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# MIPAS detection of cloud and aerosol particle occurrence in the UTLS with comparison to HIRDLS and CALIOP

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	AMTD			
J	5, 1795–1841, 2012			
-	MIPAS detection of cloud and aerosol particle occurrence			
	H. Sembhi et al.			
)	Title Page			
	Abstract	Introduction		
-	Conclusions	References		
	Tables	Figures		
	14	۶I		
-	Back	Close		
	Full Screen / Esc			
	Printer-friendly Version			
)	Interactive Discussion			

#### Abstract

Satellite infra-red emission instruments require efficient systems that can separate and flag observations which are affected by clouds and aerosols. This paper investigates the identification of cloud and aerosols from infra-red, limb sounding spectra recorded

- <sup>5</sup> by the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), a high spectral resolution, Fourier transform spectrometer on ENVISAT. Specifically, the performance of an existing cloud and aerosol particle detection method is simulated, with a radiative transfer model, in order to establish for the first time limits to confident detection of particle effects in MIPAS data. The newly established thresholds improve
   <sup>10</sup> confidence in the ability of MIPAS to detect particle injection events and plume trans-
- port in the UTLS as well as better characterised cloud distributions. The method also provides a fast front-end detection system for the MIPClouds processor, a processor designed for the retrieval of macro- and microphysical cloud properties from the MIPAS data.
- It is shown that across much of the stratosphere, the threshold for the standard cloud index in band A is 5 although values of greater than 6 occur in restricted regimes. Polar regions show a surprising degree of uncertainty at altitudes above 20 km due to potential high CIO formation and also poor signal-to-noise due to low atmosphere temperatures. The optimised thresholds of this study can be used for much of the time,
- <sup>20</sup> but time/composition dependent thresholds are recommended for MIPAS data for the strongly perturbed polar stratosphere. In the UT, thresholds of 5 apply at 12 km and above but decrease rapidly at lower altitudes. The new thresholds are shown to allow much more sensitive detection of particle distributions in the upper troposphere and lower stratosphere (UTLS), with extinction detection limits above 13 km often better than 10<sup>-4</sup> km<sup>-1</sup>, with values approaching 10<sup>-5</sup> km<sup>-1</sup> in some cases.

Comparisons of the new MIPAS results with data from HIRDLS and CALIOP, outside of the poles, establishes good agreement in distributions (cloud occurrence frequencies and clouds and aerosol top heights) with an offset between MIPAS and the other



instruments of 0.5 km between 12 and 20 km. We conclude that current infra-red limb sounders provide a very consistent picture of particles in the UTLS, allowing detection limits which are consistent with the lidar observations. Investigations of the MIPAS data for the Kasatochi volcanic eruption and the Black Saturday fires in Australia are used

 $_5$  to exemplify the usefulness of MIPAS limb sounding data for monitoring aerosol injections into the UTLS, and into the stratosphere, in particular over monthly timescales. It is shown that the new thresholds allow such events to be much more effectively monitored from MIPAS with detection limits for these case studies of  $1 \times 10^{-5} \, \text{km}^{-1}$  at  $12 \, \mu\text{m}$ .

#### 10 **1** Introduction

High altitude clouds play a fundamental role in the Earth system through their influence on climate and the Earth's energy balance (Forster et al., 2007). Such cloud formations and types are characterised by different ice crystal sizes, shapes and particle densities influenced by the temperature and humidity conditions. The combination of colder tem-

- <sup>15</sup> peratures and lower humidities in the tropical UTLS region gives rise to layers of thin cirrus composed mainly of ice crystals that have radiative implications for the tropical tropopause layer (TTL) (Jensen et al., 1996a). The presence and formation of thin tropical cirrus clouds may be important to understand the processes affecting stratospheric dehydration (Jensen et al., 1996b) as well as indicative of regions of deep convection
- <sup>20</sup> (Liu et al., 2007). In the polar regions, understanding the composition and occurrence of the polar stratospheric clouds (PSCs) is important for their role in ozone depletion at the poles (Manney et al., 2011).

Atmospheric aerosols are ubiquitous in nature and originate from natural and anthropogenic processes such as burning of savannah and crops, volcanic eruptions and industrial burning (Stephens, 1994). In the UTLS, aerosols can potentially be lofted into the stratosphere by pyro-convection where a combination of extreme convection and forest fires manifest within pyro-cumulonimbus (pyroCb) clouds (Fromm et al., 2006). Explosive volcanic eruptions can also inject polluted material including ash, sulphur



dioxide (SO<sub>2</sub>), carbon dioxide (CO<sub>2</sub>) and water vapour (H<sub>2</sub>O) directly into the UTLS with resulting plumes being transported across the globe (Prata et al, 2007; Clarisse et al, 2008). If ejected into the stratosphere, SO<sub>2</sub> can become oxidised and hydrated leading to the formation of sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) droplets within a few weeks of the <sup>5</sup> eruptions (Prata et al., 2010).

Understanding the global and localised distribution of such a variety of cloud formations and aerosols is particularly important for modelling climate radiative forcing (Randell et al., 2007), for investigating cloud-chemistry interactions such as chlorine activation in the polar stratosphere (Manney et al., 2011), and to determine the radiative implications that high cirrus clouds or aerosol enhancements can have on the radiative balance in the UTLS (Robock, 2000; Corti et al., 2005). Detection of cloud and enhanced aerosol is also an essential component for all satellite remote sensing instruments; accurate and robust cloud detection methods not only determine the quality of satellite retrievals (for example, greenhouse gas concentrations, land and sea surface temperatures) but are also valuable as a pre-processor for retrieval of cloud properties.

- temperatures) but are also valuable as a pre-processor for retrieval of cloud properties. Cloud detection techniques are generally well-established for nadir spaceborne instruments in which the detection is loosely based on brightness temperature differences (BTD) or reflectance ratios for thermal and visible sounders, respectively (Frey et al., 2008). Strabala et al. (1994) demonstrated how the BTD of 8 and 11 µm, and of
- 11 and 12 µm, can distinguish between cirrus and water clouds using brightness temperature measurements from the High Resolution Infrared Sounder (HIRS) and the Advanced Very High Resolution Radiometer (AVHRR). Although passive nadir sounders are well-equipped to measure clouds globally due to their high horizontal resolution, their limited vertical resolution cannot resolve cloud top heights with high accuracy. Ac-
- tive nadir sounders offer much higher vertical resolution. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) lidar onboard NASAs Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) offers vertical resolution better than 180 m making the most detailed measurements of clouds currently available (Winker et al., 2007).



The limb sounding technique offers some distinct attributes for the investigation of clouds and aerosol due to (a) the fine vertical resolution achieved, up to 1 km, compared to that of passive nadir sounders; (b) sensitivity to low aerosol particle amounts due to the long integrating path of the limb; (c) atmospheric radiances obtained against cold space or solar backgrounds and hence uncomplicated by surface 5 emissions/reflections. Several limb sounding instruments have utilised atmospheric radiances measured in the ultraviolet to shortwave infrared (UV-SWIR) or near Infrared (NIR) spectrum to study cloud signatures including the Stratospheric Aerosol and Gas Experiment (SAGE) instrument series (Kent et al., 1993), the Halogen Occultation Experiment (HALOE) on the Upper Atmosphere Research satellite (Hervig 10 and McHugh, 1999), the Optical Spectrograph and InfraRed Imaging System (OSIRIS) on the Swedish ODIN satellite (Bourassa et al., 2005) and the Scanning Imaging Absorption spectroMeter for Atmospheric CartograpHY (SCIAMACHY) instrument on the ENVISAT platform (Eichmann et al., 2009). Alternatively, the sub-millimetre wave region can also be used to sense clouds deeper into the troposphere and of higher cloud

<sup>15</sup> gion can also be used to sense clouds deeper into the troposphere and of higher cloud opacity as shown by the NASA Microwave Limb Sounder (MLS) missions (Wu and Jiang, 2004).

Limb instruments that sense in the thermal emission part of the spectrum provide measurements in both day and night conditions, with the possibility of obtaining, from some instruments, highly resolved cloud spectra, from which particle radius, volume distributions and cloud composition can be determined. Such infrared sensors have

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included narrowband spectrometers such as the Cyrogenic Limb Array Etalon Spectrometer (CLAES), wide range spectrometers such as the Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA), which observed atmospheric

emission spectra in the 4 to 12 µm range, and focussed limb radiometers such as the High Resolution Dynamics Limb Sounder (HIRDLS) (6.12 to 17.76 µm) that was flown on the EOS AURA platform within the NASA "A Train". Finally, the current Atmospheric Chemistry Experiment (ACE-FTS) should also be mentioned as a wide range spectrometer, although it operates in a solar occultation mode and so is rather different in



radiative transfer and coverage to the other instruments.

Mergenthaler et al. (1999) and Spang et al. (2002) demonstrated that the signatures of ice and water clouds can be captured by detailed highly-resolved spectra covering the  $12 \,\mu m$  region as demonstrated with the CLAES and CRISTA instruments, respectively.

- tively. Analysis of the HIRDLS data has shown that infra-red emission is highly suited for the study of cloud heights, especially in the tropics (Massie et al., 2010). A full review of infra-red, limb sounding instruments can be found in Hurley et al. (2011). An instrument that offers both detailed coverage of the UTLS and high spectral resolution is the MIPAS instrument that is currently obtaining high resolution atmospheric
- emission spectra and has done so near-continuously since its launch on the European Space Agency's ENVISAT platform on 1 March 2002. With close to 10 yr of continuous coverage, it allows the time evolution of UTLS clouds to be monitored in a way that has not been possible with previous infra-red limb sensors.

