# Prospects for assimilating cloudy radiances from AIRS

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**ABSTRACT**

Four-dimensional variational (4D-Var) assimilation schemes assume the linearity of their forward model in the vicinity of prior information and usually do not properly handle variables that have finer temporal and spatial scales in the real world than in the forward model. Hence cloud-affected satellite infrared radiances are discarded from numerical weather prediction 4D-Var systems despite the critical need of observations within the cloudy regions. This paper suggests the reappraisal of that choice, subject to achieving improvements in the numerical simulation of cloudiness.

A new observation operator, that computes cloud-affected infrared radiances from 4D-Var control variables, namely atmospheric temperature, humidity, ozone, surface temperature and surface pressure, is presented. The vertical distributions of cloud cover and of cloud condensate are diagnosed in the operator itself. The goal of this paper is to assess the feasibility of using it to assimilate cloud-affected infrared radiances such as those from the Advanced Infrared Sounder. It is shown that there is a potential benefit in assimilating some of the upper tropospheric channels at 4.5, 6.3 and 14.3 $\mu m$ in the presence of clouds directly in 4D-Var. This conclusion applies to the 6.3 $\mu m$ channel on-board all the geostationary satellites as well. The approach is illustrated with one-dimensional variational retrievals collocated with radiosonde observations.

## 1 Introduction

The improvement of weather forecast skill in recent years owes much to the development of Bayesian estimation techniques for atmospheric data assimilation. In particular, an increasing number of numerical weather prediction (NWP) centres opt for three- and four-dimensional variational assimilation systems (respectively 3D-Var and 4D-Var) to perform their atmospheric analyses. The variational formulation of the inverse problem (e.g. Le Dimet and Talagrand 1986, Courtier et al. 1994), together with currently available computer power allows the operational handling of large numbers of control variables (about 5 million currently at ECMWF) and of observations (about 1.5 million per 12-hour analysis cycle). It would provide statistically optimal analyses if the errors statistics of the background and of the observations were un-biased, Gaussian and perfectly known and if the problem was linear in the vicinity of the background. For instance significant non-linearities may exist in a 3D- or 4D-Var system, but they degrade the realism of the corresponding analyses and tend to limit the impact in the subsequent forecasts to short ranges. As a consequence, attempts are made to bring the Var systems as close as possible to optimality by removal of biases, by choosing Gaussian error control variables, by a careful estimation of the error statistics. by the improvement of the parameterizations of the forward operator and by avoiding observations for which the forward operator is significantly non-linear with respect to the analysis increments.

To account for cloud processes in such a framework is obviously a challenge. Indeed, fine-scale atmospheric processes significantly impact the cloud fields and result in significant non-linearities at the spatial and temporal scales of the NWP models. Further, they make cloud parameterizations particularly difficult to formulate. Consequently, infrared satellite radiances are currently not assimilated in the presence of clouds at ECMWF, even though they would inform the NWP systems about regions of the atmosphere which strongly influence the forecasts (McNally 2002). However, one may note that cloud observations also contain large-scale information, through the dynamics, which allows a realistic representation of cloud systems in NWP.

At ECMWF, an observation operator that computes cloud-affected radiances from some of the ECMWF 4D-Var control variables (temperature, humidity and ozone profiles, surface temperature and surface pressure) has been developed for data assimilation. The operator diagnoses the vertical distributions of cloud cover and of cloud condensate by taking both large-scale and convective processes into consideration. The goal of this paper is to assess the possibility of its use for assimilating cloud-affected radiances within a 4D-Var system. The assessment is based on the examination of the accuracy and of the linearity of this new observation operator for the simulation of the narrow-band channels from the Advanced Infrared Sounder (AIRS) on-board the Aqua platform.

The plan of the paper is as follows. Section 2 describes the data and the observation operator. Accuracy and linearity of the observation operator are estimated in sections 3 and 4 respectively. A one-dimensional variational (1D-Var) scheme is used in section 5 to illustrate the previous results. Concluding discussion follows in section 6.

