Status of research on the assimilation of cloud affected infrared radiances at EC

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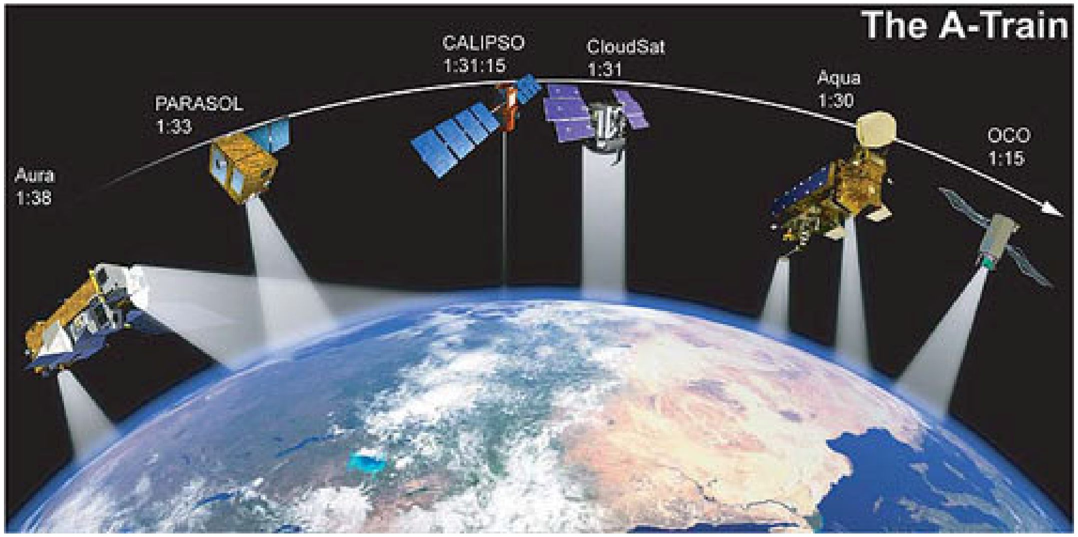
Friday, 7 December, 2007

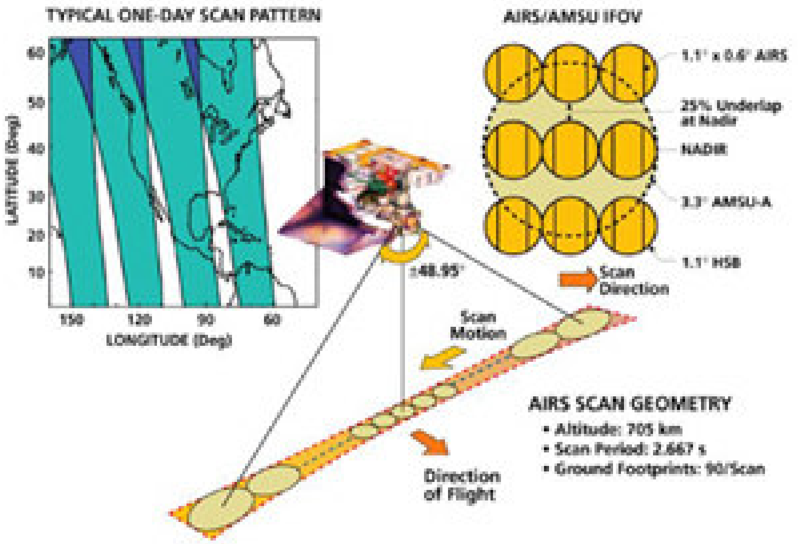
CSA ASC

Environment Canada Environnement Canada

Canada

AIRS instrument overview





- High spectral resolution infrared vertical sounder (2378 channels between 15.5 µm and 3.6µm) onboard AQUA : Provides information on temperature, humidity, ozone, etc…
- 281 channels received at CMC
- FOV 13.5 km at nadir, swath 1650 km
- One of 9 received, effective resolution 40 km

Outline

- Notions of infrared radiative transfer in the clear and cloudy case
- The future operational system for the assimilation of clear AIRS channels
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- Detailed presentation of our approach
- Theoretical 1D-var study
- 3D-var studies
- Conclusion, perspectives

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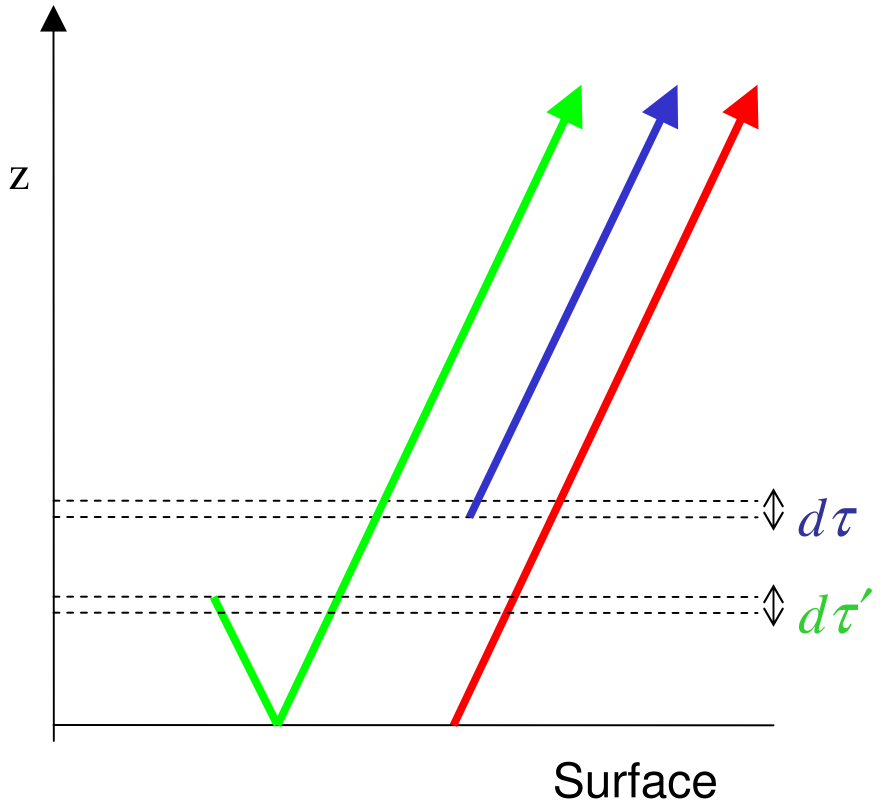
Clear sky radiative transfer (1)

(equations valid for scattering free atmosphere and local thermodynamical equilibrium)



$$I_{clear}(\nu) = \varepsilon_s \tau_s B(\nu, T_s)$$

$$+ \int_{\tau_s}^{1.0} B[\nu, T(\tau)]\, d\tau$$

$$+ (1 - \varepsilon_s)\tau_s \int_{\tau_s}^{1.0} B[\nu, T(\tau')]\, d\tau'$$

$B(\nu, T)$ Planck function

τ transmission function between TOA and current level

τ‘ transmission function between surface and current level

Clear sky radiative transfer (2)

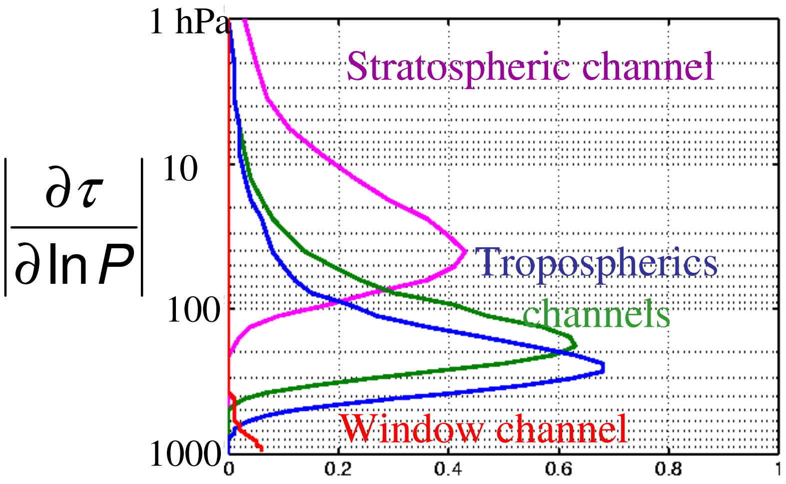
$$\int_{\tau_s}^{1.0} B[\nu, T(\tau)]d\tau = \int_{\ln P_s}^{-\infty} \underbrace{B[\nu, T(\ln P)]} \underbrace{\left(\frac{\partial \tau(\nu)}{\partial \ln P}\right)} d\ln P$$

