Progress toward the assimilation of cloudy infrared radiances at MSC

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Abstract

A simplified cloud emissivity formulation, using only 4 cloud effective parameters, was set up to take into account the effect of clouds on infrared radiance spectra. Using that formulation in a 1-D variational assimilation approach, Monte-Carlo numerical experiment indicated a strong potential impact in terms of variance reduction for retrieved temperature and humidity profiles. This cloud emissivity model was therefore introduced into the Meteorological service of Canada (MSC) 3D/4D variational assimilation code to allow an impact evaluation in a more realistic context. First 3DVAR analyses were performed. The minimization process worked successfully. Examination of the statistics in observation space put into evidence some clear issues related to bias correction and data quality control which will have to be addressed. The next step is to run assimilation cycles and to evaluate the quality of the resulting forecasts.

1. INTRODUCTION

Radiances from infrared sounders, measuring from space the thermal radiation emitted by the atmosphere and the earth's surface provide information on temperature and gas composition of the atmosphere. At NWP centers, they are used essentially to improve the temperature and water vapour fields. The impact of clouds on infrared radiances is very important and difficult to model. For that reason, the assimilation of infrared radiances has been restricted so far to clear field of views (FOV) or to clear channels (i.e. channels not affected by the presence of clouds). As the FOV observed by a typical infrared sounder (14-17 km) is cloudy approximately 75% of the time, one of the most severe limitation in the assimilation of infrared radiances, in particular those of the new generation hyperspectral infrared sounders such as AIRS (Atmospheric Infrared Radiance Sounder) or IASI (Infrared Atmospheric Sounding Interferometer), is related to cloudy radiances. The goal of this research is to find a way to assimilate cloud affected radiances in order to take full advantage of the information content present in these data.

2. DEFINITION OF THE EFFECTIVE CLOUD PARAMETERS

Under the assumption of a single layer cloud, a cloudy radiance spectrum can be calculated by combining a clear sky radiance $I_{clr}(\nu)$, an overcast radiance $I_{ovc}(P_c,\nu)$ corresponding to the cloud top pressure $\mathbf{P_c}$ and a cloud effective emissivity spectrum $N\varepsilon(\nu)$ as follows:

$$I_{cld}(\nu) = N\varepsilon(\nu) I_{ovc}(P_c,\nu) + (1 - N\varepsilon(\nu)) I_{clr}(\nu)$$

A cloud effective emissivity model giving a realistic cloud effective emissivity spectrum was set up accounting for mixed phase clouds (Rockel et al. 1991) and optical properties of liquid water (Lindner and Li 1991) and ice (Baran 2004). Multiple scattering is accounted for approximately following the Chou et al. (1999). Details on this cloud emissivity model are given in Heilliette and Garand (2007). To summarize, a cloudy radiance spectrum can be simulated using only 4 effective parameters: the cloud top pressure $\mathbf{P_c}$, the cloud effective water path **δ**, the effective radius $\mathbf{r_e}$ for liquid phase and the effective diameter $\mathbf{D_e}$ for ice phase.

3. VARIANCE REDUCTION USING 1DVAR AND MONTE-CARLO SIMULATIONS

Theoretical studies (Heilliette and Garand 2007) using Monte-Carlo simulations in a 1DVAR context showed that there is possibly a significant gain in term of variance reduction if AIRS cloudy radiances are assimilated using this cloud emissivity model. Figs. 1 and 2, show the error variance reduction profiles for temperature and water vapor for 9 cloud configurations corresponding to the combination of 3 cloud top pressures (500, 700 and 850 hPa) and 3 values of ***Nε(15μm)*** (1.0, 0.7 and 0.3). The red curve corresponds to the assimilation of channel insensitive to clouds (according to their weighting function and to the cloud top pressure estimated from CO_2 slicing). The green curve corresponds to the assimilation of all channels with our simplified cloud modelling. These results indicate a very significant reduction of the error variance associated with the assimilation of cloudy radiances.

