Cloud parameters from a combination of infrared and microwave measurements

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INTRODUCTION

Clouds are both absorbers of outgoing longwave radiation and reflectors of incoming solar radiation. Due to their crucial role, the knowledge of the horizontal and vertical distribution and the optical properties of globally distributed clouds are of fundamental importance to the understanding of the radiation and heat balance, weather and climate of the earth and the atmosphere. Measurements of radiation from space can play a big role in helping us to understand how radiation depends on cloud properties. They can also help us to identify which are the most critical cloud properties to measure. The goodness of satellite-based measurements is that they offer the only practical way of making cloud measurements over the entire global. The improvement of spatial resolution and spectral characterisations allow us to apply sophisticated retrieval procedures, which will provide new cloud products with enhanced accuracy. Since clouds are practically opaque in the infrared sounding frequencies and since the majority of the clouds are transparent in the microwave regions, it would appear that a proper combination of infrared and microwave measurements could be useful and significant data to determine the cloud coverage, the vertical cloud structure and the composition in all weather conditions. First of all the paper explores the performance of a cloud detection scheme for the Atmospheric Infrared Sounder (AIRS) data, then the improvements in retrieval cloud parameters, using high spectral resolution AIRS sounder data. together with the Advanced Microwave Sounding Unit (AMSU-A) and the Humidity Sounder for Brazil (HSB) on the Aqua mission, represents the most advanced sounding system ever deployed in space. AIRS measures simultaneously in more than 2300 spectral channels in the range of 0.4 to 1.7 µm and 3.4 to 15.4 µm. AIRS measurements are at 13.5 km resolution in infrared bands and at 2.3 km in four visible and near-infrared bands. AMSU has 42 km FOVs and is a temperature sounder (15 channels in the range of 50 to 89 GHz). HSB has 15 km FOVs and is a moisture sounder (4 channels in the range of 150 to 183MHz). AMSU and HSB are co-aligned with AIRS.

AIRS CLOUD DETECTION VALIDATION

Cloud detection depends on the contrast between cloud and the cloud free pixels. The contrast depends on wavelength, so that a multispectral approach gives reliable results. Cloud free and fully cloudy pixels differ considerably in their spectral properties and allow simple threshold techniques. Partially cloudy pixels vary from cloud free to fully cloudy and always require a decision about their cloud coverage. In the microwave region clouds have a negligible effect on the radiances. For this reason using some information coming from AMSU data can be useful to improve a cloud detection algorithm. The threshold tests, based on AIRS/AMSU inter-channel regressions, allow us to detect all the overcast FOVs. Thin clouds, cirrus and partially cloudy FOVs are detected using IR thresholds test on window channel differences. Using the line-by-line Hartcode (F. Miskolczi et al, 1989), RTTOV (J. Eyre , 1991) and RT3 (Evans et al, 1991, Amorati et al, 2002) forward models, spectral clear radiances and spectral cloudy radiances are calculated for different cloud types in order to compute the dynamic thresholds. The dynamic thresholds are a function of observing geometry and they are selected on the basis of AMSU brightness temperature, of

