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Cloud type identification algorithm to simulate MSG infrared radiance using the Radiative Transfer Model RTTOV and ALADIN forecasting output

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Abstract - *In numerical weather prediction (NWP), the big challenger in satellite data assimilation is the presence of cloud essentially the convective cloud. In this work, we focus only on the simulation of SEVIRI radiances of MSG2 satellite, using the radiative transfer operator RTTOV in its 9.3 version, by introducing the fields provided by the model ALADIN/Algeria. This simulation can have two objectives. The first one is the validation of the simulated radiances for data assimilation; the second one is to generate synthetic images that will serve as a help tool to the localization of the storms using the short time forecast. Many improvements have been made in the source code for these operators in order to try to resolve this problem. This latest model RTTOV assimilates cumuliform clouds, stratiform clouds and the ones of the upper levels as cirrus. For the simulation of these clouds, we will developed an algorithm for the identification of cloud types and cloud structure, based on the vertical profile of the cloud liquid water (CLW) and the cloud solid water (CSW) forecasted by ALADIN model at all the forty three (43) levels of the RTTOV model. A comparative study using the MSG2 data has shown on a number of weather situations, a good correlation between simulated and observed radiances, but this correlation is locally random for isolated clouds.*

Résumé - *Dans la prévision numérique du temps (NWP), le challenge le plus important dans l'assimilation des données satellitaires est la présence de nuages, essentiellement les nuages convectifs. Dans ce travail, nous nous concentrons uniquement sur la simulation de irradiances SEVIRI du satellite MSG2, en utilisant l'opérateur de transfert radiatif RTTOV dans sa version 9.3, en introduisant les champs prévus par le modèle ALADIN / Algérie. Cette simulation peut avoir deux objectifs. Le premier objectif est la validation des irradiances simulées pour l'assimilation de données. Le second est de générer des images de synthèse qui serviraient comme un outil d'aide à la localisation des tempêtes en utilisant les prévisions de temps. Nombreuses améliorations ont été apportées dans le code source pour ces opérateurs, afin de tenter de résoudre ce problème. Ce dernier modèle RTTOV assimile les nuages cumuliformes, les nuages stratiformes et ceux des niveaux supérieurs comme les cirrus. Pour la simulation de ces nuages, nous voulons développer un algorithme pour l'identification des types de nuages et la structure des nuages, basé sur le profil vertical de l'eau liquide des nuages (ELN) et de l'eau solide des nuages(ESN) prévu par le modèle ALADIN pour tous les quarante trois (43) niveaux du modèle RTTOV. Une étude comparative, en utilisant les données de MSG2, a montré sur un certain nombre de situations météorologiques, une bonne corrélation entre irradiances*

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simulées et observées, mais cette corrélation est localement aléatoire pour des nuages isolés.

Kew words: Assimilation - ALADIN - Radiative transfer model - RTTOV - MSG2 - SEVIRI.

1. INTRODUCTION

Cloudy assimilation satellite data using radiative transfer model in numerical weather prediction remains the major problem and the big challenger for the all meteorological services in the world. In the current state we use a binary mask made from satellite data, to eliminate the cloudy pixels in order to use only clear sky pixel in data assimilation (Zupanski *et al.*, 2007; Zhiquan Liu *et al.*, 2009).

Some algorithm have been developed and tested but results remain not satisfactory. In this study, we propose an algorithm to identify a cloud type as stratiform, cumuliform and the cirrus cloud, by using as input the ALADIN, Algeria version (Aire Limitée Adaptation Dynamic Development International) forecast data.

Meteosat Second Generation (MSG2) synthetic image with cloudy condition are generated using the radiative transfer model RTTOV (Radiative Transfer for TIROS-Television and Infrared Observation Satellite-Operational Vertical Sounder) in its last version 9.

In order to evaluate the proposed algorithm performance, simulated and observed images are compared.

