# CARBONGASES: RETRIEVAL AND ANALYSIS OF CARBON DIOXIDE AND METHANE GREENHOUSE GASES FROM SCIAMACHY ON ENVISAT

**O. Schneising, M. Buchwitz, M. Reuter, H. Bovensmann, and J. P. Burrows**

*University of Bremen FB1, Institute of Environmental Physics (IUP), Otto-Hahn-Allee 1, 28359 Bremen, Germany, E-mail: Oliver.Schneising@iup.physik.uni-bremen.de*

## ABSTRACT

Carbon dioxide ($CO_2$) and methane ($CH_4$) are the two most important anthropogenic greenhouse gases contributing to global climate change. Despite their importance our knowledge about their variable natural and anthropogenic sources and sinks has significant gaps. Satellite observations can add important global scale information on greenhouse gas sources and sinks provided the data are accurate and precise enough and are sensitive to the lowest atmospheric layers where the variability due to regional greenhouse gas sources and sinks are largest. SCIAMACHY onboard ENVISAT was the first and is now besides TANSO onboard GOSAT the only satellite instrument which covers important absorption bands of both gases in the near-infrared/shortwave-infrared (NIR/SWIR) spectral region. In nadir mode SCIAMACHY observes reflected and backscattered solar radiation. The daytime measurements are therefore very sensitive to near-surface greenhouse gas concentration changes except in case of significant cloud cover. The atmospheric greenhouse gas information is extracted from the SCIAMACHY spectra using the Weighting Function Modified Differential Optical Absorption Spectroscopy (WFM-DOAS or WFMD) algorithm developed at the Institute of Environmental Physics (IUP) of the University of Bremen, Germany.

In the framework of the CARBONGASES project, which is part of the Changing Earth Science Network, the afore existing data set focussing on the first three full years of the ENVISAT mission (2003-2005) is improved and extended up to end of 2009 constituting seven years of greenhouse gas information derived from European Earth observation data and closing the gap to GOSAT. The status of this retrieval activity and first results are presented.

## 1. INTRODUCTION

The carbon gases carbon dioxide ($CO_2$) and methane ($CH_4$) are the two most important anthropogenic greenhouse gases and contribute to global warming. Both gases have increased significantly since the start of the Industrial Revolution. While the carbon dioxide concentrations have risen steadily during the last decades, atmospheric methane levels were rather stable from 1999 to 2006 [1] before a renewed growth was observed from surface measurements since 2007 [12, 4]. The reliable prediction of future atmospheric greenhouse gas levels and the associated global climate change requires an adequate understanding of their sources and sinks and their spatiotemporal distribution. Unfortunately, the current knowledge of the carbon surface fluxes is limited for example by the sparseness of the ground-based network and uncertainties are large (see, e.g., Stephens et al. [17]). Theoretical studies have shown that satellite measurements in combination with models have the potential to significantly reduce these surface flux uncertainties if they are accurate and precise enough [8, 11]. Furthermore, high sensitivity to near-surface greenhouse gas concentration changes is also required because the variability due to regional sources and sinks is largest in the lowest atmospheric layers. In contrast to measurements of emissions in the thermal infrared (TIR) which are primarily sensitive to middle to upper tropospheric greenhouse gas concentrations, the usage of reflected solar radiation in the near-infrared/shortwave-infrared (NIR/SWIR) spectral region allows sensitivity to all altitude levels, including the boundary layer.

The near-infrared nadir spectra of reflected solar radiation measured by SCIAMACHY onboard ENVISAT [2] contain information on the vertical columns of these gases which are retrieved using the scientific algorithm WFM-DOAS [3, 15, 16] and which are converted to column-averaged mixing ratios, denoted by $XCO_2$ or $XCH_4$, respectively, by normalisation with the air column.