# 2 Data and model

## 2.1 Observations

The present study exploits the observations from the AIRS instrument, operated by the National Aeronautic and Space Agency (NASA). On-board the Aqua sun-synchronous polar orbiter, it observes nearly all points of the globe twice a day, moving northward across the equator at about 01:30 PM local time. It samples the infrared spectrum between 3.7 and 15.4 $\mu m$ with 2378 channels. Additionally 4 channels are located in the visible (from 0.4 to 1.0 $\mu m$). Horizontal resolution reaches 13.5 $km$ and 2.3 $km$ at nadir for the infrared and the visible channels respectively. No attempt is made to average the data. As a starting point, a subset of 324 channels for one satellite spot in eighteen has been made operationally available to ECMWF by the National Environment Satellite Data and Information Service (NESDIS). Data from cloud-free channels are assimilated with a cloud detection method described by McNally and Watts (2003).

AIRS observations for wave numbers below 2000 $cm^{-1}$ are bias-corrected using a constant offset in each channel in order to account for possible erroneous knowledge of the instrument characteristics. The offset is estimated independently from cloud-free departure statistics (McNally 2003, personal communication).

## 2.2 Observation operator

A prognostic model implies a scheme that computes the tendencies $\partial\eta/\partial t$ of some cloud quantity $\eta$ with respect to time $t$, therefore retaining cloud information from previous time-steps of the integration. A diagnostic model alternatively diagnoses the state of $\eta$ at time $t$ from other variables, thus precluding a memory of cloud variables and thus implying that cloud mass is not necessarily conserved.

The ECMWF forecast model includes a prognostic cloud scheme (Tiedtke 1989, 1993). In principle, the latter could be used in the 4D-Var physics for the assimilation of cloud information, provided that cloud variables are added in the 4D-Var control vector, that currently includes vorticity, divergence, temperature, humidity, ozone, surface temperature and surface pressure. Such a strategy would pose the acute problem of defining background error statistics for the new variables. As a consequence, a diagnostic approach has been preferred. A model has been developed and is described by Lopez and Moreau (2004) for the convection processes and by Tompkins and Janisková (2004) for the large-scale cloud processes. It uses only the existing 4D-Var control variables as input and was kept relatively simple so that thresholds and strong non-linearities do not make the 4D-Var minimization stop before reaching the absolute minimum of the cost function. The radiative transfer model to compute satellite radiances is based on the Radiative Transfer for Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (RTTOV: Saunders et al 2002) and its treatment of multilayer cloudiness is documented by Chevallier et al. (2002).

# 3 Accuracy of the observation operator

To validate the model for the 324 available AIRS channels, model fields from several time steps are needed, so that a significant amount of collocated data is accumulated. As a consequence, cloudy AIRS data are being passively monitored in the forecasting system (with ranges from 3 to 15 hours and at resolution 40 *km*), which takes the model data at observation time. Figure 1 presents the corresponding global statistics of the differences between the prognostic model and the observation for the cloud-affected AIRS channels on 30 November 2002. Other periods have been investigated and very similar results have been obtained.

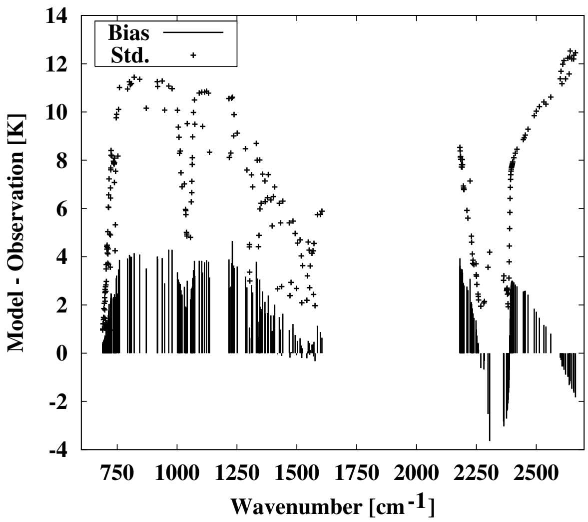


*Figure 1: Bias and standard deviation of the differences between the model and the cloud-affected observed AIRS brightness temperatures on 30 November 2002. The model uses the prognostic cloud scheme. Above 2000 $cm^{-1}$ day-time pixels are discarded.*

From the figure it is obvious that the model statistics are the best in the channels least affected by clouds. Biases are mainly positive, showing that the model underestimates the cloud radiative forcing, consistent with previous studies (e.g. Chevallier et al. 2001). A different behaviour occurs for the near-infrared channels above 2500 $cm^{-1}$. Although they are window channels, the bias reduces with increasing wavenumber and finally changes sign. This is likely caused by the absence of cloud scattering and/or of cloud reflection in the radiation model. Large negative values occur around 2300 $cm^{-1}$ for cloud-affected and for clear channels (McNally 2003, personal communication) and are being investigated.

