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Distinction between clouds and ice/snow covered surfaces in the identification of cloud-free observations using SCIAMACHY PMDs

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Abstract

SCIAMACHY on ENVISAT allows measurement of different trace gases including those most abundant in the troposphere (e.g. CO_2, NO_2, CH_4). However, clouds in the observed scenes can severely hinder the observation of tropospheric gases. Several cloud detection algorithms have been developed for GOME on ERS-2 which can be applied to SCIAMACHY. The GOME cloud algorithms, however, suffer from the inadequacy of not being able to distinguish between clouds and ice/snow covered surfaces because GOME only covers the UV, VIS and part of the NIR wavelength range (240–790 nm). As a result these areas are always flagged as clouded, and therefore often not used. Here a method is presented which uses the SCIAMACHY measurements in the wavelength range between 450 nm and 1.6 μm to make a distinction between clouds and ice/snow covered surfaces. The algorithm is developed using collocated MODIS observations. The algorithm presented here is specifically developed to identify cloud-free SCIAMACHY observations. The SCIAMACHY Polarisation Measurement Devices (PMDs) are used for this purpose because they provide higher spatial resolution compared to the main spectrometer measurements.

1. Introduction

Satellite-based passive remote sensing is commonly used to derive global information about the composition of the Earth's atmosphere. Information about the total column or even vertical profiles of different gases in the Earth atmosphere can be obtained by measuring the radiance (intensity) spectrum of sunlight reflected by the Earth's atmosphere, since these spectra contain absorption bands of gases present in the atmosphere, such as ozone. In the ultra-violet (UV), visible (VIS) and near infra-red (NIR) wavelength range the presence of clouds can strongly affect the observation of constituents in the troposphere, because clouds effectively screen the lower part of the atmosphere. When clouds are not properly accounted for, or when a significant part of the airmass of interest is below the cloud, (large) errors are introduced. Therefore, cloud detection algorithms are of crucial importance in satellite remote sensing.

The SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) is a joint German/Dutch/Belgian instrument on board the ESA ENVISAT satellite, which was launched on March 1st 2002 and is expected to operate for at least five years. SCIAMACHY's primary mission objective is to perform global measurements of trace gases in the troposphere and stratosphere (Bovensmann et al., 1999). The instrument provides column and/or vertical profile information on O_3, H_2CO, SO_2, BrO, OClO, NO_2, H_2O, CO, CO_2, CH_4, N_2O, O_2, $(O_2)_2$, and on clouds and aerosols as well. SCIAMACHY thereto measures the radiance of reflected and back-scattered sunlight in 8 channels, covering the 240–1750 nm wavelength (channels 1–6) and two IR bands 1940–2040 nm and 2265–2380 nm (channels 7 and 8, respectively) at 0.2–1.5 nm spectral resolution.

SCIAMACHY alternates between nadir and limb viewing modes for most part of the orbit. The swath of the instrument in nadir mode is 960 km, and the individual main channel measurements have a footprint on Earth ranging from 60 km×30 km to 240 km×30 km (across × along track), thereby providing global coverage in a period of six days (Bovensmann et al., 1999).

SCIAMACHY is a grating spectrometer which is highly polarisation sensitive. In order to account for the instrument polarisation sensitivity, SCIAMACHY measures the polarisation of reflected sunlight using seven broadband detectors, referred to as the Polarisation Measurement Devices (PMDs) which roughly cover the spectral range of the main spectrometer. Because the PMDs are mainly sensitive to parallel (to the instrument slit) polarised light, while the main channel spectrometer is sensitive to both polarisation components, information on the polarisation of the incoming light is obtained by combining the two measurements (Aben et al., 2003). In addition, the PMDs are read out at higher frequency than the main channel detectors which results in higher spatial resolution for these measurements (~7 km×30 km) which is why the PMDs are used in the algorithm presented here.

The predecessor of SCIAMACHY, the Global Ozone Monitoring Experiment (GOME), was launched on 21 April 1995 on-board ESA's second European Remote Sensing satellite (ERS-2). GOME is a de-scoped version of SCIAMACHY and only covers the ultraviolet, visible and near-infrared wavelength range from 240 to 800 nm with 0.2–0.4 nm spectral resolution (Burrows et al., 1999). GOME is also equipped with three broadband PMDs, measuring polarised light across its full wavelength range.

Several cloud detection algorithms were developed for use in GOME, like ICFA (Kuze and Chance, 1994), OCRA (Loyola, 1998), CRAG (von Bargen et al., 2000), CRUSA (Wenig, 2001), FRESCO (Koelemeijer et al., 2001), and GOMECAT (Kurosu et al., 1998). These methods either use the high spectral resolution measurements from the main spectrometer, or the broadband PMD measurements, or a combination of both. Some of these algorithms have been modified for use with SCIAMACHY measurements, but since GOME does not measure in the infra-red region none of these methods uses information in the infra-red wavelengths beyond 800 nm as measured by SCIAMACHY. Because both clouds and ice/snow covered surfaces are highly reflective and white in the GOME wavelength range, none of these algorithms distinguish between clouds or ice/snow covered surfaces in the observation. Without such a distinction these observations are indicated clouded and therefore often not used. A method to distinguish between clouds and ice/snow covered surfaces is thus of crucial importance to be able to identify cloud-free observations.

Here the SCIAMACHY PMD Identification of Clouds and Ice/snow method (SPICI) is presented which is a variation on previous cloud-detection algorithms. It uses, a.o. the SCIAMACHY PMD measurements in the wavelength range around 1.6 μm where the reflectivity of ice/snow covered surfaces is significantly reduced while the reflectivity of clouds is still high. Using this clear spectral difference in reflectivities a distinction between clouds and ice/snow covered surfaces in the SCIAMACHY observations can be made. The algorithm consists of two steps. In the first step the algorithm only uses PMD 2, 3 and 4 to determine the presence of clouds. Because at these wavelengths one can not separate clouds from ice/snow covered surfaces, a second step is

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needed to finally detect cloud-free observations also over ice/snow covered surfaces. Because the SCIAMACHY PMDs are not radiometrically calibrated, the SPICI algorithm is developed using collocated high spatial resolution observations from MODIS on Eos-Terra. MODIS measures the solar reflected and back scattered light in the 0.4–14.0 μm wavelength range. Therefore, MODIS can distinguish between clouds and ice/snow. The MODIS cloud detection algorithm has been extensively validated (Ackerman et al., 1998; Mahesh et al., 2004) and can therefore be used to develop and validate the SPICI algorithm applied to SCIAMACHY data.

The SPICI algorithm presented here has been tuned such that cloudy observations are rarely flagged cloud-free. This implies that it is more likely that some cloud-free observations over these surfaces are mistakenly flagged cloudy. We have chosen this conservative approach because for well-mixed tropospheric gases, such as CH_4 and CO_2, the slightest cloud-contamination affects the quality of these data products which could make them useless. Clearly, one can use the SPICI algorithm and adjust the criteria depending on the use of the data.

The structure of this paper is as follows. In Sect. 2 we describe the Polarisation Measurement Devices on-board SCIAMACHY and present some illustrations of their use in RGB-colour images of the Earth which provides the basic concept for the cloud and ice/snow algorithm SPICI presented in Sects. 3 and 4. Section 3 starts with the definition of the cloud algorithm which represents the first step in the SPICI algorithm. Section 4 deals with the actual distinction between clouds and ice/snow covered surfaces. Validation of the SPICI algorithm is presented in Sect. 5. We finish with a summary in Sect. 6.

