Detecting cloud contamination in MTG-IRS observed spectra

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Introduction

- Cloud detection is a fundamental post processing step before assimilating clear-sky radiances since clouds cover more than 70 % of the globe.
- The assimilation of cloudy radiances through their characteristics is likely to have a positive impact in the forecast quality because cloudy areas are meteorologically sensitive.
- Infrared hyper-spectral measurements provide high vertical sensitivity to temperature and humidity but are very sensitive to clouds as well.
- Geostationary observations are well adapted to look at cloud features such as cloud temporal evolution and diurnal cycle.
- MTG-IRS will then be one of the first instrument to provide such capabilities.
- The question is then will we have the capacity to detect and characterize clouds on MTG-IRS ?

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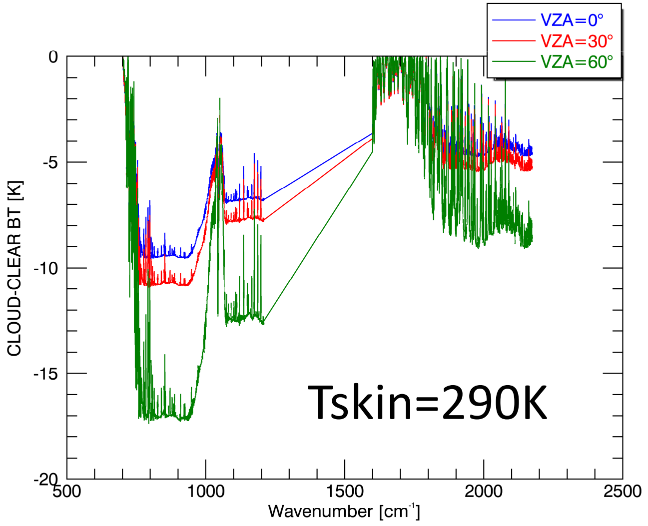
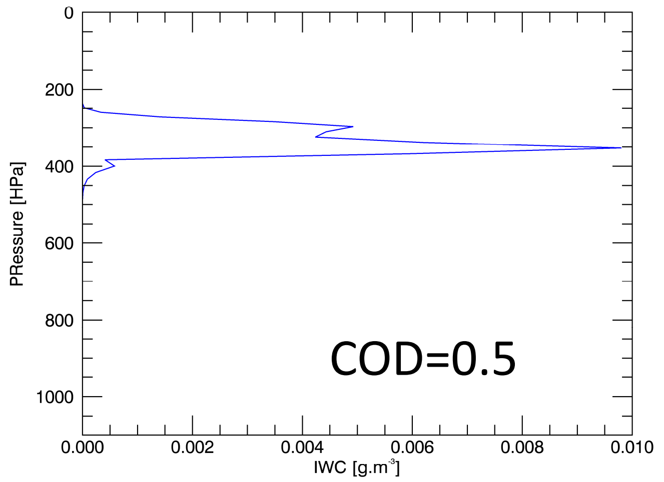
Cloud effect on MTG-IRS simulated spectra

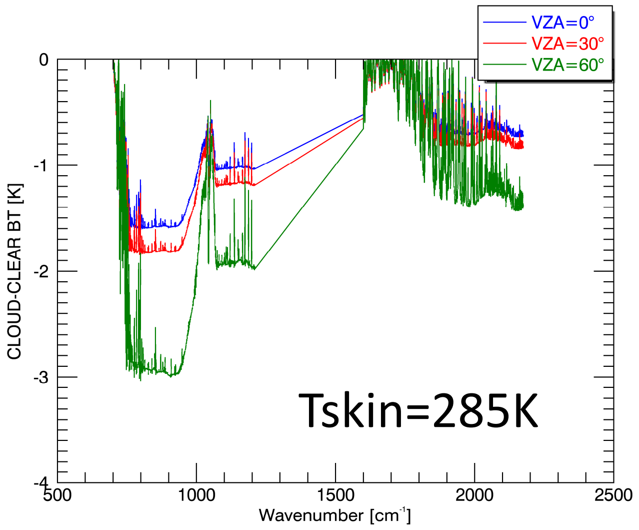
- RTTOV12 Chou scattering model and “light apodization” coefficients
- NWPSAF cloud profile dataset (selected profiles over warm ocean)
- Effect of ice cloud with 3 different viewing zenith angles (VZA)

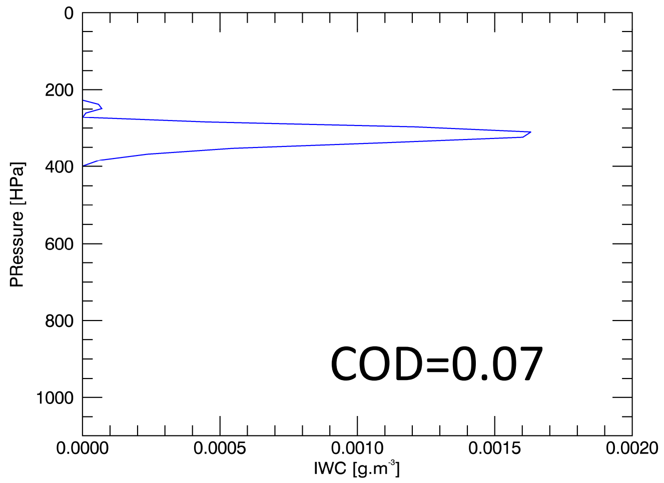




Even for cloud optical depth (COD) of 0.5, the ice cloud signal is strong (10K in window channels)

For larger VZA, the signal is even stronger (limb cooling effect)

