



Validation of MOPITT
V5 NIR CO using
MOZAIC/IAGOS
measurements

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Validation of nine-years of MOPITT V5 NIR using MOZAIC/IAGOS measurements: biases and long term stability

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Validation results from a comparison between Measurement Of Pollution In The Troposphere (MOPITT) V5 Near InfraRed (NIR) Carbon Monoxide (CO) total column measurements and Measurement of Ozone and Water Vapour on Airbus in-service Aircraft (MOZAIC)/In-Service Aircraft for a Global Observing System (IAGOS) aircraft measurements are presented. A good agreement is found between MOPITT and MOZAIC/IAGOS measurements, consistent with results from earlier studies using different validation data and despite large variability in MOPITT CO total columns along the spatial footprint of the MOZAIC/IAGOS measurements. Validation results improve when taking the large spatial footprint of the MOZAIC/IAGOS data into account. No statistically significant drift was detected in the validation results over the period 2002–2010 at global, continental and local (airport) scales. Furthermore, for those situations where MOZAIC/IAGOS measurements differed from the MOPITT a priori, the MOPITT measurements clearly outperformed the MOPITT a priori data, indicating that MOPITT NIR retrievals add value to the MOPITT a priori. Results from a high spatial resolution simulation of the chemistry-transport model MOCAGE (MODèle de Chimie Atmosphérique à Grande Echelle) showed that the most likely explanation for the large MOPITT variability along the MOZAIC-IAGOS profile flight path is related to spatio-temporal CO variability, which should be kept in mind when using MOZAIC/IAGOS profile measurements for validating satellite nadir observations.

1 Introduction

Carbon Monoxide (CO) is an important atmospheric trace gas due to its relevance for the oxidizing capacity of the troposphere (Crutzen and Zimmermann, 1991) as its reaction with the hydroxyl (OH) radical – the atmospheric detergent – is the most important sink of OH. Furthermore, CO also plays a role in regional air quality and air pollution as a precursor of tropospheric ozone (O₃) – an important component of air pollution

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– and is therefore often used for monitoring long-range transport of air pollution (e.g. Guerova et al., 2006; Konovalov et al., 2010; Nam et al., 2010; Ghude et al., 2011).

A currently important scientific question is whether the oxidizing capacity of Earth's atmosphere has been changing over the last decades (i.e. Dalsoren and Isaksen, 2006; Montzka et al., 2011). On the one hand, increased air pollution can increase the OH concentration as its formation is related to tropospheric ozone production. On the other hand, increases in CO concentrations, and to a lesser extent, in methane (CH₄) concentrations may reduce atmospheric OH concentrations as their reactions with OH form the major sink of atmospheric OH. Furthermore, changes in OH will affect the atmospheric residence time of CH₄ and ozone and thus modify the earth radiative balance by their warming effect. Because of the dominant role CO plays in the atmospheric OH budget, monitoring CO thus helps in understanding past and present changes in air pollution as well as in certain greenhouse gases. For these reasons, carbon monoxide has been identified as an Essential Climate Variable precursor by the World Meteorological Organization (WMO/GCOS).

Because of its typical atmospheric residence time of weeks to months, a reliable estimate of the global CO budget can only be provided by the use of satellite measurements. For studying long term changes in CO, it is vital that satellite measurements do not contain biases either in space and time. It is thus important that the satellite measurements are well calibrated and validated.

One of the longest records of measurements of tropospheric constituents from space is actually that of CO by the US/Canadian Measurement Of Pollution In The Troposphere (MOPITT) mission, which has been operational since March 2000. The MOPITT instrument has been providing the vertical distribution of CO from measuring thermal InfraRed (IR) radiation emitted by Earth and its atmosphere. Many scientific papers have been published using MOPITT data (e.g. Worden et al., 2013, and references therein; see also <http://www2.acd.ucar.edu/mopitt/refereed-publications>).

Apart from measuring IR radiation around 4.7 μm, the MOPITT instrument also measures in the 2.3 μm wavelength range (also known as Near InfraRed or NIR). It was

(1) how results compare with the validation results of Deeter et al. (2013), (2) can we find indications for spatial biases and (3) is there any long term drift in the MOPITT measurements, which is important for long-term monitoring of CO.

Furthermore, although used for validation of SCIAMACHY CO, there still is an important open question with regard to the use of MOZAIC/IAGOS data for satellite validation: how representative are the integrated CO profile MOZAIC/IAGOS measurements of a true vertical CO column? Because the MOZAIC/IAGOS profile measurements used for validation of CO profiles and total columns are obtained during take-off and landing of aircraft, these profiles cover a certain horizontal distance (typically 200–400 km, the so-called “profile flight path”). Because of the lower data quality of SCIAMACHY CO, considerable spatio-temporal averaging of SCIAMACHY was required to reduce SCIAMACHY CO measurement errors to acceptable levels in the study by de Laat et al. (2012). Hence, the question related to the representativity of the MOZAIC/IAGOS CO profiles did not have to be addressed in that study. However, given that MOPITT NIR measurements are of higher quality than those of SCIAMACHY – thus not requiring extensive spatio-temporal averaging – and that the size of the MOPITT pixel is considerably smaller (approximately 25 km) than the typical profile flight path distance, the question should be asked whether – and how – a single MOPITT measurement should be compared with the MOZAIC/IAGOS profiles. A clear answer to this question is important for the use of MOZAIC/IAGOS measurements in satellite validation, but has never been addressed before in detail. This validation study will address this fundamental question and will serve as a baseline for future studies on how to use MOZAIC/IAGOS profile measurements for satellite validation.

This paper is organized as follows: Sect. 2 describes the measurement and model data used in this study, as well as a detailed explanation of the criteria and methods used to collocate and compare MOPITT and MOZAIC/IAGOS measurements. Section 3 presents the validation statistics at global and continental scales. Section 4 discusses results for individual MOZAIC/IAGOS airport locations. Section 5 analyses high spatio-temporal chemistry-transport model simulations from the perspective of the

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spatial representation of MOZAIC/IAGOS CO profile measurements compared to the MOPITT CO total column measurements. Section 6 ends the paper with a summary and discussion.

