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# FRESCO+: an improved O<sub>2</sub> A-band cloud retrieval algorithm for tropospheric trace gas retrievals

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## Abstract

The FRESKO (Fast Retrieval Scheme for Clouds from the Oxygen A-band) algorithm has been used to retrieve cloud information from measurements of the O<sub>2</sub> A-band around 760 nm by GOME, SCIAMACHY and GOME-2. The cloud parameters retrieved by FRESKO are the effective cloud fraction and cloud pressure, which are used for cloud correction in the retrieval of trace gases like O<sub>3</sub> and NO<sub>2</sub>. To improve the cloud pressure retrieval for partly cloudy scenes, single Rayleigh scattering has been included in an improved version of the algorithm, called FRESKO+. We compared FRESKO+ and FRESKO effective cloud fractions and cloud pressures using simulated spectra and one month of GOME measured spectra. As expected, FRESKO+ gives more reliable cloud pressures over partly cloudy pixels. Simulations and comparisons with ground-based radar/lidar measurements of clouds shows that the FRESKO+ cloud pressure is about the optical midlevel of the cloud. Globally averaged, the FRESKO+ cloud pressure is about 50 hPa higher than the FRESKO cloud pressure, while the FRESKO+ effective cloud fraction is about 0.01 larger.

The effect of FRESKO+ cloud parameters on O<sub>3</sub> and NO<sub>2</sub> vertical column densities (VCD) is studied using SCIAMACHY data and ground-based DOAS measurements. We find that the FRESKO+ algorithm has a significant effect on tropospheric NO<sub>2</sub> retrievals but a minor effect on total O<sub>3</sub> retrievals. The retrieved SCIAMACHY tropospheric NO<sub>2</sub> VCDs using FRESKO+ cloud parameters (v1.1) are lower than the tropospheric NO<sub>2</sub> VCDs which used FRESKO cloud parameters (v1.04), in particular over heavily polluted areas with low clouds. The difference between SCIAMACHY tropospheric NO<sub>2</sub> VCDs v1.1 and ground-based MAXDOAS measurements performed in Cabauw, The Netherlands, during the DANDELIONS campaign is about  $-2.12 \times 10^{14}$  molec cm<sup>-2</sup>.

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## 1 Introduction

Clouds have significant effects on trace gas retrievals from satellite spectrometers operating in the UV/visible, such as GOME, SCIAMACHY, OMI and GOME-2. Clouds can shield trace gases from observation, but they can also enhance the sensitivity to trace gases above the clouds. Because of the relatively coarse spatial resolution of the above satellite instruments, only 5–15% of the pixels are cloud-free (Krijger et al., 2007). To correct for cloud effects on trace gas retrievals, the most relevant cloud parameters are the cloud fraction and height (Stammes et al., 2008). There are several cloud retrieval algorithms that have been developed for GOME and SCIAMACHY using the O<sub>2</sub> A-band (Koelemeijer et al., 2001; Kokhanovsky et al., 2006; van Diedenhoven et al., 2007) or using Polarisation Monitoring Devices (PMDs) (Grzegorski et al., 2006; Loyola, 2004). FRESKO (Koelemeijer et al., 2001) is a simple, fast and robust algorithm, which is also implemented in GOME-2 level 1 data processor (Munro and Eisinger, 2004).

In the FRESKO algorithm, the cloud pressure and the effective cloud fraction are retrieved from top-of-atmosphere (TOA) reflectances in three 1-nm wide wavelength windows at 758–759, 760–761, and 765–766 nm. The cloud is assumed to be a Lambertian surface with albedo 0.8, and only absorption due to O<sub>2</sub> above the cloud and the ground surface and reflections from the surface and cloud are taken into account. The FRESKO effective cloud fractions and cloud pressures have been validated globally and regionally, and the products have been used in trace gas retrievals (Koelemeijer et al., 2003; Tuinder et al., 2004; Grzegorski et al., 2006; Fournier et al., 2006).

The effective cloud fraction retrieved by FRESKO is the cloud fraction of a Lambertian cloud with albedo 0.8 yielding the same TOA radiance as the real cloud in the scene. Generally the effective cloud fraction is smaller than the geometric cloud fraction. The choice of Lambertian cloud albedo 0.8 and effective cloud fraction concept have recently been discussed by Stammes et al. (2008). The use of effective cloud fractions for the cloud correction in the O<sub>3</sub> and NO<sub>2</sub> retrievals has been investigated

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in several papers (Koelemeijer and Stammes, 1999; Wang et al., 2006; Stammes et al., 2008). The Lambertian cloud is a good approximation for cloud correction of total  $O_3$  column retrievals. For scenes with 50% cloud coverage the error in the total  $O_3$  column due to the Lambertian cloud assumption instead of a scattering cloud model is about 0.5% (Stammes et al., 2008). For tropospheric  $NO_2$  retrievals, the effective cloud fraction assumption leads to errors of about 10% (Wang et al., 2006). Here the cloud height is also important, because the large amount of tropospheric  $NO_2$  can be inside the clouds or below the clouds.

Recently, we have found that the FRESCO cloud pressures are often too low (cloud heights are too high) when the effective cloud fractions are less than 0.1. These are cases with a relatively large contribution from Rayleigh scattering, which is missing in the FRESCO algorithm. Apparently, the missing Rayleigh scattering is compensated by fitting a high cloud. Pixels with small cloud fractions are important for tropospheric trace gas retrievals. For example, in the operational tropospheric  $NO_2$  retrievals from the TEMIS project the effective cloud fractions are allowed to be less than 0.3 (Eskes and Boersma, 2003). Therefore, we improved the FRESCO algorithm by the addition of single Rayleigh scattering in the transmission and reflectance databases (forward calculations) and in the retrieval. This improved version is called FRESCO+.

The structure of the paper is as follows. In Sect. 2 we explain the principle of FRESCO+. The formulas of FRESCO+ are given in the Appendix. The FRESCO+ results and the comparisons with FRESCO are shown in Sect. 3 for simulations and real data. In Sect. 4 the effects of FRESCO+ cloud parameters on  $O_3$  and  $NO_2$  vertical column density (VCD) retrievals are discussed. The SCIAMACHY  $NO_2$  VCDs using FRESCO+ and FRESCO cloud corrections are compared with  $NO_2$  VCD from ground-based MAXDOAS measurements. Section 5 contains the conclusions.

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## 2 Principle of FRESCO+

The FRESCO+ algorithm retrieves the effective cloud fraction  $c_{\text{eff}}$  and cloud pressure  $P_c$  from the TOA reflectance at three 1-nm wide windows, namely 758–759, 760–761 and 765–766 nm. Each of the three windows contains 5 reflectance measurements (spectral data points). Due to the presence of clouds, the reflectance in the continuum window (758 nm) is larger than for a clear sky scene, whereas the depth of the strongest  $\text{O}_2$  absorption band at 760 nm and of the weaker  $\text{O}_2$  absorption band at 765 nm varies according to the height and the optical thickness of the cloud. Typical  $\text{O}_2$  A-band spectra of scenes with high and low clouds measured by GOME are shown in Fig. 1.

