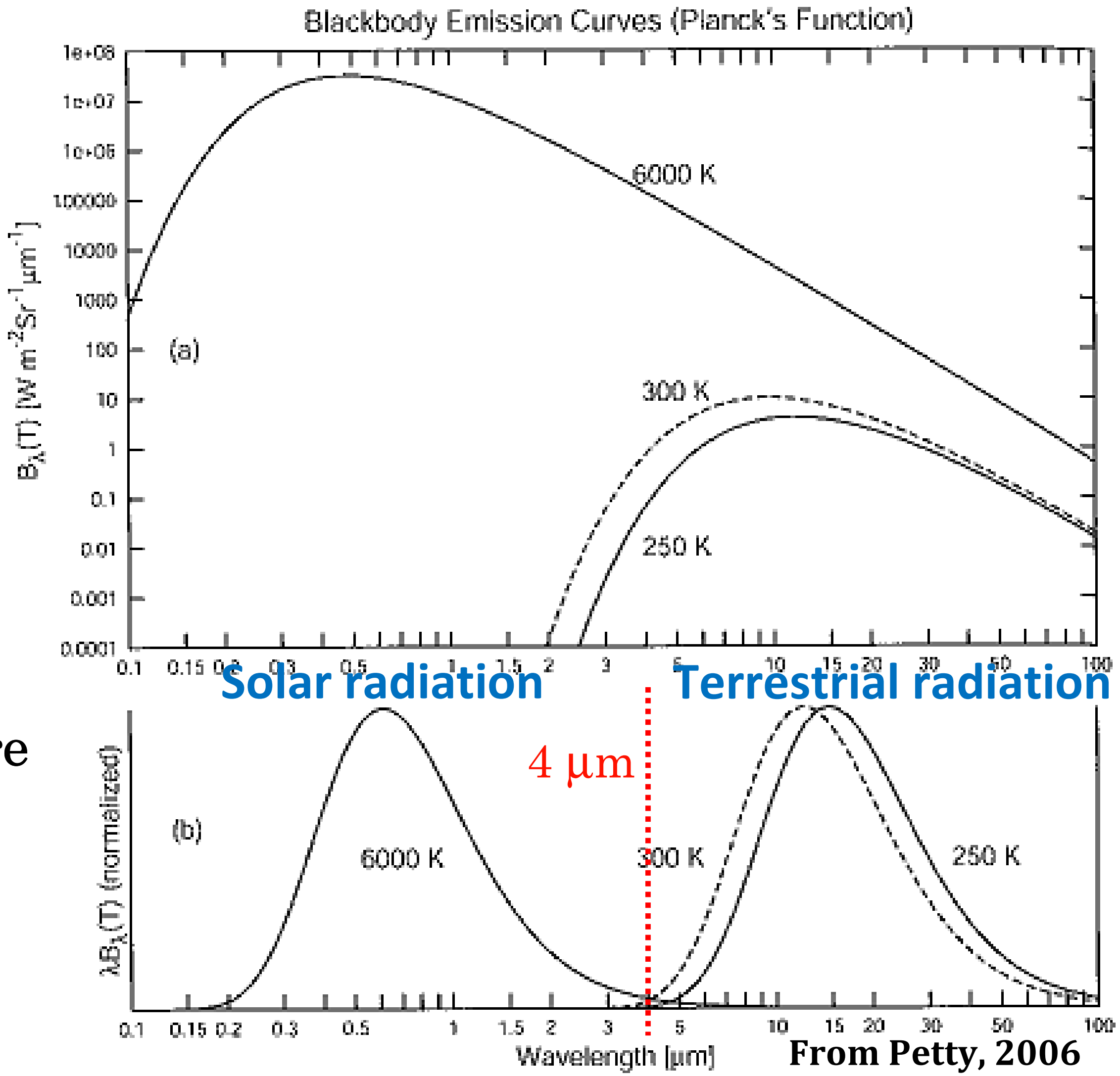
[W/m²/sr/cm⁻¹]

- Emissivity

$$\epsilon_\nu = \frac{R_\nu}{B_\nu(T)} \quad [Ø]$$

- Brightness Temperature

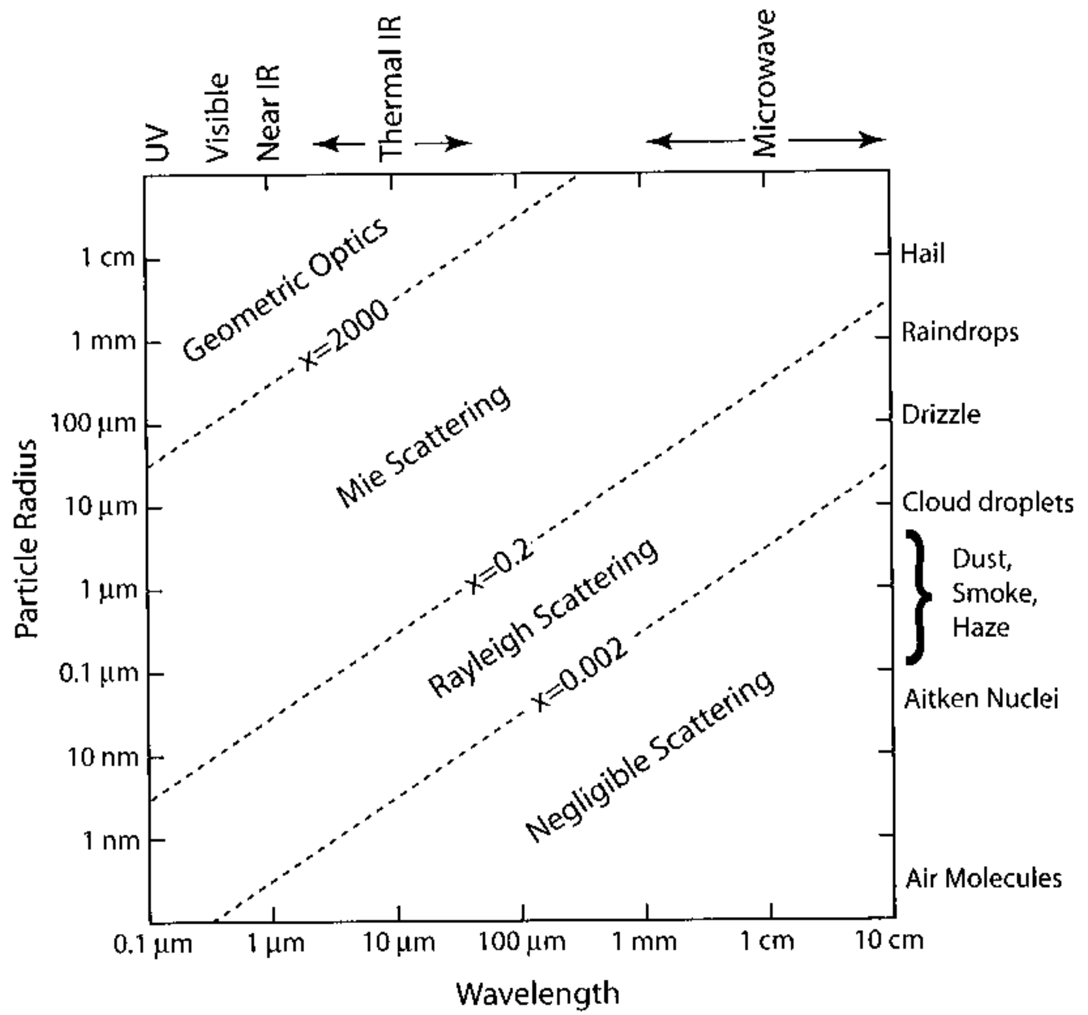
$$BT_\nu = B_\nu^{-1}(R_\nu) \quad [K]$$



From Petty, 2006

Scattering component of the source term J

- Depends on the spectral domains and on the particle size



From Petty, 2006

Size parameter

$$x = \frac{2\pi r}{\lambda}$$

IR: scattering from molecules is negligible

MW: scattering from molecules and aerosols is negligible

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Clear-Sky RTE (Schwarschild's Equation)

