Fiducial Reference Measurements for Ground-Based DOAS Air-Quality Observations

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Technical note (TN) on existing cloud classification algorithms

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Content

Acronyms and abbreviations

Acronyms and abbreviated terms that are specific for this document can be found below.

AOD	Aerosol Optical Density
CI	Color Index
DOAS	Differential Optical Absorption Spectroscopy
DSCD	Differential Slant Column Density
FoV	Field of View
FRM_4DOAS	Fiducial Reference Measurements for Ground-Based DOAS Air-Quality Observations
MAX-DOAS	Multi AXis Differential Optical Absorption Spectroscopy
R	Radiance
RTM	Radiative transfer model
SCD	Slant Column Density
SZA	Solar zenith angle
TIR	Thermal Infrared
TN	Technical Note
WP	Work Package

1 Introduction

MAX-DOAS measurements of scattered light under different elevation angles provide information on the vertical distribution of aerosols and atmospheric trace gases. With profile inversion algorithms, the MAX-DOAS measurements can be inverted to vertical profiles. This step, however, is based on RTM simulations which are usually made for cloud free conditions only.

As clouds massively affect the atmospheric light paths, MAX-DOAS measurements under cloudy conditions can generally not be used for profile retrievals (see table 1). Thus, reliable cloud information is required in order to flag cloudy MAX-DOAS measurements as dubious or invalid.

Table 1: Filter scheme of aerosol and trace gas results derived from MAX-DOAS observations. Filled circles: use of measurement is recommended; Open circles: use of measurement is not recommended. Table taken from Wang et al., 2017.

	AOD	Aerosol extinction near surface	Profile of aerosol extinction	VCD	VMR near surface	Profile of VMRs
Low aerosol	●	●	●	●	●	●
High aerosol	●	●	●	●	●	●
Cloud holes	○	●	○	●	●	●
Broken clouds	○	●	○	●	●	●
Continuous clouds	○	●	○	●	●	●
Fog	○	○	○	○	○	○
Thick clouds	○	○	○	○	○	○

Beyond simple flagging, a cloud classification (information on cloud type or cloud characteristics would allow to investigate effects of different cloud types separately and to elaborate which conditions are particularly crucial for MAX-DOAS profile measurements, while others (e.g. a stratiform cloud layer at high altitude) might be tolerated.

Cloud information might be gained from cameras mounted on the telescope, or an "all-sky" camera. However, not every MAX-DOAS instrument is equipped with such cameras. Thus, it is of particular importance for the processing of MAX-DOAS measurements to infer how far cloud information can be derived from the MAX-DOAS measurements themselves.

Here we provide a short review on existing methodologies and algorithms that derive cloud information from MAX-DOAS measurements.

2 Cloud effects

Clouds generally have a strong impact on the radiative transfer in the atmosphere. Thus, several quantities measured by the MAX-DOAS instruments are affected by clouds, and thus in turn can be used for deriving cloud information.

The main effects are:

Clouds are bright:	Clouds typically increase the radiance (R). However, e.g. in case of thick thunderstorm clouds, they might as well decrease R. Thus, R alone cannot be used in order to identify clouds.
Clouds are white:	The clear sky has a strong wavelength dependency for scattering probability (Rayleigh scattering), while scattering on cloud particles reveals only a weak wavelength dependency. Thus, clouds look white. This effect on the broadband wavelength dependency of the radiance can be quantified by a color index (CI), i.e. the ratio of radiances at 2 different wavelengths. It has, however, to be noted that only in zenith view, clouds lead in general to a whitening of the sky. In non-zenith viewing directions, depending on the viewing geometry, the cloudy and clear sky can in principle have the same color.
Clouds alter the light path:	As clouds alter atmospheric light paths, they directly affect the measured spectral signatures of "light path proxies" like the O_4 SCD; also the strength of the "Ring effect" is affected by clouds. However, as for R, the cloud might increase or decrease O_4 and Ring, depending on viewing geometry, sun position, and cloud height. Thus, the interpretation is more complex.

In addition, cloud conditions within the FoV of a MAX-DOAS telescope usually vary on short time scales (except for stratiform cloud cover). Thus, rapid changes of any of the quantities listed above indicate the appearance or disappearance of clouds or the change of cloud properties.

3 Existing studies

Cloud identification/classification algorithms for MAX-DOAS measurements have been presented in the following studies:

3.1 Takashima et al., 2009

Takashima et al., 2009, use a simple criterion to screen cloudy scenes based on a CI, using the wavelengths 500 nm and 380 nm. A simple cloud flag is defined by a CI value above 1.5, whereby the SZA dependence of the CI for cloud free sky is ignored.

