Dr Niels Bormann
European Centre for Medium-Range Weather Forecasts,
Shinfield Park, Reading, RG2 9AX, UK
Telephone: +44 118 949 9652
E-mail: Niels.Bormann@ecmwf.int

Assimilation of limb radiances from MIPAS at ECMWF using 1D and 2D radiative transfer models

Niels Bormann, Sean Healy, Mats Hamrud, Jean-Noël Thépaut (all ECMWF)

The first direct assimilation of emitted infrared limb radiances has been developed at ECMWF for data from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS, *Fischer and Oelhaf* 1996). MIPAS is a very high spectral resolution infrared limb sounder (0.025 cm^{-1} resolution) onboard Envisat, covering tangent altitudes from 6–68 km of the assimilation. Details of the assimilation are described in Bormann and Thépaut (2006) and Bormann et al. (2006).

The direct radiance assimilation was prompted by the success of nadir radiance assimilation (e.g. *Andersson et al.* 1994). The limb radiance assimilation aims at extracting temperature, humidity, and ozone information directly within the 4D-Var analysis. The study touches on a number of other novel aspects, such as extraction of ozone information from radiance assimilation, and the generation of a combined stratospheric and tropospheric humidity analysis. The latter builds on developments by *Hólm et al.* (2002) regarding a humidity control variable that caters for the large variation in humidity throughout the atmosphere.

Experiments

The assimilation experiments with the ECMWF system use the following setup:

Method	4D-Var with 12 h window
Model resolution	T511 (~40 km), 60 levels up to 0.1 hPa
Analysis resolution	T159 (~125 km), 60 levels up to 0.1 hPa
Time period	18 August 2003 - 29 September 2003 (43 days)
Other observations	Usual range of conventional observations and satellite data, including 4 AMSU-A, AIRS, GPS radio occultation bending angles from CHAMP, SBUV ozone retrievals from NOAA-16.

The MIPAS radiances are assimilated with a fast radiative transfer model (RTMIPAS, *Bormann et al.* 2005), which uses RTTOV-methodology (e.g., *Saunders et al.* 1999). Two versions of this radiative transfer model are considered here: the first one assumes horizontal homogeneity for the atmospheric input to the radiance computations (1-dimensional), and the second one takes horizontal gradients into account (2-dimensional, *Bormann and Healy* 2006). For the latter, the forward calculations use a series of 31 atmospheric profiles capturing the limb-viewing plane at approximately 40 km resolution. The 2D calculations take tangent point drift into account.

We assimilate only a subset of MIPAS radiances. 325 channels at channel-dependent tangent altitudes were selected using the method of *Dudhia et al.* (2002). The selection has been refined following experience with passive monitoring, and up to 260 channels are assimilated. Cloud screening is based on *Spang et al.* (2004) with an additional check on the clearest MIPAS channel. Biases in the limb radiances are corrected with the gamma/delta method, as further described in *Bormann and Thépaut* (2006).

The following experiments were performed:

CTL	No assimilation of MIPAS data.	**RAD**	Assimilation of MIPAS radiances with a 1D radiative transfer model.
RAD-2D	Assimilation of MIPAS radiances with a 2D radiative transfer model.	**RETR**	Assimilation of MIPAS retrievals of temperature, humidity, and ozone.

Results (1)

Analysis impact

- Overall, the assimilation of MIPAS data does not degrade the fit to other observations assimilated in the system. The statistics are similar for the radiance and the retrieval assimilation.
- MIPAS radiance or retrieval assimilation has a considerable impact on mean temperature, humidity, and ozone analyses in the stratosphere (Fig. 1). A ringing-type structure is apparent in zonal mean analysis differences above 10 hPa for temperature, especially over the poles. For humidity, the atmosphere is moistened by 20–40% throughout the stratosphere. Both aspects are similar for the radiance and the retrieval assimilation. They are supported by independent data, at least in areas covered by the independent data used (see below). For ozone, zonal mean differences introduced by the radiance assimilation differ from that introduced by the retrieval assimilation, with more structure in the tropics in the retrieval assimilation (not shown).