2. THE RTTOV MODEL

The use of the radiative transfer model (LTM) like RTTOV shows that they are a good tools to validate the field forecast by the numerical weather prediction model (Chevallier *et al.*, 2001; Morcrette, 1991; Keil *et al.*, 2003).

RTTOV9.1 is a development of the fast radiative transfer model for TOVS, RTTOV, originally developed at ECMWF (European Organization for the Exploitation of Meteorological Satellites) in the early 90's (Eyre, 1991) to simulate satellite spectral radiance in infrared and micro monde wave of TOVS. Its source code developed in Fortran 90 language can be download from the web site: http://www.metoffice.gov.uk/research/interproj/nwpsaf/rtm.

Several ameliorations has given to the code (e.g Saunders *et al.*, 1999; Matricardi *et al.*, 2001) for the new code used in this study. This model is based on the interaction of electromagnetic radiation with the different compounds of the atmosphere. Radiation is a matter of multiple processes and effects of atmospheric properties during its transfer from surface to space (Karlsson, 1997).

Clouds effect this process most in the infra-red and visible part of the spectrum. The objective of model is to transform both clear sky radiation and cloudy radiance at the up of the atmosphere to satellite radiation. It uses an approximate form of the atmospheric radiative transfer (RT) equation. If a black opaque cloud is assumed at a single level, the top of the atmosphere upwelling radiance, $L(\nu,\theta)$, at a frequency ν and viewing angle from zenith at the surface, neglecting scattering effects, is written as:

$$L(\nu,\theta) = (1 - N) \times L^{Clr}(\nu,\theta) + N \times L^{Cld}(\nu,\theta) \tag{1}$$

where, $L^{Clr}(\nu,\theta)$ and $L^{Cld}(\nu,\theta)$ are respectively the clear sky radiation and the cloudy sky radiation at the top of the atmosphere and N is cloud fraction.

2.1 Simulation by clear sky situation

If the cloud cover fraction N is set to zero, the liquid water concentration at every level is set to zero and the equation (1) can be written as:

$$\begin{aligned} L^{Clr}(\nu,\theta) &= \tau_\upsilon(\theta)\times\varepsilon_\upsilon(\theta)\times B_\upsilon(T_s) + \int_{\tau_s}^{1} B_\upsilon(T)\,d\tau \\ &+ (1-\varepsilon_s(\theta))\times\tau_s^2(\theta)\times\int_{\tau_s}^{1} \frac{B_\upsilon(T)}{\tau^2}\,d\tau \end{aligned} \tag{2}$$

where, $\tau_\upsilon(\theta)$ is the surface-to-space transmittance, $\varepsilon_\upsilon(\theta)$ is the surface emissivity and $B(\nu,T)$ is the $B_\upsilon(T_s)$ Plank function for frequency (υ), T and T_s are the layer mean temperature and the surface skin temperature.

2.2 Simulation by cloudy sky situation

If a black opaque cloud is assumed at a single level, the top of the atmosphere, the radiation by cloudy conditions is given by the following equation:

$$L^{Cld}(\nu,\theta) = \tau_{Cld}(\nu,\theta)\times B(\nu,T_{Cld}) + \int_{\tau_{Cld}}^{1} B(\nu,T)\,d\tau \tag{3}$$

where, τ_{Cld}, is the transmittance with cloudy conditions and T_{Cld}, is the cloud top temperature. The thick cloud top emissivity is assumed to be unity which is a good approximation in spectral infrared domain.

The radiation simulated by the RTTOV model in cloudy condition (Saunders *et al.*, 2008) can be computed for both the six cloud type given in **Table 1** and forty three RTTOV pressure level. The required value for concentration of the cloud type column is in units of g/m^3, and a non-zero value of concentration can be given for only one cloud type per level.