The objective of this paper is to establish new and systematic detection thresholds
 for the effects of clouds and aerosols so as to better describe the UTLS distributions of clouds and aerosols. The structure of this paper is as follows. An introduction to the MIPAS instrument and comparative instrumentation is followed by a brief summary of the current operational MIPAS cloud detection scheme. The methodology to enhance the ability to detect optically thick and thin clouds and atmospheric aerosols using
 MIPAS is described and finally some results and case studies are shown in Sect. 6 to

<sup>20</sup> MIPAS is described and finally some results and case studies are shown in Sect. 6 demonstrate the performance of the detection method.

## 2 The MIPAS instrument

MIPAS is a thermal Infrared Fourier Transform Spectrometer that measures day and night atmospheric limb emission spectra in the 685 to 2400 cm<sup>-1</sup> spectral range over

<sup>25</sup> 5 broad channels (band A: 685–970 cm<sup>-1</sup>, AB: 1020–1170 cm<sup>-1</sup>, B: 1215–1500 cm<sup>-1</sup>, C: 1570–1750 cm<sup>-1</sup> and D: 1820–2410 cm<sup>-1</sup>). Spectral and radiometric calibrations are maintained by calibrating the measurements against deep space and an onboard



blackbody. The Noise Equivalent Spectral Radiance (NESR) has remained well below the pre-flight requirements as reported in Kleinert et al. (2007), for which the relevant band, A, has a nominal NESR of 30 nW/(cm<sup>2</sup> sr cm<sup>-1</sup>) derived from in-orbit measurements on unapodised spectra. From launch to March 2004, the MIPAS observed the atmosphere from 68 to 6 km with a 3 km vertical resolution through a 3 km field of view (FOV) and 0.025 cm<sup>-1</sup> (unapodised) spectral resolution. After this the instrument configuration was modified due to accumulating anomalies associated with moving retroreflectors within the interferometer (Fischer et al., 2008). The "optimised resolution" mode has been in effect from January 2005 with the spectral resolution changed to 0.0625 cm<sup>-1</sup> (unapodised) and a nominal sampling of 1.5 km in the UTLS with operations beginning with a 35% duty cycle upgrading to 100% duty cycle since December 2007.

The instrument has good coverage of the polar regions up to 90° north and south and measurements are made at a local solar time of 10:30 and 22:30 day and night. This combined with its various scan patterns (Fischer et al., 2008) allow different regions of the atmosphere (upper stratosphere, and mesosphere for example) to be sensed providing good coverage of the upper troposphere and lower stratosphere, albeit with some gaps when upper atmosphere modes are enabled. It is in the UTLS that the distribution and evolution of cloud structures can be investigated with MIPAS spectra potentially providing information about the macro- and microphysical properties such

as cloud top height, occurrence frequencies, ice water content and particle size.

#### 3 Contemporaneous satellite instruments

Two instruments are used in this study to verify the MIPAS detection of clouds and aerosols: the HIRDLS and CALIOP. These instruments are selected because they provide the highest vertical resolutions for clouds and aerosols in the UTLS of all the relevant satellite instruments whilst also observing at the same time as the MIPAS instrument. The HIRDLS data (in an earlier version) and CALIOP data have been

# Discussion Paper AMTD 5, 1795-1841, 2012 MIPAS detection of cloud and aerosol particle occurrence Discussion Paper H. Sembhi et al. **Title Page** Introduction Abstract Conclusions References **Discussion** Paper Tables Figures Back Close **Discussion** Paper Full Screen / Esc Printer-friendly Version Interactive Discussion

compared in an earlier study by Massie et al. (2010) and shown to display similar cloud occurrence frequencies.

# 3.1 HIRDLS

The HIRDLS instrument operated between 22 January 2005 and 17 March 2008 offering an overlap period (approximately 26.5 months) with the MIPAS instrument. Following its launch on the EOS Aura spacecraft, the HIRDLS instrument showed anomalously high radiance measurements discovered to be a result of a large blockage in the HIRDLS field of view. The instrument was reconfigured and correction algorithms dealing with the blockage anomalies were applied to produce measurements with a
vertical resolution of 1.5 km and along-track profile spacing of approximately 100 km. Due to the blockage, the HIRDLS scan pattern was restricted to a single azimuth angle of 47° from the anti-flight direction with the measurements located between 87° N and 63° S.

HIRDLS cloud data are produced from channel 6, the 12.1 μm radiance channel, in
two forms; one is a cloud flag and the other consists of 12 μm extinction profiles. The "12MicronCloudFlag" is produced by analysis of enhancements along each calibrated HIRDLS radiance profile. Different regions and intensities of enhancements represent particular cloud types and flags are assigned as; 0 = clear sky, 1 = unknown cloud type, 2 = cirrus layer, 3 = extensive PSCs and 4 = opaque clouds. Polar stratospheric
clouds and tropical sub-visible cirrus cloud extinctions range from approximately 10<sup>-4</sup>

to 10<sup>-2</sup> km<sup>-1</sup>. The unknown cloud label accounts for radiance perturbations at nonpolar locations that may be influenced by volcanic or forest fire smoke clouds in the UTLS (Massie et al., 2007, 2010; Gille et al., 2011).

Extinction profiles are retrieved using an optimal estimation technique starting with the retrieval of a temperature profile which is fed into the retrieval of cloud and aerosol extinction over the full altitude range for each HIRDLS radiance profile. Trace gas estimates come from a Modelling of Ozone and Related chemical Tracers (MOZART)



climatology and the a priori estimate of cloud/aerosol extinction comes from a SAGE mid-latitude extinction profile.

Gille et al. (2011) recommends several selection criteria for the best quality HIRDLS cloud data. These include extraction of all extinction profiles with corresponding flags <sup>5</sup> between 1 and 4, extinctions between  $1 \times 10^{-2}$  and  $9 \times 10^{-5}$  km<sup>-1</sup>, the extinction precision should be between 0 and 100% and data outside of the pressure range of 215 and 20 hPa should not be used.

# 3.2 CALIOP

CALIOP lidar along with HIRDLS, forms part of the NASA "A-TRAIN" suite of instruments for which the equatorial crossing time is 01:30 and 13:30 LST. CALIOP is a nadir dual-wavelength and dual-polarization space lidar, using the 532 and 1064 nm regions to observe the backscatter signals of the Earth's atmosphere from the near-surface to 30 km. It has a variable vertical resolution that ranges from 30 m from ground to 8.2 km, 60 m from 8.2 to 20.2 km in the UTLS and 180 m from 20.2 to 30.1 km (Winker et al., 2006). Backscatter profiles collected by the CALIOP can resolve the vertical 15 structure and properties of clouds and aerosols with a high vertical resolution providing extremely valuable information on the variation and vertical extent of cloud and aerosol structures (Winker et al., 2010). A range of scientific products are available from CALIOP including profile and layer backscatter for clouds and aerosols, cloud and aerosol layer top heights as well extinction and optical depth profiles. Level 2 20 cloud and aerosol profiles from CALIOP are reported on a 60 m vertical resolution with 5 km horizontal resolution (Vaughan et al., 2004). Data from night-time overpasses are generally "cleaner" than day-time as the noise levels are larger during daytime due to increased background solar radiation.



#### 4 MIPAS cloud detection

MIPAS spectra respond to clouds that are in its line of sight in a very distinctive manner. Figure 1 shows tropical MIPAS clear sky, thin cirrus and optically thick cloud spectra taken from orbit 07386 measured in July 2003. The spectral radiance is strongly off-

set due to the additional broadband emission from the cirrus cloud and this effect is often accompanied by a dampening of trace gas features. Optically thick clouds exhibit strong radiance offsets, accompanied by either reduced spectral features or scattering lines under certain regimes (Höpfner et al., 2002). The largest radiance differences due to cloud occur in the 820 to 950 cm<sup>-1</sup> within band A, as well as some effect in bands B and D, at 1225 to 1245 cm<sup>-1</sup> and 1970 to 1985 cm<sup>-1</sup>, respectively. These cloudy spectra contain a wealth of information from which cloud information can be derived as summarised in Spang et al. (2011), including composition of PSCs (Spang and Remedios, 2003) and cloud top height (Hurley et al., 2011).

The cloud index (CI) is a simple and robust ratio (Spang et al., 2004) that takes <sup>15</sup> into account these characteristic radiance changes at particular wavelengths. It is calculated using small specially selected spectral regions, or microwindow pairs, that consist of a "control region" displaying weak trace gas emissions and a "cloud/aerosol" dominated spectral region that has little trace gas interference. A number of such pairs have been defined (Raspollini et al., 2006) for the purposes of identifying spectra in which clouds and aerosols might contaminate trace gas retrievals, producing erroneous data. The spectral regions and operational detection thresholds for MIPAS bands A, P and D are shown in Table 1. These CI thresholds are these used for cloud clearing

- B and D are shown in Table 1. These CI thresholds are those used for cloud-clearing operational trace gas retrievals for MIPAS. However, a number of studies have used higher thresholds to be more conservative. For example, Milz et al. (2005) and Moore
- et al. (2012) increased the CI for band A (CI-A) threshold to a fixed value of 4.0 to exclude optically thinner cloud contamination prior to MIPAS trace gas retrievals.

The CI-A data themselves contain key information on the characteristics of the atmosphere observed by MIPAS and band A provides the best combination of clear



atmospheric windows for detection, and signal-to-noise for cloud/aerosol particle effects. A number of studies have used the region for the retrieval of cloud properties, as shown by Höpfner et al. (2002, 2006), and Hurley et al. (2011). For a more comprehensive review of cloud identification methods and their use in cloud parameter retrievals from MIPAS, the reader is referred to Spang et al. (2011). In this study, we focus on CI-A as the cloud index associated with this band.