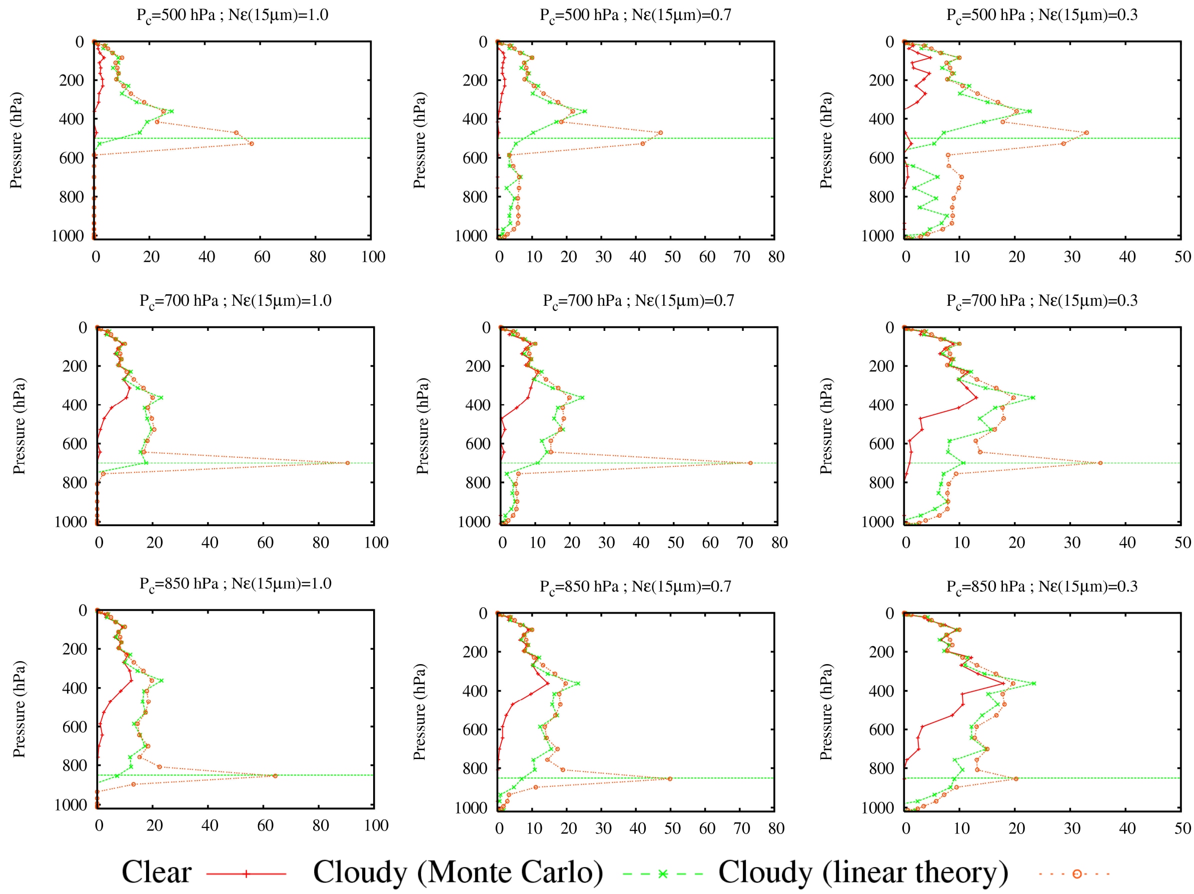

Figure 1: **Temperature error variance reduction corresponding to the assimilation of clear channels only (red line) and all radiances using the proposed cloud emissivity formulation (green line). Results shown for 9 cloud configurations. The orange line gives the expected variance reduction from linear theory in the cloudy case.**

