

**Retrieval of
macrophysical cloud
parameters from
MIPAS**

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Retrieval of macrophysical cloud parameters from MIPAS: algorithm description and preliminary validation

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Abstract

The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) onboard EN-VISAT has the potential to be particularly useful for studying high, thin clouds, which have been difficult to observe in the past. This paper details the development, implementation and testing of an optimal-estimation-type retrieval for three macrophysical cloud parameters (cloud top height, cloud top temperature and cloud extinction coefficient) from infrared spectra measured by MIPAS, employing additional information derived to improve the choice of a priori. The retrieval is applied and initially validated on MIPAS data. From application to MIPAS data, the retrieved cloud top heights are assessed to be accurate to within 50 m, the cloud top temperatures to within 0.5 K and extinction coefficients to within a factor of 15%. This algorithm has been adopted by the European Space Agency's "MIPclouds" project, which itself recognises the potential of MIPAS beyond monitoring atmospheric chemistry and seeks to study clouds themselves rigorously using MIPAS.

1 Introduction

Although much of atmospheric infrared remote sensing is based upon analysis of data to estimate constituent concentrations – where the presence of cloud particles in the measurements is treated as a source of error – it is possible to isolate measurements of cloud in order to determine the properties of clouds themselves. Arguably clouds (especially high cloud such as cirrus) represent one of the largest uncertainties in climate studies (Intergovernmental Panel on Climate Change, 2008) – and in order to have reliable estimates of radiative forcing and climatic impact, accurate distributions of cloud frequencies and properties must be available. Satellite instruments provide an opportunity to study the properties of clouds on a global scale.

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1.1 Overview of MIPAS-ENVISAT

The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) is an infrared limb-viewing instrument and was launched in March 2002 on the European Space Agency's Environmental Satellite (ENVISAT) which, with large inclination on a polar orbit in conjunction with azimuth scanning, enables global coverage pole-to-pole (European Space Agency, 2005).

MIPAS was designed to measure limb-emission spectra (primarily for trace gases such as CO₂ (used to retrieve pressure and temperature), O₃, H₂O, HNO₃, CH₄, N₂O and NO₂) at a high spectral resolution in the near- to mid-infrared from 685 cm⁻¹ to 2410 cm⁻¹. In its initial phase, MIPAS operated at a spectral sampling of 0.025 cm⁻¹, measuring spectra nominally every 3 km vertically in the troposphere – however following persistent slide malfunctions in early 2004, the sampling was decreased to 0.0625 cm⁻¹ but the measurement frequency increased to nominally every 1.5 km in the troposphere (Mantovani, 2005).

1.2 Overview of clouds from satellites

Cloud properties fall loosely into two categories: macrophysical and microphysical. Macrophysical properties are those which could be observed by the naked eye, such as the altitude of a cloud, the physical depth and extent of a cloud, or are basic thermodynamic quantities, such as the temperature at the cloud top or the temperature structure within the cloud body. Microphysical parameters are, by opposition, those which are too small to easily observe – such as the size and shape of cloud particles, and their distribution (which is often described in terms of water content), thus including properties such as number density, and influencing cloud optical depth, albedo, emissivity and transmissivity.

Whilst most of our knowledge of the microphysical properties of clouds come from in-situ measurements, predominantly by aircraft-mounted instruments (campaigns include Weickmann, 1947, over Germany, FIRE I and II over Wisconsin and Kansas,

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1992, SUCCESS over Oklahoma and Kansas, 1996, CEPEX, 1997, EUCREX over the Atlantic Ocean and mid-latitudes in Europe, 2000, and CRYSTAL-FACE over Florida, 2002), satellite instruments are particularly well-suited to observing macrophysical parameters, not least because of the large-scale geographical regions they survey.

5 As a general rule, limb-viewing instruments are competent at retrieving vertically-dependent parameters (such as cloud top height/pressure or cloud depth) with great accuracy, although have poorer horizontal-resolving potential – but are able to detect even the thinnest of clouds due to the inherently long limb pathlength. On the contrary, nadir-viewing instruments suffer from poor vertical resolution when retrieving atmospheric temperature and composition from which cloud top temperatures (and hence cloud top heights/pressures) are derived, are limited to thicker clouds, but have very good horizontal resolution. Different spectral ranges are sensitive to different cloud properties: for instance, microwave instruments often are not sensitive to ice cloud particles, whereas visible and infrared instruments are often limited to the first layer of cloud encountered and unable to measure below. It is thus important to choose to retrieve cloud properties appropriate to the satellite instrument’s capabilities.

There have been many studies on clouds over the years producing climatologies: by Barton (1983), Warren et al. (1985), Woodbury and McCormick (1983), Prabhakara et al. (1988), Wylie and Menzel (1989), Wylie et al. (1994) – but these were all limited by a lack of global coverage. Currently, the Stratospheric Aerosol and Gas Experiment (SAGE) (e.g., SAGE-III-ATBD-Team, 2002), the High Resolution Infrared Radiation Sounder (HIRS) instrument (e.g., Wylie et al., 2005), the International Satellite Cloud Climatology Project (ISCCP) (e.g., ISCCP, 2008) and the GRAPE project (e.g., Thomas et al., 2010) are actively compiling cloud climatologies. However, past and current cloud detection algorithms often miss much thin cloud in satellite measurements – and hence conventional cloud climatologies and inventories are in no way complete with respect to high thin cloud such as cirrus (Wylie et al., 2005). In fact, with the exception of SAGE, limb-viewing has not been used for cloud measurements since such instruments tend to target atmospheric composition for which cloud detection is the



only requirement, and limb-viewing cloud campaigns tend to be experimental rather than operational, hence yielding only short-time-series over a limited geographical region. Given that MIPAS should be quite sensitive to high, thin cloud if an appropriate detection mechanism is employed, it is a natural candidate to contribute climatological information about these clouds.

