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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

CO total column (TC) retrievals from MOPITT version 3 and AIRS version 5 are validated 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 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. With these corrections, CO burdens from AIRS and MOPITT 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. Interannual variations in AIRS and MOPITT retrieved CO burdens are compared with CO emissions from wild fires from the Global Fire Emission Dataset (GFED2) inventory. 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 topical emissions also accounts for most of the change in 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 less CO 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 seem to be minor due to small (< 5%) changes in concentrations of CH_4 and OH (Chen and Prinn, 2005; Prinn, et al., 2005). Contributions from wild fires were counted by van der Werf (2006); they vary from year to year globally and regionally. Global biomass burning emissions vary between 337 and 591 Tg/year, i.e., between 14% and 25% of total source. Especially large variability of wild fires is observed in Indonesia: between 0.8 and 16.7 Tg/year; in Siberia: between 4.9 and 19.8 Tg/year; South America: between 14.7 and 21.6 Tg/year. African fires burn every year and contribute ~49% in the global biomass burning emission, interannual variations are normally between 205 and 237 Tg/year (Global Fire Emission Dataset, GFED2, van der Werf, 2006). Heretofore, anthropogenic CO emissions, approximately 23% of the annual total source, have been considered relatively stable with a variation of at most a few percent from 1985 to 1997 (Duncan et al., 2007). However, 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 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 previously have been investigated (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 modeling (see numerous publications cited by Turquety et al., 2008). CO mixing ratios retrieved from AIRS spectra have been used for investigation of biomass burning and anthropogenic pollution (McMillan et al., 2005,

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2008, 2009a; Warner et al., 2007) and quantification of CO sources using top-down inverse models (Kopacz et al., 2009; Fisher et al., 2009).

MOPITT and AIRS retrievals of CO total column (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., 2009b). 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 and references therein). However, a simple global one-box model also can be used to investigate global sources and interannual variations. Our previous paper, (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, 2006). However, these estimates revealed a strange upward trend of CO emission from MOPITT data that was not confirmed by the bottom-up GFED2 inventory. Further comparing CO TC measured by MOPITT to CO TC measured by two ground-based sun-viewing spectrometers (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) and AIRS (Warner et al., 2007; McMillan et al., 2008 and 2009b). A bias of CO retrievals versus ground truth for MOPITT has been quantified to lie between −0.4% and 15.8% (Emmons et al., 2004, 2007) and for AIRS: 7–10% (McMillan et al., 2009b) with standard deviations 8–15%. However, these validation efforts, with exception of Emmons et al. (2009), have not examined long-term or even seasonal dependences of the bias and were not useful for explana-



tion of a virtual increasing trend of CO burden measured by MOPITT (Yurganov et al., 2008).

Using comparisons of MOPITT CO retrievals to in situ aircraft CO profiles, Emmons et al. (2009) confirmed the positive MOPITT 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.

Through further 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) 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). 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, 2006). The possible influence of the 2008–2009 economic recession on the CO burden in the NH is discussed.

This paper is a next step in reconciling MOPITT and AIRS (and, eventually, other

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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. (2004). The data are publicly available at http://eosweb.larc.nasa.gov/PRODOCS/mopitt/table_mopitt.html. Currently 2 versions of these data are available. Data for V3 is used in this publication. The improved V4 is now being archived as well.

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. (2009b) and are available at http://disc.gsfc.nasa.gov/AIRS/index.shtml). 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 1). Six of these belong to the NDACC and are

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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 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. Characteristics of the ground-based spectrometers are listed in Table 1. 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 change 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 are gridded separately. No efforts were made to reconcile the different vertical sensitivity functions (averaging kernels) of AIRS and MOPITT. To do this would require additional information on the "true" vertical stratifi-

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cation of CO. Differences between the two averaging kernels are especially important 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 a function of information content are displayed in Fig. 1a for the NH and Fig. 1b 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 Degrees of Freedom (DOF) of the AIRS CO retrieval as given in the AIRS level 3 standard product (McMillan et al., 2009b). 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 generally is higher than the a priori while in the SH it is lower (see Table 2, column 3). Straight dashed lines in Fig. 1 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). In 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 agreement with the ground based observations for different DOF. MOPITT V3 does not report CO TC for high latitudes. 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

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improved with MOPITT V4.