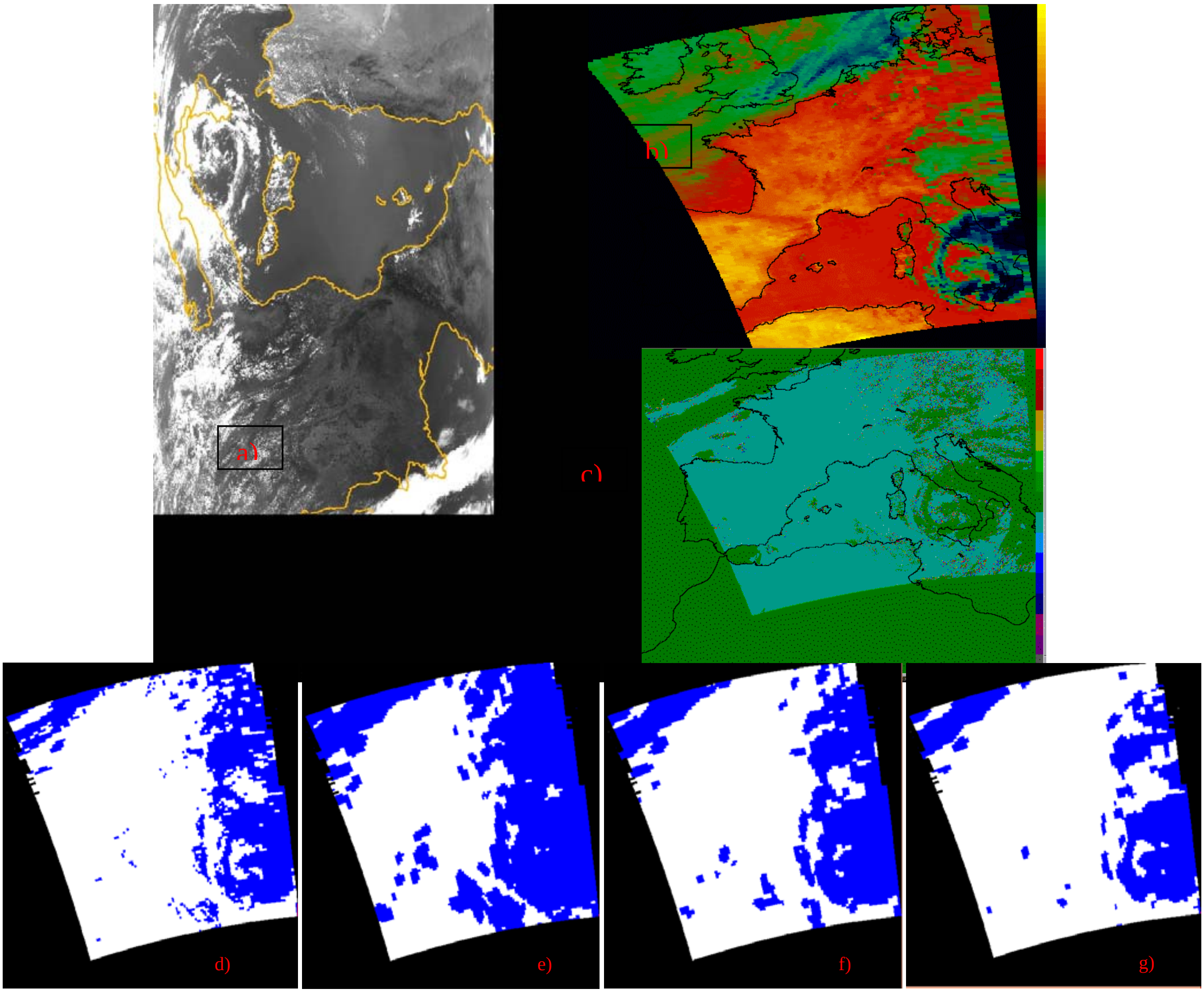

Fig.1 a) MODIS band 3, b) AIRS window channel at 909.09 cm, c) MODIS cloud mask, d) Airs cloud mask, e) MODIS cloud mask at AIRS resolution 100% clear, f) MODIS cloud mask at AIRS resolution 90% clear and g) MODIS cloud mask at AIRS resolution 70% clear. Blue pixel are cloudy, white are clear. Data from 1 August 2003.

water vapour, derived from AMSU, and on the basis of the highest AIRS brightness temperature value in the AIRS granule. In order to validate the AIRS cloud detection, the MODIS (Moderate-Resolution Imaging Spectroradiometer) cloud mask is collocated within the AIRS footprint. MODIS measures Earth radiances in two visible bands at 250m resolution, in five other visible bands at 500 m resolution and the remaining bands at 1 km resolution. The cloud detection is performed at 1 km resolution for all scenes and also at 250 m in daytime only (Ackerman et al, 1998). The AIRS cloud mask has been compared with the results derived from MODIS data. The AIRS FOVs is declared clear if a fixed percentage (70%, 90% and 100%) of MODIS pixels within AIRS IR FOV have been determined to be confident clear or probably clear. The three different cloud masks obtained in this way have been compared with the cloud mask derived from AIRS cloud detection algorithm. Figure 1 and 2 show for two different granules a MODIS channel, a window AIRS channel, the MODIS cloud mask, the AIRS cloud mask and the cloud mask derived from collocated MODIS cloud mask at different percentage. The table 1 show the comparison for 30 granules; the granules have been selected for different areas and months. When MODIS is used to validate an AIRS cloud detection scheme, it is very important to take into consideration the different spatial resolutions of sensors. The MODIS cloud-tests generates a cloud mask on the MODIS grid, and the it must be "translated" into the AIRS grid; only the clear (i.e. detected as clear) MODIS FOVs contribute to determine the percentage clear on AIRS grid. When the are many partially cloudy MODIS FOVs, it results that the AIRS is assumed to have an high fraction of cloud coverage even if this does not necessarily imply that the AIRS radiances are strongly affected by clouds. MODIS often overestimates cloud fraction on AIRS grid, then the percentages reported in Table 1 overestimate the number of failures.