The atmospheric radiation model assumed in the FRESCO+ algorithm is shown in Fig. 2. The FRESCO+ algorithm fits a simulated reflectance spectrum to the measured reflectance spectrum in the three windows, to retrieve the effective cloud fraction and cloud pressure. The simulated reflectance ( $R_{\text{sim}}$ ) at TOA is written as the sum of the reflectances of the cloud-free and cloudy parts of the pixel:

$$R_{\text{sim}} = (1 - c)T_s A_s + (1 - c)R_s + cT_c A_c + cR_c. \quad (1)$$

Here  $R_c$ ,  $T_c$  and  $R_s$ ,  $T_s$  are the single Rayleigh scattering reflectance and transmittance of the cloudy and cloud-free part of the pixel, respectively.  $T_c$  and  $T_s$  contain  $\text{O}_2$  absorption and Rayleigh scattering extinction, and are pre-calculated as a function of the solar zenith angle (SZA), viewing zenith angle (VZA), wavelength, and altitude.  $A_c$  is the cloud albedo, which is assumed to be 0.8, and  $A_s$  is the surface albedo taken from a climatology (Koelemeijer et al., 2003; Fournier et al., 2006). The surface pressure is calculated from surface elevation. The  $\text{O}_2$  transmission is calculated using a line-by-line method for a 1-pm wavelength grid using the line parameters from HITRAN 2004 (Rothman et al., 2005) and then convolved using the instrument response function at the measurement wavelength grid. Rayleigh scattering is a small but significant contribution to  $R_{\text{sim}}$  in the case of an almost cloud-free pixel. Due to single Rayleigh scattering the reflectance at 760 nm is larger than if only surface or cloud reflection would take place, while at 758 nm the reflectance is a bit smaller than without single Rayleigh

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scattering. The single Rayleigh scattering reflectances are pre-calculated and stored as a look-up-table (LUT) which has the same format as the transmission database. The Rayleigh scattering formulae used in FRESKO+ are given in the Appendix, whereas the O<sub>2</sub> transmission formulae are given in detail by Wang and Stammes (2007).

### 3 Simulation, application and validation of FRESKO+

#### 3.1 FRESKO+ and FRESKO cloud retrievals from simulated spectra

To test the FRESKO+ algorithm on simulated spectra of cloudy scenes, O<sub>2</sub> A-band reflectance spectra were simulated with the DAK (Doubling-Adding KNMI) model (De Haan et al., 1987; Stammes et al., 1989; Stammes, 2001). This is line-by-line radiative transfer model in which multiple scattering is fully taken into account. The simulations are performed for a mid-latitude-summer atmosphere consisting of 32 plane-parallel homogeneous layers with Rayleigh scattering and oxygen absorption. In this atmosphere homogeneous scattering cloud layers are inserted, with varying optical thickness and height. The cloud particle scattering phase function is a Henyey-Greenstein function with asymmetry parameter 0.85. The cloud scenes are simulated for single-layer clouds and two-layer clouds. For the single-layer cloud case, the cloud is at 7–8 km, the cloud optical thickness is 7 and the geometric cloud fraction is 0.5 and 1. The two-layer cloud case includes two cloud scenes, namely optically thin and optically thick clouds. For the optically thin clouds, the first cloud layer is at 9–10 km with optical thickness 7, and the second cloud layer is at 1–2 km, with optical thickness 14. For the optically thick clouds, the cloud layers are at the same altitude as the optically thin cloud, but the cloud optical thickness is 14 for the first layer and 21 for the second layer. In all the simulations the surface albedo ( $A_s$ ) is 0.1, the surface height is 0 km and no aerosol is included. We also simulated O<sub>2</sub> A-band reflectance spectra for a cloud-free scene to obtain reflectance spectra for partly cloudy scenes, by using the independent-pixel-approximation. The O<sub>2</sub> absorption cross-sections were calculated

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line-by-line using HITRAN 2004 line parameters, which is the same in FRESCO+ and FRESCO. For reason of comparison, the FRESCO algorithm (without Rayleigh scattering) was included in the tests. The spectra were calculated from 755 to 772 nm at 0.01 nm wavelength grid, and then convoluted with the SCIAMACHY slit function. The geometries used in the retrievals are: nadir view, and solar zenith angles (SZA) 0, 30, 45, 60, 70, and 75 degrees.

First we consider cloud-free scenes. The effective cloud fractions retrieved by FRESCO and FRESCO+ from the simulated clear sky spectra were almost 0 (less than 0.01) as expected. However, the cloud height retrieved by FRESCO was close to 8 km. The reason for this large cloud height is that Rayleigh scattering by air molecules is included in the DAK model, but not in FRESCO. So the reflectances inside the O<sub>2</sub> A-band (at 760 and 765 nm) are larger than that of a purely absorbing O<sub>2</sub> atmosphere. Using the same clear sky DAK spectra as input, the cloud heights retrieved by FRESCO+ are about 0.5 km, which is much more reasonable than the FRESCO cloud height. So we may expect that FRESCO+ will give better cloud height results for partly cloudy scenes than FRESCO. The remaining 0.5 km error in cloud height for the cloud free scene is due to the contribution of multiple Rayleigh scattering in the simulated spectra, whereas FRESCO+ only includes single Rayleigh scattering.

Next we consider scenes with single-layer and two-layer scattering clouds. Figure 3 shows the results of the FRESCO and FRESCO+ retrieved cloud heights as a function of solar zenith angle. The FRESCO and FRESCO+ retrieved cloud heights are inside the cloud for a single-layer cloud (Fig. 3a). For a two-layer cloud, FRESCO and FRESCO+ cloud heights are between the two layers (Fig. 3b). The FRESCO and FRESCO+ cloud heights generally increase with increasing SZA, because at large SZA sunlight penetrates less deep into the cloud.

In the single-layer cloud case, the FRESCO cloud heights are almost the same for the fully ( $c=1$ ) and partly cloudy ( $c=0.5$ ) scenes. The FRESCO+ cloud height for the partly cloudy scene in Fig. 3a is somewhat lower than for the fully cloudy scene. At SZA=45°, the difference between FRESCO+ and FRESCO cloud heights is -0.2 km



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for  $c=1$  ( $c_{\text{eff}}=0.4$ ) and  $-0.12$  km for  $c=0.5$  ( $c_{\text{eff}}=0.2$ ) scenes. FRESCO+ cloud heights are lower than FRESCO cloud heights due to inclusion of single Rayleigh scattering, which makes the reflectance of FRESCO+ in the  $\text{O}_2$  absorption bands larger than that of FRESCO. To simulate the same reflectance as the scene, FRESCO+ needs more  $\text{O}_2$  absorption, therefore the FRESCO+ cloud height is lower than the FRESCO cloud height.