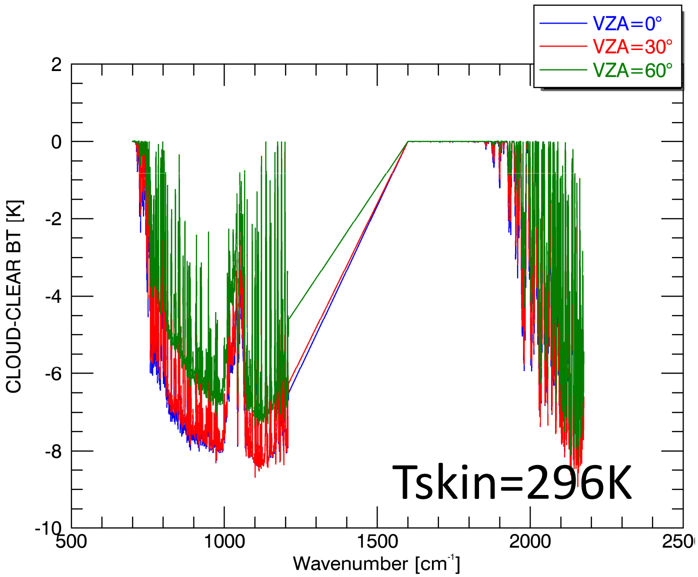


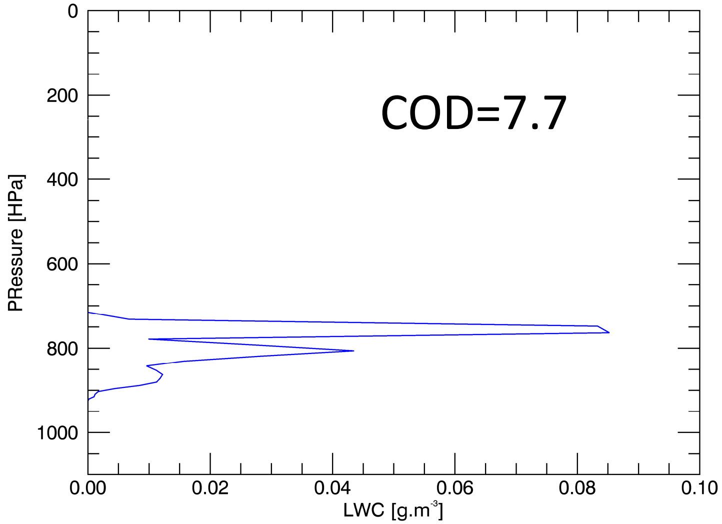


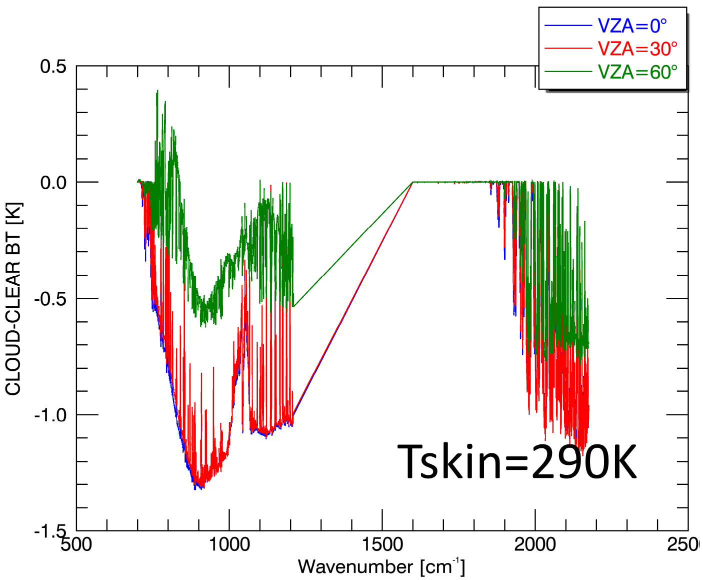
For smaller COD, the signal decreases quickly and reach the level of challenging detection

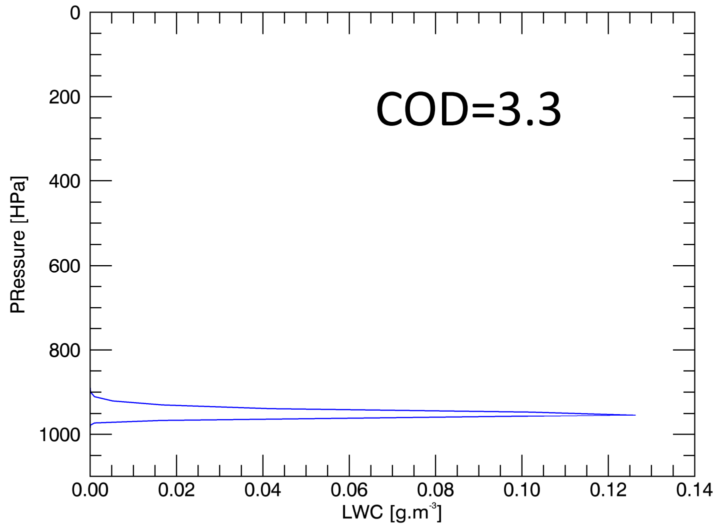
Cloud effect on MTG-IRS simulated spectra

- Effect of liquid cloud









For mid-level cloud, the cloud signal is still strong (~6-8K)

For larger VZA, the limb cooling effect seems to be compensated by the cloud scattering.

For very low-level cloud, the detection starts to be very difficult (<1K)

IR Cloud-detection schemes

- 2 types of scheme:
  - Cloud-detection only
  - Cloud-detection embedded in cloud-characterization schemes

- Detection schemes:
  - Bayesian method
  - Cluster from sub pixels imagers
  - Departure-based
  - Cumulative Discriminant Analysis

- Characterization schemes:
  - Cloud-clearing
  - Radiance ratioing method or CO_2-slicing
  - Minimum residual method
  - 1D-VAR

- NWP centres use both for detection (as post-processing) and for characterization (to constraint RTM with cloud product used as sink variables)

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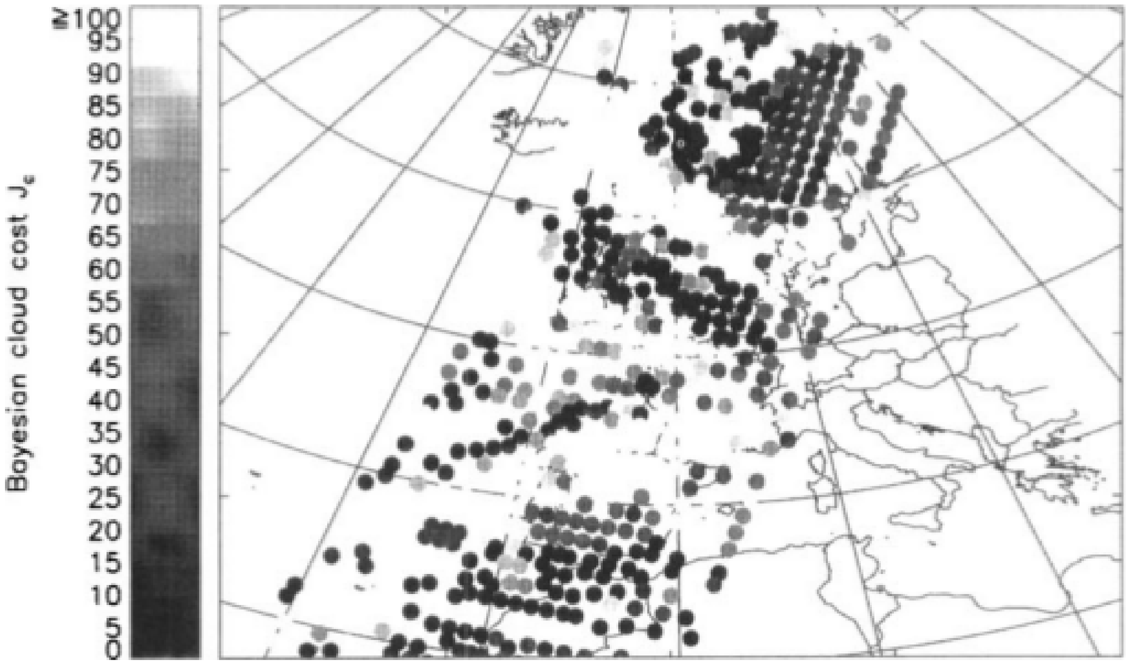
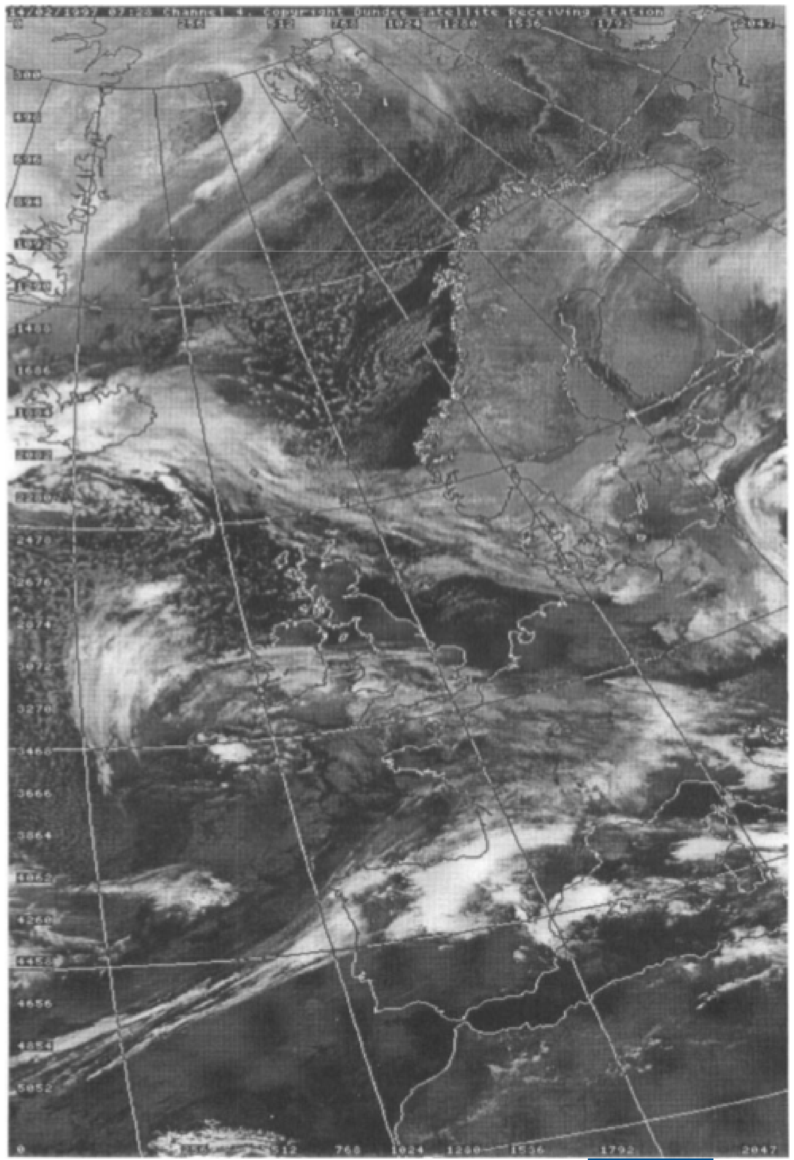
Cloud detection schemes (1/4)