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 2 (columns 4 to 6) for each site. Standard deviations of MOPITT data are generally higher 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 (e.g., 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.1a with underestimation reaching 60–80%. Meanwhile, CO TC measured by a ground-based spectrometer was greater 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 bias are illustrated in Fig. 2. 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 almost the same way: an absolute minimum is observed in December–January and a maximum in June–November. For the NH, this can be explained by the smaller sensitivity of both satellite instruments to the thinner wintertime boundary layer (BL). In general, both MOPITT (Deeter et al., 2004) and AIRS (McMillan et al., 2009b) averaging kernels rapidly decrease in the BL in comparison to the free troposphere. The inverse effect for SH MOPITT data is not explained thus far. The bias for NH AIRS data is very close to zero between June and November. However, the data for AIRS in

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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. 3. MOPITT CO TC (left graph) are scattered, but linearly depend on the "true" values supplied by the ground-based FTS below 1.6 10^{18} molec/cm^2. Conversely, AIRS data (right graph) are overestimated for the smallest measured CO measured, i.e., austral summer and at night are underestimated for the largest measured CO. 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. 4. MOPITT patterns for both hemispheres are remarkably similar, and an upward trend of bias with a slope 1.4–1.8% per year is obvious. AIRS TC deviations do not exhibit any linear trends. The NH low in 2002–2003 and the SH high in 2003–2004 coincide with periods of extensive biomass burning that impacted the validation sites (Yurganov et al., 2005; Paton-Walsh et al., 2005).

Both NH and SH 12- month sliding average biases for MOPITT are plotted in Fig. 5 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 period between 2000 and 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. 5. Corresponding curves for AIRS (Fig. 4) were extrapolated for 2008 and 2009 flatly. CO burdens measured by both sounders before and after correction are compared in the next section.

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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, 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 impact of the corrections are displayed in Fig. 6. 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 excellent 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. 2 and 3.

Figure 7 is a scatterplot of corrected AIRS CO TC as a function of corrected MOPITT 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 global CO burden analyzed in the next section, the contribution from the SH (30°–70° S) is small.

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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. 8 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 highlighting interannual variations. The global CO burden time series of MOPITT and AIRS are in a 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 only 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. What is the cause of this effect?

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 (Bergam-

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aschy 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. 8. The fact that these variations are determined mainly by variations in biomass burning is confirmed by the good correlation with GFED2 from 2000 through 2008 as also depicted in the middle panel of Fig. 8. We see that the second half of 2008, the beginning of the global economic recession, also 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.

As a matter of fact, 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. 8. 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 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

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burden during the second half of 2008.

First, we distinguish between the Northern mid latitudes and tropics. CO burden for the Southern mid latitudes is small in comparison with the other two regions. Figure 9 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. 8, 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 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 (Fig. 9b)? This could be a signal of the recession: wild fires during this time are practically absent. An alternative might be an influence of tropical emissions on the NH mid latitudes. To resolve this problem specific calculations with real meteorology are necessary.

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 latter includes also the tropical forests of New Guinea and Northern Australia. CO TC (burden divided by area) for these three regions are displayed in Fig. 10 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 TC was 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

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CO emissions shown in Fig. 10, all three regions experienced low fire activity in 2008 and consequently low CO TC over all three areas, especially Indonesia. Figure 11, presenting the same data in a form of burden anomalies, clearly indicate Indonesia and South America as the regions responsible for the tropical CO decrease. And, again, GFED2 confirms this conclusion.

5 Discussion and conclusions

5.1 AIRS vs. MOPITT

Recently, NASA elevated AIRS carbon monoxide retrievals to the status of a core product in V5 along with retrievals of temperature/moisture profiles and cloud and surface parameters. CO is the only standard product for MOPITT, so far. Although AIRS was specifically designed as a prototype next generation temperature and moisture sounder, its wide spectral coverage includes CO, CH_4, O_3, and several other minor trace gases (Aumann et al., 2003). However, starting with (McMillan et al., 2005) AIRS CO retrievals were introduced into the public domain and included in Level 2 and Level 3 data files of AIRS V5 retrievals. The detailed comparison of MOPITT and AIRS CO TC with each other and ground-based spectrometers in this paper reveal advantages and disadvantages of both satellite data sets.