In the two-layer cloud case, the FRESCO and FRESCO+ cloud heights retrieved in the optically thick cloud case is higher than that retrieved in the optically thin cloud case (see Fig. 3b). In the  $\text{O}_2$  A-band photons can penetrate to some distance into the clouds. Therefore the retrieved cloud height depends on both the cloud height and the cloud optical thickness. For the two-layer cloud scenes, the FRESCO and FRESCO+ cloud heights are very close because the clouds are optically thicker than that in the single-layer cloud scene and therefore the effective cloud fractions are larger (between 0.8–1.0). We found that the difference between the FRESCO+ and FRESCO cloud heights decreases with effective cloud fraction.

### 3.2 FRESCO+ and FRESCO cloud retrievals from GOME data

The FRESCO+ and FRESCO cloud retrievals have been compared for one month of global GOME data of January 2000. The effective cloud fraction and cloud pressure frequency distributions are shown in Fig. 4. The FRESCO+ and FRESCO effective cloud fraction distributions almost coincide except that FRESCO+ has more clouds at effective cloud fractions 1 and 0. The mean effective cloud fractions differ about 0.014, with FRESCO+ being higher, because the inclusion of single Rayleigh scattering in FRESCO+ leads to a simulated continuum reflectance that is smaller than that simulated by FRESCO. If we would exclude cloud fractions larger than 0.95, where the chi-squares of the  $\text{O}_2$  A-band fit are the largest, the effective cloud fraction difference would only be 0.005. In the cloud pressure distributions only pixels with effective cloud fractions larger than 0.1 are selected, and pixels over snow/ice are excluded. The FRESCO+ cloud pressure distribution is shifted to higher pressures as compared to

FRESCO (about 50 hPa), but the shapes of the distributions are similar. The distributions of other months show the same behaviour.

To analyze the difference between the FRESCO+ and FRESCO cloud pressures, we show in Fig. 5 these cloud pressures as a function of effective cloud fraction. For effective cloud fractions below 0.01, the cloud pressures retrieved by FRESCO are often 130 hPa – the lower limit of the FRESCO retrieval – which is not a realistic value. Figure 5 shows that the average cloud pressure retrieved by FRESCO in the smallest effective cloud fraction bin [0, 0.05] is about 250 hPa. FRESCO+ retrieves more reasonable cloud pressures than FRESCO, even if the cloud fraction is less than 0.01. On average FRESCO+ cloud pressures are about 50 hPa higher than FRESCO cloud pressures. The difference in cloud pressure between FRESCO and FRESCO+ is larger for the less cloudy pixels than for the fully cloudy pixels, which is due to the larger relative amount of single Rayleigh scattering in the reflectance. The differences found between the FRESCO and FRESCO+ cloud pressures from GOME observations agree with the simulations.

The chi-squares of the FRESCO+ and FRESCO  $O_2$  A-band fits as a function of effective cloud fractions are shown in Fig. 6. The chi-squares of FRESCO+ are smaller than those of FRESCO, which indicates an improvement of the fit in FRESCO+, especially for effective cloud fractions smaller than 0.05. However, when the effective cloud fraction is 1 (i.e. a very bright scene) the chi-squares of FRESCO+ are larger than those of FRESCO. The reason is the following. In both retrieval algorithms the procedure for very bright scenes is: when the measured reflectance at 758 nm is larger than 0.8, the cloud albedo is set to the measured reflectance at 758 nm and the effective cloud fraction is retrieved. If the retrieved effective cloud fraction is larger than 1, it is set to 1 and the chi-square is calculated for  $c_{\text{eff}} = 1$  but not the retrieved value of  $c_{\text{eff}} > 1$ . In FRESCO+ the simulated transmission in the continuum ( $T_c$  in Eq. 1) is smaller than that in FRESCO due to Rayleigh scattering extinction, which is more important at large SZA and for very bright scenes. Therefore, the simulated reflectance by FRESCO+ is smaller than the measured reflectance, which is the reason for the larger chi-squares

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at  $c_{\text{eff}}=1$ .

### 3.3 Validation of FRESCO+ cloud heights with ground-based data

Cloud heights retrieved by FRESCO+ from one year of SCIAMACHY measurements in 2005 have been compared with collocated ARM (Atmospheric Radiation Measurement) active remote sensing cloud boundaries data at SGP (Southern Great Plains) in the USA (Clothiaux et al., 2000). The SCIAMACHY pixel size is  $30 \times 60 \text{ km}^2$ , which is not easy to compare with ground-based radar/lidar measurements. The criteria we used for spatial and temporal collocation were as follows: (1) the SCIAMACHY data were selected with pixel centers within 60 km of the SGP/ARM site; (2) the SGP/ARM data were selected within one hour of the SCIAMACHY overpass time (10:00 local solar time). The ARM cloud profiles are measured every 10 s with up to 10 cloud layers per measurement. Most measurements have up to 3 cloud layers. The maximum number of collocated cloud data points in one hour is thus 3600. From this data set we calculated the ARM cloud layer height distribution, using the cloud layer heights and their frequency of occurrence. The ARM cloud layer height distributions and the collocated SCIAMACHY FRESCO+ cloud heights are shown in Fig. 7a. In this plot we have further limited the FRESCO+ effective cloud fractions to values larger than 0.2 and the time periods of ARM cloud cover to periods longer than 30 min, which corresponds to geometric cloud fractions larger than 0.5. As shown in Fig. 7a, the FRESCO+ cloud height is close to the middle of the ARM cloud profiles. This agrees with the results of FRESCO+ for simulated spectra (Sect. 3.1). As shown in Fig. 7b, the FRESCO+ cloud heights have an excellent correlation with the averaged ARM cloud profiles, with a correlation coefficient of 0.94.

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## 4 Impact of FRESKO+ cloud parameters on O<sub>3</sub> and NO<sub>2</sub> retrievals

The FRESKO+ effective cloud fraction and cloud pressure retrievals are being used in O<sub>3</sub> and NO<sub>2</sub> total and tropospheric vertical column density (VCD) retrievals performed within the DUE TEMIS project (see <http://www.temis.nl>). To investigate whether the improvement of the FRESKO+ cloud algorithm also leads to improved trace gas retrievals, we performed the following comparisons: (1) SCIAMACHY total O<sub>3</sub> from the TOSOMI product version 0.4, which uses FRESKO, was compared to version 0.42, which uses FRESKO+; (2) SCIAMACHY total and tropospheric NO<sub>2</sub> column version 1.04, which uses FRESKO, was compared to version 1.1, which uses FRESKO+; (3) a comparison of satellite retrievals using FRESKO+ with ground-based measurements of tropospheric NO<sub>2</sub> was performed.