Retrieval of cloud parameters from instruments such as MIPAS, although highly instrument-specific, are dependent upon cloud-detection algorithms as estimators of cloud location (cloud top height/pressure/depth), and as selectors of data upon which retrieval schemes are run. Generally, cloud detection methods for limb-viewing and solar occultation IR instruments (such as MIPAS) are based upon a

- *threshold on*: radiance (such as the Cryogenic Limb Array Etalon Spectrometer CLAES experiment CLAES, 2007, and High Resolution Dynamics Limb Sounder HIRDLS, Lambert et al. 1999), transmission (Atmospheric Trace Molecule Spectroscopy ATMOS experiment, Kahn et al., 2002), extinction (Improved Stratospheric and Mesospheric Sounder ISAMS, Global Change Master Directory, 2007, the Halogen Occultation Experiment HALOE, Hervig and Deshler, 2002, and the Atmospheric Chemistry Experiment ACE, Bernath, 2002) or volume mixing ratio (the Limb Infrared Monitor of the Stratosphere LIMS, NASA, 2007), which exploit the fact that clouds introduce increased radiance and extinction, but decreased transmission and a decrease in certain specific constituent volume mixing ratios, such as ozone;
- *discontinuity in*: vertical gradients of extinction (the HALOE, or of trace gas concentrations such as ozone (the LIMS), which are introduced by large gradients at the cloud top; and
- *contrast in spectral structure*: (the Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere CRISTA, Spang et al., 2004, or MIPAS (operational method as in Spang et al., 2004), and alternate method presented in Hurley et

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al., 2009), which rely upon spectral differences introduced by cloud as opposed to those present in cloud-free spectra.

The act of detection yields cursory information on cloud frequency of occurrence and a preliminary measure of cloud top height. In terms of other retrieved cloud parameters, it should be noted that of the instruments discussed ACE, ATMOS, CLAES, HALOE, HIRDLS, and ISAMS operationally retrieve(d) extinction.

1.3 Cloud information from MIPAS

There have been several attempts to retrieve cloud parameters from MIPAS spectra. Firstly, the Monte Carlo Cloud Scattering Forward Model (McCloudsFM) is a multi-scattering model developed by Ewen (2005) to accurately model IR limb emission measurements of cirrus clouds, parameterised by effective radius, number density, cloud top height and cloud depth; however, the computational time associated with the retrieval was prohibitively large, and could not be justified given assumptions made in scattering properties and a priori biases. Secondly, the Earth Observation Science Group at the University of Leicester produces near-real-time cloud top heights from MIPAS spectra from May 2008 onwards (Moore, 2008). The cloud top heights are retrieved using the operational cloud detection method called the Colour Index (CI) Method (Spang, 2004) such that the amount of cloud occurring in a given FOV is roughly anti-correlated with the value of CI. Leicester simply reports the tangent altitude at which cloud is first encountered in the MIPAS scan pattern as the cloud top height. Finally, the Karlsruhe Optimised and Precise Radiative transfer Algorithm (KOPRA) provides accurate simulations of single-scattering clouds in a horizontally symmetric atmosphere, specific to MIPAS. KOPRA has been used to simulate different cloud types, such as cirrus, liquid water clouds, and various types of PSCs – and thus can be used to retrieve the modelled microphysical properties (IMK, 2008) under certain circumstances.

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To this end a more comprehensive and operational cloud parameter retrieval algorithm specific to MIPAS has been developed – and has been adopted as the macrophysical cloud parameter retrieval of the “MIPclouds” project (e.g., Spang et al., 2008). In this work, a non-scattering forward model of the radiation emitted by a cloud in the MIPAS FOV is described, in terms of three macrophysical parameters: cloud top height, top temperature and extinction coefficient. The inverse problem is addressed using an adaptation of standard retrieval theory: a sequential retrieval in which the first guess and a priori are chosen using an estimate of cloud amount.

2 Algorithm description

The retrieval of macrophysical parameters from a set of MIPAS spectra constituting a single limb-scan is a three-stage process applied independently in different spectral intervals (“microwindows”). These stages are:

1. Isolating the continuum radiance from each spectrum;
2. Retrieving the Cloud Effective Fraction to locate the spectrum containing the cloud-top; and
3. Retrieving the macrophysical parameters from this and vertically adjacent spectra within the limb scan pattern.

The results from each microwindow are combined to produce a best estimate of the parameters, and an associated error covariance.

2.1 Microwindows

Microwindows (MWs) are small subsets of the MIPAS spectrum of a few wavenumbers in width. A set of ten MWs have been selected in the atmospheric region of 930–960 cm^{-1} (Table 1) using a modification of the MIPAS MW selection algorithm (Dudhia

et al., 2002) optimised for a joint retrieval of continuum and temperature. Figure 1 shows the positions of these microwindows relative to molecular emission features. Note that each microwindow contains CO₂ lines (for the temperature retrieval, discussed further in Sect. 2.3) whilst avoiding significant contributions from more variable gases such as H₂O.

2.2 Continuum radiance

Using pre-computed molecular transmittance spectra, τ_ν , for each altitude (based on climatological concentrations, and calculated using the radiative transfer model, the Reference Forward Model (RFM), Dudhia, 2005) it is possible to identify spectral points where molecular contributions are expected to be negligible (e.g. where $\tau_\nu > 0.95$). It should be noted that at these wavenumbers molecular scattering is also negligible.

The continuum radiance, R , and associated error, can then be established by a simple mean and standard error (i.e. using standard deviation D such that the standard error is defined as $D/\sqrt{(n-1)}$, where n is the number of points averaged). By assigning an error value based on the actual D rather than the instrument noise, some allowance is made for any residual molecular contributions.