The monthly averaged bias of MOPITT CO retrieval 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 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 similar seasonal shape (Fig. 2): negative during colder months.

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One explanation for this shape 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., 2009b). To date, the available duration of the AIRS record does not reveal any significant temporal trend in the bias.

The main problem for AIRS 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 is not a specific limitation of the AIRS V5 CO retrieval algorithm. AIRS sees only three CO lines between 2181.5 and 2221 cm^{-1} with spectral resolution ~1.8 cm (McMillan et al., 2009b). At low values of total column, they become very shallow and are more susceptible to both instrumental and cloud-clearing noise. At these low CO TC values, any retrieval algorithm becomes ineffective. 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 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. 6 and 7). 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. Improvements to

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the AIRS CO retrieval algorithm are under investigation, but 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 find global and NH CO burden 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., 2009) with the same timing as for the NH mid-latitude belt as a whole. A depletion of 12% for MOPITT 700 hPa CO concentraion 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 re-examined.

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. 9a). 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 leading causes.

One might expect the consequences of the economic recession impact on fossil fuel

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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 lower CO 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 been occurred.

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Table 1. Characteristics of sites and spectrometers.

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

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Table 2. 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)

*MOPITT V3 does not report TC for polar latitudes. In summer time, “day” and “night” at Spitsbergen are conditional due to long solar day.

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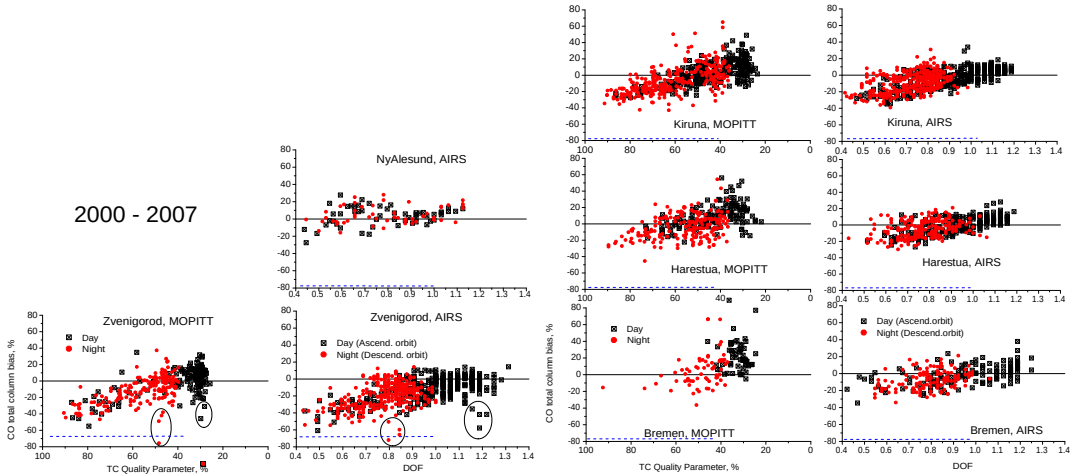


Fig. 1a. MOPITT and AIRS CO TC daily deviations from ground truth (bias) plotted as a function of information content. Total Column Quality Parameter (TCQP) for MOPITT (note a reverse scale) is the air pressure weighted means of the Profile Percent A priori determined for every grid cell (Yurganov et al., 2008). DOF for AIRS is the number of Degrees of Freedom of the retrieval (McMillan et al., 2009b). Encircled symbols correspond to a period of peat fires in August–September 2002 around Zvenigorod (see discussion in the text).