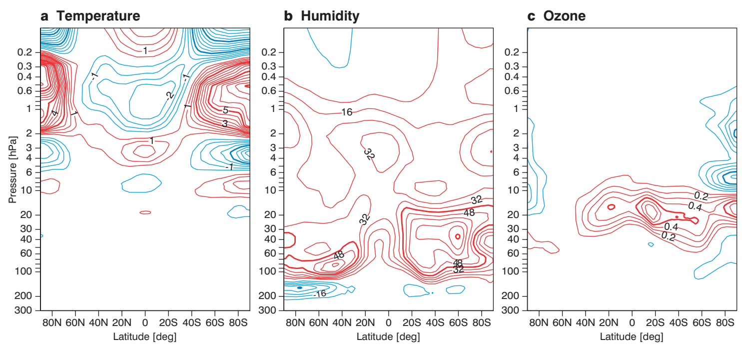

Figure 1 a) Zonal mean temperature differences between the experiments with and without assimilation of MIPAS radiances. Contour interval is 0.5 K, with positive values shown by red contour lines and negative values shown through blue lines. b) Same as a), but for humidity (relative to the experiment without MIPAS radiance assimilation), with a contour interval of 8%. c) Same as a), but for ozone volume mixing ratio with a contour interval of 0.1 ppmv.

- The radiance assimilation shows considerable sensitivity to the parameters used in the bias correction. Different bias parameters lead to large changes in the mean analyses, while at the same time other observations give little indication which bias model should be favoured (not shown).

Comparison of analyses with independent data

- For temperature and humidity, analyses with MIPAS radiance or retrieval assimilation show improved biases against independent retrievals from HALOE (temperature and humidity), POAM-III or SAGE-II (humidity; e.g., Figures 2 and 3). Overall, the radiance and the retrieval assimilation compare similarly well with these independent retrievals.

Results (2)

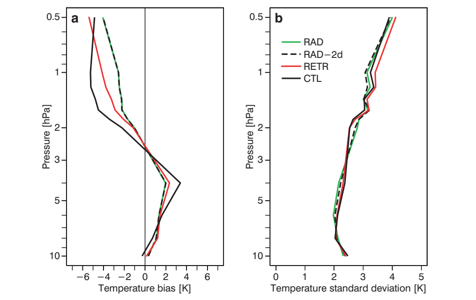

Figure 2 Comparison between HALOE temperature retrievals over the tropical region (0–20S) against analyses from the CTL (solid black), RAD (green), RAD-2D (dashed black), and RETR (red) experiment. The data covers the period 1–29 September 2003 (70 profiles), and the two panels show the bias (a) and the standard deviation (b) of the retrieval minus analyses differences.

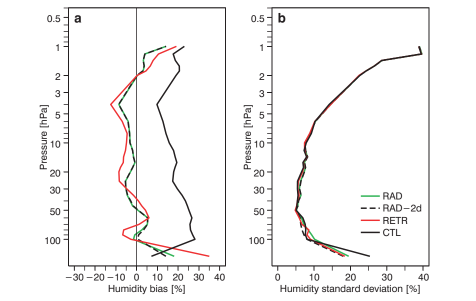

Figure 3 As Fig. 2, but for 195 SAGE II humidity retrievals over the North Polar region (60–74N), with values normalised by the mean retrieval value.

- For ozone, improvements in the bias or standard deviation are apparent for the radiance and the retrieval assimilation over the North Polar region (Fig. 4). Over the tropics and the South Polar region, analyses from the retrieval assimilation compare better with ozone sondes (Fig. 5).

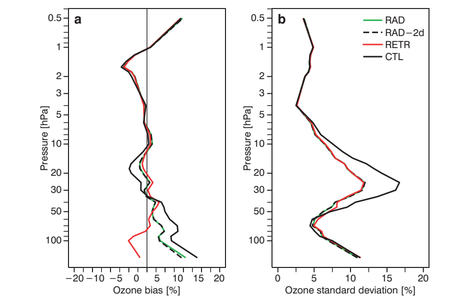

Figure 4 As Fig. 2, but for 195 SAGE II ozone retrievals over the North Polar region (60-74N), with values normalised by the mean retrieval value.

