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Analysis of global and regional CO burdens measured from space between 2000 and 2009 and validated by ground-based solar tracking spectrometers

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Abstract. Interannual variations in AIRS and MOPITT retrieved CO burdens are validated, corrected, and compared with CO emissions from wild fires from the Global Fire Emission Dataset (GFED2) inventory. Validation of daily mean CO total column (TC) retrievals from MOPITT version 3 and AIRS version 5 is performed through comparisons with archived TC data from the Network for Detection of Atmospheric Composition Change (NDACC) ground-based Fourier Transform Spectrometers (FTS) between March 2000 and December 2007. MOPITT V3 retrievals exhibit an increasing temporal bias with a rate of 1.4–1.8% per year; thus far, AIRS retrievals appear to be more stable. For the lowest CO values in the Southern Hemisphere (SH), AIRS TC retrievals overestimate FTS TC by 20%. MOPITT's bias and standard deviation do not depend on CO TC absolute values. Empirical corrections are derived for AIRS and MOPITT retrievals based on the observed annually averaged bias versus the FTS TC. Recently published MOPITT V4 is found to be in a good agreement with MOPITT V3 corrected by us (with exception of 2000–2001 period). With these corrections, CO burdens from AIRS V5 and MOPITT V3 (as well as MOPITT V4) come into good agreement in the mid-latitudes of the Northern Hemisphere (NH) and in the tropical belt. In the SH, agreement between AIRS and MOPITT CO burdens is better for the larger CO TC in austral winter and worse in austral summer when CO TC are smaller. Before July 2008, all variations in retrieved CO burden can be explained by changes in fire emissions. After July 2008, global and tropical CO burdens decreased until October before recovering by the beginning of 2009. The NH CO burden also decreased but reached a minimum in January 2009 before starting to recover. The decrease in tropical CO burdens is explained by lower than usual fire emissions in South America and Indonesia. This decrease in tropical emissions also accounts for most of the change in the global CO burden. However, no such diminution of NH biomass burning is indicated by GFED2. Thus, the CO burden decrease in the NH could result from a combination of lower fossil fuel emissions during the global economic recession and transport of CO-poor air from the tropics. More extensive modeling will be required to fully resolve this issue.

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1 Introduction

Carbon monoxide (CO) is a trace atmospheric constituent playing an important role in tropospheric chemistry as a major sink for OH (Logan et al., 1981). According to Duncan et al. (2007), oxidation of CH_4 by OH contributes ∼34% of the total CO source in the atmosphere. However, interannual variations of this source are minor due to small (<5%) changes in concentrations of CH_4 and OH (Chen and Prinn, 2005; Prinn, et al., 2005). The Global Fire Emission Database (GFED; van der Werf et al., 2006) provides satellite estimates of monthly geographical CO emission from wild fires for the years 1997–2008 as noted hereafter for several geographic areas. Global biomass burning emissions vary between 314.6 (2008) and 591.3 (1998) Tg/year, i.e., between 14% and 25% of the total source. Especially large variability of CO emissions from wild fires is observed in Indonesia: between 11.2 (2000) and 243 (1997) Tg/year; in Siberia: between 13.8 (2004, 2005) and 100 Tg/year (1998); and in South America: between 35.8 (2000) and

Table 1. Coordinates of areas used for regional burdens and emissions in degrees (negatives are for S and W).

Region	Latitude range		Longitude range	
India and Thailand	10	30	70	110
Australia	−40	−15	115	155
Indonesia	−10	5	95	145
Siberia	50	70	60	180
South America	−40	15	−80	−35
Africa	−35	15	−20	40

108.3 (2007) Tg/ year (see Table 1 for boundaries of the regions). African fires burn every year and contribute ∼49% of the global biomass burning emission with interannual variations between 149.3 (2006) and 192.1 (2001) Tg/year.

According to Duncan et al. (2007), anthropogenic CO emissions amount to approximately 23% of the annual total source and the source from eastern Asia increased by 51% from 1988 to 1997. Ohara et al. (2007) also estimated an increase of CO emissions in Asia by 1.6 times in the period 1980–2003. Duncan et al. (2007) found, however, that the CO emission growth was compensated by economic contraction in Eastern Europe, and the global source changed by only a few percent from 1985 to 1997. According to the present study, global CO burden did not show any persistent increase that can be attributed to changes in anthropogenic sources between 2000 and 2007. Conversely, the recent global economic recession may have resulted in diminished anthropogenic emissions. The search for such a signal in satellite CO observations is one of the goals of this paper.

The space-borne sensors AIRS (Atmospheric InfraRed Sounder) on the Aqua satellite and MOPITT (Measurements of Pollution in the Troposphere) on the Terra satellite supply global distributions of CO almost in real time. Interannual variations of CO as observed by MOPITT, AIRS and the decisive role of biomass burning in these variations have been investigated previously (Edwards et al., 2004, 2006; Yurganov et al., 2005, 2008; Tanimoto et al., 2009). MOPITT data have been used for quantification of CO sources using top-down inverse global model calculations (Turquety et al., 2008 and references therein). CO mixing ratios retrieved from AIRS spectra have been used for investigation of biomass burning and anthropogenic pollution (McMillan et al., 2005, 2008, 2010; Warner et al., 2007) and quantification of CO sources using top-down inverse models (Kopacz et al., 2010; Fisher et al., 2010).

MOPITT and AIRS retrievals of CO total columns (TC) or CO profiles are the product of convolution of the true CO profile with an a priori profile and averaging kernel (Deeter et al., 2004; McMillan et al., 2009). A conversion of these retrievals into emissions of CO requires employment of atmospheric models. Inverse modeling using a complex Chemical Transport Model (CTM) enables retrieval of regional and global CO sources (Turquety et al., 2008; Kopacz et al., 2010 and references therein). However, a simple global one-box model also can be used to investigate global sources and interannual variations. Yurganov et al. (2008) demonstrated a reasonable correlation between the independent CO inventory GFED2 and anomalies of emission derived from MOPITT data. GFED2 is an inventory based on satellite measurements of burned areas and fuel loads derived from Net Primary Production that in turn were calculated using Normalized Difference Vegetation Index and emission factors for CO (van der Werf et al., 2006). However, the estimates of Yurganov et al. (2008) based on MOPITT V3 data revealed a strange upward trend of CO emissions that was not confirmed by the GFED2 inventory. Further comparing CO TC measured by MOPITT V3 to CO TC measured by two ground-based sun-viewing spectrometers located in Zvenigorod (Russia) and Wollongong (Australia), Yurganov et al. (2008) found a positive instrumental drift of MOPITT with a rate of ∼1 % per year. Thus, the long-term stability of the MOPITT instrument and its retrieval algorithm required further investigation. AIRS V4 CO retrievals also were analyzed by Yurganov et al. (2008) and significant differences with both ground truth and MOPITT observations were found.

Several reports were devoted to validation of MOPITT (e.g., Barret et al., 2003; Clerbaux et al., 2008; Emmons et al., 2004, 2007; Deeter et al., 2010) and AIRS (Warner et al., 2007; McMillan et al., 2008, 2009). A bias of CO retrievals versus ground truth for MOPITT V3 has been quantified to lie between −0.4% and 15.8 % (Emmons et al., 2004, 2007) and for AIRS V5: 7–10% (McMillan et al., 2009) with standard deviations 8–15%. However, these publications, with the exceptions of Emmons et al. (2009) and Deeter et al. (2010), have not examined long-term or even seasonal dependences of the bias and were not useful for explanation of a virtual increasing trend of CO burden measured by MOPITT V3 (Yurganov et al., 2008).

Using comparisons of MOPITT CO retrievals to in situ aircraft CO profiles, Emmons et al. (2009) confirmed the positive MOPITT V3 drift found by Yurganov et al. (2008). They highlighted two likely sources of bias error in MOPITT CO retrievals. One type of bias is associated with the assumption of Gaussian variability for a-priori vertical distributions of CO mixing ratios rather than log-normal variability. A second source of potential retrieval bias is the inability of the forward model to handle profiles in polluted conditions, especially polluted boundary layers. However, both of these effects are expected to be systematic and cannot explain the temporal drift of the data. Emmons et al. (2009) concluded that an instrumental instability appears to be the major contributing cause. Throughout the operational phase of the MOPITT mission, gas pressures in both modulation cells have been slowly but steadily decreasing. This gas leakage was not properly accounted for in the V3 retrieval algorithm. The impact of these pressure drifts were confirmed through retrieval modeling simulations. The new MOPITT Version 4 product (Deeter et al., 2010) embodies algorithm enhancements which particularly improve retrieval performance.