2.3 Cloud effective fraction

The next step is to identify the spectrum containing the cloud-top. One approach could be to use a simple threshold value on the continuum radiance, but since the continuum radiance is a strong function of atmospheric temperature as well as cloudiness, finding a suitable threshold value is difficult. The standard MIPAS Cloud Index (CI) method (Spang et al., 2004) attempts to overcome this temperature dependence by taking the ratio of radiance in two spectral regions (792–796 cm⁻¹ and 832–834 cm⁻¹) which react differently to cloud presence. The physical basis of the CI method is that as the field-of-view (FOV) reaches the limit of being geometrically-fully-filled with opaque cloud, the CI → 1 (as the cloud continuum radiance overwhelms the gaseous contribution to

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the spectral signature) whereas in the cloud-free limit, CI is large. Here, instead, it is preferable to have a scheme dependent upon the continuum radiance within each MW independently, as well as one having a more physical basis. This is done via retrieval of a “Cloud Effective Fraction” (CEF).

The CEF is defined as the fraction of the FOV covered by an optically thick, isothermal cloud with a horizontal cloud-top that would give the same continuum radiance as the observed cloud, assuming both have the same Cloud Top Temperature (CTT). Thus a single parameter α (the CEF), can be used to describe the infinite range possible of cloud extinctions and spatial distributions within the actual FOV (although the concept of a single well-defined CTT in all such cases is questionable). Thus α varies from 0 (cloud-free) to 1 (thick cloud completely filling the FOV) with intermediate values which may correspond either to thick cloud filling a small part of the FOV or thin cloud filling a larger fraction.

Mathematically, the CEF, α , is defined as

$$\alpha = \frac{R_c}{B_c} \quad (1)$$

where R_c is the continuum radiance B_c is the (spectrally averaged) Planck function corresponding to the CTT.

To retrieve the CEF from a single microwindow spectrum, it is assumed that the observed radiance can be represented as originating from a homogeneous path with the lower fraction α corresponding to an optically thick cloud whilst the upper fraction $(1-\alpha)$ originates from molecular emission features above the cloud but at the same local temperature as the cloud-top. Thus, the spectrally varying radiance R_ν , is approximated as

$$R_\nu = \alpha B_c + (1-\alpha)B_c(1-\tau_\nu) \quad (2)$$

where τ_ν the same pre-computed (climatological) molecular transmittance used in Sect. 2.2. It is further assumed that the same expression will hold for other cloud types and distributions with the FOV parametrised by the same CEF value α .

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Although clearly a gross simplification, it can be made more realistic by

- (a) using microwindows containing only CO₂ lines rather than more variable absorbers, in which case the climatological τ_v is likely to be reasonably accurate;
- (b) limiting the fit to spectral points with relatively high transmittance (e.g. $\tau_v > 0.75$), in which case the assumption of molecular emission originating near the cloud top is more likely to be valid.

In practice, this works better if B_c is constrained by a priori information – for instance, by using a temperature climatology. A simple, iterative optimal estimation scheme (similar to Eq. 3) is run to solve Eq. (2) for α .

The cloud-top is identified as lying in the highest altitude spectrum where $\alpha > 0.1$.

The retrieved value of α is also used as a “measurement” in the macrophysical parameter retrieval itself (Sect. 2.4). In principle, Eq. (2) also yields an “improved” estimate of B_c but, given the crudeness of this approximation, it is preferred to re-use the original climatological temperature profile.

2.4 Macrophysical parameter retrieval

The macrophysical parameters are retrieved using an iterative optimal estimation scheme (Rodgers, 2000):

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \left(\mathbf{K}_i^T \mathbf{S}_y^{-1} \mathbf{K}_i + \mathbf{S}_a^{-1} \right)^{-1} \left(\mathbf{K}_i^T \mathbf{S}_y^{-1} (\mathbf{y} - \mathbf{f}_i) - \mathbf{S}_a^{-1} (\mathbf{x}_i - \mathbf{a}) \right) \quad (3)$$

where subscript i denotes the iteration number, \mathbf{x} contains the parameters to be retrieved, \mathbf{y} contains the measurements, \mathbf{f} is the forward model (Sect. 2.5) applied to the current iteration of \mathbf{x} , \mathbf{K} is the Jacobian matrix containing elements $\partial \mathbf{f} / \partial \mathbf{x}$, \mathbf{S}_y is the error covariance matrix of \mathbf{y} , \mathbf{a} is the a priori estimate of \mathbf{x} and \mathbf{S}_a is the error covariance of \mathbf{a} . These components are described in the following sections.

2.4.1 State vector

The state vector \mathbf{x} contains the parameters to be retrieved, and in this case is defined as

$$\mathbf{x} \equiv \begin{pmatrix} z_c \\ B_c \\ \mu_c \end{pmatrix} \quad (4)$$

- 5 where z_c is the cloud-top height (CTH), B_c is the Planck function evaluated at the cloud-top temperature T_c (CTT) at the mid-point of the microwindow, and $\mu_c = \log_{10} k_c$, where k_c is the extinction coefficient (in km^{-1}), which is a measure of the cloud extinction (CEX).

2.4.2 Measurement vector

- 10 The vector \mathbf{y} , containing the measurements used for the retrieval, is defined as

$$\mathbf{y} \equiv \begin{pmatrix} R_u \\ R_c \\ R_l \\ \alpha \end{pmatrix} \quad (5)$$

- 15 where R_c is the continuum radiance (Sect. 2.2) from the FOV containing the cloud-top, having the retrieved cloud effective fraction α , while R_u and R_l are the continuum radiances from the FOVs immediately above and below. The measurement covariance matrix \mathbf{S}_y is diagonal, with variances given by the errors from the continuum radiance and CEF retrieval. Although R_c and α are derived from the same spectrum, the argument is that α depends on the spectral structure whereas R_c is derived from the spectrally flat regions – and hence the two may be regarded as independent.

- 20 The radiance R_u from the FOV above the cloud-top is expected to have a value ~ 0 (since the CEF for this FOV will have been retrieved with a value < 0.1 , Sect. 2.3)

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and serves simply to constrain the retrieval from placing the cloud-top too high. The inclusion of the CEF in the measurement vector is discussed in the next section.

