Assimilation of cloudy AIRS observation in the French global atmospheric model: ARPEGE

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Abstract

Infrared and microwave clear-sky observations from polar orbiting satellites are assimilated in the French numerical weather prediction (NWP) model ARPEGE through a 4 dimensional variational (4D-Var) assimilation scheme and represent an important source of information. Since the end of 2006, a few stratospheric channels of the Atmospheric InfraRed Sounder (AIRS) are assimilated in ARPEGE. On the other hand, a large majority of measurements from such advanced infrared sounders are affected by clouds, and cloud contaminated observations are currently rejected by the data assimilation system. The observation operator which simulates the radiances from model fields include a radiative transfer model, RTTOV in the case of ARPEGE. Since clouds can affect the infrared observations, a cloud detection is necessary before data are assimilated. Several cloud detection schemes have been used: a cloud detection scheme based on channel ranking, called Cloud-Detect, from the ECMWF; a CO2-slicing method and a cloud detection based on the simulation of the sea surface temperature. Previous studies have shown that the two first cloud detection schemes are the most accurate ones. This paper focuses on the validation of both schemes applied to AIRS, by using independent data coming from the MODIS imager and from the POLDER radiometer. The validation of the cloud top pressure will also be discussed. It is now well known that the sensitive regions, where cyclogeneses occur, are often cloudy. This motivates our research efforts to assimilate AIRS cloudy radiances inside the 4D-Var assimilation scheme.Two approaches may be tested: the first one uses the cloud top pressure and the cloud cover derived from the CO2-slicing technique (CO2-slicing outputs are directly used by RTTOV to simulate the cloud-affected spectrum). In the second one, CO2-slicing outputs are adjusted by a prior 1D-VAR before being used by RTTOV. Preliminary experiments have been done which consisted in assimilating AIRS radiances, including those contaminated by clouds between 600 and 950 hPa, only over sea for 54 stratospheric and tropospheric peaking channels. A slightly positive impact is found for the first method. The impact of the cloudy assimilation on cloud fields in ARPEGE will be studied in this paper.

1   Introduction

Infrared and microwave clear-sky observations from polar orbiting satellites are assimilated in the French Numerical Weather Prediction (NWP) global model ARPEGE through a 4 dimensional variational (4D-Var) assimilation scheme and represent an important source of information. The Atmospheric Infrared Sounder (AIRS) onboard *Aqua* satellite makes part of a new generation of advanced satellite sounding instruments (with IASI) which allows to provide information about atmospheric temperature and humidity profiles with spectral resolution far exceeding that of previous sounders (HIRS). These highly informative observations are to be used to improve NWP analysis and forecast accuracy. On the other hand, a large majority of measurements from such advanced infrared sounders are affected by clouds (90%), and cloud-contaminated observations are currently rejected by the data assimilation system because of the deficiencies in the representation of cloud processes within the atmospheric models. Furthermore, it is now well known that the sensitive regions, where cyclogeneses occur, are often cloudy (McNally, 2002; Fourrié and Rabier, 2004). This motivates our research efforts to assimilate AIRS cloudy radiances inside the 4D-Var assimilation scheme.

Since clouds can affect the infrared observations, clouds have to be detected before data are assimilated. Indeed, unfiltered cloud observations can have a negative impact on the quality of NWP analysis. Several cloud detection schemes have been used: a cloud detection scheme based on channel ranking, called Cloud-Detect, from the ECMWF (European Centre for Medium-range Weather Forecast); a CO2-slicing method and a cloud detection based on the simulation of the sea surface temperature. Previous studies have shown that the two first cloud detection schemes are the most accurate ones (Dahoui.M., 2005).

This paper first focuses on the validation of both schemes applied to AIRS, by using independent data coming from the MODIS (Moderate Resolution Imaging Spectroradiometer) imager. The validation of the cloud top pressure will also be discussed for the CO2-Slicing scheme. After the validation of both cloud schemes, the method used to directly assimilate cloudy radiances in the 4D-VAR assimilation sheme of ARPEGE will be presented in a third part. The results in term of impact on the quality of the analysis product and on the accuracy of the forecast of this first step of assimilation of cloudy radiances will then be discussed.

2   Validation of AIRS clouds detection schemes

2.1   AIRS clouds detection scheme

2.1.1   ECMWF scheme

The ECMWF scheme (McNally and Watts, 2003) aims at detecting clear channels within a measured spectrum rather than the location of totally clear pixels. If the background spectrum is close enough from the true state of atmosphere, the cloud signature is identified by the first-guess departure of the observed spectrum from clear-sky background values. Channels are first re-ordered into a vertically ranked space that reflects their relative sensitivity to the presence of cloud. The ranking consists in assignating for each channels, a pressure level p_i (in RTTOV coordinates) at which the radiation effect of a one-layer black cloud defined as $\frac{|R_{clear}-R_{cld}^{p_i}|}{R_{clear}}$ at p_i is less than 1%. R_{clear} denotes the simulated clear radiance and $R_{cld}^{p_i}$ denotes the simulated black-body radiance at the cloud level p_i.