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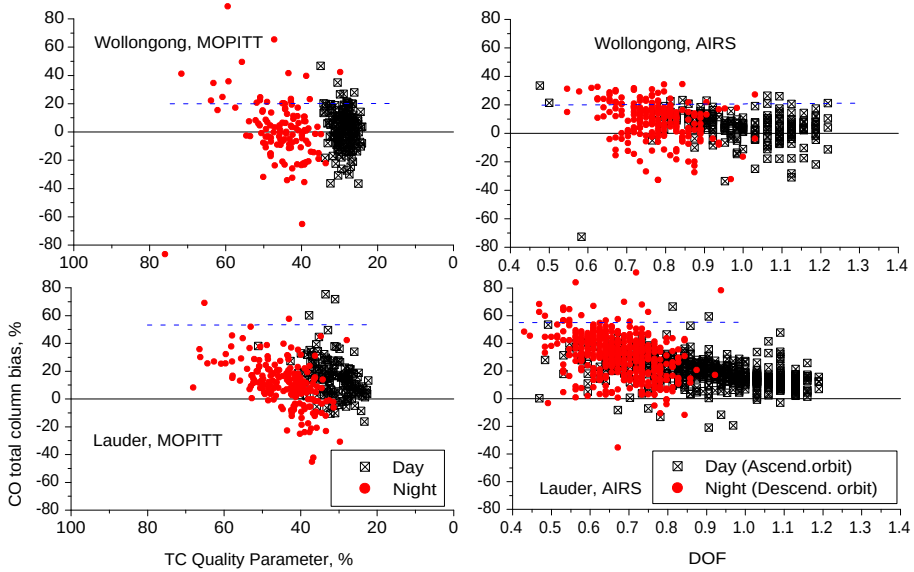


Fig. 1b. The same as Fig. 1a, but for the Southern Hemisphere.

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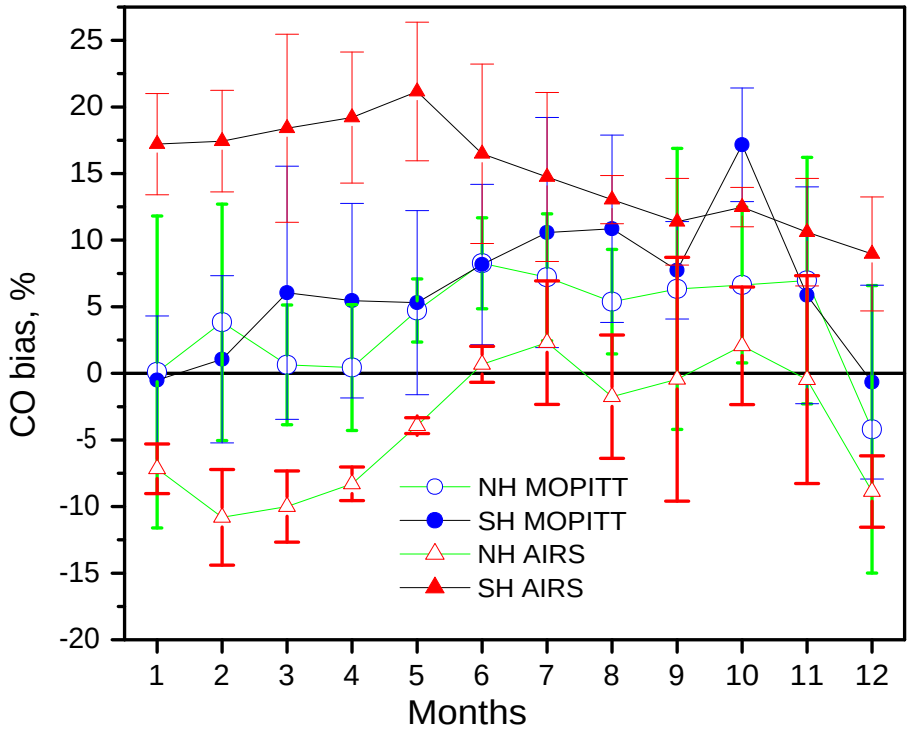


Fig. 2. Seasonal dependence of CO TC bias for two satellite sounders in both hemispheres. Monthly averaged deviations of CO TC measured by satellite sounders from those measured by ground-based spectrometers.