The Bayesian method

- Method based on Bayesian probability theory (English et al.,1999)
- Based on the channel's consistency with the assumption of no cloud (clear-sky RTM)
- Can use infrared and microwave channels
- Based on threshold on cost function





From English et al. (1999)

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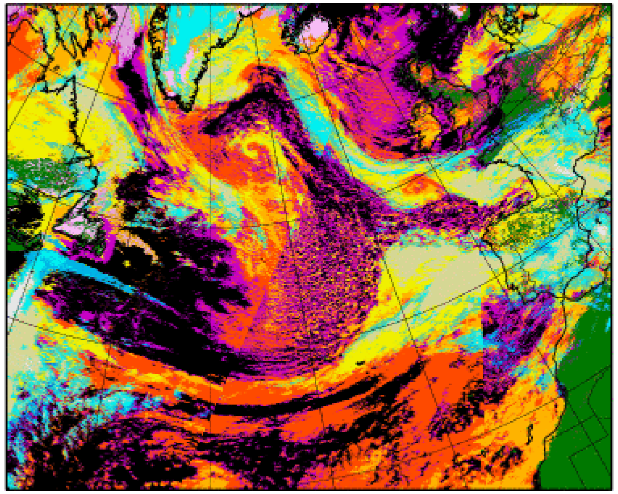
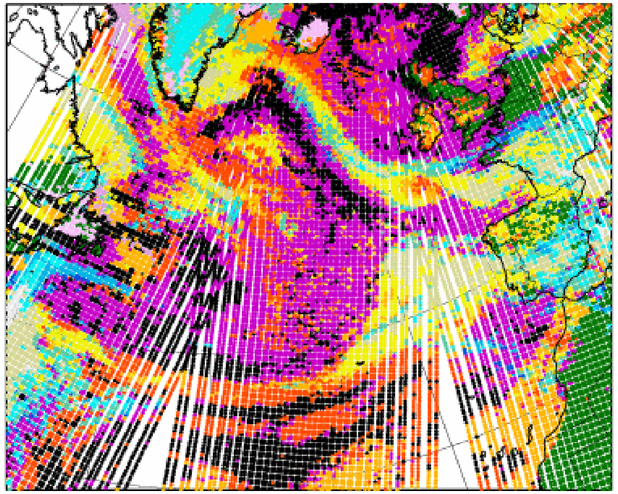
Cloud detection schemes (2/4)

The cluster method

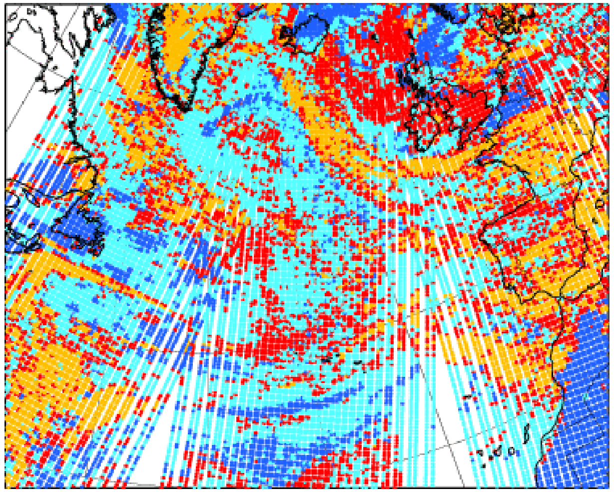
- Cloud detection comes from co-located imagers that use VIS to IR channels at lower spatial resolution.
- AVHRR cluster for IASI (Cayla, 2001; MAIA Lavanant, 2002)



AVHRR cloud type



IASI cluster



IASI coarse classification

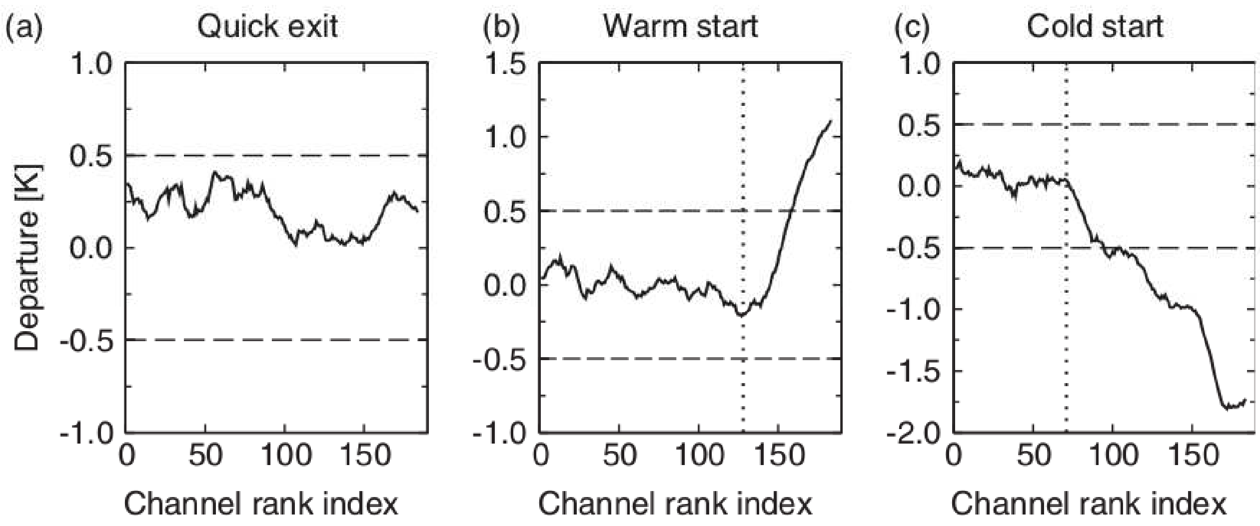
Clear **Opaque**
Semi-transparent **Complex**

- This method can be applied on AIRS with MODIS and on CrIS with VIIRS

Cloud detection schemes (3/4)

The Departure-based method

- Proposed by McNally and Watts (2003)
- Attempts to find clear channels within a potentially cloudy scene rather completely clear scene (channels whose weighting functions are entirely above the cloud top).
- The channels are reordered according to a ranking that reflects their relative sensitivity to the presence of cloud.