2.4.3 A priori information

This scheme essentially attempts to retrieve three macrophysical parameters from two non-zero continuum measurements, R_c and R_l . The usual method for dealing with such under-determined problems is to supply independent a priori information. Due to the spatial inhomogeneity of cloud structures, obtaining useful direct a priori information on any of the three retrieved parameters is impractical – however, there are indirect a priori constraints on the *relationships* between the retrieved parameters.

The first a priori constraint is represented by the CEF and is more conveniently introduced into the measurement vector itself (α in Eq. 5) rather than in the conventional a priori state vector \mathbf{a} . This acts as a constraint on the CTH and CEX values, as described in Sect. 2.3.

A second source of a priori information is the background temperature profile (obtained, for example, from climatology or meteorological analysis fields). Assuming this is not significantly perturbed in the presence of clouds, this acts as a constraint on the CTH and CTT, since the cloud-top temperature would be expected to correspond to a point on this profile.

Having identified the spectrum containing the cloud-top, the a priori estimate for the cloud-top height is set as the nominal tangent height for that measurement z_t , and its corresponding uncertainty σ_{z_a} set to ± 1 km (cf. effective FOV width $\sim \pm 1.5$ km).

For this altitude, the background temperature profile provides an equivalent radiance B_t , and uncertainty σ_{B_t} which is typically equivalent to a temperature uncertainty of ± 10 K. However, uncertainty with which z_t represents the actual cloud-top height, and the variation of radiance with altitude $b = dB/dz$ (see Eq. 8) also have to be taken into account when calculating the a priori covariance matrix elements.

There is no reasonable a priori estimate for optical thickness so it is just set at a typical mid-range value (e.g. $\mu_a = -2.5$) with a large uncertainty $\sigma_{\mu_a} = \pm 0.5$, to capture the

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range of extinction for which the cloud forward model (Sect. 2.5) is applicable.

Thus the a priori vector is given by

$$\mathbf{a} = \begin{pmatrix} z_t \\ B_t \\ \mu_a \end{pmatrix} \quad (6)$$

Assuming that the Planck function varies linearly with altitude (Eq. 8), the covariance is given by

$$\mathbf{S}_a = \begin{pmatrix} \sigma_{z_a}^2 & b^2 \sigma_{z_a}^2 & 0 \\ b^2 \sigma_{z_a}^2 & (\sigma_{B_t}^2 + b^2 \sigma_{z_a}^2) & 0 \\ 0 & 0 & \sigma_{\mu_a}^2 \end{pmatrix} \quad (7)$$

2.5 Cloud forward model

The essential assumption within the macrophysical retrieval scheme is that a cloud can be represented as a homogeneous “grey” absorber characterised by just three retrieved parameters (the cloud top height z_c , the cloud-top temperature T_c and the cloud extinction k_c).

In addition, it is assumed that the Planck function (evaluated at the spectral mid-point of the microwindow in question) varies linearly with altitude within the cloud with a known gradient, such that

$$B(z) = B_c + b(z - z_c) \quad (8)$$

where $B_c \equiv B(T_c)$ is the Planck function for the cloud top temperature, and $b = dB/dz$ is the vertical gradient ($b < 0$ in the troposphere, $b > 0$ in the stratosphere), derived from an external (e.g. climatological) estimate of the background atmospheric temperature profile.

The cloud forward model \mathbf{f} calculates the continuum radiance originating from a cloud described by z_c , T_c and k_c , and assumes that there is no spectral variation in absorption or in the Planck function over the limited spectral width of each microwindow.

2.5.1 Pencil-beams

The continuum radiance L_t of a pencil-beam (i.e. infinitesimal solid-angle) viewing at tangent height z_t within the cloud (i.e. $z_t < z_c$) is given by the standard radiative transfer equation for local thermodynamic equilibrium, assuming no molecular contributions from the atmosphere itself, and no scattering:

$$L_t = \int_s B(s) \frac{d\tau}{ds} ds \quad (9)$$

where $B(s)$ is the Planck function (evaluated at the spectral mid-point of the microwindow) along the path s , and $\tau(s)$ is the transmittance along the path s , given by

$$\tau = \exp(-k_c s). \quad (10)$$

Using simple circular geometry (ignoring refraction and assuming the Earth's radius, $r_e \gg z$), the path distance and altitude relative to the tangent point values are related by

$$(s - s_t)^2 \simeq 2r_e(z - z_t). \quad (11)$$

Equation (9) can then be solved to give

$$L_t = \left(B_c + \frac{b}{r_e k_c^2} \right) (1 - \tau) - \left(\frac{bs}{2r_e k_c} \right) (1 + \tau). \quad (12)$$

The appearance of the retrieved parameter k_c in the denominator makes this potentially numerically unstable in the optically-thin limit, so a more computationally robust approximation is preferred, such that

$$L_t \simeq \left(B_c + \frac{2}{3} b(z_t - z_c) \tau \right) (1 - \tau), \quad (13)$$

which agrees with the exact solution in the asymptotic limits of transmittance. In the optically thick limit ($\tau = 0$) cloud effectively just emits from its upper surface and $L_t \rightarrow B_c$,

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as expected, while in the optically thin limit ($\tau \rightarrow 1$) the emission effectively comes from the point one third of the vertical distance from the tangent point to the cloud-top, $L_t \rightarrow (\frac{1}{3}B_c + \frac{2}{3}B_t)(1-\tau)$, where $B_t \equiv B(z_t)$ from Eq. (8).

2.5.2 FOV convolution

The MIPAS FOV response function is represented by a vertical trapezium with a 4 km base and a 2.8 km top when projected onto the atmospheric limb. With tangent heights spaced at 3 km intervals for the original full-resolution measurements, this gives a small overlap between adjacent measurements, but a much larger overlap for the 1.5 km spacing used in the “optimised-resolution” measurements employed since 2005.