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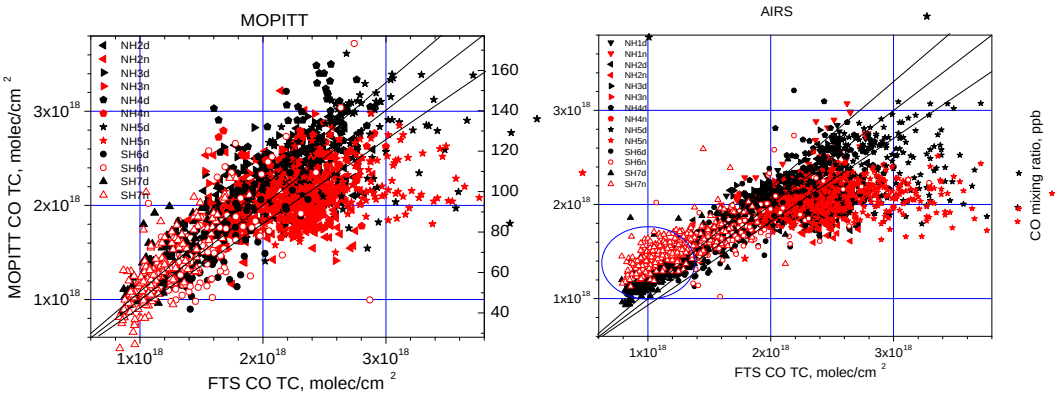


Fig. 3. Scattergrams of daily mean CO TC simultaneously measured by two satellite sounders and six FTS (MOPITT case) or seven FTS (AIRS case) for all matching days. Lines of equal TC and ±10% are shown. Ground-based sites are designated according to Table 1, e.g., NH2d means Kiruna day-time satellite 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/2.15×10^{25}).

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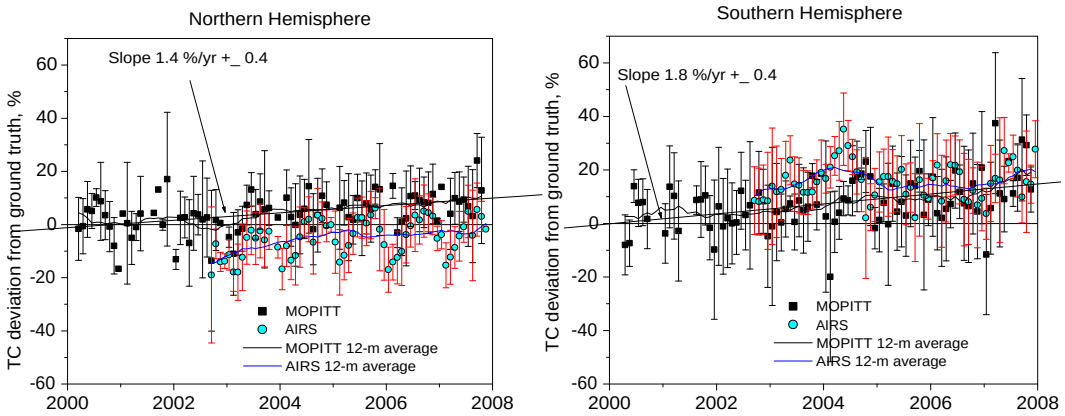


Fig. 4. Temporal stability of two sounders. Monthly mean deviations of CO TC measured by satellite sounders from those measured by ground-based spectrometers. Vertical bars represent standard deviations (black – MOPITT, red – AIRS). Black and blue lines correspond to 12-month sliding averages; straight lines for MOPITT are linear regressions.