A low-pass filter is then applied to the ranked departures to reduce the instrument noise and the cloud emissivity effect.

Finally a search for the channel at which a monotonically growing departure can first be detected permits to determine the first significant cloud contamination. Having found this channel, all channels ranked less sensitive are flagged cloud free and all channels ranked more sensitive are flagged cloudy.

2.1.2   CO2-Slicing scheme

The CO2-Slicing method (Chahine, 1974; Menzel, 1983), based on radiative transfer principles, is currently used to retrieve cloud-top pressure (CTP) and effective cloud emissivity or effective cloud amount (ECA). This method uses a simplistic cloud model: cloud is considered as a single layer of opaque or semi-transparent thin cloud with an homogeneous emissivity. The algorithm uses observed radiances of a set of AIRS channels selected in the CO2 absorption band: 124 channels situated in the spectral band between 649 cm^{-1} and 843 cm^{-1} (which is very sensitive to the presence of clouds) are used for this study. For each AIRS pixel, and for each channel of the set, the following function is calculated:

$$F_{k,p} = \frac{(R_{clear}^k - R_{meas}^k)}{(R_{clear}^{k_{ref}} - R_{meas}^{k_{ref}})} - \frac{(R_{clear}^k - R_{cld}^{k,p})}{(R_{clear}^{k_{ref}} - R_{cld}^{k_{ref},p})},$$

where:

- p: pressure level number,
- k: channel inthe CO2 band,
- k_{ref}: reference window channel (979,1279 $cm^{-}1$),
- R_{meas}^k: measured radiance in channel k,

- R^k_{clear}: simulated clear radiance in channel k,

- $R^{k,p}_{cld}$: simulated black-body radiance for channel k at the cloud level p.

The cloud-top pressure level $p_{c,k}$ assigned to each channel k is the pressure level which minimizes the function $F_{k,p}$. Before the determination of the CTP of an hypothetic cloud, a filter which distinguish channels with δTBs (δTBs represents the difference between observed brightness temperature and simulated brightness temperature) lower than the radiometric noise is applied to the algorithm. If all channels are filtered, the pixel is flagged clear.

If the pixel is cloudy, the cloud-top pressure p_c is then calculated by the following expression:

$$p_c = \frac{\sum p_{c,k} w_k^2}{\sum w_k^2}$$

where $w_k = \delta F_{k,p}/\delta lnp$ is the derivative of the cloud pressure function.

The effective emissivity is obtained for each AIRS pixel by the following expression:

$$N_e = \frac{(R^{k_{ref}}_{clear} - R^{k_{ref}}_{meas})}{(R^{k_{ref}}_{clear} - R^{k_{ref}}_{cld})}$$

If the algorithm produces a retrieved N_e smaller than 0.1, the pixel is flagged clear. The pixel is rejected if the algorithm generates a retrieved N_e lower than 0 or larger than 1.2 (non physical emissivity).

2.2 A validation based on independant datas: the imager MODIS

2.2.1 MODIS cloud description

The first part of this study aims at statistically comparing both above-descrived cloud-detection schemes applied to AIRS data onboard *Aqua* satellite. Independent data are thus required to get an accurate reference. For this study, we have used a cloud-detection scheme product based on MODIS data. The MODIS imager is a key instrument onboard the EOS *Terra* and *Aqua* satellites which provides global observations of Earth's land, sea and atmosphere in 36 spectral bands ranging from 0.41 μm to 14.385 μm (visible, near infrared and infrared regions). In this study we have used the MODIS Cloud data product file MYD06-L2, containing level 2 data collected from the Aqua platform. The determination of cloud-top properties will require the use of MODIS bands 29 and 31 to 36, along with the cloud-mask product to screen for clouds. Two output parameters were retrieved to validate our cloud-detection schemes: the Cloud-Fraction (Day and Night) and the Cloud-Top-Pressure (Day and Night). These level-2 Cloud Product parameters are produced at an horizontal resolution of 5 km at nadir and cover a five-minute time interval. We have used in this study, Cloud data products from the ICARE centre ($http://www-icare.univ-lille1.fr/archive/index.php?dir = MODIS/MYD06_L2/$) which produces and distributes remote sensing datas derived from Earth observation missions from CNES, NASA and EUMETSAT.

2.2.2 Spatial collocation of MODIS and AIRS

As noted above, MODIS cloud product will be used to evaluate the accuracy of AIRS cloud detection scheme. This requires a MODIS cloud description for each AIRS pixels. Because MODIS and AIRS are two independant instruments with different scanning geometry and resolution, the merge of MODIS into AIRS geometry is necessary. The first step is to represent each AIRS pixels as an oversized circle according to Tobin method (Tobin *et al.*, 2006): each diameter of AIRS pixel is 10% oversized; the nadir footprint is then considered as a circle with a diameter of 14.85 km (instead of 13.5 km) and at the maximum scan angle of $49,5^{\circ}$, the footprint is considered as a circle 36.3 km (instead of an ellipsis which a 33 km-long major axe). The representation of AIRS footprints as circle leads to a better computational efficiency in case of large scale collocation with as good results as without this approximation. The second step is to determine MODIS pixels that are geolocated within the AIRS footprint determinated above by a mapping algorithm. Finally, the third step is to compute the weighted average of each MODIS pixels values (in function of the relative distance between the geolocated MODIS pixel and the center of the AIRS circle) geolocated within a AIRS footprint.