This FOV function ϕ is sampled at N points (in practice, $N=9$), which determine the altitudes z_j for which the pencil-beam calculations are performed. The measured continuum radiance is then represented by a numerical convolution of the pencil-beam radiances at these altitudes (L_{t_j}), such that

$$R = \sum_{j=1}^N a_j L_{t_j} \quad (14)$$

where the coefficients a_j are determined according to the assumption that the FOV response function and the cloud radiance vary linearly between calculated points, but that the radiance varies as a step function in the interval containing the cloud-top.

2.5.3 Cloud effective fraction

As mentioned in Sect. 2.4.2, the CEF defined in Eq. (1) is included in the measurement vector, therefore has to be evaluated by the forward model. Using Eq. (14)

$$\alpha = \frac{\sum_{j=1}^N a_j L_{t_j}}{B_c}. \quad (15)$$

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Noting that, for optically thick cloud, $L_{\uparrow} \sim B_c$ (Eq. 13) for pencil-beams which intersect the cloud, and $L_{\uparrow} = 0$ for pencil-beams above the cloud top, this expression for α effectively just depends on the weights a_j , which depend only on z_{\uparrow} .

2.5.4 Definition of cloud forward model

5 Thus, the cloud forward model \mathbf{f} is simply Eq. (14) applied to each of the FOVs available in the measurement vector \mathbf{y} , along with the definition of the CEF, α , given in Eq. (15). Furthermore, since these are analytic expressions, analytic derivatives are used to calculate elements of the Jacobian matrix \mathbf{K} .

2.6 Combining microwindow results

10 2.6.1 Statistical combination

Retrievals, \mathbf{x}_k , and associated covariances, \mathbf{S}_{xk} , are obtained from each of the $M = 10$ microwindows. These results can then be combined using the standard statistical procedure for independent estimates, such that

$$\hat{\mathbf{S}}_x^{-1} = \sum_{k=1}^M (\mathbf{S}_{xk})^{-1} \quad (16)$$

$$15 \quad \hat{\mathbf{x}} = \hat{\mathbf{S}}_x \sum_{k=1}^M (\mathbf{S}_{xk})^{-1} \mathbf{x}_k \quad (17)$$

where $\hat{\mathbf{x}}$ and $\hat{\mathbf{S}}_x$ represent the combined estimate and its covariance. There is an assumption here that the retrieved parameters do not vary spectrally – at least across the tens of wavenumbers represented by the selected microwindows (cloud-top radiances are converted to cloud-top temperatures prior to the combination). Extinction, of course, does vary spectrally – however over the small spectral range sampled by the

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MWs, this variation is not great. It also ignores the fact that the same a priori temperature climatology is used for each estimate, so the separate microwindow results are not strictly independent.

2.6.2 Spike tests

- 5 This combination step also allows a spike-test to be applied – that is, a removal of results from any microwindows which deviate significantly from the mean. The χ^2 statistic is computed for each microwindow individually

$$\chi_k^2 = (\mathbf{x}_k - \hat{\mathbf{x}})^T \hat{\mathbf{S}}_x^{-1} (\mathbf{x}_k - \hat{\mathbf{x}}), \quad (18)$$

- 10 and if the microwindow with the highest χ^2 value exceeds the average χ^2 by some factor (e.g. 2) its results are removed from the combination and the test repeated for the remaining microwindows.

2.6.3 Error inflation

- 15 In theory, the covariance $\hat{\mathbf{S}}_x$ should contain the random error information on the retrieved values. However, it is recognised that this is an optimistic assumption since it makes no allowance for the forward model errors or approximations. If the different microwindows produce a large scatter of results, then the standard deviation D of this distribution is likely to be a better estimate of the actual uncertainty, although this does not necessarily allow for forward model errors either since all microwindows make the same assumptions. A three-element vector of scale-factors \mathbf{e} is constructed to take the maximum of these, such that

$$e_m = \max\left(1, \frac{D_m}{\sigma_m}\right) \quad (19)$$

20 where σ_m is the square root of diagonal element mm in the matrix $\hat{\mathbf{S}}_x$ (i.e. the uncertainty in parameter x_m according to the covariance matrix) and D_m is the actual standard deviation of the parameter x_m from the different microwindow results.

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The retrieval covariance is then “inflated” to produce the final covariance, such that

$$\hat{\mathbf{S}}'_{x\,mm} = \mathbf{e}_m^2 \hat{\mathbf{S}}_{x\,mm}. \quad (20)$$

2.7 Operational considerations

The retrieval scheme described attempts to extract the maximum cloud information (i.e. three parameters) from the spectra, and assumes that continuum radiances from the FOV containing the cloud-top, as well as the FOV immediately below, are available (R_c and R_l).

In an operational processor, it is desirable to have alternative schemes available to perhaps retrieve fewer parameters in situations where the full retrieval fails (due to an insufficient number of microwindows providing retrievals which converge or pass the spike test), or if insufficient measurements are available (most commonly when the cloud-top is detected in the lowest spectrum in the limb scan).

Assuming that a cloud-top has been detected somewhere in the scan, the operational algorithm attempts the following retrieval schemes in sequence until one returns valid results for at least three microwindows.

1. If available, using the measurement from the sweep below the cloud-top R_l (i.e. the cloud-top not located in the lowest sweep in the scan), with a priori extinction information given by $\mu_a = -2.5$ (i.e. mid-range value). This is the full three parameter retrieval (z_c, T_c, μ_c) from three measurements (R_c, R_l, α) (plus the nominally zero radiance measurement R_u from the sweep above the cloud-top).
2. As (1) but setting $\mu_a = -1.0$, giving a “thick cloud” assumption ($k_c = 0.1 \text{ km}^{-1}$). Such a large initial guess value of extinction reduces the Jacobians with respect to this parameter to nearly zero, effectively leaving just two parameters (z_c, T_c) to be retrieved from three measurements (R_c, R_l, α).
3. As (2) but without R_l – that is, the “thick cloud” assumption allowing for retrieval of two parameters (z_c, T_c) from only one sweep using two measurements (R_c, α).

