Use of MODIS imager to help dealing with AIRS cloudy radiances

Lydie Lavanant *, Mohamed Dahoui **, Florence Rabier *, Thomas Auligné *****

** Météo-France, Centre de Météorologie Spatiale, BP 147, 22300 Lannion Cedex France*
*** Maroccan Meteorological Service*
**** Météo-France, Centre National de Recherche Météorologique, 42 av. Coriolis, 31057 Toulouse Cedex France*

Summary

The atmospheric Infrared Sounder (AIRS) was launched in May 2002 on board the AQUA platform. This new high spectral resolution instrument provides 2378 channels covering the spectral range between 650 cm^{-1} to 2700 cm^{-1} which allow a good “stand-alone” description of the clouds in the fov by processing an adapting subset of channels.
For the time being, in most operational analysis systems, the assimilation of the satellite radiances is limited to the cloud-free pixels. The assimilation of the AIRS radiances in clear conditions is already defined at Météo-France and is presented in full details in this issue (Auligné and al, 2003). In parallel, developments are on-going for the assimilation of the AIRS cloudy radiances.
This paper focuses on the validation of various cloud-detection schemes applied to AIRS spectra. The clouds are detected and characterized, in height and cover, by using the NESDIS, ECMWF, CO_2-slicing and MLEV schemes. Short description of the four methods is given in this paper. AIRS radiances biases correction is required before any cloud detection and is presented. The resulting AIRS cloud description is then evaluated by using independent information retrieved with the Météo-France cloud mask applied to co-registered MODIS imager data and taken as our reference.
Status on this comparison and on the validation for a ten days period over the North-East Atlantic is presented.

Introduction

The validation of “stand-alone” AIRS cloud–detection schemes was primarily done for a better understanding of the capability of the high spectral resolution for an improved cloud description. The second issue of that work was to determine their remaining limitations compared to the imager capabilities. It was also a way for starting the definition of a more precise cloud detection scheme using the full high spectral resolution for the future METOP/IASI instrument.

As we do not have a direct broadcast system for the AQUA platform at the CMS, we got level1b MODIS, AIRS and AMSU data provided by the NASA/GSFC DAAC web site for only a ten days period from 10 to 20 April 2003 in the North Atlantic. The desarchived 35 granules cover different interesting day and night situations with a variety of cloud types. Only sea situations have been processed. The AIRS data are full resolution spectra and the level1b files contain the localization data for all the instruments which avoids re-doing that complex pre-processing. The first period from 10 to 15 April was used as a training period for the computation all the necessary thresholds and biases coefficients of the models and the validation is done on the second period from 16 to 20 April.

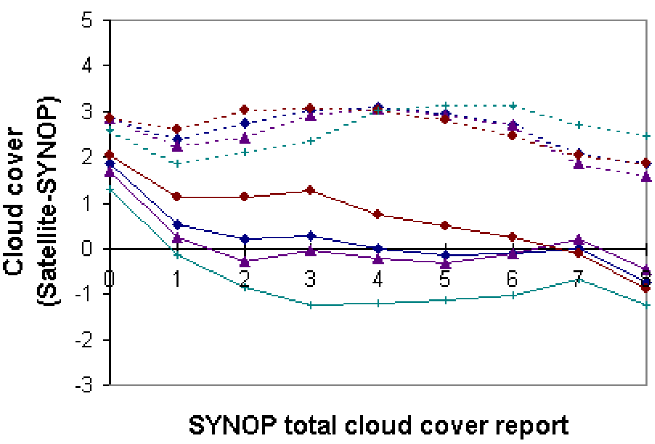
For simulating clear radiances necessary in the ECMWF, CO_2-slicing and MLEV schemes, we used the RTTOV-7 forward model together with the nearest in time and location French ARPEGE NWP atmospheric background. Same biases corrections were applied to the 3 schemes and the same sub-set of channels was used in ECMWF and CO_2-slicing models.