Table 1: Cloud types available in RTTOV-9

1	Stratus Continental	STCO
2	Stratus Maritime	STMA
3	Cumulus Continental	CUCC
4	Cumulus Continental pollué	CUCP
5	Cumulus Maritime	CUMA
6	Cirrus	CIRR

As input parameters, RTTOV needs the following mandatory fields provided by the numerical weather prediction model: temperature, specific humidity, cloud liquid water, cloud ice water, cloud cover as three dimensional field and surface pressure, skin temperature, 2-meter temperature, 2-meter specific humidity, 10-meter wind as two dimensional filed.

3. THE ALADIN FORECAST MODEL

ALADIN is a short range NWP hydrostatical model developed in 1992 by an consortium of European country (French, Belgium, hungry etc). in 2005 Algeria became a member ship of the consortium and the ALADIN version used in this work is the operational version of Algeria that running on NEC SX9 Meteo France computer. The model centred on Algeria covers an area of 2800 × 2800 km^2 at a horizontal resolution of 0.12 × 0.12 deg ($\approx$ 12 km), the vertical discritization is 60 levels and boundary conditions are taken from French meteorological global model (ARPEGE).

4. CLOUD TYPE IDENTIFICATION ALGORITHM

Clouds reflected solar radiation, trap some of the outgoing infrared radiation emitted by the earth, also cloud emits radiation in the infrared part of electromagnetic spectrum according their own temperature. Their vertical extension, therefore their top temperature, their concentration in liquid water or solid water varies significantly whether we are on land or sea surface. Based on these two principles, we can develop an algorithm for identifying the type of cloud.

4.1 Sea and soil type discrimination

For discrimination between sea and land, we use for all pixels a binary mask (1 for sea and 0 land). In case of land, we have classified the different types of soil (desert, stones soil, clay sol) by creating a clear sky image in the visible channel 0.8 µm using the minimum reflectance technique for one decade combined with 10.8 infrared channels.

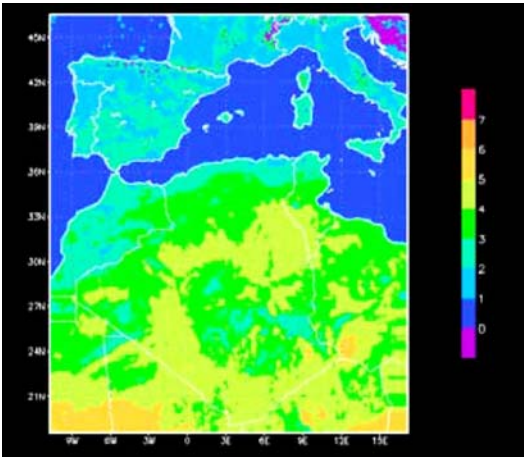


Fig. 1: Sea and different type of sol chart

4.2 Contained liquid water and solid water discrimination

This second discrimination is based on the calculation of contained liquid and solid water in a cloud using the vertical profile for cloud liquid (CLW) water and cloud solid water (CSW) forecasted by ALADIN model. These values vary within the cloud type (Dufour, 1961). It is between 0.01 and 1 g/m^3, with 0.3 g/m^3 as mean value in stratiform cloud and is between 0.01 and 5 g/m^3, with 0.3 g/m^3 as mean value in cumuliform cloud. For precipitable cloud as cumulonimbus this value can exceeded 10 g/m^3. Cloud liquid and solid water can be transformed in liquid and solid water concentration in cloud with the following equations:

$$C_{clw} = \left(\frac{\text{CLW (level)} \times \text{Patm (level)} \times 100\ \text{Ma}}{\text{Ra}} \right) \times 1000 \qquad (g/m^3) \qquad (4)$$

$$C_{csw} = \left(\frac{\text{CSW (level)} \times \text{Patm (level)} \times 100\ \text{Ma}}{\text{Ra}} \right) \times 1000 \qquad (g/m^3) \qquad (5)$$

Where, C_{clw} : Concentration of liquid water in cloud, C_{csw} : Concentration of solid water in cloud, Ma : Mean molar mass of dry air, Ra : Universal gas constant, Patm : Atmospheric pressure at RTTOV level and level: RTTOV level (1 to 43)