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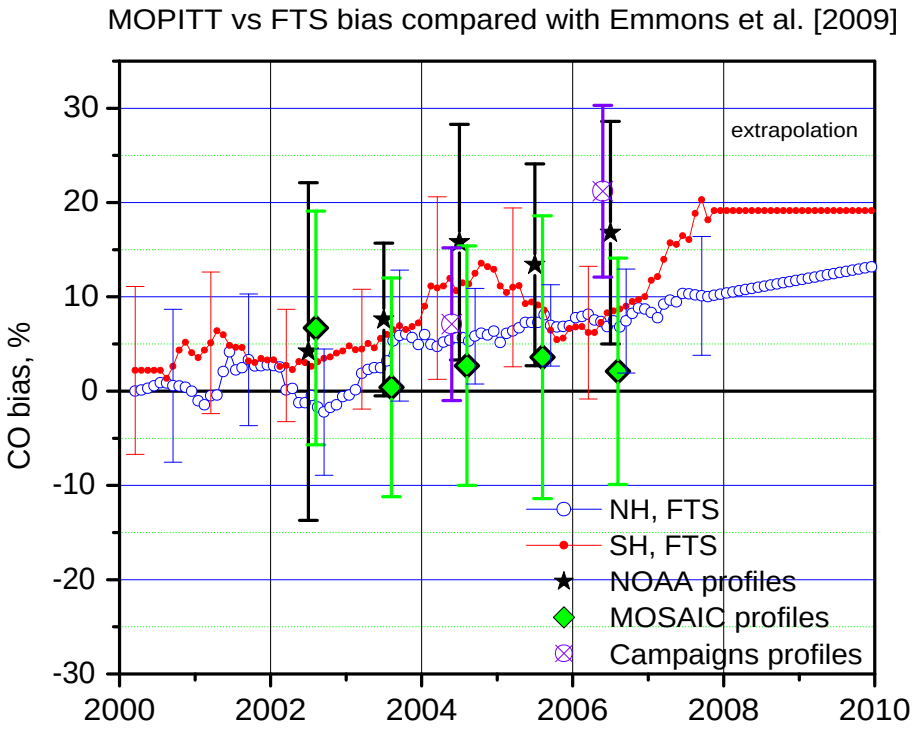


Fig. 5. CO TC bias used as MOPITT correction factor in comparison with other validation results. MOPITT bias vs. FTS is sliding average of monthly means until December 2007 and an extrapolation thereafter. Emmons et al. (2009) validation results are plotted for comparison.

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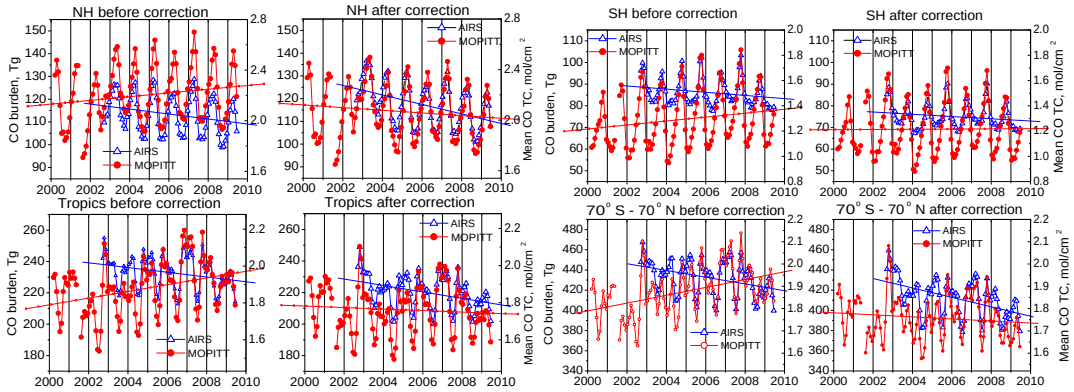


Fig. 6. Effect of correction for four latitudinal belts. Monthly mean CO burdens in Tg for latitudinal belts: 30° N–70° N (NH), 30° S–30° N (Tropics), 30° S–70° S (SH) before, left, and after, right, correction obtained from comparison with ground-based instruments. The right-side scale corresponds to mean TC in 10^{18} molecules cm^{-2}. Red and blue straight lines are linear regressions.