Through an investigation of MOPITT's V3 time-dependent bias in the present paper, we propose a method for correcting the published CO TC measured by both MOPITT and AIRS (Sect. 2). Data from four Northern Hemispheric (NH) and two Southern Hemispheric (SH) observatories belonging to the Network for Detection of Atmospheric Composition Change (NDACC) together with data from a Russian grating spectrometer near Moscow are used for validation. Corrected CO total column retrievals from MOPITT V3 and AIRS V5 are integrated globally and over three latitudinal belts (Northern and Southern mid-latitudes and tropics) and compared (Sect. 3). Most recently (Deeter et al., 2010) MOPITT V4 was released. Our paper demonstrates a good agreement between MOPITT V4 and V3 corrected after comparison with ground-based spectrometers.

Finally, a box model and mass balance approach is applied to CO global anomalies, and we derive the global source anomaly under the assumption of negligible interannual variations of OH (Sect. 4). The source anomalies supplied by both sensors are in excellent agreement with independently calculated anomalies of CO emitted from biomass burning (updated GFED2, van der Werf et al., 2006). The possible influence of the 2008–2009 economic recession on the CO burden in the NH is discussed.

This paper is an example of reconciling MOPITT and AIRS (and, eventually, other sounders) to provide a consistent long-term record of global CO observations since March 2000. In light of the limited life-times of space-borne sensors, their different characteristics, and varied retrieval algorithms, this is a critical requirement in developing a long-term CO climate data record.

2 Comparison of satellite data with measurements from the ground

2.1 Satellite-borne sounders and ground-based spectrometers

The satellite-borne MOPITT instrument is a part of the Terra platform launched in December, 1999; MOPITT CO measurements commenced in March, 2000. Terra is in a near polar sun-synchronous orbit with a descending equator crossing time of approximately 10:30 a.m. local time (ascending 10:30 p.m.). MOPITT is a thermal IR nadir-viewing gas correlation radiometer described in detail by Drummond (1992) and Deeter et al. (2003). The data are publicly available at ftp://l4ftl01.larc.nasa.gov/MOPITT/. Currently, 2 versions of these data are available. Data for V3 (Deeter et al., 2003) are used in this publication. The improved V4 (Deeter et al., 2010) is now being archived as well.

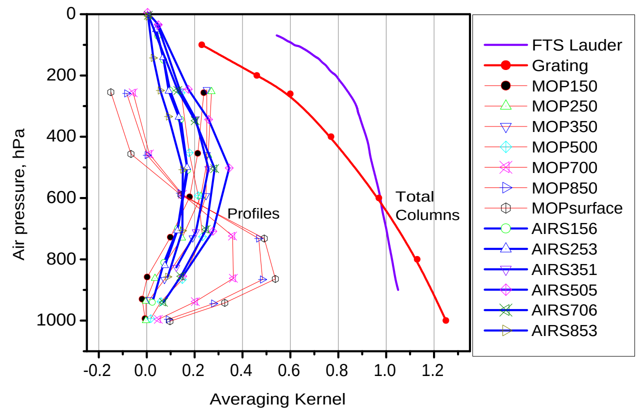

Fig. 1. Examples of averaging kernels for interferometer BRUKER IFS 120HR installed in Lauder, New Zealand (Rinsland et al., 2002), grating spectrometer in Zvenigorod, Russia (Yurganov et al., 2002), MOPITT V3 (Deeter et al., 2004) for 9 September 2000, over the tropical Atlantic, red lines, and AIRS V5 (30 August 2006, 40.1° N, 95.6° W), blue lines. Designation MOP150 means averaging kernel for 150 hPa level, etc.

Launched onboard NASA's Aqua satellite on 4 May 2002, the AIRS cross-track scanning grating spectrometer provides vertical profiles of the atmosphere with a nadir 45 km field-of-regard across a 1650 km swath (Aumann et al., 2003; Chahine et al., 2006).

Aqua also is in a near polar sun-synchronous orbit, but with an ascending equator crossing time of approximately 01:30 p.m. local time (descending 01:30 a.m.). AIRS' wider swath and cloud clearing algorithm (Susskind et al., 2003) provides near global coverage twice per day. AIRS V5 CO retrievals are detailed by McMillan et al. (2009) and are available at http://disc.sci.gsfc.nasa.gov/AIRS). Standard Level 3 data (daily, gridded to 1° latitude and 1° longitude) were used for both instruments.

CO TC amounts were measured at seven observatories in both hemispheres using Sun-viewing spectrometers (Table 2). Six of these belong to the NDACC and are equipped with Bruker Fourier Transform Spectrometers (FTS). The daily mean CO TC data are available at: ftp://ftp.cpc.ncep.noaa.gov/ndacc/station/. The Zvenigorod Research Station is affiliated with the Institute of Atmospheric Physics (IAP), Russian Academy of Sciences, near Moscow, and utilizes a solar tracking 0.2 cm^{-1} resolution Ebert/Fastie-type grating spectrometer (Yurganov et al., 2002, 2008).

The total uncertainty of the CO TC amounts measured by FTS is estimated at 6.5% (Paton-Walsh et al., 2005) and typical standard deviations of individual retrievals are between ±2 and ±6%. The accuracy of the grating spectrometer in Zvenigorod is estimated at 5–6% (Yurganov et al., 2002). The altitude sensitivity functions for both the FTS and

Table 2. Characteristics of ground-based sites and spectrometers used in this study.

Site #	Site	Coordinates	Altitude, m a.s.l.	Type of spectrometer	Typical resolution, cm^{-1}	Typical number of spectra per day
1	NyAlesund, Spitsbergen	78.92° N 11.94° E	20	Bruker IFS 120HR	0.005–0.02	2–3
2	Kiruna, Sweden	67.84° N 20.41° E	419	Bruker IFS 120HR	0.005–0.02	2–3
3	Harestua, Norway	60.22° N 10.75° E	596	Bruker IFS 120M	0.005–0.02	6–18
4	Bremen, Germany	53.11° N; 8.85° E	27	Bruker IFS 125HR	0.005–0.02	2–3
5	Zvenigorod, Russia	55.70° N, 36.80° E	200	Grating, home-made	0.18–0.23	10–25
6	Wollongong, Australia	34.45° S 150.88° W	30	Bomem DA-8	0.005–0.02	3–6
7	Lauder, New Zealand	45.04° S 169.68° W	370	BRUKER IFS 120HR	0.005–0.02	3–4

grating spectrometers maximize near the surface and slightly decrease throughout the troposphere. The vertical decrease in sensitivity for the Zvenigorod grating instrument is somewhat larger due to its lower spectral resolution. Examples of averaging kernels for ground-based and space based spectrometers are plotted in Fig. 1. An averaging kernel equal to unity in the entire troposphere would be ideal for measuring CO total column, and FTS is mostly close to this ideal instrument. As a matter of fact, satellite sensors, especially AIRS, are far from that. So, comparisons with ground truth, e.g., FTS and grating spectrometer data, are necessary. Retrieval algorithms are based on the HITRAN 2000 spectral line parameter compilation (Rothman et al., 2003) and passed the procedure of intercomparison (Hase et al., 2004). Spectral parameters for CO and water vapor lines near 4.6 µm have not changed significantly since 2000.

Target uncertainties of both sounders for CO total column are ±10%. For this analysis, the criterion for temporal coincidence was the same calendar day (in UTC); a similar condition was used by Clerbaux et al. (2008). Spatial coincidence requires a satellite observation in the same 1° latitude×1° longitude grid cell as the ground-station. The nominal spatial offset is 50 km with a maximum difference of 150 km. This condition is stricter than the 1000 km offset permitted by Clerbaux et al. (2008).

2.2 Comparison and quantification of correction factors

In this analysis, both AIRS and MOPITT level 3 CO TC amounts were compared to daily mean CO TC amounts measured by the ground-based spectrometers. For both satellite instruments, day and night data were gridded separately. Both algorithms used the same uniform global-wide a priori vertical CO distribution. Vertical sensitivity functions (averaging kernels) of AIRS and MOPITT were different, but no efforts were made to reconcile them. Luo et al. (2007) proposed adjustment of MOPITT V3 data with numbers of Degrees of Freedom (DOF) between 1.1 and 1.7 to data of Total Emission Spectrometer (TES) that had DOF between 1.0 and 1.4. They noted that an adjustment of data with smaller DOF to data with larger DOF is not possible. AIRS DOF was never larger than 1.3 (Fig. 2) and normally was smaller than that of MOPITT. In view of the goal of this paper, i.e., assessments of CO variations, an adjustment of MOPITT data to the AIRS data with smaller DOF was not considered here. However, different vertical sensitivities (Fig. 1) must be kept in mind, especially for situations when the real CO profile significantly differs from the a priori CO profile. Situations with polluted boundary layers are one example of this, e.g., the Russian peat fires in August–September 2002 (see Edwards et al., 2004 and a discussion below).