- Upward direction μ=cos(θ) for an homogeneous plane-parallel atmosphere bounded by a specular reflecting surface
- Source function is atmospheric emission (no scattering and no solar contribution)

$$\mu \frac{dR(\mu)}{dz} = -k_a R(\mu) + k_a B(T)$$

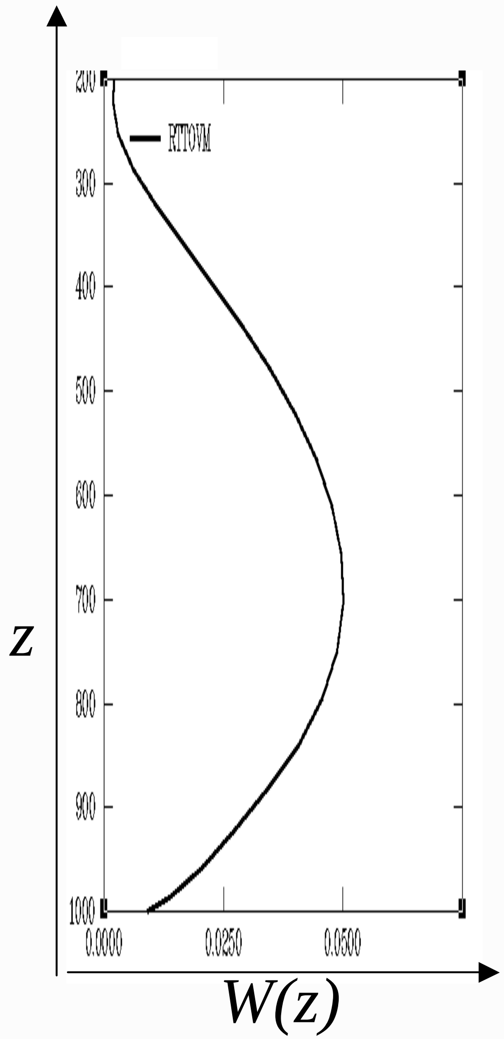
- **Optical depth, transmittance and weighting function**

$$\tau_a = \int_{z_1}^{z_2} k_a dz \qquad t(\mu) = e^{(-\tau_a/\mu)} \qquad W(z) = \frac{dt(z)}{dz}$$

$$R_{clr}(\mu) = t_{tot}(\mu)\varepsilon_{sfc}(\mu)B(T_{sfc}) + \int_{t_{tot}}^{1} B(T)dt + [1-\varepsilon_{sfc}(\mu)]t_{tot}^2(\mu)\int_{t_{tot}}^{1} \frac{B(T)}{t^2}dt$$

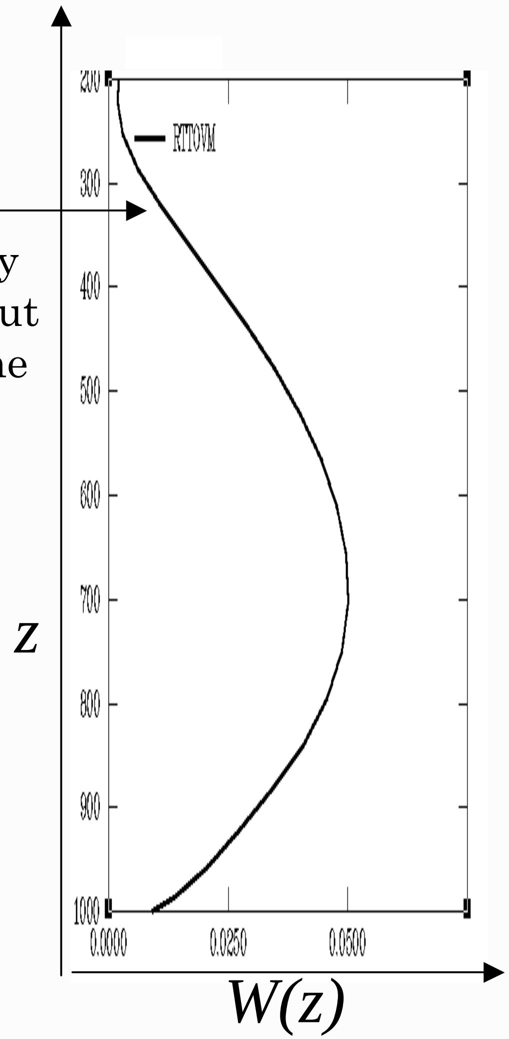
- 1st term is due to surface emission
- 2nd term is due to upwelling atmospheric emission
- 3rd term is due to downwelling atmospheric emission reflected by surface