This relies on the CEF retrieval in order to separate the two parameters.

3 Preliminary validation and application of algorithm

3.1 Example results: 1 April 2003

In this section, all measurements registered by MIPAS on 1 April 2003 have been processed using the described algorithm to highlight the products calculated and available for further analysis. Figure 2 shows the retrieved values of CTH, CTT and CEX, along with the errors stemming from the retrieval process itself (from the retrieval error covariance matrix). Generally, the values reported are sensible. Furthermore, the types of retrieval, as discussed in Sect. 2.7, are identified by different symbols – and profiles in which there is deemed to be no cloud present are identified by a cross, giving an indication of the proportion of vertical scans taken through the atmosphere having cloud present somewhere in the scan.

3.2 Application of algorithm to a test month: April 2003

As the algorithm seems capable to retrieve trustworthy estimates of the simulated cloud parameters, the algorithm can be applied with a degree of confidence to real MIPAS data, and be expected to yield sensible results. A full month's data taken in April 2003 is used as a test ensemble. Preliminary validation is carried out qualitatively, by comparing results with the ISCCP high-cloud climatology (ISCCP, 2008) – keeping in mind that ISCCP infrared cloud products are determined from nadir-measurements (which will penetrate further vertically into clouds, and hence report lower cloud heights) and are known to miss much high, thin cloud. Furthermore, ISCCP does not report extinction values, but rather optical depths, so these can really only be utilised to judge qualitatively what opacity clouds occur where. Figure 3 shows the results of application of this retrieval algorithm to MIPAS data, along with ISCCP data, from April 2003.

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It is immediately obvious that, with the chosen cloud detection method, the macrophysical cloud parameter retrieval presented here provides information on higher clouds (such as cirrus) which ISCCP clearly misses. MIPAS shows cloud top heights increasing toward the equator, which is expected due to increasing tropopause height toward the tropics, while ISCCP finds lowered cloud top heights at the equator. Furthermore, ISCCP seems to predominately miss high cloud, as either a result of its cloud detection method, or its nadir-geometry. Cloud top temperatures are largely anti-correlated with cloud top heights in both the MIPAS and ISCCP results, as expected. Comparing cloud opacities, it is qualitatively obvious that MIPAS sees – and retrieves – more thin cloud than does ISCCP, as supported by the relative frequency of smaller extinction values reported over the globe – and particularly in regions such as the tropics where optically-thin cirrus is ubiquitous. This is a function of ISCCP products having been retrieved from nadir measurements, which are typically sensitive only to cloud opacities larger than 0.01, highlighting again the suitability of limb-sounding instruments such as MIPAS for cloud analysis and study.

As well, analysis of the retrieved errors from the retrieval covariance matrix \mathbf{S}_x gives a quantitative estimate of the quality of the retrieved results. Figure 4 shows the distribution of the retrieval errors for the month's worth of MIPAS data. Generally, the retrieval is able to estimate the cloud top height within 50 m, cloud top temperature within 0.5 K, and extinction to within 15%.

Typically around 25% of sampled MIPAS scan profiles are cloud free throughout the atmosphere, about 40% of vertical scans are retrieved with the full Type 1 retrieval, whilst about 25% are retrieved with the Type 2 retrieval and about 10% with the Type 3 retrieval. The proportion of unsuccessful retrievals is less than 1%.

3.3 Comparison of CEF and CI detection mechanisms

Section 2.3 describes the method used to select measurements as containing cloud and as the CI Method is the traditionally used method, this section seeks to assert that the CEF is reasonable as a cloud detection method, and in fact, may capture more

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optically-or-geometrically thin cloud. In this section, application of both CEF and CI cloud detection methods to the same set of spectra. This set of spectra is selected as all those spectra measured below 30 km above which the CEF method first detects a cloud top, which will give a realistic selection of clear and cloudy examples. Comparison between the two detection mechanisms is made using real MIPAS data for all measurements registered on 1 April 2003.

Figure 5 shows the results of this comparison, highlighting that the CEF scheme detects more cloud than does the CI method. It is plausible that the scatter of points at higher CI are indeed cloudy cases, as there appears to be larger scatter than attributable to normal variations of temperature and trace-species concentrations. Furthermore, if the thresholds are applied and cloud detection is carried out, the CEF scheme detects more cloud particularly in regions where thin cloud such as polar stratospheric clouds or cirrus are expected. In general, the CEF method selects far more measurements as cloud-contaminated – which should yield a more complete selection of cloud data upon which to create climatological analysis.

It is worth noting that the percentage of spectra identified as containing cloud is dependent upon the choice of threshold applied to each detection method. For instance, at the operation threshold of 1.8, the CI method detects cloud in 9.8% of the studied set of spectra. The CEF method will select 9.8% of the spectra as containing cloud if its threshold is modified to 0.32 (instead of the suggested 0.1), although it is worth noting that both methods do not choose all the same individual cases as cloud-contaminated. If the CI threshold for cloud is loosened to 4.0, it selects 17.6% of the spectra in the set as cloudy – a percentage which can be matched by setting the CEF threshold to 0.08.

Application of CEF and CI cloud detection methods to MIPAS data highlights that the CEF method detects more possible cloud, including thin cloud which is so frequently missed from current cloud climatologies such as ISCCP (ISCCP, 2008).

4 Conclusions

This study confirms that cloud top height, cloud top temperature and extinction coefficient can be successfully retrieved by modelling clouds quite simply and by using an optimal estimation-type retrieval whereby an estimate for CEF initiates the retrieval close to the correct cost minimum. The retrieval algorithm has been tested and found reliable on real MIPAS data. The retrieval errors associated with application of this algorithm to this data can be used to determine a measure of confidence for how well the forward model represents realistic scattering clouds. From this, CTH is retrieved to within 50 m, CTT to within 0.5 K and k_{ext} within a factor of 15% (these errors, associated with the retrieved parameters, are in the retrieval error covariance matrix \mathbf{S}_x), although there do exist cases in which higher error exists.