### 4.1 Impact of FRESKO+ cloud parameters on total O<sub>3</sub> retrievals

For a partly cloudy pixel the total O<sub>3</sub> vertical column density,  $N_t$ , is given by (Van Roozendael et al., 2006):

$$N_t = \frac{N_s + wM_{\text{cloudy}}N_g}{M}, \quad (2)$$

where  $M$  is the total air mass factor (AMF) of the partly cloudy pixel,  $N_s$  is the measured slant column density,  $M_{\text{cloudy}}$  is the AMF for a fully cloudy scene, and  $N_g$  is the vertical column density below the cloud, which is also called the “ghost column”.  $N_g$  is computed by integrating the ozone profile from the surface to the cloud pressure level.

$M$  is given by the radiance-weighted sum of the AMFs of the clear and cloudy parts of the pixel:

$$M = wM_{\text{cloudy}} + (1 - w)M_{\text{clear}}, \quad (3)$$

where  $w$  is the weighting factor, and  $M_{\text{clear}}$  is the AMF for a clear scene. The weighting factor  $w$  is the fraction of the photons that originates from the cloudy part of the pixel,

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and can thus be written as (Martin et al., 2002):

$$w = \frac{cR_{\text{cloudy}}(P_c)}{R}. \quad (4)$$

where  $c$  is the (effective) cloud fraction,  $R_{\text{cloudy}}(P_c)$  is the average reflectance over the fit window for a scene that is fully covered with a cloud located at pressure  $P_c$ , and  $R$  is the measured reflectance for the pixel. It is important to mention that in the  $\text{O}_3$  and  $\text{NO}_2$  retrieval algorithms of TEMIS, clouds are also assumed to be Lambertian reflectors with albedo of 0.8, like in the FRESCO(+) algorithm.

The correlation between the total  $\text{O}_3$  vertical column densities retrieved using FRESCO and FRESCO+ cloud products for one day of global SCIAMACHY data is shown in Fig. 8. For this day (10 January 2007) the global averaged difference in  $\text{O}_3$  total column is only 0.2 DU. Differences for other days are similar. Apparently, the improvement in the FRESCO+ cloud product has a small effect on total  $\text{O}_3$  column retrievals. Since the effective cloud fractions from FRESCO and FRESCO+ are very similar, the difference in the  $\text{O}_3$  vertical column is mainly due to the cloud pressure difference. The cloud pressure affects the cloud air mass factor  $M_{\text{cloudy}}$  and the ghost column  $N_g$  in Eq. (2). The differences between FRESCO+ and FRESCO cloud heights cause only small differences in the total  $\text{O}_3$  AMFs and in the ghost columns, because of the relatively low tropospheric  $\text{O}_3$  amount. Because  $\text{O}_3$  is mainly in stratosphere, the FRESCO+ cloud pressure improvement only weakly affects total  $\text{O}_3$ .

#### 4.2 Impact of FRESCO+ cloud parameters on tropospheric $\text{NO}_2$ retrievals

The cloud correction approaches for the total and tropospheric  $\text{NO}_2$  vertical column density retrievals are similar as for the total  $\text{O}_3$  retrievals, which are given by Eqs. (2–4). However, the  $\text{NO}_2$  air mass factor depends on the  $\text{NO}_2$  profile, because a large fraction of  $\text{NO}_2$  resides in the troposphere where Rayleigh scattering and scattering by aerosols and clouds is important. Therefore, the tropospheric  $\text{NO}_2$  air mass factor  $M_{tr}$  is obtained by multiplying the elements of the troposphere-only a-priori  $\text{NO}_2$  profile  $x_a$

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with the elements of the altitude dependent air mass factor  $m_l$  as follows (Eskes and Boersma, 2003):

$$M_{tr} = \frac{\sum_l m_l(b) \cdot x_{a,l}}{\sum_l x_{a,l}}, \quad (5)$$

where the elements of the altitude dependent air mass factor depend on the set of model parameters  $b$  including cloud fraction, cloud height and surface albedo. The tropospheric NO<sub>2</sub> VCD is given by:

$$N_{tr} = \frac{N_s - N_{s,st}}{M_{tr}(x_a, b)}. \quad (6)$$

In the TEMIS processing the a priori NO<sub>2</sub> profile is derived from a chemistry-transport model.

As shown in Fig. 9 both the total NO<sub>2</sub> columns and the tropospheric NO<sub>2</sub> columns retrieved from SCIAMACHY using the FRESKO+ and FRESKO cloud products correlate well. Note that the tropospheric NO<sub>2</sub> VCDs are only reported for pixels with effective cloud fractions less than 0.3. For most of the pixels the NO<sub>2</sub> columns using FRESKO+ and using FRESKO are almost the same, because there is no tropospheric NO<sub>2</sub> or no clouds. Therefore, the globally averaged NO<sub>2</sub> columns are similar. However the largest differences occur for the larger tropospheric NO<sub>2</sub> columns.

The effect of cloud pressure differences on tropospheric NO<sub>2</sub> AMFs and NO<sub>2</sub> ghost columns is shown in Fig. 10. The difference between the ghost columns using FRESKO+ and using FRESKO increases for cloud pressures larger than about 700 hPa; using FRESKO+, the NO<sub>2</sub> ghost columns are clearly smaller than using FRESKO. The difference in tropospheric NO<sub>2</sub> AMFs also increases with cloud pressure; the tropospheric NO<sub>2</sub> AMFs are larger using FRESKO+ than using FRESKO. According to Eq. (2), the increase of AMF and decrease of ghost column both yield a lower tropospheric NO<sub>2</sub> VCD, especially for highly polluted scenes.

We can understand the results of Figs. 9 and 10 as follows. High NO<sub>2</sub> concentrations occur mainly in the boundary layer, roughly below 2 km. For polluted pixels with low

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clouds even small cloud height differences can cause large differences in NO<sub>2</sub> ghost columns. For polluted pixels with high clouds, when FRESCO and FRESCO+ cloud heights are both above the NO<sub>2</sub> layer, differences in ghost column are small, so differences in NO<sub>2</sub> VCD are also small. The global cloud height frequency distribution from SCIAMACHY shows that the cloud pressure peaks at about 800 hPa. So, globally there are more low clouds than high clouds, and the impact of the FRESCO+ cloud height on tropospheric NO<sub>2</sub> retrievals is significant.

### 4.3 Comparison with ground-based measurements of tropospheric NO<sub>2</sub>

To demonstrate that the FRESCO+ cloud parameters are an improvement for tropospheric NO<sub>2</sub> retrievals from satellite, we compared tropospheric NO<sub>2</sub> columns from SCIAMACHY (v1.1 and v1.04) with ground-based measurements of tropospheric NO<sub>2</sub> columns measured with Multi-AXis DOAS (MAXDOAS) instruments.