Weighting function

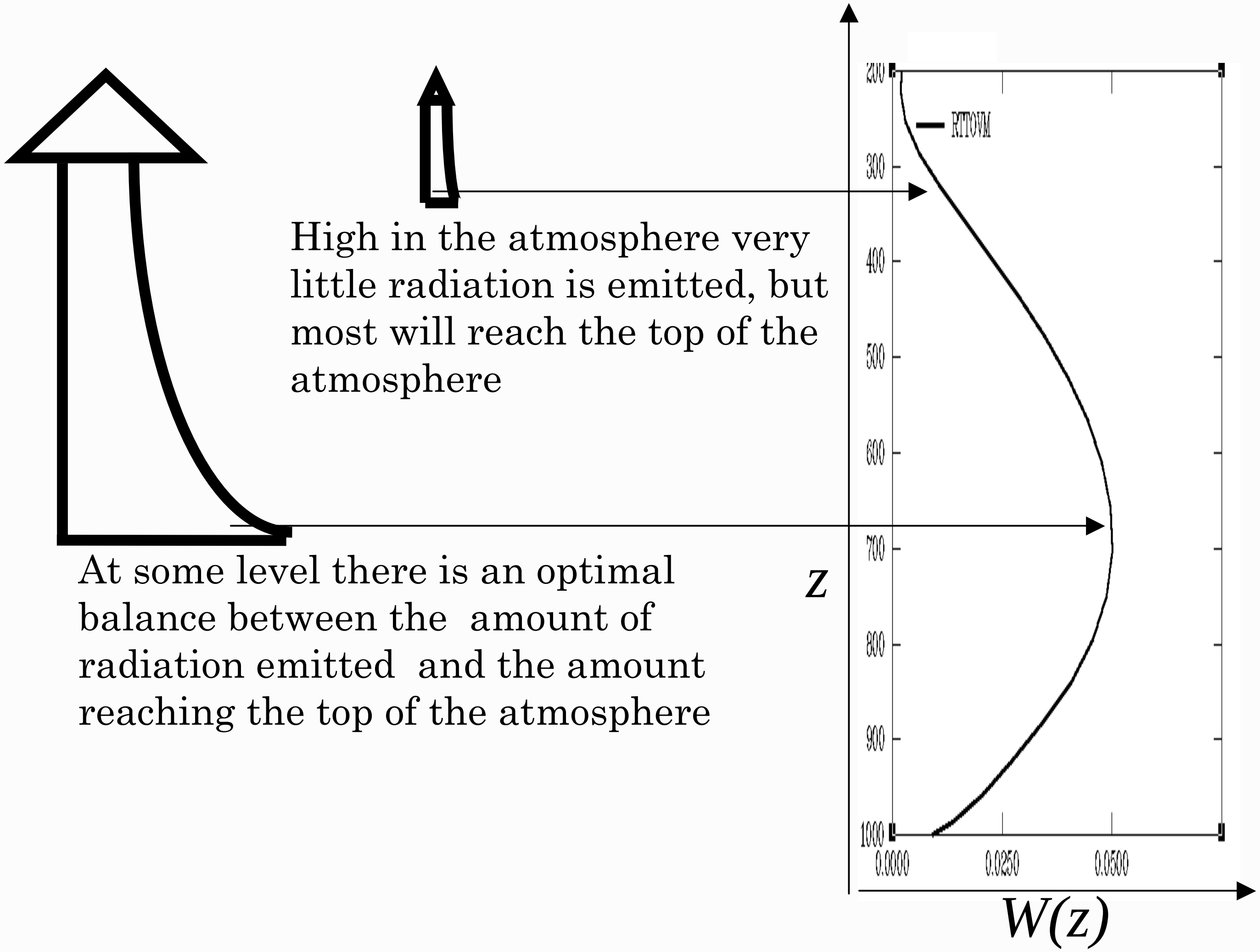


Weighting function

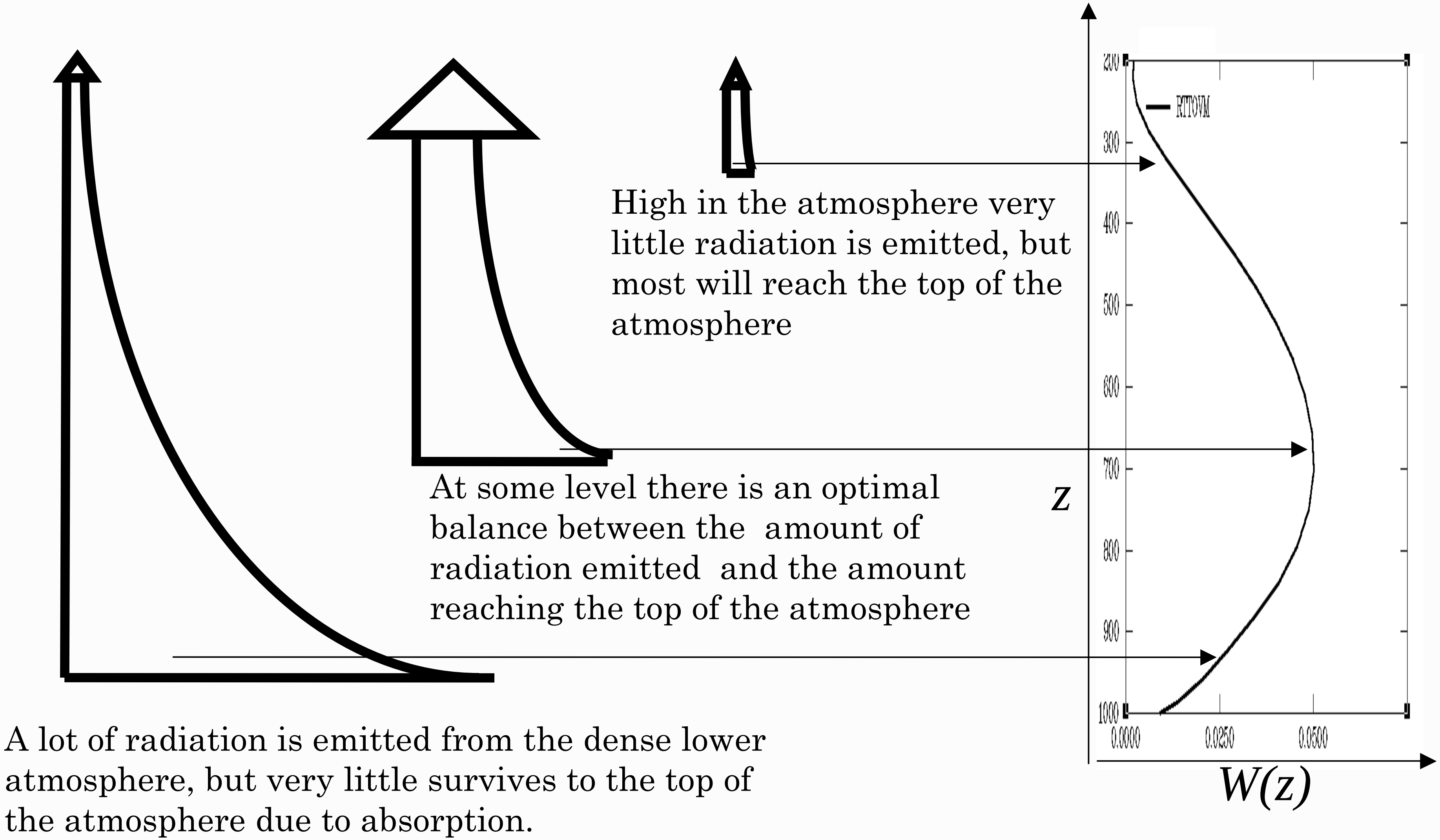
High in the atmosphere very little radiation is emitted, but most will reach the top of the atmosphere



Weighting function



Weighting function



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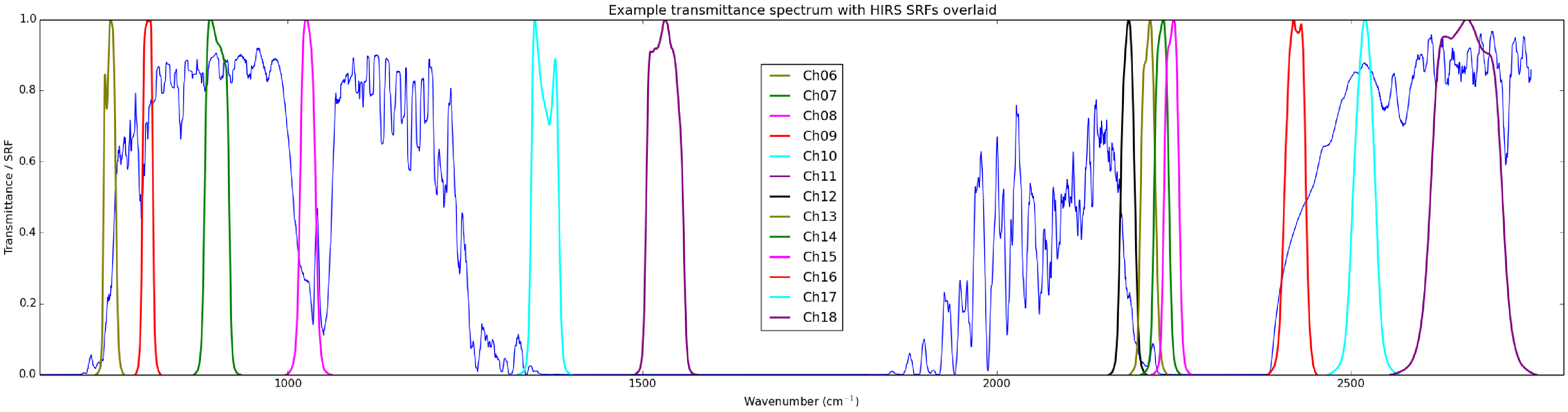
Polychromatic channels

- Passive IR/MW sensor channels are not monochromatic



- Ideally, we would solve the RTE at many wavelengths and integrate the resulting radiances over the channel spectral response function (SRF)

- In pratice, we integrate transmittances over the SRF and solve the RTE once per channels

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Atmospheric transmittance

- The atmospheric transmittance is given by the absorption coefficient:

$$k_a(z) = \sum_{i=1}^{k} N_i(z)\sigma_{a,i}(z)$$

  - ➢ N is the number density of atmospheric molecules i
  - ➢ σ is the absorption cross section (from continuum and absorption lines M)

$$= \sum_{i=1}^{k} N_i(z)[\sigma_{cont,i}(\nu, z) + \sum_{j=1}^{M_i} S_{ij}(z) f_{ij}(\nu - \nu_{ij}, P, T)]$$

  - ➢ S is the line strength
  - ➢ f is the line shape simulated with a certain function (Voigt)
  - ➢ ν is the line position
- The different line values are provided by spectroscopic database (HITRAN, GEISA)
- Continuum formulation (ex MT_CKD for H_2O)