It should be noted that the greatest error is expected to result from the error in the initial forward model assumption of horizontal homogeneity – that is, that a cloud can be represented by a single flat cloud top height, a single extinction coefficient and a consistent temperature structure throughout the body of the cloud. Horizontal homogeneity is a simplification of the geometry and optics of real clouds – but there are infinite possible cloud fields and it is impossible to retrieve inhomogeneous fillings of the MIPAS FOV without prior knowledge of the geometry of the inhomogeneity. Thus, whilst the assumption of horizontal homogeneity is insufficient to fully represent reality, it is the closest representation that can be accomplished without some other a priori knowledge such as a limb imager coinciding with the FTS view.

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Table 1. Microwindows for cloud macrophysical parameter retrievals from MIPAS spectra, ordered in terms of priority of selection. Note that the boundaries are multiples of 0.125 cm^{-1} so are consistent with both the “full-resolution” (0.025 cm^{-1} grid) and “optimised-resolution” (0.0625 cm^{-1} grid) spectra.

MW#	Wavenumber Range [cm^{-1}]
1	937.625–940.625
2	941.125–944.125
3	944.500–947.500
4	955.750–958.750
5	948.625–951.125
6	936.000–937.625
7	934.500–935.875
8	953.500–955.000
9	951.875–953.250
10	958.750–960.875

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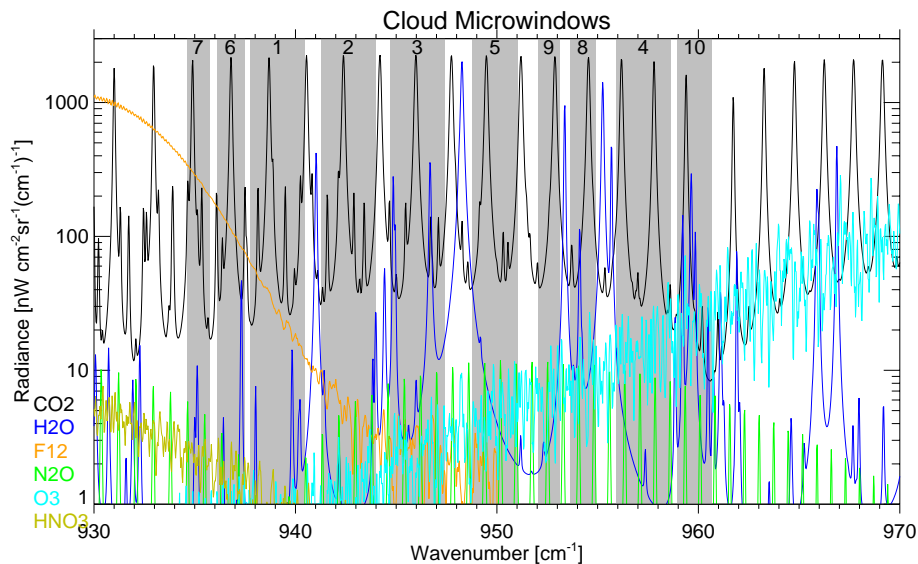


Fig. 1. Modelled full-resolution MIPAS spectrum for a tangent height of 9 km separated by constituent major emitters, in the spectral region of selected MWs listed in Table 1– with MW spectral regions shaded.

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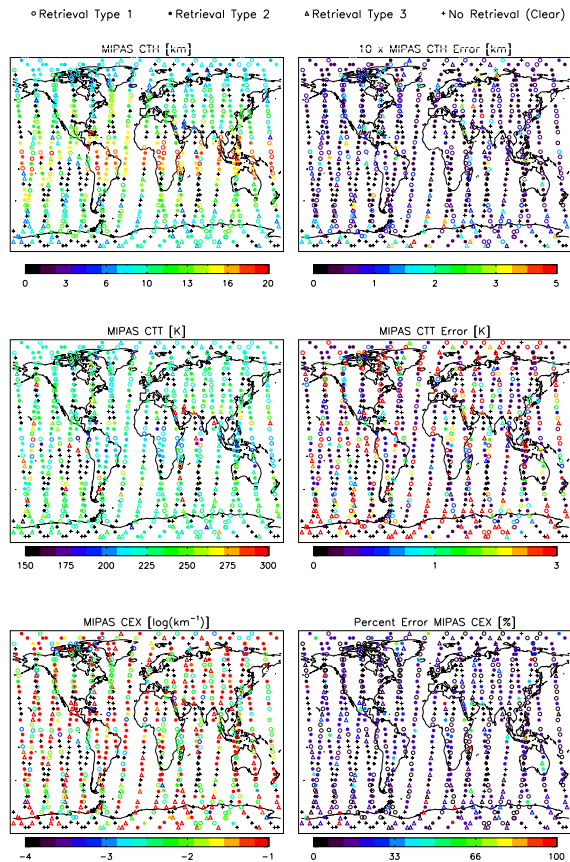


Fig. 2. Application of algorithm to all MIPAS measurements taken on 1 April 2003. Retrieved parameters (left column) of CTH (top panels), CTT (middle panels) and k_{ext} (bottom panels) and errors thereof (right panels) are given, noting the type of retrieval, corresponding to the available measurement FOVs.