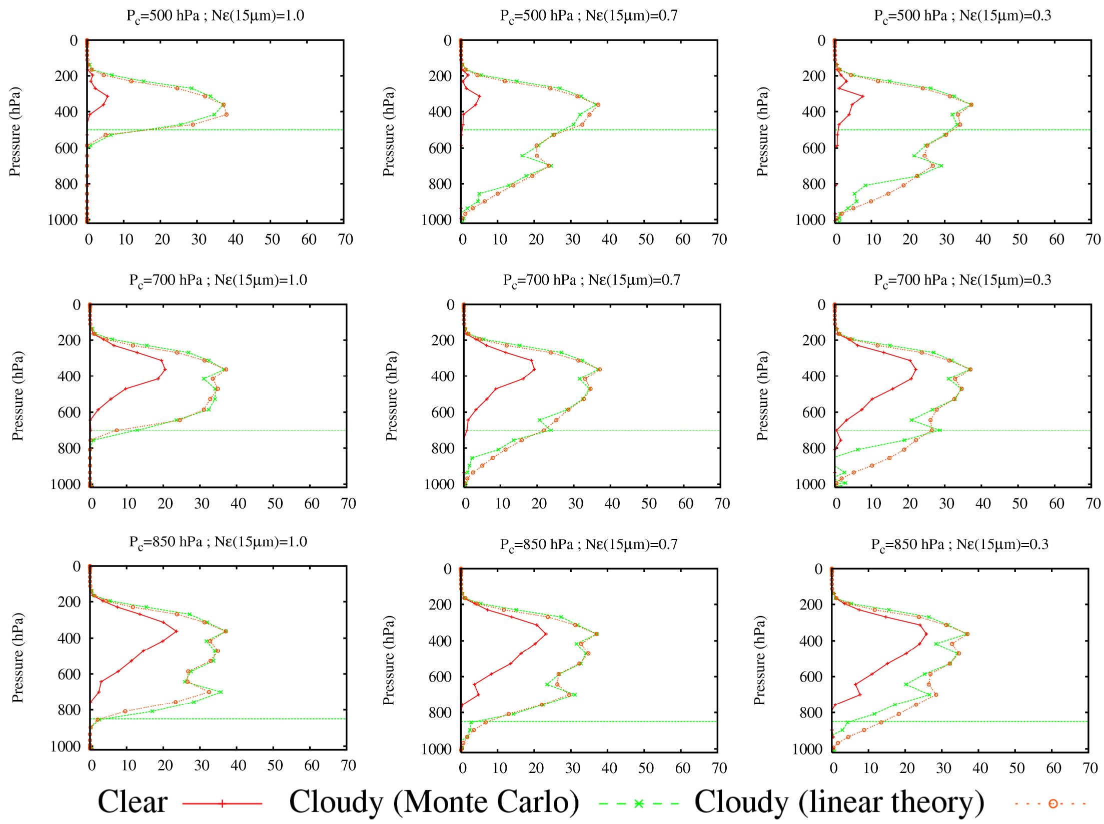

Figure 2: **Same as Fig. 1 but for the humidity variable (logarithm of specific humidity).**

4. IMPLEMENTATION IN 3D/4DVAR

Following these promising results, it was decided to introduce this simplified cloud modeling in MSC's 3D/4DVAR assimilation code. To do so, a cloud parameter vector **z** is added to the atmospheric state vector **x** to form a new variable $\tilde{\mathbf{x}}$. This vector of cloud parameters **z** contains the 4 cloud parameters already mentioned for each AIRS FOV. These cloud parameters are local to each AIRS observation. In this approach, there is no modification of the model cloud field. The goal is to gain information on temperature and water vapor as close as possible to the cloud top and possibly below in the case of a semi-transparent cloud. This new experimental approach of assimilation of cloudy radiances was designed to be a natural extension of the future operational assimilation of AIRS (see Garand et al. 2007). The corresponding 3DVAR cost function can be written as follows:

$$J_c(\tilde{\mathbf{x}}) = \left\{ \underbrace{(\mathbf{x}-\mathbf{x_b})^t \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_b})}_{\text{Background term}} + \underbrace{(\mathbf{z}-\mathbf{z_b})^t \mathbf{C}^{-1}(\mathbf{z}-\mathbf{z_b})}_{\text{Cloudy background term}} + \underbrace{(\mathbf{H}_c(\tilde{\mathbf{x}})-\mathbf{y})^t \mathbf{O}^{-1}(\mathbf{H}_c(\tilde{\mathbf{x}})-\mathbf{y})}_{\text{Observation term with cloud}} \right\}$$

The first guess cloud top pressure and cloud effective emissivity 15 μm (from which the entire spectrum can be inferred via modeling) are provided by the CO_2 slicing algorithm. The first guess effective radius and diameter are set to 13 μm and 25 μm respectively.

To date, from a technical point of view, the cloud emissivity model was successfully introduced in the 3D/4D variational assimilation code. The fast radiative transfer code RTTOV-8 (Matricardi et al. 2004) was modified to allow cloud emissivity to be frequency dependent. A first important point to check is the ability of the assimilation code to minimize properly the cost function. In particular, the gradient of the cost function with respect to the state vector, including the local cloud parameters, must be calculated with care. The analytic gradient of our code was validated against finite difference estimation. Fig. 3 shows the variation of the cost function during the minimization for assimilation experiments using only AIRS data in clear and cloudy conditions. The experiments labeled “incremental” correspond to situation where the tangent linear of the observation operator is used to evaluate changes in the cost function during the minimization whereas during the experiments labeled “non-incremental” the full observation operator (non-linear) is used instead. It can be seen that the minimization of the cost function performs well but requires more iterations in the cloudy case. The difference between the incremental and the non-incremental is modest but slightly larger in the cloudy case. The small increase in the dimension of the minimization problem (the dimension of **z** is of the order of 10^4 whereas the dimension of **x** is of the order of 10^6) suggests that a better preconditioning of the minimization could reduced significantly the number of iterations to achieve the minimization.