In addition, Takashima et al., 2009, calculate a cloud-base height based on relative humidity derived from the H_2O profiles retrieved with MAX-DOAS.

3.2 Gielen et al., 2014

Gielen et al., 2014, present a "simple and versatile cloud-screening method for MAX-DOAS retrievals". Three different flags are derived:

- a sky condition flag, derived from the CI, which classifies a 90° measurement as either "good", "mediocre", or "bad" (Fig. 1).
- a broken cloud flag, derived from rapid changes of the CI.
- a multiple scattering flag, derived from rapid changes of the O_4 DSCD (30°-90°), which is needed in order to identify clouds in presence of high aerosol load.

Generally, these flags can all identify clouded scenes, as demonstrated by comparisons with TIR cloud cover.

The cloud flags were derived for three different instruments under different atmospheric conditions, and the CI was defined differently for all three instruments (I_{405}/I_{670}, I_{347}/I_{420}, and I_{405}/I_{550} for Xianghe, Brussels, and Jungfraujoch, respectively). The sky condition flag requires RTM calculations for each CI definition in order to account for the SZA dependency, and the measured time series needs to be sufficiently long in order to be able to normalize the CI between the extremes (maximum: cloud free; minimum: clouded).

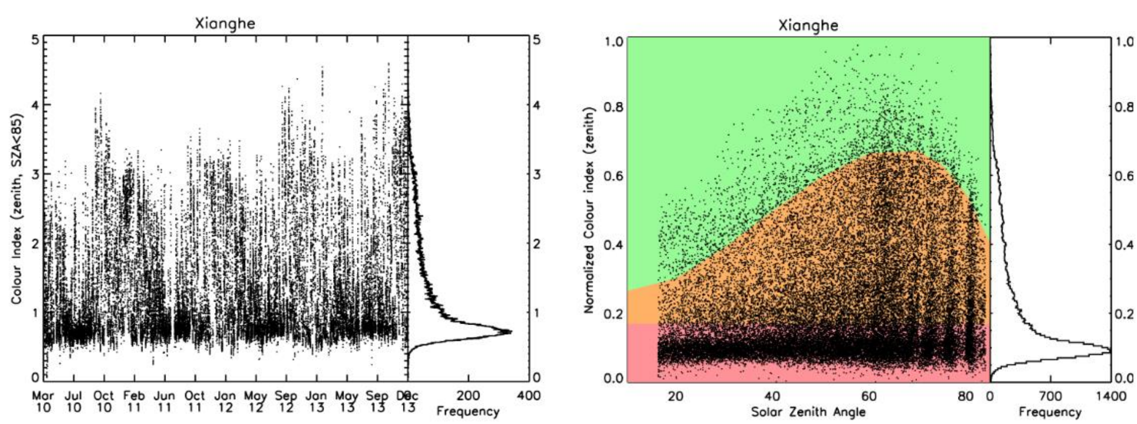

Figure 1: Left: Zenith CI values and frequency distribution for Xianghe.
Right: The normalized CI values (points) versus SZA. The green, orange and red regions correspond to the "good", "mediocre" and "bad" regions as defined by the sky flag. Figures taken from Gielen et al., 2014.

3.3 Wagner et al., 2014

Wagner et al., 2014, present a multi-step cloud classification scheme which is intended to categorize the cloud conditions for a MAX-DOAS elevation sequence.

The classification identifies clear sky conditions based on the absolute value of the CI at zenith, and uses its temporal variability to detect rapid changes in cloudiness, corresponding to clear sky, between clouds or broken clouds. The variability of the CI with elevation angles is used to detect continuous clouds (low variability) or clear sky conditions with high aerosol load (high variability, while CI at zenith varies smoothly with time).

In addition, in case of a low CI, the O_4 SCD and its elevation angle dependency are used to detect thick clouds and fog, respectively.

The full scheme is shown in Fig. 2.