Infrared atmospheric transmittance

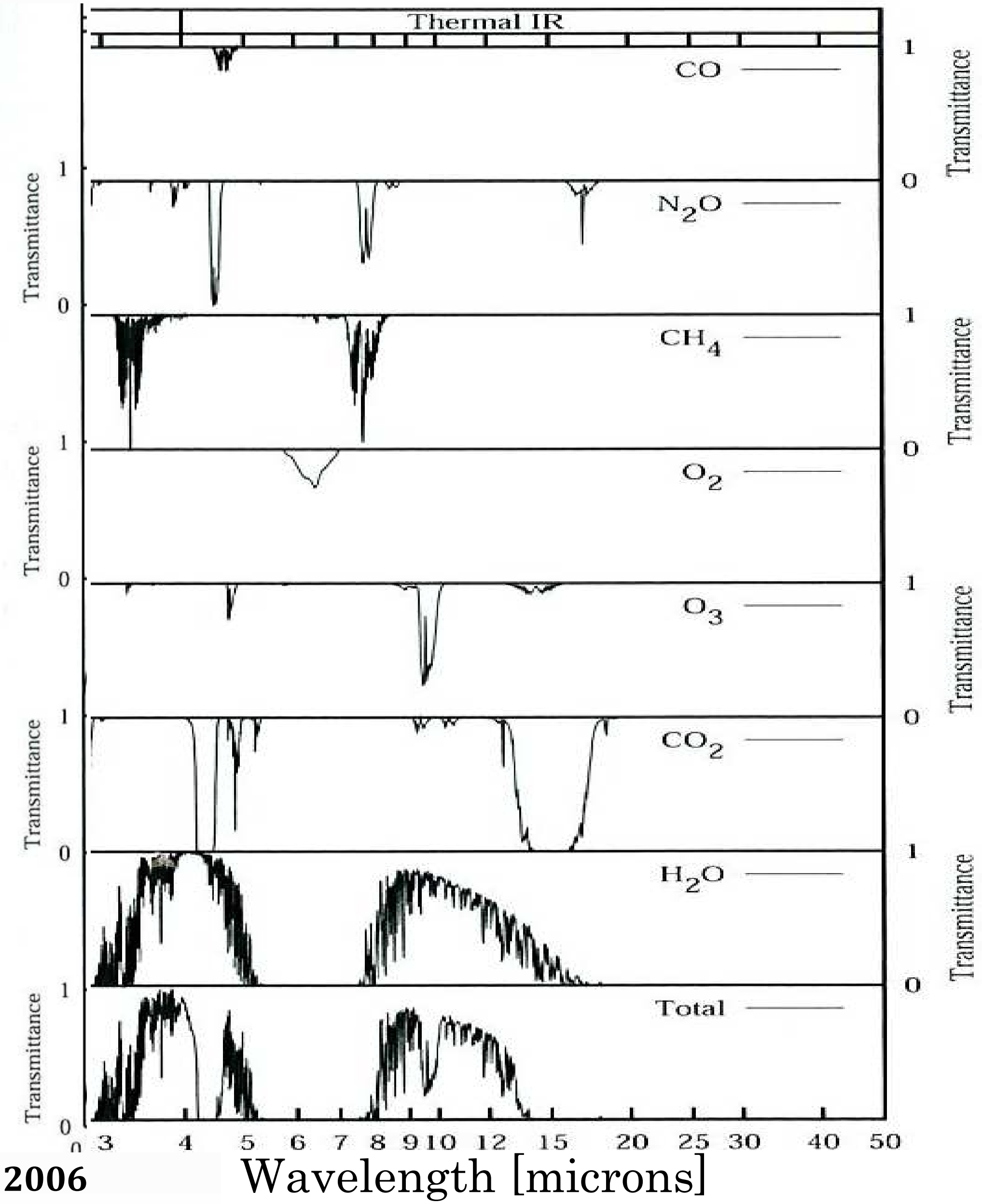
- Main absorbers:
  - Uniformely-mixed:

  CFCs, N_2, O_2, etc…
  - Variable:

  H_2O, O_3, CO_2, CH_4, N_2O, CO

- Transmittances are provided by Line-by-line (LBL) models (ex LBLRTM, GENLN2,…)

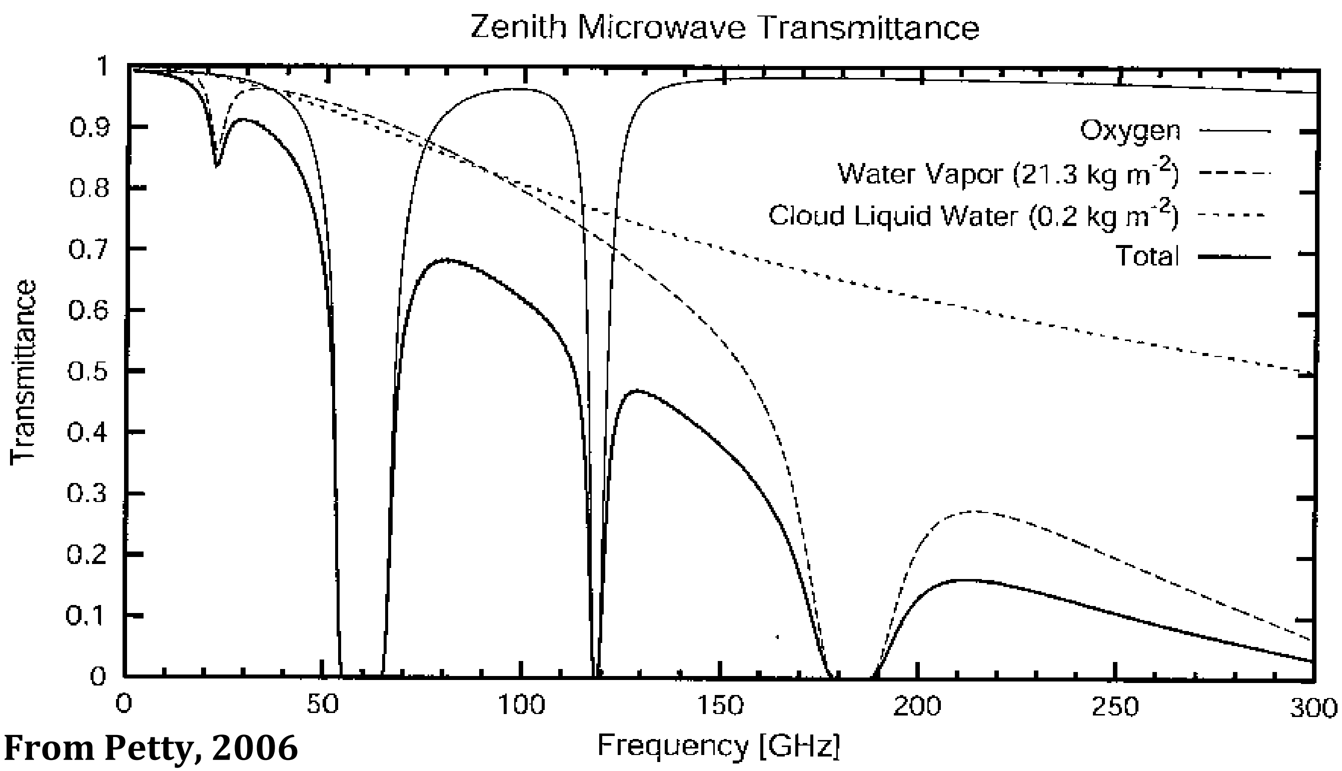
- Atmospheric profiles have to be assumed (ex: US76 standard)



From Petty, 2006

MW atmospheric transmittance

- Main absorbers: H_2O (22 GHz, 183 GHz) and O_2 (50-70 GHz, 118 GHz)
- Transmittances are calculated by Line-by-line (LBL) models (ex LBLRTM, AMSUTRAN,…)
- Atmospheric profiles have to be assumed



From Petty, 2006

Fast atmospheric transmittance model 1/2

- Line-by-line model are very accurate but too slow in operational context
- Fast methods were developed in the mid 70s by McMillin & Fleming
  - Idea: perform a multivariate Taylor expansion of the formulation of the ratio between transmittances of 2 adjacent layers (effective transmittance)
  - Absorption optical depth in a channel *i* from TOA to level *j* is predicted as :

$$\tau_{abs,i,j} = \tau_{abs,i,j-1} + \sum_{k=1}^{K} a_{i,j,k} X_{i,k}$$

- *a* are the coefficients and *X* the predictors (*K* values)
- Predictors are functions of atmospheric variables (*P*, *T*, absorber) and secant (inverse cosine of zenithal angle).

Fast atmospheric transmittance model 2/2

- Coefficients are calculated from training dataset of atmospheric profiles representating the natural variability of atmospheric gases.
- 2 methods for the vertical coordinates: fixed pressure level (McMillin and Fleming, 1976) or fixed absorber level (McMillin et al., 1979)

- RTTOV: Improved « Fixed pressure level » method
  - 83 ECMWF profiles from Chevallier et al. (2006) interpolated at 101 levels between 0.005 and 1100 hPa
  - Coefficients are provided at 51 levels (54 levels in RTTOV-11).