For technical reasons, the diagnostic model cannot be used yet for passive monitoring in the forecasting system. As a consequence, diagnostic and prognostic brightness temperature are compared independently to the real AIRS data, using the Meteosat-7 6.3 $\mu m$ cloud mask for 30 November 2002 at 12 UTC. For each cloud-affected quadrant, equivalent AIRS brightness temperatures are computed using the diagnostic and the prognostic scheme. Rather than using a constant zenith angle, the Meteosat-7 angle is used. Corresponding statistics are presented in Figure 2.

Since the diagnostic model has been tuned to radiation observations, the biases between diagnostic and prognostic brightness temperatures nearly cancel the biases between prognostic ones and observations. Standard deviations are slightly smaller between the two models than with observations, but are here much smaller than the observation "random" variations. Therefore the variance explained by the model is as high as about 70% on an average, with smaller values in the Tropics, in particular at 11 $\mu m$ (not shown).

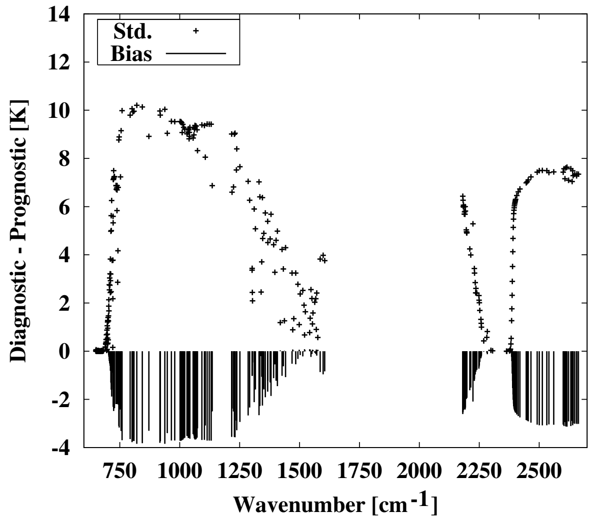


*Figure 2: Bias and standard deviation of the differences between the model diagnostic and prognostic AIRS brightness temperatures. Model data correspond the Meteosat-7 disk on 30 November 2002 at 12 UTC. Clear points are removed using the Meteosat-7 cloud detection. In contrast to Figure 1, stratospheric channels are not removed.*

# 4 Linearity of the observation operator

The linearity assumption is tested here for perturbations $\delta\mathbf{x} = \mathbf{x} - \mathbf{x}^b$, $\mathbf{x}$ being the analysis control vector and $\mathbf{x}^b$ its background value, that are of the order of magnitude expected in 4D-Var, i.e. comparable to the background errors. Consequently, the perturbations are defined based on the principal components of the ECMWF operational background error matrix **B** (Rabier et al. 1998, Derber and Bouttier 1999). Temperature errors vary with latitude and humidity error statistics are a function of relative humidity. Temperature and humidity errors are un-coupled. One $\delta\mathbf{x}$ is then a Gaussian perturbation applied to all principal components at once. This ensures that **B** is the covariance matrix of the perturbations.

The choice is made here to use the atmospheric profiles within the Meteosat-7 disk on 30 November 2002 at 12 UTC as a dataset sampling very diverse atmospheric conditions. For each cloud-affected quadrant, the correlation between the tangent-linear perturbations $\mathbf{H}\delta\mathbf{x}$ (where $\mathbf{H}$ is the adjoint of the observation operator $H$) to the AIRS brightness temperatures and the non-linear ones $H[\mathbf{x}^b + \delta\mathbf{x}] - H[\mathbf{x}^b]$ is computed using an ensemble of 100 perturbations. The zenith angle is set to that of Meteosat-7. The PDF of the correlations is shown for each channel in Figure 3. Stratospheric channels are easily identified because they correspond to the narrow PDFs close to unity, around wave-numbers 500 $cm^{-1}$ and 2300 $cm^{-1}$. Channels that both have a sensitivity in the troposphere and systematically correspond to high correlations (e.g. above 0.85) can be found in the $H_2O$ $\nu_2$ band (around 1500 $cm^{-1}$) and next to the stratospheric channels (in the lower-wavenumber part of the $CO_2$ $\nu_2$ band -around 700 $cm^{-1}$- and around 2250 $cm^{-1}$) only. Those few channels sound the upper troposphere only and are less affected by clouds. Channels with sensitivities lower down in the troposphere show high non-linear behaviours. Reducing the humidity perturbations by a factor of two only slightly increases the correlations (not shown). This indicates that improvements in the quality of the background in the forthcoming years are not likely to change the status of those channels with respect to linearity.