- Frequency distributions of CI-A tend to follow a distinctive bi-modal behaviour where cloud/aerosol saturated radiances peak close to CI-A values of approximately 1.5. Closer to 6, the CI-A values indicate that these radiances are influenced by trace gas signatures. Spang et al. (2004) noted that CI-A is less than 2 for thick opague cloudy
- spectra and usually greater than 5 for clear-sky; values between 2 and 5 are associated with optically thinner cirrus clouds or aerosol. Höpfner et al. (2009) used a fixed threshold of 4.5 to detect PSCs.

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- The CI detection method works well within the UTLS region where it can capture the signatures of cirrus and PSCs but it does have some limitations. Spang et al. (2002) and Greenhough et al. (2005) found that upper tropospheric water vapour can give rise to CI-A values similar to those of clouds and that it can be difficult to distinguish between the two at lower altitudes (below 9 km). At higher altitudes (close to 30 km) the CI method starts to become less valid as the radiances decrease and the propagation
- <sup>20</sup> of instrument noise becomes more apparent. The sensitivity of this CI behaviour to clouds and aerosol can be maximised by improving the thresholds of detection. Such thresholds should successfully trap out the variable atmospheric trace gas signatures from the cloud and aerosol signatures in the radiances, essentially, acting as a "barrier" between particles and trace gases. In this study, we derive suitable thresholds,
- and for the first time for MIPAS, we systematically focus the studies on the detection of cloud/aerosols rather than simply flagging cloudy spectra for trace-gas retrievals purposes.



#### 5 A simulation method for improved detection thresholds

To find suitable thresholds for MIPAS cloud and aerosol detection, a simulation approach is employed in which MIPAS spectral microwindows have been modelled using a radiative transfer model. This requires knowledge of global and seasonally varying atmospheric trace gases, upper tropospheric water vapour variability and MIPAS characteristics. Furthermore such a method allows appropriate thresholds to be determined independently from real MIPAS spectral data.

The simulations are performed as follows: a set of CI microwindow radiances are simulated using the Reference Forward Model (RFM), a line-by-line radiative transfer model developed at the University of Oxford specifically for the simulation MIPAS spectra (Dudhia, 2005). From each pair of CI microwindows, an index is calculated that effectively acts like a "gas index". As no cloud or enhanced aerosol are included in the simulations the calculated indices represent the sensitivity of CI with respect to trace gas variability in the atmosphere thereby acting as a barrier between trace gas and cloud-induced CI values; the approach of finding the "gas limit" also has the ad-

<sup>15</sup> and cloud-induced Cr values, the approach of initiality the gas initial also has the advantage of not requiring the modelling of clouds and aerosols in the radiative transfer model. Using indices from an ensemble of simulations, the optimised cloud detection thresholds are generated for a range of latitude and altitude regions as described in the following sections.

#### 20 5.1 Simulation characteristics

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Version 4.28 of the RFM was used for the simulation of MIPAS-like radiances where calculations are based on the transmittance for each gas that contributes to the spectral region of interest. Spectral calculations are performed on a fine mesh grid of 0.0005 cm<sup>-1</sup> resolution and interpolated internally onto a user-defined wave-number range and resolution. Voigt line shapes and atmospheric water vapour continuum are represented within the simulations and local thermodynamic equilibrium (LTE) of the atmosphere is assumed.



Table 2 summarises the input and simulation setup used for calculations for the CI-A spectral microwindows. A realistic representation of background trace gases is of key importance and these come from the Reference Atmospheres for MIPAS: Standard Atmospheres (RAMstan) climatological database that contains temperature, pres-

- <sup>5</sup> sure and concentration profiles of up to 36 atmospheric constituents (Remedios et al., 2007). Profiles can be chosen either from version 3.1 of the standard atmospheres database that describe mean concentrations over 5 latitude bands (90 to 30° N/S, 60 to 30° N/S, 30 to 30° N/S) with estimates of extreme conditions (given by maximum and minimum profiles) or from version 4 of the Initial Guess 2 (IG2) climatology that contain
- <sup>10</sup> profiles varying latitudinally over six bands that are 90 to 65° N/S, 65 to 20° N/S and 20 to 0° N/S and seasonally for January, April, July and October. As it has been shown that upper tropospheric water vapour can produce CI values similar to those of clouds (Spang et al., 2004), it is important that the variation of water vapour is well represented at lower altitudes.
- <sup>15</sup> Water vapour profiles used in the simulations consisted of concentration profiles calculated theoretically by considering the saturation mixing ratio that describes the maximum water vapour that a parcel of air can hold at a chosen pressure and temperature. Profiles of saturation mixing ratio were calculated from the saturation vapour pressure (Vömel, 2011), with respect to water vapour and ice, for global RAMstan standard
- and IG2 pressure and temperature profiles. To verify the range of the calculated water vapour concentrations, comparisons were made to ensembles of ECMWF water vapour profiles for each latitude band from which the minimum, maximum and mean water vapour concentrations were also extracted. Consequently, the theoretical water vapour profiles from the maximum standard RAMstan atmospheres for each latitude band were too large and therefore these profiles were removed from the analysis.

#### 5.2 Calculation of improved thresholds

The simulations provide an ensemble of theoretical radiances for the CI microwindows from which "gas only" index profiles can be calculated for each IG2 latitude band. Using



this information, the most effective way to determine the barrier between trace gas and cloud influence in the index profiles would be to derive a threshold based on the minimum index at each altitude from each ensemble of index profiles. However, a further component to be accounted for in the calculation of the thresholds is the impact of random instrument noise through the MIPAS microwindows. For MIPAS, noise 5 is quantified by the NESR that varies in magnitude for each MIPAS band. Kleinert et al. (2007) reported that the NESR ranges from  $30 \text{ nW/(cm}^2 \text{ sr cm}^{-1})$  in band A to  $3 \text{ nW/(cm}^2 \text{ sr cm}^{-1})$  in band D. The propagation of noise into each microwindow can be calculated as the error on the index. Thus, for each microwindow in guestion, the noise propagation is calculated by.

$$\sigma_{\mathsf{mw}i} = \frac{\mathsf{NESR}}{\sqrt{\mathsf{NPTS}_{\mathsf{mw}i}}}$$

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where *i* represents the microwindow;  $\sigma_{mw}$  is the error due to noise calculated in the microwindow; NESR is the noise estimated in terms of radiance  $(nW/(cm^2 sr cm^{-1}))$ for the band and "NPTS<sub>mw</sub>" is the number of spectral points in the microwindow under analysis. The noise from each microwindow (MW) can be used to determine the total noise  $\sigma_{\text{total}}$ , impact on each index profile (Eq. 2).

$$\sigma_{\text{total}} = \sqrt{\left(\frac{\sigma_{\text{mw1}}}{\text{MW1}}\right)^2 + \left(\frac{\sigma_{\text{mw2}}}{\text{MW2}}\right)^2}$$

Finally, the optimal threshold for each latitude band, accounting for natural trace gas variation, upper tropospheric water vapour and instrument noise can be calculated as:

<sup>20</sup> Thres<sub>OPT\_CI</sub> = Index<sub>minimum</sub> – 
$$3\sigma_{total}$$

where, Index<sub>minimum</sub> is the minimum index at each altitude and latitude band investigated and  $\sigma_{total}$  is the total instrument error on the index.

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(1)

(2)

(3)

#### 5.2.1 Threshold characteristics for CI-A

The optimal thresholds calculated from the above recipe to capture the seasonal, altitude and latitude dependency of the CI-A are shown in Fig. 2, assuming the noise of 30 nW/(cm<sup>2</sup> sr cm<sup>-1</sup>). First, the most conservative threshold profile was chosen for each latitude band. The threshold profiles were then adjusted slightly for finer latitude banding over the mid-latitude and polar transition using a linear interpolation method. In the upper troposphere from 10 to 12 km, all threshold profiles vary from approximately 2 to 5 indicative of the region where the variability of H<sub>2</sub>O will have the largest impact on the CI-A thresholds. For such regions, knowledge of the H<sub>2</sub>O profiles most relevant to the situation considered will always yield improved cloud detection. Since the optimised threshold is effectively an annual average, the threshold values in the troposphere will be determined by the highest water vapour concentrations in the simulation profiles corresponding to summer conditions. Therefore if the true atmosphere is drier and this is known, thinner clouds will be detectable. Above the tropopause

- to 25 km, the thresholds remain in the range of 5 to 7 representing the particle influenced/clear sky barrier captured by the trace gas variability considered. In the tropics above 25 km, the thresholds remain relatively constant between 5 and 7 indicating that neither trace gas variability nor the instrument noise has much impact on the thresholds in this region (expected since the signal-to-noise will vary approximately with tempera-
- ture which does not vary by large amounts in the tropics). Variations between individual RFM simulations were found to be less than 0.5 in the index profiles (with noise) in the stratosphere in the tropics and of the order of 1.0 to 1.5 in the mid-latitudes.

In contrast, the polar thresholds  $(90-80^{\circ} \text{ N} \text{ and } 90-80^{\circ} \text{ S} \text{ profiles})$  above 25 km start to reach values of 2 or less. It is here where the instrument NESR can be comparable

to (or lower than) the polar atmospheric radiances and this threshold behaviour is influenced mainly by the large temperature gradients observed in the polar stratosphere throughout the seasons. During polar winter when the temperatures are at a minimum, MIPAS radiances reduce accordingly meaning that as the instrument noise starts to



become dominant thus causing the thresholds to reduce. However, this is not the only effect, and in the next section, polar stratosphere thresholds are considered explicitly.

