Assimilation of Cloud-Affected Infrared Radiances at Environment Canada

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Abstract:

An overview of approaches used at major operational meteorological centers for the assimilation of cloud-affected infrared radiances is presented. Currently these approaches are all based on effective cloud parameters and the assumption of a single-layered field of view. More detailed information is given about the assimilation of cloud-unaffected (operational) and cloud-affected (experimental) infrared radiances at Environment Canada. Results of a first 4D-Var cycle assimilating cloud-affected AIRS and IASI radiances are presented in terms of forecast validation against radiosondes and analyses. These results indicate a mixture of positive and negative impacts. A second 4D-Var assimilation cycle is described, aiming at minimizing potential difficulties by limiting the cloud-affected radiance assimilation to temperature channels within the 13-14.5 µm region.

1. Introduction

Until very recently, Numerical Weather Prediction centers routinely assimilated only infrared radiances identified as free from cloud contamination. This condition represents an important limitation because the field of view (FOV) of a typical infrared sounder (~14-17 km diameter) is cloud-affected approximately 75% of the time (Wylie and Menzel 1999). To limit the probability of cloud contamination, selection criteria had to be restrictive. Consequently, there is a substantial loss of available information in regions thought to be of highest meteorological interest (McNally 2002). Research on the assimilation of cloud-affected infrared radiances lead in recent years to the use of simplified cloud models using effective parameters for the assimilation of cloud-affected infrared radiances in particular conditions. The purpose of this paper is to describe work performed on this subject at Environment Canada.

This article is organized as follows. Section 2 briefly describes the AIRS and IASI instruments and the channel selection. In Section 3, the assimilation setup of cloud-unaffected radiances at CMC is described. In Section 4, different approaches using effective parameters for the assimilation of cloud affected radiances at various operational meteorological centers are outlined. Then CMC's approach for cloud affected radiances is described in more detail in Section 5. Results of a first 4D-Var assimilation cycle are shown in Section 6. Conclusions of the mixed results of this first cycle are discussed, and a new experiment is described in Section 7 based on a more conservative approach. The conclusion exposes some perspectives.

2. Description of AIRS and IASI instruments

The Atmospheric Infra-Red Sounder (AIRS) is an American research instrument which was launched into earth-orbit on May 4, 2002 onboard the Aqua satellite. Aqua is part of NASA's ‘A-train’, a series of high-inclination, sun-synchronous satellites in low earth orbit designed to make long-term global observations of the Earth and its atmosphere. This grating spectrometer measures radiation emitted by the Earth and its atmosphere in the thermal infrared range at high spectral resolution (2378 channels between 649 cm^{-1} and 2666 cm^{-1}). The measured radiances give information on temperature, water vapor, ozone, greenhouse gases (such as CO_2, CO, CH_4 and N_2O) and also surface and clouds. A subset of 281 AIRS channels is received at Environment Canada from NOAA-NESDIS. Since July 2008, 87 temperature and water vapor sounding AIRS channels are assimilated operationally at Environment Canada in cloud-unaffected conditions (see first line of table 1).

The Infrared Atmospheric Sounding Interferometer (IASI) is an operational European instrument which was launched into earth-orbit on October 19, 2006 onboard the METOP satellite. This instrument measures radiation emitted by the earth and its atmosphere in the thermal infrared range at high spectral resolution (8461 channels giving a continuous spectrum between 645 cm^{-1} and 2760 cm^{-1}). IASI radiances give similar information to that provided by AIRS. A subset of 616 AIRS channels is received at Environment Canada from NOAA-NESDIS. IASI cloud-unaffected radiance operational assimilation should start at EC before the end of year 2010.

	LW T channels (15 µm)	**Boundary layer channels (above sea only)**	**Ozone channels**	**H_2O channels (6.3 µm)**	**SW T channels**	**Total**
Operational	20	10		33	24	87
Control 1	20/43	10/19		33/66	24	87/128
Exp1. when cloud-affected	20/43	10/19		33/66		53/128
Control 2	55/53	10/19		33/10	24	122/82
Exp2. when cloud-affected	55/53					55/53

Table 1: Repartition of the channels selected for assimilation for the operational configuration, the two control experiments and each test experiment in cloud-affected mode. When two numbers are present the first is for AIRS and the second for IASI else the number is for AIRS.

