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Comparison of Cloud Parameters from GOME-2 and Assessment of Cloud Impact on Tropospheric NO_2 and HCHO Retrievals †

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Abstract: In recent decades, there has been an increasing interest in making use of satellite measurements for identifying trends in atmospheric composition and climate. Instruments like GOME-2 and TROPOMI are dedicated to air-quality and global trace gas monitoring. For the accurate retrieval of columnar information of the trace gases, cloud correction is necessary. This work is meant to examine the quality of the GOME-2 operational cloud product from AC SAF and to propose enhancements of the current dataset to improve the retrieval of the NO_2 and HCHO tropospheric gases.

Keywords: cloud parameters; oxygen A-band; TROPOMI and GOME-2 satellite observations

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1. Introduction

In the framework of the ESA Climate Change Initiative (CCI+) precursors project, a big effort been devoted to the assessment of the quality of long-term global trace gases datasets, like nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), formaldehyde (HCHO), and ammonia (NH3), which act as precursors for aerosols and ozone. Such datasets have been accumulated using Earth observation satellites over the last decades via sensors like ERS-2 GOME, ENVISAT SCIAMACHY, MetOp-A/B/C GOME-2 and IASI, Aura OMI, Sentinel-5 Precursor TROPOMI and Terra MOPITT. The ultimate goal is to reduce the gap between existing climate data records and the requirements specified by the Global Climate Observing System (GCOS) for the systematic generation of Essential Climate Variables (ECVs). Here, the impact of clouds on the tropospheric NO_2 and HCHO for GOME-2 sensor is evaluated with the focus on the OCRA (Optical Cloud Recognition Algorithm)/ROCINN (Retrieval of Cloud Information using Neural Networks) algorithm. A comparison of GOME-2A cloud parameters from the EUMETSAT Satellite Application Facility on Atmospheric Composition Monitoring (AC SAF) against the FRESCO+ (Fast Retrieval Scheme for Clouds from the Oxygen A band) algorithm is performed for the full time-series over selected regions with diverse HCHO and NO_2 conditions.

2. GOME-2 on the MetOp Satellites

The GOME-2 instruments on the MetOp satellites produce global-scale routine monitoring of the abundance and distribution of ozone and associated trace gas species. The first sensor of the series MetOp-A was launched on 19 October 2006 as part of the Initial Joint Polar System (IJPS) in co-operation with NOAA in the USA. The second polar-orbiting satellite, MetOp-B, was launched on 17 September 2012 and the third and last polar-orbiting satellite in the series, MetOp-C, was launched on 7 November 2018. The MetOp satellites are flying on a sun-synchronous orbit with a repeat cycle of 29 days and an equator crossing time of 09:30 LT in a descending mode. GOME-2 is a nadir-scanning UV-VIS-NIR spectrometer [1] covering the spectral range between 240 and 790 nm. There are 15 pairs of polarization measurement devices (PMD) channels defined, which measure the parallel component (PMD-p) and the orthogonal component (PMD-s). The state of (linear) polarization is measured via 15 broadband channels, at 15 wavelengths. The default swath width of the GOME-2 scan is 1920 km, which enables global coverage in about 1.5 days. GOME-2 ground pixels have a footprint size of 80×40 km^2 in the forward scan, much finer than those of GOME/ESR-2 (320×40 km^2), but coarser than those of SCIAMACHY/ENVISAT (60×30 km^2), OMI/AURA (24×13 km^2 at nadir) and TROPOMI/Sentinel-5P (5.5×3.5 km^2 at nadir).