The existing WFMDv1.0 data set [15, 16] is based on Level 1 calibration version 5 (L1v5) and covers the time period 2003-2005. To process data after 2005 the usage of L1v6 is required. Other changes with the improved WFMDv2.0 algorithm developed within the framework of the CARBONGASES project (aside from the Level 1 version update) compared to WFMDv1.0 include: (i) an extended look-up table including additional ground heights and additional albedos covering all naturally occurring surface types by means of interpolation, (ii) use of improved HITRAN 2008 [14] spectroscopy plus Jenouvrier et al. [9] $H_2O$ update in the methane fitting win-

*Proc. 'ESA Living Planet Symposium', Bergen, Norway 28 June – 2 July 2010 (ESA SP-686, December 2010)*

dow instead of HITRAN 2004 [13], (iii) modified pixel masks to get best possible results until 2009, (iv) CarbonTracker release 2009 instead of release 2007 [10] for correcting the $XCH_4$ data, (v) SCIAMACHY Absorbing Aerosol Index v4.1 [18] instead of EarthProbe/TOMS AAI [7] for filtering out strong aerosol contaminated ground scenes of the $XCO_2$ data, in particular desert dust storms. The resulting data constitute seven years (2003–2009) of greenhouse gas information derived from European Earth observation data improving and extending afore existing WFM-DOAS retrievals.

## 2. RESULTS

All SCIAMACHY spectra (Level 1b version 6 converted to Level 1c by the ESA SciaL1C tool using the standard calibration) for the years 2003–2009 which have been made available by ESA/DLR, have been processed using the improved retrieval algorithm WFM-DOAS version 2.0.

As already mentioned in the introduction, the WFMDv2.0 data sets are optimised for the time period 2003-2009 by choosing a static detector pixel mask for the carbon dioxide retrieval and due to proceeding detector degradation in the spectral range used for the methane retrieval three different static detector pixel masks dependent on the analysed time period for methane to get best possible results for the early years and stability until end of 2009 at the same time (see Fig. 1). Since November 2005 only one remaining detector pixel in the Q-branch of the $2\nu_3$ methane band, which is the spectral region in the fitting window where the strongest absorption occurs, is serviceable. Therefore, the methane retrieval results since November 2005 are expected to be of reduced quality with regard to noise compared to the prior time period where more Q-branch detector pixels are available.

Figs. 2 and 3 show global 3-year averages of quality filtered retrievals of $XCO_2$ and $XCH_4$, respectively, covering the years 2003-2005 revealing quite similar results for WFMDv1.0 and WFMDv2.0 which demonstrates the consistency of the two data sets for the overlapping time period. However, exactly identical retrieved patterns cannot be expected because the sampling is slightly different, for example due to the switch to the SCIAMACHY Absorbing Aerosol Index or differences in the number of available SCIAMACHY spectra for the different calibration versions. Furthermore, the look-up table improvements for high latitude and high reflective scenes necessarily lead to deliberate deviations in these cases. For instance, the low bias over high mountains, e.g., the Himalaya Range, compared to model simulations for WFMDv1.0 $XCH_4$ disappears in the WFMDv2.0 methane data set.

A significant part of the $CO_2$ spatial variations shown in Fig. 2 results from the irregular sampling of the SCIAMACHY $XCO_2$. For example, the mid- and

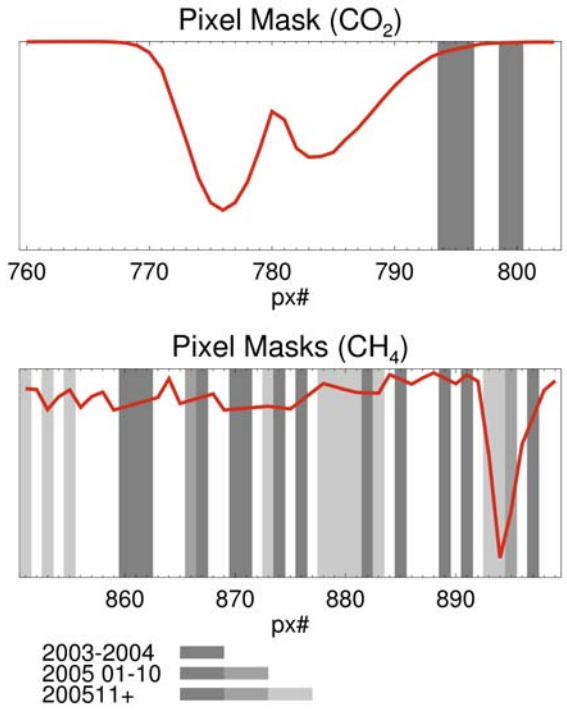


*Figure 1. Detector pixel masks used in WFMDv2.0. Due to proceeding detector degradation in channel 6+ three different static pixel masks dependent on the analysed time period are used for the $CH_4$ retrieval.*