2 Data

2.1 MOPITT V5 NIR

This paper uses the same MOPITT V5 data as in the validation paper of Deeter et al. (2013) which builds on earlier work for MOPITT V4 as outlined in Deeter et al. (2009, 2010) and Worden et al. (2010). We refer to both papers and references therein for the details of the MOPITT V5 retrievals and dataset. We suffice here with a few remarks about MOPITT V5 NIR data relevant for this study.

First of all, the MOPITT NIR CO retrievals obtain information from 2.3 μm first overtone band which is the same wavelength range used by SCIAMACHY. This wavelength range is dominated by reflected solar radiation rather than thermal IR radiation emitted by Earth and the atmosphere. An advantage of this wavelength range is that the vertical sensitivity of NIR retrievals is much more uniform with height (Gloudemans et al., 2008) than that of IR retrievals, which are particularly sensitive to temperature differences between Earth's surface and the atmosphere. On the other hand, the NIR measurements are – amongst others – also determined by the Earth surface NIR reflectance properties. As a result, due to the very low reflectivity of oceans at NIR wavelengths, the signal-to-noise over cloud-free oceans is too low for meaningful NIR retrievals. Hence, only daytime observations over land are available for MOPITT NIR. Note that the combined use of CO and CH₄ retrievals in SCIAMACHY enables meaningful retrievals over clouded ocean scenes as CH₄ is used to provide information on the cloud height. However, since MOPITT does not provide CH₄ measurements, the same methodology cannot be applied for MOPITT NIR.

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2.3.3 MOPITT collocations along MOZAIC/IAGOS profile path

Because the MOZAIC/IAGOS profile measurements de facto are not true vertical profiles but rather follow sort of a slant path through the atmosphere during ascent and descent of the aircraft – see later Sect. 5 and Fig. 5, the horizontal distance covered by the MOZAIC/IAGOS profiles typically ranges from 200 to 400 km, with minimum and maximum distances covered for the data used in this study varying between 71 and 444 km with a mean and median distance both just over 300 km.

For the comparison with MOPITT NIR measurements, we define a collocation with MOZAIC/IAGOS as follows: measurement should be made during the same day (UTC time), and the MOPITT pixel center should be collocated within 25 km of the MOZAIC/IAGOS profile path. The number of MOPITT collocations per MOZAIC/IAGOS profile varies strongly as – apart from the MOPITT pixels size and orbit width – cloud cover and land-sea masks also play a role. For approximately 50 % of the MOZAIC/IAGOS measurements, there are 10 or more MOPITT collocations. This percentage gradually decreases with increasing number of collocations: for 25 %/10 %/5 % of the MOZAIC/IAGOS sub-columns, there are more than 19/27/32 MOPITT collocations, respectively (see Supplement Table S1). The maximum number of MOPITT collocations for a MOZAIC/IAGOS profile was 46. Hence, it is important to realize that each MOZAIC/IAGOS profile measurement typically is assigned to multiple MOPITT measurements.

2.3.4 MOPITT averaging kernel and MOPITT a priori

The MOPITT averaging kernels are applied to the logarithm of the MOZAIC/IAGOS mixing ratio profiles, following Deeter et al. (2013):

$$\text{comparison profile} = X_{\text{a priori}}^{10_{\log}} + A \left(X_{\text{MOZAIC/IAGOS}}^{10_{\log}} - X_{\text{a priori}}^{10_{\log}} \right)$$

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- MOPITT profiles must start below 800 hPa.
- MOPITT measurements are collocated with MOZAIC/IAGOS if the pixel center lies within 25 km distance of the MOZAIC/IAGOS flight path.
- Every single MOPITT measurement collocated with a MOZAIC/IAGOS flight path is considered a collocation with that MOZAIC/IAGOS measurement, resulting in multiple collocations with a single MOZAIC/IAGOS profile measurement.
- MOPITT averaging kernel and a priori are applied to the vertically extended MOZAIC/IAGOS profile for each single MOPITT collocation.
- After convolution with the MOPITT averaging kernel and a priori, the MOZAIC/IAGOS profiles are vertically integrated to total columns for comparison with MOPITT total columns.

2.4 MOCAGE

To investigate the representation of a CO total column based on the MOZAIC/IAGOS profile measurements – which covers a horizontal distance – compared to true total CO columns as measured by MOPITT, results from a high resolution ($0.2^\circ \times 0.2^\circ$) simulation of the regional chemistry-transport model MOCAGE have also been analyzed.

The MOCAGE model (MODèle de Chimie Atmosphérique à Grande Echelle) (Peuch et al., 1999) is a 3-D-CTM which covers the planetary boundary layer, the free troposphere, and the stratosphere. It provides a number of optional configurations with varying domain geometries and resolutions, as well as chemical and physical parameterization packages. It has the flexibility to use several chemical schemes for stratospheric and tropospheric studies. For example, the MOCAGE main scheme is a detailed chemical scheme with 89 prognostic variables and 372 reactions.

MOCAGE is used for several applications: operational chemical weather forecasting in Météo-France (Dufour et al., 2004), tropospheric as well as stratospheric research studies (e.g. Josse et al., 2004; Michou et al., 2005; Ricaud et al., 2009a, b), and data

assimilation research, (e.g. Cathala et al., 2003; Pradier et al., 2006; Clark et al., 2007; Semane et al., 2007; El Amraoui et al., 2008a, b; Semane et al., 2009). MOCAGE can be forced dynamically by external wind and temperature fields from the Météo-France reanalysis ARPEGE (“Action de Recherche Petite Echelle Grande Echelle”).