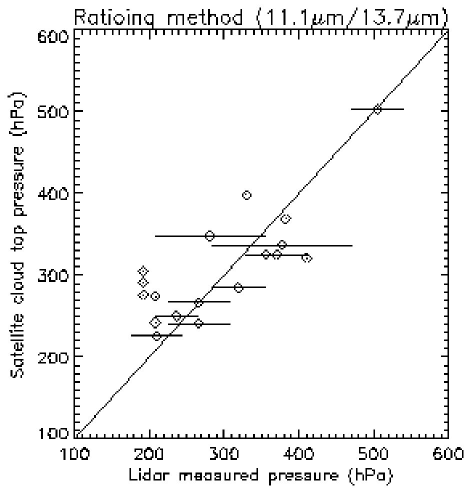
MODIS cloud description

The Moderate Resolution Imaging Spectroradiometer (MODIS) on board the AQUA satellite, is primarily designed for cloud imaging and sea surface temperature. The cloud mask used in this study is an adaptation to MODIS of the NWC SAF package with only MODIS channels similar to SEVIRI channels used (LeGléau and Derrien, 2002). Three output parameters are retrieved; the clear/cloud flag, the cloud type and the cloud top temperature and height.

The cloud mask is based on the fact that the spectral behavior of clouds and earth surfaces are different in window channels. The method chosen is a multispectral technique applied every pixel which is efficient in term of computing time and is relatively easy to adapt. The method was prototyped with AVHRR and GOES imagery and tuned to SEVIRI and MODIS spectral conditions even before data were available. The thresholds are applied to various combinations of channels and depend on the geographical location, on the solar illumination and viewing geometry of the pixel. Thresholds are computed in-line from constant values from experience, from tabulated functions defined off-line through RTTOV simulations, from external data such as NWP forecast fields of land surface temperature and total water vapor content and from climatological atlas of sea surface temperature and albedo. For opaque clouds, the cloud top temperature is obtained through the best fit between simulated and measured 10.8µm brightness temperatures. For high semi-transparent clouds, two methods are used: the CO_2-slicing method which makes use of the fact that the variation of the radiance with height and cloudiness is not the same for a window channel as for a CO_2 sounding channel. An alternative approach called the H_2O/IRW intercept method based on an IR window and a WV channel histogram analysis, is applied when the CO_2-slicing method fails.

Estimations of the accuracy and limits of the cloud mask have extensively been done for AVHRR/HIRS and GOES data during several years, by the NWC SAF team. Validation for MODIS and SEVIRI is in progress. Figures 1 illustrate the efficiency of the cloud mask with the measurement conditions. The left figure shows the comparison of the cloud cover (in octa) automatically derived from GOES-East measurements and visually observed in meteorological stations (SYNOP observations) over continental mid-latitude regions. The right figure shows the accuracy of the cloud top pressure retrieved with HIRS sounding channels, similar to MODIS channels 32 and 34, when compared to coincident lidar observations.





Figures 1. Imager cloud mask accuracy. The left figure shows the comparison of the cloud cover (in octa) from GOES-East data and SYNOP observations in mean and standard deviation for different illumination (day, night, twilight, all) and for continental mid-latitude regions. The right figure concerns the cloud top pressure retrieved with HIRS compared to coincident Lidar measurements (Courtesy NWC SAF team).
For more details see www.meteorologie.eu.org/safnwc

MODIS and AIRS mapping

The processing of the MODIS pixels mapped inside the AIRS fov is an efficient way to detect small amount of clouds because of its high spatial resolution, to determine the number of cloud layers and the complexity of the situation. Also, the imager processing provides accurate cloud top pressures for opaque layers, mainly at medium or low levels. For semi-transparent clouds, the method used for computing the layer temperature is a CO_2-slicing method but with less channels than for AIRS. The two methods are then complementary.

The mapping of MODIS and AIRS is based on their navigation information given in the level1b data and on the scan geometry of the two instruments. An adjustment in line and pixel of the MODIS data in the AIRS fov is done through the minimization of the differences between AIRS brightness temperatures convoluted on MODIS 32 filter and corresponding MODIS observations averaged on the AIRS ellipse. The adjustment depends on the AIRS scan position. Precise ifov adjustment was also tested using the VIS/NIR AIRS imager but for our test dataset the method did not improve the results. Figure 2 shows the statistics of the departure for a four days period corresponding to 20 day and night granules. Figures 3 give an example for one granule of the cloud types inferred with the MODIS cloud mask and for the same granule of the differences between AIRS and MODIS for MODIS channel 32 at the AIRS resolution.