#### 5.2.2 Polar stratosphere thresholds

Additional threshold profiles were calculated for the north and south pole specifically for polar vortex conditions where the simulations included enhanced chlorine monoxide 5 (CIO) with reduced stratospheric temperature and  $O_3$ . It should be noted that no variable H<sub>2</sub>O profiles were included in these calculations since the stratosphere is relatively dry. To ensure the chosen temperatures and O<sub>3</sub>/CIO concentrations were representative of north and south polar vortex conditions, Fig. 3 of Manney et al. (2011) was consulted. For the north pole, an enhanced layer of CIO reaching concentrations up 10 to 1.6 ppbv between 15 and 25 km was introduced with reduced stratospheric temperatures to 195 K and O<sub>3</sub> as low as 1 ppmv over this layer. For the south pole, the CIO layer was set to concentrations up to 1 ppbv, with O<sub>3</sub> as low as 0.5 ppmv and temperature as low as 190 K. The calculated index profiles are displayed in Fig. 2 and show that, within the polar vortex conditions, the resultant thresholds can reduce severely, 15 particularly above 20 km where they are heavily influenced by the enhancement of CIO, reduction in  $O_3$  and the steep temperature gradient introduced by the vortex. To demonstrate this large impact of polar temperature variability in further detail, Fig. 3

- shows non-vortex index profiles calculated using January and July IG2 profiles for the north and south poles from 15 to 30 km. The solid lines represent the index profiles for January and July and the dotted lines represent the range of the corresponding  $\sigma_{total}$ for both hemispheres. As expected, there are large fluctuations in  $\sigma_{total}$  from the index profile driven by the steep temperature gradients. In essence, these thresholds show a large degree of uncertainty with changes in the thresholds dictated by the varying stratospheric temperatures with season. Therefore, although the use of the annual
- average polar thresholds will certainly discriminate many PSCs, and particularly thick PSCs, caution should be exercised in situations of strong stratospheric polar ozone



depletion. For these cases, individual analyses are recommended according to the specific atmospheric conditions prevailing in the study period.

## 5.2.3 Threshold detection limits

To understand the extinction detection range encompassed by the thresholds, a set of CI-A microwindow simulations were performed using the profiles from the IG2 database 5 and a representative background aerosol extinction profile for each IG2 latitude band for all seasons on 1 km vertical grid. A "cloud" was added to each simulation by perturbing the extinction profile up to  $1 \times 10^{-3}$  km<sup>-1</sup> at each 1 km altitude. CI-A values between 2 and 4 were found to correspond to extinctions at  $12 \,\mu m$  between  $5 \times 10^{-3}$ and  $1 \times 10^{-3}$  km<sup>-1</sup> respectively and values from 4 to 6, correspond to extinction ranges 10 from  $1 \times 10^{-3}$  to  $5 \times 10^{-5}$  km<sup>-1</sup> respectively For CI-A values falling below 2, the extinction detectable is  $1 \times 10^{-2}$  km<sup>-1</sup> or greater. This range of extinction values that are detectable in the 12 µm spectral region indicates that optically thick cirrus clouds as well as thick aerosol layers (such as those from volcanoes or wildfire burning events) should be discernable with the optimised threshold profiles derived here. Above 13 km, particles can be detected up to CI-A values of 5 and, in the stratosphere, it is possible to detect particles in some regions with CI-A up to 6 or higher giving detection limits above 13 km of  $1 \times 10^{-4}$  km<sup>-1</sup> and down to  $1 \times 10^{-5}$  km<sup>-1</sup> in parts of the stratosphere.

#### 6 Cloud detection results

- Given that the detection system described in the previous section takes into account the seasonal and latitude dependency of the radiance changes in the cloud microwindows, it should effectively capture short- and long-term cloud behaviour as well as specific events likely to perturb the particulate concentrations of the atmosphere. All detection results shown in the following sections will be demonstrated by the Cloud and Aerosol Top Height (CATH) where the cloud or acrosol layer height is inferred directly from the
- <sup>25</sup> Top Height (CATH) where the cloud or aerosol layer height is inferred directly from the



reprocessed Level 1b emission spectrum measurements as obtained from the ESA operational IPF5.0 (version 5.0) processor. MIPAS tangent height measurements are based on calculated engineering altitudes provided with each L1B spectral radiance profile. Prior to March 2004 when MIPAS was in its "full resolution" mode (FR) an <sup>5</sup> elevation pointing error was discovered between the North and South poles (Kiefer et al., 2007) but this has been corrected to 0.5 km accuracy in Version 5.0. All data used in this paper are obtained in the "optimised resolution" mode (OR) that do not suffer from this bias, thus, no altitude correction is necessary. It has been found that the engineering altitudes from the OR retrievals show a 0.3 km low bias compared to retrieved MIPAS altitudes (M. Kiefer, personal communication, 2012).

The CATH is calculated by assessment of each cloud index profile (derived directly from MIPAS Level 1b spectral profiles) against the corresponding latitudinal and altitude thresholds. The tangent altitude at which the threshold ceases to be larger than the CI value is declared the CATH and this is the tangent altitude at which cloud or aerosol particles are being detected within the MIPAS FOV. It should be noted that due to a

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- 3 km FOV, an uncertainty of  $\pm 1.5$  km can be associated with each CATH measurement. Another parameter than is used in the cloud comparisons is the Cloud Occurrence Frequency (COF) that is defined as the ratio of cloudy data to total points within a defined altitude range.
- In the following sections the CATHs are used to investigate specific atmospheric 20 events to assess the efficiency and success of the detection method. Section 6.1 shows the results of a statistical comparison of MIPAS with HIRDLS and CALIOP cloud information for selected periods in 2007 and 2008. The detection thresholds are then applied to two localised events which illustrate the significance of the new de-
- tection thresholds; one is the Australian "Black Saturday" bushfires of February 2009 25 (Sect. 6.2) with comparison to measurements taken from the CALIOP lidar and the second is the detection of Mount Kasatochi volcanic eruption of August 2008 in Sect. 6.3.



#### 6.1 Inter-comparison of MIPAS CATH and COF with HIRDLS and CALIOP

The periods of data chosen for a statistical comparison of MIPAS and HIRDLS are June-July-August (JJA) 2007 and December-January-February (DJF) 2007/2008 as this accounts for the 100 % duty cycle of MIPAS in its OR mode, it allows for an analysis

of the seasonal variations in clouds and also this period was not subjected to any major volcanic eruptions meaning that the background cloud distributions can be analysed. HIRDLS cloud data are selected for these periods by fulfilling the data selection criteria as described in Sect. 3.1 from which the HIRDLS CATH is extracted by searching for the topmost altitude at which the cloud and aerosol flags are non-zero in each HIRDLS profiles measurement.

Figure 4 shows the maps of mean CATH for JJA 2007 and DJF 2008 from MIPAS and HIRDLS between 50° N and 50° S and 12 to 20 km gridded onto a regular a 5° latitude and 10° longitude grid. In JJA, both MIPAS and HIRDLS detect regions of high clouds up to 17.5 km over the west Pacific ocean, equatorial Africa and the North

- <sup>15</sup> American and Asian Monsoon regions. In the mid-latitudes, both instruments detect cloud bands between 12 and 14 km and are in relatively good agreement through the tropical/mid-latitude transition regions. In DJF, the shift in the cloud pattern following the movement of the inter-tropical convergence zone (ITCZ) is evident in both MIPAS and HIRDLS with the highest clouds located within the 20° N and 20° S band over the
- west Pacific, equatorial America, Africa and Indonesia. The MIPAS detection locates clouds at 18 km over the east Pacific Ocean in comparison to HIRDLS which shows clouds closer to 17 km. The most striking features to notice in both seasons are the strong agreement in the distribution of clouds in the tropics and sub-tropics with regions of more persistent cloud systems, such as the Asian Monsoon in JJA and the Pacific cold trap region in DJF, are well identified in both datasets.

To compare the occurrence of clouds in both instruments over the period of interest, the mean COF over a 12 to 20 km column, gridded 5° latitude and 10° longitude grid, is analysed. MIPAS and HIRDLS cloud data are binned onto a regular 1 km vertical



grid from 12 to 20 km. The COF is calculated as the number of clouds divided by the total number of measurements in each grid box in each altitude bin. Figure 5 shows the mean COF for MIPAS and HIRDLS for JJA 2007 and DJF 2008 between 50° N and 50° S. Bands of mean COF between 5 and 10% flowing through the midlatitudes are evident in both datasets in both seasons analysed. In the tropics, the mean COF is close to 45% in both seasons. However, the greatest mean COF values (up to 60%) coincides with the regions of highest clouds over localised over the north American and Asian Monsoon regions in JJA, and over the tropical landmasses and

tropical Pacific ocean in DJF. Overall, the occurrence patterns are in excellent agree ment although MIPAS cloud distributions tend to show a more widespread pattern with HIRDLS demonstrating a more compact distribution. This is in line with the fact that the HIRDLS instrument measured profiles on a denser network approximately 110 km spacing as opposed to MIPAS which is closer to 440 km spacing.

To further quantify the differences between the mean CATH from MIPAS and HIRDLS and to verify the range of CATH observed in MIPAS, comparisons of the JJA 2007 and DJF 2008 CATH are made to those inferred from CALIOP measurements. In this analysis, CATH are extracted from CALIOP level 2 cloud/aerosol layer 5 km (version 3.01) data products where the CALIOP CATH selection of feature (cloud or aerosol) height is based on determining the highest cloud or aerosol layer boundary in each measure-

<sup>20</sup> ment. The altitude (reported in km) at which this occurs is simply the cloud/aerosol height as measured by CALIOP.