From Eresmaa (2014)

IASI 189 CO_2 channels
Threshold on the absolute value of the departure (±0.5K)

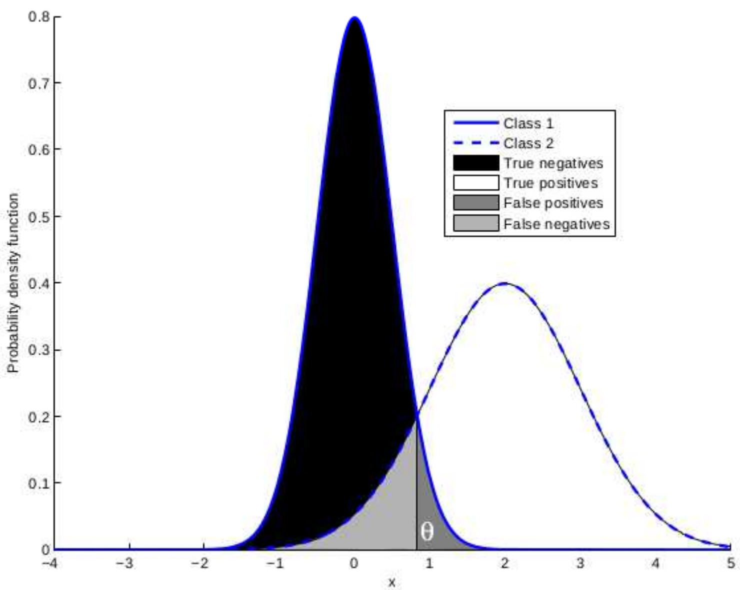
Then identify the rank where the cloud signal is first identifiable and reject all channels above this rank

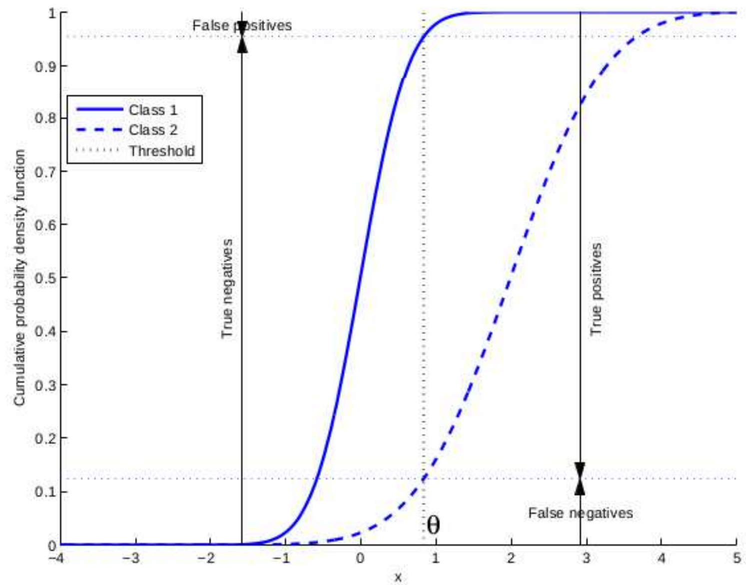
- Method can be improve when using AVHRR cluster (Eresmaa, 2014)

Cloud detection schemes (4/4)

The Cumulative Discriminant Analysis method

- MTG-IRS cloud detection scheme
- Probabilistic approach to the definition and calculation of threshold for cloud-free scenes.
- Need a training dataset to set the threshold.
- The methodology uses principal component decomposition of radiances.
- The methodology provides a quality indicator of the retrieved status of the FOV.
- The CDA has been tested on IASI (Amato et al., 2014) and agreements above 80% are found with AVHRR cluster and SEVIRI (except over polar regions)





General representation of cloud in IR

The single-layer approach

- The cloudy radiance of a single FOV is given by:

$$R_\nu^{cld}(\theta_{sat}) = (1 - N_e)R_\nu^{clr}(\theta_{sat}) + N_e R_\nu^{ovc}(\theta_{sat}, p_{cld})$$

  - Satellite zenith angle θ_{sat}
  - Clear-sky radiance R_ν^{clr}
  - Effective cloud fraction N_e
  - Overcast radiance R_ν^{ovc}
  - Cloud top pressure p_{cld}

- The effective cloud fraction is the product of the cloud fraction and the cloud emissivity

$$N_e = N\epsilon_\nu^{cld}$$

- The grey-cloud approximation corresponds to a constant cloud emissivity
- The overcast condition corresponds to an opaque cloud whose top is at p_{cld}

Cloud characterization schemes (1/4)

The cloud-clearing method

- Firstly proposed by Smith et al. (1967)
- For two adjacent FOVs, the single layer model are:

$$R_\nu^1 = (1 - N_e^1) R_\nu^{clr} + N_e^1 R_\nu^{ovc}$$

$$R_\nu^2 = (1 - N_e^2) R_\nu^{clr} + N_e^2 R_\nu^{ovc}$$

- If Ne*=Ne1/Ne2, then the clear radiance is given by:

$$R_\nu^{clr} = \frac{(R_\nu^1 - N_e^* R_\nu^2)}{(1 - N_e^*)} \qquad N_e^* = \frac{(R_\nu^{clr} - R_\nu^1)}{(R_\nu^{clr} - R_\nu^2)}$$

- Assumptions:
  - The atmospheric profiles and surface characteristics are the same
  - The overcast cloud top pressure and temperature are the same

- The cloud-clearing method can be also applied to 2 co-located instruments such as HIRS/MSU (Eyre and Watts, 1987) or AIRS/MODIS (Li et al., 2005) and is still used by NOAA/NESDIS on IASI/AMSU/MHS (Susskind et al., 2003).

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Cloud characterization schemes (2/4)

The CO_2-slicing method

- The method is described in Chahine (1974) or Menzel et al. (1983)

- The method is based on ratioing pair of channels and search for the pressure that minimize the difference between observation and simulation

$$F_\nu(p_{cld}) = \frac{R_\nu^{clr} - R_\nu^{obs}}{R_{\nu_0}^{clr} - R_{\nu_0}^{obs}} - \frac{R_\nu^{clr} - R_\nu^{cld}(p_{cld})}{R_{\nu_0}^{clr} - R_{\nu_0}^{cld}(p_{cld})} \qquad N_e = \frac{R_{\nu_0}^{clr} - R_{\nu_0}^{obs}}{R_{\nu_0}^{clr} - R_{\nu_0}^{cld}(p_{cld})}$$

- Different pairs ν, ν_0 of channels can be used : EC uses 13 pairs for IASI and choose for the median values of retrieved p_{cld} and N_e (Garand et al., 2011)

- One reference ν_0 (window channel) is used at CNRM for AIRS with 124 channels in CO_2 band (Pangaud et al., 2009)

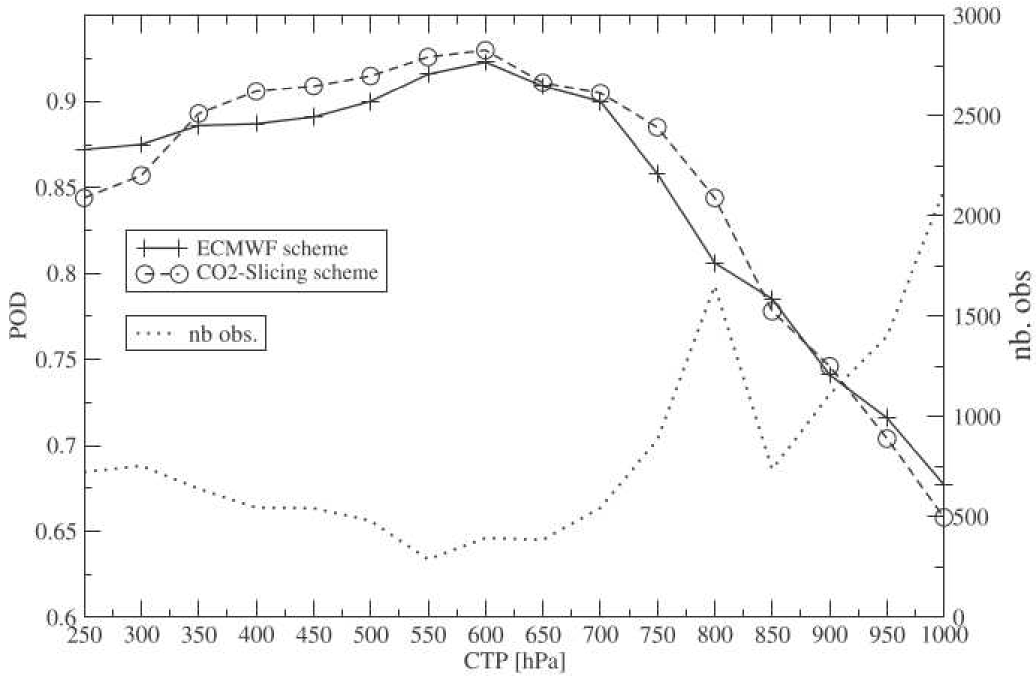
Cloud characterization schemes (3/4)

The Minimum Residual Method

- The method is described in Eyre and Menzel (1989)
- The cloud parameter are retrieved by the best fit which minimizes:

$$J = \sum_{\nu} [R_{\nu}^{obs} - R_{\nu}^{cld}(p_{cld}, N_e)]$$

- The number of channels can be 2 or more.