From the MODIS cloud type and temperature characteristics, up to 3 cloud layers are allowed in the AIRS ellipse, each of them with a cloud cover, a cloud classification and a top temperature. A situation is declared clear if less than 5% of MODIS pixels are cloudy in the ellipse.

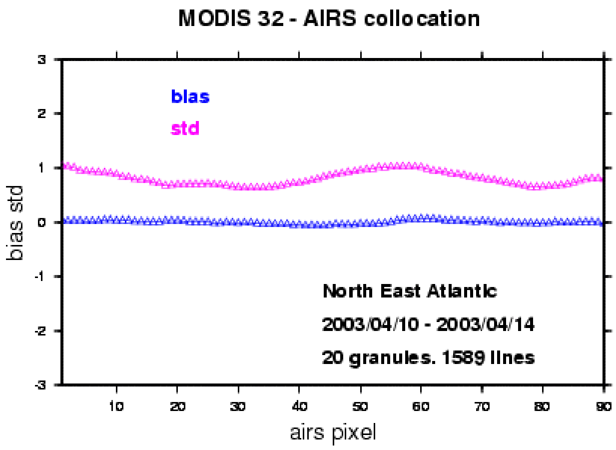
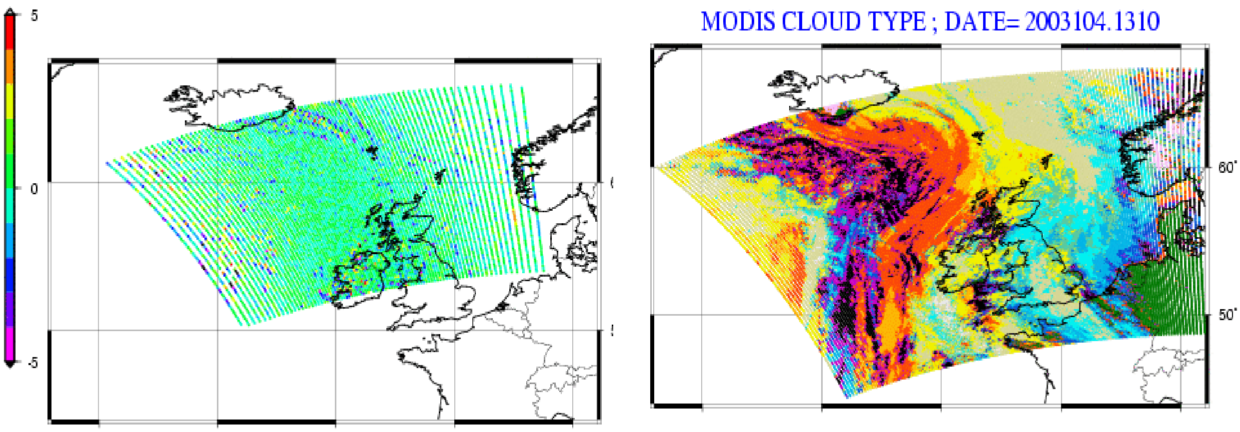


Figure 2: statistics in bias (blue) and standard deviation (in red) function of the AIRS scan position between AIRS and MODIS Tbs for the MODIS filter 32. Day and night data. 20 granules for 4 days



Figures 3: in right example for one granule of the cloud types inferred with MODIS and in left for the same data the differences at the AIRS resolution between AIRS and MODIS for MODIS 32.

AIRS bias correction

The comparison of observed and computed radiances shows the presence of systematic errors arising mainly from errors in the radiative transfer model, instrument measurement/calibration problems or problems in the model fields themselves. The model we used in this study to evaluate the biases of each AIRS channel j in the CO_2 band is based on the collocated AMSU-A observations:

$$A_0(j) + \sum_{i=1,8} (A_i(j) * (y_i - \overline{y_i})) + A_9(TWVC - \overline{TWVC}) + A_{10}(T_s - \overline{T_s}) + A_{11} * \sec$$

Y = AMSU 6, 8,9,10,11,12,13,14
Ts = Surface temperature
Sec= secant of the viewing angle

In our case, for this dataset and this part of the spectrum, the results were slightly better using a correction based on AMSU-A data than with the Harris and Kelly (2001) model usually used in the course of NWP assimilation.