weighting function

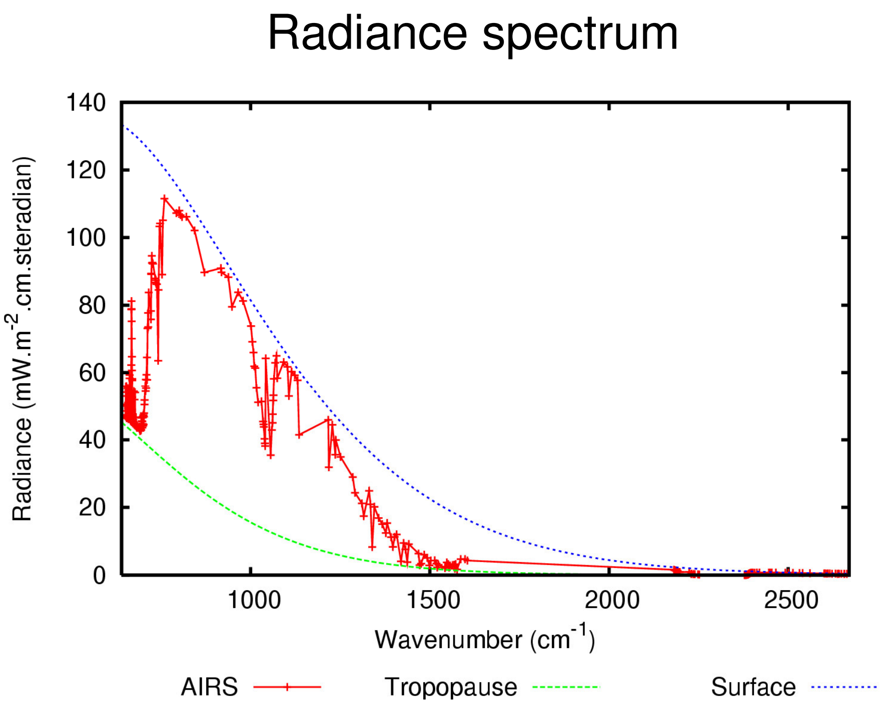
Temperature

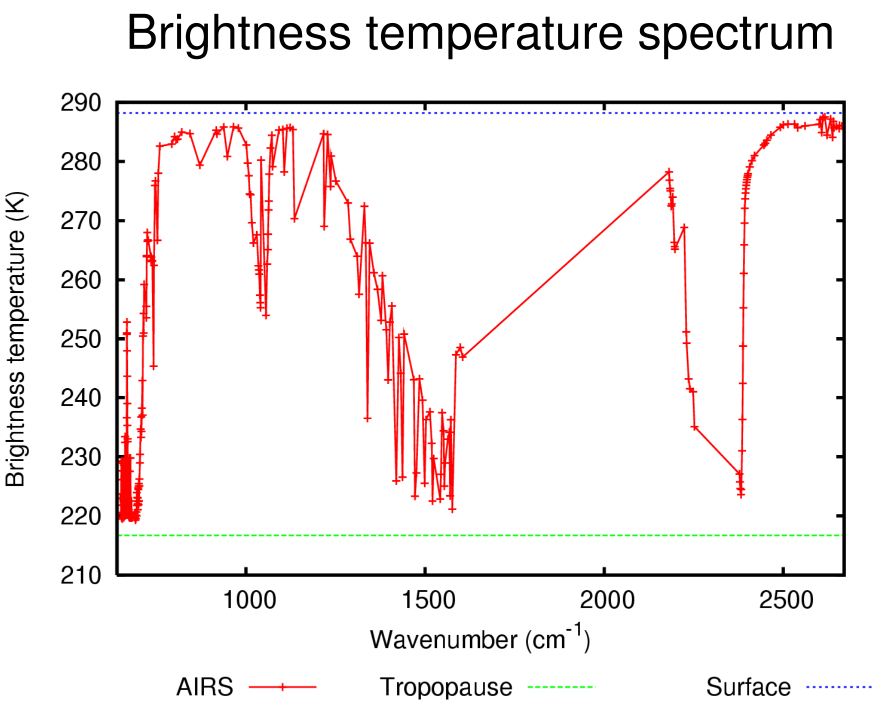
Atmospheric composition

Weighting functions of 4 AIRS channels

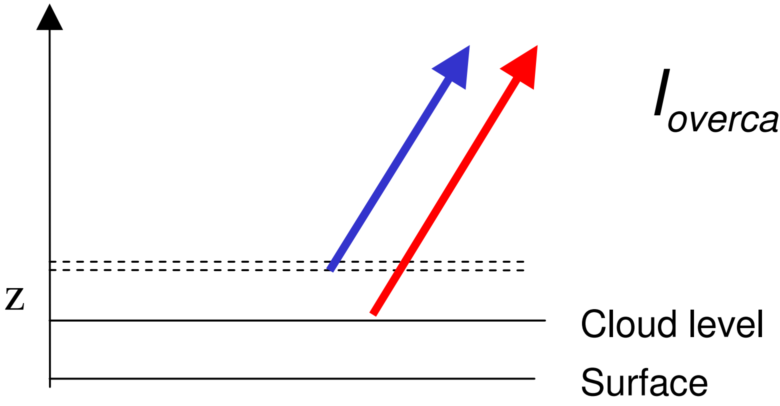


Clear sky radiative transfer (3)



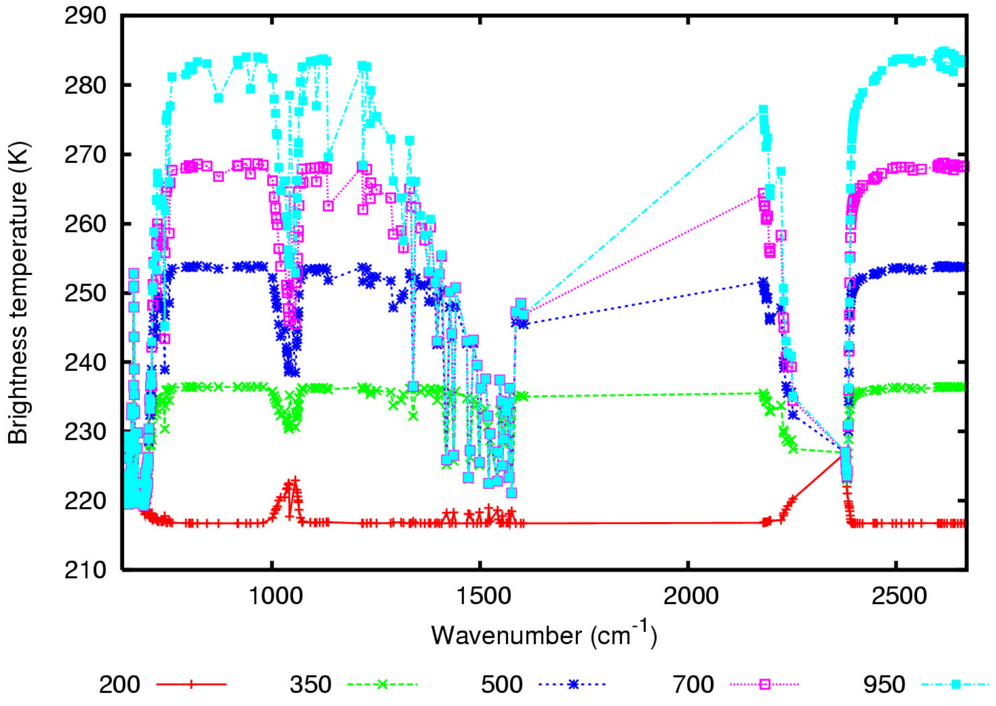


Cloudy radiative transfer : overcast black cloud



$$I_{overcast}(\nu, P_c) = \tau_c B(\nu, T_c) + \int_{\tau_c}^{1.0} B[\nu, T(\tau)]\, d\tau$$

Simulated spectra for different cloud top pressures P_c:



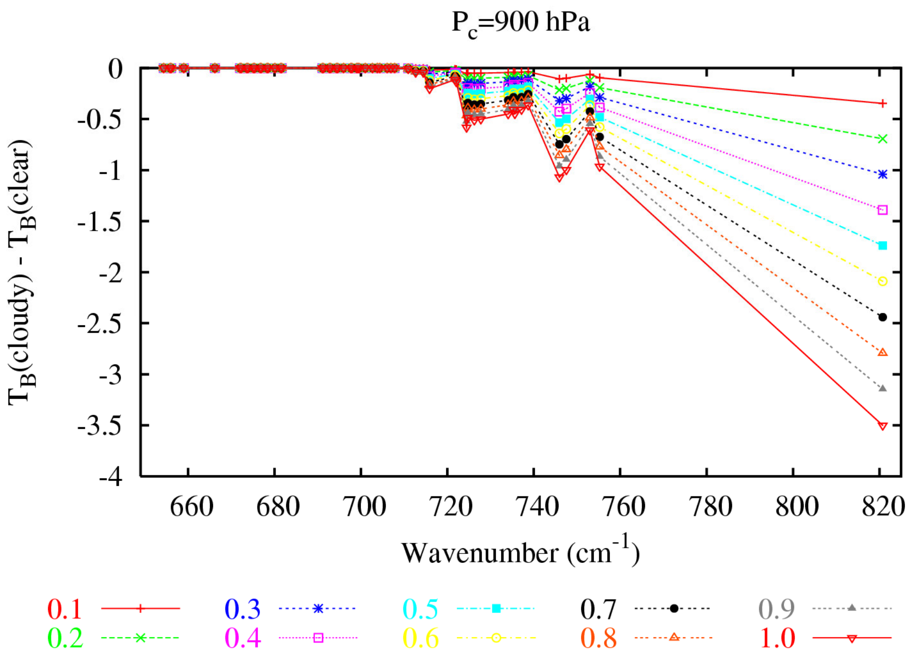
Cloudy radiative transfer : grey cloud

$$I_{grey}(\nu) = N\varepsilon(\nu) I_{overcast}(\nu, P_c) + \left(1 - N\varepsilon(\nu)\right) I_{clear}(\nu)$$

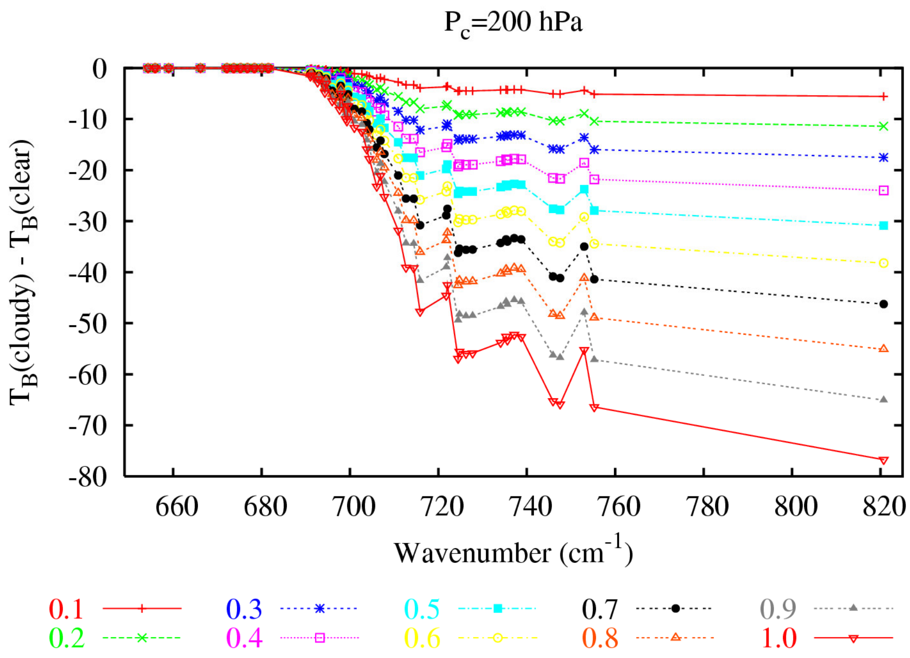
N : geometrical cloud fraction : i.e. fraction of the satellite field of view covered by clouds
ε(ν): cloud spectral emissivity different of 1.0 if semi-transparent cloud
Nε(ν): cloud effective emissivity

Simulated spectra for different cloud top pressures and cloud effective emissivity

Low cloud case



High cloud case



Cloudy radiative transfer : sophisticated cloud radiative modeling

e.g. use of RTTOVCLOUD

Necessary inputs :

- Cloud fraction profile
- Cloud liquid (or ice) water content profiles
- Hydrometeor size (and shape for ice) distributions

And even more sophisticated:

- 3D cloud field
- Monte-Carlo
- Etc…

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AIRS QUALITY CONTROL (QC)

1. Gross check: BT > 150 K, BT < 350 K
2. NESDIS noise flag = 0 (OK). Recently found important: local info.
3. Cloudy or clear ? Based on window channel+ trial T profile

   * Garand-Nadon 1998 algorithm

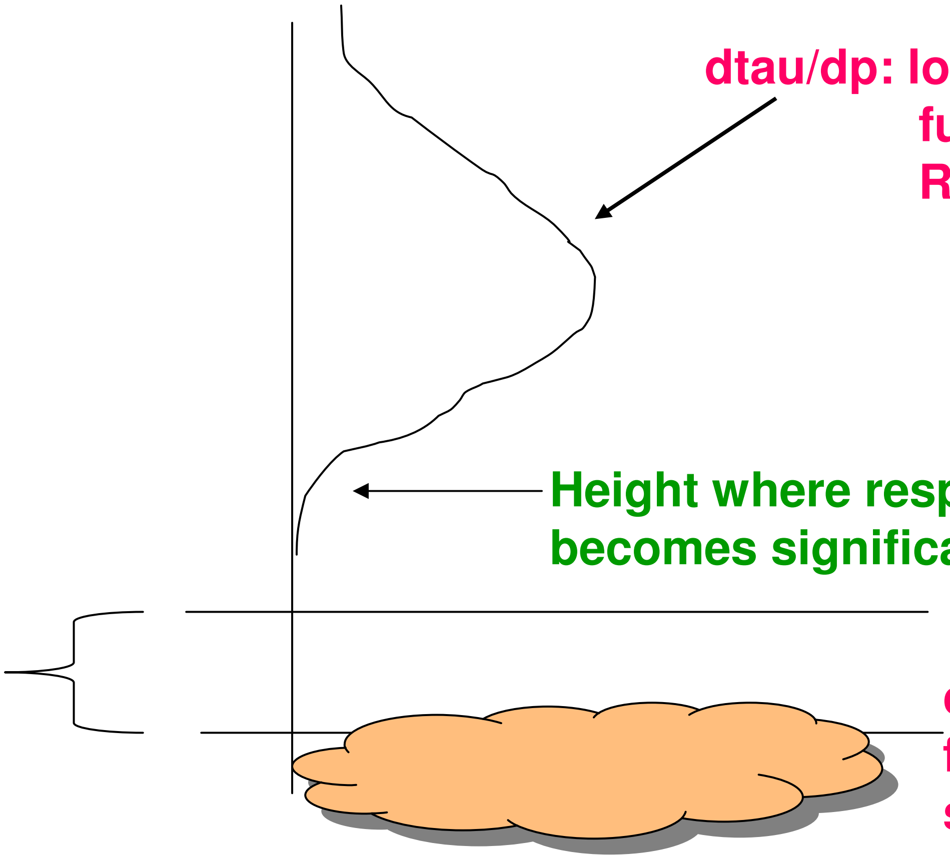
   * NESDIS daytime cloud fraction > 5% = cloudy

   * Invert RTE for TS using BT(window) assuming trial T,q profile perfect

   - if |TS(window) – TS(guess)| > 2K(ocean) or 4K(not ocean), cloudy
4. If cloudy, is the radiance cloud-affected? Answer from CO_2 slicing of cloud height estimate + local response function: cloud must be below level where response function (dtau/dp) becomes significant + security margin of at least 50 hPa

Is the radiance clear?

- CO_2 slicing: 12 estimates of cloud height from as many channels coupled with a reference profile peaking near the surface. Mean of valid estimates used.
- Security margin is max (50 hPa, std among valid estimates)



dtau/dp: local response function from RTTOV output

Height where response becomes significant

security margin

cloud height from CO_2 slicing

CO_2 slicing

For the pair: Reference and k channels (12.2 to 14.4 µm)
Reference channel peaks low (sensitive to all clouds). Other channels peak at various heights. From $I_o = I_{clr}(1-N\varepsilon) + N\varepsilon\, I_{cld}$

$$(I_{clr}-I_o)_k \,/\, (I_{clr} - I_o)_{ref}$$

$$- [N\varepsilon(I_{clr}-I_p)]_k \,/\, [N\varepsilon(I_{clr} - I_p)]_{ref} = F(p)$$

$N\varepsilon$ cancels, assuming same emissivity in k and ref channels.
F(p) minimum defines top pressure cp.
Effective cloud fraction then obtained from either channel:

$$N\varepsilon = (I_{clr} - I_o) \,/\, (I_{clr} - I_{cp})$$

If no well defined minimum: cp based on window channel BT matched with guess T profile. $N\varepsilon$ is then unity.