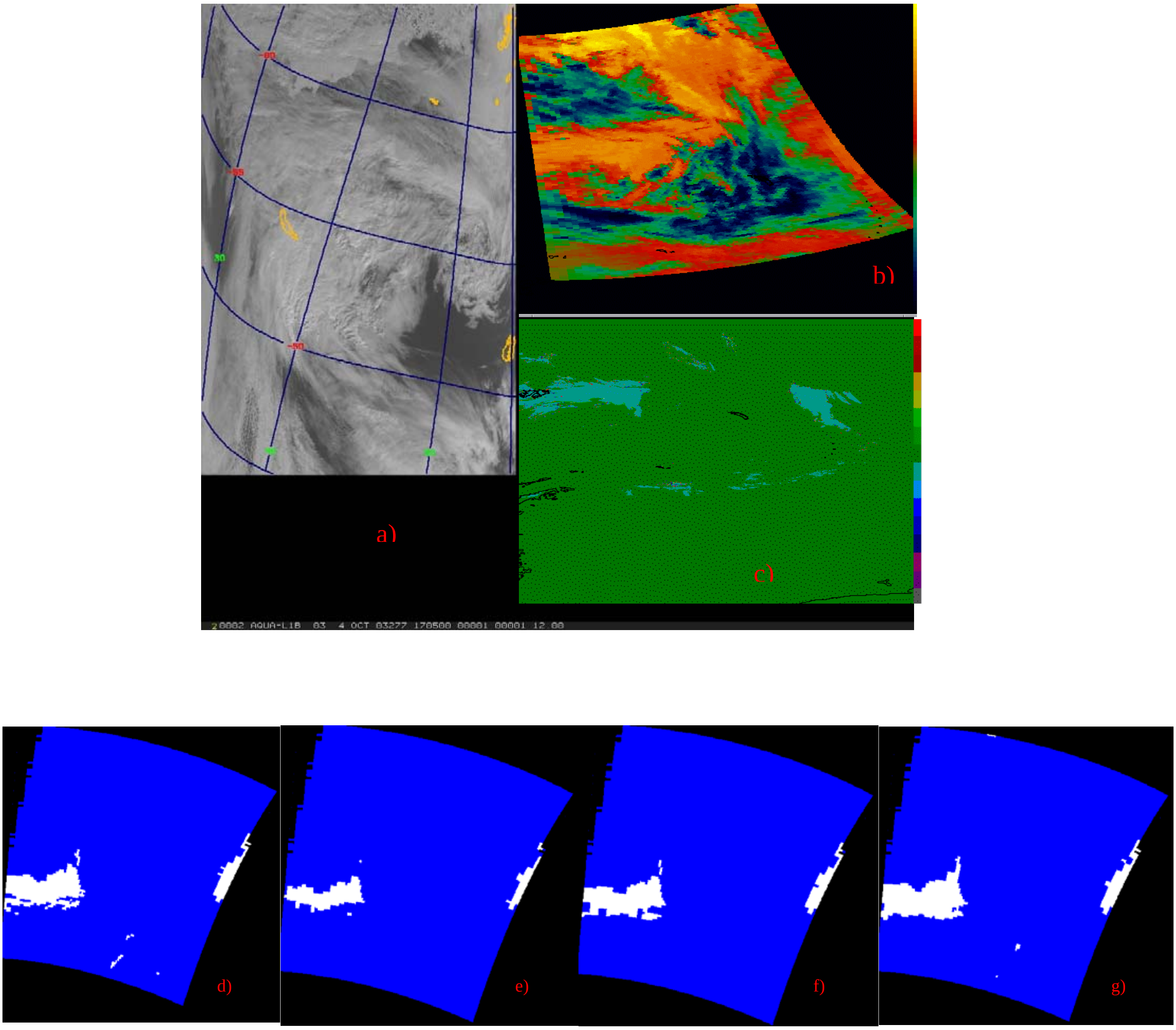

Fig.2 a) MODIS band 3, b) AIRS window channel at 909.09 cm, c) MODIS cloud mask, d) Airs cloud mask, e) MODIS cloud mask at AIRS resolution 100% clear, f) MODIS cloud mask at AIRS resolution 90% clear and g) MODIS cloud mask at AIRS resolution 70% clear. Blue pixel are cloudy, white are clear. Data from 4 October 2003.

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30 granules	FOVs detected exactly
70%	82.7%
90%	95.8%
100%	92.3%

Tab.1 Comparison between AIRS and MODIS at AIRS resolution cloud masks.

CLOUD TOP HEIGHT: SINGLE CLOUD LAYER

CO_2 slicing (Wylie/Menzel, 1989, 1991) has been extensively used to retrieve cloud top pressure and cloud effective emissivity using High Resolution Infrared Radiation Sounder (HIRS) and MODIS data. Clouds at various levels of the atmosphere can be detected using radiances around the broad CO_2 absorption band at 15 μm. Radiances near the centre of the absorption band are only sensitive to upper levels, while the radiances from the wings of the band are sensitive to lower levels of the atmosphere. Based on radiative transfer principles, this technique is independent of intrinsic cloud properties and knowledge of the fraction of cloud cover is not required. It also allows both the calculation of the cloud top altitude and the cloud emissivity from a temperature profile and the profiles of atmospheric transmittance for two spectral channels sufficiently close. The accuracy of the cloud height estimation can be greatly improved through application to high resolution spectra. Difficulties arise when the differences between the clear and cloudy radiances for a spectral band are smaller than the instrument noise.