The coefficients were computed on the training period from all AIRS situations declared clear with MODIS mapped in the fov and they were then applied on every AIRS situation of the second time period. The correction is done before the AIRS cloud detection and identically for the ECMWF, CO_2-slicing and MLEV methods. Indeed, the accuracy of the retrieved cloud information highly depends on the correct simulation of the clear radiance Rclr. Figures 4 show, for this second period, the statistics in bias and standard deviation of the departure between RTTOV7 simulated and observed brightness temperatures before (lower figure) and after (upper figure) the bias correction.

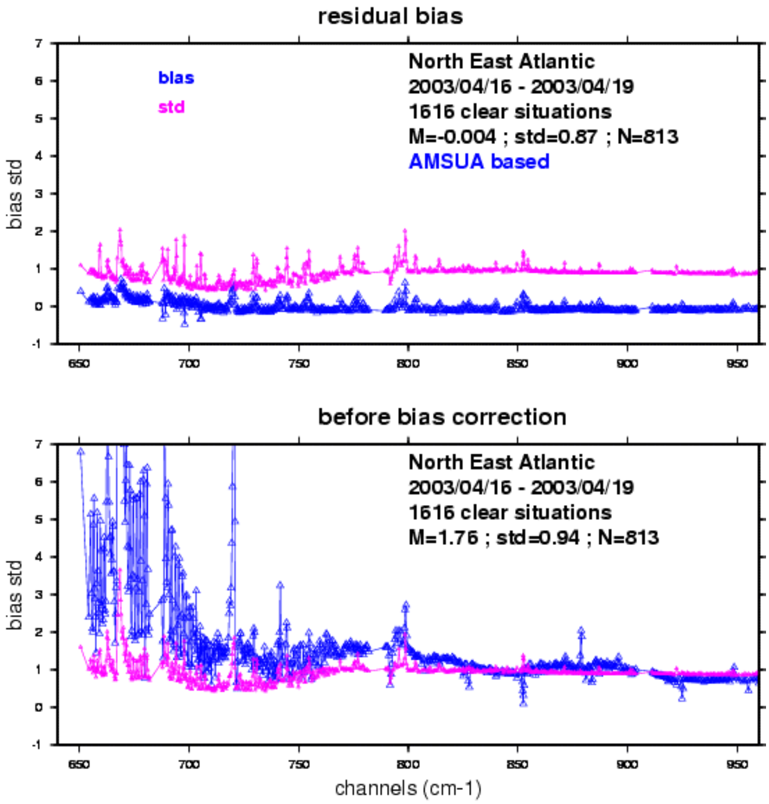


Figure 4: statistics in bias (blue curves) and standard deviation of the departure between RTTOV7 simulated and observed brightness temperatures before (lower figure) and after (upper figure) the bias correction.

NESDIS AIRS cloud detection

The purpose of the NESDIS cloud detection scheme (Goldberg and Zhou, 2002) is the detection of the clear situations, without any cloud characterization in height. It is a very fast model based on an empirical combination of 3 tests applied to AIRS channels and co-registered AMSU-A channels:

1. $AIRS_{sim}$_2112– AIRS_2112 < Thres1 (=2K)
   The simulated AIRS channel 2112 (2391 cm-1) is function of AMSU-A 4, 5, 6 and of the scan and solar zenith angles

and

2. AIRS_2226 (2532cm-1) – AIRS_843 (937.92cm-1) < Thres2 (=10K) (night)
3. Thres3 < SST_{guess} - SST_{sim} < Thres4
   The guess sea surface temperature comes from the nearest French NWP forecast field. The simulated SST is function of the observed AIRS channel numbers 791 (918.747cm^{-1}), 914 (927.122cm^{-1}), 1285 (1228.225cm-1) and 1301 (1236cm-1).