Algorithm

Beginning

- loop I
- loop J
- Pixel(I, J)
- Read ALADIN output(T, H, CLW, CSW, N, O_3, T_s, Pa, u, v, T_{2m}, H_{2m})
- Interpolation on the 43 RTTOV pressure level
- Compute satellite zenith angle
- Read mask(I, J) and soil type
- loop level

```
if (CLW(level) > 10^-8) then
    if (mask = 1) then
        if (Cclw < 1) then
            Cloud(2, level) = Cclw          Stratus Maritime        (STMA)
            Nebul(2, level) = N
        else
            Cloud(5, level) = Cclw          Cumulus Maritime        (CUMA)
            Nebul(5, level) = N
        endif
    else
        if (Cclw < 1) then
            Cloud(1, level) = Cclw          Stratus Continentale    (STCO)
            Nebul(1, level) = N
        else
            Cloud(3, level) = Cclw          Cumulus Continentale    (CUCC)
            Nebul(3, level) = N
        endif
    endif
else
```

if $(\mathrm{CLW(level)} > 10^{-8})$ and $\mathrm{CLW(level)} < 10^{-8}$ then

$\mathrm{Cloud(6, level)} = C_{csw}$ Cirrus (CIRR)

$\mathrm{Nebul(6, level)} = N$

endif

endif

- end loop level

- Identification of cloud type
- CALL RTTOV
- RTTOV output Infrared simulated radiance for the eight MSG2 channels (IR039, IR087, IR097, IR108, IR124, IR134, WV062, WV072)

- End loop J
- End loop I

end

end algorithm

N.B. The cumulus continental pollue case (CUCP) is not integrated in this algorithm.

5. SATELLITE DATA

Satellite data used in the comparative study are received from geostationary satellite MSG2 every fifteen minutes. Image data are coded on ten bits with three kilometer (03) as spatial resolution on the satellite sub point. The numerical count for the eight channels (IR3.9, WV6.2, WV7.3, IR8.7, IR 9.7, IR10.8, IR12, IR13.4) are transformed in a spectral radiance (Rosenfeld, 2004), and interpolated with Bessel four point method on the rectangular ALADIN grille.

6. RESULTS AND DISCUSSION

To test the cloud type identification algorithm performance, we realized a several simulations for the month of February 2010, following a comparative study between the observed MSG2 image and synthetic image generated by RTTOV model.

The infrared selected channels are the 10.8 and 13.4 μm and the statistical parameters computed are: the root mean square error (RMSE), the BIAIS and correlation coefficient (R) according these equations.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(O_i - S_i)^2}{N}} \tag{6}$$

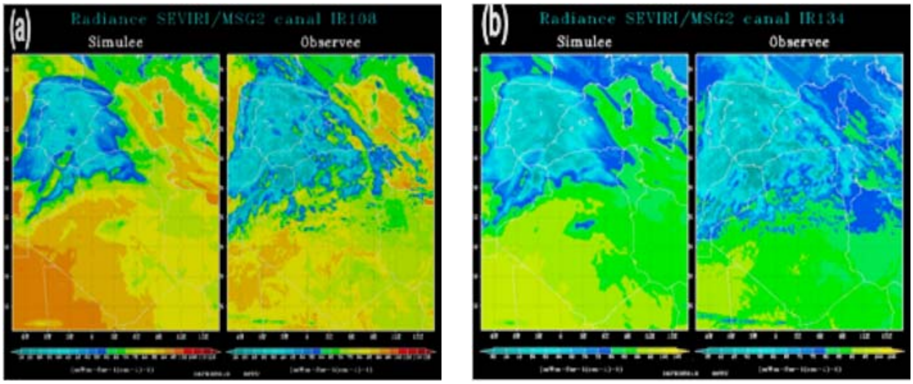
$$\mathrm{BIAIS} = \frac{\sum_{i=1}^{N}(O_i - S_i)}{N} \tag{7}$$

$$R = \frac{\sum_{i=1}^{N}(O_i - \overline{O}) \times (S_i - S_i)}{\sqrt{\sum_{i=1}^{N}(O_i - \overline{O})^2 \times \sum_{i=1}^{N}(S_i - \overline{S})^2}} \tag{8}$$

where, O_i : Pixel values of the observed image and S_i : pixel values of the synthetic image.