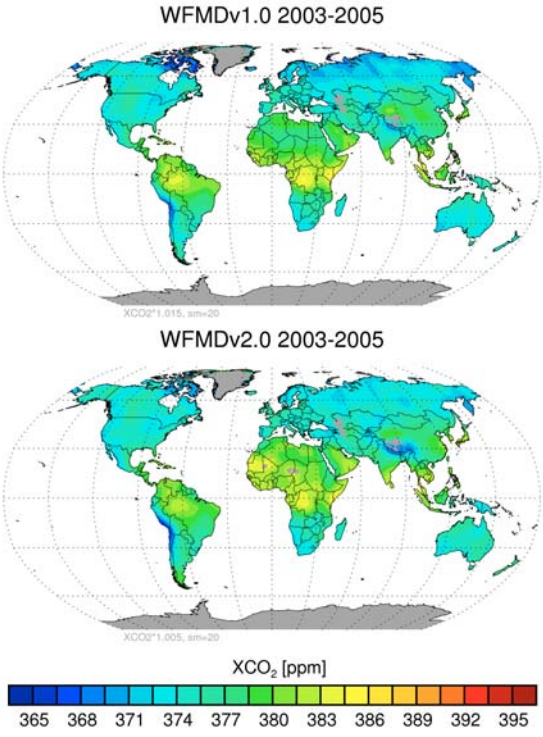


*Figure 2. Comparison of WFMDv1.0 and v2.0 $XCO_2$ for 2003-2005 demonstrating the consistency of the two data sets for the overlapping time period.*

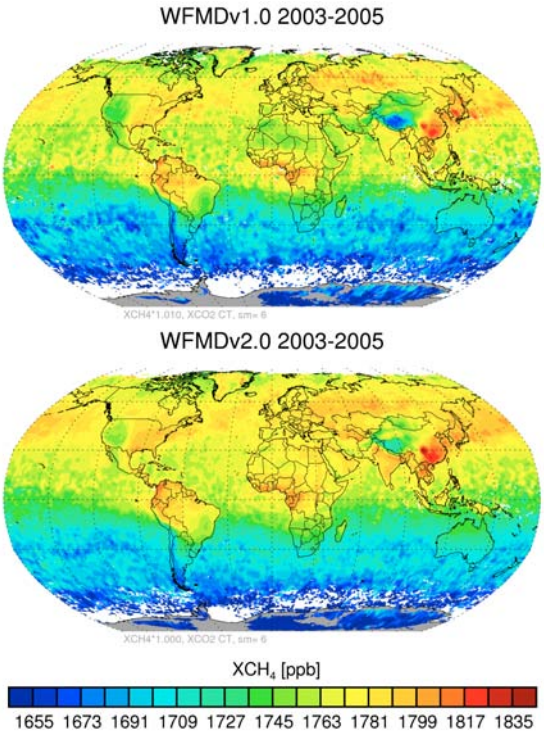


*Figure 3. As Fig. 2 but for $XCH_4$.*

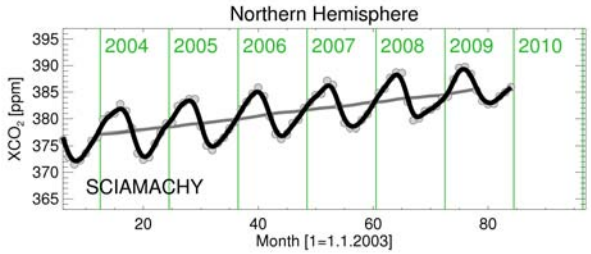


*Figure 4. SCIAMACHY WFMDv2.0 northern hemispheric $XCO_2$ based on monthly means (coloured circles). The saturated solid line has been smoothed using a four-month Hann window. The pale solid line represents the corresponding deseasonalised trend.*