Figure 6 shows normalised distributions of gridded mean CATH for JJA 2007 and DJF 2008 binned into 0.5 km grid boxes between 12 and 20 km for MIPAS, HIRDLS and CALIOP. In both seasons the shapes of the distributions are similar for all instru-<sup>25</sup> ments showing two peaks indicating their sensitivity to upper tropospheric clouds as well as optically thinner cirrus clouds close to the tropopause. The overall distribution of CALIOP CATH over the 12 to 20 km altitude range has a similar shape to both MIPAS and HIRDLS, however, the CALIOP distribution is more consistent with the HIRDLS CATH data with MIPAS showing an offset up to +0.5 km against CALIOP CATH. A



consistent feature in both seasons is that MIPAS cloud altitudes appear to be approximately 0.5 km higher than both HIRDLS and CALIOP. Given that the error on a MIPAS cloud measurement may be close to 1.5 km owing to the 3 km FOV, and that a 0.5 km error can be assumed from the HIRDLS 1 km FOV, a difference of up to 1 km or less between MIPAS and HIRDLS falls well within the expected systematic difference.

Recently Version 6 HIRDLS cloud top data has been compared to 8 yr (1997–2005) of HALOE data in the HIRDLS data quality document (Gille et al., 2011). The HIRDLS cloud top heights are biased low by up to 1 km to the HALOE data in the tropics and mid-latitudes, a low bias similar to the MIPAS-HIRDLS comparisons but smaller. Over-

<sup>10</sup> all, it therefore seems that the limb sounders give very good agreement and a consistent picture in the tropics and mid-latitudes compared to CALIOP.

# 6.2 Black Saturday bushfires as observed by MIPAS and CALIOP

The "Black Saturday" bushfires were an unprecedented occurrence in which approximately 4500 km<sup>2</sup> of land burned uncontrollably in Victoria, Australia from 7 February to 14 March 2009 (CSIRO, 2011). Recently, Pumphrey et al. (2011) investigated enhancements of CO and other combustion by-products including hydrogen cyanide (HCN) and ethanenitrile (CH<sub>3</sub>CN) within the plumes using MLS version 2.2 retrieved profiles for February and March 2009. They observed CO enhancements to the north of New Zealand at 100 hPa, and anomalously high concentrations reaching up to 46 hpa
(close to 20 km) several days after the fires began with CO concentrations reaching levels 3 times higher than background concentrations. Trajectory analyses showed

- that these polluted air masses originated over Victoria and traversed across southeast Australia after becoming trapped in an anti-cyclonic system to the north of New Zealand.
- <sup>25</sup> Work done by Siddaway and Petelina (2011) showed the transport of smoke plumes by detection of limb solar-scattered radiance enhancements from the OSIRIS instrument. The authors showed that the main plume travelled eastwards to the North of New Zealand from 11 February reaching altitudes between 16 and 18 km. The location of



the smoke plume matched the enhanced pollutants measured by MLS with the primary smoke plume near-stationary over northeast New Zealand. In the following weeks, the plume was traceable across the Southern Hemisphere for at least 6 weeks with some advection up to 21 km.

- Figure 7 shows a map of CATH in the 15 to 20 km layer for the Black Saturday event and the corresponding CI-A values are shown in Fig. 8. The figures clearly show an area of elevated CI-A at latitudes south of 28° S; MIPAS observations in other years show that CI-A values are typically greater than 8 in this region. Analysis of the CI-A values corresponding to the MIPAS CATH within the bushfire plumes shows that many
- <sup>10</sup> of the CI-A values lie in the 4 to 7 range. In terms of extinctions, this corresponds to aerosol material of approximately  $7 \times 10^{-4}$  to  $1 \times 10^{-5}$  km<sup>-1</sup>, respectively. Given this range of CI-A values, the optimised threshold profiles perform well and capture the additional aerosol injection efficiently. Using the operational CI-A threshold of 1.8 would in fact completely fail to detect the MIPAS measurements in the bushfire outflow region
- as it is designed primarily to detect optically thick cirrus clouds. Using a fixed threshold of 4 would improve on the plume detection compared to 1.8 but would still in fact miss much of the wider plume reaching the UTLS. Thus, in the case of detecting wildfire influence in the UTLS, the improved detection thresholds offer a unique sensitivity that cannot be achieved with the fixed threshold process.

To provide some inter-comparison of the range of CATH captured by MIPAS during the bushfires, MIPAS and CALIOP CATH night-time data are compared for 7 to 16 February 2009 from 10 and 50°S and over the 15 to 20 km range and are shown in Fig. 9. The CALIOP data are averaged onto a  $4 \times 4^{\circ}$  latitude/longitude grid so that the data correspond more directly to a MIPAS horizontal spacing close to 400 km. It should

<sup>25</sup> also be noted that the MIPAS measurements are obtained approximately 3 h before the CALIOP measurements thus some differences are expected. The general pattern of CATH distributions show that clouds occur over North Australia within the tropical belt at altitudes close to 18 km as seen by CALIOP and MIPAS. The Pacific Ocean region to the east of Australia generally shows lower clouds (close to 15 km/16 km) or virtually



no tropopause clouds in both MIPAS and CALIOP. The key features observed in both datasets are the position of the plume located at 180 to 210° longitude and the elevated CATH observed to the north of New Zealand with CATH reaching as high as 19.5 km in CALIOP and 20 km in MIPAS.

- The MIPAS detection has captured the spatial extent and scale of the plume outflow well and the improved detection thresholds show a reasonable sensitivity to the cloud and aerosol material ejected from pyroCb plumes. No CALIOP data were available for the remainder of February. However, analysis of MIPAS CATH for this period captures the gradual movement of plume northwest towards Australia from 16 February, eventually moving westwards across Australia and over the Indian Ocean by 28 Febru-
- ary 2009. These positions of the bushfire plume measured in MIPAS during February are in very good agreement with smoke plume detected with the OSIRIS instrument (Siddaway and Petelina, 2011).

#### 6.3 MIPAS detection of Mount Kasatochi aerosols

- <sup>15</sup> On 7 to 8 August 2008, the Mount Kasatochi volcano, situated on the Alaskan Aleutian Islands at 52° N, 175° W, began erupting with 3 major explosive events releasing pyroclast, ash and SO<sub>2</sub> reaching altitudes up to 18 km (Waythomas et al., 2010). Prata et al. (2010) exploited SO<sub>2</sub> features in Atmospheric Infrared Sounder (AIRS) spectral measurements to study the partial columns of UTLS, based on the 1363 and 2500 cm<sup>-1</sup>
- <sup>20</sup> spectral regions. Using these retrievals in conjunction with ash detection from the 800– 1200 cm<sup>-1</sup> spectral range, it was found that Kasatochi ash and UTLS SO<sub>2</sub> appeared to disperse from the volcano simultaneously travelling together towards North America for the first few days after the eruption. Overall they estimated an SO<sub>2</sub> mass loading of approximately 1.7 Tg was released into the atmosphere from Kasatochi alone. The
- evolution and transport of the Kasatochi plume stratospheric layer have been well documented with measurements from limb and nadir sounders. Bourassa et al. (2010) used 750 nm extinction retrievals from OSIRIS measurements to investigate the stratospheric aerosol formation following the Kasatochi eruptions. Using zonally-averaged



aerosols extinctions from March 2008 (pre-eruption) to May 2009 they observed the development of a stable stratospheric aerosol layer from 15 to 21 km from 4 weeks after the eruption over the mid and high latitudes with the stratospheric aerosol layer persisting until March 2009. Sioris et al. (2010) similarly observed stratospheric aerosol
 <sup>5</sup> enhancements over the same timescales using NIR extinction retrievals from the ACE-FTS instrument in which the aerosol enhancements were observed up to 19 km in the Northern Hemisphere.

The addition of volcanic material into the UTLS region from the Kasatochi volcano can potentially produce strong signatures in MIPAS spectra with large radiance enhancements allowing detection of volcanic spectra possible from MIPAS. Figure 10 shows northern hemispheric MIPAS CATH observed between 60 and 40° N from 7 August to 31 August 2008. Evidence of elevated CATH are observed directly over the source region at 52° N with Kasatochi influence initially observed up to 20 km. CATH between 17 and 19 km are observed extending over North America, passing across the

- <sup>15</sup> North Atlantic at latitudes close to 45° N. This range of heights for the Kasatochi plumes observed in MIPAS is similar to those in the ACE-FTS and OSIRIS measurements. Examination of CALIOP lidar images for 10 August 2008 similarly show layers of volcanic material between 16 and 19 km over the Kasatochi region that gradually move across North America by 20 August 2008. Such transport across the Northern Hemisphere
- <sup>20</sup> on the consecutive days analysed shows very strong agreement with SO<sub>2</sub>, ash and aerosol detection from the Infrared Atmospheric Sounding Interferometer (IASI), AIRS and the Ozone Monitoring Experiment (OMI) as reported in the studies of Karagulian et al. (2010) and Kristiansen et al. (2010).