2.3 Comparison of the ECMWF scheme and the CO2-Slicing scheme with MODIS imager

2.3.1 Data sets

Due to downloading ressource limitations, the comparison is limited to the Atlantic region from 60° South to 60° North ; only situations over sea have thus been processed. The validation is performed within a ten day and ten night period: from 01 to 10 September 2006. The validation was performed from 13h00 to 15h30 UTC during daytime and from 02h00 to 04h30 UTC during night-time (when AQUA is above Atlantic ocean). A total of 6538 AIRS pixels during daytime and 9168 AIRS pixels during night-time have been processed. For both cloud-detection algorithms, the same subset of 124 channels is used (those situated in the CO2 band).

2.3.2 Results and discussion

Once AIRS and MODIS data are collocated, categorical contingency tables will split data into 4 different categories (see following table) which will then be used to compute some verification scores to evaluate the accuracy in term of detection of both cloud-detection scheme.

HITS	FALSE ALARMS	*forecasted cloud*
MISSES	CORRECT REJECTIONS	*non forecasted cloud*
observed cloud	*non observed cloud*	N=total

The verification scores are :

- the frequency bias (BIAS) which gives the ratio of the forecast cloud frequency to the observed cloud frequency:

$$BIAS = \frac{HITS + FALSE\,ALARMS}{HITS + MISSES}$$

- the proportion of correct (PC) which gives the fraction of all forecasts (by MODIS) that were correct:

$$PC = \frac{HITS + CORRECT\,REJECTIONS}{N}$$

- the probability of detection (POD and POD') which measures the fraction of observed events that were correctly forecast by MODIS (POD is a cloudy pixel event and POD' is a clear pixel event):

$$POD = \frac{HITS}{HITS + MISSES}$$

$$POD' = \frac{CORRECT\,REJECTIONS}{CORRECT\,REJECTIONS + FALSE\,ALARMS}$$

- the false alarm ratio (FAR) which gives the fraction of forecast event that were observed to be non-events:

$$FAR = \frac{FALSE\,ALARMS}{HITS + FALSE\,ALARMS}$$

- the non detection rate (NDR) which measures the fraction of observed events that were badly forecast:

$$NDR = 1 - POD$$

In this study, clear/cloudy thresholds have been chosen according to Lavanant (Lavanant *et al.*, 2004): a pixel is flagged cloudy by MODIS if the retrieved cloud fraction is more than 5% and a pixel is flagged cloudy by CO2-Slicing if the retrieved cloud fraction is more than 10%. With the Cloud-Detect scheme, a pixel is flagged cloudy if all channels used in this algorithm are cloud-free. As mentionned in part 2.1.2, the CO2-Slicing scheme can produce a non physical retrieved N_e. According to Dahoui (Dahoui.M., 2005), these pixels with non-physical N_e are clear in most of cases but we have noticed that some of these pixels are flagged cloudy by MODIS (about 30%) and we thus made the choice not to evaluate these pixels.

The following table gives the main results in term of accuracy of detection for both cloud-detection scheme during day and night:

	Cloud-Detect		CO2-Slicing	
	Day	Night	Day	Night
BIAS	89%	83%	83%	87%
PC	80%	76%	78%	80%
POD	82%	78%	78%	82%
POD'	65%	63%	76%	63%
FAR	6%	6%	7%	7%
NDR	18%	22%	22%	18%

Results show that a small percentage of "FALSE ALARMS" is found for both schemes: between 6 and 8% and between 3.5 and 4.5% respectively for the Cloud-Detect scheme and the CO2-Slicing scheme (not shown). These percentages can mainly be explained by two reasons: (*i*) the bias correction could be not stringent enough and systematic biases remain and (*ii*) schemes are tuned to reject some doubtful clear pixels instead of assimilate a cloudy pixel as a clear one (Dahoui.M., 2005). A small percentage of "MISSES" is also found for both schemes (about 20% for the Cloud-Detect scheme and 18% for the CO2-Slicing scheme): it can be explained by (*i*) the lower spatial resolution of AIRS according to MODIS (13.5 km against 5 km) which prevent the detection of fractional clouds (sub-pixel clouds) by AIRS; (*ii*) the weakness of both cloud detection schemes to detect low clouds (as we will see below). However, this percentage is not due to a bad choice of clear/cloudy threeshold for MODIS (5%) as results are worst with a 10% threshold (not shown).