The MOCAGE simulations used in this paper were performed within the ESA-ISOTROP project (see acknowledgements). We only use the results of free runs from the ISOTROP ozone Nature runs over a European domain (see later Figure 5) for two periods lasting three months (June–September 2003 and November 2003–January 2004). For these simulations, anthropogenic emissions are based on the TNO-MACC emission inventory used for the LOTOS-EUROS model at $0.2^\circ \times 0.2^\circ$ resolution (Kuenen et al., 2011; Denier van der Gon et al., 2010), complemented by EMEP $0.5^\circ \times 0.5^\circ$ shipping emissions. No seasonal variability of these anthropogenic emissions is assumed. The biogenic emissions are available on the model resolution but fixed per month following Simpson et al. (2003). Biomass burning emissions are based on GFED V3 (daily on $1^\circ \times 1^\circ$).

3 Validation statistics

Figure 1a shows the comparison of all MOZAIC/IAGOS – MOPITT collocation pairs for the 2002–2010 period. Due to the large spatial extent of a single MOZAIC/IAGOS measurement, the number of collocations for a single MOZAIC/IAGOS profile measurement can be as large as 46 MOPITT measurements. The variability in MOPITT CO total columns along the MOZAIC/IAGOS flight path is represented by the vertical bars in Fig. 1a. The results indicate that MOPITT CO variability is very large along the MOZAIC/IAGOS profile path relative to the CO total column range, and this range is larger than seen in the comparison with the NOAA data as presented in Deeter et al. (2013; their Fig. 4). Nevertheless, the correlation between MOPITT and MOZAIC/IAGOS CO total columns is still similar between both studies and the bias is a slightly smaller (see Table 1).

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indicate no statistically significant drift in the differences, despite considerable month-to-month differences.

To further investigate the MOZAIC/IAGOS–MOPITT comparison, the same analysis was performed for four different areas: North America (Fig. 2c and d), Europe (Fig. 2e and f), Asia (Fig. 2g and h) and the rest of the world (Fig. 2i and j). The corresponding time series for a select number of representative airports can be found in Supplement Figs. S1 and S2. Table 2 summarizes the results of the regressions for these regions. For North America, no statistically significant drift in the differences is detected. For Europe we see a statistically significant but very small drift in the raw data but not in the monthly mean data. Note that the significance level of the regression is smaller for the raw data than for the monthly mean data, despite a much larger range in the raw data. This suggests that the use of a standard linear regression is not fully appropriate for the raw data.

For Asia, a statistically significant drift in the differences of $-0.04 \pm 0.02 \times 10^{18}$ molecules cm^{-2} is detected in both raw and monthly mean data. For the rest of the world, excluding Windhoek to avoid that Windhoek dominates the statistics as Windhoek by far provides the most measurement points and has a particularly strong seasonal cycle and thus large range of column values (see Supplement Table S2), there is no significant drift in both the raw data and the monthly mean data.

The data density for Asia is much smaller than for Europe or North America (see probability distributions in Fig. 2f and h). In particular, after 2006 only data from Hyderabad is available. Since Hyderabad shows a small negative bias (see Supplement Fig. S2f), it is likely that the drift for Asia is artificial. To test this idea, the regression statistics were calculated after correcting the Hyderabad data for its bias compared to MOZAIC/IAGOS and results are included in Table 2. Clearly, the drift becomes insignificant after correcting for the Hyderabad bias, confirming that care has to be taken with calculating drifts based on combined data.

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4 Individual station data

Figure 3 shows an example of the comparison between MOPITT and MOZAIC/IAGOS based total column measurements for Windhoek, Namibia, which is a location with a particular strong seasonal cycle due to strong biomass burning emission in the regions between August and November. MOPITT and MOZAIC/IAGOS compare very well with regard to the absolute column values and the seasonal cycle. However, the MOPITT data shows a considerable spread among the MOPITT measurements collocated with the MOZAIC/IAGOS measurements. Nevertheless, compared to the MOPITT a priori statistics, the actual MOPITT measurements compare better for all statistical measures. In addition, the MOPITT measurements capture the high outliers during the biomass burning season not present in the a priori data, thus proving that the MOPITT measurements do add value to the a priori MOPITT data. Furthermore, when considering the MOPITT variability along the MOZAIC/IAGOS profile path (the “range” data; see Sect. 3, Table 1) statistics improve even further for both the correlation and the root-mean-square differences. In addition, there is no significant drift in the differences during this period. Overall, the agreement between MOPITT and MOZAIC/IAGOS is very good for this particular location: the bias is insignificant, the root-mean-square difference is approximately 10 % of the mean column and the correlation is 0.66 (R^2), while the statistics improve when taking the MOPITT flight path variability into account ($R^2 = 0.78$; smaller root-mean-square difference).

Figure 4a–c shows the statistics of the 35 airports with most collocations. Indicated are three parameters: correlation (a), bias (b) and root-mean-square differences (c). Each statistic is calculated for the average MOPITT column, the adjusted average MOPITT columns based on the observed MOPITT variability along the flight path (“range” data, see Sect. 3), and the MOPITT a priori.

In general, correlations are moderate to high, typically between 0.6 and 0.9, and the statistics for the MOPITT “range” data are 0.05 to 0.1 points higher than for the average MOPITT data. However, correlations between MOZAIC/IAGOS and the MOPITT

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MOPITT and IAGOS/MOZAIC. Figure 4b shows that when comparing MOPITT with MOZAIC/IAGOS the majority of biases are – in absolute sense – smaller for the MOPITT measurements comparison relative to the MOPITT a priori comparison by a factor of 2 or more (see also Supplement Table S2b).

5 A different approach for evaluating the added value of MOPITT NIR measurements is by assessing those situations where the MOZAIC/IAGOS measurements deviate significantly from the MOPITT a priori. It could be expected that particularly in those situations – the a priori deviates from reality – MOPITT adds information to the a priori. Based on an analysis similar to the one performed for Fig. 1 we checked
10 the comparison of the MOPITT NIR and MOZAIC/IAGOS measurements for cases where the MOZAIC/IAGOS measurements deviated – in absolute sense – more than $0.3/0.4/0.5 \times 10^{18}$ molecules cm^{-2} from the MOPITT a priori (corresponding fraction of measurements qualifying for this filter are 11 %, 7 % and 4 % of the total number of MOZAIC/IAGOS measurements, respectively; see also Table 3). These are clearly
15 the “outliers” for which one would expect MOPITT measurements to outperform the MOPITT a priori.