3. Assimilation of Cloud Unaffected IR Radiances at EC

The cloud-affected radiance assimilation setup at EC is designed as a complement to the currently operational cloud-unaffected assimilation setup. It is therefore relevant to describe this operational system. The cloud detection scheme is described in Garand (2004). If a given AIRS or IASI field of view is declared cloudy, the well known CO_2 slicing algorithm (Smith 1978, Menzel 1983) will provide a retrieval of cloud top pressure Pc and effective fraction $N\varepsilon$. This method is based on the assumption of a grey body cloud with only one layer located at Pc with emissivity ε covering a fraction N of the field of view. The cloud-affected radiance at frequency ν, $I_{cld}(\nu)$ is then given as a linear combination of the clear radiance $I_{clr}(\nu)$ and of the overcast cloudy radiance $I_{ovc}(\nu,P_c)$ for a blackbody cloud located at pressure P_c as stated by Equation (1) :

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

Equation (1) can be solved for P_c and $N\varepsilon$ given the observed cloud-affected radiance for a pair of channels and the clear and overcast radiances calculated from model fields (mostly temperature and water vapor). In the operational system, 12 pairs of channels (with a common reference channel) are used and the mean of the cloud parameter estimates is retained. The revised system uses 13 independent pairs (no common reference channel) and retains the median cloud height and corresponding effective cloud fraction.

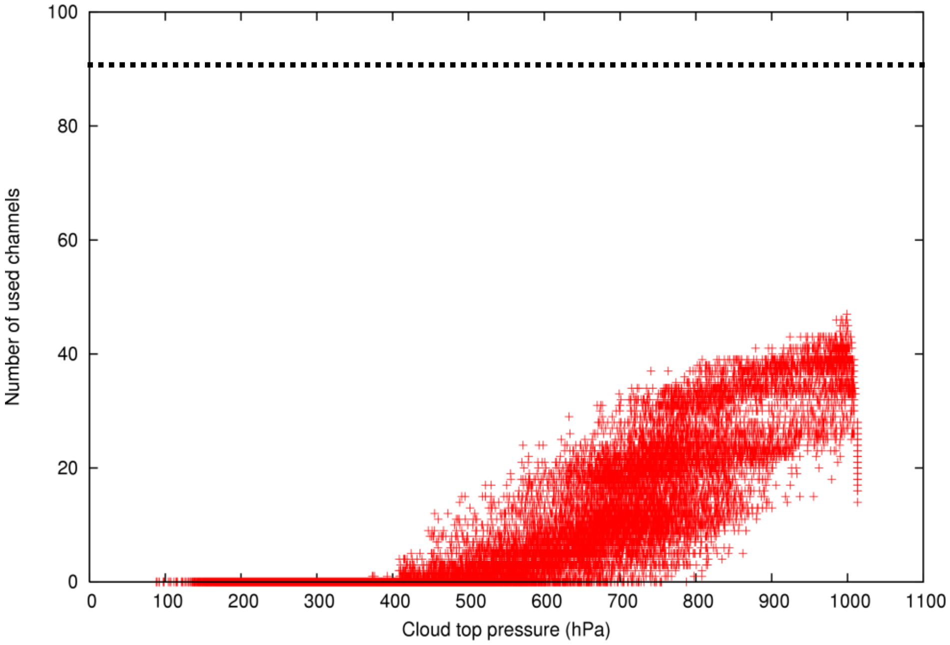

Figure 1: Scatter plot of the number of assimilated AIRS channels as a function of the cloud top

The local weighting function calculated by RTTOV 8.7 is then used, with a margin of security, to decide which channel is cloud affected or not. Only cloud unaffected channels are assimilated. As a consequence, the limitation in the number of assimilated radiances is quite severe. To illustrate this point, Figure 1 shows the number of channels assimilated as a function of cloud top pressure from CO_2 slicing. The dotted line is here for reference and indicates the number of channels assimilated for clear sky oceanic situations at night. Fig. 1 reveals that none of the channels are assimilated when the cloud top pressure is lower than 400 hPa.