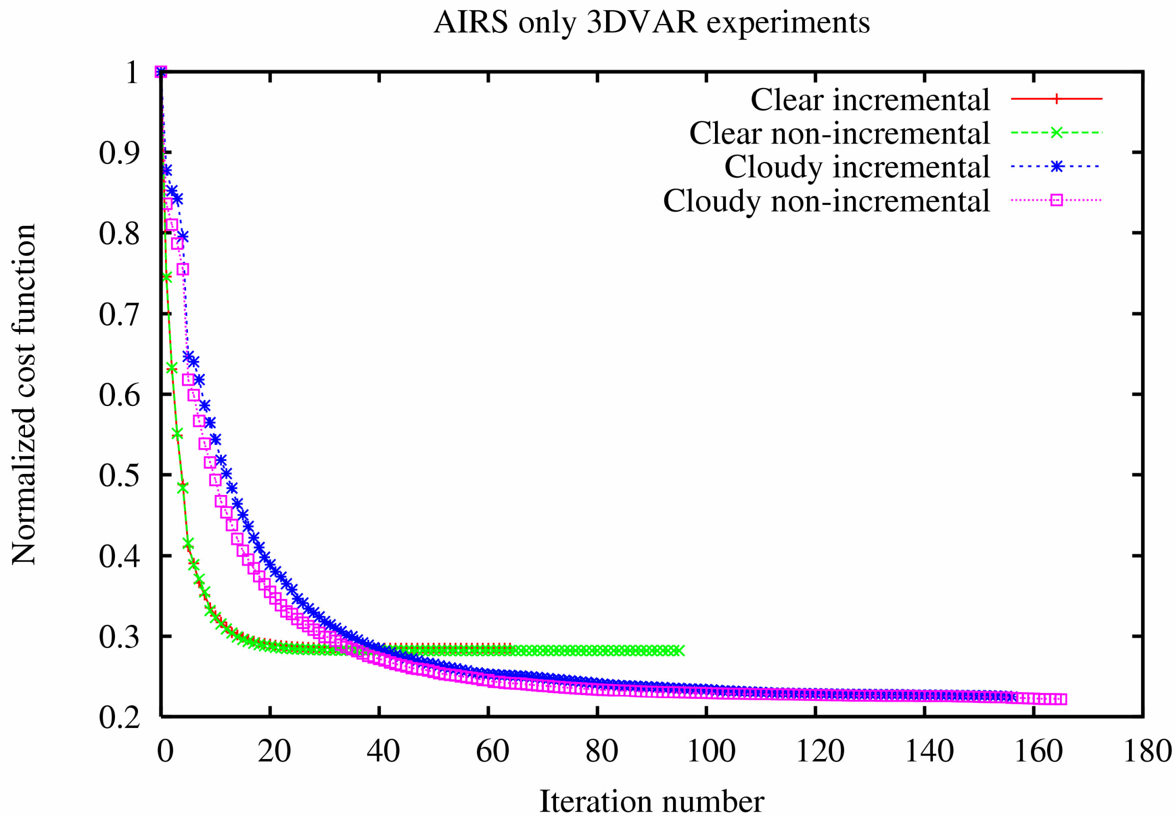

Figure 3: **Variation of the 3DVAR cost function (normalized by its value at the beginning of the minimization) during the minimization in the clear and cloudy cases. Results for incremental and non-incremental experiments are shown.**

5. FIRST 3DVAR RESULTS

First 3DVAR analyses were produced using this modified code. Figure 4 shows the increase in the number of channels used for the assimilation experiments performed. To start with, the observation error statistics and the bias correction methodology used for the assimilation of clear radiances remained unchanged for the cloudy radiance assimilation. No specific screening based on cloud parameters was applied. Figure 5 provides some statistics in brightness temperature space. As expected, the assimilation process reduced the standard deviation and the bias in both cloudy and clear cases. In the cloudy case, biases before and after the assimilation are relatively important which may indicate that clear radiance bias correction is deficient when applied to cloudy radiances. Standard deviations in the cloudy case are only slightly larger than in the clear case, which is seen as a good sign. These first results suggest that some quality control criteria specific to cloudy cases will be required.