2. SCIAMACHY Polarisation Measurements Devices

SCIAMACHY is a highly polarisation-sensitive instrument due to the instrument's gratings and mirrors. Neglect of such an instrument's polarisation sensitivity can lead to errors in the radiances of several tens of percents at wavelengths where the instrument polarisation sensitivity is highest. In order to correct for this polarisation sensitivity, SCIAMACHY measures the polarisation of reflected sunlight using seven broadband detectors, referred to as Polarisation Measurement Devices (PMDs, see Table 1). In this paper we focus on four PMDs (PMD 2 to 5) that cover the visible and near-infrared wavelength range from 450 nm to 1700 nm. The PMDs are read out at 40 Hz, but are down-sampled to 32 Hz for processing. This still gives a much better spatial resolution than the main spectral channels where the fastest read-out occurs at 8 Hz, and more commonly at 1 Hz. This high PMD spatial resolution allows us to study clouds and ice/snow in more spatial detail which is the reason why we use the PMDs in the SPICI algorithm and not the main spectrometer measurements.

The measured signal for each PMD can be written as:

$$R_{\mathrm{PMD}} = \sum_{i=\lambda_{\mathrm{start}}}^{\lambda_{\mathrm{end}}} M_{1,i} I_i (1 + \mu^P_{2,i} q + \mu^P_{3,i} u), \tag{1}$$

where R_{PMD} is the PMD read-out signal, and where $M_{1,i}$, $\mu^P_{2,i}$ and $\mu^P_{3,i}$, indicate per main spectral channel diode i the PMD sensitivity to the different Stokes Parameters, I, q=Q/I, u=U/I, respectively, summed over the wavelength range for which the PMD is sensitive (λ_{start} and λ_{end}, respectively). As μ^P_3 is very small for all PMDs (except PMD 7), the PMDs are mostly sensitive to I and q. In the remainder of this paper we consider only the intensity I to be linear to R_{pmd} as detected by the PMD. The error on the intensity measured by the PMD introduced by ignoring q is only a few percent, as both q-values and $\mu^P_{2,i}$ are generally smaller then 0.1. This is not the case in the wavelength range of PMD1 where both the instrument polarisation sensitivity is high and the polarisation of the scattered sunlight can be strong. Therefore PMD1 is not used in the present algorithm.

Figure 2 displays the coloured Earth surface as constructed from PMD 2, 3, and 4 measurements, in blue, green and red, respectively. The image shows the world as measured by SCIAMACHY, as cloud-free as possible. The Earth surface was gridded to 0.25°×0.25° cells. Each PMD measurement, corrected for viewing and solar zenith angle, was inserted into the grid-cell closest to the central footprint of that measurement between November 2002 and October 2003. The measurement with lowest PMD 2 (blue) intensity was stored in each grid-cell, as clouds would show bright in PMD 2. In this way the most cloud-free possible RGB-colour image of the Earth is obtained.

The image shows a highly reddened Earth because PMD 4 measures light in the near- infra-red wavelength range, and not really in the red, and particularly vegetation surfaces highly reflect in the near-infrared. Combining the different PMD 2, 3, and 4 measurements somewhat differently results in a much more familiar colour image[1]. The image shows that PMD 2, 3, and 4 can be used as broadband intensity measurements.

A similar map can be made by applying the near-infrared PMDs. Figure 3 shows again the Earth surface, but now PMD 6, 5 and 4, are used for red, green and blue respectively. This image is constructed using only February and March 2003 SCIAMACHY data, in order to clearly show the effects of winter at the northern latitudes. Full cloud-free global coverage is therefore not achieved because of the shorter period. As such many clouds are still visible as green-grey patches, because at certain locations no cloud-free observation was present during this period. However note the clear difference between clouds and ice/snow as clouds are a green-grey, but ice/snow shows up as clear purple at the Poles and the snowy northern high latitudes. A purple colour indicates a strong intensity in both red (PMD 6) and blue (PMD 4) and at the same time a low intensity in green (PMD 5). This difference will be exploited to distinguish between clouds and ice/snow covered surfaces in Sect. 4.

[1]By taking the natural log of:
R: 1.0×PMD 3+0.1×PMD 4,
G: 0.5×PMD 2+0.5×PMD 3+0.1×PMD 4,
B: 1.0×PMD 2
with a minimum value of 8.5 and a maximum of 11.0

3. Cloud recognition

Clouds can easily be spotted in any visual Earth image from space, because in the visible wavelengths, clouds are bright and white whereas the background on which they appear is usually not. Obviously, this is not the case when there is snow or ice in the background, but these cases will be addressed in the next section. The degree of 'whiteness' can be used to detect the presence of clouds. Saturation in the Hue-Saturation-Value (HSV) colour space (Foley et al., 1990), which is a transformation from the Red-Green-Blue (RGB) colour value, can be used as an indication of 'whiteness' which is applied here to identify clouds.

Each PMD readout is first converted into a weighted red, green and blue colour value using SCIAMACHY PMD 4, 3 and 2, respectively. As mentioned before, PMD 1 is not used because of its strong polarisation sensitivity. The weighting factors were derived by assuming that fully clouded scenes are white, having equal red, green and blue intensities. Clouded scenes were visually selected and the PMD read-outs normalised to PMD 3. The thus derived weighting factors for the different PMDs are given in Table 2. The PMD signals are converted into RGB-values as follows:

$$\begin{aligned} R(ed) &= R_{\mathrm{PMD4}}/A_r \\ G(reen) &= R_{\mathrm{PMD3}}/A_g \\ B(lue) &= R_{\mathrm{PMD2}}/A_b, \end{aligned} \tag{2}$$

where A_r, A_g, A_b are the weighting factors, given in Table 2.

The saturation, S, or the 'whiteness' can then be derived from these RGB-values as follows:

$$S(aturation) = \frac{max(R,G,B) - min(R,G,B)}{max(R,G,B)}, \tag{3}$$

where $max(R,G,B)$ and $min(R,G,B)$ are, respectively, the highest and lowest value of R, G, and B. A threshold can then be determined for which all scenes with a saturation-value below this threshold are clouded. A large advantage of using a saturation thresh-

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old instead of individual PMD thresholds is that no correction for solar zenith angle or viewing angle is needed, because the derived saturation is a ratio of different PMDs.

In order to derive the required saturation threshold SCIAMACHY observations are compared to MODIS (MODerate resolution Imaging Spectroradiometer) on-board the Terra (EOS AM) satellite. Terra is in a sun-synchronous, near-polar, descending orbit at 705 km and has an equator crossing time of 10:30 UT, only half an hour later than SCIAMACHY, making it useful for collocated comparisons. Terra MODIS covers the entire Earth's surface every 1 to 2 days, with a swath of 2330 km across track and 10 km along track (in nadir), with spatial resolution between 250 m×250 m and 5 km×5 km, depending on wavelength. Several of the spectral bands are used for the MODIS Cloud Mask product which provides a daily global Level 2 data product at 1 km×1 km spatial resolution. The MODIS algorithm employs a series of visible and infrared threshold and consistency tests to indicate confidence levels that an unobstructed (=cloud-free) view of the Earth's surface is observed. MODIS cloud mask gives 4 possible values: confident clear (3), probably clear (2), probably cloudy (1), and confident cloudy (0). The probably clear and cloudy values are most often found at the edges of clouds, and indicate partially clouded scenes. This MODIS cloud product is used to determine the cloud identification in the SCIAMACHY observations.

As the MODIS footprint (1 km×1 km) is much smaller then the SCIAMACHY PMD footprint (7 km×30 km), all MODIS observations that fall within a single SCIAMACHY PMD observation are combined and their cloud values (between 0 and 3) are averaged. On average between 100 and 250 MODIS footprints fall within a single SCIAMACHY PMD footprint. In the remainder of this study we refer to PMD observations with an average MODIS cloud value above 2.95 as "clear" and with a value below 0.05 as "clouded". This corresponds for example to only ~2 out of one hundred (100) collocated MODIS observations with the wrong signature.