4. Comparison of Approaches Using Effective Parameters

The assimilation of cloud affected infrared radiances is very challenging. Therefore, operational centers who first tackled the problem chose as a starting point to use a simplified approach based on equation (1) and rely on effective cloud parameters. A more realistic description of the cloud would require a profile of liquid water, a profile of ice, a profile of information on size distribution for droplets and ice particles (generally through a size parameter called effective radius or effective diameter), and consideration of cloud overlapping layers. As infrared radiances are mostly sensitive to the cloud top (except for very thin clouds) all these parameters would be poorly constrained by the observations. Furthermore, background information provided by the model on these parameters is not necessarily sufficiently reliable to be useful. The situation could be improved in the future by the simultaneous use of infrared and microwave radiances, but this is out of the scope of the present state of research in that field.

An overview of the different approaches for cloud-affected radiance assimilation used at several meteorological centers is given in Table 2. The table is not intended to give an exhaustive description of each approach but rather to present the main ideas. Four operational centers were selected for their infrared cloud-affected radiance assimilation: the UK met-Office (Pavelin et al. 2008), Meteo-France (Pangaud 2009), ECMWF (McNally 2008) and EC.

Examination of the table indicates that there is not yet a consensual approach. Nevertheless, some points emerge: the cloud parameters are all estimated by a combination of the observed radiances and the background temperature field using different retrieval techniques (minimum residual, CO_2 slicing, 1D-Var). No use is made of model cloud variables. Two different strategies are present. The first one, used by the UK-Met and Météo-France, is to restrict the assimilation of cloud-affected radiances to weakly cloud-affected radiances. The second one, used by ECMWF and EC, is to restrict the assimilation to near-overcast situations. EC is the only center attempting to model cloud emissivity.

	UKMET	**Météo -France**	**ECMWF**	**CMC**
Background value for cloud parameters	From *1Dvar* initialized by minimum residual (9 channels) method with big background errors	*CO_2 slicing* (124 pairs with the same reference channel at 979.13 cm^{-1})	*Minimum residuals* (using 2 or 3 channels)	*CO_2 slicing* (13 pairs of channels with different reference channels)
Variable cloud parameters in 4D-Var ?	no	No	yes	yes
Cloud parameters	P_c, Nε	P_c, Nε	P_c, Nε (only P_c is variable)	P_c, δ, r_e, D_e (only the 2 first are variable)
Conditions for 'cloudy' assimilation	Above sea Radiances weakly affected by clouds	Above sea 600 hPa<P_c<950 hPa Nε >0.1	Above sea 100 hPa<P_c<900 hPa Overcast cloud	Above sea 250 hPa<P_c<P_s-100 hPa Nε >0.75
Cloud ε modeling	no	no	no	yes
Obs. error for cloud params.	0	0	5 hPa for P_c 0 for Nε	from CO_2 slicing estimates
Implemented operationally?	yes	yes	yes	no
Assimilated channels	92 AIRS for 1D-Var pre-processing. In 4D-Var?	54 in the CO_2 15 μm band (AIRS)	Same as cloud unaffected cases except for SW channels	15 μm CO_2 only

Table 2: Comparison of the approaches using cloud effective parameters for the assimilation of cloud-affected radiances.

5. Assimilation of cloud-affected infrared radiances at EC

The simplified radiative transfer modeling used for the assimilation of cloud-affected radiances at EC is based on equation (1) and the use of a cloud emissivity model:

$$N\varepsilon(\nu) = 1 - \exp\left[-k_{cld}\ \ \nu, r_e, D_e, P_c\ \ \delta\right] \tag{2}$$