6.1 Forecast range 08 Feb 06UTC 2010

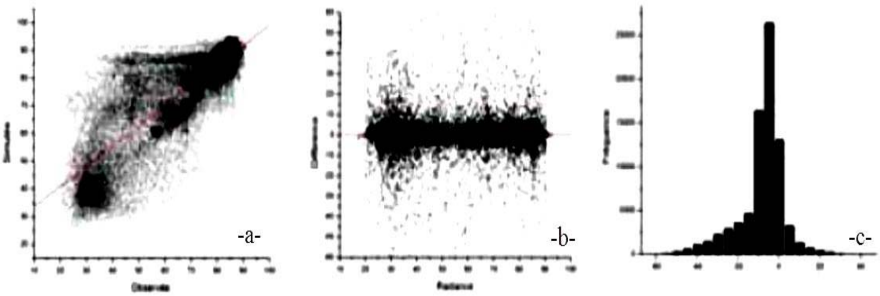
The visual analysis of Fig. 2a- and 2b- shows that the developed algorithm reproduces with realistic way the spatial configuration both in the infrared 10.8 µm and 13.4 µm channels.



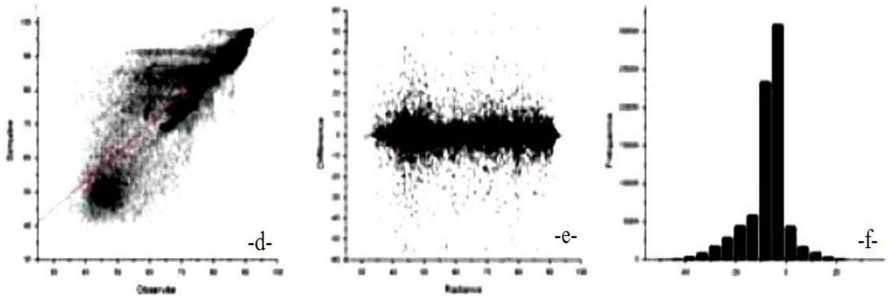
-a- Channel IR 10.8 µm -b- Channel IR 13.4 µm

Fig. 2: Radiance in mW/m^2sr^2 $(cm^{-1})^{-1}$

This likeness is well visible in high scale for the uniform cloudy system, however it is locally not clear for isolated and mesoscale cloud system and depends of capability of the ALADIN model to forecast the cloud type. The high values of the radiances observed represent every clear sky pixel and shows a good similitude between observed and simulated images; it confirm the performance of model RTTOV for this type of situations.



-a- Correlation, -b- Difference, -c- Difference Frequency histogram



-d- Correlation, -e- Difference, -f- Difference Frequency histogram

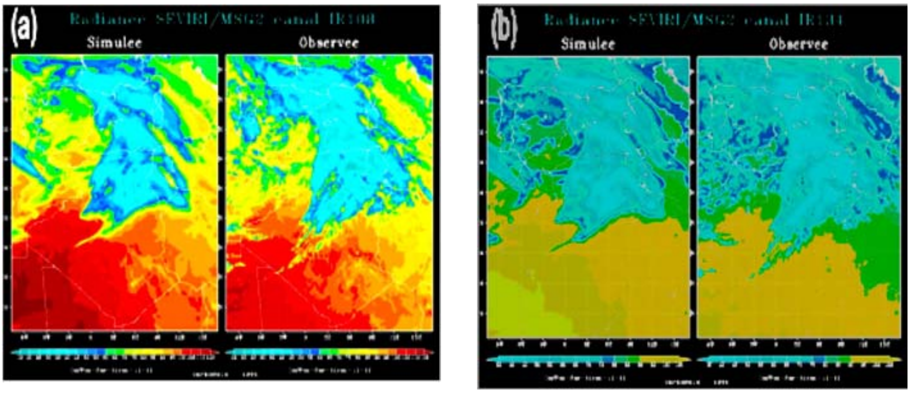
Fig. 3: -a- Correlation, -b- Difference, -c- Difference Frequency histogram (MSG2 observed, RTTOV simulated radiance channel 10.8 µm), respectively -d-, -e- et -f- for the 13.4 µm channel