Table 3 shows the results of that comparison: for MOZAIC/IAGOS – MOPITT a priori differences within the threshold range, the correlations between MOZAIC/IAGOS and the MOPITT a priori (0.92–0.95) are slightly better than the correlations between
20 MOZAIC/IAGOS and the MOPITT NIR measurements (0.88–0.93; columns 2 and 3/4 in Table 3). However, correlations are very high and differences in correlations are small (0.01–0.08). On the other hand, for MOZAIC-MOPITT a priori differences outside the threshold range the MOPITT NIR measurements clearly outperform the MOPITT a priori: differences in correlation coefficients are 0.15–0.18 larger depending
25 on the threshold value (columns 6/7 in Table 3) for MOPITT NIR measurements compared to the MOPITT a priori. Even the MOPITT measurements not corrected for the MOZAIC/IAGOS flight path variability outperform the MOPITT a priori by 0.1–0.13 according to their correlation (columns 6/8 in Table 3). This analysis shows that the

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the statistical similarity between the model results and the MOZAIC/IAGOS–MOPITT comparison indicates that the spread among MOZAIC/IAGOS collocated MOPITT NIR columns is indeed very likely related to CO variability. Note that overall, CO is underestimated in MOCAGE based on the comparison with MOZAIC/IAGOS, a common feature in chemistry-transport modeling (i.e. Shindell et al., 2006).

6 Summary, conclusions and discussion

In this paper MOPITT V5 NIR CO total column measurements were validated against CO total columns based on MOZAIC/IAGOS profile measurements obtained for the period 2002–2010. Results from our comparison agree with those of Deeter et al. (2013), with a correlation of 0.86, a root-mean-square difference of 0.23×10^{18} molecules cm^{-2} and no bias. When taking the MOPITT observed flight-path CO column variability into account these numbers are 0.91 for the correlation, 0.18×10^{18} molecules cm^{-2} for the root-mean-square differences and no bias. For Deeter et al. (2013) these numbers are a correlation of 0.91 and a root-mean-square difference of 0.18×10^{18} molecules cm^{-2} , and a bias of 0.08×10^{18} molecules cm^{-2} . No MOPITT V5 NIR bias was identified and no long-term drift – indicative for MOPITT calibration errors – was found, consistent with Deeter et al. (2013). In addition, correlations were similar, and also on regional scales no biases and drifts were found for the MOPITT–MOZAIC/IAGOS comparison.

Because MOPITT V5 NIR measurements are to some extent determined by the MOPITT a priori, it was also investigated if the validation results improve when taking the MOPITT a priori into account. It is by no means trivial that the validation results improve over the comparison with the MOPITT a priori: the MOPITT a priori is based on a global chemistry-transport model climatology that includes the seasonal cycle, geographical and vertical variations in CO that drive CO total column variability. To test whether there is added value in the MOPITT NIR CO measurements, MOZAIC/IAGOS measurements that deviated from the MOPITT a priori were used to validate the MOPITT NIR measurements. Results showed that the MOPITT NIR measurements

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outperformed the MOPITT a priori, showing that the MOPITT NIR measurements indeed “add value” to the MOPITT a priori. Additionally, biases between MOPITT and MOZAIC/IAGOS were – in absolute sense – smaller by a factor of 2 or more than biases between the MOPITT a priori and MOZAIC/IAGOS.

Validation of MOPITT measurements against MOZAIC/IAGOS measurements is hampered by the spatial footprint of MOZAIC/IAGOS measurements. The vertical profile of MOZAIC/IAGOS measurements obtained during take-off or landing of commercial aircraft typically covers between 200 and 400 km. Results from high spatio-temporal simulations by the regional chemistry-transport model MOCAGE over Europe and collocated with MOZAIC/IAGOS measurements indicate that indeed there can be large variability in CO total columns along the MOZAIC-IAGOS profile path. The CO total column based on the MOZAIC/IAGOS profile measurements is thus not fully representative for the true vertical CO total column, and this representation error has to be kept in mind. A comparison of MOPITT and MOZAIC/IAGOS using a simple methodology to assess this representation error indeed shows similar variability. However, there is no uniform general method how to quantify the representation error. This error is location specific and depends on typical atmospheric transport patterns and proximity of emission sources. It is therefore advised to carefully consider use of MOZAIC/IAGOS station by station.

The MOZAIC/IAGOS measurements nevertheless provide a highly valuable dataset for validation of MOPITT NIR CO total column measurements as they cover the entire MOPITT measurement period and provide information for locations not covered by the validation results presented in Deeter et al. (2013; only North America). Care has to be taken when comparing single MOZAIC/IAGOS measurements with MOPITT measurements due to the different air masses sampled. In addition, although the representation error of CO total column measurements based on MOZAIC/IAGOS data is not crucial for the comparison of CO total columns, use of MOZAIC/IAGOS measurements of for example ozone (O_3) or nitrogen dioxide (NO_2) to validate tropospheric ozone column

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measurements from satellites may be more sensitive to this representation error due to, for example, larger spatio-temporal variability.

Finally, it is worth mentioning that recent advances in assimilation of satellite measurements of CO can be useful for the validation of MOPITT CO. The assimilation results provide information that can be compared with both satellite as well as in situ measurements. Hence, they may bridge the “representation gap” between satellite and in situ measurements.