These average MODIS cloud values over a SCIAMACHY PMD observation can be compared to the saturation-value S for each individual PMD observation. For this, collocated observations (lat. 14°–54° N, long. 7° W–18° E) of SCIAMACHY (~10:15 UT) and MODIS (∼10:50 UT) on 16 June 2004 were compared. The selected region avoids ice/snow covered areas. Figure 4 shows the number of SCIAMACHY PMD observations with a particular saturation or 'whiteness' for "clouded", "clear" and all remaining (mixed) scenes according to the MODIS data. The "clouded" and "clear" curves show two clearly distinct distributions in saturation-value, indicating that this parameter can be used to differentiate between clouded and clear scenes. Observations which are partly clouded show more variation in saturation-value, because an average of the "clouded" and "clear" scenes is found. As we want to keep the number of mistakenly flagged cloud-free observations to a minimum, we use a threshold saturation-value of 0.35 in the remainder of the study. However, for studies focusing on clouds (instead of clear scenes) or where an occasional cloud is not a problem a threshold of 0.25 can be used, increasing the number of detected "clear" scenes.

Figure 5 shows a spatial comparison between the used SCIAMACHY (∼10:15 UT) and MODIS (∼10:50 UT) observations on 16 June 2004. All SCIAMACHY PMD observations with a saturation below 0.35 are indicated as clouded, those with a higher saturation-value as clear. The colours indicate where the methods agree (light green, pink) or disagree (yellow, mauve). The agreement is very good, only in a few cases there is a disagreement. The most troubling disagreements are when MODIS indicates a (maybe) cloud, while SCIAMACHY PMD saturation-value indicates a clear scene, or vice versa. These cases only occur at the edge of clouds, likely due to movement (or formation) of clouds in the 35 min in-between the observations. For example, around 5° longitude and 32° latitude a cloud apparently moved to the east, as SCIAMACHY indicates clear scenes on the east of the cloud while MODIS (35 min later) indicates these scenes as clouded. On the west side of the cloud the reverse happens, confirming that the cloud moved to the east. Also the cloud cover over northern Europe for this morning is extremely patchy, resulting in some disagreements between MODIS and SCIAMACHY cloud identification. Note that all mixed scenes from Fig. 4 coincide with these cloud edges.

As already stated before, the above cloud detection scheme is based upon the ‘whiteness’ – in the visible wavelength range – of the scene, and therefore does not distinguish between clouds and ice/snow covered surfaces. This is a problem for many cloud detection algorithms, but SCIAMACHY’s infra-red PMDs allow for differentiating between clouds and ice/snow covered surfaces as shown in the next section.

To summarise:

$$Cloud : S(aturation) \leq 0.35 \tag{4}$$

4. Ice recognition

All existing cloud detection algorithms using PMDs are derived from GOME algorithms, which are unable to distinguish between white ice/snow and white clouds because the GOME wavelength range is limited to 800 nm. However SCIAMACHY infra-red PMDs allow for differentiation between clouds and ice/snow covered surfaces.

To illustrate the different spectral behaviour of clouds and ice/snow, several SCIAMACHY observations over the South Pole were selected which according to MODIS were either “clouded” or “clear” scenes. The spectral behaviour of these observations as measured with the SCIAMACHY main spectrometer is shown in Fig. 6. For comparison purposes the spectra are normalised to their PMD 4 response. While for wavelengths lower then 1400 nm the behaviour is similar, above 1400 nm (at the PMD 5 wavelengths) clouds become bright again while ice and snow covered surfaces remain dark. Comparing PMD 4 and PMD 5 will therefore allow ice/snow covered surfaces to be differentiated from clouds due to their spectral behaviour, as clouds are relatively bright in both PMDs while ice/snow covered surfaces become much darker in PMD 5. While it should also be possible to use PMD 6 for this purpose, PMD 6 suffers from a very low signal-to-noise ratio, making it unsuitable for comparison with PMD 4.

The preferred approach would be to compare the expected ratio for PMD5 and PMD4 from theory with the measured ratio between PMD 5 and PMD 4. However, the required absolute calibration of SCIAMACHY PMDs does not exist, and only a relative calibration of the PMDs to the main spectrometer was measured. The relative calibration is

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too uncertain and of too low signal-to-noise ratio to derive an accurate enough absolute calibration for the purposes of determining the ratio between PMD 5 and PMD 4 accurately. Therefore the ratio to differentiate between clouds and ice/snow surfaces is empirically determined using collocated MODIS observations. Again, the advantage of using a ratio instead of individual PMDs is that no correction for solar zenith angle or viewing angle is needed.

Collocated MODIS and SCIAMACHY observations are used, this time observed over the South pole on 24 January 2003 between 08:30–09:10 UT by SCIAMACHY and at 08:50 UT by MODIS. As in the previous section all MODIS observations within a single PMD observation are averaged for comparison. Figure 7 shows the number of SCIAMACHY PMD observations with a particular ratio between PMD 5 and PMD 4 for “clouded” and “clear” scenes according to averaged collocated MODIS data. As the observations are over the South Pole all “clear” scenes are observing snow or ice surfaces. The “clouded” and “clear” curves show two clearly distinct distributions, indicating that the ratio between PMD 5 and PMD 4 can be used to differentiate between clouds and ice/snow covered surfaces. All PMD observations with a ratio $R_{\mathrm{PMD}\ 5}$ / $R_{\mathrm{PMD}\ 4}$ below 0.4 appear to be ice/snow covered surfaces. In general, however, most SCIAMACHY observations occur over more diverse scenes than only ice/snow covered surfaces and clouds as here over the South Pole. The ratios of other scenes can vary and must therefore be verified, as care must be taken not to mistakenly identify clouds as ice/snow covered surfaces.

Figure 8 shows the number of SCIAMACHY PMD observations as a function of the ratio between PMD 5 and PMD 4 for “clouded” and “clear” scenes according to averaged collocated MODIS data for the scene over Europe in the previous section. Most “clear” scenes (observing sea, desert and vegetation) have a high $R_{\mathrm{PMD}\ 5}/R_{\mathrm{PMD}\ 4}$ ratio around 1.8, but we see a different distribution for the “clouded” scenes, varying mostly between 0.2 and 1.2. However, in these particular observations we expect to find little ice/snow covered surfaces as the observations were made in mid-summer June. If here a threshold of 0.4 was used several clouds would have been -mistakenly- identified as ice/snow covered surfaces. Therefore, a lower limit than 0.4 for the ratio $R_{PMD\ 5}/R_{PMD\ 4}$ must be used. Figure 8 suggests a value of 0.2, but studying ratios over several other SCIAMACHY orbits in the summer, shows that the lower limit for cloudy observations in the ratio is around 0.16, as illustrated in Fig. 9, which shows the SCIAMACHY data for 23 August 2002. No comparison with MODIS was made for this data, so no distinction is made between "clouded" and "clear" scenes, but when comparing to the ratios from 16 June 2004 (Fig. 8), the similarity in the distributions is clear. In order to avoid mistakenly identifying clouds as ice/snow, we choose a ratio between PMD 5 and PMD 4 of 0.16 to distinguish between cloud-free ice/snow covered surfaces and clouds, knowingly overestimating the amount of clouds compared to cloud-free ice/snow scenes. For observations over the South Pole or studies less sensitive to clouds a larger ratio up to 0.4 can be chosen.