The statistical results show well a good correlation around 0.8 between observed and simulated data for 10.8 µm channel, lightly higher 0.84 for the 13.4 µm channel.

The BIAIS and RMSE values are respectively -8.22 and 13.63 for the 10.8 µm channel and -7.43 and 11.11 for the 13.4 µm channel. Negative values of BIAIS indicate that the data are over-estimated by the RTTOV model.

6.2 Forecast range 08 Feb 18UTC 2010

Such as the 06 h forecast range, the visual analyze of Fig. 4a- and Fig. 4b- images shows a good similarity between MSG observed and RTTOV simulated images.

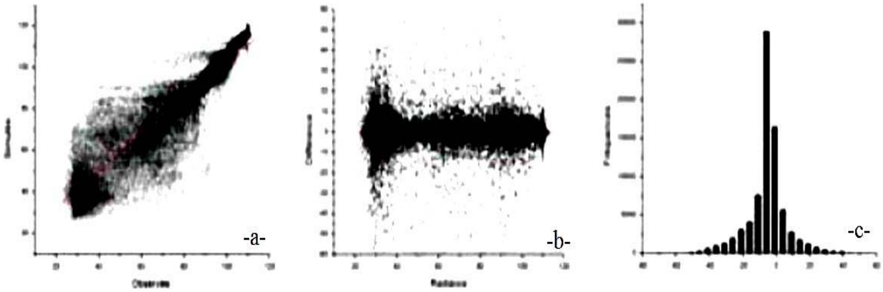


-a- Channel IR 10.8 µm

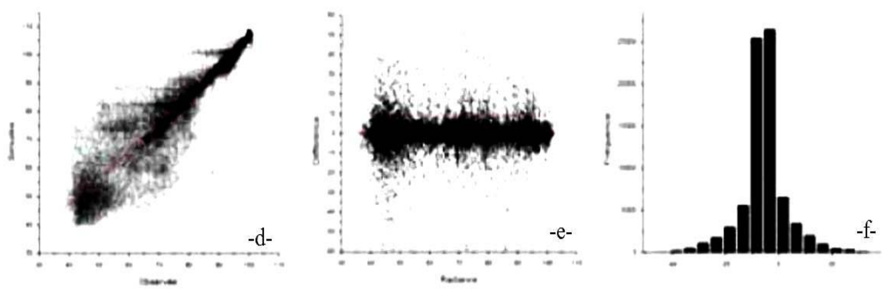
-b- Channel IR 13.4 µm

Fig. 4: Radiance in mW/m^{2}sr^2 (cm-^{1})$^{-1}$

Detailed analysis shows still that broken or isolated cumuliform cloud are missing on the simulated image which can be developed under the horizontal resolution of NWP model; consequently, they are not forecasted and depends on the hydrostatic convection scheme used in the ALADIN model.