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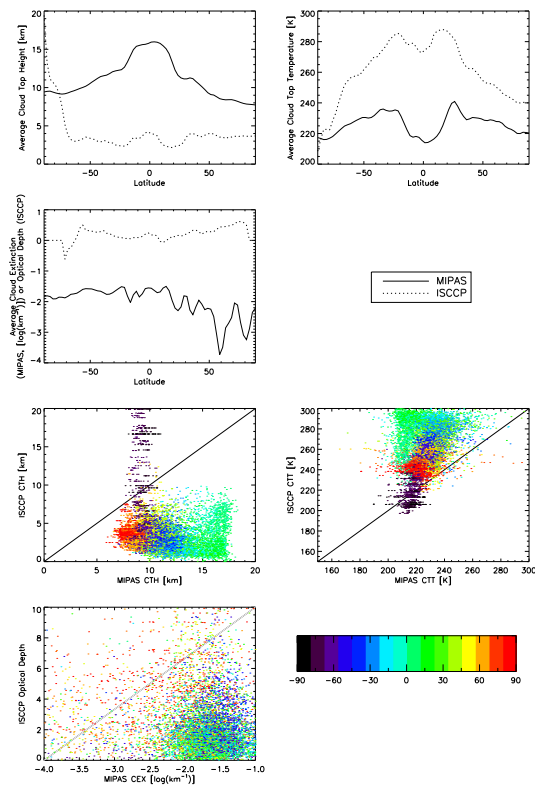


Fig. 3. Top panels: Zonally-averaged retrieved cloud top height (top left), cloud top temperature (top right) and logarithm of extinction coefficient (bottom left) when algorithm is applied to a month's worth of MIPAS data (solid lines), along with corresponding ISCCP quantities (dotted lines). Bottom panels: Scatterplot showing average cloud top height (top left), cloud top temperature (top right) and cloud extinction (bottom left) in a 2.5° by 2.5° latitude/longitude grid for MIPAS and ISCCP. Solid line shows one-to-one limit. Points colour-coded by latitude.

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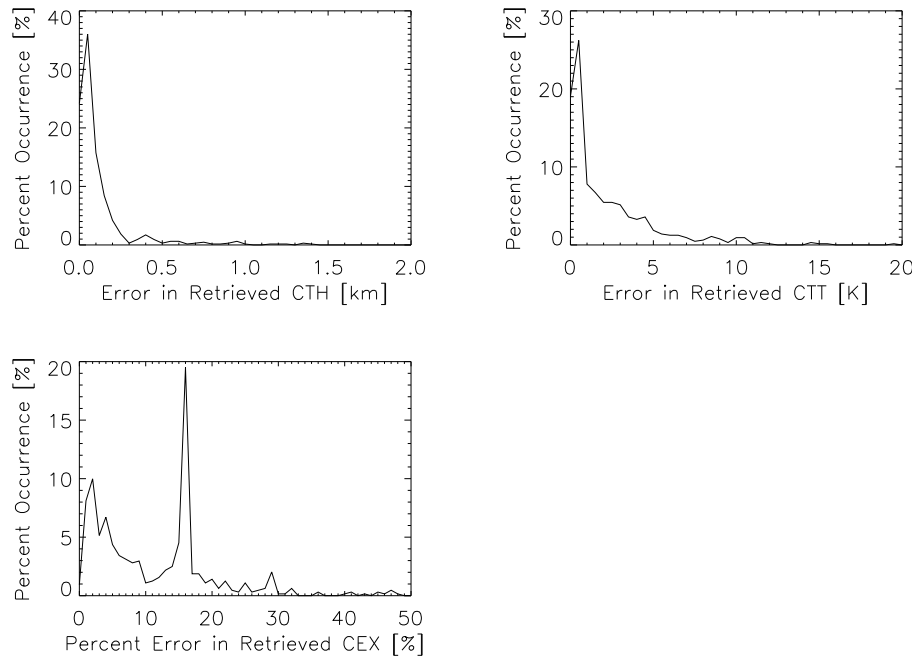


Fig. 4. Retrieval errors for cloud top height (top left), cloud top temperature (top right) and extinction coefficient (bottom) from application of algorithm to all MIPAS measurements taken in April 2003.

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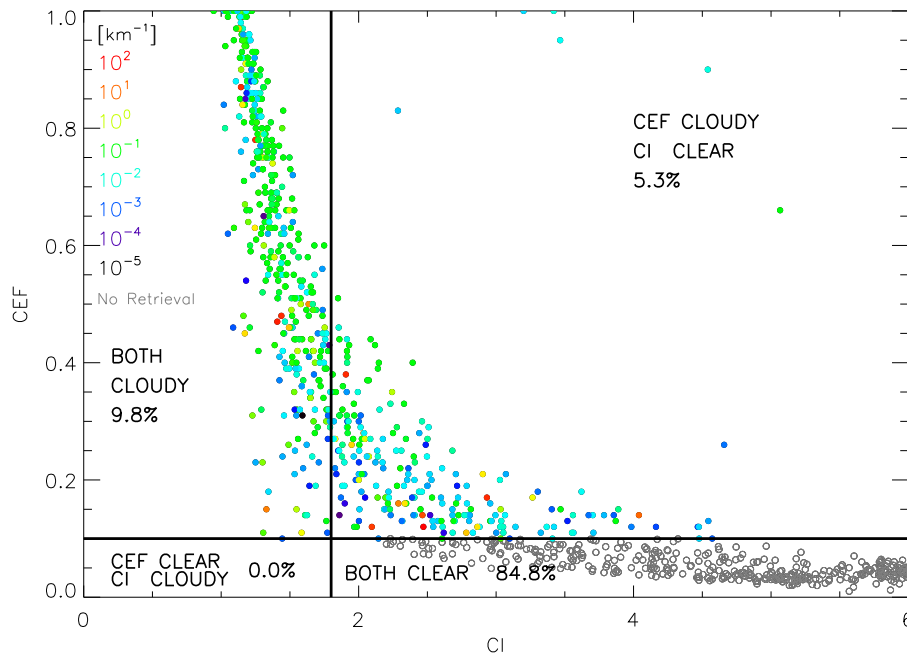


Fig. 5. Correlation between CI and CEF (evaluated in MW1) colour-coded by extinction coefficient (for those cases for which the retrieval has been evaluated) and by open circles for clear scans, for all spectra above the cloud top (if any) measured MIPAS on 1 April 2003. CI is anti-correlated and CEF is correlated with cloud amount. Horizontal line shows the CEF threshold (above which cloud occurs) and vertical line shows the CI threshold (to the left of which cloud occurs).

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