The radiance from a partially cloudy air column region can be written as:

$$R_\lambda = \alpha R_\lambda^{cloud} + (1-\alpha) R_\lambda^{clear}$$

where α is the fractional cloud cover; R_λ^{clear} and R_λ^{cloud} are respectively the clear and the cloudy radiance for a given spectral channel λ.
The cloud radiance is given by:

$$R_\lambda^{cloud} = \varepsilon_\lambda R_\lambda^{bc} + (1-\varepsilon_\lambda) R_\lambda^{clear}$$

where ε_λ is the emissivity of the cloud, and R_λ^{bc} is the radiance from a completely opaque cloud. Using the Radiative Transfer Equation it is possible to write:

$$R_\lambda^{clear} = B_\lambda(T(p_s))\tau_\lambda(p_s) + \int_{p_s}^{0} B_\lambda(T(p))d\tau_\lambda$$

and

$$R_\lambda^{bc} = B_\lambda(T(p_c))\tau_\lambda(p_c) + \int_{p_c}^{0} B_\lambda(T(p))d\tau_\lambda$$

where p_c is the cloud top pressure. Integrating by part and subtracting the two terms to obtain the following relation:

$$R_\lambda - R_\lambda^{clear} = \alpha\varepsilon_\lambda \int_{p_s}^{p_c} \tau_\lambda(p) dB_\lambda$$

Following the work of Chahine (1974) to assign a cloud top pressure to a given cloud element, the ratio of the deviations in observed radiances, R_λ and the corresponding clear air radiances, R_λ^{clear} , for two spectral channels of frequency λ_1 and λ_2 viewing the same FOV can be written as

$$\frac{R_{\lambda_1} - R_{\lambda_1}^{clear}}{R_{\lambda_2} - R_{\lambda_2}^{clear}} = \frac{\varepsilon_{\lambda_1} \int_{p_s}^{p_c} \tau_{\lambda_1}(p) dB_{\lambda_1}}{\varepsilon_{\lambda_2} \int_{p_s}^{p_c} \tau_{\lambda_2}(p) dB_{\lambda_2}}$$