Deviations of satellite retrieved CO TC from ground truth as functions of information content are displayed in Fig. 2a for the NH and Fig. 2b for the SH. Information content of CO TC measured by MOPITT is represented by the Total Column Quality Parameter (TCQP). TCQP was introduced by Yurganov et al. (2008) as the air pressure weighted mean of the Profile Percent a priori reported for every pressure level, and also for every grid cell and every day. Information content of CO TC measured by AIRS is estimated in terms of the DOF of the AIRS CO retrieval as given in the AIRS level 3 standard product (McMillan et al., 2009). For DOF approaching zero or TCQP approaching 100% the information content of the retrieval drops to zero and the CO TC measured by the sounder is expected to approach the a priori value. Both AIRS V5 and MOPITT V3 CO retrieval algorithms utilize the same a priori CO profile equivalent to 1.80×10^{18} molecules/cm^2. In the NH, CO TC is generally larger than the a priori while in the SH it is smaller (see Table 3, column 2). Straight dashed lines in Fig. 2 indicate the deviation of the a priori from the average CO TC for each site. For all sites except Ny-Alesund, the retrieved CO approaches the a priori for low information content.

Day and night MOPPIT data are plotted separately. Similarly, AIRS retrievals for ascending orbits (around noon of local time) are reported separately from descending orbits (around midnight of local time). At polar latitudes during the summer the sun may be over the horizon or just below even at midnight. Ny-Alesund (79° N) data illustrate a negligible difference between "night-time" and "day-time" retrievals. These Arctic AIRS data demonstrate also a surprisingly good

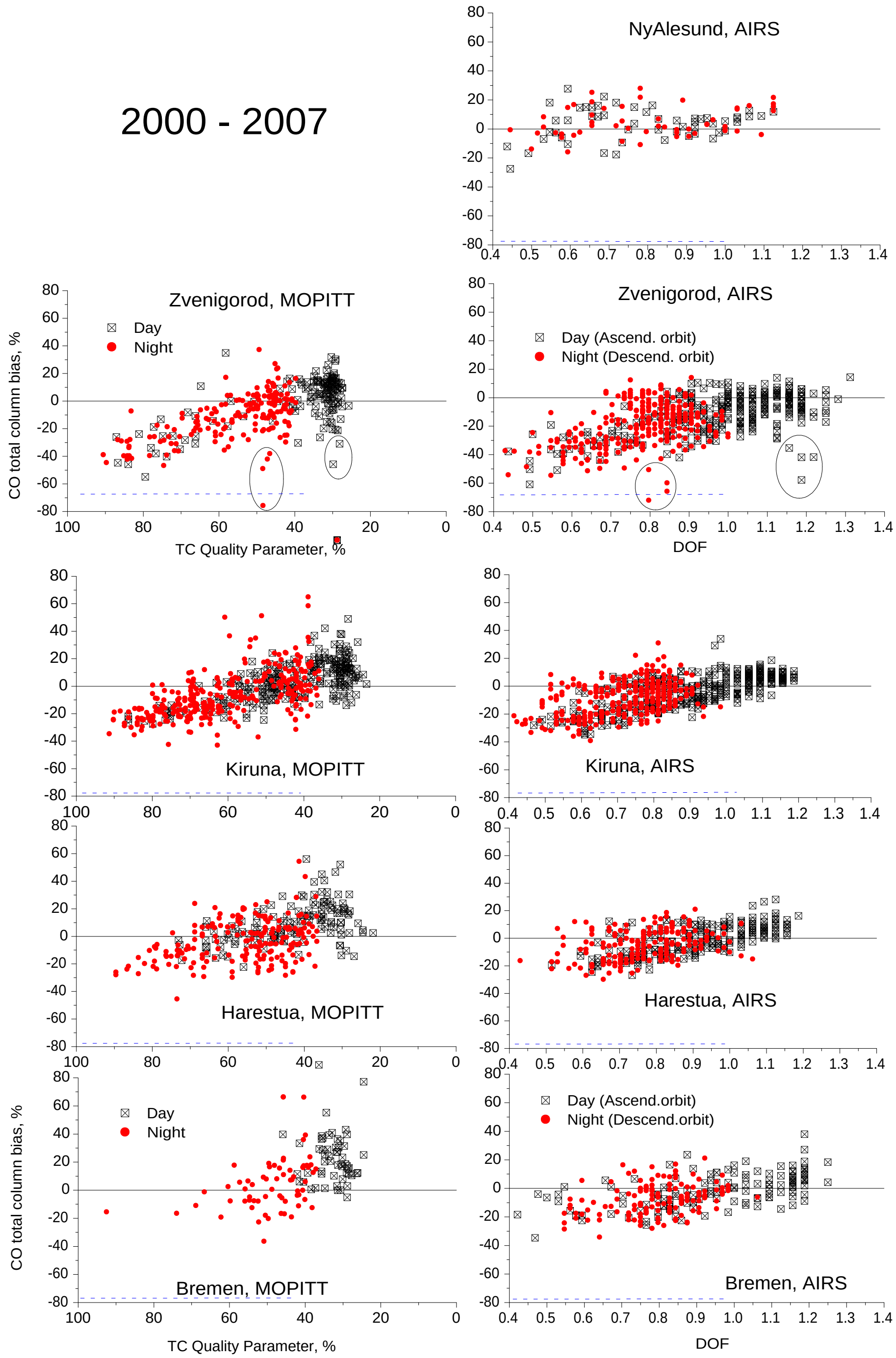

Fig. 2a. MOPITT and AIRS CO TC daily deviations from ground truth (in another words, satellite minus FTS) plotted as a function of information content. Total Column Quality Parameter (TCQP) for MOPITT (note a reverse scale) is the air pressure weighted means of the Profile Percent A priori determined for every grid cell (Yurganov et al., 2008). DOF for AIRS is the number of Degrees of Freedom of the retrieval (McMillan et al., 2009). Encircled symbols correspond to a period of peat fires in August–September 2002 around Zvenigorod (see discussion in the text).

agreement with the ground based observations for different DOF. There have been no MOPITT V3 measurements matching FTS data for Ny-Alesund. For consistency of comparison between the two sounders, no data above 70°, including that from Ny-Alesund, was used in the validation or data analysis. This point might be improved with MOPITT V4.

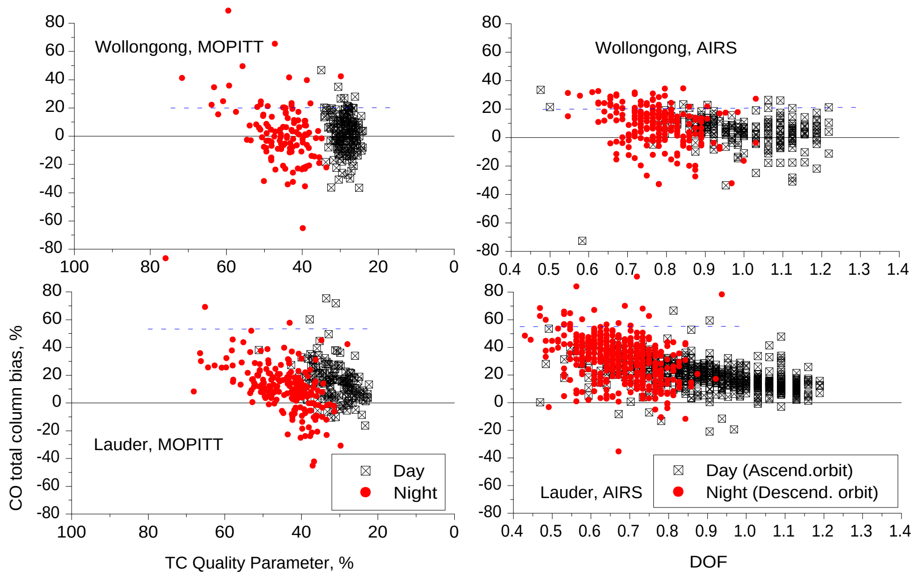

Fig. 2b. The same as Fig. 2a, but for the Southern Hemisphere.

Table 3. Compilation of validation data and comparison with available campaigns.