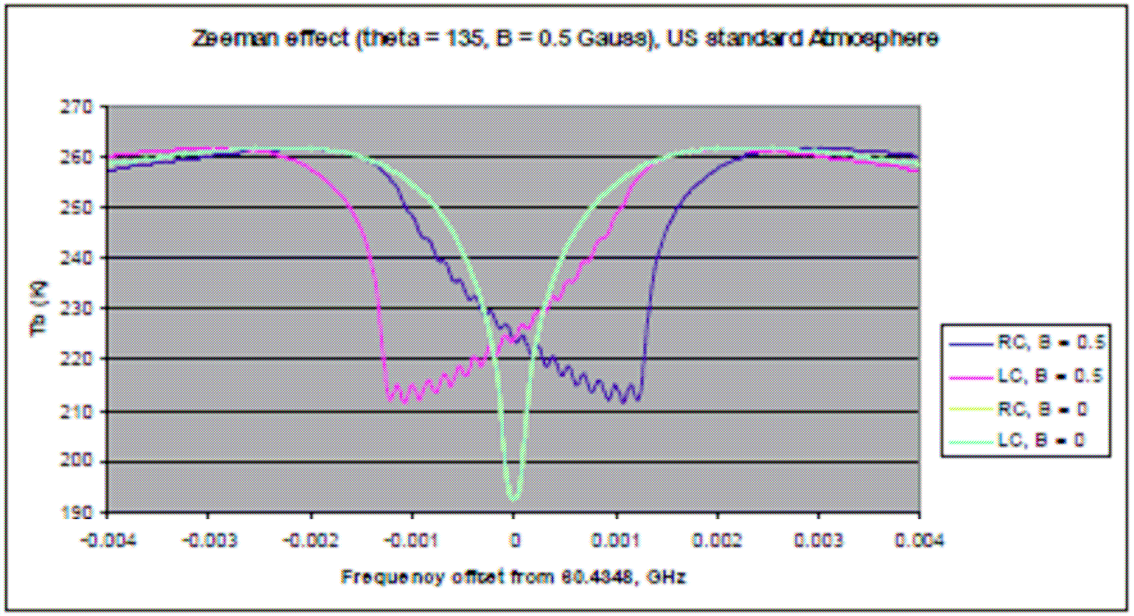
- CRTM: ODPS (Chen et al., 2010; similar to RTTOV) / ODAS methods (improvement of OPTRAN v6 (McMillin et al, 2006))
  - 48 UMBC profiles (Strow et al., 2003) interpolated at 101 levels

Predictors selection

- The number of predictors depends on absorbers
- RTTOV:
  - At first, K=10 for both uniformly-mixed gases and H_2O (Eyre, 1991)
  - Nowadays, there are 3 versions of predictors:
    1) Predictors version 7: K=10 (uniformly-mixed gases), K=15 (H_2O), K=11 (O_3) (Saunders et al., 1999)
    2) Predictors version 8: K=10 (uniformly-mixed gases), K=12 (H_2O), K=11 (O_3), K=4 (H_2O-cont), K=10 (CO_2)
    3) Predictors version 9: add more molecules for hyperspectral sounders by optimal selection (Matricardi et al., 2004)
- CRTM:
  - A selection of number of K is done over a pool of 18 predictors (McMillin et al., 2006; Chen et al., 2010)

Zeeman effect

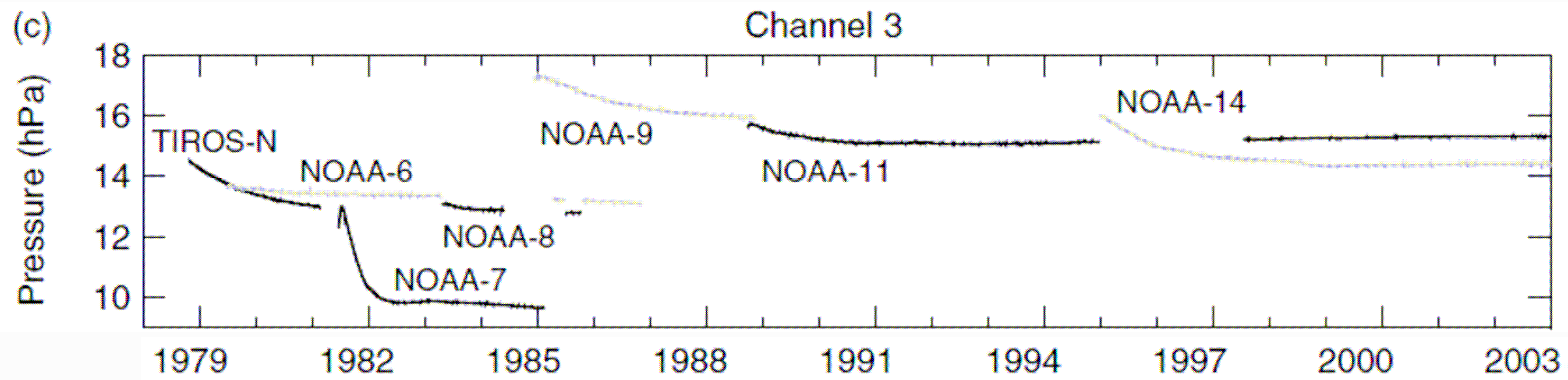
- Effect of splitting a spectral line into several components in the presence of a static magnetic field
- Affect high peaking MW channels, error up to 0.5K (for AMSU-A) and up to 10K (for SSMIS mesospheric channels)



- Fast model (Han et al., 2007) for RTTOV/CRTM
- Predictor-based optical depth correction for each channels of impacted instruments (AMSU and SSMIS)

Variations of in cell pressures on SSU

- Pressure Modulated Radiometer (PMR) with CO_2 gas cell
- The nominal mean pressure cell of each channel provides measurement sensitivity at very high altitude (1.5, 5 and 15 hPa)
- But, mean pressure cell changes after launch causing a change in the channel SRF (Kobayashi et al.,2009)



- Adapted coefficients are required for reanalysis
- Both CRTM/RTTOV have implemented a correction of the optical depth that depends on the input mean pressure cell

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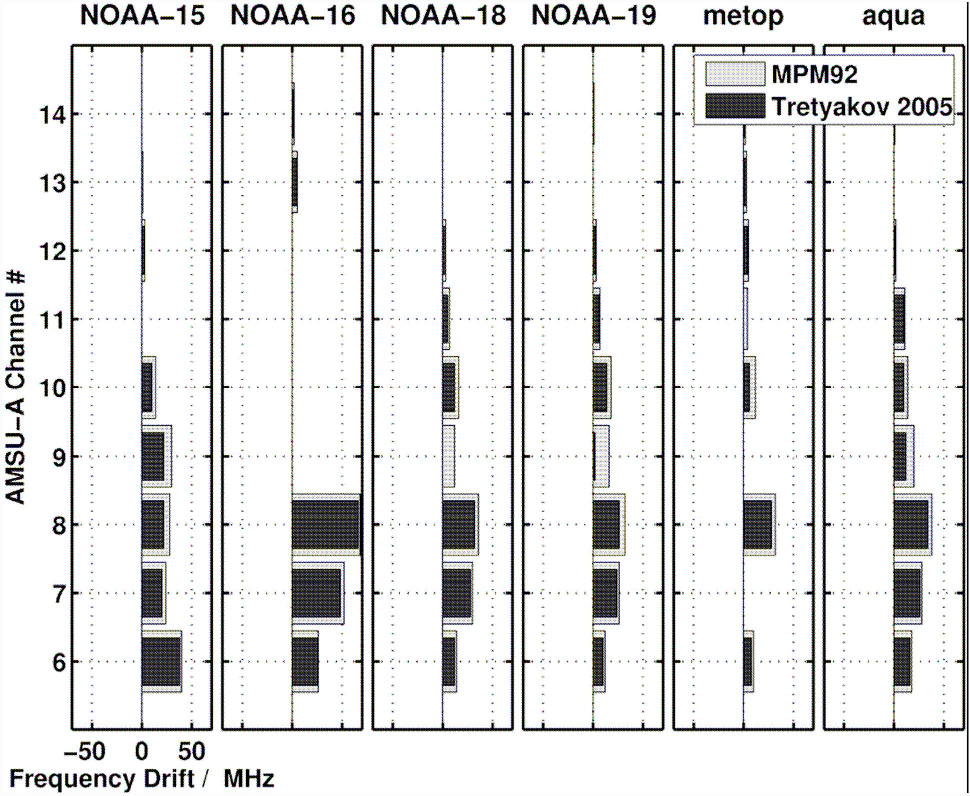
Other effect on coefficient