⇨ Method allows to obtain equivalent cloud fraction from single FOV

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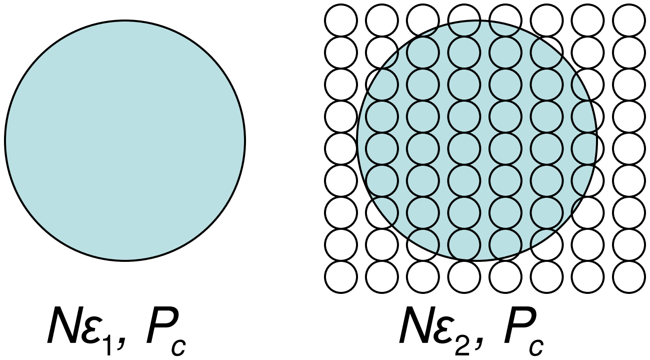
Various approaches for cloudy radiances assimilation: The conservative approach

- 2 main options :
  - Assimilate only “clear” fields of view: used operationally at UK Met and Meteo France
  - Assimilate only “clear channels” i.e. channels not affected by clouds (channels whose weighting function peak above the cloud in a cloudy FOV): used at ECMWF and here at CMC for the AIRS radiances.

Various approaches for cloudy radiances assimilation: Use of cloud cleared radiances (1)

- Cloud cleared radiances: radiances corrected to remove the effect of clouds
- Example: the N* method (Smith, 1968)

Consider 2 adjacent FOVs:



$$N^* = \frac{(N\varepsilon)_1}{(N\varepsilon)_2} = \frac{I_{obs1} - I_{clear}}{I_{obs2} - I_{clear}}$$

$$I_{clear} = \frac{N^* I_{obs2} - I_{obs1}}{N^* - 1}$$

Spectral variation of N* is neglected

Estimation of N*:

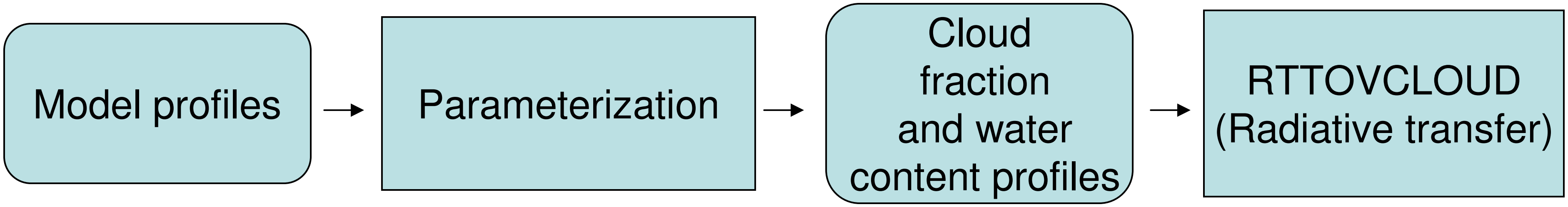
- use of spatially and temporally co-located sub-pixel observations (like MODIS or AVHRR)
- use of a window channel (easy to calculate I_{clear} with T_s only)
- use of microwave data to estimate the clear infrared radiance
- etc…

Various approaches for cloudy radiances assimilation: Use of cloud cleared radiances (2)

- Potential problems with cloud cleared radiances:
  - Cloud cleared radiances are not “true” observations
  - Homogeneity of error statistics ?
  - Loss of data due to transmission and processing delay
- But:
  - Cloud cleared radiances seem to be used with success for retrieval of T, H_2O and O_3 profiles
  - Their use in an assimilation system is under study at ECMWF (?)

Various approaches for cloudy radiances assimilation: Full blown cloudy radiance assimilation

- Include a sophisticated, realistic cloud modeling in the observation operator and perform the assimilation
- Problem: high non linearity of the observation operator


Model profiles → Parameterization → Cloud fraction and water content profiles → RTTOVCLOUD (Radiative transfer)

Approach tried by Chevallier et al. 2001 (ECMWF) and Dahoui (2006) in his PhD thesis

Proposed approach

Use of a simplified cloud radiative modeling using effective parameters: like cloud top pressure and effective emissivity.
Approach under study here and at other centers:
-Météo-France (N. Fourrié)
-UK Metoffice (E. G. Pavelin)
-ECMWF (T. Auligné) ??

- Semi-transparent mono-layered cloud with effective emissivity $N\varepsilon(\nu)$:

$$I_{cld}(\nu) = N\varepsilon(\nu) I_{overcast}(\nu, P_c) + (1 - N\varepsilon(\nu)) I_{clear}(\nu)$$

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Cloud emissivity model (1)

$$N\varepsilon(\nu) = 1 - \exp\left[-k_{cld}(\nu)\delta\ \right]$$

δ: effective cloud depth
k_{cld} cloud effective optic properties accounting approximately for scattering following Chou et al. 1999 :

$$k_{cld}(\nu) = k_{ext}(\nu)\left[\left(1 - \omega(\nu)\right) + b(\nu)\omega(\nu)\right]$$

With ω the single scattering albedo, k_{ext} the extinction coefficient and b the backscattered fraction :

$$b = \frac{1}{2}\int_0^1 d\mu \int_{-1}^0 \overline{P}(\mu,\mu')d\mu'.$$

Cloud emissivity model (2)

- Liquid cloud optical properties from Lindner and Li (2000) parameterization as a function of the effective radius r_e.
- Ice cloud optical properties from Baran et al. (2004, 2002 and 2005 private communication) for hexagonal column ice crystals as a function of the effective diameter D_e.

Optical properties are combined given the liquid fraction f_w from Rockel et al. (1991)

$$f_w = \begin{cases} 0.0059 + 0.9941 \exp\left[-0.003102 (T_c - 273.16)^2\right] \ ; & T_c < 273.16 \\ 1.0 \ ; \quad T_c > 273.16 & \end{cases}$$

$$k_{ext} = f_w k_{ext}^w + (1 - f_w) k_{ext}^i \qquad \omega = \frac{f_w k_{ext}^w \omega^w + (1 - f_w) k_{ext}^i \omega^i}{f_w k_{ext}^w + (1 - f_w) k_{ext}^i}$$

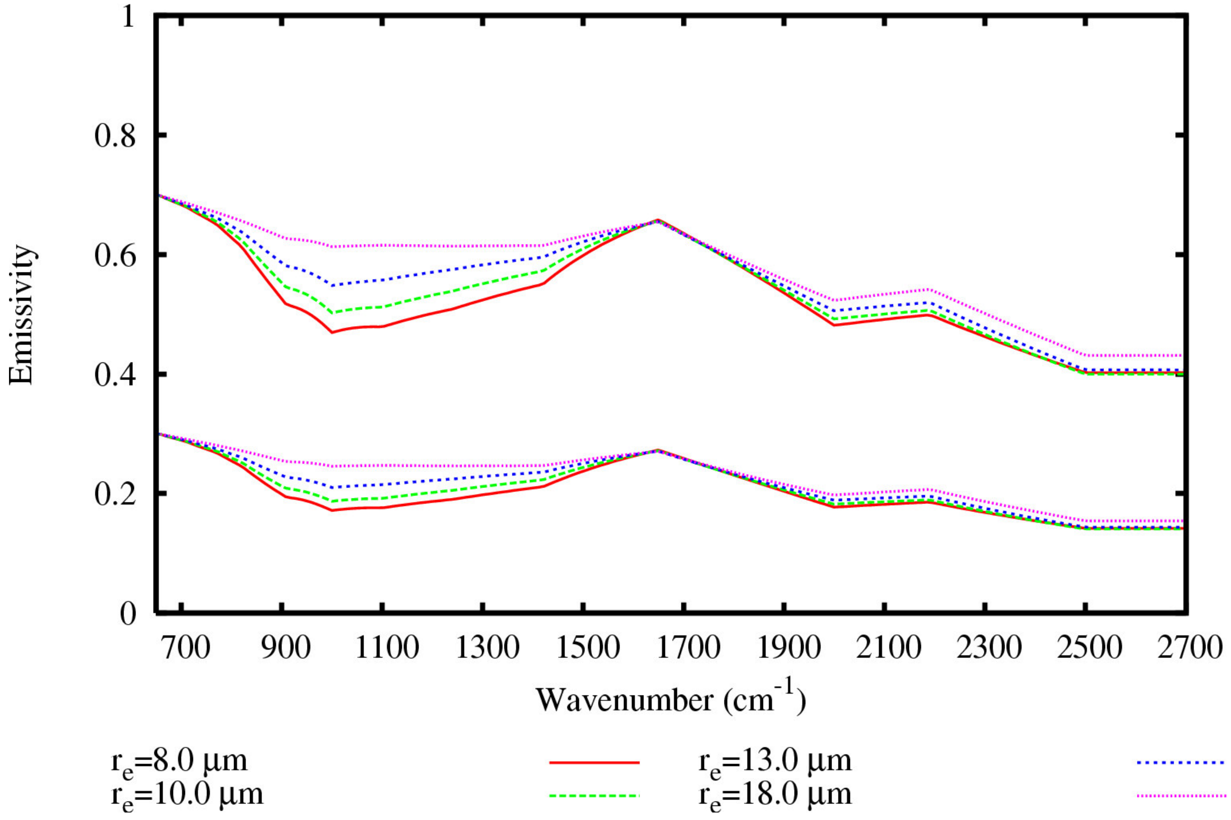
$$b = F(g) \approx \frac{1 - g}{2} \quad \text{with} \quad g = \frac{f_w k_{ext}^w \omega^w g^w + (1 - f_w) k_{ext}^i \omega^i g^i}{f_w k_{ext}^w \omega^w + (1 - f_w) k_{ext}^i \omega^i}$$