Figure 10 allows a spatial comparison between the used SCIAMACHY (08:30–09:10 UT) and MODIS (08:50 UT) observations on 24 January 2003 over the South Pole. All SCIAMACHY PMD observations with a saturation-value below 0.35 are indicated clouded, and those with a higher saturation as clear. In the next step, all indicated clouded scenes with a ratio between PMD 5 and PMD 4 below 0.16 are re-assigned as ice/snow covered surfaces. The legend indicates where the methods agree or disagree. The agreement is very good. The only notable disagreement is when a SCIAMACHY PMD observation is identified as clouded whereas MODIS assigned clear. In the east part the number of clouds is thus overestimated by SCIAMACHY compared to MODIS, but this is to be expected due to the low ratio (0.16 instead of 0.4) used for differentiating between ice/snow and clouds. For our purpose the most troubling disagreements would be where MODIS indicates a cloud, while SCIAMACHY PMD saturation-value indicates a clear ice/snow scene (dark blue). Only in a few single cases this happens at the (western) edges of the central cloud complex, likely due to movement of the clouds in the time in-between the observations. Also SCIAMACHY indicates a few single scenes as being clear (light blue), while over the South Pole all clear scenes should show ice/snow. However for the purpose of removing clouded scenes this is not relevant.

To summarise:

$$
\begin{aligned}
&Ice/Snow : \frac{R_{\mathrm{PMD}\ 5}}{R_{\mathrm{PMD}\ 4}} < 0.16\ \&\ S < 0.35 \\
&Cloud \quad : \frac{R_{\mathrm{PMD}\ 5}}{R_{\mathrm{PMD}\ 4}} \geq 0.16\ \&\ S < 0.35
\end{aligned}
\tag{5}
$$

5. Method validation

In order to validate the SPICI method a final comparison was made between SCIAMACHY (13:48–14:12 UT) and collocated MODIS (14:40 UT) data observed on 30 June 2002. These observations are partly over Greenland, the Atlantic Ocean and eastern Canada, combining clouded, clear and ice/snow scenes within the same orbit. This allows a direct validation of the SPICI method as presented in the previous sections. Again all MODIS observations within a single PMD observation are averaged. Figure 11 shows the comparison. Again the agreement is very good. Over Greenland ice/snow scenes are indicated where the sky is clear according to MODIS (light purple), while over the ocean the SPICI method indicated normally clear (light green) or clouded (pink) skies at the exact same locations as MODIS. Only a few single/individual disagreements (blue, mauve) show-up, all occurring at the edge of large cloud complexes or over patchy cloud regions. Again most likely this is due the movement of the clouds in the time between the SCIAMACHY and MODIS observations.

Figure 12 is a more quantitative comparision between SPICI and MODIS, showing for each individual SCIAMACHY PMD observation the ratio of $R_{\mathrm{PMD}\ 5}/R_{\mathrm{PMD}\ 4}$ versus the saturation. Each observation is assigned a colour according to its average MODIS cloud value, e.g. red for clear (around MODIS cloud value 3) and blue for clouded (around MODIS cloud value 0).

In the upper quadrant, defined by a saturation-value larger then 0.35, almost all observations are clear scenes according to MODIS (red). Only a few single/individual

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disagreements show-up (blue symbols), but visual inspection showed that these cases are the earlier mentioned cases at the edge of large clouds complexes or over patchy cloud regions. Almost all clouded observations according to MODIS (blue) lie in the lower-right quadrant, where the saturation is smaller than 0.35 and ratio $R_{\mathrm{PMD}\ 5}/R_{\mathrm{PMD}\ 4}$ is larger than 0.16. The lower-left quadrant, where the saturation is smaller than 0.35, but the ratio of $R_{\mathrm{PMD}\ 5}/R_{\mathrm{PMD}\ 4}$ is smaller than 0.16, shows mostly observations that MODIS indicates as (probably) clear scenes allowing the underlying ice/snow surfaces to be observed. All this combined shows the very good agreement between MODIS and SPICI.

6. Summary

For the accurate detection of well-mixed tropospheric gasses the use of cloud-free observations is extremely important. The NIR SCIAMACHY PMD measurements allow to distinguish between clouds and ice/snow covered surfaces, which in the visible wavelengths is very complicated. In this paper the SPICI method is presented which allows for fast and simple identification of cloud-free SCIAMACHY PMD observations also in the presence of ice/snow covered surfaces. The method employs the ratios of different SCIAMACHY PMD measurements which makes the approach very robust with respect to e.g. calibration uncertainties. The threshold values are defined using collocated observations with the well known and validated high-spatial resolution MODIS data. The SPICI method is very easily implemented, requiring only a few numbers, for those studies that require cloud-free scenes and can be summarised as follows:

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$$
\begin{aligned}
R(ed) &= R_{\mathrm{PMD4}}/0.795\\
G(reen) &= R_{\mathrm{PMD3}}/1.000\\
B(lue) &= R_{\mathrm{PMD2}}/0.750\\
Saturation &= \frac{max(R,G,B)-min(R,G,B)}{max(R,G,B)} \le 0.35\\
Cloud-free &: S \ge 0.35\\
Ice/Snow\ clear &: S < 0.35\ \&\ \frac{R_{\mathrm{PMD\ 5}}}{R_{\mathrm{PMD\ 4}}} \le 0.16\\
Cloud &: S < 0.35\ \&\ \frac{R_{\mathrm{PMD\ 5}}}{R_{\mathrm{PMD\ 4}}} \ge 0.16
\end{aligned} \tag{6}
$$

The thresholds can be somewhat relaxed in cases where some cloud-contamination is acceptable.

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References

Aben, I., Tanzi, C., Hartmann, H., Stam, D., and Stammes, P.: Validation of space-based polarization measurements by use of a single-scattering approximation, with application to the global ozone monitoring experiment, Applied Optics, 42, 3610–3619, 2003. 817

Ackerman, S. A., Strabala, K. I., Menzel, W. P., Frey, R. A., Moeller, C. C., and Gumley, L. E.: Discriminating clear sky from clouds with MODIS, J. Geophys. Res., 103, 32 141–32 158, 1998. 819

Bovensmann, H., Burrows, J. P., Buchwitz, M., Frerick, J., Noel, S., Rozanov, V. V., Chance, K. V., and Goede, A. P. H.: Sciamachy: Mission objectives and measurement modes, J. Atmos. Sci., 56, 127–150, 1999. 817

Burrows, J. P., Weber, M., Buchwitz, M., Rozanov, V., Ladstätter-Weißenmayer, A., Richter, A., Debeek, R., Hoogen, R., Bramstedt, K., Eichmann, K., Eisinger, M., and Perner, D.: The Global Ozone Monitoring Experiment (GOME): Mission Concept and First Scientific Results., J. Atmos. Sci., 56, 151–175, 1999. 818

Foley, J., van Dam, A., Feiner, S., and Hughes, J.: Computer Graphics: Principles and Practice, Addison-Wesley, 1990. 822

Koelemeijer, R. B. A., Stammes, P., Hovenier, J. W., and de Haan, J. F.: A fast method for retrieval of cloud parameters using oxygen A band measurements from the Global Ozone Monitoring Experiment, J. Geophys. Res., 15, 3475–3490, 2001. 818

Kurosu, T. P., Chance, K., and Spurr, R. J. D.: "Cloud Retrieval Algorithm for the European Space Agency's Global Ozone Monitoring Experiment", Proceedings of SPIE, EUROPTO Series: Satellite Remote Sensing of Clouds and the Atmosphere III, edited by: Russel, J. E., 495, 17–26, 1998. 818