If the frequencies are close enough, then $\varepsilon_{\lambda_1} \approx \varepsilon_{\lambda_2}$ and the cloud top pressure can be determined minimising the difference between the left and the right side. The left side (cloud radiative forcing) of the Equation is determined from the satellite observed radiances in a given FOV and the cleared radiance. The right side is calculated from a temperature profile and the profiles of atmospheric transmittance for the spectral frequency as a function of p_c, the cloud top pressure. CO_2 cloud top pressure is estimated when the cloud forcing (clear minus cloud radiance) is greater than five time the instrument noise level.
In order to apply the CO_2 slicing technique to AIRS data, it is necessary to select the best pairs of frequency to be used in the cloud top retrieval. The used method selects all the channels in the CO_2 absorption band whose weighting functions peak between 200 mb and 900 mb. It uses all the possible combinations of these channels, with the first channel of the pair always associated with the lower wavenumber one. Then the CO_2 slicing technique is applied to retrieve the cloud top heights, using all the selected channel pairs. Finally it selects the number of pairs that best satisfy the radiative transfer equation for all the spectral channels. For each FOV the different solutions found are used to evaluate a cost function:

$$\chi = \sum_1^N \varphi_{\lambda i}^2$$

where N is the total pairs of channels and the φ_{λ_i} is defined in this way:

$$\varphi_{\lambda_i} = \left(R_{\lambda_i} - R_{\lambda_i}^{clear}\right) - \alpha\varepsilon_i \int_{p_s}^{p_c} \tau_{\lambda_i}(p) dB_{\lambda_i}$$

The solutions associated to the smallest values of χ are averaged to determine the cloud top height. Increasing the number of used channels pairs in average causes an improvement in the accuracy of the cloud top height retrieval. At the end the algorithm selects 36 pairs of channels.
The cleared AIRS brightness temperature have been estimated using the Kriging cloud scheme (Cuomo et al. 1999). In order to improve the number of AIRS FOVs cleared, MODIS data have been introduced in the scheme. The root mean square error of the Kriging clear brightness temperatures estimates is well below 0.5 °K for any AIRS channels and the bias is about to ±0.1 °K.
Figure 3a shows cloud top pressure estimate using MODIS data, figure 3b using AIRS data. Figure 4a shows the comparison between the cloud top pressure estimate by MODIS and that estimates by AIRS. The MODIS collocated points are also used to determine the scene homogeneity within the AIRS footprint; only homogeneous AIRS FOVs have been used in this comparison. Figure 4b show the comparison with ground based measurements (radar and lidar for different side); only homogeneous AIRS FOVs have been used.

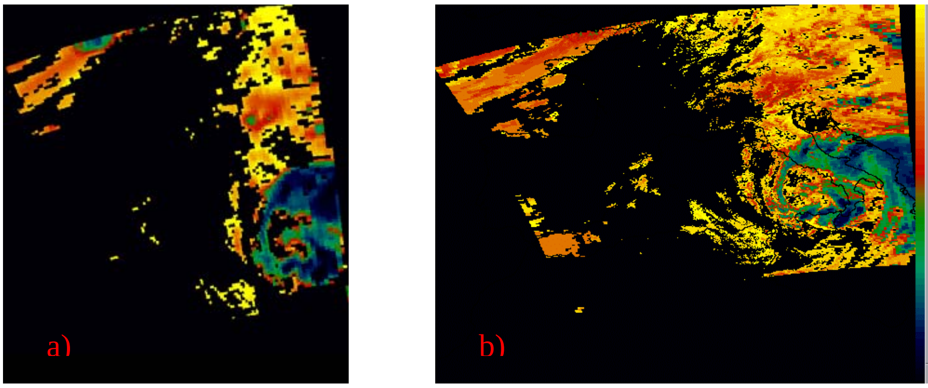

Fig.3 a) AIRS top cloud pressure , b) MODIS top cloud pressure. Data from 1 August 2003.