# 5 Application in one dimension

A 1D-Var scheme is used to illustrate the previous findings about the accuracy and the linearity of the infrared satellite radiances. The principle of the 1D-Var is similar to that of 4D-Var, but the control vector $\mathbf{x}$ represents only a single column and there is no time dimension. In the present case, the background $\mathbf{x}^b$ comes from the ECMWF short-range forecasts, the observations are the 35 near-linear AIRS channels at 6.3 and 14.3 $\mu m$ described below. Consistent with the present discussion, the forward operator is linearized around the background state $\mathbf{x}^b$ during the 1D-Var minimisation. Background error statistics for the control variables (temperature and humidity) are the ones used in the ECMWF operational model. Observation error standard deviations are defined conservatively from the departure statistics presented in Figure 1. Error correlations of 0.8 are arbitrarily specified between channels. Observations are bias-corrected with respect to the background by removing the biases shown in Figures 1 and 2.

The 35 near-linear AIRS channels are selected among the subset of 324 from the following three quantitative criteria: the cloud impact on the brightness temperature (estimated from the model simulations) must be more than 0.5 $K$ on an average, the correlations between linear and non-linear increments must exceed 0.85 (from Figure 3), and the standard deviations of the differences between diagnosed and observed brightness temperatures (computed from the numbers in Figures 1 and 2 and simply assuming uncorrelation between each other) must be below 6 $K$. Further, 4.5 $\mu m$ AIRS channels are not used here because of the solar radiation, but could be used during night-time. Among the 35, 13 channels are located about 14.3 $\mu m$ and 22 channels are located about 6.3 $\mu m$. At 6.3 $\mu m$ water vapour absorption impedes cloud absorption and accurate linear channels can be found with lower weighting functions (i.e. which peak as low as about 400 $hPa$) than at 14.3 $\mu m$.

The 1D-Var is applied to satellite radiances for November 2002 and February 2003, that have been collocated with 00 and 12 UTC operational radiosondes. AIRS radiances are processed only when cloudiness is detected in 22 channels at least among the 35.

The information content of the observations is necessary small, since large observation errors and small background errors have been specified. For instance, the degree of freedom for signal (e.g. Rodgers 2000) is about 0.2 for the temperature profile and 1.0 for the humidity profile. Owing to the relatively low weighting functions of some of the 6.3 $\mu m$ channels selected, the 6.3 $\mu m$ spectral band is more informative than the 14.3 $\mu m$ one. This is illustrated by the average self-sensitivity for the observations (e.g. Cardinali et al. 2003), which is about 6% and 1% respectively at 6.3 $\mu m$ and 14.3 $\mu m$.

Results are presented for collocations in the northern hemisphere mid-latitudes (between 30 and 70°N) and for 1.5 $hour \times$ 80 $km$ time-space windows. They actually mainly represent Europe because of the orbital characteristics of the satellites and of the location of the operational radiosondes. Inputs and outputs of the 1D-Var are compared with the collocated radiosondes in terms of relative humidity. For atmospheric temperatures below 243 $K$, only Vaisala RS90 radiosondes are used (Nash 2002).

1D-Var relative humidity increments reach a maximum at 400 $hPa$, with root mean square values of 0.10 respectively (not shown). Figure 4 indicates that the 1D-Var method reduces the differences between the model upper tropospheric relative humidity and the radiosondes measurements by up to 0.015. Interestingly, the difference reduction is about the same when cloud-free observations are processed with clear-sky observation error statistics and no cloud processes in the observation operator (not shown). Obviously, no perfect fit between the model and the observations can be achieved because of significant measurement and collocation errors. Most importantly, the 4D resolution of the information is not exploited by the 1D-Var but is expected to impact analysis variables like the wind components, as for the 4D-Var assimilation of clear-sky radiances from a single Meteosat channel (Köpken et al. 2003).