At the time of this study, only pre-launch coefficients were available and slightly different results may be found using the post-launch values.
The NESDIS cloud detection is interested because it does not need to apply a channel bias correction. Also, it is relatively independent of atmospheric prior information, except for sea surface temperature. However, to be accurate, it is important to tune the different thresholds to the concerned time period and geographical location. Figure 5 shows simulated AIRS SST compared to NWP SST for the training dataset. Thresholds of -0.6K and 3.3 K allow the detection of about 99% of the clear situations and more than 95% of the cloudy situations.

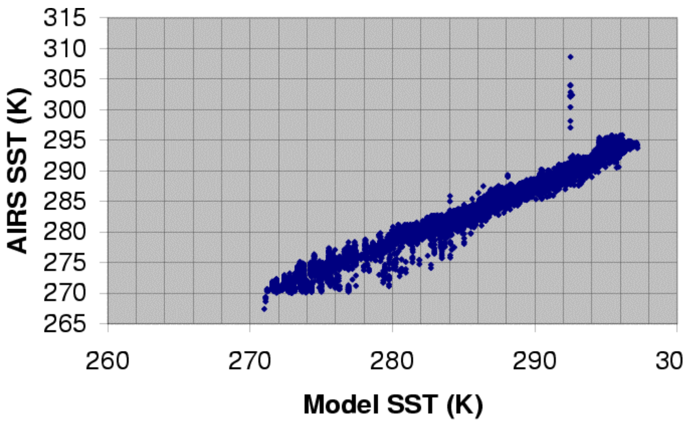


Figure 5: simulated AIRS SST compared to NWP SST for the training dataset.

ECMWF AIRS cloud-free channels selection

The ECMWF scheme (McNally and Watts, 2003) aims to detect channels affected by clouds. Unaffected channels are potentially useful for the NWP assimilation system.
The scheme performs the detection in several steps as follows:

- Simulated AIRS spectra are generated using the nearest NWP forecast profile and the RTTOV7 forward model. Bias correction is applied on each channel.
- Each channel is assigned to the lowest P_k level at which the radiation effect of one opaque cloud layer at P_k, defined as $(|Rclr - Rcld(P_k)|)/Rclr$, is less than 1%. The (measured – simulated) Tbs are then sorted according to the assigned level into five spectral bands at 15, 9, 7, 4.5 and 4.2µm.
- A low pass filter is applied on the ranked information in order to smooth the instrument noise and the cloud emissivity effect.
- Based on the assumption that, when looking downwards, a cloud signal monotonically increases in the channels ranked space, all channels with a (measured – simulated) value less than a threshold are considered as cloud free channels above the cloud layer.

In this study, only the 15µm band was used which concerns 124 channels from the 281 selected channels sent at that time in near-real time by NOAA to European NWP centers. A unique cloud status was given per AIRS fov and not per channel.

CO_2-Slicing Cloud characterization

Calculation of the cloud-top pressure and the effective emissivity is done with the CO_2-slicing method as described by Menzel and Stewart (1983) and Smith and Frey (1990).

$$\frac{(Rclr - Rmeas)_k}{(Rclr - Rmeas)_{ref}} - \frac{Ne_k\,(Rclr - Rcld)_k}{Ne_{ref}\,(Rclr - Rcld)_{ref}} = fpc$$

Rmeas: measured radiance
Rclr: clear radiance computed from a collocated forecast for the same fov
Rcld: black-body radiance at the cloud level n
k= channel in the CO_2 band
ref= reference window channel = 979.1279 cm-1

To summarize the method, the function fpc is computed for each pressure level of the RTTOV7 forward model and the cloud top pressure is the level which minimizes the function. This is done for several channels and the final cloud pressure is the weighted average:

$pcld = \Sigma\,(pcld(k)\,w^2(k)) / \Sigma w^2$

with $W = \delta f_{pc} / \delta \ln p$ the derivative of the cloud pressure function

Then, the effective emissivity is computed for the reference window channel by:

$N\varepsilon = (Rclr - Rmeas)_{ref} / (Rclr - Rcld)_{ref}$

The method assumes that the cloud is a thin layer. A first test determines the situation clear if the departure between clear and cloudy radiances is less than the radiometric noise*sqrt(2) for all the channels. The cloud resulting information is flagged bad if the retrieved cloud emissivity is smaller than 0 or larger than 1.2

We used the CO_2-slicing method for the same 124 selected channels than for the ECMWF scheme from 649.612 cm-1 to 843.913 cm-1. This spectral region provides the best sensitivity to both cloud-top pressure and effective emissivity.