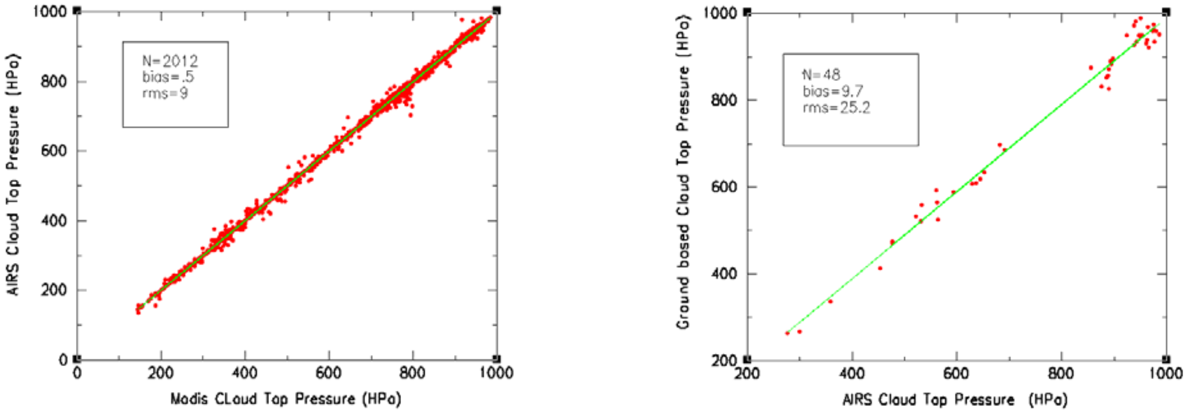

Fig.4 a) Comparison between the cloud top pressure estimate by MODIS and that estimates by AIRS, b) comparison with ground based measurements.

CLOUD TOP HEIGHT: TWO CLOUD LAYERS

When you consider two levels cloud (upper and lower cloud) , the cloud forcing can be expressed as:

$$R_\lambda - R_\lambda^{clear} = \alpha_l \varepsilon_l (1-\alpha_h \varepsilon_h) \int_{p_s}^{p_{cl}} \tau_\lambda(p) dB_\lambda + \alpha_{h\varepsilon_h} \int_{p_s}^{p_{ch}} \tau_\lambda(p) dB_\lambda$$

where α_l is the fractional cloud cover and ε_l the emissivity of the lower cloud, α_h is the fractional cloud cover and ε_h the emissivity of upper cloud; p_{cl} is the lower cloud top height and p_{ch} is the upper cloud top height. in this case there are four unknown variables: $\alpha_l \varepsilon_l$, $\alpha_h \varepsilon_h$, p_{cl} and p_{ch}. For each spectrally close pairs of CO_2 absorption band (700 – 753 cm-1), all possible $\alpha_l \varepsilon_l$ and $\alpha_h \varepsilon_h$ values are calculated as a function of cloud top height, p_{cl} and p_{ch} by means of the following expression:

$$\alpha\varepsilon = \frac{R_w - R_w^{clear}}{B_w(T(p_c)) - R_w^{clear}}$$

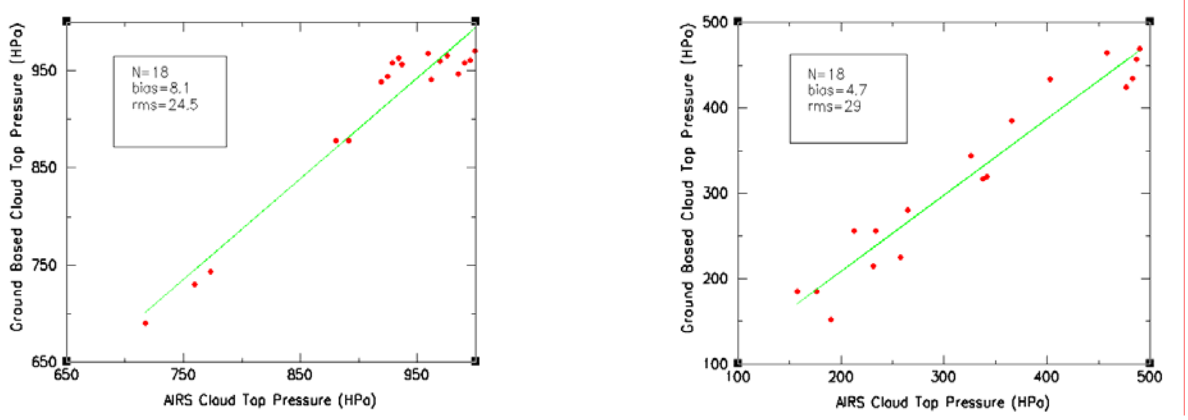

Fig.5 Comparison between the cloud top pressure estimate by AIRS and that estimate by ground based instruments for two cloud level.