Cloud emissivity model (3)

- To summarize a full cloud radiance spectrum can be simulated using only 4 parameters :
  - The cloud top pressure **P_c** (gives also the cloud temperature T_c)
  - The effective cloud depth δ
  - The cloud effective radius **r_e** (liquid phase)
  - The cloud effective diameter **D_e** (ice phase)

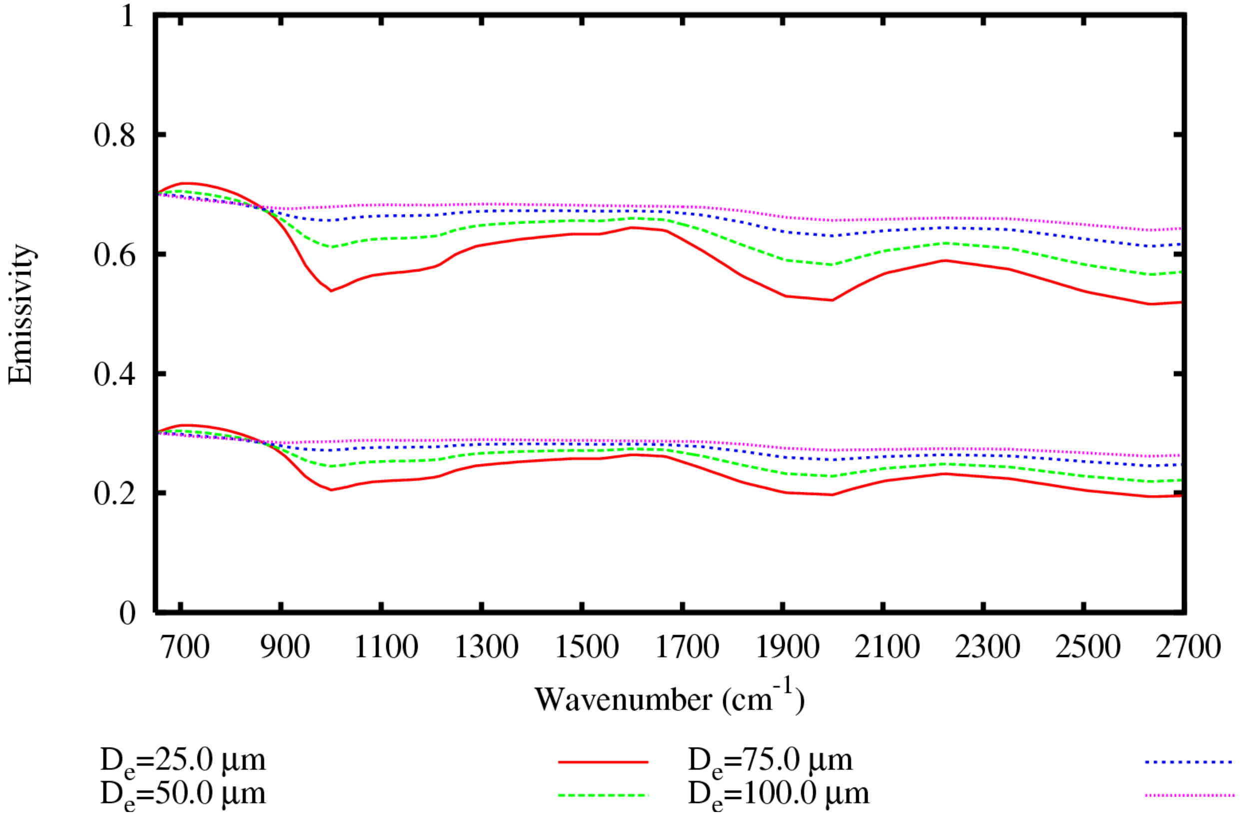
Examples of cloud emissivity spectra (1)

Liquid Water cloud: 15 μm emissivity set to 0.7 or 0.3



Examples of cloud emissivity spectra (2)

Ice Water cloud: 15 µm emissivity set to 0.7 or 0.3



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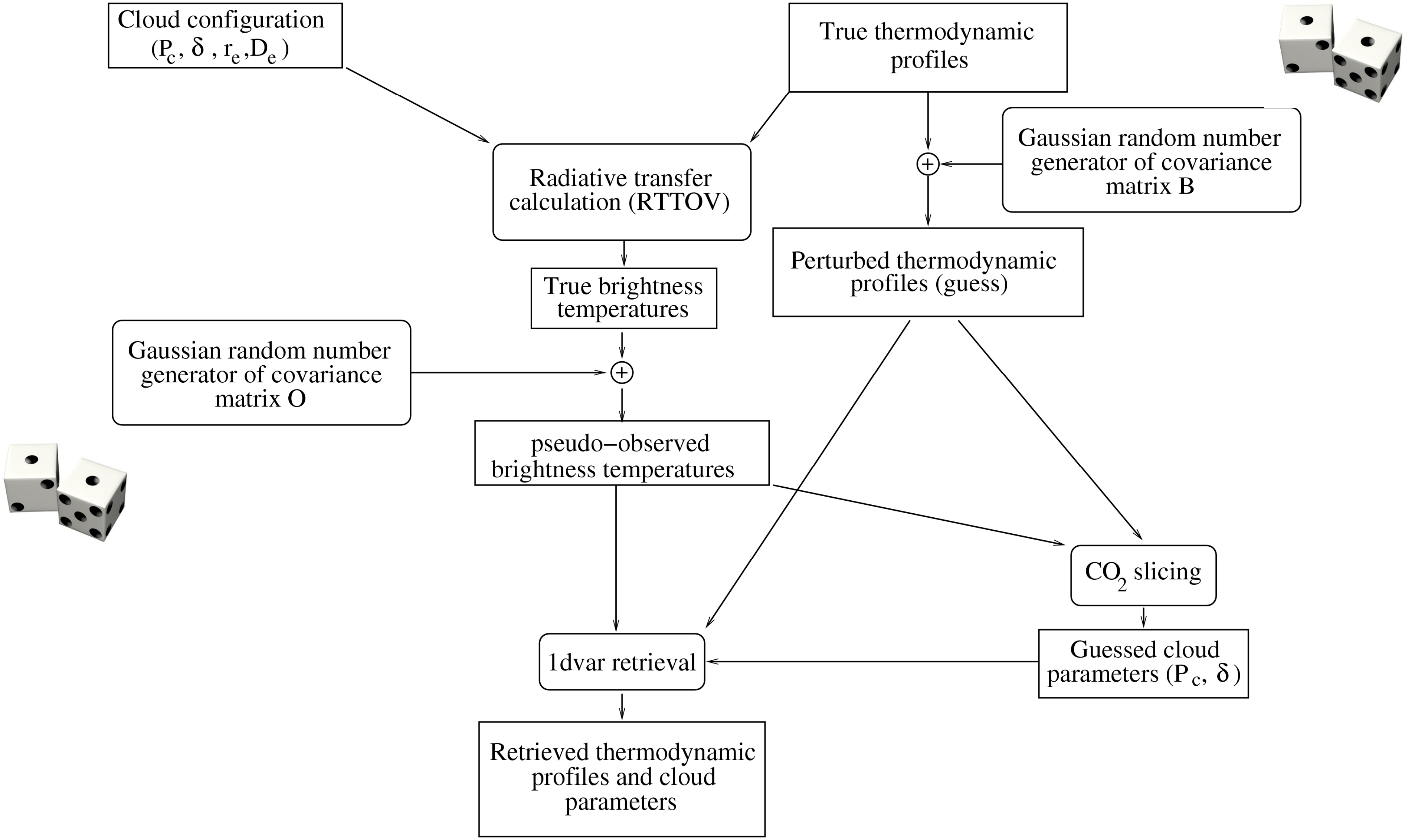
Principle of the Monte-Carlo experiments (1)



Cloud configuration (P_c, δ, r_e, D_e)

True thermodynamic profiles

Gaussian random number generator of covariance matrix B

Radiative transfer calculation (RTTOV)

Perturbed thermodynamic profiles (guess)