As we can see in the above-writen table, the Cloud-Detect scheme seems to produce better results during daytime: 89% (BIAS) of forecast clouds are actually observed (83% during night-time), 82% (POD) of the observed clouds are actually forecast (78% during night-time), the detection of clear pixels (POD') and the proportions of correct (PC) are also better during daytime. An opposite diagnostic can be made for the CO2-Slicing scheme: both BIAS, PC and POD are better from 2 to 4 % during night-time. POD', much better during daytime, is the only remaining exception for the CO2-Slicing. These day/night statistics are made under the hypotesis of same performances of MODIS during the day and during the night. Although a sea surface temperature (SST) test has been implemented to improve the MODIS cloud mask during the night (Baum, 2006), we did not find any study which compare the day/night performances of the MODIS cloud mask.

Furthermore, performances of both schemes are comparable in BIAS, PC, POD, FAR and NDR (the CO2-Slicing is more accurate than Cloud-Detect during night-time but the latter is more accurate during daytime). However, the detection of clear sky pixel which is comparable for both schemes during night-time is much more performant for CO2-Slicing during daytime.

Figure 1 highlights the accuracy of cloud detection (POD) according to cloud-top pressure for both schemes in a diurnal cycle. As we can see, the detection of high clouds (cloud-top pressure <400 hPa) is better during night-time (except betwen 300 and 400 hPa for the Cloud-Detect scheme). This could be explained to a better accuracy of the SST used in both scheme during night-time. Performances of both schemes are comparable during night-time but the Cloud-Detect is more performant to detect this kind of cloud during daytime. The detection of medium clouds (between 400 and 800 hPa) delivers the best results. This detection is better for CO2-Slicing during night-time than for the Cloud-Detect but the latter is better during day-time. Finally the detection of low clouds (cloud-top pressure >800 hPa) delivers the worst results. This detection is better during night-time for both schemes.
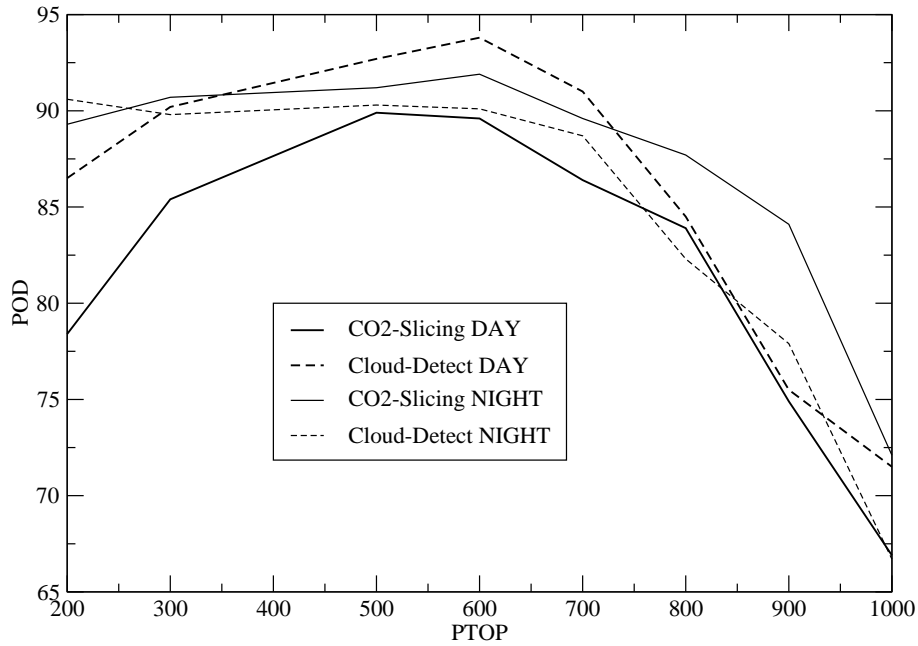
5

Figure 1: Efficiency of the cloud detection according to the retrieved PTOP from MODIS. Validation from 09/01/06 to 09/10/06. The thick solid line represents the potential of detection of clouds of the CO2-Slicing during the day, the thich dashed line represents the potential of detection of clouds of the Cloud-Detect during the day, the thin solid line represents the potential of detection of clouds of the CO2-Slicing during the night and the thin dashed line represents the potential of detection of clouds of the Cloud-Detect during the night
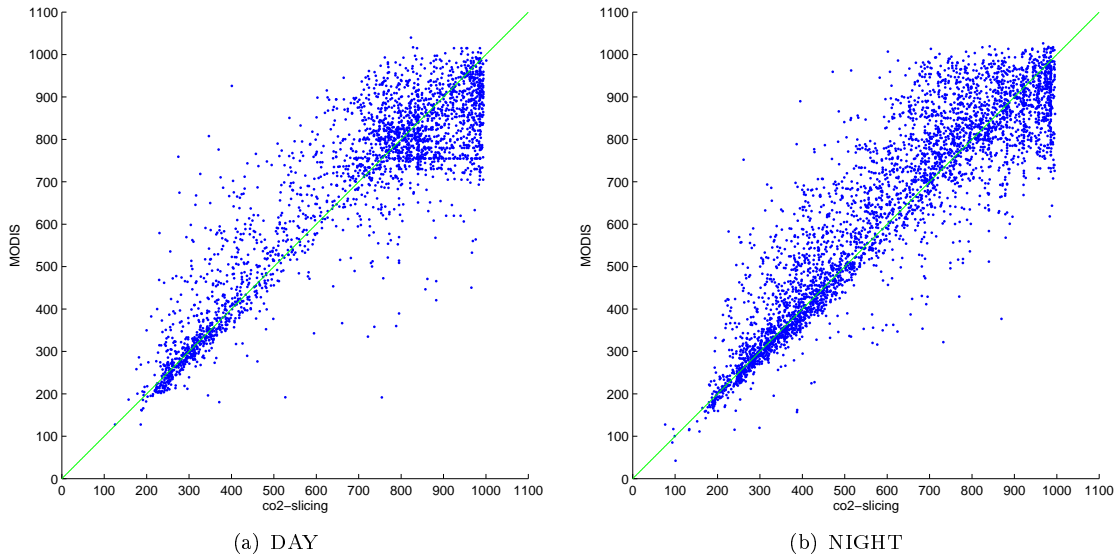