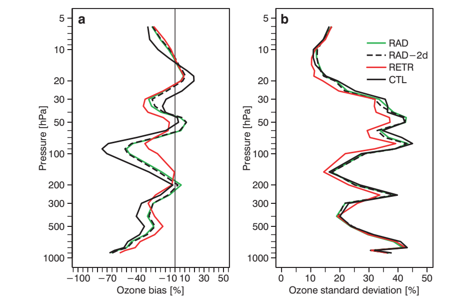

Figure 5 As Fig. 2, but for 49 ozone sondes over the South Polar region (60-90S), with values normalised by the mean retrieval value.

2D vs 1D operator for radiance assimilation

The performance of the 2D operator versus the 1D operator for the radiance assimilation has been compared in detail. The 2D operator shows small, but consistent benefits for humidity and, to a lesser extent, ozone. The main findings are:

- The 2D operator leads to smaller differences between the modelled and the observed radiances ("First Guess departures"), particularly for lower tangent altitudes and more strongly absorbing channels (Fig. 6). This is because the 2D operator allows to make better use of the First Guess information in the assimilation and has smaller forward model error.

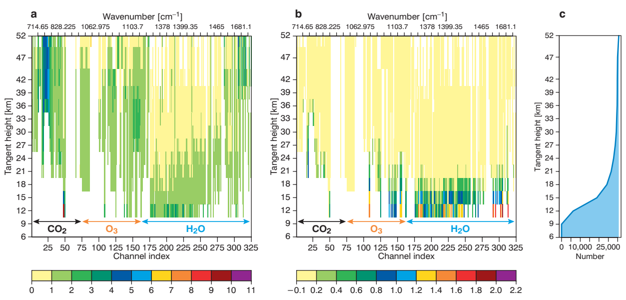

Figure 6 a) Standard deviation of observation minus First Guess departures for used MIPAS radiances from the experiment RAD-2D as a function of channel index and nominal tangent altitude. The values have been normalised by the instrument noise in each channel. Wavenumbers of selected channels are provided in the top axis for orientation. Correction of MIPAS radiance biases has been applied. b) Difference between the standard deviation of FG departures for the experiment RAD and the experiment RAD-2D as a function of channel index and nominal tangent altitude. The values have been normalised by the instrument noise in each channel. c) Number of clear sweeps per tangent altitude.

- The smaller First Guess departures lead to smaller analysis increments for humidity and, to a lesser extent, ozone in the lower stratosphere/upper troposphere region in areas where strong horizontal gradients prevail (e.g., Fig. 7). Increments are the adjustments made to the model First Guess fields as a result of assimilating observations. The smaller increments indicate a better consistency of the assimilation. Note, however, that the RAD and the RAD-2D experiments use the same observation error (which includes forward model error).
- When compared against the own analyses, 5-day humidity forecasts from the RAD-2D experiment show smaller forecast errors for humidity in the lower stratosphere/upper troposphere region than the RAD experiment (Fig. 8).

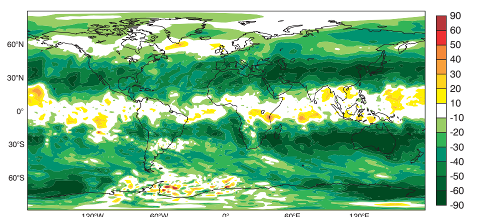

Figure 7 Differences in the root mean square (RMS) of the humidity increments at model level 21 (approx. 44 hPa) between the experiment RAD-2D and the RAD experiment, relative to the RMS of the increments in RAD [%]. Green areas indicate a reduction of increments from using the 2D operator.