True brightness temperatures

Gaussian random number generator of covariance matrix O

pseudo–observed brightness temperatures

CO$_2$ slicing

1dvar retrieval

Guessed cloud parameters (P_c, δ)

Retrieved thermodynamic profiles and cloud parameters

Principle of the Monte-Carlo experiments (2)

$\mathbf{x}$: vector of temperature and humidity profiles, surface pressure, skin surface temperature
$\mathbf{z}$: cloud parameters vector
$\mathbf{y}$: vector of brightness temperatures

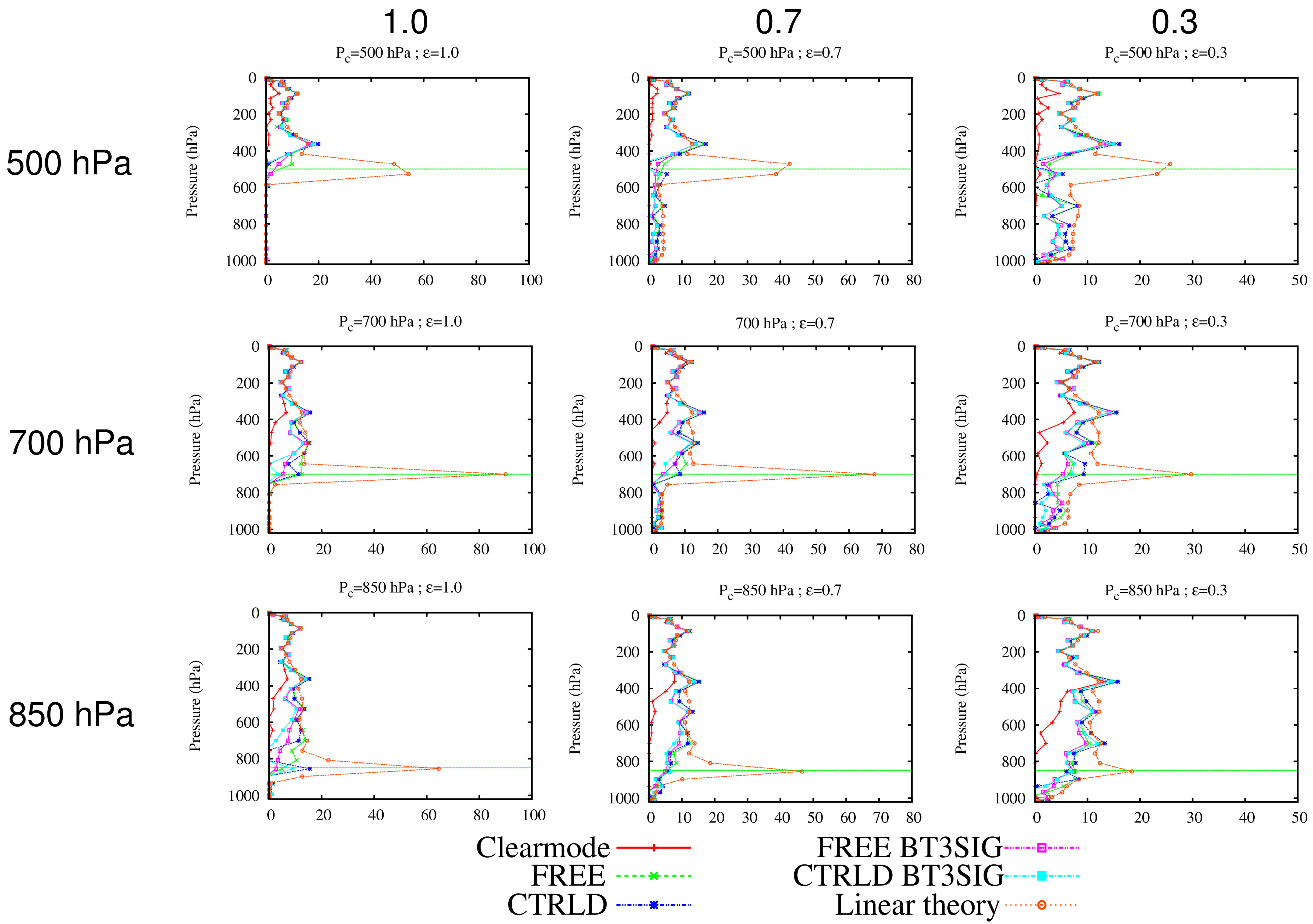
$$\tilde{\mathbf{x}} = (\mathbf{x}, \mathbf{z})$$

$$J_c(\tilde{\mathbf{x}}) = \left\{ \underbrace{(\mathbf{x}-\mathbf{x_b})^t \mathbf{B}^{-1} (\mathbf{x}-\mathbf{x_b})}_{\text{Background term}} + \underbrace{(\mathbf{z}-\mathbf{z_b})^t \mathbf{C}^{-1} (\mathbf{z}-\mathbf{z_b})}_{\text{Cloudy background term}} + \underbrace{(\mathbf{H}_c(\tilde{\mathbf{x}})-\mathbf{y})^t \mathbf{O}^{-1} (\mathbf{H}_c(\tilde{\mathbf{x}})-\mathbf{y})}_{\text{Observation term with cloud}} \right\}$$

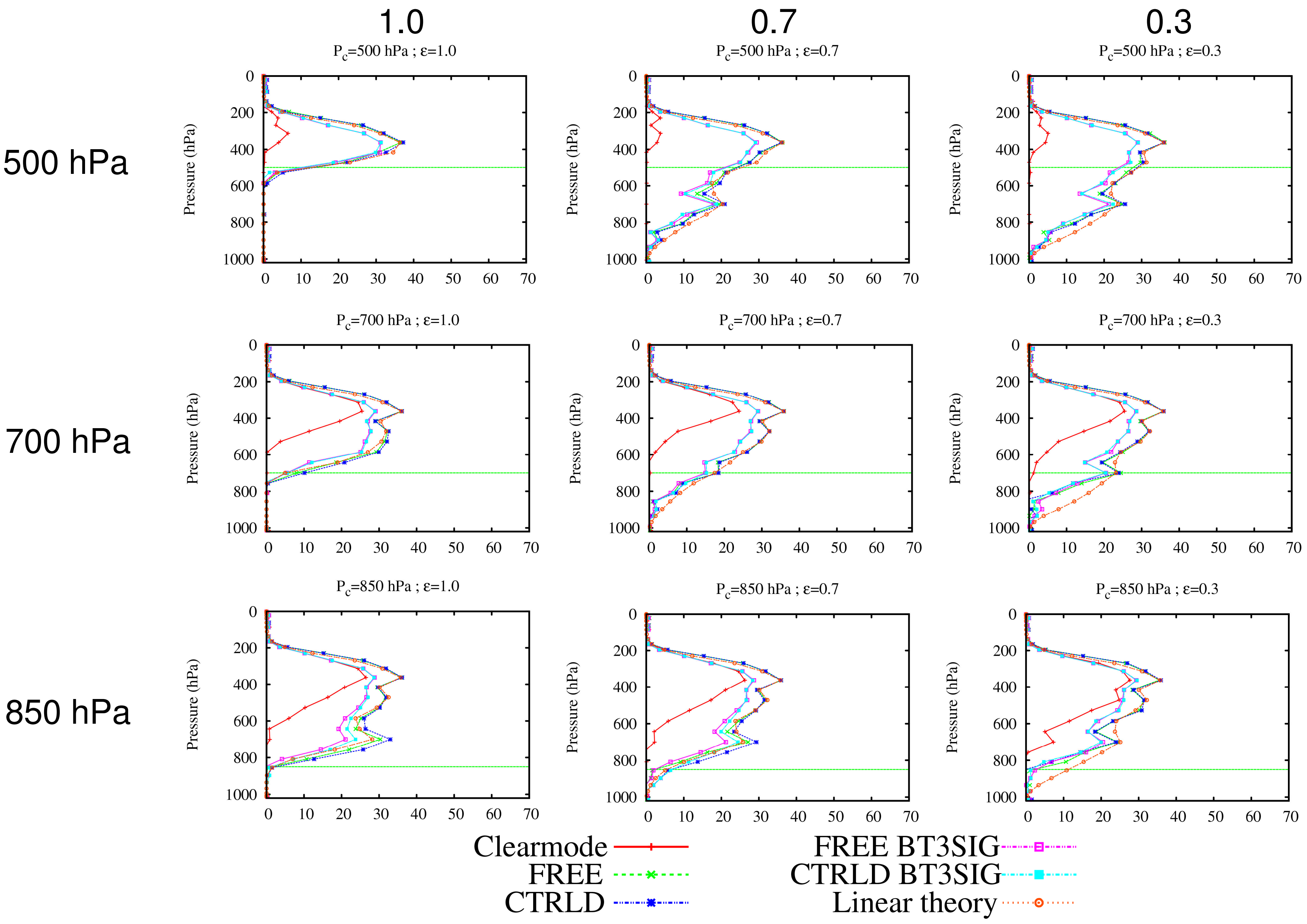
$\mathbf{x_a}$ obtained by minimization of the 1Dvar cost function with cloud J_c