Kuze, A. and Chance, K. V.: Analysis of cloud top height and cloud coverage from satellites using the O2 A and B bands, J. Geophys. Res., 99, 14 481–14 491, 1994. 818

Loyola, D.: A New Cloud Recognition Algorithm for Optical Sensors, in: IEEE International Geoscience and Remote Sensing Symposium, volume 2 of IGARSS 1998 Digest, 572–574, 1998. 818

Mahesh, A., Gray, M. A., Palm, S. P., Hart, W. D., and Spinhirne, J. D.: Passive and active detection of clouds: Comparisons between MODIS and GLAS observations, Geophys. Res. Lett., 31, 4108, doi:10.1029/2003GL018859, 2004. 819

von Bargen, A., Kurosu, T., Chance, K., Loyola, D., Aberle, B., and Spurr, R. J.: Cloud retrieval algorithm for gome (crag), Report ER-TN-DKLR-CRAG-007, European Space Agency (ESA/ESTEC), Noordwijk, 2000. 818

Wenig, M.: Satellite Measurements of Long-Term Global Tropospheric Trace Gas Distributions and Source Strengths, PhD thesis, University of Heidelberg, Germany, 2001. 818

Table 1. Wavelength ranges SCIAMACHY Polarisation Measurement Devices, containing 80% of the signal.

PMD	range (nm)	
1	310–365	
2	455–515	
3	610–690	
4	800–900	
5	1500–1635	
6	2280–2400	
7	800–900	(U-sensitive)

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Table 2. Derived weighting factors for the different PMDs, as used in Eq. (2).

A_r	0.795
A_g	1.000
A_b	0.750

Fig. 1. Earth surface as seen by SCIAMACHY PMD 2, 3, and 4, as blue, green and red, respectively. The Earth surface was gridded to 0.25°×0.25° cells, with each grid-cell filled with the darkest PMD 2 (blue) intensity between November 2002 and October 2003. Some cloud-structures are still present. The image shows a reddened Earth as the PMD 4 is in the near infrared and not red.

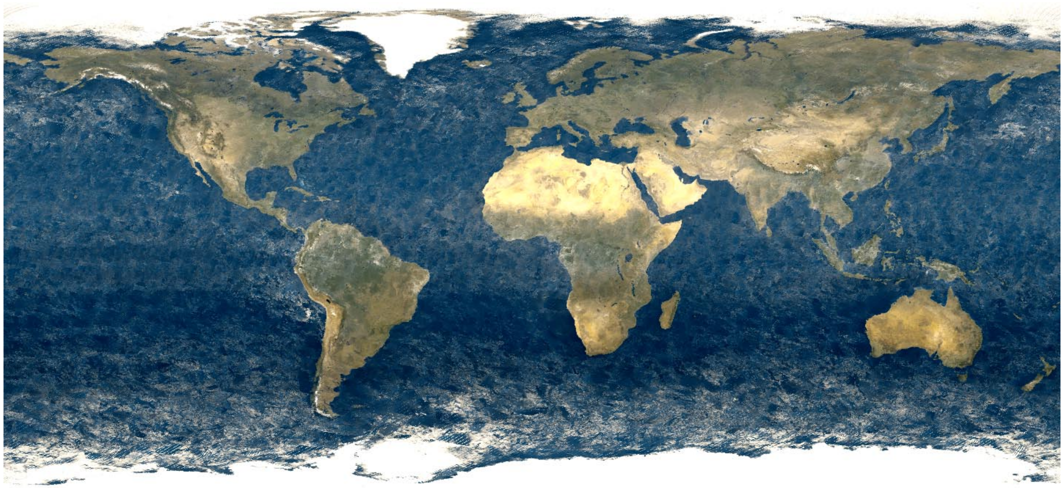

Fig. 2. Similar to Fig. 1, Earth surface as seen by SCIAMACHY PMD 2, 3, and 4, as blue, green and red constructed as described in the text.

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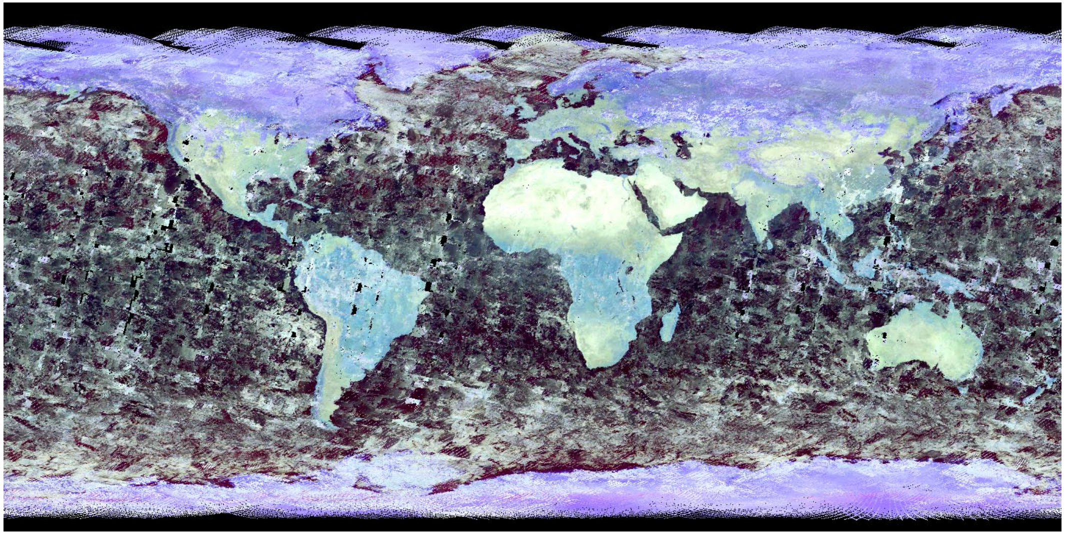

Fig. 3. Similar to Fig. 1, showing the Earth surface as seen by SCIAMACHY PMD 4, 5, and 6, as blue, green and red, respectively, during the months February and March 2003. The ice-caps and snowy northern latitudes show up in purple, while clouds appear green-grey.

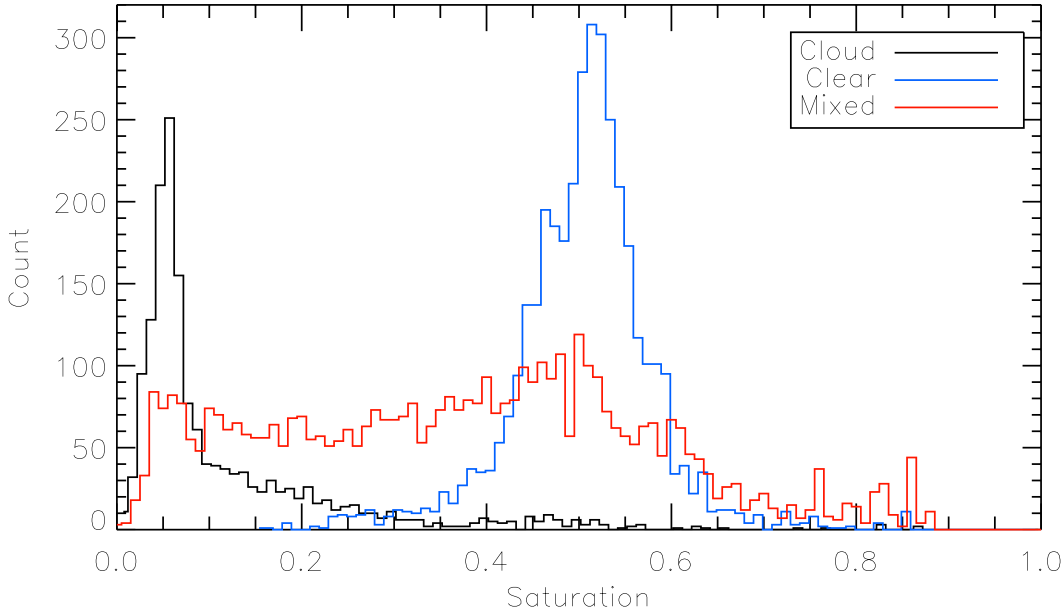

Fig. 4. Comparison between saturation-value of SCIAMACHY PMD observations that are either "clouded" (black), "clear" (blue) or mixed (red) according to collocated MODIS data averaged over the SCIAMACHY PMD footprint. Observations are from 16 June 2004.