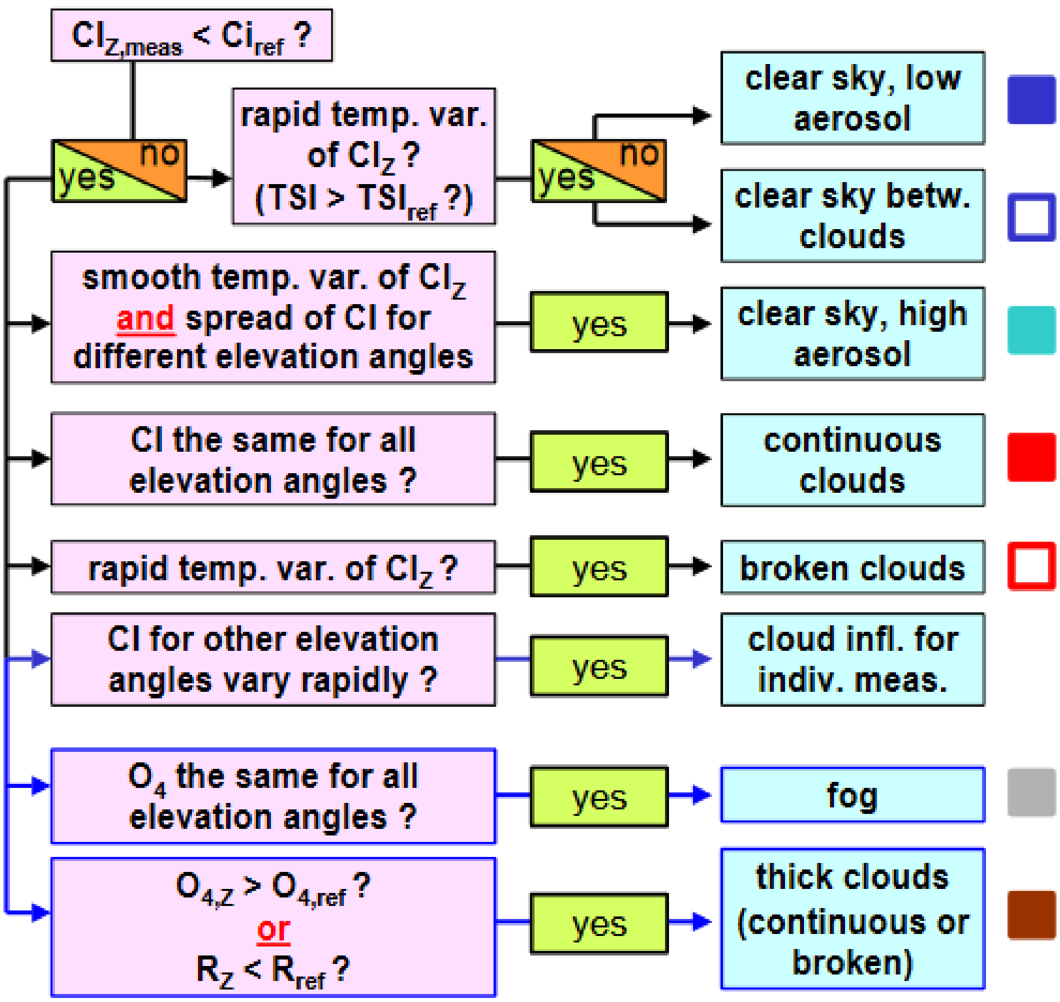

Figure 2: Cloud classification scheme. Paths with black arrows indicate the primary classification results: only one primary classification result can be attributed to a given elevation sequence. Paths with blue arrows indicate secondary classification results, which complement the primary classification results. Figure taken from Wagner et al., 2014.

The algorithm has been demonstrated to successfully classify various cloud conditions from the MAX-DOAS measurements themselves. However, the given thresholds for the CI have to be derived for the specific instrument. An application of the cloud classification scheme to measurements from a different instrument required several modifications (Wang et al., 2015).

Like for the algorithm by Gielen et al. (2014), also for the algorithm by Wagner et al. (2014) the measured time series needs to be sufficiently long in order to provide good statistics for the different cloud conditions.

3.4 Wagner et al., 2016

Wagner et al., 2016, present an advanced cloud classification scheme. It is generally based on the scheme presented in Wagner et al., 2014. The major achievement is an absolute calibration of CI and O_4 SCDs based on RTM calculations under well-defined atmospheric conditions and viewing geometries:

- The CI is calibrated based on the SZA dependency of the minimum values (i.e. clouded observations).
- The O_4 SCD is calibrated based on cloud-free observations around 36° SZA, where the impact of AOD has been found to be negligible.

With these calibrations, Wagner et al. 2016 provides a cloud classification scheme which is applicable to any MAX-DOAS measurement time series. However, recent studies have shown that the provided threshold values might have to be refined when applied to other instruments or measurement conditions.

4 Cloud classification within FRM4DOAS-2.0

Within FRM4DOAS 2, the topic of cloud screening is in focus of a dedicated work package. A cloud classification should be developed in order to flag clouded sequences from the profile inversion. The respective cloud classification results will be validated against simultaneous sky cameras.

Beyond the output of existing algorithms, also more specific information should be derived. In particular the algorithm to be developed should try to flag individual elevation angles rather than complete scans if possible.

The cloud classification algorithm for FRM4DOAS-2.0 is planned to base on Wagner et al., 2016. Validation results might require modifications and improvements of this algorithm. The flagging of individual viewing angles will have to be added.

5 References

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