MLEV cloud characterization

The Minimum Local Emissivity Variance scheme (Huang and al, 2003) takes advantages of semi-continuous high spectral resolution spectra. It is a physical method which assumes the slow spectral variation of the cloud emissivity in the CO_2 band. The method simultaneous retrieves the cloud altitude and the effective emissivity spectrum.

For a cloudy or a partially-cloudy fov, the effective cloud emissivity spectrum is given by:

$N\varepsilon(\nu) = (R_{meas}(\nu) - R_{clr}(\nu)) / (R_{cld}(\nu) - R_{clr}(\nu))$

The altitude level which ensures the smallest local variation of the effective emissivity is considered as the optimal cloud top pressure solution. For that, we compute the local variances over $\Delta\nu$=5cm-1 local bands:

$Var_{loc}(\nu) = \Sigma\,[N\varepsilon(\nu) - moy(N\varepsilon(\nu))]^2$ in $[\nu - \Delta\nu/2, \nu + \Delta\nu/2]$

The cloud pressure is the one which minimizes the mean value $\Sigma[Var_{loc}(\nu)]$ in the CO_2 spectral band between 650 cm-1 and 850 cm-1.

For this method, we also used RTTOV-7 and the same NWP background as for the previous two methods for simulating the AIRS clear radiances at each level, for each situation and all channels in CO_2 band. However, we did not yet implement a channel sensitivity to pressure of the local variance $\delta Var_{loc}(\nu) / \delta \ln p$ as we did it in the CO_2-slicing method.