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Table 2. Regression statistics of MOZAIC/IAGOS–MOPITT differences for the period 2002–2010 for all data (Raw) as well as monthly means. For North America, the data from the airport of Philadelphia, New York, Washington, Toronto, Montreal, Dallas, Atlanta, Vancouver, Portland and Los Angeles are used. For Europe, data from Frankfurt, Munich, Vienna and London is used. For Asia, data from Osaka, Tokyo, Beijing, Hyderabad and Teheran are used. Values are in molecules $\text{cm}^{-2} \text{year}^{-1}$, uncertainties denote the $1-\sigma$ value. Figure 2c–j show the figures corresponding to the North America, Europe, Asia and Rest-of-the-world data in a similar fashion as Fig. 2a and b. Rest-of-the-world data combines all locations not covered by the North America, Europe and Asia statistics and also excludes Windhoek, Namibia.

	Raw	Monthly	Deeter et al. (2013)
Global	$0.005 \pm 0.003 \times 10^{18}$	$0.003 \pm 0.008 \times 10^{18}$	$-0.003 \pm 0.004 \times 10^{18}$
North America	$0.009 \pm 0.007 \times 10^{18}$	$0.007 \pm 0.011 \times 10^{18}$	
Europe	$0.014 \pm 0.004 \times 10^{18}$	$-0.001 \pm 0.008 \times 10^{18}$	
Asia	$-0.040 \pm 0.013 \times 10^{18}$	$-0.044 \pm 0.022 \times 10^{18}$	
Asia ¹	$-0.007 \pm 0.013 \times 10^{18}$	$-0.013 \pm 0.036 \times 10^{18}$	
Rest ²	$0.006 \pm 0.008 \times 10^{18}$	$0.014 \pm 0.020 \times 10^{18}$	

¹ Drift statistics after correcting for the Hyderabad bias.

² Drift statistics without Windhoek, Namibia.

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Table 3. Correlation statistics of the comparison between MOPITT and MOZAIC/IAGOS. The sigma value (10^{18} molecules cm^{-2}) indicates the absolute threshold difference between MOZAIC/IAGOS and the MOPITT a priori for which the statistics are calculated. The “P” column indicates either the number of measurements (N) or the correlation coefficient (R). The “Delta” row indicates if the statistics are calculated based on the data selection for which the difference between MOZAIC/IAGOS and MOPITT a priori CO total columns is above or below the chosen threshold difference (Δ). The “Comparison” row indicates for which comparison the statistics are calculated (MOPITT a priori, “Apr”, or MOZAIC/IAGOS, “MOZ”). The “MOPITT” row indicates, in case of a comparison with MOZAIC/IAGOS, if the mean MOPITT CO total column along the MOZAIC/IAGOS profile path is used (“mean”) or the MOPITT CO total columns after taking the MOPITT NIR column variability below the MOZAIC/IAGOS profile path into account (“+ Δ ”), as described in Sect. 3.

Column	1	2	3	4	5	6	7	8
P	N	R	R	R	N	R	R	R
Delta	$< \Delta$	$< \Delta$	$< \Delta$	$< \Delta$	$> \Delta$	$> \Delta$	$> \Delta$	$> \Delta$
Comparison		Apr	MOZ	MOZ		Apr	MOZ	MOZ
MOPITT			mean	+ Δ			Mean	+ Δ
$\Delta = 0.3$	7965	0.96	0.88	0.93	1015	0.69	0.79	0.84
$\Delta = 0.4$	8364	0.95	0.88	0.93	616	0.66	0.79	0.84
$\Delta = 0.5$	8640	0.93	0.88	0.92	340	0.65	0.78	0.81

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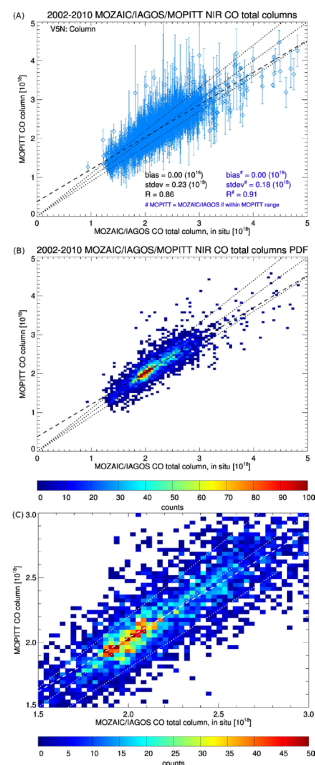


Figure 1. Comparison of all MOPITT and MOZAIC/IAGOS CO total columns for the period 2002–2010. The vertical bars in **(A)** indicate the range of MOPITT CO total columns that were collocated with the MOZAIC/IAGOS profile path. **(B)** shows the scatter distribution of the comparison in **(A)**. **(C)** shows a zoom in of **(B)**. For the blue statistics in **(A)** the MOPITT total column is set equal to the MOZAIC/IAGOS total column if the MOZAIC/IAGOS total column value falls within the MOPITT range of CO total columns. The dotted lines in **(B)** and **(C)** indicate the 1 : 1 line and the $\pm 10\%$ range, the dashed lines indicate the ordinary linear regression through all data.

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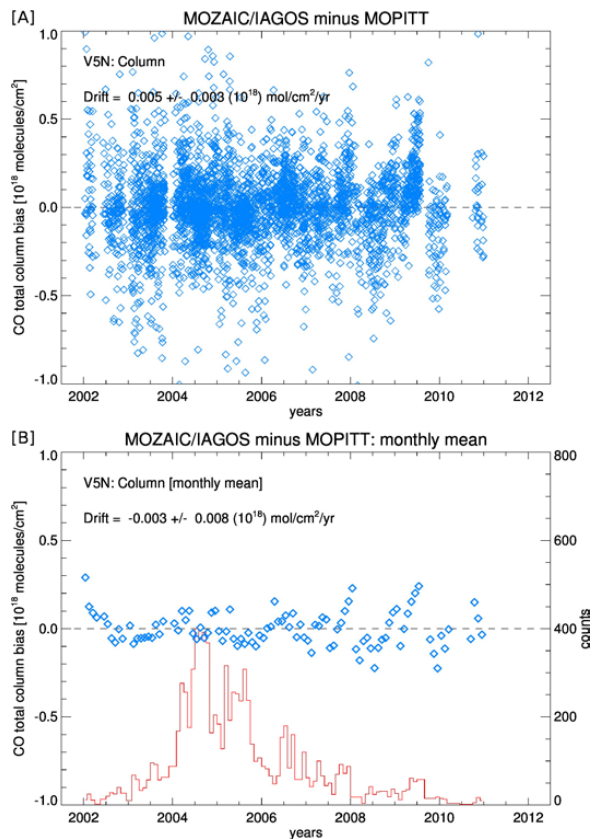