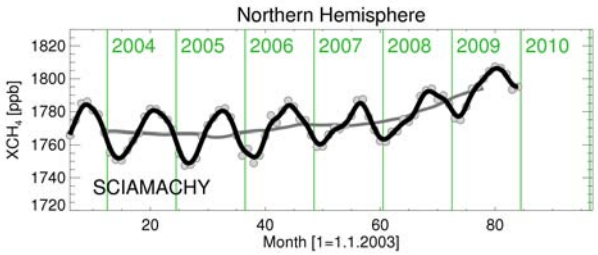


*Figure 5. As Fig. 4 but for $XCH_4$.*

high-latitudes of the northern hemisphere are strongly weighted towards late spring, summer, and early autumn, where $CO_2$ is known to be much lower than for the (true) yearly average. This uneven weighting is due to the significantly higher cloud cover in winter but also because of larger solar zenith angles and snow coverage. As a result, most of the measurements in winter are automatically filtered out by the implemented quality filtering scheme. Clearly visible in Fig. 3 are major methane source regions and the interhemispheric gradient.

Figs. 4 and 5 confirm that the SCIAMACHY retrieval results are stable with time also after 2005 in consequence of the used detector pixel mask approach. Fig. 4 shows the WFMDv2.0 $XCO_2$ retrieval results for the northern hemisphere based on monthly data. Clearly visible is the seasonal cycle and the steady atmospheric $CO_2$ increase with time primarily caused by the burning of fossil fuels for the whole considered multi-year time period. The magnitude of increase is quite uniformly distributed globally.

Fig. 5 shows the temporal evolution of retrieved SCIAMACHY methane based on monthly means as well as the corresponding deseasonalised trend for the northern hemisphere analogue to Fig. 4 for carbon dioxide. Due to proceeding detector degradation in the spectral range used for the methane column retrieval and the corresponding availability of considerably less detector pixels the results since November 2005 are noisier. The standard deviation of the monthly means since the pixel mask alteration at the end of October 2005 is on average about twice as large. Nevertheless, the seasonal cycle of the monthly means can still be clearly observed because hemispheric monthly means provide a lot of measurements for averaging. The figure demonstrates that after years of near-zero growth, atmospheric methane started to increase again in recent years which is qualitatively consistent with the findings of Rigby et al. [12] and Dlugokencky et al. [4] for surface methane concentrations. In this context it has to be pointed out that a static pixel mask is used for 2006–2009 containing only detector pixels that are not turning dead or bad during this period to ensure that the observed growth is not artificially introduced by proceeding detector degradation.

WFMDv2.0 has been used for a first comparison with the operational GOSAT Level 2 products version 00.50 as downloaded via the GOSAT User Interface Gateway Service. Because the operational GOSAT product is still rather fragmentary this initial comparison focusses on June/July 2009 where GOSAT v00.50 data are available for almost every day during this period. Figs. 6 and 7 show the corresponding comparisons for carbon dioxide. Also included is $XCO_2$ from CarbonTracker using 2008 values plus 2 ppm (denoted CarbonTracker $2008^{\#}$) because results for 2009 are not available yet. The two satellite $XCO_2$ data sets have been obtained from two different sensors using two different retrieval algorithms. In contrast to GOSAT the SCIAMACHY data have been derived using a single constant $CO_2$ mixing ratio vertical profile to ensure that the spatio-temporal variability of the retrieved $XCO_2$ is entirely coming from the measured spectra and not influenced or caused by a-priori assumptions. To allow a quantitative comparison all data sets have been gridded using a $1^\circ \times 1^\circ$ latitude/longitude grid.

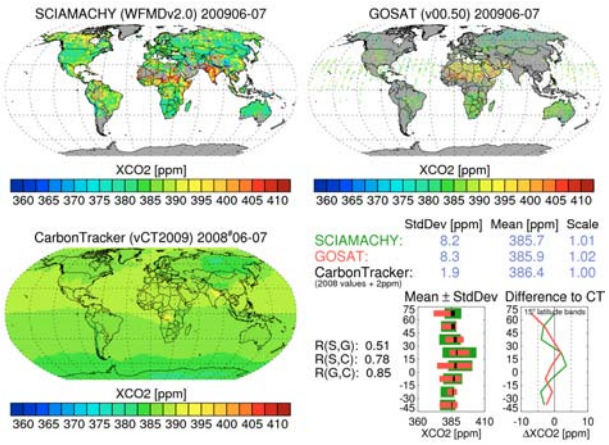


*Figure 6. Comparison of SCIAMACHY WFMDv2.0 $XCO_2$ (top left) with GOSAT v00.50 (top right) for June/July 2009. Also shown is $XCO_2$ obtained using NOAA's CarbonTracker (bottom left, using 2008 values plus 2 ppm). In the bottom right part statistical information for the global data sets is given (standard deviations, $XCO_2$ mean values, and applied $XCO_2$ scaling factors). The two panels in the bottom right corner show the latitude dependence of $XCO_2$ and its standard deviation in $15^\circ$ latitude bands (right) and the difference of SCIAMACHY (green) and GOSAT (red) $XCO_2$ with respect to CarbonTracker. Also shown are the corresponding correlation coefficients R (S=SCIAMACHY, G=GOSAT, C=CarbonTracker).*