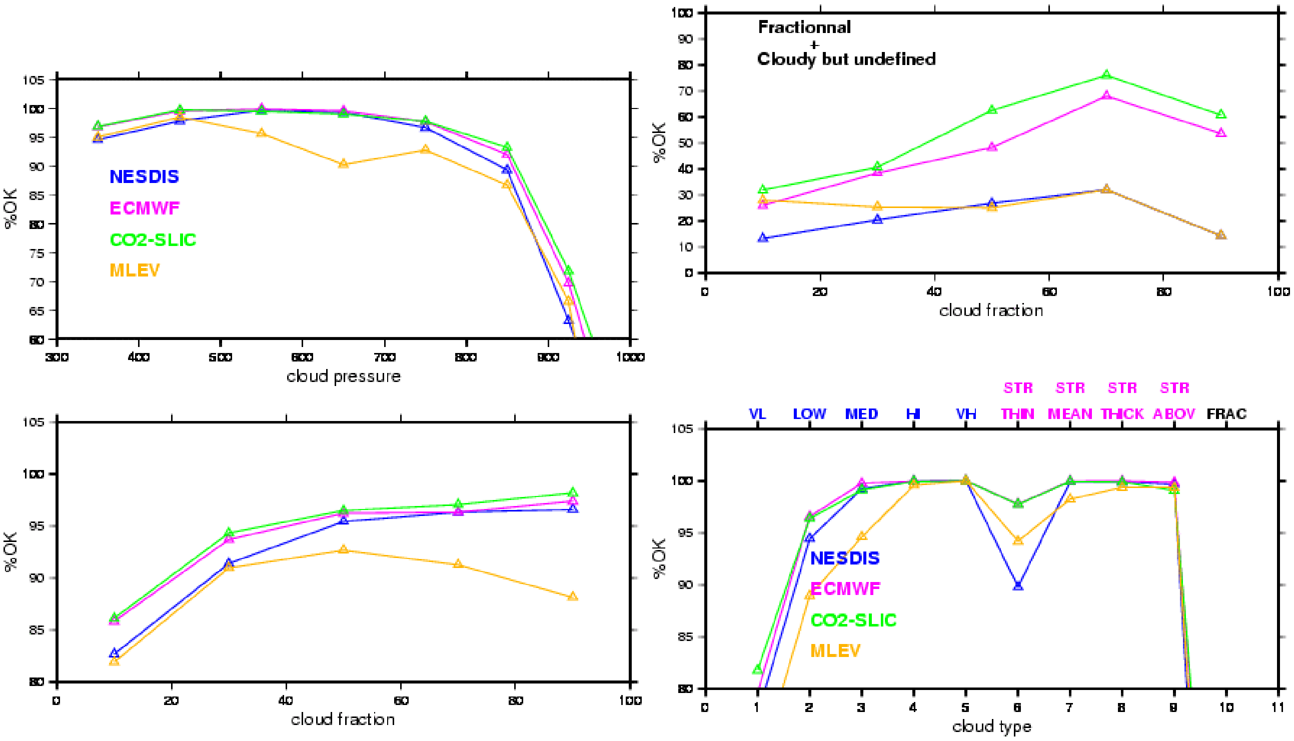
Results

The following results correspond to the processing of the second part of the dataset from 16 to 20 April. Dynamic coefficients and thresholds applied in the treatment have been first determined on the training part of the dataset.

	Clear sit. correctly detected		Cloudy sit. correctly classified	
	Day	night	day	night
Number of situations	2799	5470	28510	57719
NESDIS	83.42%	85.52%	87.83%	94.80%
ECMWF	82.67%	88.45%	88.07%	94.36%
CO2-slicing	75.85%	84.11%	89.05%	94.62%
MLEV	76.77%	82.07%	84.33%	91.45%

Table 1: Overall cloud masks efficiency in % of the four schemes for day and night illumination.

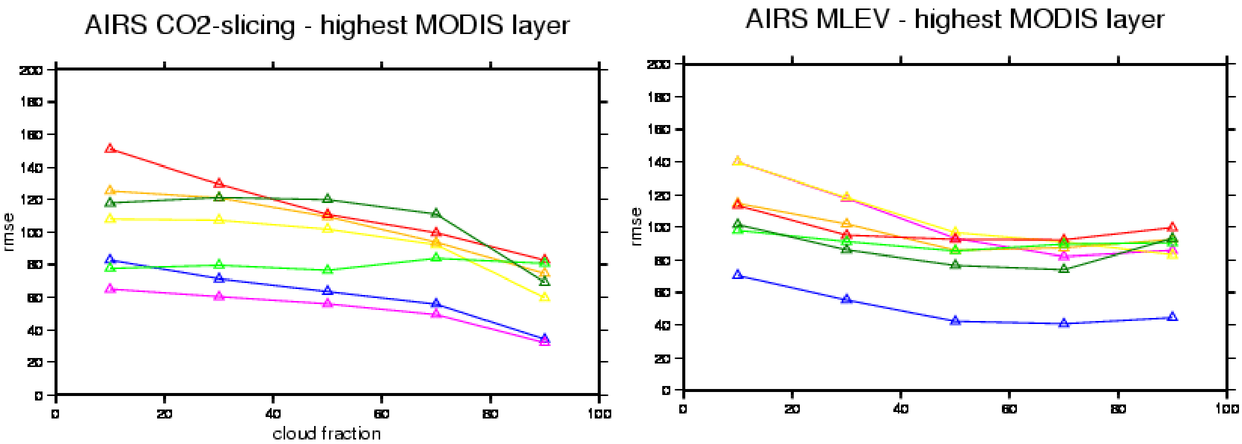
For all the granules, we did a systematic visual comparison (not shown here) of the different cloud parameter fields with the corresponding MODIS fields. For all schemes and granules, synoptic cloud patterns are correctly detected. Table1 shows the overall cloud masks efficiency for the different schemes when compared to MODIS. It should be noted that of course the MODIS mask has its own weakness which contributes to the comparison. Nevertheless, the results are very encouraging indicating that the clouds can be efficiently detected with AIRS alone. Results during the night seem systematically better; this could be due to a better accuracy of the background SST used in the four models.



Figures 6: cloud-detection masks efficiency in %, function of the cloud layer cover (lower left figure), of the cloud pressure (upper left) and with the different cloud categories (lower right) given by MODIS. The categories are for opaque clouds Very low, Low, Medium, High, and Very high and for semi-transparent clouds Thin, Mean, Thick optical thickness and clouds above others. A last category defines fractional clouds at the MODIS resolution. The upper right figure is a 'zoom' for the fractional and unclassified clouds by MODIS.