# 6 Conclusion

An observation operator has been developed, that computes cloud-affected satellite brightness temperatures from some of the ECMWF 4D-Var control variables: temperature, humidity and ozone profiles, surface temperature and surface pressure. It comprises a diagnostic cloud scheme with a representation of large-scale and convective processes and a radiation model. In order to evaluate the capability of 4D-Var systems to handle satellite infrared observations in the presence of clouds, its accuracy and its linearity have been assessed. Results have been illustrated within a 1D-Var framework.

A first important result of the present study concerns the diagnostic cloud scheme. It is expected not to perform as well as the prognostic scheme in dynamic mode for long integrations, but in static mode the comparison between model and observations was not qualitatively sensitive to whether the diagnostic model or the reference prognostic cloud scheme is used. Further, the two schemes should have similar sensitivities, since one of them is a simplified version of the other one. As a consequence, it seems that the diagnostic model could be used in the 4D-Var observation operator in lieu of the prognostic model, which would avoid the introduction of cloud variables in the 4D-Var control vector.

Secondly, it is clear that the channels that are the most impacted by clouds are very non-linear for temperature and humidity perturbations of the order of the current background errors in global NWP. In addition large errors were shown for these channels, both in terms of bias (which could be removed) and of standard deviations. Non-linearities actually reveal the deficiency of the NWP background in resolving the ambiguity of the cloud-affected radiances in terms of temperature and humidity information. These observations can be pre-processed by a local non-linear retrieval method, as is done for the geostationary atmospheric motion vectors. Alternatively a cloud variable for which the problem would be rather linear, like the cloud effective emissivity, could be introduced among the 4D-Var control variables. However, the specification of the corresponding error statistics would be critical for such an approach, since these ones would partly drive the distribution of the observation information on the various control variables. And it is not obvious that better methods than ad-hoc ones can be defined.

In contrast, the observation operator showed much more linear and accurate behaviour for some of the upper tropospheric channels, at 4.5, 6.3 and 14.3 $\mu m$. It is worth emphasising two features of the approach. First, accuracy is achieved in these channels despite a lower spatial resolution compared to the observations, which seems to indicate that the representativeness error is not a significant issue here. Second, the focus is on temperature and humidity fields and not on cloud variables, since the latter are diagnosed from the former. An obvious advantage is that temperature and humidity analysis increments are likely to improve the forecast far away from the analysis (e.g. Marécal and Mahfouf 2002). On the other hand, the accuracy of the present observation operator is still limited and only part of the information of the observations can be extracted.

The conclusion of our assessment is that there is a potential benefit in assimilating cloud-affected satellite radiances at 4.5, 6.3 and 14.3 $\mu m$ from the AIRS instrument *directly in 4D-Var*. The assimilation of the 6.3 $\mu m$ channel on-board all the geostationary satellites seems particularly attractive as well (Chevallier et al. 2004). This would avoid blending 4D-Var and local retrieval methods to exploit these channels in the presence of cirriform clouds. Scientific developments to the current 4D-Var systems may still be needed, for instance to improve the estimation of background error statistics, or to harmonize the resolution of the observations and the variable model resolutions within the incremental formulation. This is a concern for all types of assimilated observations.

A similar study is being performed for a selection of microwave channels in the presence of clouds and rain (Moreau et al. 2003). Channels in strong water vapour absorption bands, for instance at 22.235 $GHz$ or 183.31 $GHz$, are well modelled (Chevallier and Bauer 2003) and may be sufficiently linear for direct 3D- or 4D-Var assimilation.

