MIPAS OBSERVATIONS OF CLOUDS AND THEIR EFFECTS ON LEVEL 2 TRACE GAS PRODUCTS

John J. Remedios [(1)] **and Reinhold Spang** [(1)]

[(1)] *EOS, Space Research Centre, University of Leicester, England, email: j.j.remedios@le.ac.uk, r.spang@le.ac.uk.*

ABSTRACT

The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) instrument measures the intensity of atmospheric radiation emitted in the infra-red spectral region at high spectral resolution in five bands ranging from 685 cm^{-1} to 2410 cm^{-1}. Clouds affect the appearance of the measured spectra at all wavelengths which are sensitive to emission from the layer of atmosphere containing the cloud. Both low resolution (cloud continuum) and high resolution features (complicated spectral lineshapes) can be observed due to the MIPAS resolution of 0.025 cm^{-1} (unapodized). This has two implications. Firstly, spectra containing clouds must be identified and flagged prior to retrievals of trace gas concentrations at level 2. Secondly, the cloud information constitutes valuable products in themselves. In this paper, the success of the cloud detection scheme is reported and the MIPAS level 2 data are examined to demonstrate the effects of the clouds and the quality of the data given cloud flagging. The results are excellent and the cloud detection method will be included in the next update of the MIPAS operational processor. The results presented also support the quality of the MIPAS reference atmospheres which are available for use by other instrument teams.

1 INTRODUCTION

The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) on ENVISAT is an infra-red Fourier transform spectrometer which observes radiation emerging from the Earth's limb. Vertical profiles of the radiance are obtained by scanning the limb between 6 and 68 km at a spacing of 3 km in the lower atmosphere. Five channels are employed covering a complete wavenumber region between 685 cm^{-1} (14.60 µm) and 2410 cm^{-1} (4.15 µm) at "high" resolution (nominally 0.035 cm^{-1} apodised). In the current operational processor, seven products (temperature and trace gases) are obtained by inversion of the radiance signal to product profiles. This processor includes only limb spectra at the tangent altitudes above 12 km although it has now been shown that useful information exists from 6 km upwards (Carli *et al.*, these proceedings [1]) and this may be included in future updates. In fact, a large number of additional products are possible from MIPAS throughout the scanned height range including information on many trace gases, aerosol/cloud particles and potentially winds. It is the purpose of this paper to focus on cloud effects.

Historically, evidence for the infra-red detection of clouds in limb views has been obtained primarily from observations by radiometers integrating the infra-red spectrum over passbands of typically 10 to 100 cm^{-1}. For example, data from the Upper Atmosphere Research Satellite demonstrated the influence of layers of sub-visible cirrus through statistical/seasonal analyses by Mergethaler *et al.* [2] and Massie *et al.* [3]. Such clouds were shown to exist at upper tropospheric altitudes with occurrence frequencies of up to 40% in the tropics. Polar stratospheric clouds were also observed by the same instruments on UARS and a number of studies, e.g. Taylor *et al.* [4] and Hervig *et al* [5] inferred aspects of the distribution and characteristics of PSCs in both the Arctic and Antarctic. Two aspects were very clear from these limb sounding studies: 1) the vertical resolution and geometry of limb sounding provided a unique view of very important, high altitude clouds (above 6 km) with small particle sizes (less than 20 µm mean radius); 2) the identification of clouds and subsequent flagging (cloud clearing) were central to good retrievals of trace gas profiles from infra-red instruments. It became clear, pre-launch that, although MIPAS is a spectrometer which allows mitigation of some of the cloud effects on trace gas retrievals, it would be necessary to develop a cloud detection method so as to avoid errors in the operational products. The importance of this is shown in this paper.