- Modification of the channel SRF after launch:
  - MODIS: 5 bands shifted (Tobin et al., 2006)
  - HIRS
  - AMSUA



Liu and Bell, 2014

- Adapt atmospheric profiles for old instrument needed for reanalysis

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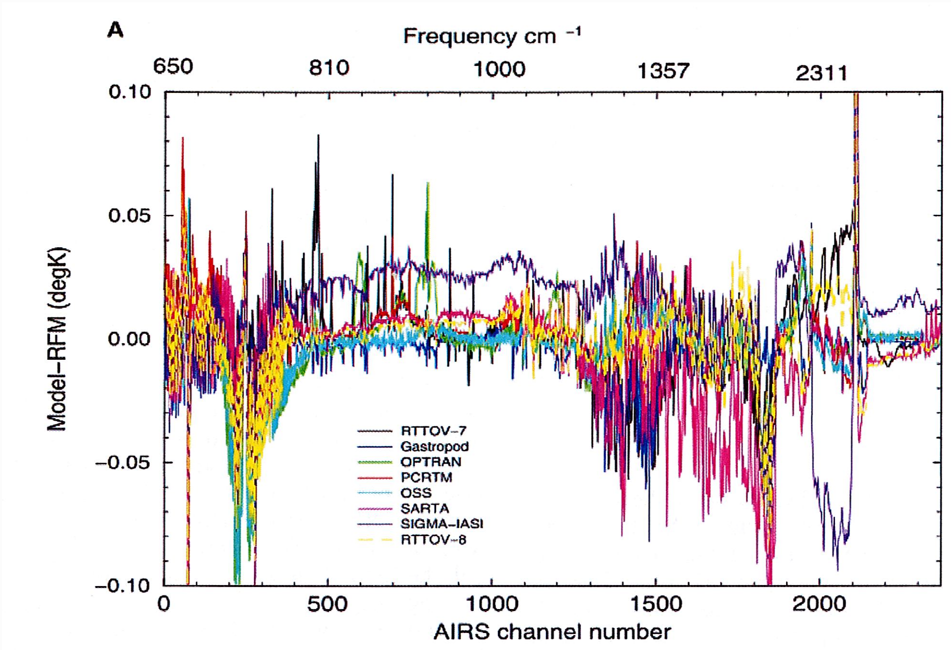
Clear-sky Validation (1/3)

- LBL / Fast forward and jacobians models comparison (Garand et al., 2001)
  - 7 IR + 4 MW channels, 42 atmospheric profiles, 29 models
- Main results:
  - LBL models agree to within 0.05-0.15 K
  - IR BTs are reproduced to within 0.25 K
  - MW BTs are reproduced to within 0.1 K
  - Jacobians intercomparison was usefull to detect some problem in out-of-limits profiles, continuity in level-to-TOA transmittances, and vertical interpolation
- Issues:
  - Airmass dependence of bias
  - Ozone and water vapor spectroscopy
  - Intercomparison at narrow IR channels (AIRS or IASI)

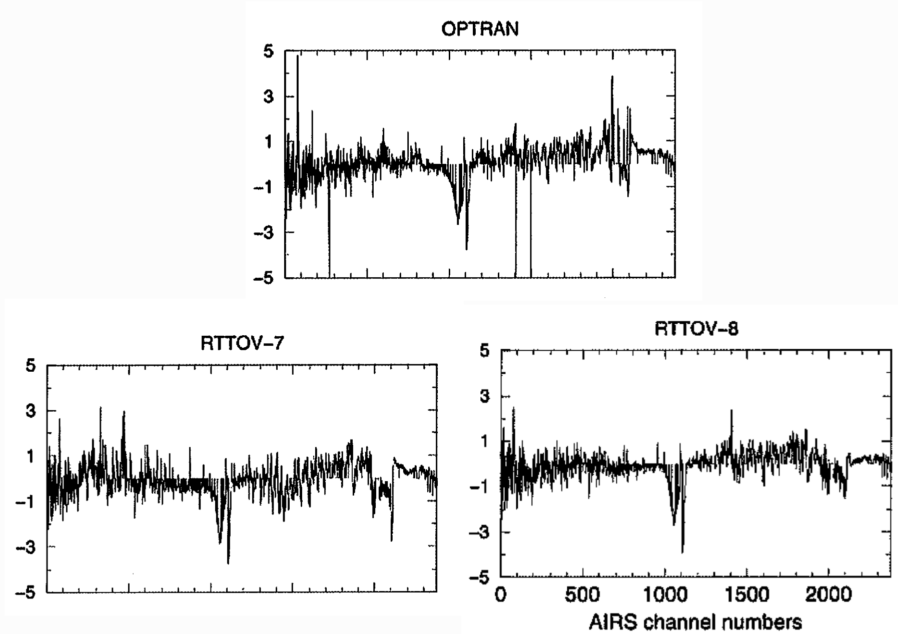
Clear-sky Validation (2/3)

- Intercomparisons with real satellite data (Saunders et al, 2007)
  - One AIRS spectra (ARM site), 49 profiles, 14 models

Models together



Models vs AIRS



  - Fast RTMs agreed to ± 0.1K
  - Difference with AIRS observations is typically ± 1K (up to ± 3K)
  - Sources of error: input profiles and surface

Clear-sky Validation (3/3)

- Intercomparisons with real satellite data in operational environment (Matricardi, 2009)
  - IASI: RTTOV vs 3 LBL models (kCARTA, GENLN2, LBLRTM)
  - 12h 4D-Var windows (IFS c33R1) during 1-15 april 2008 period
  - 3 regions were studied (NH, Tropical, SH)

- Main Results
  - Bias are generally within ± 1K in all regions
  - In CO_2 bands the bias is higher for one LBL model and highlight the effect of treatment of line mixing in the model.
  - In O_3 band, bias up to 2K probably (same for all LBL) due to some error in the input profiles
  - Possible systematic moist bias in ECMWF tropical field due to higher bias in H_2O band.

Models or Atlases for Surface Emissivity

- Infrared:
  - Ocean: Infrared Surface Emissivity Model (ISEM, Sherlock, 1999)
    - Channel average emissivity predicted as function of satellite observation from Masuda surface emissivity model (Masuda, 1988)
  - Land: UWIREMIS atlas (Borbas and Ruston, 2010) for any IR instrument
    - Combine MODIS retrieval and PC analysis on laboratory spectra
    - Provide monthly mean and standard deviation
    - Include snow and sea ice surfaces
- Microwave
  - Ocean: FASTEM Model (version 4 and 5, Liu et al., 2011)
  - Land:
    - CNRM Atlas (Karbou et al., 2005) only AMSU and MHS
    - TELSEM (Aires et al., 2011) based on SSMIS, mean and full covariance matrix.

Cloudy-Sky Infrared RTE

- RTTOV Grey cloud approximation (Eyre, 1991)

$$R(\mu) = (1 - N)R_{clr}(\mu) + NR_{cld}(\mu)$$

$$R_{cld}(\mu) = t_{cld}(\mu)B(T_{cld}) + \int_{t_{cld}}^{1} B(T)dt$$

  - R_{cld} is the overcast cloudy radiance
  - N is the fractional cloud cover (single layer and cloud top emissivity=1)
- Op. at ECMWF (McNally, 2009):
  - Cloud cover and cloud top pressure retrieved by « CO_2-slicing »
  - Only 100%-overcast scenes are assimilated (N=1)
- Produce ambiguities for very thin cloud and multi-layered cloud (Pavelin et al., 2008)
- Difficulty to detect low cloud with « CO_2-slicing » method for cloud retrieval
- CRTM has a similar approach.