Figures 6 give more details on the cloud-detection masks efficiencies for different characteristics of the cloud layers (cloud cover, pressure and types) inferred with MODIS. For all schemes, small amount of clouds are still difficult to be retrieved. Also some clouds near the surface are missed. From a personal discussion with G. Aumann, the use of the super-window channel at 2616cm-1 (which is not a MODIS channel) should greatly improve the detection of small amounts and low-level clouds. This channel is already used in the NESDIS post-launch detection scheme and we will introduce it in the other methods for future test experiments.
The comparison with the cloud classification shows that thin semi-transparent clouds are difficult to be detected. For these situations, the AIRS footprints are generally completely overcast and the problem is mostly due to the insensitivity of the sounding-based methods to thin optical thickness layers (use of constant and identical thresholds…). The addition of specific threshold cirrus tests from the large imager experience should improve the detection. Also, the description of the atmosphere on more pressure levels could improve the sensitivity of the methods mainly for the MLEV method.
The MLEV scheme appears to be very sensitive to the measurement noise which is important and extremely different between adjacent channels for AIRS on the CO_2 band and an additional treatment to filter the noise through a PCA method has to be added. Detection of mid-tropospheric layers is mainly affected by the noise. Simulations with the METOP/IASI noise characteristics indicate that the method could give results as accurate as the other methods.

Figures 7 show preliminary accuracy estimations of AIRS cloud top pressures inferred with the CO_2-slicing and MLEV, function of the MODIS cloud cover. In case of several cloud layers, the AIRS information is compared to the MODIS highest cloud level. The purpose is to get an incertitude for the selection of unaffected cloud channels above the cloud fields. As said previously, the MODIS cloud top height is also based on a CO_2-slicing method and in the left figure the root mean square of errors is mainly due to the combined incertitude of the same method for two different instruments and to the average with AIRS of the complexity of the situation. Firsts results with the MLEV methods are encouraging: the method seems very sensitive to the top cloud layer in case of multi-layers and more stable with the cloud cover and the cloud height. Not shown here, the comparison with the underlying layers gives worse results. This has to be confirmed with further experiments.



Figures 7: cloud top pressures accuracy for the CO2-slicing and MLEV methods compared to MODIS for different layer levels; <400hPa, 400-500hPa, 500-600hPa, 600-700hPa, 700-800hPa, 800-900hPa, >900hPa.

Conclusion

For all schemes, the synoptic cloud patterns, in cloud detection and height characterization, are correctly detected.

Concerning the cloud detection, for the four schemes, we have a general good agreement with the MODIS cloud mask above 900hPa but the sensitivity to clouds is poor near the surface and for fractional or unclassified clouds.
ECMWF and CO_2-slicing methods are very efficient and give similar results. However, the MODIS description inside the AIRS fov is still useful for the 'difficult' situations, for small amount of clouds, fractional or thin semi-transparent clouds.
The NESDIS model with pre-launch coefficients is less efficient for the thin semi-transparent and fractional categories. However, thresholds depending on location, computing in-line from atlas or forecast, could surely improve the detection. We must note that the NESDIS scheme gives really good information considering that the model is fast, simple and independent of any forecast profile.
In this study, the MLEV method was less efficient than the others, mainly for detecting mid-tropospheric layers and fractional clouds. From simulations, it appears that the method is very sensitive to the measurement noise. We did not try here to filter the AIRS measurement noise, except by only removing all channels with an NeDt, as provided by NOAA, larger than 0.6K but a better treatment is required.

Concerning the cloud top pressure determination, only retrieved in this study with CO_2-slicing and MLEV, for multi layers situations, both methods are better correlated with the highest layer and the MLEV scheme seems more efficient, with a good coherence with MODIS even for small fraction. This of course has to be confirmed on other test cases.

This comparison will be extended to other test cases. This will be the opportunity to improve the MLEV method, by filtering the AIRS measurement noise with a PCA method as described by Huang and Antonelli, 2001, by implementing in the scheme the channel sensitivity to pressure of the local variance. Also, concerning the NESDIS method, we will use the post launch model as described in Goldberg, 2003.

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