2 CLOUD DETECTION METHOD

Development of a cloud detection method for MIPAS, pre-launch, was able to draw heavily on experience obtained by

Proc. of Envisat Validation Workshop, Frascati, Italy, 9 – 13 December 2002 (ESA SP-531, August 2003)

the authors in working with data from the CRyogenic Infrared Spectrometer and Telescopes for the Atmospheres (CRISTA) experiment (Offermann *et al.* [6]). The CRISTA experiment obtained low resolution spectra (2 cm^{-1}) data between 710 and 2400 cm^{-1} during two short missions of the CRyogenic Infrared Spectrometer and Telescopes for the Atmospheres (CRISTA); observations were made in November 1994 and August 1997. Four important points have arisen from a number of studies of CRISTA data carried out by the authors: 1) it has been shown that clouds can be detected and cloud height estimated using a spectral ratio test; 2) a characteristic spectral signature to PSCs at 820 cm^{-1} has been identified as arising from the presence of HNO_3 dissolved as the nitrate ion (Spang and Remedios, submitted to GRL); 3) a combination of 1) and 2) have been used to differentiate sub-visible cirrus, ice PSCs and HNO_3-dominated PSCs; 4) retrievals of trace gases have been performed for weak cloud (limb optical thickness less than ~0.2 in the infra-red). These aspects are all highly relevant to MIPAS which in addition has the advantage of high spectral resolution enabling better retrieval of trace gases in the presence of optically thin clouds.

In order to build a cloud detection algorithm that was robust, it was decided to develop a cloud detection method that could be verified using the CRISTA data. The method employed for MIPAS is that demonstrated for CRISTA by Spang *et al.* [7] namely the ratio of the integrated radiances in two "mesowindows" which each react differently to the presence of clouds. This simple and robust method was first implemented for CRISTA for a pair of mesowindows, 788–796 cm^{-1} (MW1) and 832–834 cm^{-1} (MW2), where the ratio CI = MW1/MW2 is such that the cloud index (CI) is large for cloud free conditions (CI>4), close to one for optical thick conditions (spectra similar to a black body) and in-between for the transition region from optically thin to optically thick. Definition of a threshold value for CI enables a "cloud top height" to be allocated. This corresponds to the top height at which the signature of a cloud is observed within a single limb scan. Forward model simulations show that in the height regime 12 to 40 km a ratio of CI=2 or less (for this mesowindow) can only be produced by a radiation background anomalously enhanced by aerosols or clouds. The temperature dependence of CI_{CR} is especially weak (<1%/K in the 10-30 km range).

3 CLOUD MESOWINDOWS FOR MIPAS

The spectral interval originally employed for CRISTA falls in MIPAS band A (cloud index denoted by CI-A). It is desirable to have a cloud flag per spectral channel of MIPAS for two reasons: 1) there may be an invalid spectrum in channel A whilst the other channels (AB, B, C and D) contain valid spectra; 2) different cloud indices may have different sensitivities to cloud effects. Candidate mesowindow pairs were therefore identified by forward modelling of the spectra using a state of the art line-by-line radiative transfer code, the Oxford Reference Forward Model or RFM (Dudhia [8]); reference atmosphere profiles were taken from Remedios [9] and spectral data from the HITRAN 1996 database. These mesowindow pairs were then tested on CRISTA data to ensure good statistics. Suitable mesowindow pairs were found in channels B and D (CI-B and CI-D) respectively. Density of spectral lines and variability of the cloud index with altitude prevented similar pairs of mesowindows being defined in channels AB and C. Current threshold values and altitude ranges for use of each ratio are shown in Table 1.

Table 1: Cloud detection settings for MIPAS

Cloud Index MIPAS Band	MW1 (cm^{-1})	MW2 (cm^{-1})	Cloud Index threshold value	CRISTA defined altitude range (km)	Preliminary MIPAS in-flight altitude range (km)
CI-A	788.20 – 796.25	832.3 – 834.4	1.8	8-60	10*-45
CI-B	1246.3 – 1249.1	1232.3 – 1234.4	1.2	8-50	10*-40
CI-D	1929.0 – 1935.0	1973.0 – 1983.0	1.8	8-32	12*-30

* The height range will be extendable to lower altitudes for mid and high latitudes.