FTS 2000–2007 averages, mean biases and standard deviations for matching days						
Site	Overall Mean FTS TC, $\times 10^{18}$ mol/cm^2	MOPITT V3 bias±STD		AIRS V5 bias±STD		# of matching days
		Day	Night	Day	Night	
NyAlesund*	2.19	–	–	3.6±7.8	5.3±9.8	49
Kiruna	2.13	5.6±12	3.3±16	−0.72±9.9	−5.2±10.7	422
Harestua	2.30	11.1±14	−0.95±15	0.44±10	−3.2±9.9	252
Bremen	2.30	22.7±18	6.4±20	−0.20±12	−6.0±11	138
Zvenigorod	2.59	5.0±13	−5.8±15	−9.0±12	−15.4±13	574
Wollongong	1.50	0.70±13	0.57±18	4.5±9.7	7.3±13	544
Lauder	1.16	15.5±14	9.6±16	17.9±9.3	26.1±15	651

AIRS Validation data for comparison (McMillan et al., 2008)

Region and campaign	Coordinates	Period	Bias and STD
INTEX-A/ICARTT US from Pacific to Atlantic	30° N–50° N	1 July 2006–11 August 2006	25±17 (unconvolved) 7.7±4.7 (convolved)

* There are no MOPITT V3 data matching NyAlesund, Spitsbergen surface measurements . In summer time, "day" and "night" at NyAlesund are conditional due to the long solar day.

AIRS and MOPITT CO biases demonstrate similar dependences on the information content for both day time and night time observations. We assumed the data with TCQP between 0 and 60% for MOPITT and DOF >0.7 for AIRS to be most reliable. Mean biases and standard deviations for these ranges are listed in Table 3 (columns 3 to 6) for each site. Standard deviations of MOPITT data are generally larger than those of AIRS data. In part, this could be due to the 1.3% per year increasing drift of the MOPITT bias (see below). Also, it should be noted that the overall mean CO TC for Zvenigorod is 12–18% higher than the CO TC over other the European sites. The Zvenigorod spectrometer does not participate in the NDACC FTS intercomparison programs (Hase et al., 2004). However, sporadic comparisons with FTS and aircraft in situ CO profiles have revealed no discrepancies larger than 5–10% (Yurganov et al., 2002). Somewhat higher CO TC over Zvenigorod could be due to the influence of Moscow, small regional peat fires, and transport from Western Europe. Four days with strong peat fires around Moscow are highlighted in Fig. 2a with differences between the ground-based and satellite measurements of 60–80%. Meanwhile, CO TC measured by the ground-based spectrometer was larger than 6×10^{18} molecules/cm^2. Large scale aerosol pollution was also observed by Terra/MODIS over the European part of Russia during this period (Edwards et al., 2004).

Seasonal dependences of AIRS and MOPITT CO TC biases are illustrated in Fig. 3. Nearly all the points, except for SH AIRS, are inside the ±10% corridor. MOPITT data in the NH and SH as well as AIRS data for the NH are biased relative to the ground truth in the same way: an absolute minimum is observed in December–January and a maximum in June–November. In the NH, wintertime boundary layer (BL) is getting thinner, anthropogenic CO on the BL accumulates due to lower photochemical destruction, meanwhile a-priori stays to be the same year round, and, as a result, underestimation of both instruments is increasing. The inverse effect for SH MOPITT data (lower bias in summer, than in winter) is not explained thus far. A clue for explanation might be a different character of the CO cycle there and lower role of anthropogenic emission.

The bias for NH AIRS data is very close to zero between June and November. However, the data for AIRS in the SH, are significantly overestimated, especially during the cleaner austral summer (January–May). Scatterplots for all matches of the two sounders shed more light on this discrepancy, see Fig. 4. MOPITT CO TC (left graph) are scattered, but depend linearly on the “true” values supplied by the ground-based FTS below 1.6 10^{18} molec/cm^2. Conversely, AIRS data (right graph) overestimate CO for small CO columns (i.e. during austral summer) and underestimate CO for large CO columns, especially at night.

This effect also is further discussed below in a wider comparison of MOPITT and AIRS data in the SH. In the Discussion Section, we propose an explanation. Some of the largest CO TC points belong to the NH winter period where underestimation is explained by the wintertime thermal stratification discussed previously.

For the investigation of long-term variations of CO TC, temporal stability of the instruments is highly important. To verify this stability, the daily means for high information content (see above) have been averaged by month and over 4 sites in the NH (without Ny-Alesund) and 2 sites in the SH respective hemisphere, see Fig. 5. MOPITT patterns for both hemispheres are remarkably similar, and an upward trend of bias with a linear regression slope of 1.4–1.8% per year is evident.

Some deviations in bias from linearity were observed in 2002–2003 in the NH (both instruments) and in 2003–2004 in the SH (AIRS). Yurganov et al. (2005) analyzed satellite, ground-based spectroscopic, and in-situ sampling data for CO for the NH. They found that the influence of strong Siberian forest fires of both 2002 and 2003 was hemisphere-wide. Moreover, this effect was larger for surface layer everywhere in the hemisphere and less for the TC, also for all

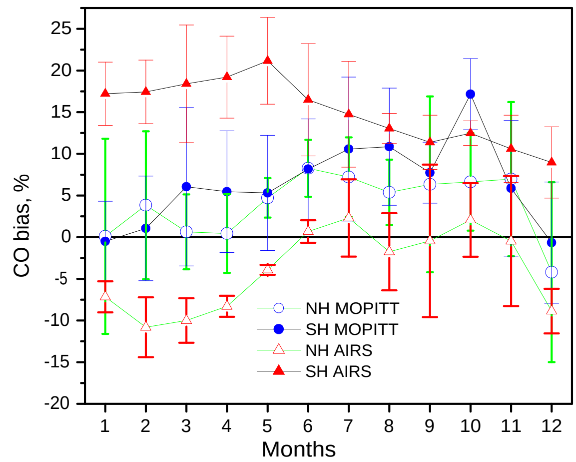

Fig. 3. Seasonal dependence of CO TC bias for two satellite sounders in both hemispheres. Monthly averaged deviations of CO TC measured by satellite sounders from those measured by ground-based spectrometers.

analyzed sites. So, the pyrogenic pollution of BL was not restricted by the areas close to fires, but spread over the entire hemisphere in 2002–2003. Lower sensitivity of satellite sensors to the BL caused higher underestimation of the TC. According to Fig. 5, this effect was higher for AIRS, than for MOPITT. However, this explanation does not work for the AIRS overestimation of 2003–2004 in the SH. The AIRS V6 that is now under development has to be specifically validated for this period of time.

Both NH and SH 12-month sliding average biases for MOPITT are plotted in Fig. 6 and compared with other MOPITT validation studies. The results of this paper and cited validation results agree within the uncertainty limits. The bias as a function of time for the periods 2000–2007 and 2003–2007 was used for correcting the global and hemispherical CO burdens measured by MOPITT and AIRS, respectively. For 2008 and 2009 the MOPITT bias was extrapolated as shown in Fig. 6. Corresponding curves for AIRS (Fig. 5) were extrapolated for 2008 and 2009 flatly. CO burdens measured by both sounders before and after correction are compared in the next section.

3 Comparison of corrected MOPITT and AIRS retrievals

For further analysis, AIRS and MOPITT CO TC values were integrated over 3 latitudinal belts: 30° N–70° N (NH), 30° S–30° N (Tropics), 30° S–70° S (SH), and globally (without polar latitudes, i.e., 70° S–70° N) to yield the CO burden in Tg. In the following analysis, one should remember that the volumes of CO TC validation data are different for these three belts: 4 sites in the NH, 2 sites in the SH, and none in the tropics. In the absence of TC validation data in the tropics,

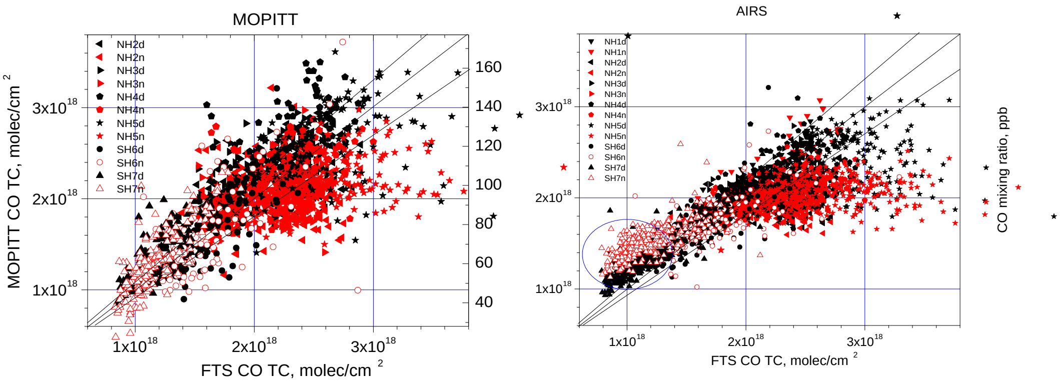

Fig. 4. Scattergrams of daily mean CO TC simultaneously measured by two satellite sounders and six FTS (MOPITT case) or seven FTS (AIRS case) for all matching days. Lines of equal TC and ±10% are shown. Ground-based sites are designated according to Table 1, e.g., NH2d means Kiruna day-time satellite measurements, SH7n means Lauder night-time satellite measurements, etc. Encircled points for AIRS are for the lowest measured TC. Right scales are approximate mean mixing ratios in ppb ($TC/2.15\times10^{25}$).