In equation (2), r_e, the effective radius, is a size parameter associated to the liquid droplet size distribution, D_e, the effective diameter, is a size parameter associated to the ice particles size distribution, and δ, the effective cloud depth, is related to integrated water content. The two size parameters r_e and D_e could have been retrieved from the observed radiances (using strongly cloud sensitive channels) but it was decided, to start with, to use climatological values for these parameters (i.e. D_e = 55µm and r_e = 12µm). Equation (2) is implicitly based on the hypothesis that the cloud covers the whole field of view (i.e. $N = 1$). The k_{cld} parameterization is based on optical properties for liquid and ice water and accounts approximately for scattering. The dependency on P_c comes from the fact that temperature is needed to specify cloud phase through cloud temperature. More detailed information on the cloud emissivity model is given in Heilliette and Garand 2007. Practically, δ is determined from $N\varepsilon$ retrieved from CO_2 slicing by inversion of equation (2). This cloud modeling was introduced in EC 4D-Var and the cloud parameters (only P_c and δ for now) are allowed to vary during the minimization of the cost function. It is worth emphasizing that these parameters are local and associated to an AIRS or IASI observation at a given location and time (they are not related to cloud models fields). The state augmentation technique, already used in variational bias correction for example (see Auligné et al. 2007) was used. The resulting (3D-Var for simplicity) cost function can be written this way:

$$J_c(\tilde{\mathbf{x}}) = \left\{ \underbrace{(\mathbf{x}-\mathbf{x_b})^{\mathrm{t}}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_b})}_{\text{Background term}} + \underbrace{(\mathbf{z}-\mathbf{z_b})^{\mathrm{t}}\mathbf{C}^{-1}(\mathbf{z}-\mathbf{z_b})}_{\text{Cloudy background term}} + \underbrace{(\mathbf{H}_c(\tilde{\mathbf{x}})-\mathbf{y})^{\mathrm{t}}\mathbf{O}^{-1}(\mathbf{H}_c(\tilde{\mathbf{x}})-\mathbf{y})}_{\text{Observation term with cloud}} \right\} \tag{3}$$

Here $\boldsymbol{x}$ is the atmospheric control vector, $\boldsymbol{z}$ is the local cloud parameters effective control vector, $\tilde{\mathbf{x}} = (\mathbf{x}, \mathbf{z})$ is the augmented control vector, $\boldsymbol{B}$ is the background error covariance matrix for the atmospheric state, $\boldsymbol{C}$ is the background error covariance matrix for the cloud parameters, $\boldsymbol{O}$ is the observation error covariance matrix, $\boldsymbol{H_c}$ is the observation operator including the simplified cloud modeling (RTTOV 8.7 plus the cloud emissivity model), $\boldsymbol{y}$ is the observation vector; quantities indexed with the letter b correspond to background state. The $\boldsymbol{C}$ matrix is diagonal in this work.

The minimization of the cost function proved to be difficult in 4D-Var mode. It was found necessary to introduce a diagonal change of variable in cloud parameter space

$$z \longrightarrow Z = k(z - z_b) \qquad \text{with} \qquad k = \sqrt{\frac{1}{\sigma_c^2} + \sum_{\text{channels i}} \left(\frac{1}{\sigma_{oi}} \frac{\partial H_i}{\partial z} \right)^2} \tag{4}$$

In equation (4), σ_c stands for the background error for the cloud parameter z (on the diagonal of the $\boldsymbol{C}$ matrix) and σ_{oi} for the observation error for channel i (diagonal of $\boldsymbol{O}$ matrix).The sum on index i in equation (4) is running on cloud-affected assimilated channels. Technically, this corresponds to a preconditioning using the diagonal of the Hessian matrix, which can be shown to be the optimal diagonal preconditioning.

6. Results from the first 4D-Var assimilation cycle

A first 4D-Var assimilation cycle using cloud-affected AIRS and IASI radiances was run for 18 days in winter 2008. The control experiment used the following data:

- Conventional data (radiosondes, etc…).
- Quickscat winds.
- AMSU-A and AMSU-B microwave radiances.
- SSM-I and ***SSM-I-S*** microwave radiances.
- ***GEORAD radiances***.
- AIRS infrared radiances (87 channels).
- ***IASI infrared radiances (128 channels).***
- GPS radio-occultation (refractivity profiles).
- ***Humidity from aircrafts***.

(Bold italicized refers to data types not yet operationally assimilated).