The in-flight altitude range was determined from early MIPAS data for approximately 4100 profiles which were available for September 2002 (between the 7th and the 17th). Cloud indices for all three mesowindow pairs were computed off-line and are shown in Figure 1 which represents the first global map of cloud top heights from MIPAS data. The data have also been examined as as vertical profiles (Figure 2) and inter-compared. Excellent agreement was found with a total of 1067 cloud occurrences detected through CI-A, 1158 through CI-B and 1292 through CI-D when the threshold values in Table 1 were applied. Furthermore, 96% of those detected from CI-A in this period were also detected using CI-B and 98% of those detected from CI-B were flagged using CI-D. This implies that either CI-D, for example, is more sensitive to clouds or else the threshold value is set slightly more stringently for CI-D. Below 12 km, forward model calculations show that water vapour can a problem in the tropics and could limit the use of CI-D here; this effect could also be present for the other cloud indices below 10 km. Preliminary investigation suggests that at other latitudes CI-D displays more sensitivity to clouds than the other indices. The low altitude thresholds for all three indices are therefore set somewhat conservatively at this stage and could be extended downwards following further research. At high altitudes, the reduction in the upper altitude threshold from MIPAS to CRISTA is because of the lower signal-to-noise in MIPAS spectra for a single spectrum. Finally, it is worth remarking that CI-D shows a distinct day/night difference due to emission from NO in the atmosphere primarily from the thermosphere.

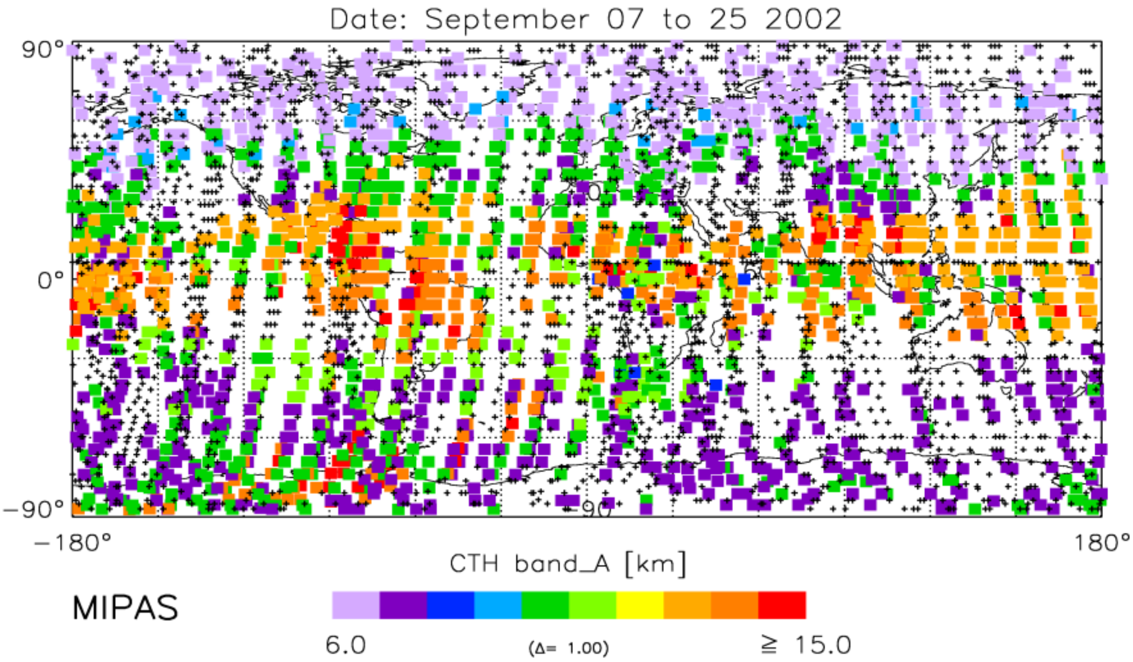

Figure 1: The first global cloud top height map computed from MIPAS level 1b data using CI-A with a threshold of 1.8. The appearance of cirrus clouds in the tropical upper troposphere and polar stratospheric clouds in the Antarctic polar winter can be observed.