The ground-based data include results from the three MAXDOAS instruments (BIRA/IASB, Bremen and Heidelberg) operated during the DANDELIONS (Dutch Aerosol and Nitrogen Dioxide Experiments for vaLidation of OMI and SCIAMACHY) campaigns held at Cabauw (52° N, 5° E) in May–July 2005 and September 2006. The tropospheric NO<sub>2</sub> VCDs are retrieved using a geometrical approximation valid for boundary-layer NO<sub>2</sub>, as described in [Brinkma et al. \(2008\)](#) and subsequently interpolated at the time of the SCIAMACHY overpasses. SCIAMACHY data are selected within a 200 km radius around Cabauw, leading to 72 points of comparison with ground-based measurements. As can be seen in Fig. 11, the distribution of the differences between SCIAMACHY NO<sub>2</sub> VCD retrievals using FRESCO (v1.04) and ground-based measurements is asymmetric, showing more positive deviations. In contrast, the SCIAMACHY NO<sub>2</sub> product using FRESCO+ (v1.1) is closer to the MAXDOAS results, and the differences show a more symmetric distribution. The statistics of the tropospheric NO<sub>2</sub> column differences (SCIAMACHY minus MAXDOAS) are given in Table 1. One can see that the mean and median differences are closer to zero when the FRESCO+ cloud product is used in the SCIAMACHY retrievals. The overall

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mean difference between the SCIAMACHY NO<sub>2</sub> VCD (v1.1) and ground-based MAX-DOAS NO<sub>2</sub> VCD is  $-2.12 \times 10^{14}$  molec cm<sup>-2</sup> with a corresponding standard deviation of  $1.02 \times 10^{16}$  molec cm<sup>-2</sup>.

## 5 Conclusions

5 An improved version of the FRESKO cloud algorithm, FRESKO+, has been presented. This version includes Rayleigh scattering which is important for less cloudy scenes. The FRESKO+ algorithm has been applied to simulated O<sub>2</sub> A-band spectra and to GOME and SCIAMACHY satellite measurements of the O<sub>2</sub> A-band spectra. It appears that FRESKO+ yields more accurate cloud heights in less cloudy scenes. The FRESKO+ cloud pressure is about 50 hPa higher in the monthly global average than the FRESKO cloud pressure due to the addition of single Rayleigh scattering. The effective cloud fractions from FRESKO and FRESKO+ differ only by about 0.01 in the monthly global average.

15 For the first time FRESKO+ cloud height retrievals have been compared to ground-based Lidar/Radar cloud height measurements and a good correlation was found. From these measurements and simulations we found that the FRESKO+ and FRESKO cloud heights are closer to the middle of the clouds than to the top of the clouds in the scene. This is important to realize when applying FRESKO+ cloud heights in trace gas corrections and in cloud pressure comparisons.

20 As a first application we compared the total O<sub>3</sub> columns retrieved from SCIAMACHY using FRESKO+ and FRESKO data in the cloud correction. It appears that the retrieved total O<sub>3</sub> columns are very similar using FRESKO+ or FRESKO cloud products (0.2 DU difference), because the cloud height improvement of FRESKO+ weakly affects stratospheric trace gas retrievals. As a second application, we applied FRESKO+ to NO<sub>2</sub> retrievals from SCIAMACHY. Here we found a large impact of the FRESKO+ improvement on tropospheric NO<sub>2</sub> retrievals. The cloud height improvement influences the ghost column of tropospheric NO<sub>2</sub> directly, especially for highly polluted cases. The

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cloud height improvement also affects the tropospheric NO<sub>2</sub> air mass factors, because they depend on the NO<sub>2</sub> profile and the profile of the scatterers.

Finally, we compared SCIAMACHY tropospheric NO<sub>2</sub> column retrievals using FRESKO+ and FRESKO to ground-based MAX-DOAS measurements performed during the DANDELIONS campaign in Cabauw. We found that the SCIAMACHY tropospheric NO<sub>2</sub> columns using the FRESKO+ cloud product in the cloud correction, agree better with the ground-based data than using the FRESKO cloud product. We conclude that FRESKO+ is an improvement of FRESKO algorithm, not only in the physics of the retrieval algorithm, but also in the application of the cloud product for tropospheric trace gas retrievals.

## Appendix A

In this appendix, the formulae for the FRESKO+ simulations of the O<sub>2</sub> A-band reflectance are given, which is an update of the FRESKO formulae given by Koelemeijer et al. (2001).

### A1 Rayleigh scattering cross section and phase function

The Rayleigh scattering cross section,  $\sigma_R$ , is calculated with the formula (Bates, 1984):

$$\sigma_R = (32\pi^3/3N^2\lambda^4)(n_{\text{air}} - 1)^2 F'_k(\text{air}), \quad (\text{A1})$$

where  $(n_{\text{air}} - 1)$  is the refractive index, and  $F'_k(\text{air})$  is the effective King correction factor. The effective King correction factors and refractive index for air are chosen at 750 and 800 nm from Table 1 in Bates (1984), and are linearly interpolated between 750 and 800 nm.

The Rayleigh scattering phase function (without polarization) is given by

$$F_R(\Theta) = \frac{3(1 - \rho_n)}{4(1 + \rho_n/2)} \left( \cos^2 \Theta + \frac{1 + \rho_n}{1 - \rho_n} \right), \quad (\text{A2})$$

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with

$$\cos \Theta = -\cos \theta \cos \theta_0 + \sin \theta \sin \theta_0 \cos(\varphi - \varphi_0), \quad (\text{A3})$$

where  $\Theta$  is the scattering angle,  $\theta$  is the viewing zenith angle,  $\theta_0$  is the solar zenith angle,  $\varphi$  is the viewing azimuth angle, and  $\varphi_0$  is the solar azimuth angle.  $\rho_n$  is the depolarization factor; at 750 nm  $\rho_n=0.02786$ .

## A2 Atmospheric optical thickness and transmission

The atmospheric optical thickness and transmission is determined by oxygen absorption and Rayleigh scattering. The absorption is calculated from the number density of  $\text{O}_2$  molecules ( $n_{\text{O}_2}$ ) and the  $\text{O}_2$  absorption cross section,  $\sigma_{\text{O}_2}(\lambda)$ , along the light path.  $\sigma_{\text{O}_2}(\lambda)$  depends on the atmospheric temperature and pressure but this is omitted from the notation. The absorption coefficient (in 1/m) is given by:

$$k_{\text{abs}}(\lambda, z) = n_{\text{O}_2}(z)\sigma_{\text{O}_2}(\lambda, z). \quad (\text{A4})$$

The Rayleigh scattering coefficient is calculated from the air density ( $n_{\text{air}}$ ) and the Rayleigh scattering cross section ( $\sigma_R(\lambda, z)$ ),

$$k_{\text{sca}}(\lambda, z) = n_{\text{air}}(z)\sigma_R(\lambda, z). \quad (\text{A5})$$

The total atmospheric optical thickness,  $\tau$ , is the sum of the absorption and scattering contributions:

$$\tau(\lambda, z_r, \theta, \theta_0) = \int_{z_r}^{\infty} (k_{\text{abs}}(\lambda, z) + k_{\text{sca}}(\lambda, z))(S_{\text{sp}}(\theta_0, z - z_r) + (S_{\text{sp}}(\theta, z - z_r))) dz. \quad (\text{A6})$$

Here  $S_{\text{sp}}(\theta_0, z - z_r)$  and  $S_{\text{sp}}(\theta, z - z_r)$  are the spherical light path factors from the sun to the reflector and from the reflector to the satellite (Koelemeijer et al., 2001).  $z$  is height in the atmosphere,  $z_r$  is the altitude of the reflector (surface or clouds).  $\theta_0, \theta$  are the solar zenith angle and viewing zenith angle at surface height.