For details of AIRS and IASI channel selection for assimilation see Table 1. The 'cloudy' experiment adds cloud affected AIRS and IASI radiances. In cloudy mode, only channels specified in Table 1 are assimilated. The model used is the global GEM with 800x600 grid points, 80 vertical hybrid levels and a model top at 0.1 hPa. The bias correction of infrared radiances differs in the two experiments: in the control, a linear bias correction (a*BT+b) using the uncorrected brightness temperature as a predictor is used whereas in cloudy mode a constant bias is applied. This is judged appropriate as it is not clear at present how to characterize cloud-affected radiance biases in a more complex form. Background error associated to the cloud parameters are estimated from the following equations:

$$\sigma_{\mathrm{b}\,\delta} = \frac{2.0}{\left(\dfrac{\partial BT_{window}}{\partial \delta}\right)} \quad \text{and} \quad \sigma_{\mathrm{bP_c}} = \frac{2.0}{\left(\dfrac{\partial BT_{window}}{\partial P_c}\right)} \tag{5}$$

The assimilation of cloud-affected radiances was restricted by the following quality control criteria:

- Assimilation of cloud-affected radiances above sea only
- No assimilation of AIRS shortwave channels
- Restriction to mid-level clouds with 250 hPa < P_c < P_s-100 hPa
- Restriction to near overcast situations ($N\varepsilon > 0.9$)
- Exclusion of situations with temperature inversion leading to an ambiguous solution for the CO_2 slicing algorithm
- Restriction to situation where the solution of the CO_2 slicing is well defined ($\sigma_{Pc} < 50$ hPa, $\sigma_{N\varepsilon} < 0.1$)
- To limit the impact of uncertainty on cloud phase, no assimilation if the impact of the difference between ice and liquid cloud emissivity on brightness temperature is too high.

Table 3 illustrates the increase in assimilated radiances in cloudy mode.

	CONTROL1	**CLOUDY1**	**INCREASE**
AIRS	2997 FOVS 66189 rad.	3185 FOVS 71939 rad.	+6% FOVS +8% rad.
IASI	3958 FOVS 155696 rad.	4258 FOVS 183042 rad.	+7% FOVS +17% rad.

Table 3: Increase in the number of AIRS and IASI radiances and field of view assimilated between the control and the first 4D-Var assimilation experiment.

In terms of score of forecasts against radiosondes and analysis, the impact of assimilating cloud affected radiances was mixed and overall slightly negative. A positive impact was observed on North-America in terms of GZ anomaly correlation (see Figure 2) at several levels. However a negative impact was observed in the Tropics in terms of temperature anomaly correlation (see Figure 3). At present, causes for the negative impact in the Tropics are not identified. One possibility is incorrect partitioning between temperature and humidity in analysis increments.

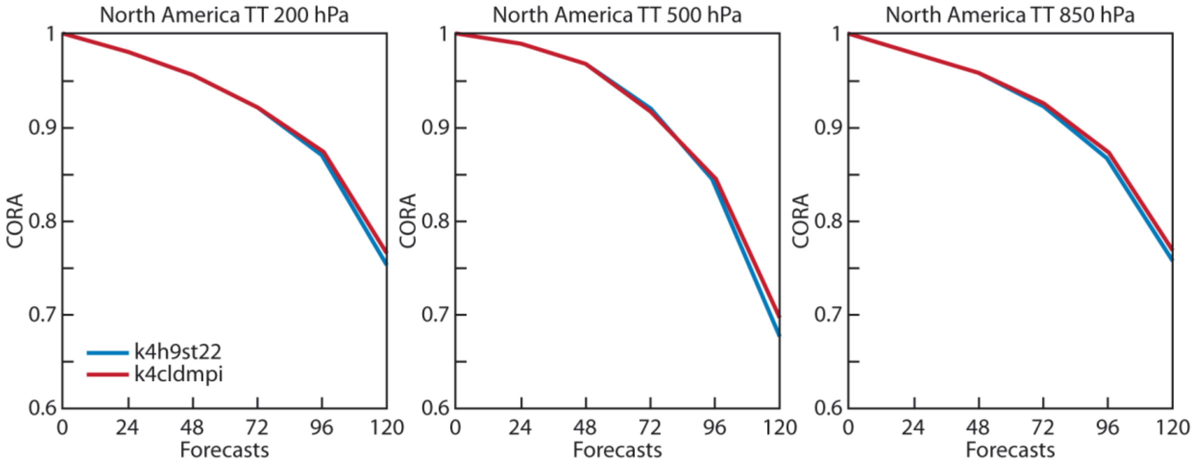

Figure 2: Correlation anomaly scores for temperature at 200 hPa, 500 hPa and 850 hPa for North America in the first 4D-Var assimilation experiment. Blue curve is for the control, red for the experiment.