From Pangaud et al. (2009)

Pangaud et al. (2009) compared CO2-slicing and MRM on 10 days of AIRS and compare with MODIT CTP

The 2 methods provide similar results, the POD is maximum for high and mid-level clouds

Cloud characterization schemes (4/4)

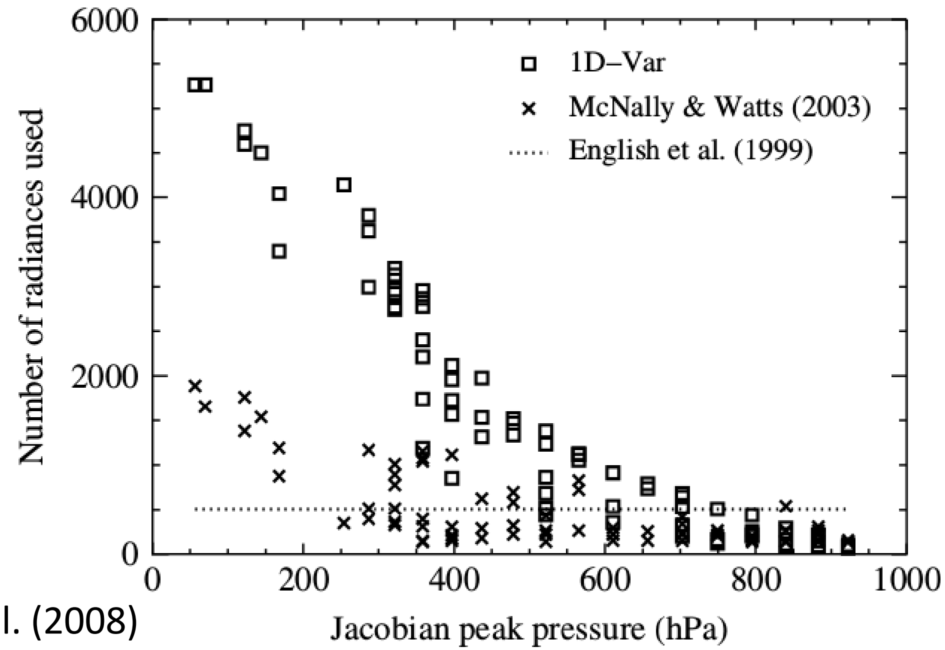
The 1D-VAR method

- Method firstly described in Eyre (1989)
- Applied on hyper-spectral simulations (Pavelin et al., 2008)
- Based on optimal estimation theory: Minimization of the following cost function

$$J(\mathbf{x}) = (\mathbf{x} - \mathbf{x}_0)^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}_0) + (\mathbf{y} - \mathbf{y}(\mathbf{x}))^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{y} - \mathbf{y}(\mathbf{x}))$$

- Provide better cloud products as compared with CO_2-slicing and MRM because cloud parameters are retrieved together with T and q profiles.

- Better cloud detection as compared with Departure-Based or Bayesian schemes (based on 13495 AIRS simulations from ERA40).



From Pavelin et al. (2008)

Error sources

- For all schemes, errors are coming from:
  - Radiative transfer modelization for both clear-sky (instrument SRF and spectroscopy) and cloudy-sky (single layer cloud model),
  - Background profiles,
  - Instrument noise,
  - Surface temperature and emissivity (especially over land).

- The importance of one source of error compared with others depends on the cloud type:
  - For high cloud (high thermal contrast), the error from background profile is not significant

- Some error sources are more difficult to estimate:
  - Definition of error covariance matrices (non-diagonal terms)
  - Undetected aerosols (desert dust & volcanic ash)
  - 3D effects on RTM

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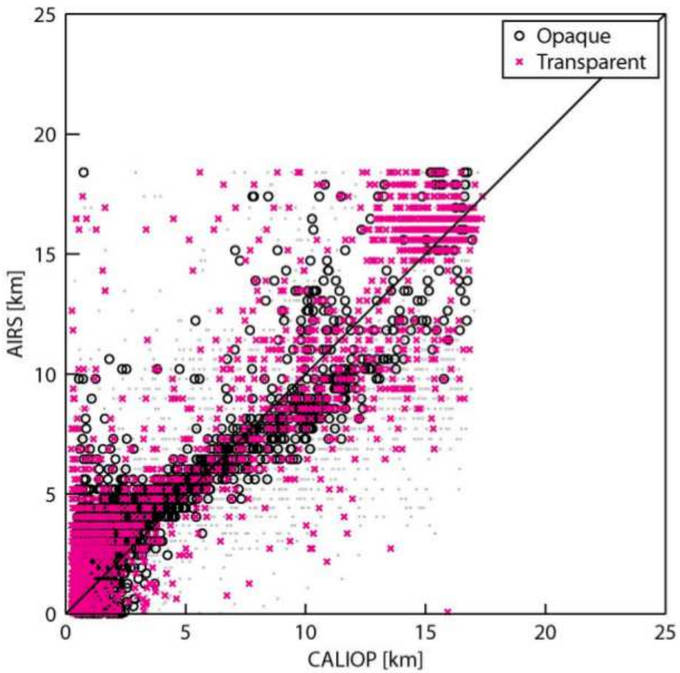
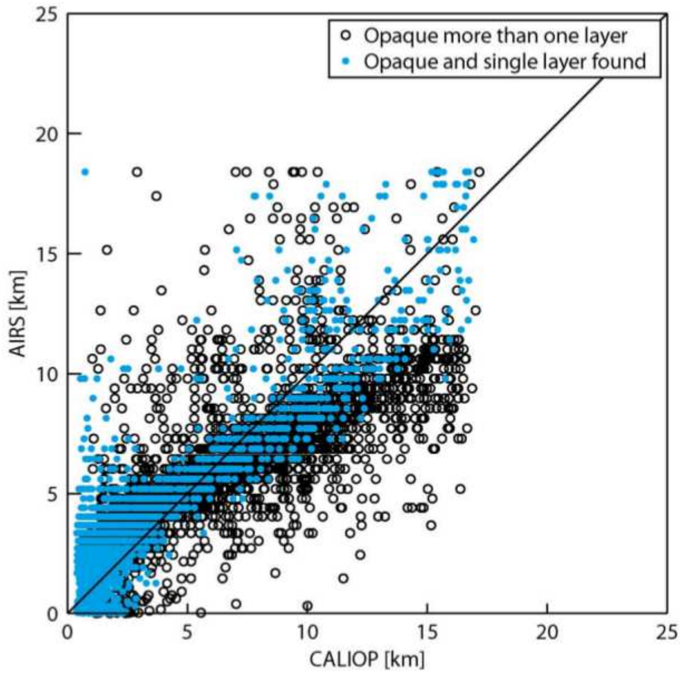
Cloud product validation