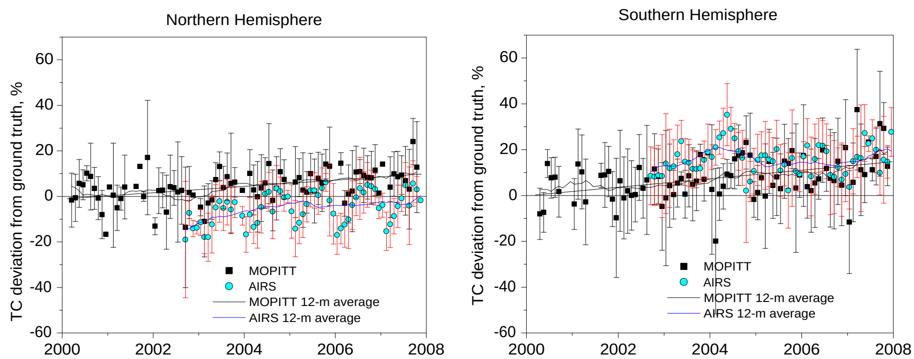

Fig. 5. Temporal stability of two sounders in both hemispheres. Monthly mean deviations of CO TC measured by satellite sounders from those measured by ground-based spectrometers. Vertical bars represent standard deviations (black – MOPITT, red – AIRS). Black and blue lines correspond to 12-month sliding averages; straight lines for MOPITT are linear regressions with slopes (1.4±0.4)% per year (NH) and (1.8±0.4)% per year (SH).

we have extrapolated the available validation results and assumed the correction factors can be represented by averages between those determined for the NH and SH.

The impacts of the corrections are displayed in Fig. 7 and Table 4. First, the correction removes the increasing trend of MOPITT CO TC data and brings them closer to the AIRS CO TC data. The NH belt demonstrates the best result of the correction and the best final agreement between the two sets of satellite data. For all belts, the larger slopes of the linear regressions for AIRS are explained by the large CO burdens in 2002–2003 and the longer period of measurements for MOPITT. For the SH, reasonable agreement between MOPITT and AIRS is observed between July and November for all years. During periods of smaller CO burden (i.e. smaller CO TC in austral summer and autumn) AIRS overestimates TC by ∼20%. This overestimation error by AIRS was discussed above with regard to Figs. 3 and 4.

Figure 8 compares corrected AIRS V5, corrected MOPITT V3, and MOPITT V4 downloaded from the NASA archive. The data were integrated for the same latitudinal belts in the Northern and Southern Hemispheres as used in Fig. 7. A good agreement between our corrected MOPITT V3 (V3corr) and MOPITT V4 is found in both hemispheres except for the period before the failure of the MOPITT cooler (2000–May 2001) where the disagreement amounts to 15%. The good general agreement between V3corr and V4 speaks to the higher quality of the new version, especially the removal of the apparent V3 temporal trend. The substantial differences between these two versions in 2000– 2001 require special consideration and explanation. Overall, Fig. 8 confirms the use of corrected MOPITT V3 and AIRS V5 in the following analysis.

Figure 9 presents a scatterplot of corrected AIRS CO TC as a function of corrected MOPITT V3 CO TC. Except at the lowest values of CO TC, disagreements between these data sets are well below ±10% (dashed lines). An explanation of the apparent non-linearity of AIRS data for the lowest CO TC is offered in the Discussion Section. However, for the

Table 4. Bias (AIRS.V5-MOPITT.V3) and STD of monthly mean burdens for Northern hemisphere, tropics, Southern hemisphere, and globally (70° S –70° N) in % for the common period of measurements (September 2002–June 2009). Slopes of regression lines (% per year); MOPITT: March 2000–June 2009; AIRS: September 2002–June 2009. All data are presented before and after correction.

Region	Mean difference between AIRS and MOPITT, %			
	before		after	
	Mean	STD	Mean	STD
NH	−7.94992	3.689258	2.180879	3.064989
TR	1.255042	1.688821	2.029148	1.252721
SH	19.27559	15.05463	9.458471	13.98705
GL	1.831075	3.706045	4.792675	2.955915
	Slopes, % per yr			
	AIRS V5		MOPITT V3	
	before	after	before	after
NH	−0.95951	−1.77419	0.669533	−0.55061
TR	−0.64724	−0.92928	1.036036	−0.24426
SH	−0.84198	−0.69057	1.33515	0.073699
GL	−0.76954	−1.12833	0.928058	−0.257

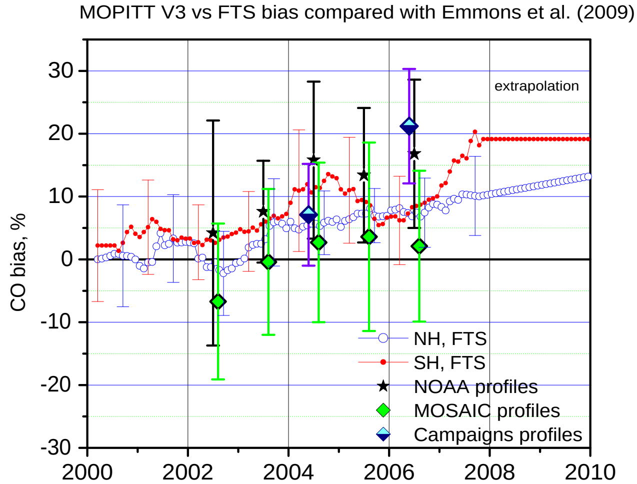

Fig. 6. CO TC bias used as MOPITT V3 correction factor in comparison with other validation results. The MOPITT bias vs. FTS is a sliding average of monthly means until December 2007 and an extrapolation thereafter. Emmons et al. (2009) validation results are plotted for comparison.

global CO burden analyzed in the next section, the contribution from the SH (30°–70° S) is small. Again, the similarity of the two scatterplots in Fig. 9 attests to the validity of the derived correction for MOPITT V3 and its use in the following analysis.

4 CO global emission anomalies between 2000 and 2009: Did the economic recession of 2008-2009 impact global CO?

4.1 Global CO burden

In our previous paper that used uncorrected MOPITT data (Yurganov et al., 2008), we found a good correlation of CO top-down estimates of emission anomalies with CO bottom-up emission estimates from biomass burning alone (GFED2). The agreement improved after removing a linear 1% per year trend from the MOPITT data. At that time, further analysis required more validation data. In this paper, we utilize a larger volume of archived FTS validation data as well as AIRS V5 data. As previously presented, we have confirmed the increasing drift of MOPITT V3 and quantified correction factors. Therefore, we expect to improve the accuracy of our top-down to bottom-up comparison. Additionally, we examine the changes in global CO burden due to any impact of the 2008–2009 global economic recession.

In this section we investigate the interannual variations in the global (without polar latitudes) CO burden measured by AIRS and MOPITT sounders and corrected using the comparison with ground-based spectrometers. The top panel of Fig. 10 presents the global CO burden anomalies relative to the period between January 2004 and December 2007. Calculation of anomalies is equivalent to removing the seasonal cycle and highlights interannual variations. The global CO burden time series of MOPITT and AIRS are in reasonable agreement with a mean difference of −0.7 Tg and STD=8.7 Tg for the overlapping period. Recall that this is out of a global CO burden of approximately 400 Tg, i.e., STD ∼2%. Maximum differences between the two satellite global CO burdens are ±15 Tg in 2003/2004 and 2006/2007. However, both sounders observed a diminution of the global CO burden after July 2008 and a recovery after November 2008.