To quantify the efficiency of the optimised thresholds for the detection of volcanic plume material, the Kasatochi CI-A values for 7 to 31 August in the 15 to 20 km range are shown in Fig. 11. The CI-A values largely vary between 4 and 6 within the main transport region of Kasatochi across North America; this CI-A range is fully encompassed with the optimised thresholds and therefore the plume influenced MIPAS measurements are captured sufficiently well. In comparison to the fixed threshold method,

# Discussion Paper AMTD 5, 1795-1841, 2012 MIPAS detection of cloud and aerosol particle occurrence Discussion Paper H. Sembhi et al. **Title Page** Introduction Abstract Conclusions References **Discussion** Pape Tables Figures Back Close Discussion Full Screen / Esc Printer-friendly Version Paper Interactive Discussion

a CI-A threshold value of 2 of 4 would not succeed in identifying such material accurately and therefore result in a rather sporadic detection of volcanic intrusions from MIPAS.

- To observe the evolution of the aerosol layer from MIPAS, Fig. 12 shows the frequency distributions of MIPAS CATH for selected months from February 2008 to February 2009; this selection contains a pre-eruption phase and up to 7 months after the eruptions. The difference between February and August 2008 is marked by a distinctive shift in the peak CATH of approximately 3 km between the two months, with a general enhancement in the 11 to 18 km range in August; highest values of CATH in February 2008 were typically 14 km. By September 2008, the CATH data shows a
- distinctively broader pattern spread over the 12 to 19 km range initiated by the increase in aerosol as reported by Bourassa et al. (2010) and Sioris et al. (2010). In particular, the growth in the 15 to 19 km layer during September and October is likely to be due to the growth of stratospheric aerosol over a few weeks as reported by Sioris et
- al. (2010). By October the distribution becomes peaked at 15 km, a difference of 5 km compared to February 2008. As December 2008 is reached, the change in the CATH distribution suggests a return to the normal situation is beginning with the normalised distribution peak shifting to 13 km. By February 2009 the distribution appears to have become clearer and becomes closer to that observed in the pre-eruption phase indicat-
- ing that the Kasatochi aerosol influence no longer exists in the Northern Hemisphere region. In this case the CATH indicator with the improved thresholds has proved an excellent demonstration of the MIPAS capability to detect weak aerosol intrusions into the stratosphere, comparable with the measurements of systems such as OSIRIS.



## 7 Conclusions

In this study, improved threshold profiles for the detection of clouds from the MIPAS instrument were derived specifically to maximise the identification of the cloud and aerosol particles throughout the UTLS. Within this region, the method allows for sta-

tistical evaluation of cloud occurrence frequencies, monitoring of CATH, detection of individual particle injection events, and tracking of plumes and dispersing aerosol layers. Consequently, a second purpose fulfilled by this scheme is to separate cloud-and aerosol-influenced spectra from clear-sky spectra in an independent, efficient and computationally fast manner, allowing cloud and aerosols properties to be probed in
 more detailed and computer-intensive retrieval schemes. This is a primary use of the method in the MIPclouds processor (Spang et al., 2011) and for this reason it is also

suitable for the MIPAS operational processor.

The variability of the calculated threshold profiles over the globe are indicative of the radiance changes in the 12  $\mu m$  spectral region due to the influence of both atmospheric

- <sup>15</sup> trace gas variations and instrumental noise effects. In tropical and mid-latitude conditions, the optimised thresholds are quite reflective of conditions over the year so that, although conservative, seasonal variations are small. CI-A thresholds allow detection of particles up to values of 5 above 13 km with some regions allowing detection up to values of 7. At 10 km, i.e. in the troposphere, detection is more limited in the tropics due to high water vapour but particle detection in the polar troposphere is much more
- <sup>20</sup> due to high water vapour but particle detection in the polar troposphere is much more sensitive (thresholds of 4 or higher).

The polar stratospheric thresholds show a larger degree of uncertainty over the changing seasons meaning the polar regions would be better treated with a different approach in which time and atmospheric composition dependency are considered.

<sup>25</sup> Certainly, caution should be exercised in interpreting detections of PSCs when atmospheric chemical composition is strongly perturbed and temperatures are low.

The application of the tropical and mid-latitude thresholds to a statistical based cloud comparison showed that large-scale features and general cloud distributions (as



represented by cloud occurrence frequencies) observed by MIPAS and HIRDLS are in excellent agreement with MIPAS tending to show marginally broader distributions. Over the 12 to 20 km range, MIPAS CATH are up to 0.5 km higher than those detected by HIRDLS and CALIOP and the likely cause of this bias is the effect of the larger MIPAS FOV, however, this difference is within the limits of the systematic line of sight

pointing error on the MIPAS CATH measurements.

The detection of the Black Saturday and Kasatochi plumes have demonstrated that the improved thresholds can be used to track fire injections and volcanic plumes into the lower stratospheric and across the globe on timescales ranging from days to months.

- The range of CI-A values found to correspond to these events indicate that the addition of such particles into the UTLS with extinctions values down to 1 × 10<sup>-5</sup> km<sup>-1</sup> or lower are well encapsulated within the optimised thresholds where the traditional fixed CI-A method would fail. This system proves to be an invaluable tool for the detection of pollution events where clouds and aerosols can have an important role in the chemical processes in the UTLS, affect the radiaitve properties of the stratosphere (Kravitz and CI-A).
- Robock, 2011) or compromise transport safety (for example, volcanic ash emission affecting aircraft engines, Prata et al., 2008).

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#### References

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20

- Bourassa, A. E., Degenstein, D. A., and Llewellyn, E. J.: Climatology of the subvisual cirrus clouds as seen by OSIRIS on Odin, Adv. Space Res., 36, 807–812, 2005.
- Bourassa, A. E., Degenstein, D. A., Elash, B. J., and Llewellyn, E. J.: Evolution of the stratospheric aerosol enhancement following the eruptions of Okmok and Kasatochi: Odin-OSIRIS measurements, J. Geophys. Res., 115, D00L03, doi:10.1029/2009JD013274, 2010.



- Clarisse, L., Coheur, P. F., Prata, A. J., Hurtmans, D., Razavi, A., Phulpin, T., Hadji-Lazaro, J., and Clerbaux, C.: Tracking and quantifying volcanic SO<sub>2</sub> with IASI, the September 2007 eruption at Jebel at Tair, Atmos. Chem. Phys., 8, 7723–7734, doi:10.5194/acp-8-7723-2008, 2008.
- <sup>5</sup> Corti, T., Luo, B. P., Peter, T., Vomel, H., and Fu, Q.: Mean radiative energy balance and vertical mass fluxes in the equatorial upper troposphere and lower stratosphere, Geophys. Res. Lett., 32, L06802, doi:10.1029/2004GL021889, 2005.
  - CSIRO: Q & A Victorian Bushfires, available at: http://www.csiro.au/resources/ Victorian-Bushfires-QA, 2011.
- <sup>10</sup> Dudhia, A.: The Oxford Reference Forward Model, available at: http://www.atm.ox.ac.uk/RFM/, 2005.
  - Eichmann, K.-U., von Savigny, C., Reichl, P., Robert, C., Steinwagner, J., Bovensmann, H., and Burrows, J. P.: SCODA: SCIAMACHY Cloud detection algorithm from limb radiance measurements, ATBD version 2.0, 2009.
- <sup>15</sup> Fischer, H., Birk, M., Blom, C., Carli, B., Carlotti, M., von Clarmann, T., Delbouille, L., Dudhia, A., Ehhalt, D., Endemann, M., Flaud, J. M., Gessner, R., Kleinert, A., Koopman, R., Langen, J., López-Puertas, M., Mosner, P., Nett, H., Oelhaf, H., Perron, G., Remedios, J., Ridolfi, M., Stiller, G., and Zander, R.: MIPAS: an instrument for atmospheric and climate research, Atmos. Chem. Phys., 8, 2151–2188, doi:10.5194/acp-8-2151-2008, 2008.
- Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and Van Dorland, R.: Changes in Atmospheric Constituents and in Radiative Forcing, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon,
- <sup>25</sup> S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.
  - Frey, R. A., Ackerman, S. A., Liu, Y., Strabala, K. I., Zhang, H., Key, J. R., and Wang, X.: Cloud Detection with MODIS Part 1: Improvements in the MODIS cloud mask for Collection 5, J. Atmos. Ocean. Tech., 25, 1057–1072, 2008.
- Fromm, M., Tupper, A., Rosenfeld, D., Servranckx, R., and McRae, R.: Violent pyro-convective storm devastates Australia's capital and pollutes the stratosphere, Geophys. Res. Lett., 33, L05815, doi:10.1029/2005GL025161, 2006.



- Gille, J., Gray, L., Cavanaugh, C., Choi, K. Y., Coffey, M., Craig, C., Karol, S., Hepplewhite, C., Khosravi, R., Kinnison, D., Massie S., Nardi, B., Rivas, M. B., Smith, L., Waterfall., and Wright, C.: HIRDLS High Resolution Dynamics Limb Sounder, Earth Observing System (EOS) Data Description and Quality Version 6 (V6), SC-HIR-1511F, 2011.
- <sup>5</sup> Greenhough, J., Remedios, J. J., Sembhi, H., and Kramer, L. J.: Towards cloud detection and cloud frequency distributions from MIPAS infra-red observations, Adv. Space Res., 36, 800–806, 2005.

Hervig, M. and McHugh, M.: Cirrus Detection using HALOE Measurements, Geophys. Res. Letts, 26, 719–722, 1999.