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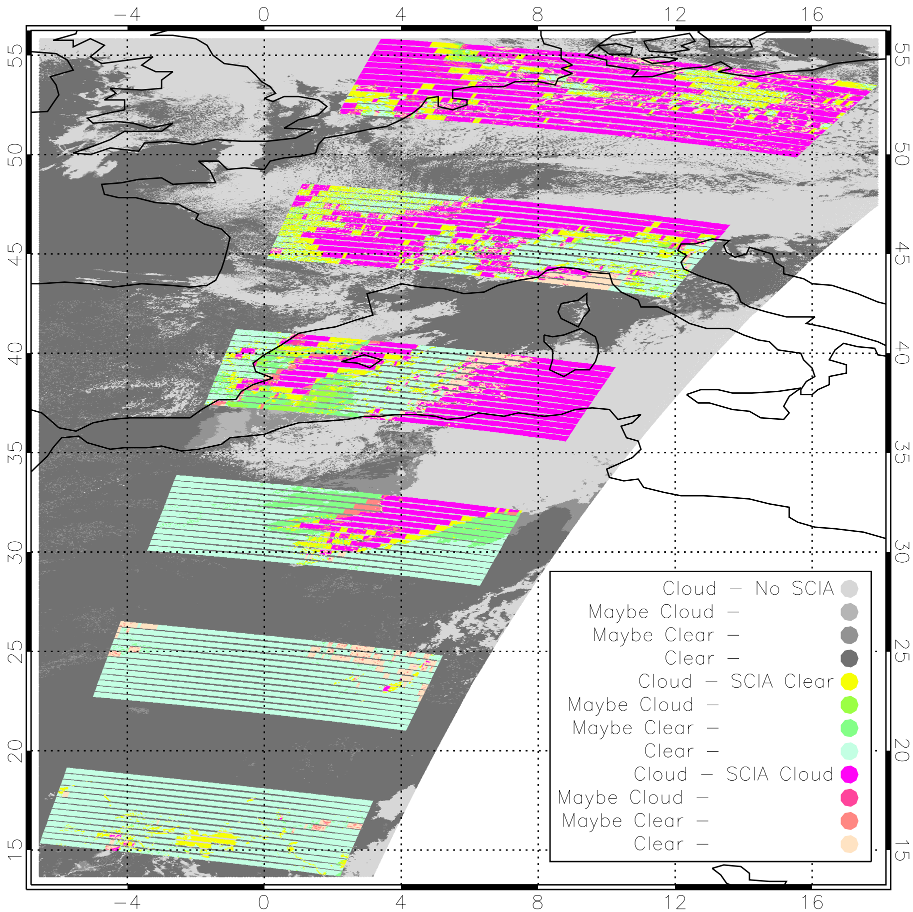

Fig. 5. Comparison between SCIAMACHY (∼10:15 UT) SPICI and MODIS (∼10:50 UT) observations on 16 June 2004. The legend indicates the colours used for all possible different (dis)agreements between MODIS (lefthand-side of legend) and SCIAMACHY SPICI (righthand-side). Note that the plotted MODIS observations are at 1 km×1 km resolution while the SCIAMACHY observations are ∼7 km×30 km.

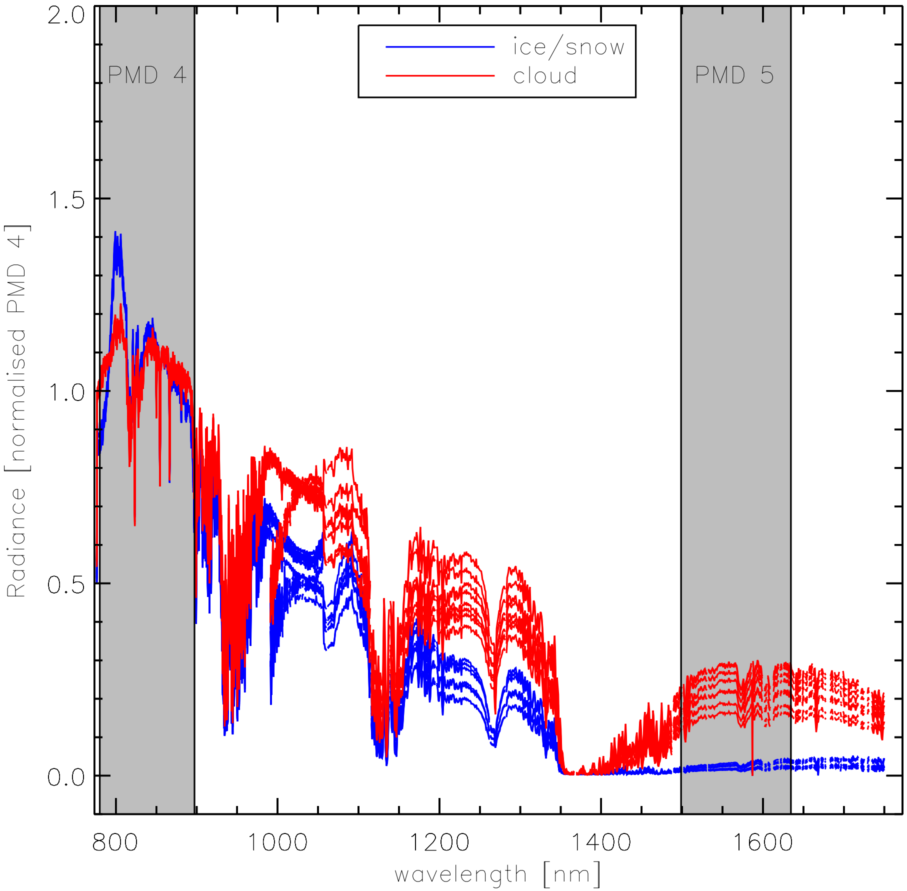

Fig. 6. Comparison between spectral behaviour of several clouded (red) and snow (blue) scenes as measured by SCIAMACHY (over the South pole during polar summer). The wavelength range of PMD 4 and 5 are indicated. The measurements are normalised to the PMD 4 wavelength range. Clouds are much brighter relative to snow at PMD 5 wavelengths.