All –Sky Microwave upward RTE

- Source function contribution from emission and scattering from hydrometeors

$$J(\mu) = (1 - \omega_0)B(T) + \frac{\omega_0}{2}\int_{-1}^{1} R(\mu)P(\mu;\mu')d\mu'$$

  - Single scattering albedo $\omega_0 = \frac{k_s}{k_e} = \frac{k_s}{(k_a + k_s)}$
  - Phase function $P(\mu;\mu')$

- The RTE cannot be solved analytically
- RTTOV uses the Delta-Eddington approximation (Bauer et al., 2006)
- CRTM has 2 RTE solvers:
  - Advanced Adding-Doubling (Liu and Weng, 2006)
  - Successive Order of Interaction (Greenwald et al., 2005)

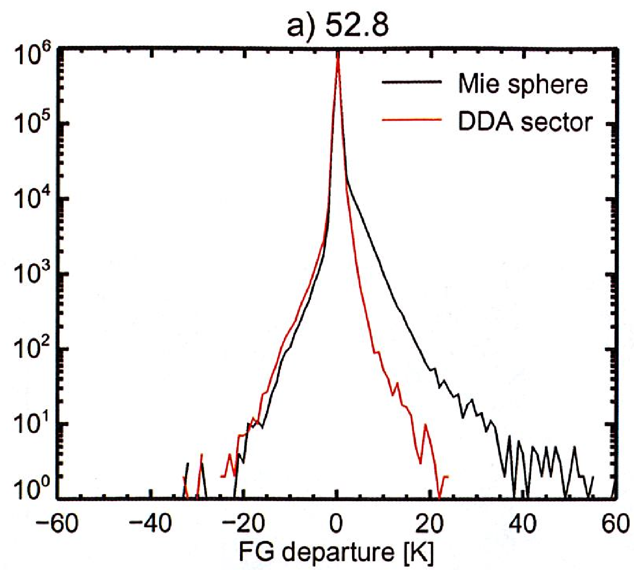
Cloudy-sky validation

- With full scattering model for RTTOV MW (Bauer et al., 2006)
  - ECMWF 1D+4DVar rain assimilation (8290 profiles)
  - Errors less than 0.5 – 1 K
  - Issue on the treatment of the cloud overlap

- With collocated observations and retrievals for CRTM IR+MW
  - AMSUA, MHS and AVHRR / CloudSat over ocean (Chen et al., 2008)
  - MW: Good agreement with larger bias below 2.4 K and larger RMS below 3.9 K for AMSU and MHS
  - IR: Bias of 2 K and SD between 3 and 6 K depends on the cloud type

MW cloud and precipitation model improvement

- Four hydrometeors are considered (Liquid cloud, ice cloud, rain and snow)
- Mie theory is used to calculate optical properties (single scattering albedo, extinction)
  - Assumption: perfect sphere
- New model for ice and snowflakes (Geer and Baordo, 2013) : LUT DDA optical properties (Liu et al., 2008) with new particle size distribution model (Field et al., 2007)



Histogram of FG departure [K] for the month of June 2012

SSMIS channel at 52.8 GHz

Cloud Overlap (only for RTTOV)

- To efficiently take into account the cloud fraction (CF) profile input.

- MW (used op.):
  - Maximum CF and single cloud layer assumed (Bauer et al., 2006)
    - ➠ Layer with CF max is often not the one with the closer to reality optical depth
  - Average CF and single cloud layer assumed (Geer et al., 2009)
    - ➠ Decreasse RMS error by 40% in rainy areas

- IR (not used op.): Matricardi (2005)
  - Maximum random overlap
  - Too slow for multiple layered clouds

- CRTM is planning to add similar methods

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IR cloud scattering for RTTOV (Matricardi, 2003)

- IR: Chou scaling (Chou et al., 1999)

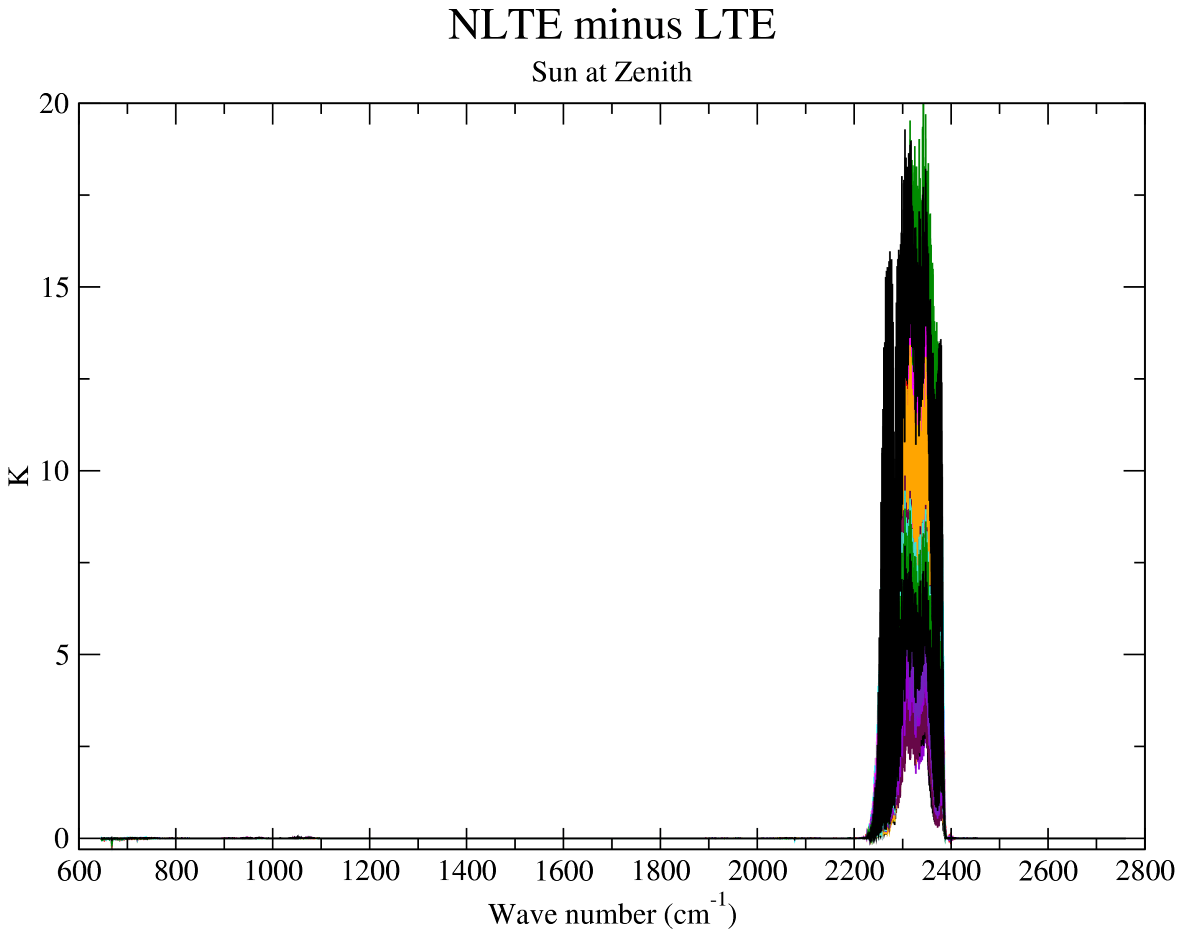
$$\tau_{tot} = \tau_a + b\tau_s$$

  - b is the backscattering fraction

- Liquid cloud: optical properties for 5 types of cloud (2 stratus and 3 cumulus clouds) are tabulated in function of LWC.
- Ice cloud: Parametrization of optical properties in function of IWC from aircraft measurements
- New channel selection for IASI (Martinet al., 2013) for cloudy retrievals 144 new channels added to current 366 channels of Collard (2007)
- Test of feasability to add the cloud variables to the state vector of the assimilation system (Martinet et al., 2014)
- O-B departure analysis of all sky-IASI data is less than 10K (Okamoto et al., 2013)

Non Local Thermodynamic Equilibrium (NLTE)

- In real atmosphere, LTE can break down at extremely high altitude where spontaneous emission is low and when other sources of radiation are present.
- Ex: Significant NLTE emission in CO_2 band during daytime above 40 km.