- Accurate validation of N_e is not obvious
- p_{cld} (or CTH) can be compared with active instruments (Lidar or radar)
- Ex: AIRS CTH versus CALIOP retrieval (Di Michele et al., 2013)
  - 30 days of CY36R2 (35228 match-ups)





From Di Michele et al. (2013)

  - Better CTH correlation for opaque and single layer cloud
  - AIRS mean error = -96 ±115 hPa (homogeneous opaque)

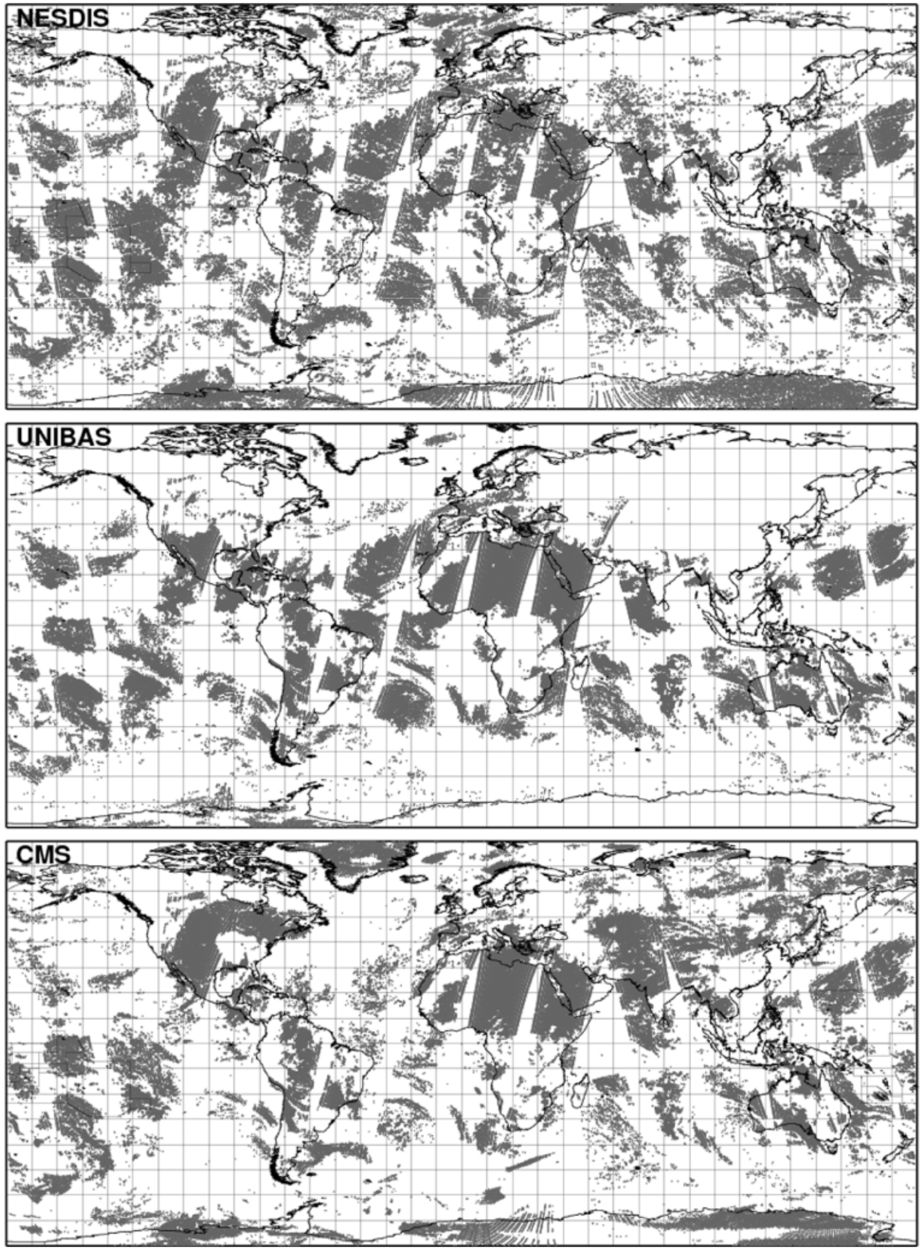
Cloud product intercomparison

- Comparison of IASI clouds product on 12h (Lavanant et al., 2011)

Affiliation	Detection	Characterization	Nb. channels	RTM
EC	AVHRR	CO_2-slicing	13 CO_2 pairs	RTTOV8.7
ECMWF	Departure-based	MRM	189	RTTOV9.3
JMA	AVHRR	MRM	74	RTTOV9.3
CMS	AVHRR	CO_2-slicing	40 CO_2	RTTOV9.3
CNRM	Departure-based	CO_2-slicing	36	RTTOV8.7
MetOffice	MRM	1D-VAR	92	RTTOV7
MetOffice	Bayesian	NO	4 window	RTTOV7
NOAA/NCEP	MRM	MRM	165	CRTM
NOAA/NESDIS	CCR	CCR	69	SARTA
UNIBAS	Regression tests	NO	148	Sigma-IASI

- + different surface models and background profiles (short range forecast)

Clear-sky detection comparison



- Example for 3 schemes (2 of them do only detection: NESDIS and UNIBAS)
- The 3 schemes agree well except over land and polar regions
- Over 9 schemes, the proportion of correct detection are found within 75-85 % , except MetOffice Bayesian scheme
- MetOffice Bayesian scheme is very conservative and reject almost all land FOV.

From Lavanant et al. (2011)

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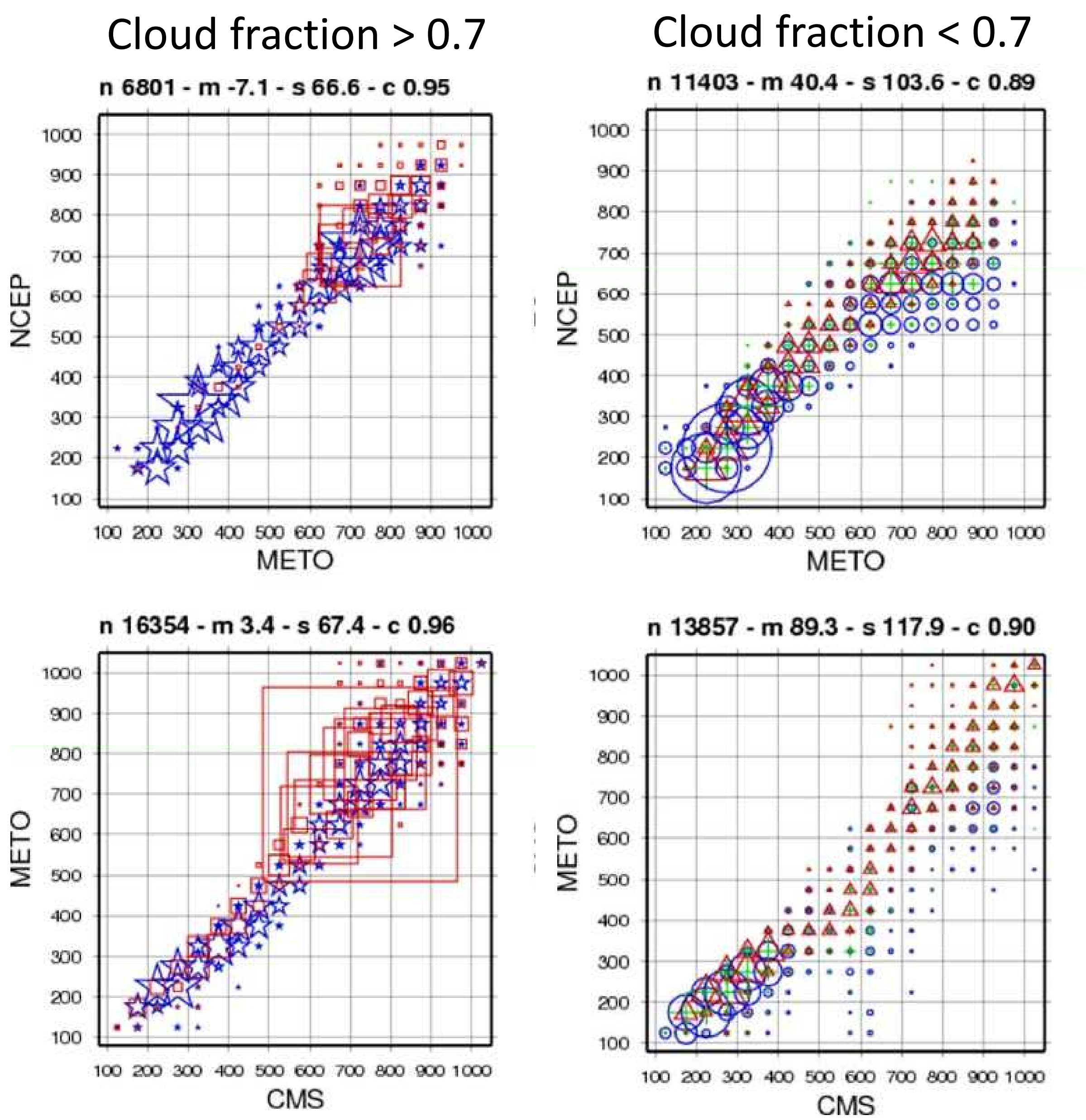
Cloud products intercomparison