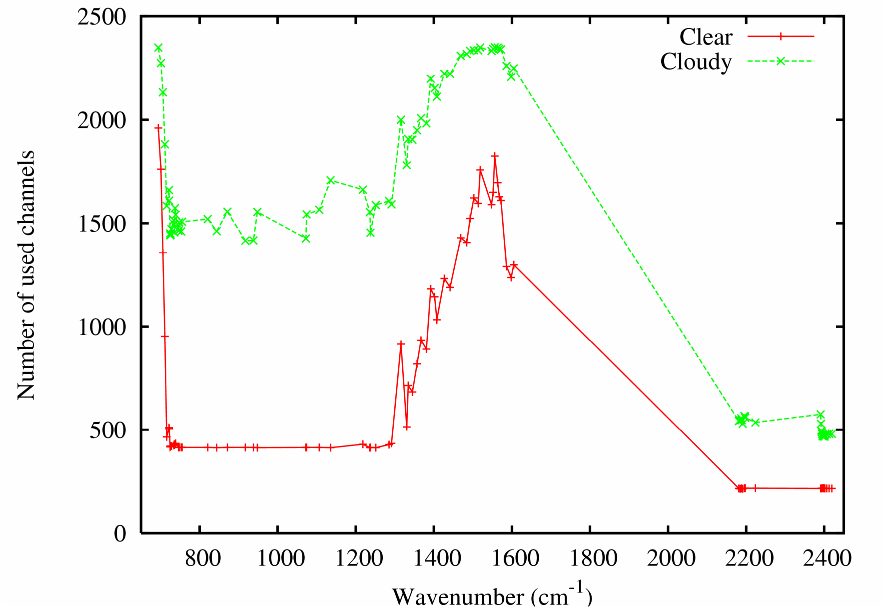

Figure 4: **Number of assimilated radiances for each AIRS channel in the clear (red line) and cloudy (green line) cases.**

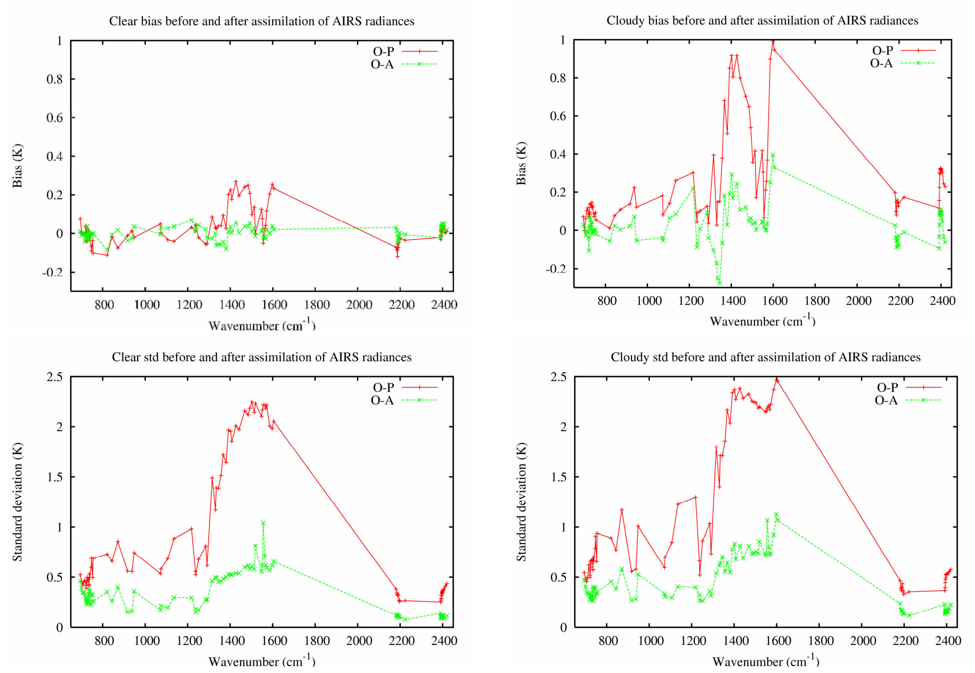

Figure 5: **Bias and standard deviation of departures from observations before (red line) and after (green line) assimilation of radiances in the clear (left panels) and cloudy (right panel) cases.**

6. CONCLUSION

A simplified cloud emissivity model, using only 4 cloud effective parameters and allowing to model the impact of clouds on infrared radiance spectra was set up and introduced into MSC's 3D/4D variational assimilation code. First 3DVAR analyses were performed with this modified code. The minimization process was successful, which is a significant achievement. Examination of the statistics in observation space put into evidence some clear issues related to bias correction and data quality control which will have to be addressed. The next step is to run assimilation cycles to evaluate the impact on forecasts and the sensitivity of that impact to quality control criteria.

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