We assume the month-to-month changes in global CO burden (Tg/month) are caused by month-to-month changes in CO sources and a sink proportional to the CO monthly anomaly. 85% of the sink is reaction with OH in the troposphere (Bergamaschy et al., 2000). Following Yurganov et al. (2004, 2005, 2008) the CO sink can be estimated using standard [OH] month-latitude-altitude distributions proposed by Spivakovsky et al. (2000). Since 2000 only a 20% flat diminution of calculated (OH) has been proposed by Wang et al. (2008); we have made no changes in the Spivakovsky et al. (2000) [OH] before a confirmation of this result. These simple calculations enable one to convert burden anomalies into source anomalies as depicted in the middle panel of Fig. 10. The linear correlation coefficient of AIRS CO emissions vs. GFED2 is 0.63 with a slope of 0.38 (0.20 and 0.21, respectively, for MOPITT). We see that the second

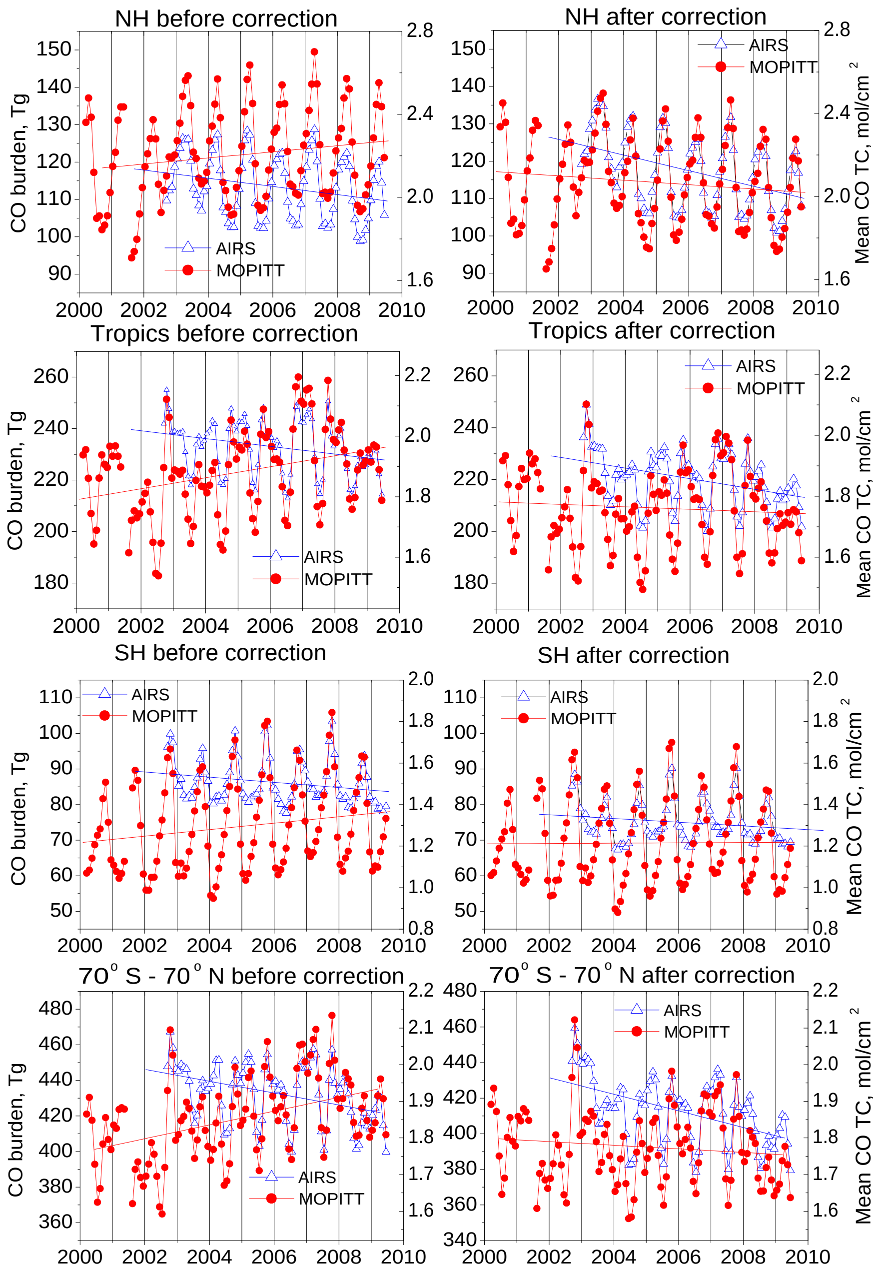

Fig. 7. Effect of correction for four latitudinal belts. Monthly mean CO burdens in Tg for latitudinal belts: 30° N–70° N (NH), 30° S–30° N (Tropics), 30° S–70° S (SH) before (left) and after (right) correction obtained from comparison with ground-based instruments. The right-side scale corresponds to mean TC in 10^{18} molecules cm^{-2}. Red and blue straight lines are linear regressions for MOPITT and AIRS, respectively (see also Table 4).

half of 2008, the beginning of the global economic recession, is characterized by less biomass burning. The decrease in biomass burning appears to have resulted from less intense tropical fires as discussed below. This fortunate coincidence complicates the separation of these two effects.

Top-down and bottom-up estimates both are subject to errors. To assess the current magnitude of these errors, GFED2 anomalies were subtracted from the combined average of MOPITT and AIRS emission anomalies (bottom panel of Fig. 10). This difference is supposed to represent variations of all other CO sources and sinks except biomass burning. The STD of these differences is equal to ±7.9 Tg/month with no obvious temporal trend. From this, we conclude the impact of the global economic recession did not exceed our accuracy, i.e., 8 Tg/month. Assuming global CO emissions from fossil fuels to be 338 Tg/year, or 28 Tg/month (Duncan

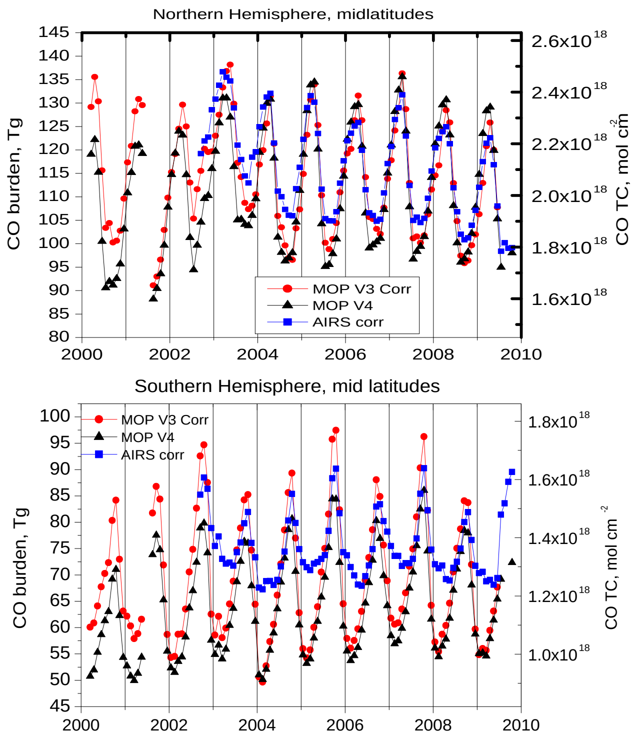

Fig. 8. Comparison of CO total burdens measured by two sounders over the Northern and Southern Hemispheres in the same latitudinal belts as in Fig. 7. Note the general good agreement between our corrected MOPITT V3 and the new MOPITT V4.

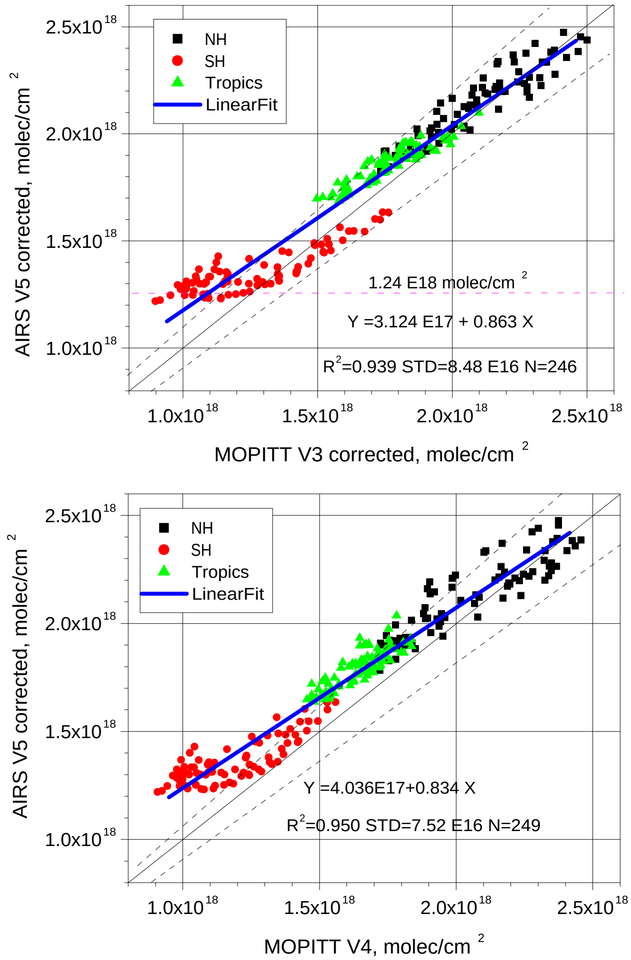

Fig. 9. Comparison of monthly mean CO TC measured by AIRS (V5 corrected) and by MOPITT (V3 corrected and V4) and averaged over mid-latitudes of both hemispheres and over tropics.

et al., 2007), the upper limit for the monthly drop of CO from fossil fuel is estimated at 30% during the autumn of 2008.