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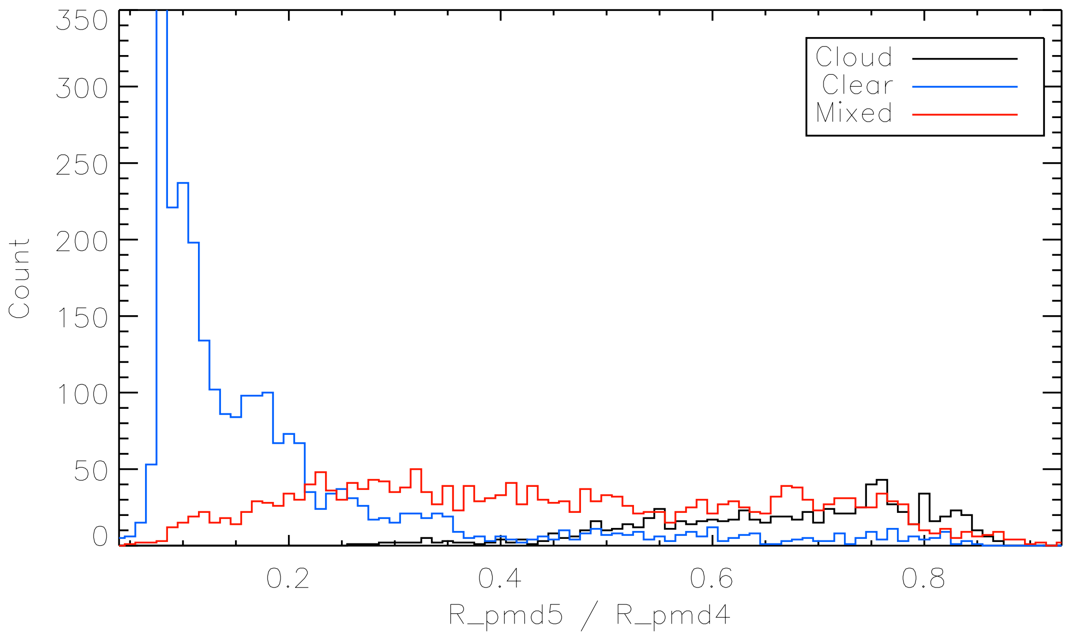

Fig. 7. Number of occurrences of certain ratios between PMD 5 and PMD 4 for "clouded" (black), "clear" (blue) and mixed (red) scenes according to MODIS over the South pole on 24 January 2003.

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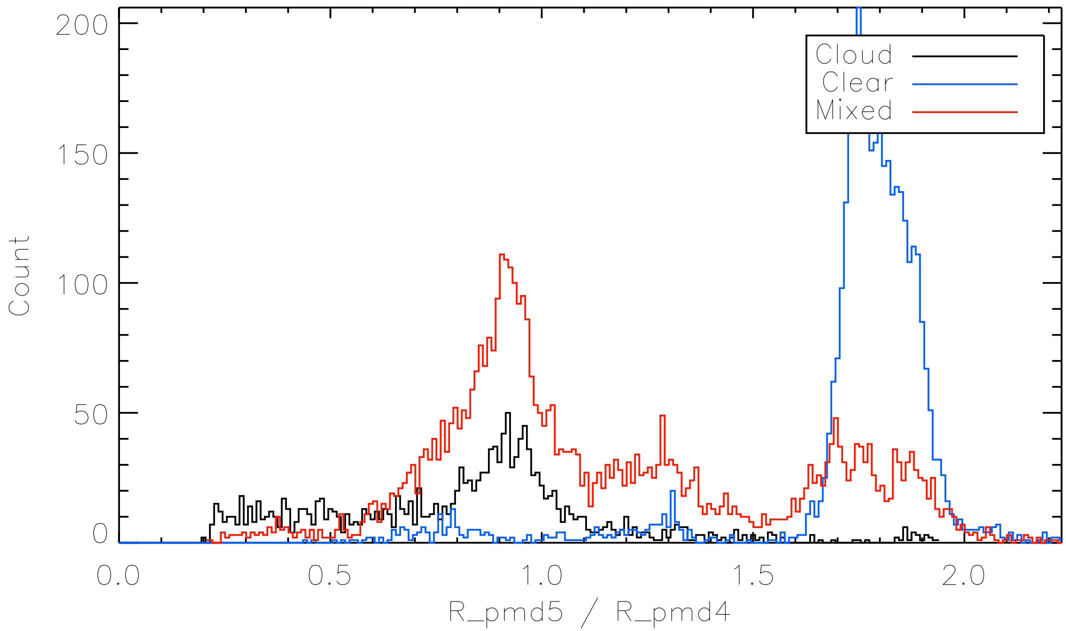

Fig. 8. Number of occurrences of certain ratios between PMD 5 and PMD 4 for "clouded" (black), "clear" (blue) and mixed (red) scenes according to MODIS over Europe on 16 June 2004.

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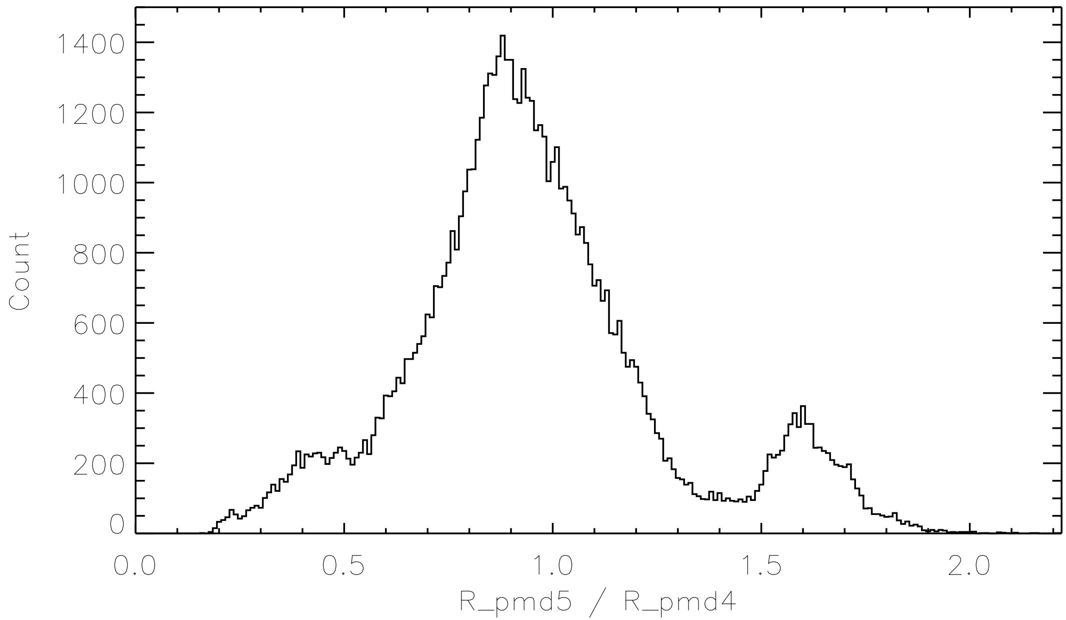

Fig. 9. Number of occurrences of certain ratios between PMD 5 and PMD 4 over Europe on 23 August 2002.