Figure 2. Time series plots showing the MOPITT bias trends based on the comparison with MOZAIC/IAGOS. **(A)** shows the comparison for all data, i.e. all MOPITT total columns collocated with MOZAIC/IAGOS measurements. The lower plot shows the comparison based on monthly means and includes the number of measurements that comprise the monthly means (red line).

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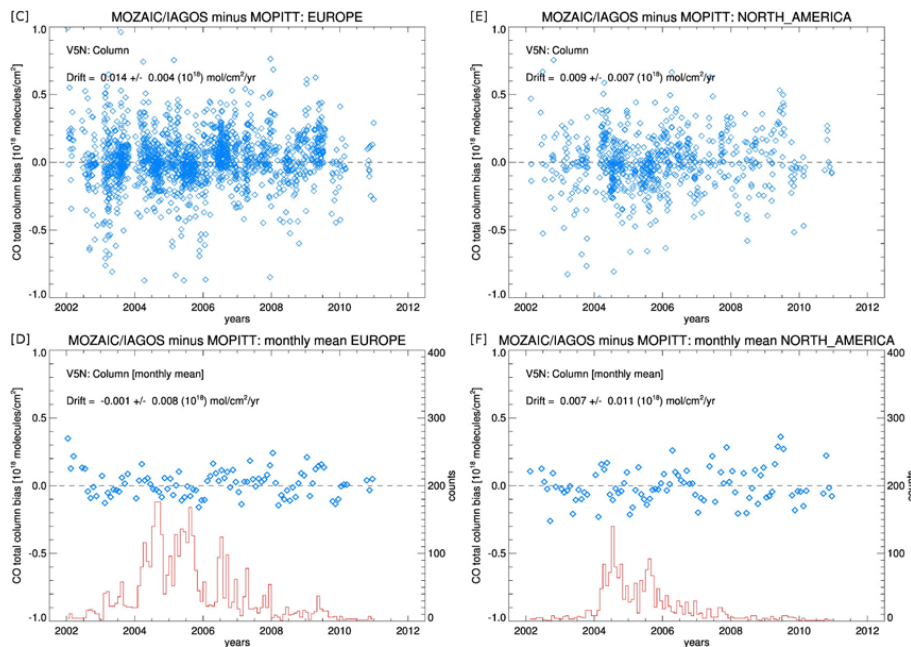


Figure 2. (C and D) and (E and F) as Fig. 2a and b but for Europe and North America only, respectively.

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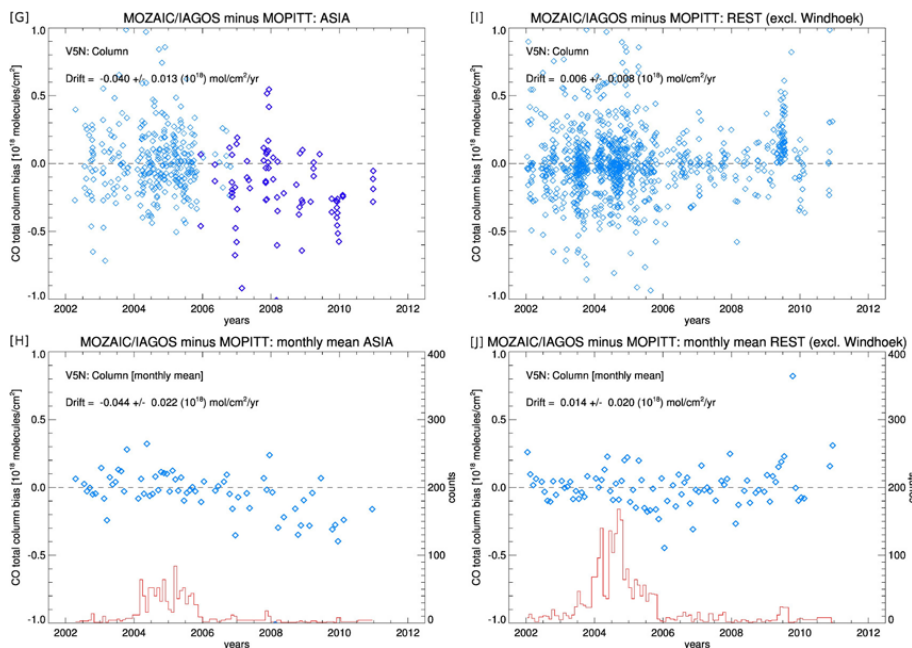


Figure 2. (G and H) and (I and J) as Fig. 2a and b but for Asia and the Rest of the World (excluding Windhoek, Namibia), respectively. The dark blue squares in the upper left plot show the Hyderabad measurements.