(a) DAY

(b) NIGHT

Figure 2: Cloud Top Pressure accuracy for CO2-Slicing for Day (left) and Night (right) according to MODIS Cloud Top Pressure. Validation from 01/09/06 to 10/09/06

The retrieved PTOP from CO2-Slicing exhibits a quite good correlation with the PTOP inferred with MODIS for both day (figure 2(a)) and night (figure 2(b)). This result seems normal because the MODIS cloud height is based on a CO2-Slicing method. The difference observed in figure 2 (specially for low

clouds) are thus mainly due to the complexity of the situation and to the incertitude of both instruments. We can notice a better correlation for high and medium clouds (from 100 to 500 hPa) than for low clouds (from 600 to 1000 hPa). Highlighting a trend here is not obvious but for the majority of pixels, the CO2-Slicing puts the cloud higher than MODIS (especially during the night).

3 Assimilation of cloud-affected Infra-red satellite radiances

In the previous chapter, the cloud detection scheme validation permitted first to consolidate our skill in term of assimilation of clear radiances, namely a good detection and rejection of pixels contaminated by clouds. With the CO2-Slicing method, tools are also made available to classify an AIRS pixels in function of the nature of a potential cloud. In the following chapter we will use these characterization tools to assimilate cloudy radiances.

3.1 Methodology : direct use of the CO2-Slicing cloud parameters

The observation operator for the assimilation of cloudy radiances consists in this work of a cloud scheme (CO2-Slicing) and a radiative transfer model (RTM), RTTOV : in this approach, cloud parameters (CTP and ECA) are retrieved from infrared radiance measurements using the CO2-Slicing algorithm and are then directly used as inputs of RTTOV which will then simulate the cloud-affected spectrum. In this method, ECA and CTP are thus determined in the beginning of the assimilation cycle with no adjustments during the minimisation.

3.2 Simulation study framework

3.2.1 Satellite data

This study uses data from AIRS. We have used in this study a subset of 54 channels located in the temperature long-wave window chosen among the 2378 channels available on AIRS instrument: 20 stratospheric channels with weighting-functions peaking from 69 to 102 hPa and 34 upper-tropospheric channels with weighting-functions peaking from 122 to 478 hPa. This channel subset is is the operationnal one in Météo-France since July 2008. The assimilation period of this study is 5 week long, from the 01/09/06 to the 05/10/06. First experiments have been run in a simplified framework: AIRS radiances have been assimilated, included those contaminated by clouds between 600 and 950 hPa, only over sea.

3.2.2 Model data

The NWP model used in this work is ARPEGE (Courtier et al., 1991) which is Météo-France operational global model. The code version used here is the CY32t0 with a 4 dimensional variational (4D-VAR) assimilation. Satellite radiance data are bias corrected using the variational bias correction VarBC (Dee, 2004; Auligné et al., 2007). As we have seen in the part 3.1, the model needs a RTM to simulate radiances from atmospherical, geophysical and spectroscopical variables. In this work, we use a fast RTM, the 8.5 version of RTTOV which is the operational version of RTTOV in Météo-France.

Two different types of experiments have been run to test the impact of the direct assimilation of cloudy radiances: the first one (B0A8) assimilates cloudy radiances in the configuration presented in part 3.1; the second one (B0A9) is a reference experiment which only assimilates clear radiances, similarly to an operational configuration.

3.3 Results

3.3.1 Impact on analyses

The impact of the assimilation of cloudy radiances on the analysis will be evaluated by comparing biases and root mean square (RMS) errors of both analyses and background with respect to various observations, for the experiment and the reference. This impact will be evaluated over 18 days, from the 12/09/06 to the 30/06/09.