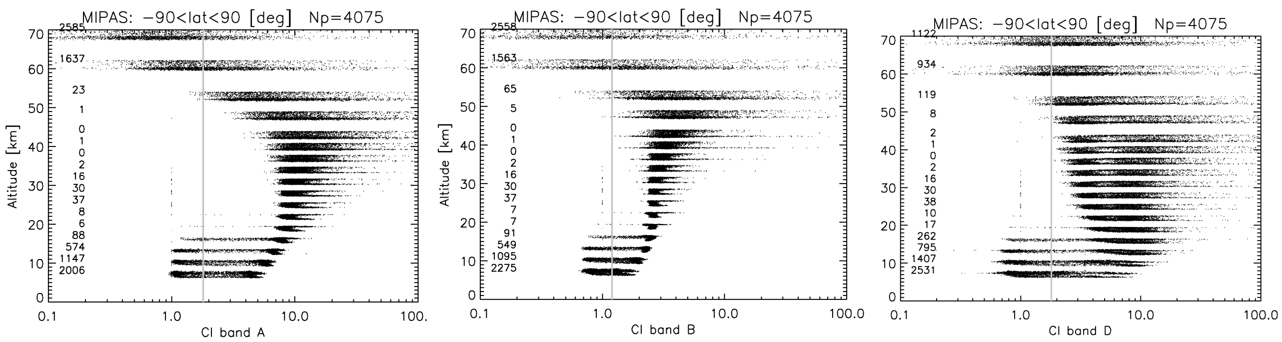

Figure 2: Comparison of the three cloud indices for the MIPAS detector bands A, B, and D. Threshold-values for clouds are indicated by the gray vertical lines. Measurements at all latitudes between September 7 and 17. Numbers for observations below the cloud threshold are superimposed.

4 EFFECTS OF CLOUDS ON MIPAS LEVEL 2 TRACE GAS RETRIEVALS

The critical question for the cloud detection and flagging, as far as the level 2 processor is concerned, is the correct setting of the cloud flag and hence the threshold values for the cloud indices. There are a number of ways to examine cloud effects on the level two trace gas mixing ratios, for example, scatter plots of retrieved trace gas concentrations versus cloud index value, comparisons of the altitude dependence of trace gas concentrations to means and standard deviations from reference atmospheres, and comparisons of zonal mean cross-sections of retrieved and reference atmospheres. In this paper, the altitude dependence of the retrieved ozone and methane trace gas concentrations is examined with respect to the MIPAS standard atmospheres (Remedios [9]).

Figure 2 shows a comparison between MIPAS data and the MIPAS reference atmospheres for the tropical region (defined as 20ºS to 20ºN) as observed by MIPAS in September 2002. Available data allowed 930 profiles to be included in the analysis which was performed both for the unflagged level 2 data (as currently output by the operational processor) and for level 2 data which were flagged for the effects of clouds. Both the individual points and the average of the MIPAS data are plotted to allow comparison to the mean and variability of the reference atmospheres; variability is represented by maximum/minimum profiles. Above 20 km, it is clear that the average MIPAS ozone and methane data agree very well with the mean reference profile. Retrieved ozone appears to be slightly higher at the peak of the ozone profile by about 10%. In the higher part of the atmosphere, the retrieved ozone decreases at a slightly faster rate than the reference profile. Very encouragingly, the scatter in the MIPAS data compares well with the sigma from the reference atmosphere, particularly for ozone. There is evidence that the scatter in the methane data is higher than the reference variabilities. Below 20 km, cloud effects make a considerable difference to both ozone and methane values. The unflagged level 2 data show values which can be an order of magnitude higher than would be expected from the reference atmosphere. Use of a cloud flag (CI-A<1.8 was employed here) moves the average to much smaller values in closer agreement with the reference state. Here, methane constitutes a better test than ozone for the cloud effects because of our relative lack of knowledge of upper tropospheric ozone values globally. The methane plot suggests that the cloud threshold might not be stringent enough since small deviations are still observed in the flagged methane data near 12 km. As the upper troposphere might be expected to appear relatively well-mixed for methane, this geophysical test provides a good validation for the cloud thresholds.