- Höpfner, M., Oelhaf, H., Wetzel, G., Friedl-Vallon, F., Kleinert, A., Lengel, A., Maucher, G., Nordmeyer, H., Glattor, N., Stiller, G., von Clarmann, T., Fischer, H., Kröger, C., and Deshler, T.: Evidence of scattering of tropospheric radiation by PSCs in mid-IR limb emission spectra: MIPAS-B observations and KOPRA simulations, Geophys. Res. Lett., 29, 1278, doi:10.1029/2001GL014443, 2002.
- Höpfner, M., Larsen, N., Spang, R., Luo, B. P., Ma, J., Svendsen, S. H., Eckermann, S. D., Knudsen, B., Massoli, P., Cairo, F., Stiller, G., v. Clarmann, T., and Fischer, H.: MIPAS detects Antarctic stratospheric belt of NAT PSCs caused by mountain waves, Atmos. Chem. Phys., 6, 1221–1230, doi:10.5194/acp-6-1221-2006, 2006.

Höpfner, M., Pitts, M. C., and Poole, L. R.: Comparison between CALIPSO and MI-

- <sup>20</sup> PAS observations of polar stratospheric clouds, J. Geophys. Res., 114, D00H05, doi:10.1029/2009JD012114, 2009.
  - Hurley, J., Dudhia, A., and Grainger, R. G.: Retrieval of macrophysical cloud parameters from MIPAS: algorithm description, Atmos. Meas. Tech., 4, 683–704, doi:10.5194/amt-4-683-2011, 2011.
- Jensen, E. J., Toon, O. B, Selkirk, H. B., Spinhirne, J. D, and Schoeberl, M. R.: On the formation and persistence of subvisible cirrus clouds near the tropical tropopause, J. Geophys. Res., 101, 21361–21375, 1996a.
  - Jensen, E. J., Toon, O. B, Pfister, L., and Selkirk, H. B.: Dehydration of the upper troposphere and lower stratosphere by subvisible cirrus clouds near the tropical tropopause, Geophys.
- <sup>30</sup> Res. Lett., 23, 825–828, 1996b.
  - Karagulian, F., Clarisse, L., Clerbaux, C., Prata, A. J., Hurtmans, D., and Coheur, P. F.: Detection of volcanic SO<sub>2</sub>, ash, and H<sub>2</sub>SO<sub>4</sub> using the Infrared Atmospheric Sounding Interferometer (IASI), J. Geophys. Res., 115, D00L02, doi:10.1029/2009JD012786, 2010.



- Kent, G. S., Winker, D. M., Osborn, M. T., and Skeens, K. M.: A model for the separation of cloud aerosol in SAGE II occultation data, J. Geophys. Res., 98, 20725–20735, 1993.
- Kiefer, M., von Clarmann, T., Grabowski, U., De Laurentis, M., Mantovani, R., Milz, M., and Ridolfi, M.: Characterization of MIPAS elevation pointing, Atmos. Chem. Phys., 7, 1615– 1628, doi:10.5194/acp-7-1615-2007, 2007.

5

30

- Kleinert, A., Aubertin, G., Perron, G., Birk, M., Wagner, G., Hase, F., Nett, H., and Poulin, R.: MIPAS Level 1B algorithms overview: operational processing and characterization, Atmos. Chem. Phys., 7, 1395–1406, doi:10.5194/acp-7-1395-2007, 2007.
- Kravitz, B. and Robock, A.: The climate effects of high latitude eruptions: The role of the time of year, J. Geophys. Res., 116, D01105, doi:10.1029/2010JD014448, 2011.
- Kristiansen, N. I., Stohl, A., Prata, A. J., Richter, A., Eckhardt, S., Seibert, P., Hoffmann, A., Ritter, C., Bitar, L., Duck, T. J., and Stebel, K.: Remote sensing and inverse transport modeling of the Kasatochi eruption sulfur dioxide cloud, J. Geophys. Res., 115, D00L16, doi:10.1029/2009JD013286, 2010.
- <sup>15</sup> Liu, C., Zipser, E. J, and Nesbitt, S.: Global distribution of tropical deep convection: Different perspectives from TRMM infrared and radar data, J. Climate, 20, 480–503, 2007.
  - Manney, G. L., Santee, M. L., Rex, M., Livesey, J., Pitts, M. C., Veefkind, P., Nash, E. R., Wohltmann, I., Lehmann, R., Friodevaux, L., Poole, L. R., Schoeberl, M. R., Haffner, D. P., Davies, J., Dorokhov, V., Gernandt, H., Johnson, B., Kivi, R., Kyrö, E., Larsen, N., Levelt, P.,
- Makshtas, A., McElroy, C. T., Nakajima, H., Parrondo, A. C., Tarasick, D. W., von der Gathen, P., Walker, K. A., and Zinoviev, N. S.: Unprecedented Arctic ozone loss in 2011, Nature, 489, 469–473, 2011.
  - Massie, S., Gille, J., Khosravi, R., Lee, H., Kinnison, D., Francis, G., Nardi, B., Eden, T., Craig, C., Halvorson, C., Coffey, M., Packman, D., Cavanaugh, C., Craft, J., Dean, V., Ellis, D.,
- Barnett, J., Hepplewhite, C., Lambert, A., Manney, G., Strawa, A., and Legg, M.: High Resolution Dynamics Limb Sounder observations of polar stratospheric clouds and subvisible cirrus, J. Geophys. Res., 112, D24S31, doi:10.1029/2007JD008788, 2007.
  - Massie, S. T., Gille, J., Craig, C., Khosravi, R., Barnett, J., Read, W., and Winker, D.: HIRDLS and CALIPSO observations of tropical cirrus, J. Geophys. Res., 115, D00H11, doi:10.1029/2009JD012100, 2010.
  - Mergenthaler, J., Roche, A. E., Kumer, J. B., and Ely, G.: Cryogenic Limb Array Etalon Spectrometer observations of tropical cirrus, J. Geophys. Res., 104, 22183–22194, 1999.



- Milz, M., von Clarmann, T., Fischer, H., Glatthor, N., Grabowski, U., Höpfner, M., Kellmann, S., Kiefer, M., Linden, A., Mengistu Tsidu, G., Steck, T., Stiller, G. P., Funke, B., Lopez-Puertas, M., and Koukouli, M. E.: Water vapor distributions measured with the Michelson Interferometer Passive Atmospheric Sounding on board ENVISAT (MIPAS/ENVISAT), J. Geophys. Res.,
- <sup>5</sup> 110, D24307, doi:10.1029/2005JD005973, 2005.
   Moore, D. P. and Remedios, J. J.: Growth rates of stratospheric HCFC-22, Atmos. Chem. Phys., 8, 73–82, doi:10.5194/acp-8-73-2008, 2008.
  - Moore, D. P., Remedios, J. J., and Waterfall, A. M.: Global distributions of acetone in the upper troposphere from MIPAS spectra, Atmos. Chem. Phys., 12, 757–768, doi:10.5194/acp-12-757-2012. 2012.
- 10

Prata, A. J., Carn, S. A., Stohl, A., and Kerkmann, J.: Long range transport and fate of a stratospheric volcanic cloud from Soufrière Hills volcano, Montserrat, Atmos. Chem. Phys., 7, 5093–5103. doi:10.5194/acp-7-5093-2007. 2007.

15

- Prata, A. J., Gangale, G., Clarisse, L., and Karagulian, F.: Ash and sulphur dioxide in the 2008 eruptions of O kmok and Kasatochi: Insights from high spectral resolution satellite measurements, J. Geophys. Res, 115, D00L18, doi:10.1029/2009JD013556, 2010.
- Pumphrey, H. C., Santee, M. L., Livesey, N. J., Schwartz, M. J., and Read, W. G.: Microwave Limb Sounder observations of biomass-burning products from the Australian bush fires of February 2009, Atmos. Chem. Phys., 11, 6285–6296, doi:10.5194/acp-11-6285-2011, 2011.
   Randall, D. A., Wood, R. A, Bony, S., Colman R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R. J., Sumi, A., and Taylor, K. E.: Cilmate Models and Their Evaluation, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate
- <sup>25</sup> Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Raspollini, P., Belotti, C., Burgess, A., Carli, B., Carlotti, M., Ceccherini, S., Dinelli, B. M.,

Dudhia, A., Flaud, J.-M., Funke, B., Höpfner, M., López-Puertas, M., Payne, V., Piccolo, C., Remedios, J. J., Ridolfi, M., and Spang, R.: MIPAS level 2 operational analysis, Atmos. Chem. Phys., 6, 5605–5630, doi:10.5194/acp-6-5605-2006, 2006.



Prata, A. F.: Satellite detection of hazardous volcanic clouds and the risk to global air traffic, Nat. Hazards, 51, 303–324, doi:10:1007/s11069-008-9273-z, 2008.

- 1826
- Vaughan, M., Young, S., Winker, D., Powell, K., Omar, A., Liu, Z., Hu, Y., and Hostetler, C.: 30 Fully automated analysis of space-based lidar data: an overview of the CALIPSO retrieval algorithms and data products, Proc. SPIE, 5575, 16-30, 2004.
- data, J. Appl. Meteorol., 33, 212-229, 1994.
- 11, 33013–33094, doi:10.5194/acpd-11-33013-2011, 2011. Strabala, K. I., Ackerman, S. A., and Menzel, W. P.: Cloud properties inferred from 8-12 micron

Stephens, G.: Remote Sensing of the Lower Atmosphere: An Introduction, Oxford Univ. Press,

- Spang, R., Arndt, K., Dudhia, A., Höpfner, M., Hoffmann, L., Hurley, J., Grainger, R. G., Griessbach, S., Poulsen, C., Remedios, J. J., Riese, M., Sembhi, H., Siddans, R., Waterfall, A., and Zehner, C.: Fast cloud parameter retrievals of MIPAS/Envisat, Atmos. Chem. Phys. Discuss.,
- Spang, R., Remedios, J. J., and Barkley, M. P.: Colour indices for the detection and differentiation of cloud types in infra-red limb emission spectra, Adv. Space Res., 33, 1041-1047, 2004.

doi:10/1029/2001JD000698, 2002.