We first can remark that RMS errors are almost not impacted by the assimilation of cloudy radiances (not shown). On the other hand, both background and analysis biases are improved at many geographic locations and for many parameters. We have only shown in this paper the most significant improvements:

- improvements of background and analysis biases to conventional data in Northern Hemisphere: temperature (figure 3(b)) and zonal winds (figure 3(a)) from radiosoundings) and zonal and meridional winds from winds profilers (figure 3(c)). All these improvements are better for background biases then for analysis biases.

- improvements of background and analysis biases for satellites data: especially for SSMI in the Tropics (figure 3(d)) and AMSU-A in northern hemisphere (not shown).

(a) Zonal wind from radiosonds in HN

(b) Temperature from radiosonde in HN

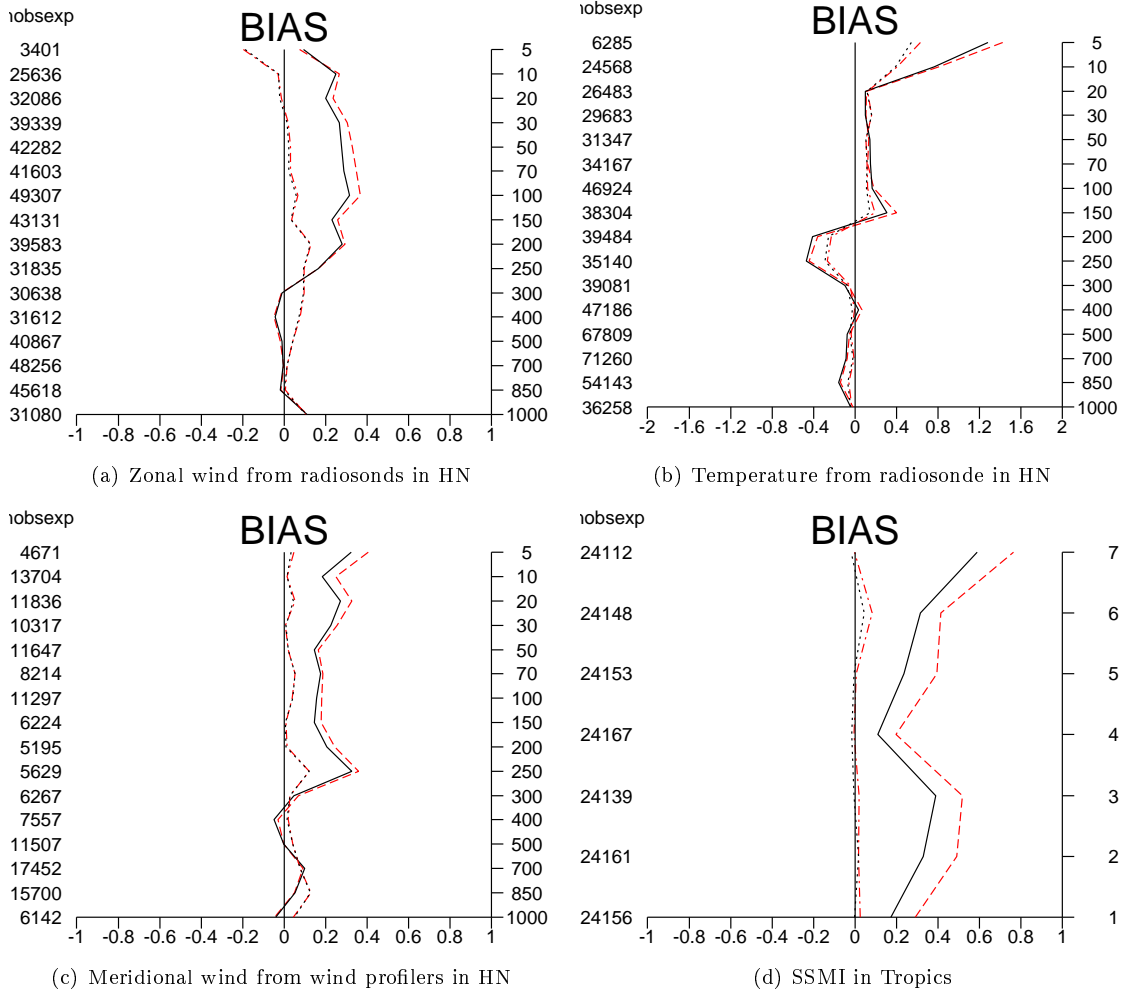(c) Meridional wind from wind profilers in HN

(d) SSMI in Tropics

Figure 3: Biases from B0A8 and B0A9 (ref) from 12 to 30/09/06. The solid-black line represents the background departure of B0A8, the dot-black line represents the analysis departure of B0A8, the dot-dashed red line represents the analysis departure of B0A9 (ref) and the dashed-red line represents the background departure of B0A9 (ref)

3.3.2 Impact on forecasts

The impact of the assimilation of cloudy radiances on the forecasts will be determined by comparing the forecast objective score with respect to radiosoundings data from both experiment and reference. This impact is globally neutral for wind and humidity.

For the geopotential (figure 4(a) and figure 4(b)), we can notice a significant improvement of the forecast in the stratosphere for all domains and for all ranges of forecast.