The GOME-2 trace gas column products and cloud information products are generated by the German Aerospace Center (DLR) in the framework of the AC SAF project, which is part of the EUMETSAT Polar System (EPS) ground segment. The total column amounts of NO_2 and HCHO are computed with a classical DOAS-AMF fitting algorithm [2–4]. The spectral fitting windows for NO_2 is in the wavelength range between 425.0 and 450.0 nm and for HCHO at a wavelength range of 328.5–346.0 nm. The algorithm has two major steps: (a) a DOAS least-squares fitting for the trace gas slant column density (SCD), and (b) the Air Mass Factor (AMF) calculation in order to make the conversion from the SCD to the final trace gas vertical column density (VCD) by dividing the SCD with the AMF. The AMF is computed using a radiative transfer model (RTM), and depends on the (a priori) vertical trace gas profile, the GOME-2 viewing geometry, and the surface properties, as well as on cloud and aerosol properties. The accuracy of the AMF is mostly limited by the current knowledge on these external parameters. In the current work, we focus on the dependence of the AMF on the cloud product.

3. The OCRA-ROCINN Tandem for the Retrieval of Cloud Properties

Two algorithms, OCRA and ROCINN [5,6], are synergistically used for retrieving the cloud information from the GOME-2 sensor series. The fundamental idea of OCRA is to separate the measured reflectance into two components: a cloud-free background and a residual contribution expressing the influence of clouds [7]. OCRA uses combined broadband spectral windows from UV (322–384 nm), VIS (400–557 nm) and NIR (569–804 nm). A monthly global cloud-free composite with a spatial resolution of 10×40 km^2 is constructed by merging cloud-free reflectances obtained from GOME-2A data from April 2008 until June 2013. This composite is also used for GOME-2B and GOME-2C. The radiometric cloud fraction is determined by examining separations between measured reflectances and their cloud-free composite values. The OCRA cloud fraction retrieved for the PMD measurements (10×40 km^2) is then averaged to the resolution of the main science channels (80×40 km^2), where it is used by ROCINN as a priori input. ROCINN is the follow-up algorithm to retrieve within the O_2 A-band window two additional cloud properties; the cloud height and cloud albedo [8]. By using the independent pixel approximation (IPA) concept [9,10], the sun-normalized radiances can be expressed as the summation of two components for the cloud-free and cloudy part of the pixel with respect to the retrieved OCRA cloud fraction. Several cloud scenarios, covering the full vector space, are simulated using VLIDORT (Vector Linearized Discrete Ordinate Radiative Transfer radiances) [11] for two different cloud models. The simplistic approach for the Cloud-as-Reflecting-Boundaries (CRB) assumes that the cloud behaves as a Lambertian reflector.

Line-by-line transmittances are calculated using line spectroscopic information for the O_2 A-band from the HITRAN (high-resolution transmission molecular absorption) database. The information on the surface albedo quantity is taken from the MERIS black-sky albedo climatology [12].

A more sophisticated cloud model within ROCINN is the Cloud-As-Layer (CAL) model, which considers a layer of liquid water particles with their scattering properties derived from the Mie theory [13,14]. The retrieved quantities are the cloud top height and the cloud optical thickness. This model has been extensively used for the TROPOMI sensor on Sentinel-5 Precursor as described in [15]. The TROPOMI cloud products have been validated against other satellites like VIIRS, MODIS and ground-based radar/lidar instruments from CLOUDNET [16]. Other inter-comparison studies between TROPOMI cloud products have shown the importance of the cloud properties' accuracy on the tropospheric trace gas retrievals [17].

4. Results with Full Time Series Comparison for the GOME-2A Sensor

The OCRA/ROCINN CRB cloud algorithm has been compared to the FRESCO+ v7 algorithm for the full time series (2007–2018). For the OCRA/ROCINN algorithm, the operational GOME-2A product from EUMETSAT AC SAF was used [18]. For FRESCO+ cloud properties [19], we used the dataset produced in the framework of the QA4ECV (Quality Assurance for Essential Climate Variables) project [20]. FRESCO+ is a cloud retrieval algorithm in the O_2 A-band. Three wavelength windows are used: (1) 758–759 nm (no absorption), (2) 760–761 nm (strong absorption), and 765–766 nm (moderate absorption). Each window comprises five GOME-2 wavelengths. FRESCO+ involves a forward RTM to build the Look-Up Tables (LUT) for the transmission database due to oxygen absorption, including the single Rayleigh scattering computations in a separate LUT [21].