- Statistics calculated for 1000 realizations for each cloud configuration :
  - Bias: $\mathbf{b} = \langle \mathbf{x}_t - \mathbf{x}_a \rangle$
  - Analyzed covariance: $\mathbf{A}_{ij} = \langle (\mathbf{x_{ti}} - \mathbf{x_{ai}} - \mathbf{b_i})(\mathbf{x_{tj}} - \mathbf{x_{aj}} - \mathbf{b_j}) \rangle$
  - Variance reduction: $\mathbf{V_r} = diag(\mathbf{I} - \mathbf{AB}^{-1})$
  - Degrees of freedom for signal: $DFS = Trace(\mathbf{I} - \mathbf{AB}^{-1})$

Variance Reduction for temperature profiles



Variance reduction for water vapor profiles



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Proposed 3D/4Dvar assimilation

Addition to the state vector **x** of a *local* estimate of the 4 cloud parameters at each AIRS observation location

$$\mathbf{x} \rightarrow \tilde{\mathbf{x}} = (\mathbf{x}, \mathbf{z})$$

x: model fields
z : local cloud effective parameter vector

$\mathrm{Dim}(\mathbf{x}) \sim 10^6\text{-}10^7$
$\mathrm{Dim}(\mathbf{z}) = 4N_{obs} \sim 10^4$

$$J_c(\tilde{\mathbf{x}}) = \left\{ \underbrace{(\mathbf{x}-\mathbf{x_b})^t \mathbf{B}^{-1} (\mathbf{x}-\mathbf{x_b})}_{\text{Background term}} + \underbrace{(\mathbf{z}-\mathbf{z_b})^t \mathbf{C}^{-1} (\mathbf{z}-\mathbf{z_b})}_{\text{Cloudy background term}} + \underbrace{(\mathbf{H}_c(\tilde{\mathbf{x}})-\mathbf{y})^t \mathbf{O}^{-1} (\mathbf{H}_c(\tilde{\mathbf{x}})-\mathbf{y})}_{\text{Observation term with cloud}} \right\}$$

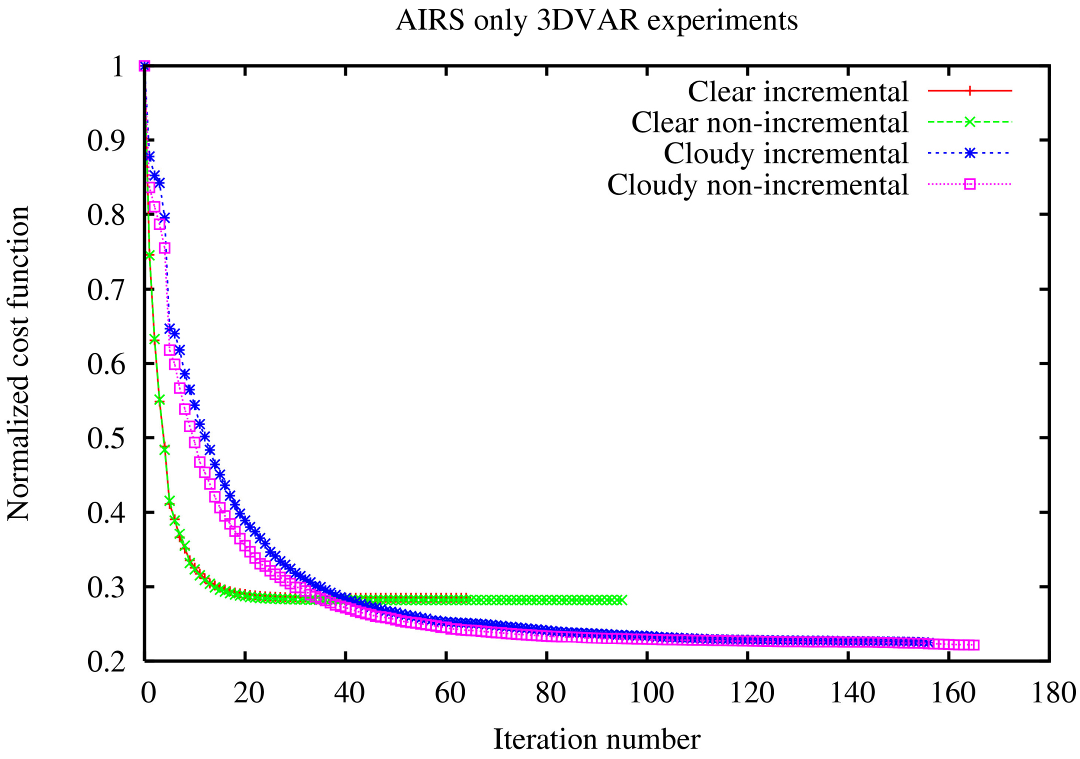
z_b : cloud background state from CO_2 slicing and climatology

H_c cloudy observation operator combining RTTOV 8.7 and the cloud emissivity model

Thank to the help of Jacques Hallé our cloudy radiance assimilation was incorporated in a modified version of the assimilation code version 10.0.2

3D/4Dvar assimilation : first results (1)

Successful minimization of the cost function. Number of iterations in the cloudy case might be reduced by a better preconditioning.



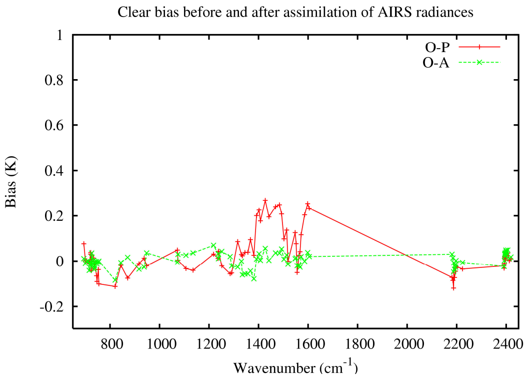
3D/4Dvar assimilation : first results (2)