For the temperature (figure 5(a) and figure 5(b)), the impact is less significant but still positive, especially over Europe and in Tropics. This impact is mainly situated in the tropophere.

(a) Europe
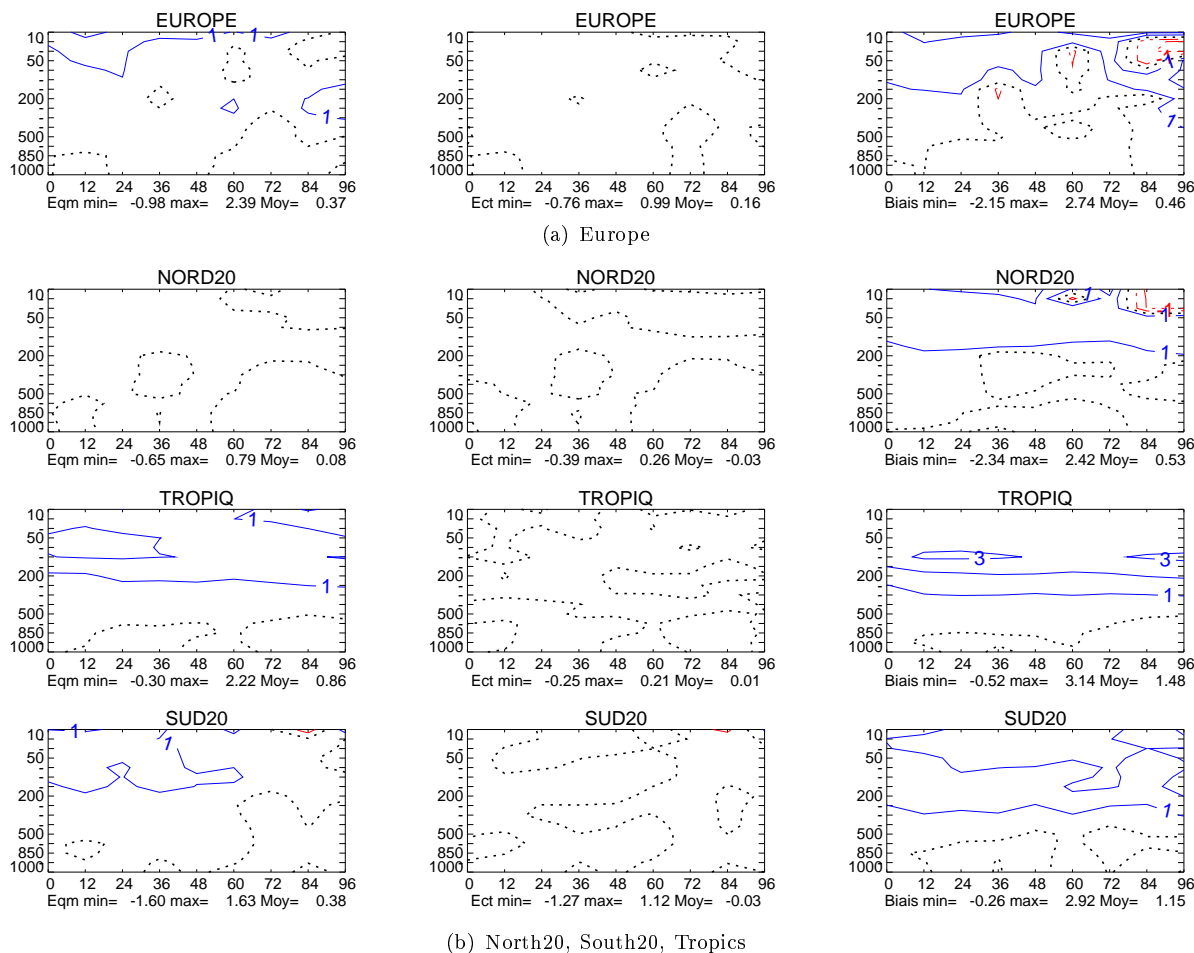
(b) North20, South20, Tropics