4.2 What regions contributed to the 2008 global CO burden diminution?

Regional variations in CO burden are significantly influenced by air mass exchange between regions. This can be accounted for by calculations of CO transport, but this is beyond the scope of our investigation. However, we can draw some qualitative conclusions about contributions from different areas in the observed decrease of global CO burden during the second half of 2008.

First, we distinguish between the Northern mid-latitudes and tropics. The CO burden for the Southern mid-latitudes is small compared to the other two regions. Figure 11 presents anomalies of GFED2 fire emissions and CO burdens measured by the two satellite sounders. Green lines are anomalies of total global AIRS CO burdens transferred from Fig. 9, top panel, and plotted for comparison. MOPITT and AIRS data are in general agreement with two exceptions in the tropics: 2003–2004 and 2006–2007. Their different vertical sensitivities may be a cause of these discrepancies. Data for 2008, however, agree well for both the tropics and the NH.

Comparing AIRS/MOPITT anomalies in these two regions with those for the globe (that is sum of anomalies in three areas selected in this paper) it is evident the tropics play a decisive role in the late 2008 decrease. This is confirmed by the independent GFED2 inventory (black line on the top panels). The question remains: what is the cause of the negative anomaly in the NH centered on January 2009 (Fig. 11b)? This could be a signal of the recession as Fig. 11b does not show any anomaly of wild fires in the NH during this time. Alternatively, transport of CO-poor air from the tropics could have influenced the NH mid-latitudes. To resolve this problem, specific calculations with real meteorology are necessary but are beyond the scope of the present study.

Next, we investigate which parts of the tropics were responsible for the CO decrease. Again, this can be achieved using a combination of space-measured CO and GFED2. Three areas in the tropical belt are known to be sources of fire-emitted CO: South America, Africa, and Indonesia. The

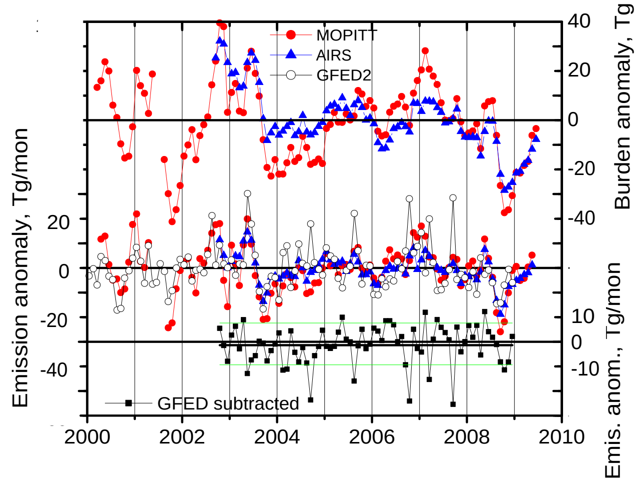

Fig. 10. Global CO emission anomalies derived from MOPITT and AIRS data and compared to GFED2. Top panel, right-hand scale: Anomalies of global (70° S to 70° N) monthly mean CO burden observed by the two satellite sounders. Middle panel, left-hand scale: Anomalies of monthly mean CO global emissions calculated from burden anomalies assuming the reaction with OH is the only sink for CO and [OH] according to Spivakovsky et al. (2000). Bottom panel, right-hand scale: Averaged MOPITT and AIRS emission anomalies minus fire CO emission anomalies from GFED2, representing all other changes except wild fires. Straight green lines correspond to ±STD.

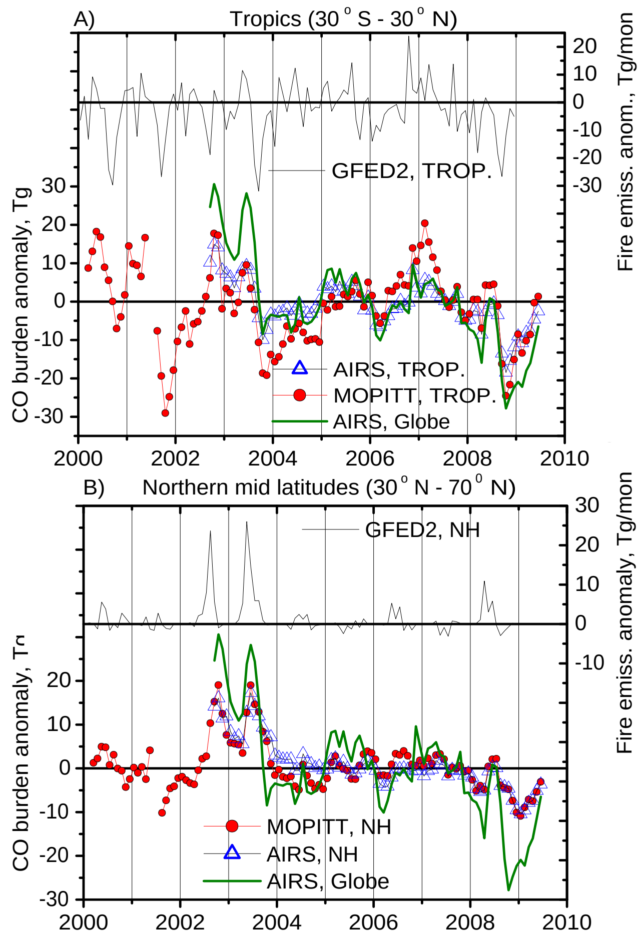

Fig. 11. CO burden regional anomalies compared with emission from biomass burning. **(A)** Top panel: anomalies of CO emission from biomass burning according to GFED2. Bottom panel: anomalies of CO burden for the tropical belt measured by the two satellite sounders as corrected in Sect. 2. The anomalies of global burden are shown for comparison. **(B)** The same as in (A), but for Northern mid-latitudes.

latter includes also the tropical forests of New Guinea and Northern Australia. The mean CO TCs (burden divided by area) for these three regions are displayed in Fig. 12 in comparison to GFED2 emissions. As discussed before, the corrected CO TC from the two satellite sounders agree well except where CO TC$<1.6\times10^{18}$ molecules/cm^2. During the reference period, between January 2004 and December 2007, year-to-year CO fluctuations over Africa were small. However, large CO TCs were observed in the two other areas: Indonesia in 2002, 2004 and 2006, and South America in 2002, 2005, and 2007. Some of these fire events have been studied previously (Nassar et al, 2009; Yurganov et al., 2008). As evidenced by the GFED2 CO emissions shown in Fig. 12, all three regions experienced low fire activity in 2008 and consequently low CO TC over all three areas, especially Indonesia. Figure 13 presenting the same data as Fig. 12 but in the form of burden anomalies, clearly shows that low emissions in Indonesia and South America explain low tropical CO burden in accordance with the GFED2 data. Torres et al. (2009) also detected unusually low aerosol loading and fire activity in the Southern Tropics in 2008 using OMI observations. The 2008 fire reduction in South America was confined to a 62% reduction in fire activity in Brazil versus that of 2007.

5 Discussion and conclusions

5.1 AIRS vs. MOPITT

The monthly averaged bias of MOPITT CO retrievals varies during the year between 0 and 10% for both hemispheres, more specifically 34° to 43° S and 50° to 80° N (Emmons et al., 2009). They provide a detailed analysis of this bias, and removing it is a major goal of the MOPITT V4 CO retrievals. Our analysis presented in Sect. 2.2 confirms the positive temporal drift of MOPITT CO retrievals found by Yurganov et al. (2008) and Emmons et al. (2009). To date, the only explanation for this drift is a leakage of CO from MOPITT's onboard gas cells (Emmons et al., 2009).