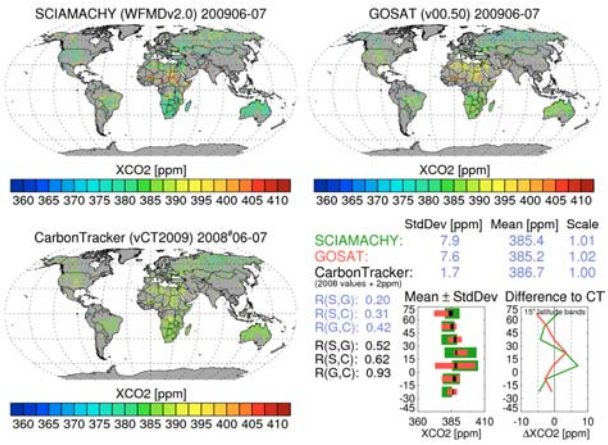


*Figure 7. As Fig. 6 but only using those grid cells where data from all three data sets are available. Additionally shown are the correlation coefficients for all spatially co-located $1^\circ \times 1^\circ$ grid cells in light blue.*

Different scaling factors have been applied to the SCIAMACHY and GOSAT data sets so that the mean values are approximately equal.

Fig. 6 shows the comparison of all data after quality filtering. As can be seen, the standard deviation of the CarbonTracker $XCO_2$ is much lower compared to the two satellite data sets which exhibit a similar standard deviation. Also shown is an analysis of the latitudinal $XCO_2$ dependence of the three data sets (bottom right panels). For this purpose mean values and standard deviations have been computed for $15^\circ$ latitude bands (left panel). Also shown is the difference to CarbonTracker (right panel). The correlation of the latitudinal dependences between the satellite and CarbonTracker $XCO_2$ is comparably high for both sensors (about 0.8, respectively).

To minimise the effects from the different spatial sampling, Fig. 7 shows results for the same comparison as shown in Fig. 6 but using only those locations during June/July 2009 where observations from both sensors are available. As can be seen, this results in a significant reduction of the number of grid cells available for comparison. The temporal co-registration criteria have however not been changed. A data point in a given grid cell corresponds to the given bimonthly period but not necessarily to the same day(s). Because of the different orbits and the different sampling strategies a comparison based on the daily data would result in too few data points for comparison. In addition to the correlation of the latitudinal dependence, the correlation coefficients computed using all spatially co-located $1^\circ \times 1^\circ$ grid cells in the three maps displayed in Fig. 7 are shown in light blue. The correlation coefficients are fairly low (0.2–0.4) because of the relatively large scatter of the satellite data products.

Figs. 8 and 9 show the analogue comparisons of all and collocated quality filtered data for methane. Also included is $XCH_4$ from the EC-JRC TM5 model using 2003 values plus 30 ppb (denoted TM5 $2003^\#$) because results for 2009 are not available yet. In contrast to the carbon dioxide results, the standard deviation of the SCIAMACHY $XCH_4$ is about twice as large as for the GOSAT retrievals due to the loss of important detector pixels in the spectral range used for the methane retrievals. The interhemispheric gradient is obvious in all data sets. As a consequence the correlations of the latitudinal dependences are high (about 0.8-0.9, respectively).

A more detailed comparison with GOSAT data is planned as soon as a version of the operational GOSAT product is available which covers the period from the start of the mission to the end of 2009 consistently without significant gaps. Nevertheless, the first results discussed here already give an indication that the SCIAMACHY and GOSAT data sets are largely consistent.