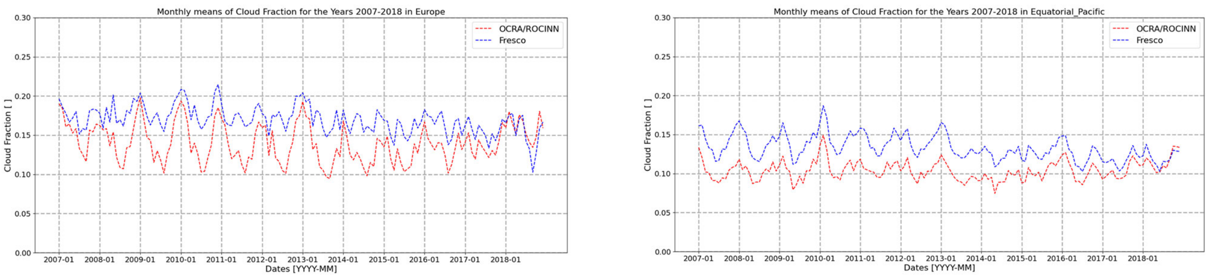
Note that OCRA produces a radiometric cloud fraction without making any assumptions on the cloud albedo, whereas FRESCO+ produces an effective cloud fraction assuming a fixed cloud albedo of 0.8. The comparisons are performed over selected regions with diverse NO_2 and HCHO conditions, summarized in Table 1. The cloud data from AC SAF and QA4ECV datasets have been filtered according to the following criteria:

- Only forward scan pixels are considered;
- Solar Zenith Angle must be lower than 85 degrees;
- Pixels over snow/ice conditions are excluded;
- Pixels with a cloud fraction higher than 0.4 are excluded because these are not used in tropospheric trace gases retrievals.

Table 1. The comparisons have been focused on the following regions with diverse HCHO and NO_2 conditions.

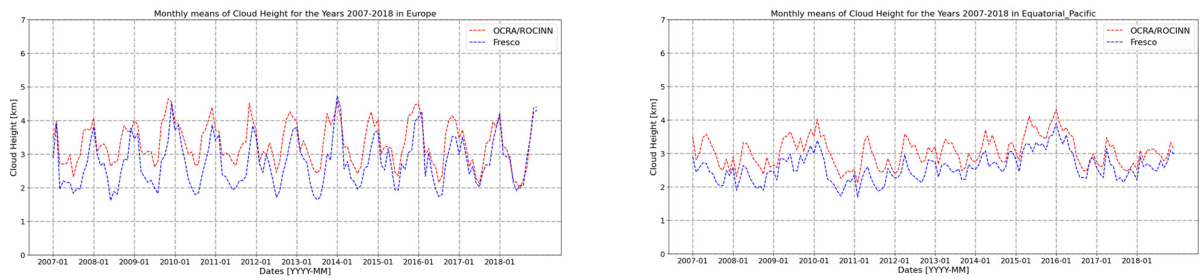
Region	Region Type	Geophysical Coordinates Latitude, Longitude
Amazon	Biomass Burning	10° S–5° N, 50–75° W
Africa south of Equator	Biomass Burning	15° S–0, 10–35° E
SE US	Biogenic emission	30–40° N, 75–95° W
Europe	Anthropogenically polluted	35–50° N, 10° W–20° E
Northern China	Anthropogenically polluted	29–37° N, 112–121° E
Equatorial Pacific	Clean remote	15° S–15° N, 120–180° W