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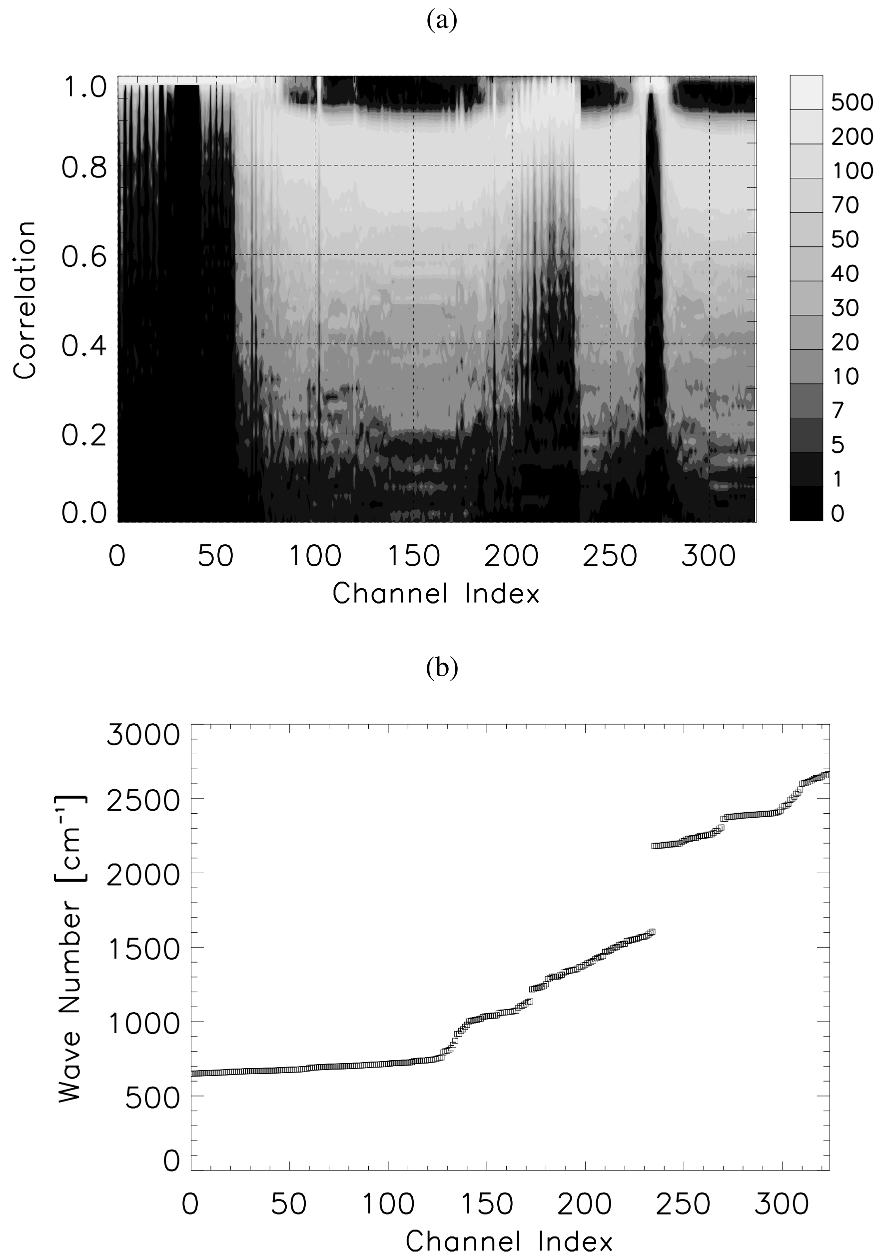


*Figure 3: Figure (a) presents the bi-dimensional histogram of the correlation between linear and non-linear brightness temperature perturbations for each one of the 324 AIRS channel subset. The input temperature and humidity perturbations follow the statistics of the ECMWF background error. Negative correlations are not represented. The correspondence between channel index and wave number is shown in Figure (b).*

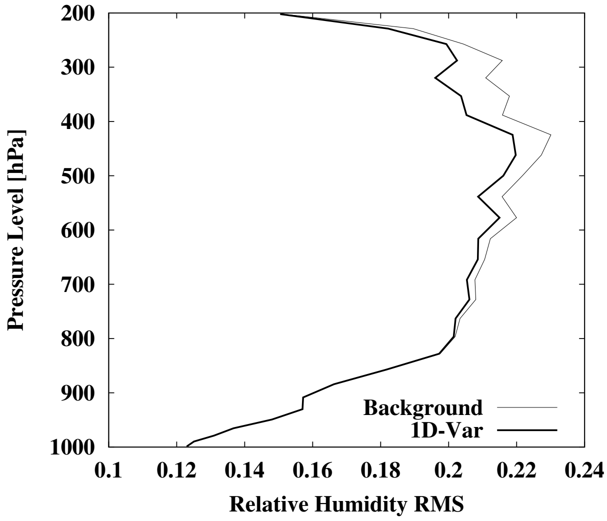


*Figure 4: Root mean square (RMS) difference between the model relative humidity and collocated radiosonde measurements for November 2002 and February 2003 in the northern hemisphere mid-latitudes. Relative humidity is defined between zero and one. The model profile is either the background or the 1D-Var retrieval. AIRS data are processed when cloudiness is detected in 22 channels at least among the 35. Statistics include about 250 cases in the upper troposphere and about 1500 in the lower troposphere.*