Similar work has been performed for the other MIPAS operational products and the conclusion is the same for all species: the cloud detection scheme is necessary for level 2 retrieved data to be utilised fully. Hence the cloud detection scheme and threshold settings outlined here will be implemented in the MIPAS operational processor. The authors will also work with ESA to provide cloud index profiles so that users may implement their own cloud flagging prior to use of level 2 data

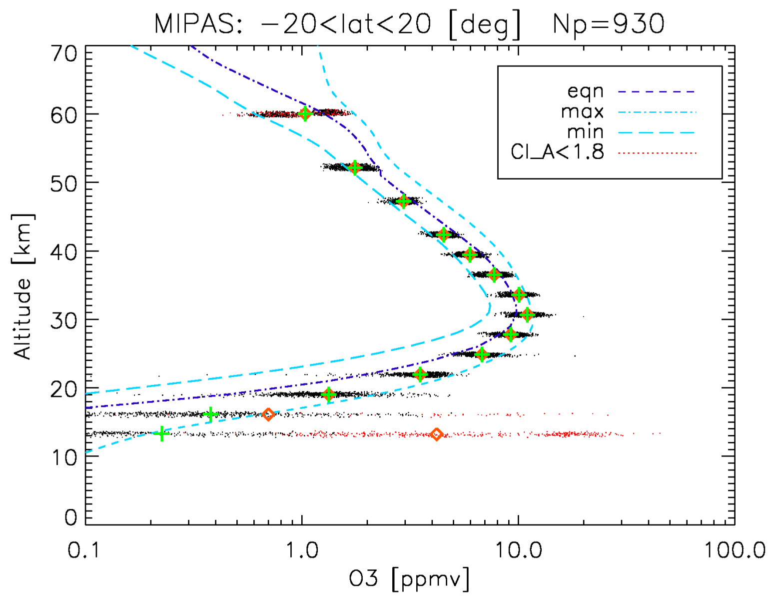

Figure 2: Comparison of the MIPAS tropical data for ozone in September 2002. Black and red dots are the MIPAS retrieved data with diamonds for the mean of the unflagged MIPAS retrievals and crosses for the mean of the cloud-flagged data (see 20 km and below); black=non-cloudy data, red=cloud affected data as detected by the cloud test with CI-A. The tropical reference atmosphere is the dot-dashed line and the dashes are references representing the expected minimum and maximum extremes of the mixing ratio at each altitude.

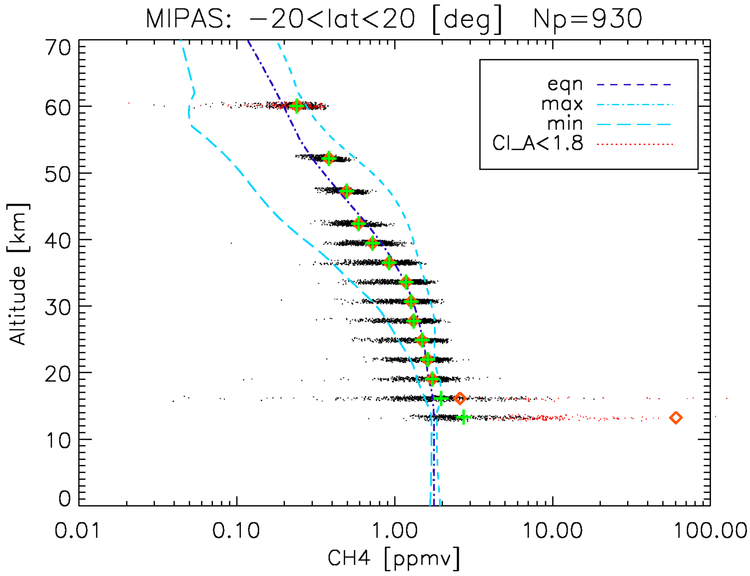

Figure 3: Comparison of the MIPAS tropical data for methane in September 2002. Black and red dots are the MIPAS retrieved data with diamonds for the mean of the unflagged MIPAS retrievals and crosses for the mean of the cloud-flagged data (see 20 km and below); black=non-cloudy data, red=cloud affected data as detected by the cloud test with CI-A. The tropical reference atmosphere is the dot-dashed line and the dashes are references representing the expected minimum and maximum extremes of the mixing ratio at each altitude.