Monthly means have been calculated for the full time series (2007–2018) for AC SAF and QA4ECV cloud parameters. The comparison of cloud fraction and cloud height is limited to the regions of Table 1. The cloud fractions from OCRA/ROCINN are lower than those from FRESCO+. However, this is not seen during the last years, 2017–2018, because of an artificial trend in the OCRA cloud fraction. The reason for this trend is the GOME-2 degradation that is not corrected in the Level-1 product. To compensate for this instrument degradation, a soft-correction as a function of time and viewing geometry is computed based on the former years of the sensor's lifetime. A fourth-order polynomial is fitted to the PMDs mean reflectances (see Equation (2) in [6]). For the years after 2013, the degradation effect is partially removed from the PMD reflectances using extrapolated soft-correction factors. As stated in Section 2, the global cloud-free composites are based on GOME-2A data from April 2008 until June 2013. Therefore, the data after 2013 do not have the optimal soft-correction factors. Consequently, the OCRA cloud fractions and ROCINN cloud heights gradually degrade after 2013. The cloud heights from the OCRA/ROCINN algorithm are in general higher than the ones retrieved from FRESCO+. The relative differences depend on the season and the region. Here, we present the cloud fraction and cloud height comparisons only for two regions in Figures 1 and 2, respectively. For the Equatorial Pacific, the differences in both cloud fraction and height do not follow a strong seasonal pattern like in other regions. For Europe, the smallest differences between the two algorithms are found in January and the highest in June–July. Especially for this region, the two algorithms show a good agreement in their cloud height retrievals; the cloud height relative differences are close to zero for the winter months.



(**a**) (**b**)

Figure 1. Time series of cloud fraction for two regions, (**a**) Europe and (**b**) Equatorial Pacific, are compared for the two retrieval algorithms.



(**a**) (**b**)

Figure 2. Time series of cloud height for two regions, (**a**) Europe and (**b**) Equatorial Pacific, are compared for the two retrieval algorithms.

Clouds influence the NO_2 and HCHO retrieval through the albedo effect related to the increase in reflectivity for cloudy scenes, the shielding effect on the column below the cloud, and the enhancement of the optical light path due to multiple scattering inside clouds. The presence of clouds is considered in the AMF calculation using GOME-2 cloud parameters based on the OCRA/ROCINN algorithm. Due to the artificial trend that is observed in the OCRA cloud fractions from 2018 (originating from the GOME-2A instrument degradation effects), the NO_2 and HCHO column calculations cannot be optimal when a cloud correction is applied. One mitigating solution is to use clear-sky AMF that are provided directly in the AC SAF Level-2 products. The impact on the NO_2 and HCHO VCD has not been quantified yet. However, from initial comparisons for HCHO of the full time series on two regions Amazon and Northern China, it seems that the HCHO VCD will slightly decrease [22].

5. Discussion

The full time series comparison between the AC SAF and QA4ECV cloud data showed that the cloud properties have similar seasonal variations. The best period for drawing conclusions is between April 2008 and June 2013 due to the accurate degradation correction in OCRA colors and temporal match with the clear-sky composite maps. The QA4ECV cloud fraction (derived from the FRESCO+ algorithm) is systematically higher than the AC SAF cloud fraction (derived from the OCRA/ROCINN CRB algorithm), while the cloud heights are larger in the AC SAF products compared to the QA4ECV. The differences between OCRA and FRESCO+ cloud fraction may originate from the different spectral fitting windows since OCRA uses broadband wavelength bands covering the whole UV-VIS-NIR spectrum. The cloud height differences originate primarily from the different line-by-line models and forward models used in ROCINN and FRESCO+. The artificial peak in the cloud fraction due to instrument degradation effects has a direct impact on the NO_2 and HCHO VCDs if the cloud correction is applied. This effect can be mitigated if the clear-sky AMFs are used. However, it is planned to improve the operational GOME-2 cloud products by extending the instrument degradation soft-correction to the whole time series instead of using the extrapolated factors.

Author Contributions: A.A. developed the methodology to build up the two datasets, with the scientific guidance of P.V. A.A. carried out the data analysis and wrote the manuscript. F.R., R.L., D.L., V.M.G., S.S., I.D.S., F.B., L.G.T., P.S. and S.C. have provided comments for the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The OCRA/ROCINN cloud data are included in the operational GOME-2 products and can be accessed from the official AC SAF ftp-site: ftp://acsaf.eoc.dlr.de (accessed on 5 May 2023). The GOME-2 FRESCO+ cloud data can be downloaded from the TEMIS website: https://www.temis.nl/fresco/ (accessed on 5 May 2023).

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