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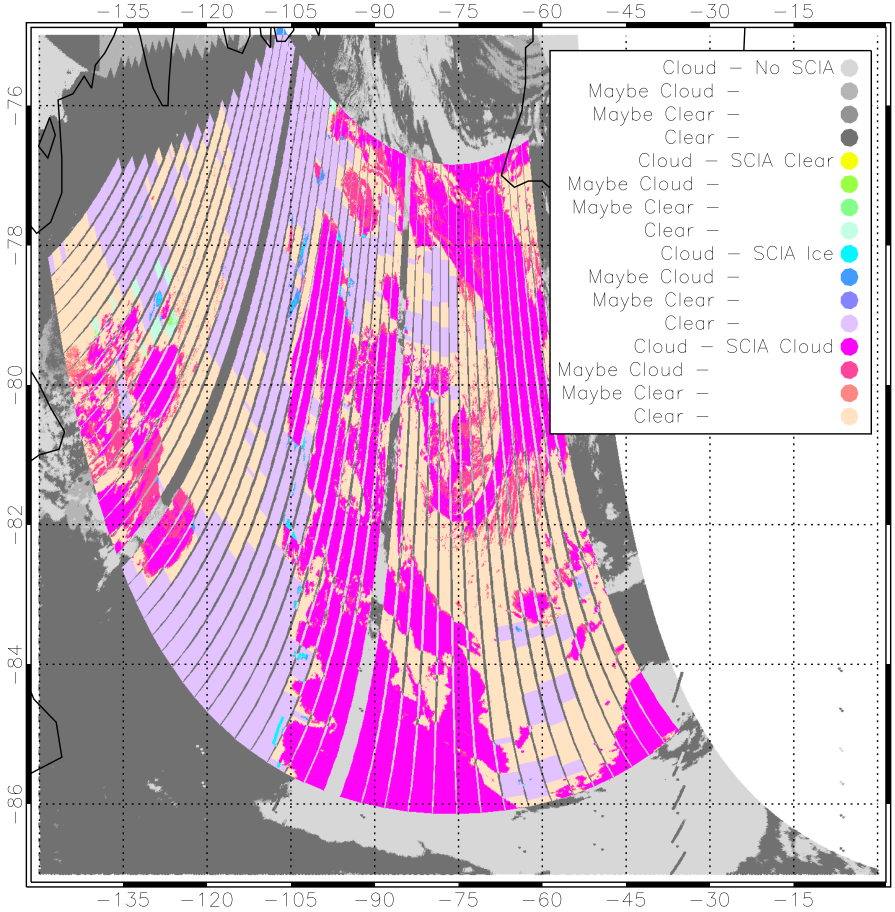

Fig. 10. Comparison between clouds and ice/snow observations as identified by SCIAMACHY (08:30–09:10 UT) SPICI and MODIS (08:50 UT) on 24 January 2003 over the South pole, colour-coded as indicated in the legend.

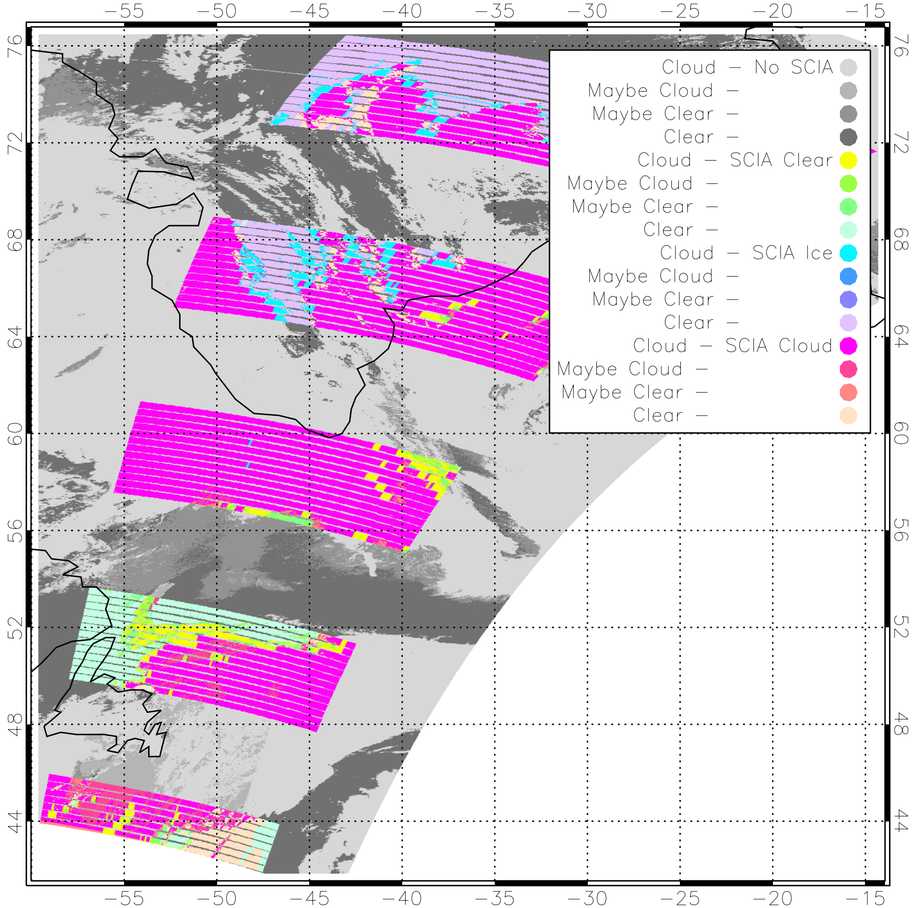

Fig. 11. Similar to Fig. 10, but now showing results over Greenland, the Atlantic Ocean and Eastern Canada. Comparison between SCIAMACHY (13:48–14:12 UT) SPICI and MODIS (14:40 UT) on 30 June 2002, colour-coded as indicated in the legend.

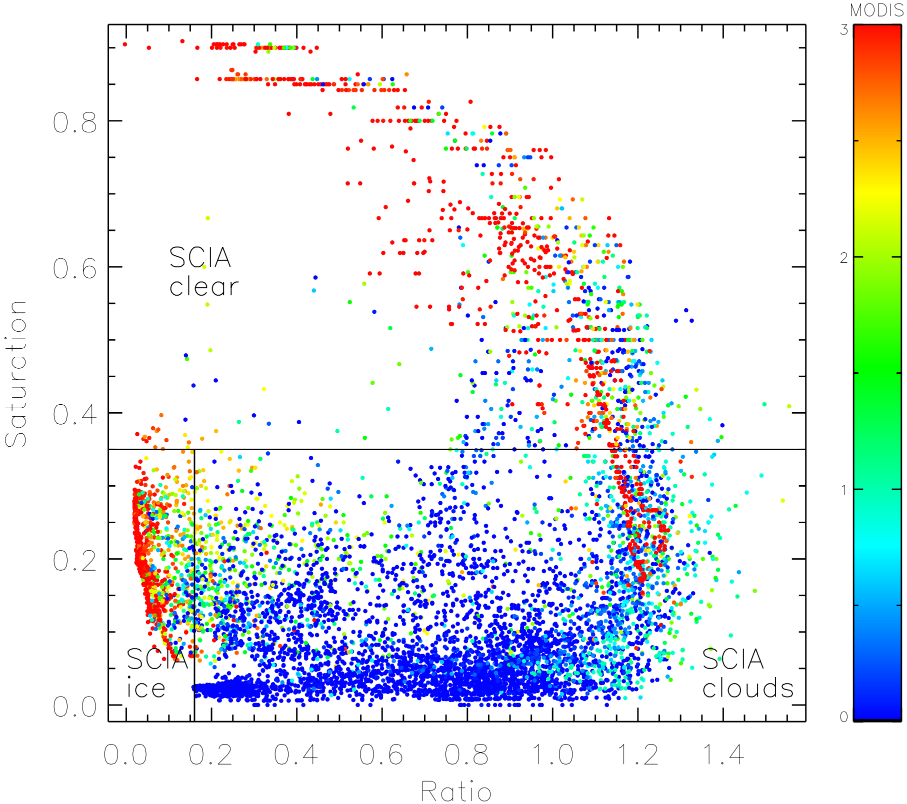

Fig. 12. Scatterplot showing for each SCIAMACHY PMD observation the ratio of $R_{PMD\ 5}/R_{PMD\ 4}$ versus the saturation-value with each observation colour-coded according to the average MODIS cloud value, ranging between confident clear (3) and confident cloudy (0). Data shown is for 30 June 2002. Also shown are the thresholds used in this paper for SPICI for different classifications: saturation≥0.35 is cloud-free, saturation<0.35 and ratio≥0.16 is clouded, and saturation<0.35 and ratio<0.16 is cloud-free ice/snow covered surfaces.

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