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The transmittance from TOA to  $z_r$ , assuming a reflector at altitude  $z_r$ , and back from  $z_r$  to TOA is now given by:

$$T(\lambda, z_r, \theta, \theta_0) = e^{-\tau(\lambda, z_r, \theta, \theta_0)}. \quad (\text{A7})$$

The transmittances  $T$  are stored in a look-up-table (LUT).

### 5 A3 Single Rayleigh scattering reflectance

The single Rayleigh scattering reflectance,  $R_R$ , is calculated with the formula (see Fig. 2) (Hovenier et al., 2005),

$$R_R(\lambda, z_r, \mu, \mu_0, \varphi - \varphi_0) = \frac{F_R(\mu, \mu_0, \varphi - \varphi_0)}{4\mu_0\mu} \int_{z_r}^{\infty} k_{\text{sca}}(\lambda, z) T(\lambda, z, \mu, \mu_0) dz, \quad (\text{A8})$$

10 where  $T(\lambda, z, \mu, \mu_0)$  is the transmittance,  $\mu_0 = \cos \theta_0$ ,  $\mu = \cos \theta$ . We have to modify Eq. (A8) for the spherical light path:

$$R_R(\lambda, z_r, \theta, \theta_0, \varphi - \varphi_0) = \frac{F_R(\theta, \theta_0, \varphi - \varphi_0)}{4 \cos \theta_0} \int_{z_r}^{\infty} k_{\text{sca}}(\lambda, z) T(\lambda, z, \theta, \theta_0) S_{\text{sp}}(\theta, z) dz. \quad (\text{A9})$$

15 Since we can neglect the wavelength dependence of the Rayleigh scattering phase function  $F_R$  in the O<sub>2</sub> A-band, we can multiply by the phase function in Eq. (A9) after the convolution with the slit function. Therefore, the reflectances are stored in a look-up-table (LUT) as:

$$R_1(\lambda, z_r, \theta, \theta_0) = \int_{z_r}^{\infty} k_{\text{sca}}(\lambda, z) T(\lambda, z, \theta, \theta_0) S_{\text{sp}}(\theta, z) dz. \quad (\text{A10})$$

20 Another advantage of using Eq. (A10) is that the azimuth is not needed in the reflectance LUT, which now has the same parameters as the FRESCO+ transmittance LUT. The factor  $F_R(\theta, \theta_0, \varphi - \varphi_0)/(4 \cos \theta_0)$  is calculated in the FRESCO+ retrieval program according to the measurement geometry. In the main text,  $R_s$  and  $R_c$  are  $R_R$  for clear sky and cloudy cases, respectively.  $R_c = R_R(\lambda, z_c, \theta, \theta_0, \varphi - \varphi_0)$ ,  $R_s = R_R(\lambda, z_s, \theta, \theta_0, \varphi - \varphi_0)$ , where  $z_c$  is the cloud height, and  $z_s$  is the surface height.

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*Acknowledgements.* Funding was provided by the Netherlands Institute for Space Research (SRON) through the FRESCO+ project (EO-067). SCIAMACHY validation activities at BIRA-IASB are funded by the PRODEX CINAMON project. The MAXDOAS measurements during the DANDELIONS campaign were supported by the EU FP6, through the ACCENT NoE. ARM data is made available through the US Department of Energy as part of the Atmospheric Radiation Measurement Program.

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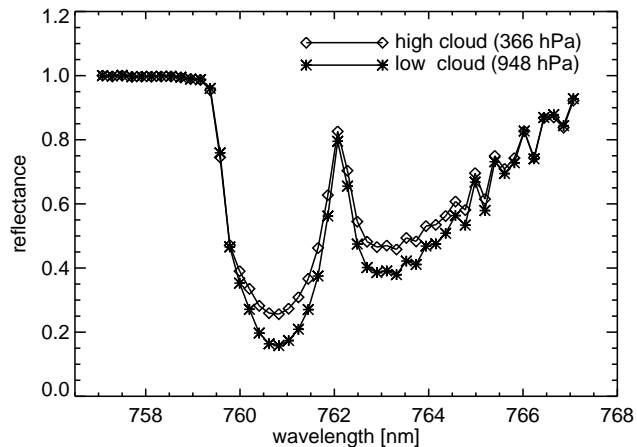
**Table 1.** Statistics for tropospheric NO<sub>2</sub> column differences (in units of  $1.0 \times 10^{15}$  molec cm<sup>-2</sup>) between SCIAMACHY and MAXDOAS measurements, for different effective cloud fraction ranges.

| $c_{\text{eff}}$ range | SCIA FRESCO – MAXDOAS<br>( $1.0 \times 10^{15}$ molec cm <sup>-2</sup> ) |        |        | SCIA FRESCO+ – MAXDOAS<br>( $1.0 \times 10^{15}$ molec cm <sup>-2</sup> ) |        |        |
|------------------------|--|--------|--------|---|--------|--------|
|                        | Mean   | Median | Stddev | Mean  | Median | Stddev |
| $\leq 0.5$             | 2.7  | 1.9    | 10.7   | -0.91   | 0.34   | 8.9    |
| $\leq 1.0$             | 2.8  | 1.9    | 11.9   | -0.21   | 0.92   | 10.2   |

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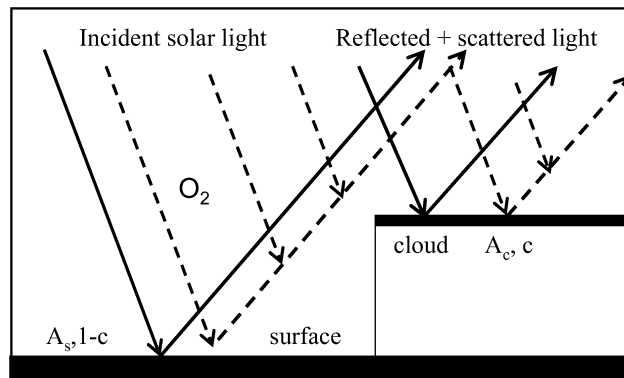
**Fig. 1.** Typical O<sub>2</sub> A-band spectra measured by GOME. The spectra are normalized at 758 nm to show the relative depth of the band for clouds at different heights.