5 CONCLUSIONS

A cloud detection scheme has been successfully implemented in the prototype operational processor. This cloud scheme will be effective from 10 km to 45 km and further work should refine the scheme such that altitudes below 10 km can be adequately addressed. The cloud detection scheme has been shown to be necessary to utilise level 2 retrieved data fully. A further consequence of this test has been to demonstrate the excellent agreement in the tropical region between the mean and variabilities of cloud-flagged MIPAS gas concentration data and the corresponding quantities for reference atmospheres. This also demonstrates the quality of the reference atmospheres. Finally, the cloud data are valuable in themselves and should be made available as an additional MIPAS product (s). For example, the use of appropriate radiance ratios could enable maps of polar stratospheric cloud (PSC) types to be obtained. Such information has potential as part of a Global Monitoring for the Environment and Security (GMES) system for atmospheric ozone.

Further work is necessary to fully optimise the cloud detection thresholds, particularly at altitudes below 12 km in the tropics. In addition, the provision of cloud information for the AB and C bands should be examined; cloud flagging in these channels is likely to require information from within microwindows because of the density of lines in the spectra and saturation effects. Since the variability of trace gases, and water vapour in particular is uncertain, the cloud index approach should be validated over a period of 12 months. Long term activities should include consideration of the effects of large injections of volcanic aerosol into the upper troposphere/lower stratosphere, and the effects of any drifts in instrument performance.

Finally, the cloud index detection information for MIPAS will provide valuable information to the Atmospheric Chemistry Validation Team (ACVT) involved in ENVISAT/MIPAS validation. Therefore, cloud index profiles are now being processed in near real-time (NRT) and maps of cloud top height can be found at http://www.leos.le.ac.uk/mapscore.

6 ACKNOWLEDGEMENTS

This work has been funded through the ESA Expert Support Laboratory with support also from the European Commission through the MAPSCORE project EVK2-CT-2000-00077. The authors would like to acknowledge H. Nett, J. Langen and the ESL team for helpful discussion and data access.

7 REFERENCES

1. **Carli, B., *et al.*, Analysis of MIPAS measurements with the level 2 near real-time code, these proceedings.**
2. **Mergenthaler, J. L., A. E. Roche, J. B. Kumer, and G. A. Ely, Cryogenic Limb Array Etalon Spectrometer observations of tropical cirrus *J. Geophys. Res*., 104, 22,183-22,194, 1999.**
3. **Massie, S.T. *et al.*, Spectral signatures of polar stratospheric clouds and sulfate aerosols, *J. Atmos. Sci., 51*,3027,3044, 1994.**
4. **Taylor, F.W. *et al.*, Properties of Northern Hemispheric Polar Stratospheric Clouds and Volcanic Aerosol in 1991/92 from UARS/ISAMS Satellite Measurements, *J.Atmos.Sci*, 51, 3019-3026, 1994.**
5. **Hervig, M.E., *et al.*, Polar stratospheric clouds due to vapor enhancement: HALOE observations of the Antarctic vortex in 1993, *J. Geophys. Res., 102*, 28,185-28,193, 1997.**
6. **Offermann, D., K. U. Grossmann, P. Barthol, P. Knieling, M. Riese, and R. Trant, The CRyogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) experiment and middle atmosphere variability, *J. Geophys. Re*s., 104, 16,311-16,325, 1999.**
7. **Spang, R., G. Eidmann, M. Riese, P. Preusse, D. Offermann, L. Pfister, and P. H. Wang, CRISTA observations of cirrus clouds around the tropopause, *J. Geophys. Res*., 107(D23), 8174, doi:10/1029/2002JD000698 , 2002.**
8. **Dudhia, A., private communication, http://www.atm.ox.ac.uk/RFM/, 1997.**
9. **Remedios, J.J., Extreme Atmospheric Constituent Profiles for MIPAS, *Proceedings of the European symposium on atmospheric measurements from space*, ESTEC, Nordwijk, Netherlands, 20-22 January, Vol. 2, 779-783, 1999.**