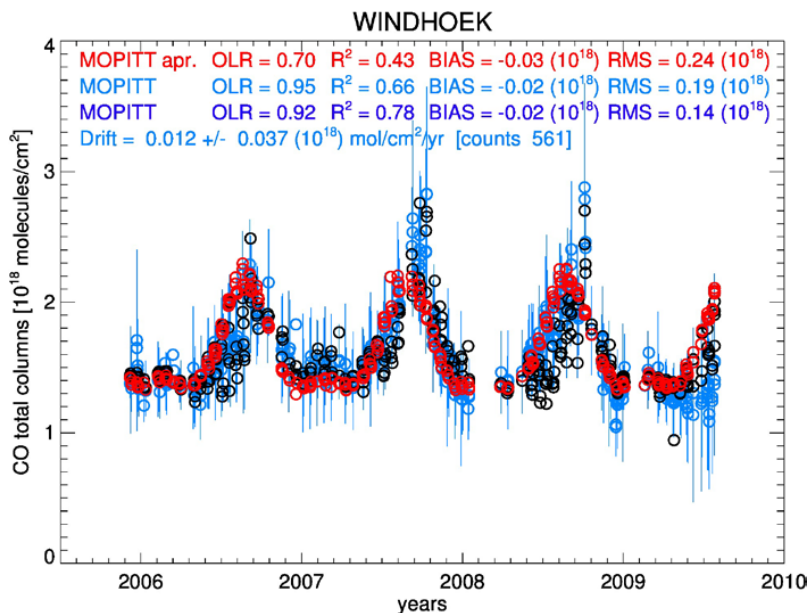


Figure 3. Time series of CO total columns at Windhoek, Namibia, for MOZAIC/IAGOS (black) as well as MOPITT measurements (blue) and the MOPITT a priori (red). The MOPITT measurements show the mean (circle) and the range of MOPITT measurements (line) that coincide with a single MOZAIC/IAGOS measurement. The statistics represent the Ordinary Linear Regression (OLR) coefficient, the explained variance (square of correlation coefficient: R^2), the bias and the root-mean-square (RMS) differences. For the dark blue statistics (so-called “RANGE”), we assume that if the MOZAIC/IAGOS column falls within the range of MOPITT total column measurements along the MOZAIC/IAGOS flight path, the MOPITT column equals the MOZAIC/IAGOS column. The drift statistics are calculated for the basic MOZAIC/IAGOS–MOPITT comparison without consideration of the MOPITT range along the MOZAIC/IAGOS flight path.

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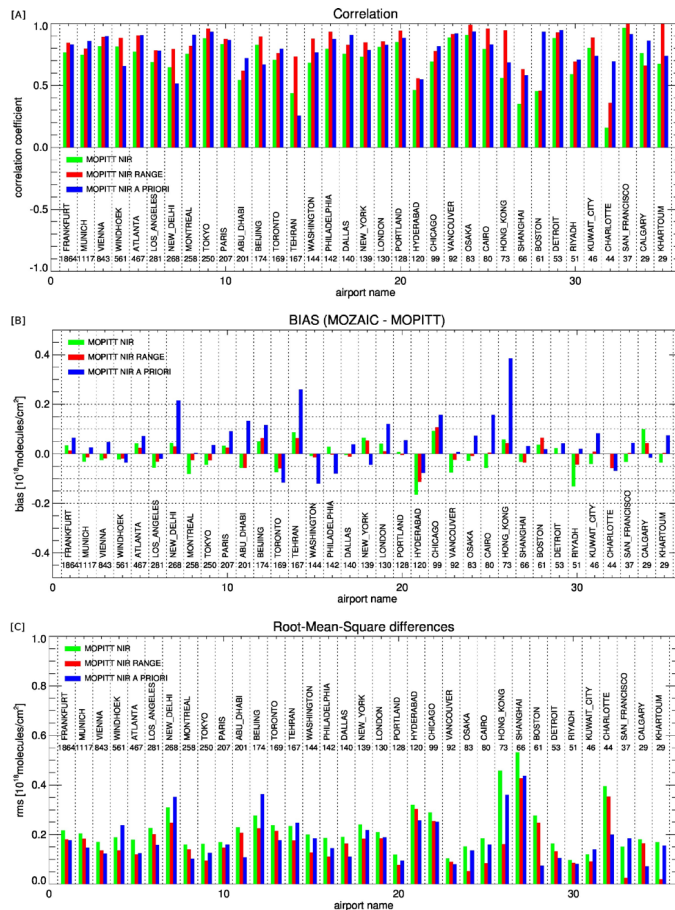


Figure 4. Statistics as shown in Fig. 3 for the 35 airport locations with the most MOPITT–MOZAIC/IAGOS collocations. The stations are ordered left-to-right according to decreasing number of collocations.

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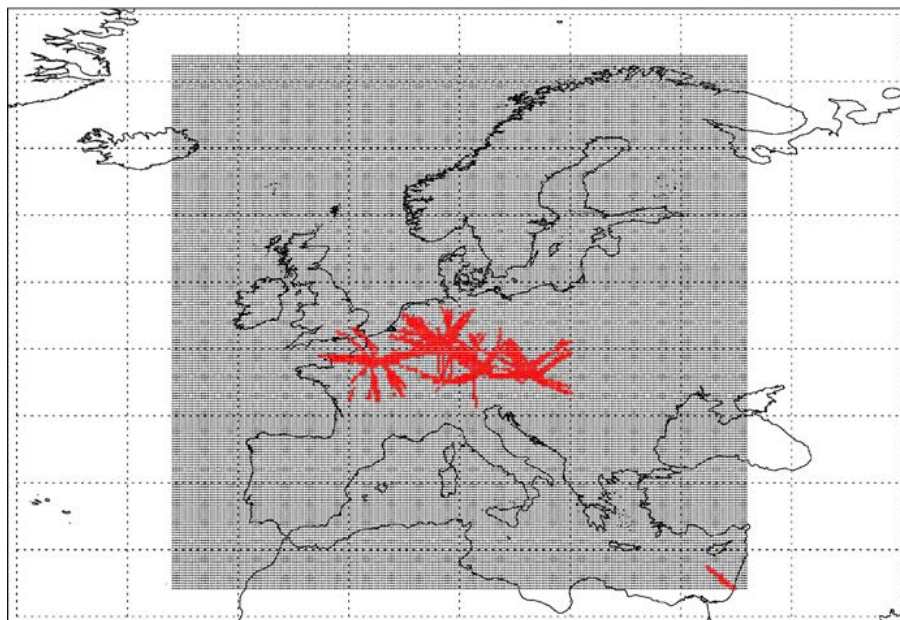


Figure 5. MOCAGE regional chemistry-transport model domain and corresponding MOZAIC/IAGOS profile measurements (flights paths; red) that were made during the two periods for which the MOCAGE simulations were available (June–August 2003 and November 2003–January 2004).