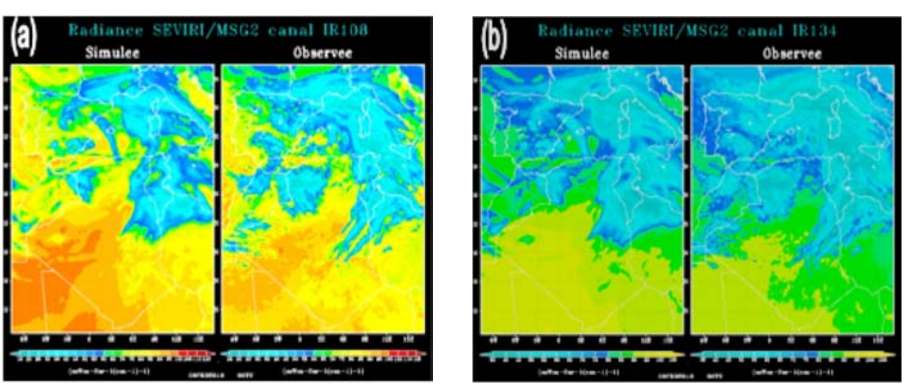
-a- Correlation, -b- Difference, -c- Difference Frequency histogram



-d- Correlation, -e- Difference, -f- Difference Frequency histogram

Fig. 5: -a- Correlation, -b- Difference, -c- Difference Frequency histogram (MSG2 observed, RTTOV simulated radiance channel 10.8 µm), respectively -d-, -e- et -f- for the 13.4 µm channel

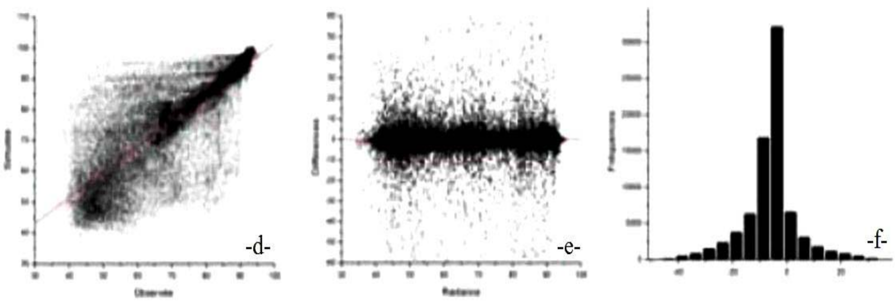
6.3 Forecast range 09 Feb 00UTC 2010



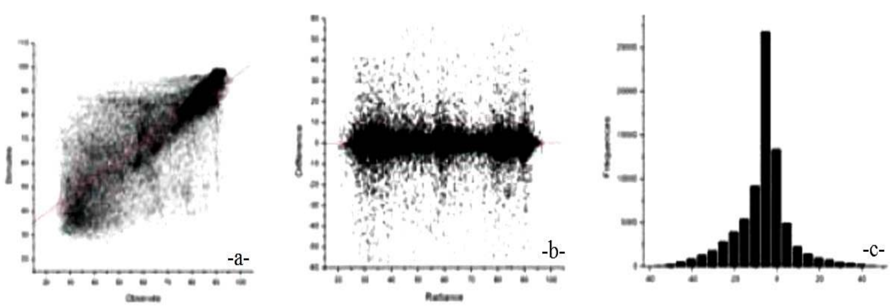
-a- Channel IR 10.8 µm -b- Channel IR 13.4 µm

Fig. 6: Radiance in mW/m^{2}sr^2 (cm-^{1})$^{-1}$

As far as twenty four forecast hours, we observed still a good similarity between the two configurations (observed, simulated) with though a difference for cloud localized in the west of Algeria, Morroco and southern of Spain due to a light degradation of ALADIN quality at twenty four forecasting hours of discontinuous field as cloud cover fraction. This degradation requires a new data assimilation using satellite radiance data in order to correct the forecasting output model to create new initial conditions data.