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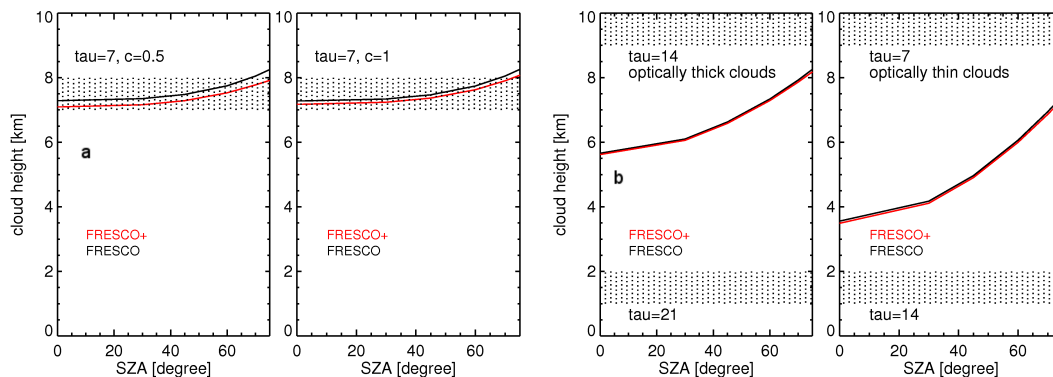


**Fig. 2.** Atmospheric radiation model used in FRESCO+. The cloud and surface are both assumed to be Lambertian reflectors. Three light paths are considered: (1) from sun to surface to satellite, (2) from sun to cloud to satellite, (3) from sun to atmosphere to satellite according to single Rayleigh scattering. (1)+(2): solid lines, (3): dashed lines. Along all three paths  $O_2$  absorption and Rayleigh scattering extinction are included in the forward model simulation.

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**Fig. 3.** FRESKO+ and FRESKO retrieved cloud heights using simulated spectra from a line-by-line multiple scattering model. Cases: **(a)** single-layer clouds, optical thickness  $\tau=7$ , cloud height at 7–8 km, and geometric cloud fraction  $c=0.5$  and 1. **(b)** two-layer clouds; cloud layer 1 at 9–10 km, cloud layer 2 at 1–2 km. Optically thick cloud:  $\tau_1=14$ ,  $\tau_2=21$ . Optically thin cloud:  $\tau_1=7$ ,  $\tau_2=14$ , geometric cloud fraction  $c=1$ .

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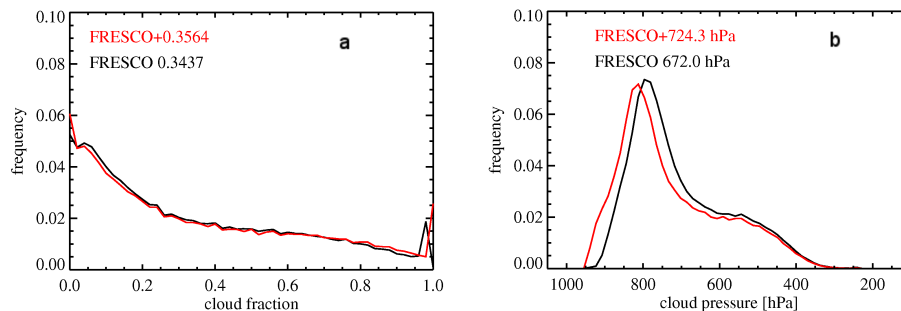
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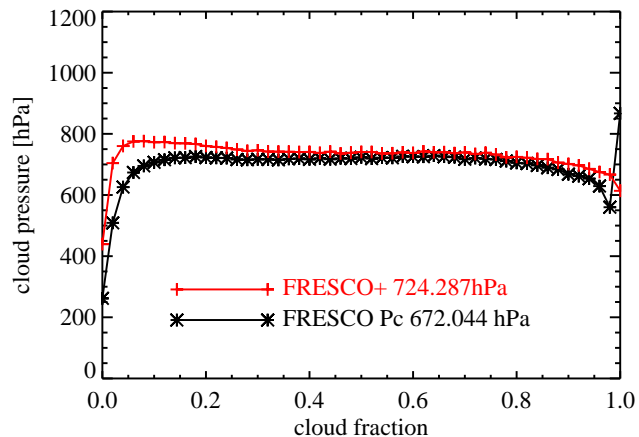


**Fig. 4.** (a) Frequency distributions of FRESKO+ and FRESKO effective cloud fractions for one month of global GOME data in January 2000; (b) same but for cloud pressures. The distributions are normalized to 1. The average values are given in the legends. The snow/ice pixels are not included in the distributions.

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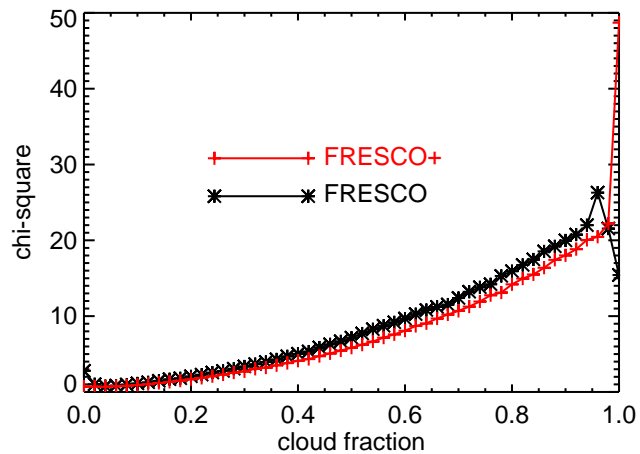


**Fig. 5.** Cloud pressure from FRESCO+ and FRESCO as a function of effective cloud fraction for the same data as in Fig. 4.

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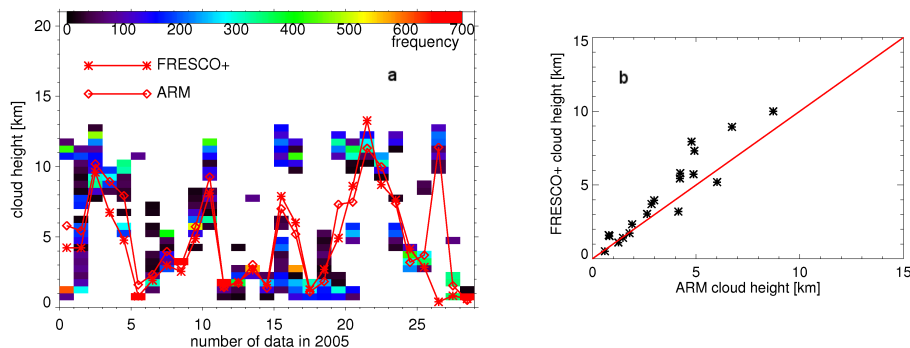


**Fig. 6.** Chi-square (in arbitrary units) of the O<sub>2</sub> A-band fits from FRESCO+ and FRESCO as a function of effective cloud fraction for the same data as in Fig. 4.