20

25

March 1994.

cuss., 7, 9973-10017, doi:10.5194/acpd-7-9973-2007, 2007.

- phys. Res. Lett., 30, 1875, doi:10.1029/2003GL017231, 2003. Spang, R., Riese, M., Eidmann, G., Offermann, D., Pfister, L., and Wang, P. H.: CRISTA observations of cirrus clouds around the tropopause, J. Geophys. Res., 107, 8174,
- atmospheric spectra of polar stratospheric clouds measured by the CRISTA instrument, Geo-15
- spheric Chemistry Experiment (ACE) observations of aerosol in the upper troposphere and 10 lower stratosphere from the Kasatochi volcanic eruption, J. Geophys. Res., 115, D00L14. doi:10.1029/2009JD013469.2010. Spang, R. and Remedios, J. J.: Observations of a distinctive infra-red spectral feature in the
- 5 Robock, A.: Volcanic eruptions and climate, Rev. Geophys., 38, 191–219, 2000. Siddaway, J. M. and Petelina, S. V.: Transport and evolution of the 2009 Australian Black Saturday bushfire smoke in the lower stratosphere observed by OSIRIS on Odin, J. Geophys. Res., 116, D06203, doi:10.1029/2010JD015162, 2011.

Remedios, J. J., Leigh, R. J., Waterfall, A. M., Moore, D. P., Sembhi, H., Parkes, I., Greenhough, J., Chipperfield, M. P., and Hauglustaine, D.: MIPAS reference atmospheres and

comparisons to V4.61/V4.62 MIPAS level 2 geophysical data sets, Atmos. Chem. Phys. Dis-

Sioris, C. E., Boone, C. D., Bernath, P. F., Zou, J., McElroy, C. T., and McLinden, C. A.: Atmo-

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Discussion Paper

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5, 1795-1841, 2012

# MIPAS detection of cloud and aerosol particle occurrence

H. Sembhi et al.





- Vömel, H.: Saturation Vapour Pressure Formulations, available at: http://cires.colorado.edu/ ~voemel/vp.html, 2011.
- Waythomas, C. F., Scott, W. E., Prejean, S. G., Schneider, D. J., Izbekov, P., and Nye, C. J.: The 7-8 August 2008 eruption of Kasatochi Volcano, central Aleutian Islands, Alaska, J. Geophys. Res., 115, B00B06, doi:10.1029/2010JB007437, 2010.
- 5 Winker, D. M., Hostetler, C. A, Vaughan, M. A., and Omar, A. H.: CALIOP Algorithm Theoretical Basis Document: Part 1. CALIOP instrument and Algorithms Overview, PC-SCI-202, Part 1, Release 2.0, 2006.
  - Winker, D. M., Hunt, W. H., and McGill, M. J.: Initial performance assessment of CALIOP, Geophys. Res. Lett., 34, L19803, doi:10.1029/2007GL030135, 2007.
- Winker, D. M., Pelon, J., Coakley, J. A., Ackerman, S. A, Charlson, R. J., Colarco, P. R., Flamant, P., Fu, Q., Hoff, R. M., Kittaka, C., Kubar, T. L., LeTreut, H., McCormick, M. P., Megie, G., Poole, L., Powell, K., Trepte, C., Vaughan, M. A., and Wielicki, B. A.: The CALIPSO Mission: A Global 3D View of Aerosols and Clouds, B. Am. Meteorol. Soc., 19, 1211-1229, doi:10.1175/2010BAMS3009.1.2010.
- 15

10

Wu, D. L. and Jiang, J. H.: EOS MLS Algorithm Theoretical Basis for Cloud Measurements, Technical Report, D-19299, Jet Propulsion Laboratory, 2004.



<b>AMTD</b> 5, 1795–1841, 2012				
MIPAS detection of cloud and aerosol particle occurrence				
H. Sembhi et al.				
Title	Title Page			
Abstract	Introduction			
Conclusions	References			
Tables	Figures			
I	۶I			
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Back	Close			
Full Scre	Full Screen / Esc			
Printer-friendly Version				
Interactive	Interactive Discussion			

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**Table 1.** Spectral regions and operational CI thresholds for MIPAS for cloud-clearing trace gas retrievals (Raspollini et al., 2006).

MIPAS band	MW1 (cm <sup>-1</sup> )	MW2 (cm <sup>-1</sup> )	Operational threshold
CI-A	788.20–796.25	832.3-834.4	1.8
CI-B	1246.3–1249.1	1232.2–1234.4	1.2
CI-D	1929.0–1935.0	1973.0–1983.0	1.8

Table 2. Details of MIPAS cloud microwindow simulations.

Simulations				
Microwindows	MW1 = 788.20–796.2 MW2 = 832.3–834.4			
Instrument characteristics	Apodised instrument line shape (ILS) and the MIPAS field of view (FOV) convolutions at each spectral and tangent height calculation			
Trace gas climatology	Leicester RAMstan IG2 climatological database for temperature (K), pressure (hPa) and concentration profiles of CO <sub>2</sub> , O <sub>3</sub> , N <sub>2</sub> O, CO, CH <sub>4</sub> , O <sub>2</sub> , NO, NO <sub>2</sub> , HNO <sub>3</sub> , CIO, N <sub>2</sub> , F11, F12, F22, CCI <sub>4</sub> , N <sub>2</sub> O <sub>5</sub> and CIONO <sub>2</sub> Latitude bands: 90 to 65° N/S, 65 to 20° N/S and 20 to 0° N/S Seasons: January, April, July, October			
Background aerosol	Latitudinally-averaged extinction profiles retrieved from MIPAS-E spectra using the Optimal Estimation Re- trieval Algorithm or OPERA (Moore et al., 2008). The profiles are extended up to 30 km by merging with a scaled "background" extinction profile from the HALOE.			
Water vapour representation	Profiles are calculated from saturation vapour mixing ratio profiles using temperature and pressure from the RAMSTAN climatology. Data used are from the mini- mum and mean standard atmospheres, the mean IG2 temperature and pressure profiles per latitude band and the maximum $H_2O$ from the European Centre for Medium-Range Weather Forecasting (ECMWF). All saturation vapour pressures are calculated using the Goff-Graatch formula (Vömel, 2011)			
Altitude grid	1 km resolution from 6 to 30 km			
Spectral and cross section	"mipas_hitranpf3.3.bin" modified HITRAN database containing updated $C_2H_6$ , HNO <sub>3</sub> line information.			





**Fig. 1.** Tropical MIPAS L1b spectra from orbit 07386 at 12 km between 685 and 970 cm<sup>-1</sup> for clear sky (black), thin cloud (red) and optically thick cloud conditions (blue). The thick cloud spectra are heavily offset due to the change in radiance and loss of spectral features when optically thick clouds are in the MIPAS LOS.





**Fig. 2.** CI-A threshold profiles for MIPAS from 10 to 30 km. Threshold profiles have been smoothed and interpolated on to a grid of 90–80, 80–65, 65–40, 40–20° and 20 to 0° for Northern and Southern Hemispheres. Profiles are colour-coded for each latitude band (see legend); dotted lines show north and south pole thresholds calculated for polar vortex conditions (enhanced CIO; reduced stratospheric temperature and O<sub>3</sub>).





**Fig. 3.** Variation of index profile and  $\sigma_{\text{total}}$  for the north and south poles. Solid lines represent the calculated index threshold and dotted lines representing the range in  $\sigma_{\text{total}}$ . The large variation in  $\sigma_{\text{total}}$  reflects the impact of the change in stratospheric temperatures throughout the poles for both seasons.









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Fig. 5. Mean MIPAS and HIRDLS COF for June-July-August 2007 and December-January-February 2007/2008 in the range of 12 to 20 km (binned onto a 1 km vertical grid) between 50° N and 50° S on a 5° latitude and 10° longitude grid. Top left: MIPAS JJA 2007, top right: HIRDLS JJA 2007; bottom left: MIPAS DJF 2008 and bottom right HIRDLS DJF 2008.



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**Fig. 6.** Normalised frequency distributions of mean MIPAS and HIRDLS gridded CATH for DJF 2008 for data from 12 to 20 km, between 50° N to 50° S on a 5° latitude and 10° longitude grid compared to corresponding gridded mean CALIOP CATH.





**Fig. 7.** Map of MIPAS CATH in the 15 to 20 km layer for 7 to 16 Februay 2009 near Victioria Australia. The blue triangle indicates position of Victoria (located at 38° S 143° E) where the Black Saturday bushfires originated.





**Fig. 8.** Map of MIPAS CI-A in the 15 to 20 km layer for 7 to 16 February 2009 near Victoria Australia. The blue triangle indicates position of Victoria (located at 38° S 143° E) where the Black Saturday bushfires originated.



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**Fig. 9.** Comparison of MIPAS and CALIOP CATH from 7 to 16 February 2009 near Victoria Australia. The blue triangle indicates position of Victoria (located at 38° S 143° E) where the Black Saturday bushfires originated.











**Fig. 11.** Map of MIPAS CI-A corresponding to CATH in the range of 15 to 20 km between 60 and 40° N from 7 August (first Kasatochi eruption) to 31 August 2008. Location of Mount Kasatochi at 52° N, 175° W is indicated by the blue triangle.





**Fig. 12.** Frequency distribution of all MIPAS CATH from 60 to 50° N for the selected months of February 2008 (pre-Kasatochi), August 2008 (during Kasatochi eruptions) to the post-Kasatochi eruption period of October 2008, December 2008 and February 2009.