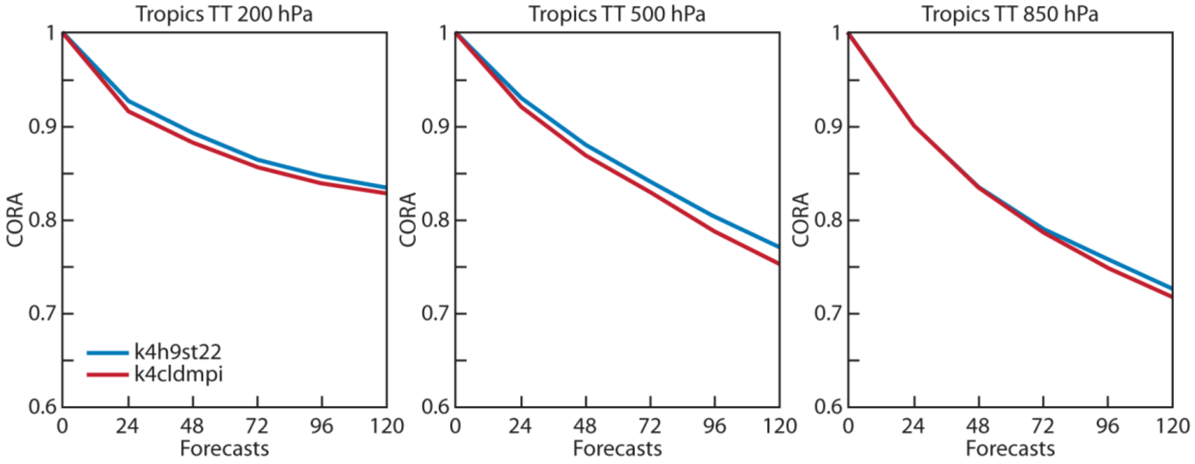

Figure 3: Correlation anomaly scores for temperature at 200 hPa, 500 hPa and 850 hPa for the Tropics in the first 4D-Var assimilation experiment. Blue curve is for the control, red for the experiment.

7. Description of a second assimilation cycle

As the results of the first 4D-Var assimilation experiment were mixed, a second experiment was planned. Firstly, some channels thought to be problematic were removed in both control and ‘cloudy’ experiments. In particular, the number of IASI water vapor channels was reduced from 66 to 10 and some high peaking stratospheric channels were removed. Perhaps more importantly, the assimilation in cloudy mode is now restricted to longwave temperature sounding channels in the 13-15.5 µm region. The rationale is that assimilating only temperature channels eliminates potential problems linked to water vapor. As well the cloud parameters were retrieved from that same region of the spectrum. Finally, the variation of cloud emissivity is then strongly limited so that errors associated with emissivity modeling are minimized. In both the control and experiment, the data thinning is reduced from 250 km to 150 km to increase data density (this change is unrelated to cloud-affected radiance assimilation but was shown to have a positive impact). Another concern of the previous cycle was the bias-correction. It was decided to use a bias correction for AIRS and IASI radiances using four geopotential thicknesses and viewing angle as predictors, as we had indications of a resulting positive impact in the Tropics from that change. To increase the impact of the assimilation of cloud-affected radiances, it was also decided to decrease the threshold on cloud effective fraction from 0.9 to 0.75. A recent study showed that the CO_2-slicing technique tends to underestimate the number of overcast situations. At the time of this writing, this last 4D-Var assimilation experiment is running.

8. Conclusion

Results of first 4D-Var cloud-affected assimilation experiments performed at EC presented were mixed but encouraging. Positive impacts were noted at several levels in a broad region such as North America. A revised 4D-Var experiment limiting the assimilation to temperature sensitive channels is expected to give better results. The goal remains to extract additional information from cloud-affected radiances without violating too severely the underlying hypothesis of a single layer cloud FOV. The more fundamental problem of assimilation information on cloud water content is not solved using these methods. More physically-based approaches should probably be envisaged in the future.

9. References

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