Figure 4: Forecasts objective scores for the geopotential with respect to radiosounds data from the 01/09/06 to the 04/10/06. The left column represents the root mean square error, the middle column represents the standart deviation, the right column represents the bias
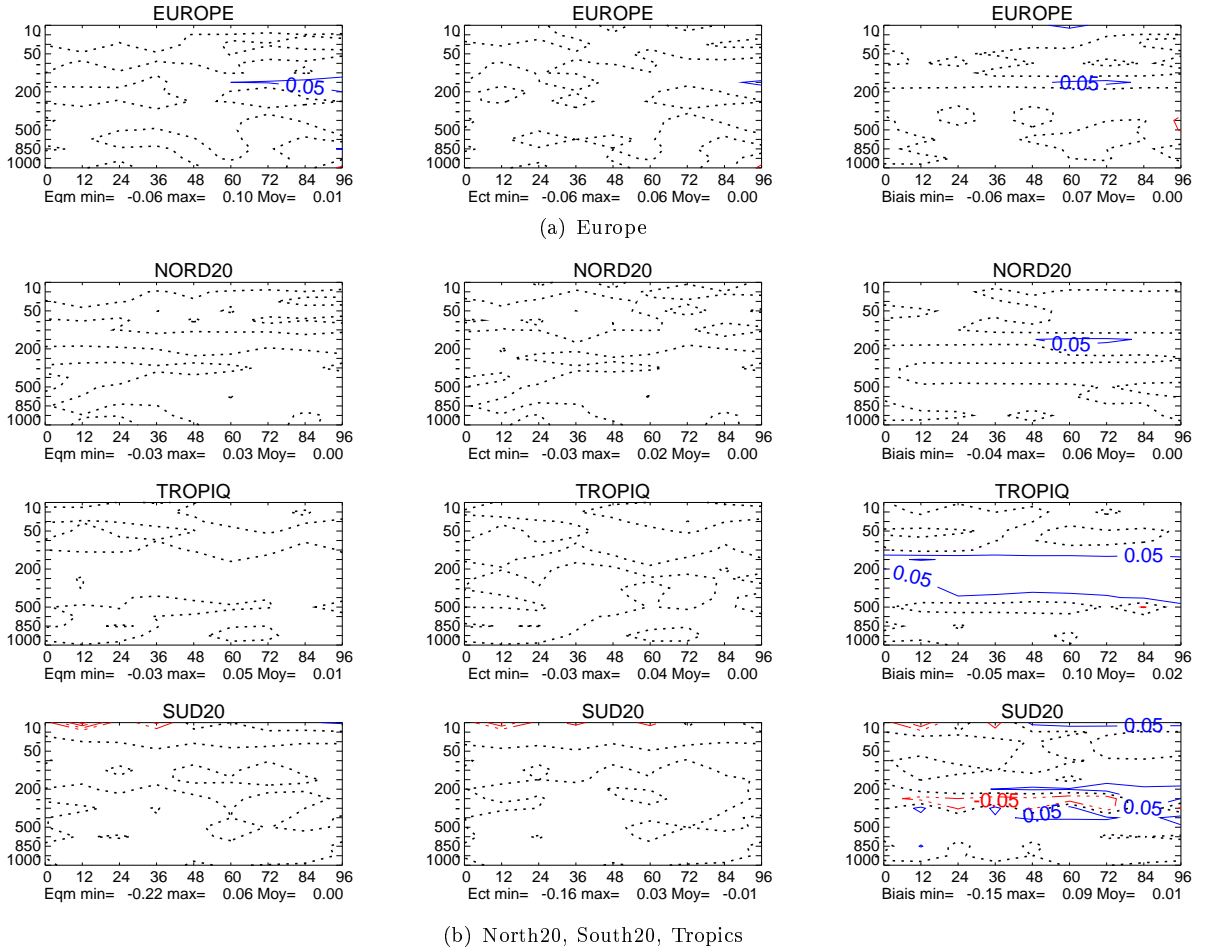
(a) Europe

(b) North20, South20, Tropics

Figure 5: Forecasts objective scores for the gtemperature with respect to radiosounds data from the 01/09/06 to the 04/10/06. The left column represents the root mean square error, the middle column represents the standart deviation, the right column represents the bias

4 Conclusion and future developments

The goal of this paper was first to validate two cloud-detection schemes: The Co2-Slicing and the Cloud-Detect scheme. We have seen that both schemes exhibit quite good results and comparable performances, with best performances during day for the Cloud-Detect scheme and best performances during night for the CO2-Slicing. The cloud detection performances fluctuates with respect to the elevation of the cloud considered: the detection is better for medium clouds (400-800 hPa) and worse for low clouds (800-1000 hPa) for both schemes. We have also seen that the retrieved PTOP from CO2-Slicing exhibits a quite good correlation with the PTOP inferred from MODIS for both day and night. We also have noticed a better correlation for high and medium clouds (from 100 to 500 hPa) than for low clouds (from 600 to 1000 hPa).

Once the validation of both cloud-detection schemes made, we have used the CO2-Slicing cloud-characterization tools to directly assimilate cloudy radiances in ARPEGE, in a simplified framework. First results are promising in term of improvement on analyses and forecasts : analyses and background biases are reduced for most of conventional data and for some of satellites data. Forecasts are also improved especially for geopotential and temperature.

The next step will consists in assimilating cloudy radiances in a more realistic framework: assimilation of cloudy radiances between 400 and 950 hPa over sea and over land. Others assimilation techniques will also be conducted: in a first time, a prior adjusment of cloud parameters by a 1D-VAR scheme before being used by RTTOV could help to reduce characterizations errors (detection of low clouds and some caracterisation errors in term of cloud-cover or CTP). In a second time, the adjustment of cloud parameters could be made into the 4D-Var minimization process so as to obtain cloud parameters more consistent with others control variable. The assimilation of cloud-affected radiances will then be extended to IASI data.

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