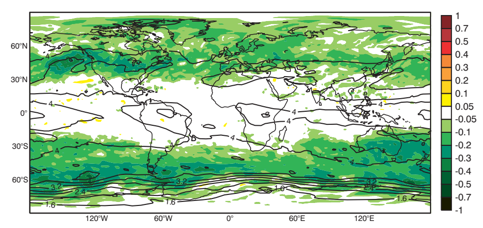

Figure 8 Difference in the RMS of the humidity forecast error [ppmv] for the 5-day forecast at model level 24 (approx. 80 hPa) between the RAD and the RAD-2D experiment. Green indicates a reduction in the forecast error for the RAD-2D experiment compared to RAD. Both forecasts have been verified against their own analyses. Black contours indicate the mean humidity field of the RAD experiment [ppmv].

Conclusions

Our experiments demonstrate the feasibility of direct assimilation of limb radiances in a variational data assimilation system. Details of the study can be found in *Bormann and Thépaut* (2006) and *Bormann et al.* (2006). The study is the first direct assimilation of limb radiances, and the above papers discuss also the many aspects in which the limb radiance assimilation could be developed further.

Acknowledgements

Niels Bormann was funded through the ASSET project (Assimilation of Envisat Data), a shared-cost project co-funded by the Research Directorate General of the European Commission within the activities of the Environment and Sustainable Development sub-programme of the 5th Framework Programme. Sean Healy was supported through the EUMETSAT/ECMWF Fellowship agreement. All MIPAS data used copyright ESA.

References

Andersson, E., J. Pailleux, J.-N. Thépaut, J.R. Eyre, A.P. McNally, G.A. Kelly, and **P. Courtier**, 1994: Use of cloud-cleared radiances in three/four-dimensional variational assimilation. *Quart.J.Roy.Meteor.Soc.*, **120**, 627–653.

Bormann, N., and **S. Healy**, 2006: A fast radiative-transfer model for the assimilation of MIPAS limb radiances: Accounting for horizontal gradients. *Quart.J.Roy.Meteor.Soc.*, **132**, *in press.*

Bormann, N., M. Matricardi, and **S.B. Healy**, 2005: A fast radiative transfer model for the assimilation of infrared limb radiances from MIPAS. *Quart.J.Roy.Meteor.Soc.*, **131**, 1631–1653.

Bormann, N., and **Thépaut, J.-N.**, 2006: Assimilation of MIPAS limb radiances in the ECMWF system. Part I: Experiments with a 1-dimensional observation operator. *Quart.J.Roy.Meteor.Soc.*, **132**, submitted (see also *Technical Memorandum 495*, ECMWF, Reading, UK, 30 pp [available under www.ecmwf.int/publications/library/do/references/list/14].

Bormann, N., Healy, S.B., and **Hamrud, M.**, 2006: Assimilation of MIPAS limb radiances in the ECMWF system. Part II: Experiments with a 2-dimensional observation operator and comparison to retrieval assimilation. *Quart.J.Roy.Meteor.Soc.*, **132**, submitted (see also *Technical Memorandum 496*, ECMWF, Reading, UK, 26 pp [available under www.ecmwf.int/publications/library/do/references/list/14]

Dudhia, A., V.L. Jay, and **C.D. Rodgers**, 2002: Microwindow selection for high-spectral-resolution sounders. *Applied Optics*, **41**, 3665–3673.

Fischer, H., and **H. Oelhaf**, 1996: Remote sensing of vertical profiles of atmospheric trace constituents with MIPAS limb emission spectrometers. *Applied Optics*, **35**, 2787–2796.

Hólm, E., E. Andersson, A. Beljaars, P. Lopez, J. Mahfouf, A. Simmons, and **J.-N. Thépaut**, 2002: Assimilation and modelling of the hydrological cycle: ECMWF's status and plans. *Technical Memorandum 383*, ECMWF, Reading, UK, 55 pp [available under www.ecmwf.int/publications/library/do/references/list/14].

Saunders, R., M. Matricardi, and **P. Brunel**, 1999: An improved fast radiative transfer model for assimilation of satellite radiance observations. *Quart.J.Roy.Meteor.Soc.*, **125**, 1407–1426.

Spang, R., J. Remedios, and **M. Barkley**, 2004: Colour indices for the detection and differentiation of cloud types in infra-red limb emission spectra. *Adv.SpaceRes.*, **33**, 1041–1047.