from all the solutions we select the best ones that satisfy the radiative transfer equation for all spectral channels. In the same way. we define a cost function in the same way as we did for the single cloud layer and the solutions associated to the smallest values of χ are averaged to determine the upper and lower cloud top height. Increasing the number of used channel pairs in average causes a improvement in the accuracy of the cloud top height retrieval. At the end the algorithm selects 44 pairs of channels. Figure 5 shows the comparison with ground based measurements, only homogeneous AIRS FOVs have been used. The MODIS collocated points are also used to determine the scene homogeneity within the AIRS footprint.

CLOUD THICKNESS

In order to estimate the cloud thickness, cloud water content (CWC, liquid or ice) from AMSU measurements has been estimated using a neural network based algorithm A large set of vertically inhomogeneous clouds based on radiosonde profiles has been applied to the infrared and microwave transfer code RT3. The neural network algorithm uses the radiances at AMSU-B (HSB) frequencies. Water and temperature profiles from AIRS/AMSU or ECMWF have been used. Surface emissivity is adjusted according to the surface type. Simulated brightness temperature are compared to the observed AIRS and AMSU data. If the difference between the observed and the estimated reach a minimum, the retrieval process finished. Figure 6a show cloud thickness for a single cloud level and figure 6b e 6c for two cloud level.

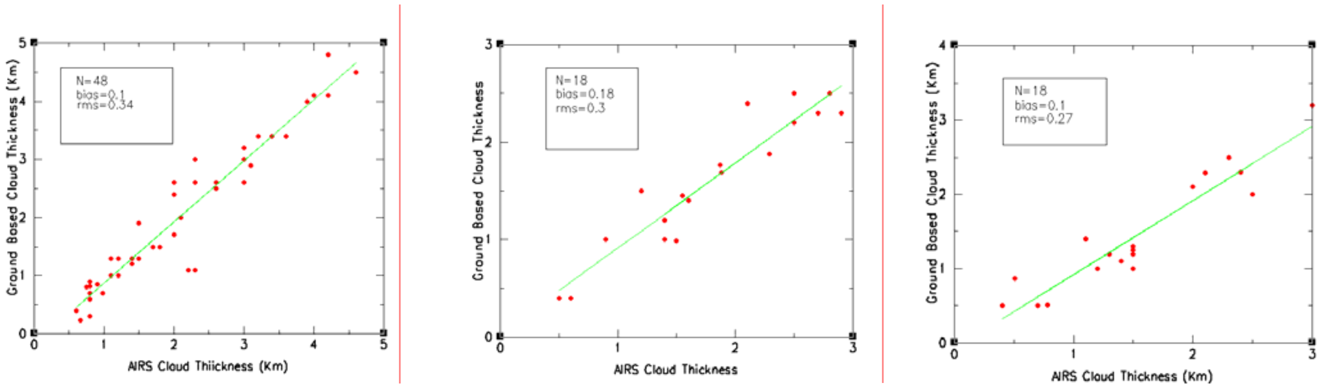

Fig.6 a) Cloud thickness for a single cloud level and b) and c) for two cloud level .

CONCLUSION AND FUTURE WORK

Since clouds are practically opaque in the infrared sounding frequencies and since the majority of the clouds are transparent in the microwave regions, it would appear that a proper combination of infrared and microwave measurements could be useful and significant data to determine the cloud coverage, the vertical cloud structure and composition in all weather conditions. The paper examines the combination of AMSU and AIRS data in the horizontal and in the vertical cloud structure retrieval. The results have been compared for homogenous AIRS pixels with ground based measurements. In the future cloud mask validation based on MSG (SEVIRI) data will be carried out, SEVIRI is a very useful tool for the clouds investigation. Validation, based on ground based measurements, will be extend to a large data set.

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