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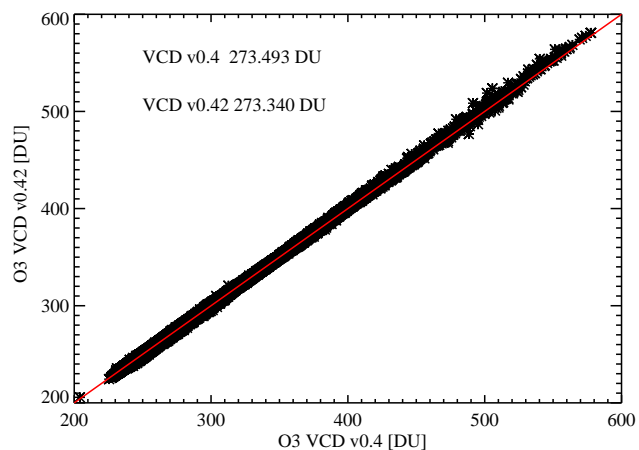


**Fig. 7.** (a) Comparison between collocated SCIAMACHY FRESCO+ cloud heights and ground-based radar/lidar cloud profiles, for 29 days in 2005 on which SCIAMACHY overpasses of the SGP/ARM site occurred. The color indicates the occurrence of clouds as detected by the radar/lidar. (b) Correlation of FRESCO+ cloud height and the average cloud height from the radar/lidar profiles for the same data as in (a), with correlation coefficient of 0.94. Only effective cloud fractions larger than 0.2 are used.

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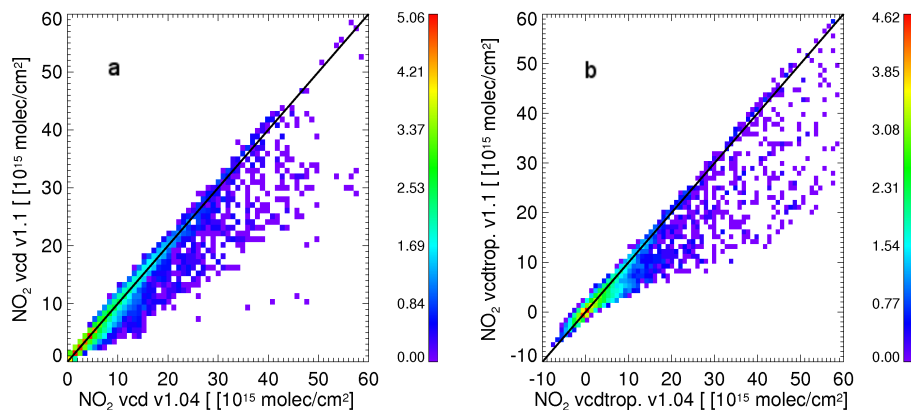


**Fig. 8.** Correlation of the  $O_3$  vertical column densities for one day of global SCIAMACHY data on 10 January 2007. The  $O_3$  column v0.4 uses FRESCO and the  $O_3$  column v0.42 uses FRESCO+.

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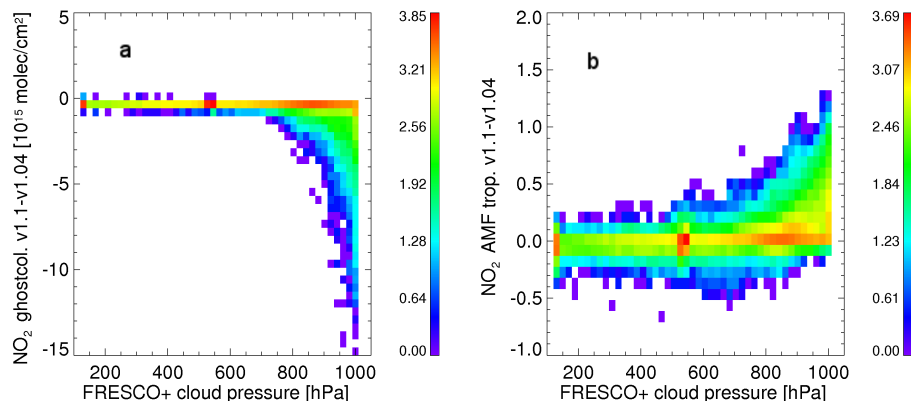
**Fig. 9.** (a) Correlation of total NO<sub>2</sub> columns using FRESCO+ (v1.1) and using FRESCO (v1.04) for six days of global SCIAMACHY data on 5–10 January 2007. The color scale indicates the density of data points in a logarithm sense. (b) Correlation of the tropospheric NO<sub>2</sub> columns for the same SCIAMACHY measurements. The black solid line gives the 1:1 relation between the datasets.

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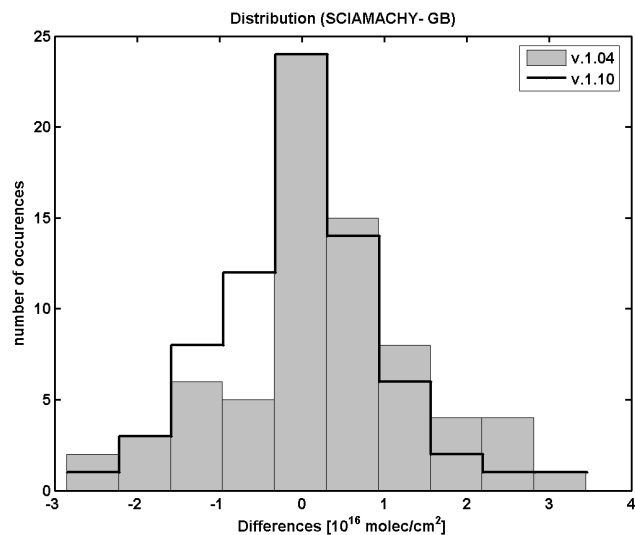


**Fig. 10.** (a) Difference in  $\text{NO}_2$  ghost columns between using FRESCO+ clouds (v1.1) and FRESCO clouds (v1.04), as a function of FRESCO+ cloud pressure. (b) Similar as (a) but for the difference in tropospheric  $\text{NO}_2$  air mass factors. The same SCIAMACHY data as in Fig. 9 were used. The color scale indicates the density of data points in a logarithmic sense.

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**Fig. 11.** The distribution of differences between tropospheric NO<sub>2</sub> columns from SCIAMACHY and ground-based MAXDOAS measurements. SCIAMACHY v1.04 uses FRESCO, whereas v1.1 uses FRESCO+.

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