## 3. SUMMARY

It was shown that the WFMDv2.0 carbon dioxide and methane retrieval results based on improved Level 1 version 6 calibration are consistent with the afore existing data set for the overlapping time period and that stability can be achieved until the end of 2009 when using an appropriate detector pixel mask approach. The steady increase of atmospheric carbon dioxide can be clearly observed with SCIAMACHY for the whole time period analysed (2003-2009). The methane results show that af-

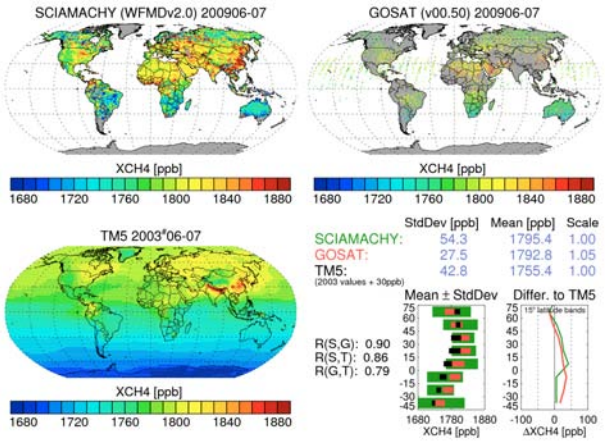


*Figure 8. Comparison of SCIAMACHY WFMDv2.0 $XCH_4$ (top left) with GOSAT v00.50 (top right) for June/July 2009. Also shown is $XCH_4$ obtained using the EC-JRC TM5 model (bottom left, using 2003 values plus 30 ppb). In the bottom right part statistical information for the global data sets is given (standard deviations, $XCH_4$ mean values, and applied $XCH_4$ scaling factors). The two panels in the bottom right corner show the latitude dependence of $XCH_4$ and its standard deviation in $15^\circ$ latitude bands (right) and the difference of SCIAMACHY (green) and GOSAT (red) $XCH_4$ with respect to TM5. Also shown are the corresponding correlation coefficients R (S=SCIAMACHY, G=GOSAT, T=TM5).*

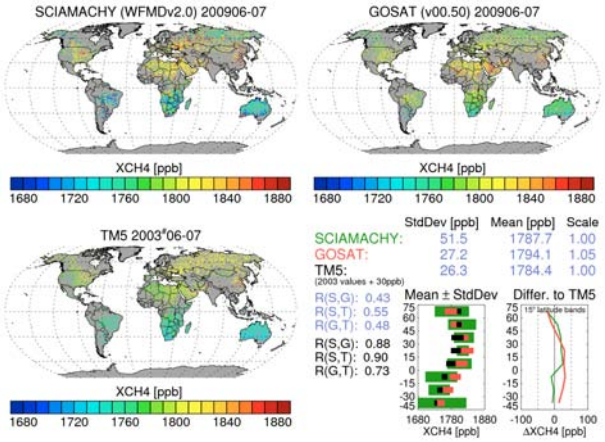


*Figure 9. As Fig. 8 but only using those grid cells where data from all three data sets are available. Additionally shown are the correlation coefficients for all spatially co-located $1^\circ \times 1^\circ$ grid cells in light blue.*

ter years of near-zero growth, atmospheric methane has started to increase again in recent years which is consistent with surface measurements.

Initial comparisons of the SCIAMACHY WFMDv2.0 data with the operational GOSAT Level 2 products indicate that the results from the two different sensors using two different retrieval algorithms are largely consistent.

## ACKNOWLEDGEMENTS

We thank ESA and DLR for providing us with the SCIAMACHY Level 1 data and the SCIAMACHY calibration team (DLR, SRON, University of Bremen, ESA, and others) for continuously improving the quality of the spectra. CarbonTracker 2009 results were provided by NOAA ESRL, Boulder, Colorado, USA from the website at `http://carbontracker.noaa.gov`. We also thank Peter Bergamaschi from EC-JRC for providing the TM5 methane model runs. SCIAMACHY Absorbing Aerosol Index data were obtained from the TEMIS website (`http://www.temis.nl/airpollution/absaai/`). The GOSAT data have been obtained via the GOSAT User Interface Gateway (via GOSAT RA1 project CONSCIGO).

The research leading to these results has received funding from the ESA project CARBONGASES which is part of The Changing Earth Science Network, the ESA project ALANIS: Methane, the European Union's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement no. 218793 and 212095 (MACC and CityZen), and from the University and the State of Bremen.

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