-a- Correlation, -b- Difference, -c- Difference Frequency histogram



-d- Correlation, -e- Difference, -f- Difference Frequency histogram

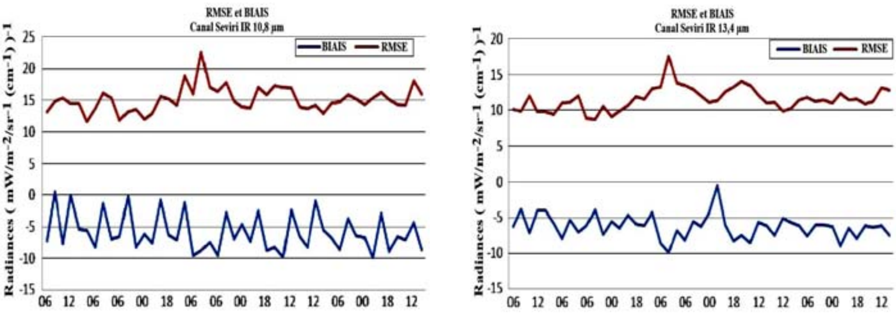
Fig. 7: -a- Correlation, -b- Difference, -c- Difference Frequency histogram (MSG2 observed, RTTOV simulated radiance channel 10.8 μm), respectively -d-, -e- et -f- for the 13.4 μm channel

We can notice a light degradation in correlation coefficient in comparison with the two previous forecasts range (06 and 18 UTC), but the BIAIS and the RMSE are practically as well as the 06 h and 18 UTC forecasting range.

6.4 Global validation

In order to validate the cloud type identification algorithm implemented in RTTOV model, we have performed simulations for thirteen days (February 2010) for different weather situations by calculating the following statistical parameters: the correlation coefficient, the root of the mean square error (RMSE) and the BIAS between observed and simulated data.

The graphics Fig. 8a- and Fig. 8b- shows well that the observed values over-estimates the simulated values for every realized simulations. The observed peaks on the BIAIS curves and the weak values of the RMSE corresponding well to simulation done at 12 forecasting range, while the maximum values of BIAIS are representative of simulation in cloudy situation, specially in high occurrence frequency of broken or isolated clouds and not forecasted by ALADIN.



a- 10.8 µm infrared channel b- 13.4 µm infrared

Fig. 8: BIAIS and RMSE curves in function with forecasting rang (00, 06, 12, 18 hours during 15 successive February 2010 days)

The mean values of the BIAIS and RMSE of the whole period of simulation are respectively around -5 et 15 $mW/m^2sr^2 (cm^{-1})^{-1}$ for 10.8 infrared channel and -5 et 12 $mW/m^2sr^2 (cm^{-1})^{-1}$ for 13.4 infrared channel. Three factors may be at the origin quality of RTTOV simulation, quality of ALADIN forecasting used as input for RTTOV; the efficient of cloud type identification algorithm and the RTTOV model performance.

7. CONCLUSION

The assimilation of satellite radiance by clear sky situation in numerical weather prediction (NWP) is made directly by calling the RTTOV code using the ALADIN forecast filed as input, but for more complex cloud types/or multi-layer clouds, the problem is too complicated. In this work, we focused on the satellite simulation radiance by cloudy situation and for this way; we implemented two routines in the RTTOV code.

The first one is the cloud type identification routine based on the liquid and solid water forecasted by ALADIN, and the second routine is the satellite zenith angle witch any pixel is observed. A comparative study between the observed MSG2 images and the synthetic images simulated by RTTOV is done using a visual graphics tools and statistical methods.

The statistical results show a good correlation between simulated and observed data for the clear sky regions and homogeneous cloud structured; however the correlation may be random and not significative for broken and isolated (convective) cloud structure which in a most cases is not forecasted by numerical weather prediction model as ALADIN. The root of the mean square error (RMSE), the BIAIS and the correlation can quantify the simulated errors. The RMSE values are around 15 % for the 10.8 µm channel and 12 % for the 13.4 µm channel. The negative values of the BIAIS indicate that the simulated values over-estimate the observed values.

The simulation of synthetic image using a radiative transfer model is good help and monitoring tools for forecasters to validate the forecasting model output, and also to validate the microphysics used in the schemes implemented in these models. We think that the use of a model with a Meso-NH microphysical scheme as input for RTTOV will give better results.

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