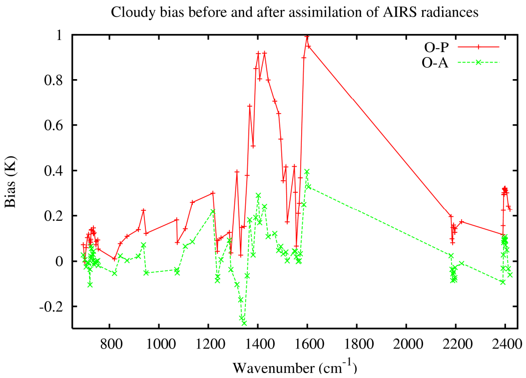
CLEAR

CLOUDY

Larger bias for the cloudy analysis

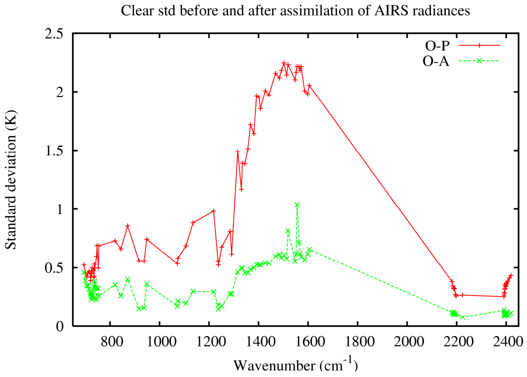
BIAS

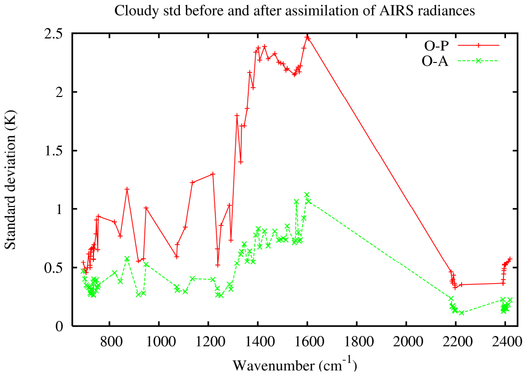




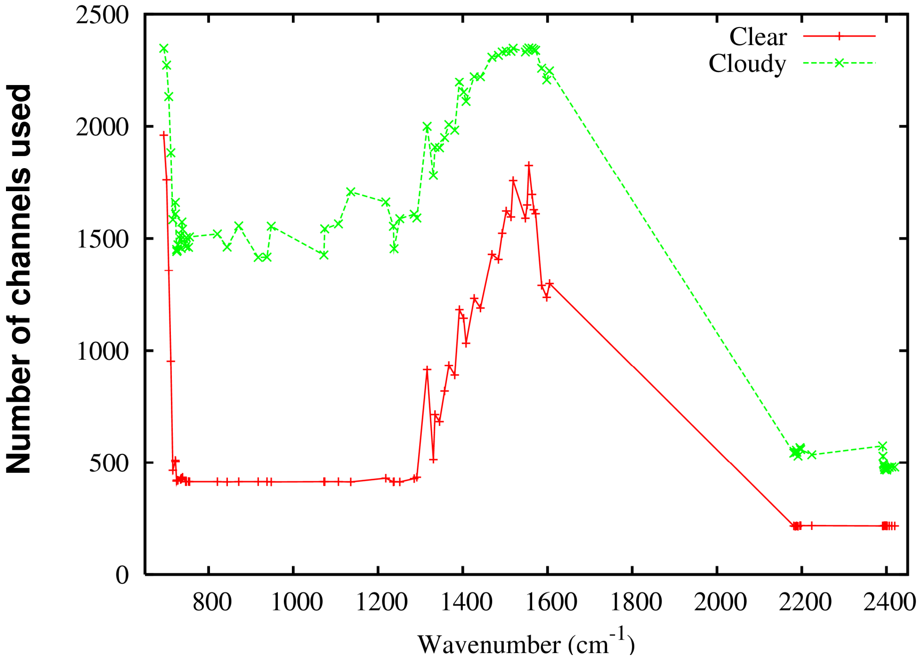
Similar standard deviations

STD





3D/4Dvar assimilation : first results (3)



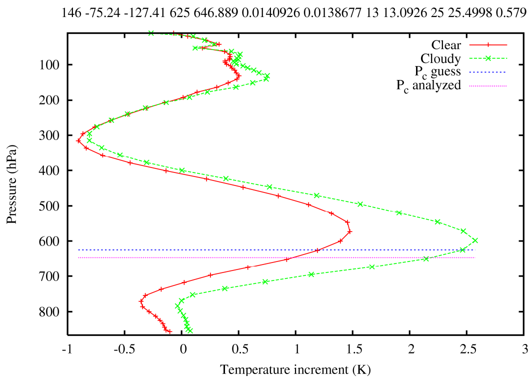
Significant increase in the number of AIRS radiances assimilated

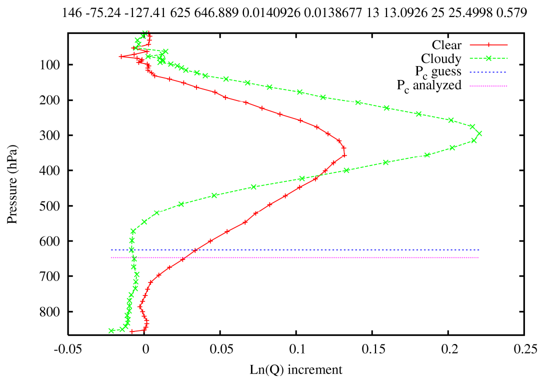
3D/4Dvar assimilation : first results (4)

Sample increment
profiles located at the
AIRS FOV

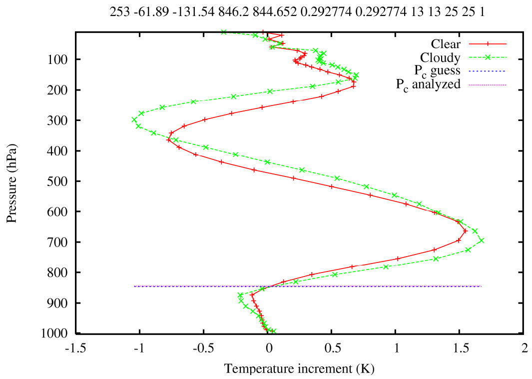
T

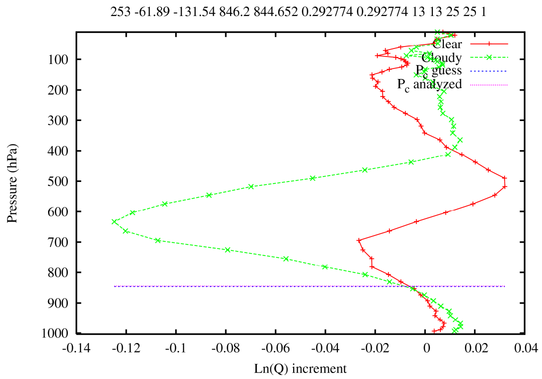
Ln(Q)


146 -75.24 -127.41 625 646.889 0.0140926 0.0138677 13 13.0926 25 25.4998 0.579


146 -75.24 -127.41 625 646.889 0.0140926 0.0138677 13 13.0926 25 25.4998 0.579

Overcast
cloud


253 -61.89 -131.54 846.2 844.652 0.292774 0.292774 13 13 25 25 1

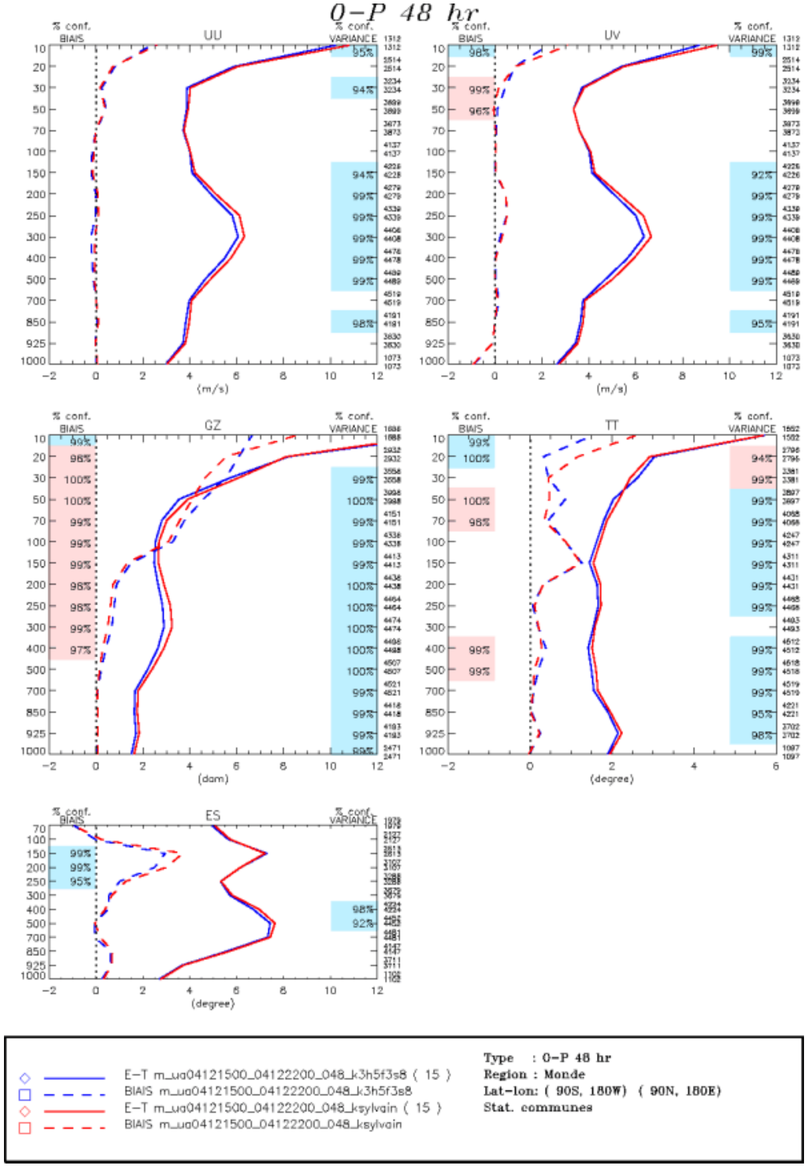

253 -61.89 -131.54 846.2 844.652 0.292774 0.292774 13 13 25 25 1

Semi-transparent
cloud
(Nε=0.579)

3D/4Dvar assimilation : first results (5)

Small assimilation cycle to test our approach.
1 week cycle (with 48 h forecasts)
From 20041215 to 20041222
Blue: reference
Red: cloudy
Flat bias correction
Very preliminary quality control
Overall negative impact but not catastrophic with some (small) good Points

Double the number of AIRS radiances assimilated



Conclusion, perspectives

- A new approach for cloudy infrared assimilation was set up and incorporated in CMC’s 3D/4D variational assimilation code
- Technically, the assimilation “mechanics” work
- For the first time cloud parameters are part of the 3DVAR minimization as opposed to keeping fixed in the minimization 1DVAR estimates
- Work is needed to improve bias correction and quality control
- Use of sub-pixel information (AVHRR for IASI, MODIS for AIRS) may help