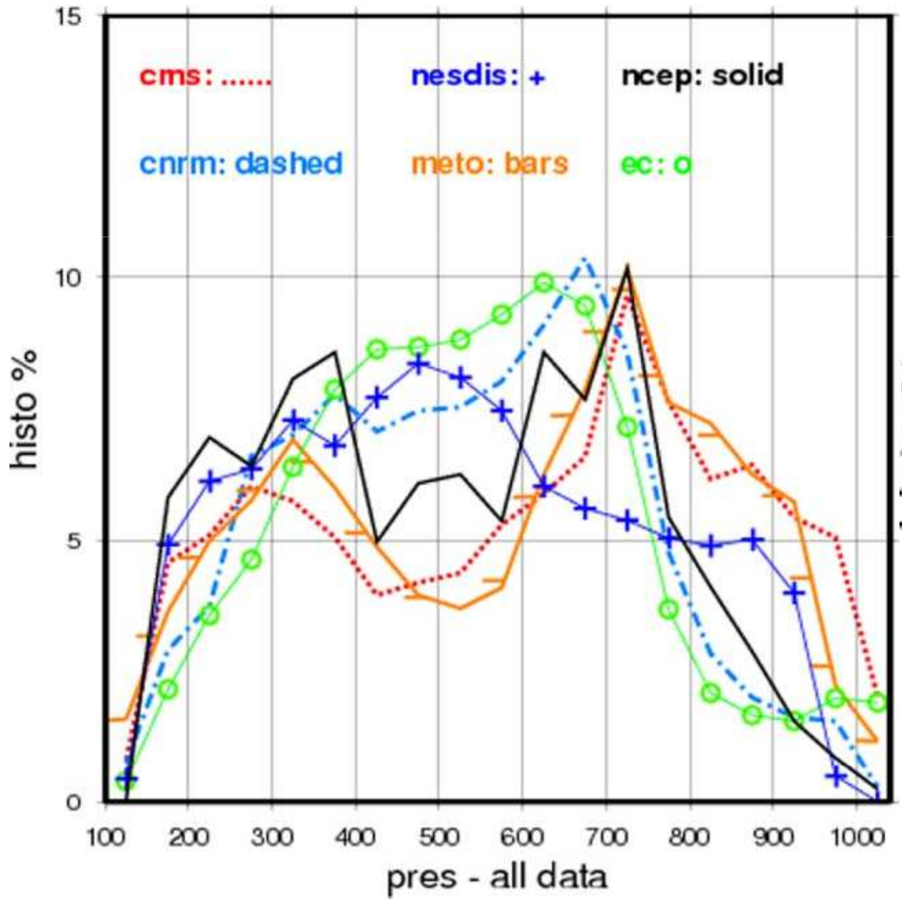
Agreement between schemes always better for high clouds even for small N_e (blue circle)

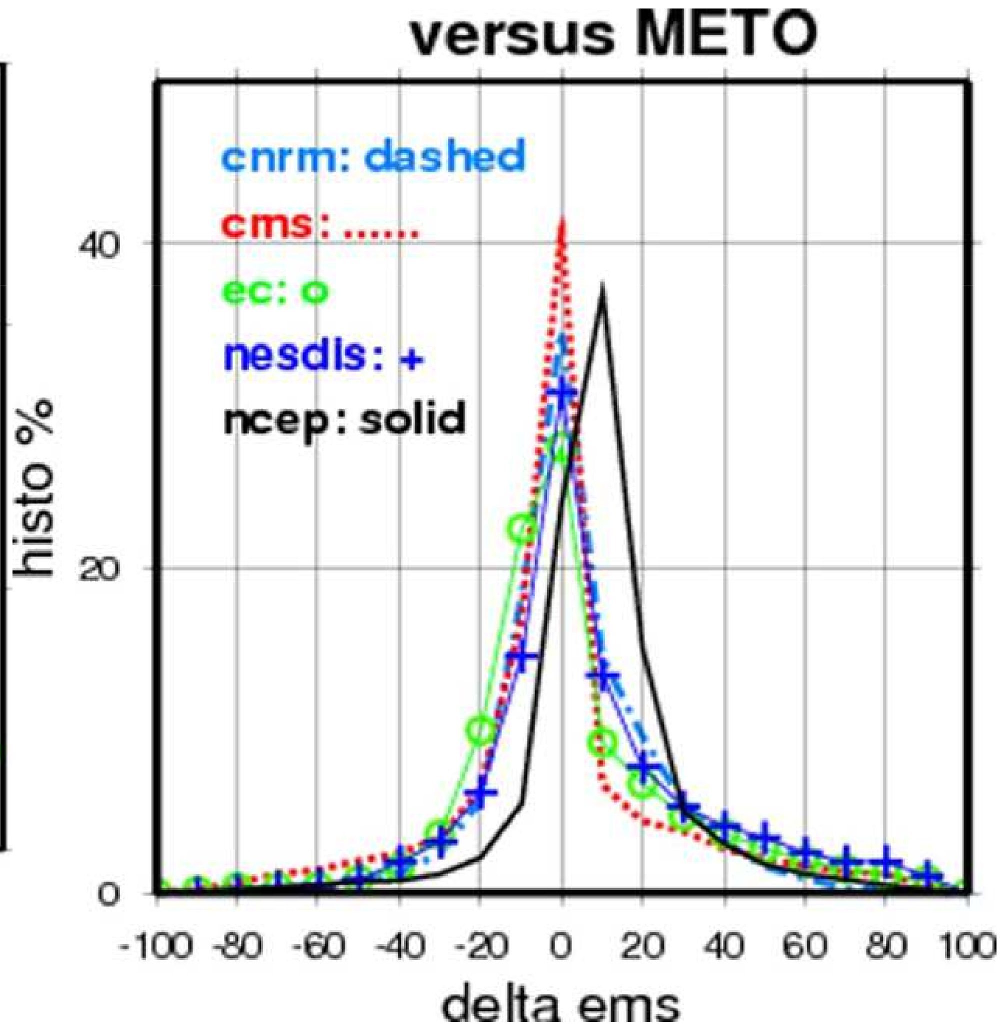
For middle and low level cloud, agreement decreases quickly with N_e

Standard deviation of p_{cld} difference is found around 100-150 hPa with biases of 50 hPa.