➢LBLRTM simulations for 83 profiles

➢ΔBT between 2.5 and 20K

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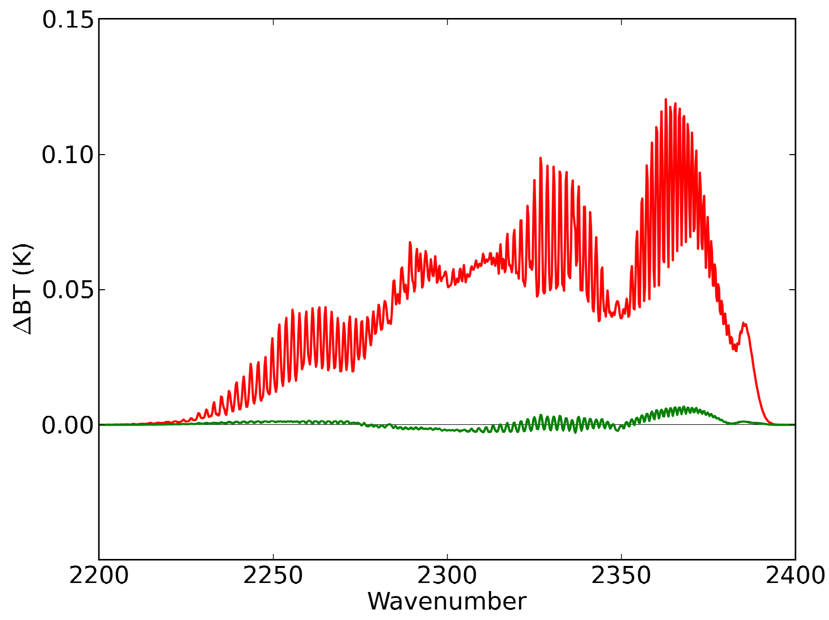
Fast NLTE correction

- Method developed from CRTM (Chen et al., 2013)

$$R^{NLTE} = R^{LTE} + \Delta R^{NLTE}$$

$$\Delta R^{NLTE}(\mu, \mu_s) = c_0(\mu, \mu_s) + c_1(\mu, \mu_s)T_1 + c_2(\mu, \mu_s)T_2$$

- *R* is the channel radiance as calculated by LBLRTM (with or without NLTE)
- where $c_{0\text{-}2}$ are coefficients derived from statistical regression of the fit function against the training data
- T_1 = mean temperature between 0.005 and 0.2 hPa
- T_2 = mean temperature between 0.2 and 52 hPa.
- Mean Bias is 0.01K (green) and max SD is 0.1 K (red)



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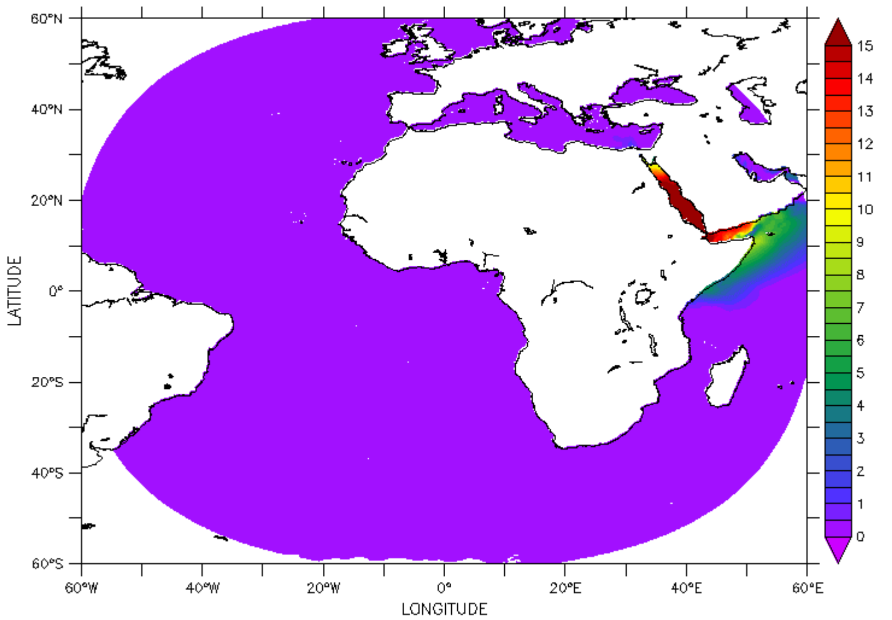
Solar contribution (RTTOV only)

- New term in the souce function

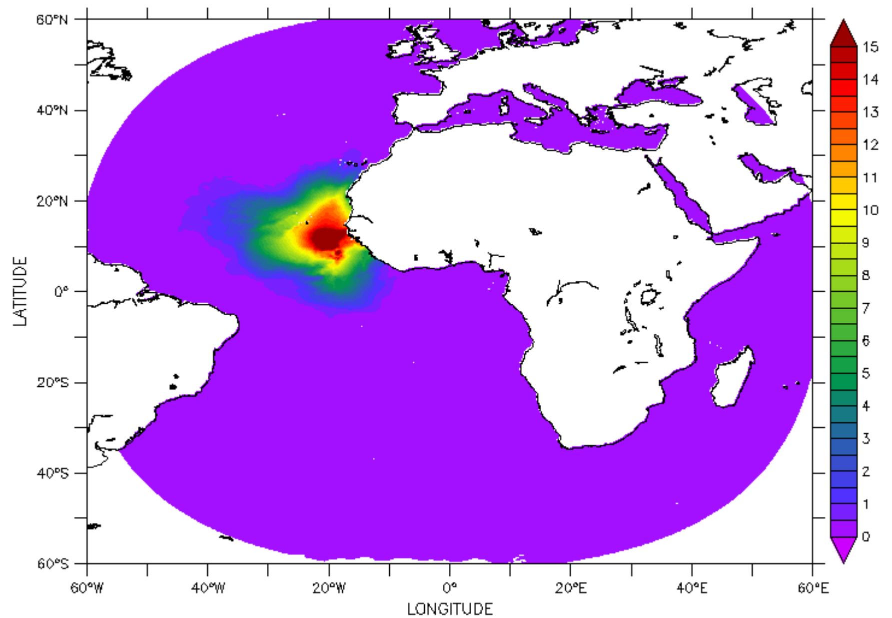
$$J_s = \frac{k_s}{4\pi} P(\mu, \phi; \mu_s, \phi_s) F_s \mu_s e^{-(\tau_e/\mu_s)}$$

- Ex: ΔBT at 3.8 microns for SEVIRI simulated observations

6UT



15UT



- Max ΔBT : 15K at 3.8, 0.05 at 8.7 and 0.02K at 11 and 12 microns
- BUT increase the calculation time by 40%

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Perspectives for faster satellite radiance assimilation

- Crucial in the futur with new instruments:
  - IASI-NG : more channels
  - IRS/MTG: more measurements

- New techniques are already developed
  - Reconstructed spectra based on principal component
  - PC-RTTOV (Marco Matricardi)
  - Ex: 165 IASI channels vs 20 PCs: 25% reduction in the overall cost of assimilation with marginal improvement

  - Optimal sampling of the absorption coefficients
  - OSS model (Moncet et al., 2003)
  - In theory this method is better to handle scattering than current fast RTM.

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Conclusion

- RTTOV and CRTM fast RTM have proven their efficiency to assimilate radiances in clear-sky (IR) and all-sky (MW)
- They have already implemented new capabilities (IR cloud scattering, NLTE, solar contribution, lambertian surface, aerosol, VIS/NIR simulations)
- Perspectives:
  - Improvement in spectroscopic database that are being continuously updated:
    - Water vapor continuum (CAVIAR)
    - CLBL NOAA project
  - Improvement in cloud optical properties modelization
  - Improvement in IR cloud overlap
  - SO_2 as active gas
  - Validation of new version for clear and cloudy-sky
  - In the future, even if computers will be faster, we will have to make models faster as well.

Thank you for your attention