As presented in Sect. 2.2, the AIRS bias in the NH mid-latitudes is less than that of MOPITT but has a

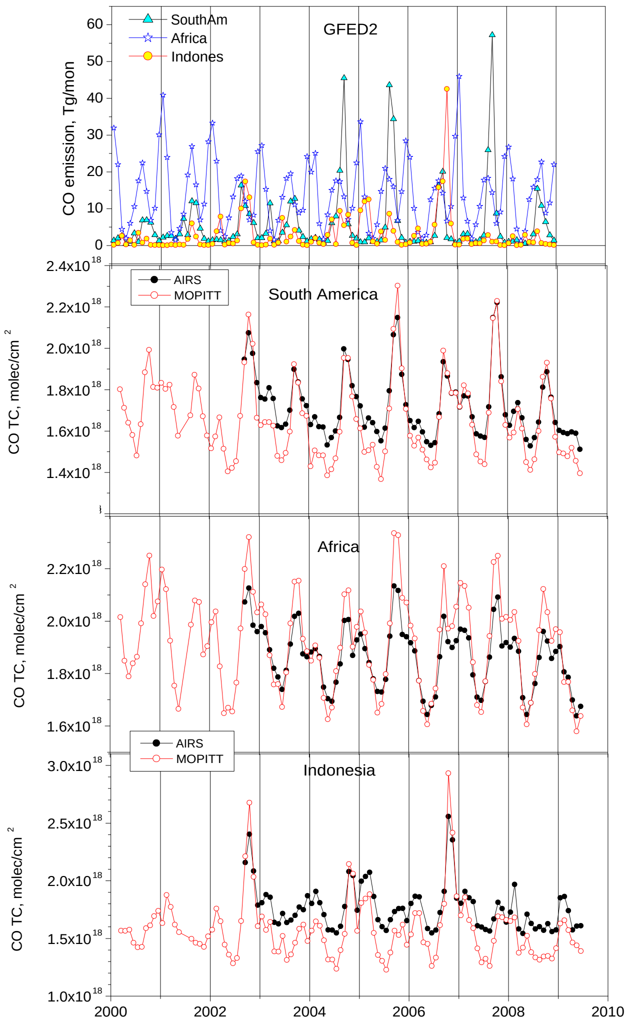

Fig. 12. Corrected monthly mean CO TC from the two satellite sounders averaged over three tropical regions subjected to biomass burning and in comparison with GFED2 emissions.

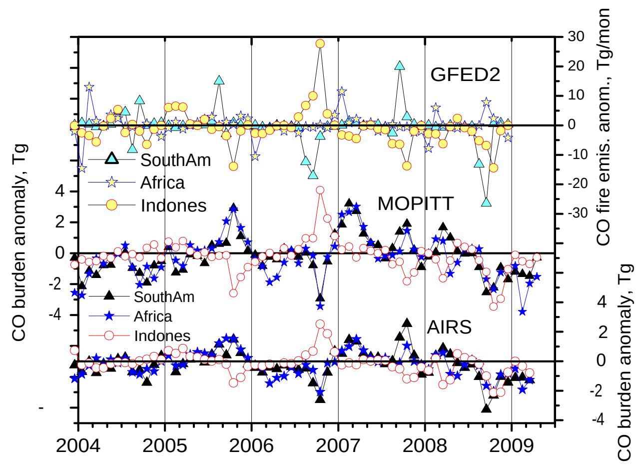

Fig. 13. Anomalies of CO fire emissions according to GFED2 and anomalies of CO burdens measured by MOPITT and AIRS for three regions since 2004.

similar seasonal dependence (Fig. 3): negative during colder months. One explanation for this dependency is an underestimation of tropospheric CO by the satellite sounders due to colder wintertime boundary layers exhibiting a smaller temperature contrast with the lower free troposphere (Deeter et al., 2004). The thinner wintertime boundary layers also are more challenging for the two satellite sounders to resolve due to their inherently weak sensitivity to these regions (Deeter et al., 2004; McMillan et al., 2009). To date, the available duration of the AIRS record does not reveal any significant temporal trend in the bias.

The main problem for AIRS V5 CO retrievals are their low sensitivity to CO for TC$<1.6\times10^{18}$ molecules/cm^2 as is often observed in the SH. This effect manifests as a restricted dynamic range where retrieved CO TC rarely goes below some minimum level. Tests with an alternative CO retrieval algorithm indicate this may not be a specific limitation of the AIRS V5 CO retrieval algorithm. Because AIRS was not designed specifically to observe CO, its spectral coverage of the CO band ranges from 2181.5 to 2221 cm^{-1} with a spectral resolution ∼1.8 cm (McMillan et al., 2009). At low TC values, the three strongest CO lines in this spectral interval become very shallow and more susceptible to both instrumental and cloud-clearing noise. Thus, any AIRS retrieval algorithm will be more dependent on the a priori CO profile at low CO TC values. MOPITT appears to be free of this limitation due to its effectively higher spectral resolution close to the natural width of these lines (∼0.1 cm^{-1}) and wider spectral coverage that includes both the P and R branches of the CO band (Drummond, 1982).

In this paper we have reconciled CO TC retrievals from these two satellite sounders by subtracting time-dependent biases derived through comparisons with CO TC measured by seven ground-based spectrometers. Correction factors were calculated on an annual basis ignoring seasonal variations of the bias. The main target of this correction was to exclude the temporal drift of MOPITT CO retrievals. As a result, the differences between the monthly mean burdens measured by the two satellite sounders in both hemispheres turned out to be well within ±10% (Figs. 7, 8, and 9). This empirical correction is useful for the presented investigation of interannual variations in CO burden and emission anomalies. However, it is far more preferable for such reconciliation to occur through improvements in the underlying retrieval algorithms. This work is done for MOPITT V4. As we demonstrate, the new MOPITT V4 CO retrievals closely resemble our corrected V3 TC, and thus appear to have rectified the temporal drift seen in MOPITT V3 retrievals. Improvements to the AIRS CO retrieval algorithm are under investigation. However, their effectiveness for low CO TC values may be restricted by the design of AIRS.

5.2 2008 CO depletion and its causes

Validated and reconciled MOPITT and AIRS data sets show very similar interannual variation in the global, NH and Tropics CO burden (Figs. 10, 11, 13) even though their vertical sensitivities are somewhat different and not taken into account in this comparison. The global and NH CO burdens were 10% lower than usual during the second half of 2008 and early 2009. An even larger decrease (−18% in January 2009) was observed in the boundary layer over Lamont, Oklahoma, USA (Yurganov et al., 2010) with the same timing as for the NH mid-latitude belt as a whole. The larger CO percent decrease observed from the ground (as well as larger increases in 2002 and 2003, according to Yurganov et al., 2005) versus that seen from satellite can be explained by the surface nature of CO sources. A depletion of 12% for MOPITT 700 hPa CO concentration was reported by Witte et al. (2009) for China and interpreted as a result of efforts to improve Beijing's air quality for the 2008 Olympic Games. However, their analysis did not account for MOPITT's upward instrumental drift of ∼3% over the 2–3 year period they considered. The global and NH CO decrease we find indicate that the Witte et al. (2009) estimates of the effect of the 2008 Olympic Games on Chinese CO abundances should be reexamined.

Is this CO decrease the result of less intense wild fires or lower emissions from fossil fuel? This large-scale depletion is not unprecedented, a similar one was observed in the second half of 2001 by MOPITT (Fig. 11a). The observed seasonal coincidence with the 2001 event is not fortunate; biomass burning that determines interannual variations of CO usually is more intense during the second half of the year. GFED2 fire emission assessments for the tropical belt independently exhibit a decrease during the second half of 2008 as it did for 2001.

The first conclusion from our analysis is that the tropical latitude belt played a decisive role in the global CO burden decrease. Specifically, CO fire emissions from South America and Indonesia were lower during the second half of 2008 than during the reference period between 2004 and 2007. An explanation of this decrease in fire activity is beyond the scope of this paper, but it seems likely that ENSO and other variations in atmospheric circulation and precipitation would be the leading causes.

One might expect the consequences of the economic recession impact on fossil fuel emission would manifest first in the Northern mid-latitudes where fossil fuel consumption is largest. CO depletion was observed there by both sounders, but the timing of this decrease is later than in the tropics and at much smaller amplitude in Tg. This time lag could indicate both a different cause of this effect and a delay due to transport of CO-poor air from the tropics to the Northern mid-latitudes. To quantify the contribution of changes in anthropogenic emissions on the CO depletion in the NH will require calculations of air exchange between the tropical belt and the mid-latitudes. Qualitatively, both natural and anthropogenic variations in CO emissions could have occurred.

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