From Lavanant et al. (2011)

Cloud products intercomparison





From Lavanant et al. (2011)

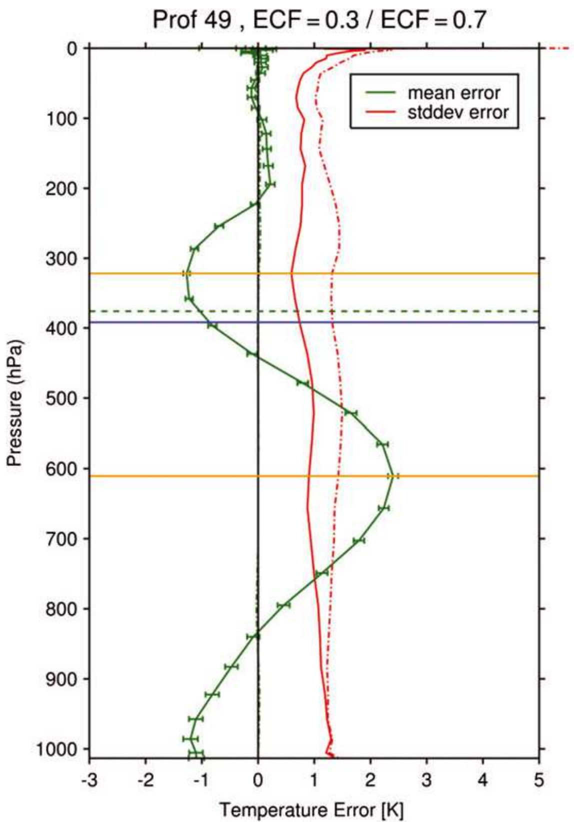
- Most schemes have two main peaks around 700-800 and 300 hPa (except EC and NESDIS
- Most schemes show same departure of Ne relative to MetOffice (except NCEP)

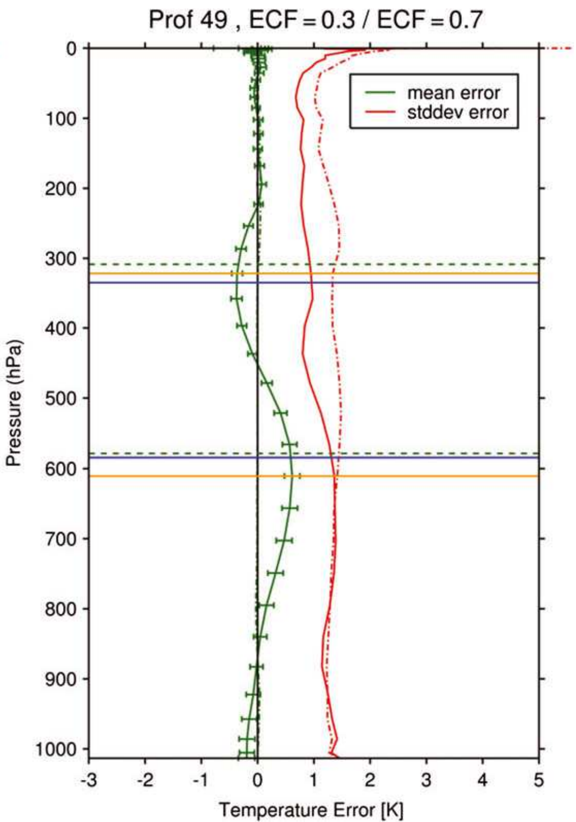
Beyond the single-layer cloud model

- All methods have difficulty with multi-layered clouds (which represents at least 40 % of the cases)
- **2 layers model (Smith et al., 1970)**

$$R_\nu^{cld} = (1 - N_{e1})(1 - N_{e2}){R_\nu}^{clr} + N_{e1}R_\nu^{ovc}(p_{cld1}) + N_{e2}(1 - N_{e1})R_\nu^{ovc}(p_{cld2})$$

- Assumption: Random overlap between cloud layers and $p_{cld1} < p_{cld2}$
- Show potential improvement when applied to IASI with 1DVAR (Prates et al., 2014)





The two layer model has higher skill in determining the position of the upper layer and the atmospheric profiles

From Prates et al. (2014)

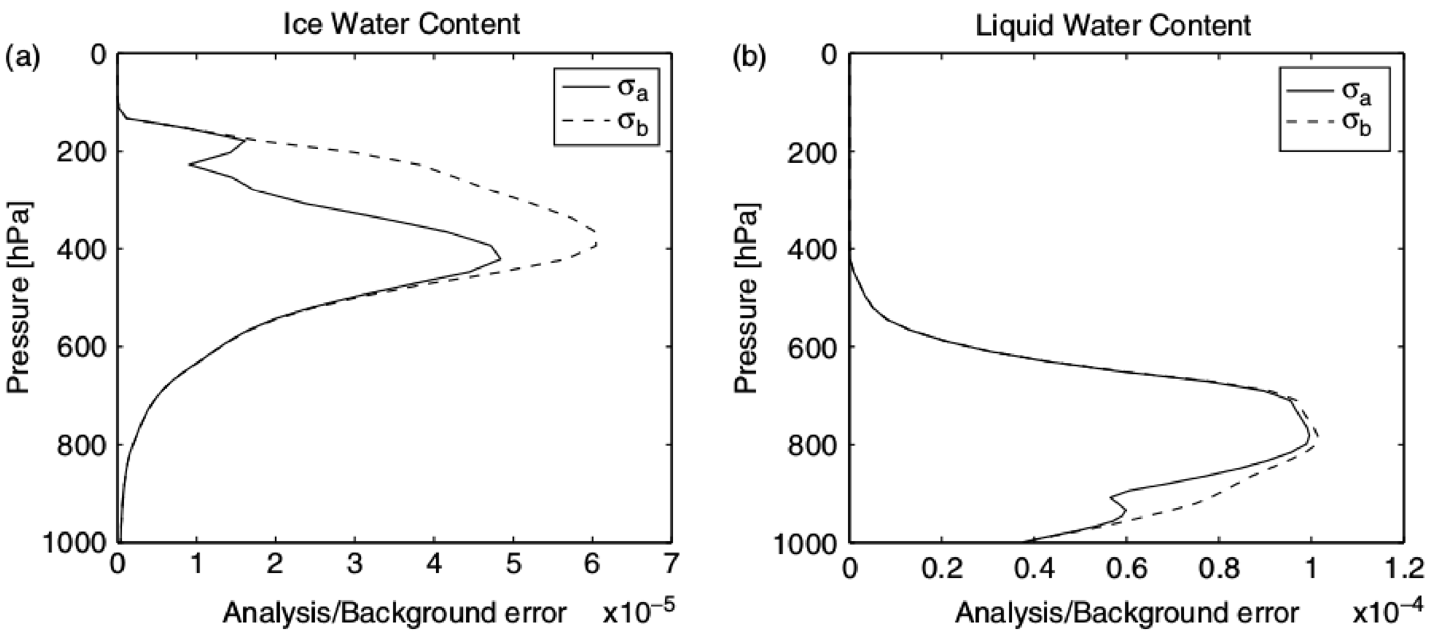
Beyond the single-layer cloud model

- **The cloud scattering approach**
- The source function contains thermal radiation and scattering.

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

- Fast RTMs exist (including Jacobians: RTTOV, CRTM)

1. Background radiances including scattering (Okamoto et al., 2014)
2. NWP cloud variables IWC(z) and LWC(z) are retrieved with 1DVAR (Martinet et al., 2014)
   - Very problematic to deal with cloud fraction profile N(z)



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From Martinet et al. (2014)

Conclusion

- Since the paper of Smith et al. (1967), 50 years of theoretical studies, sensitive studies and operational applications have been produced by the NWP community to detect and characterize clouds from IR sounders.

- Yes, we will be able to do it for MTG-IRS.

- However, source of errors coming from the instrument performance (SRF, noise) will have to be known.

- Other sources of error will continue to be improved (RTM, background profiles and surfaces properties)

- With the single layer cloud model, we will still have problem to deal with multi-layered and fractional clouds.

- Research on application and theoretical study considering new cloud models must be supported by operational centres.

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Thank you for your attention