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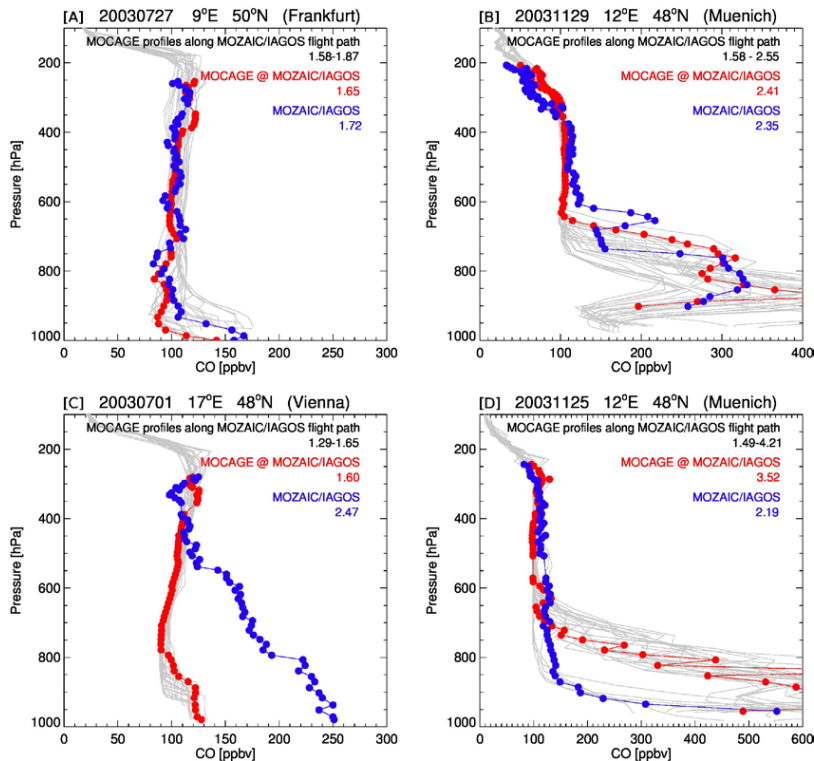


Figure 6. Comparisons between MOZAIC/IAGOS and MOCAGE CO profile measurements. The MOCAGE profiles collocated with the MOZAIC/IAGOS flight path profile are displayed in grey, the MOCAGE profile measurements exactly collocated with MOZAIC/IAGOS is in red. The corresponding MOZAIC/IAGOS profile is shown in blue. Indicated are also the date, the approximate geographical location of the MOZAIC/IAGOS profile measurement including departure or landing airport and the values of partial columns for the MOZAIC/IAGOS profile as well as the corresponding MOCAGE profile along the MOZAIC/IAGOS profile and the range of MOCAGE partial columns along the MOZAIC/IAGOS profile path (in 10^{18} molecules cm^{-2}).

Validation of MOPITT V5 NIR CO using MOZAIC/IAGOS measurements

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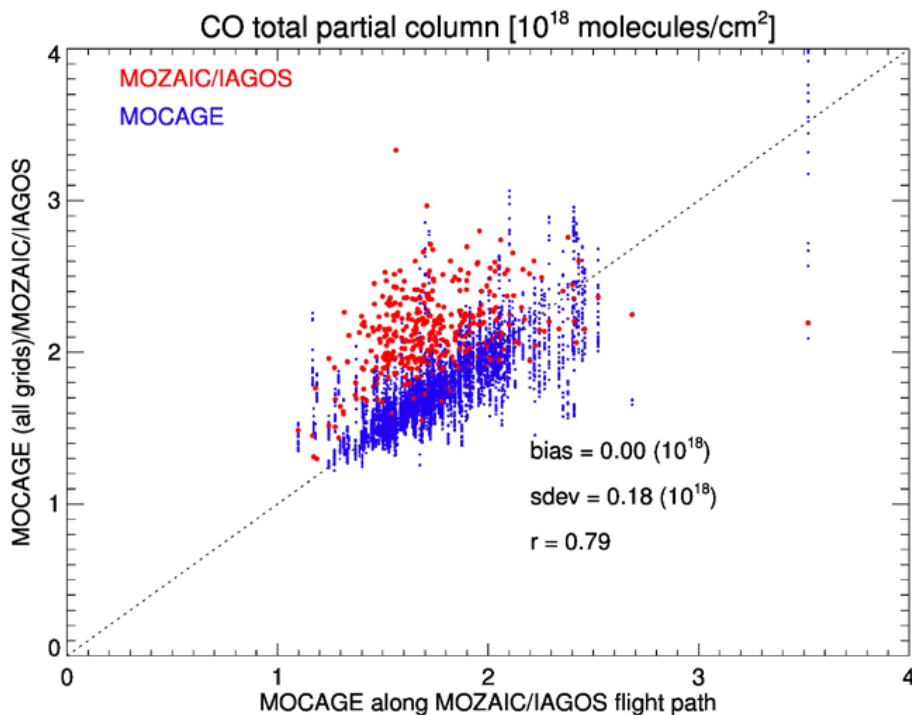


Figure 7. Comparison of all MOCAGE and MOZAIC/IAGOS partial CO total column measurements made for the period June–August 2003 and November 2003–January 2004. No attempt was made to extend the profiles beyond the maximum measurement height; columns here thus represent partial columns. The horizontal axis shows the MOCAGE total column based on the MOZAIC/IAGOS profile path collocations, the vertical axis shows the corresponding MOZAIC/IAGOS total column (red) and the MOCAGE CO total columns collocated with the MOZAIC/IAGOS flight path profile (blue), the latter for which the statistics are also printed.

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