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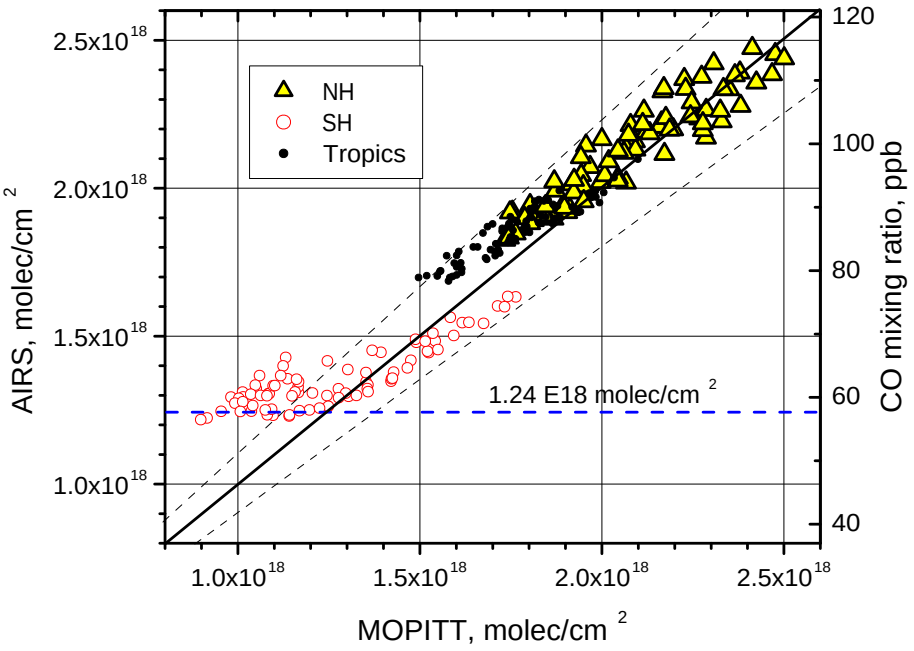


Fig. 7. Comparison of AIRS and MOPITT monthly mean CO TC averaged over mid latitudes of both hemispheres and over tropics. Correction according to validation by FTSs has been applied.

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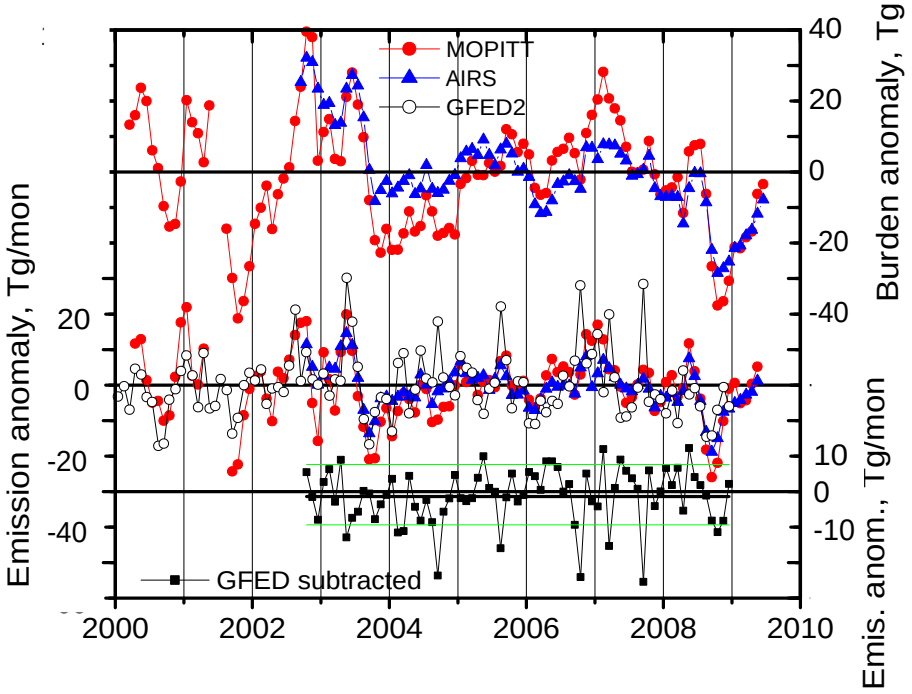


Fig. 8. Global CO emission anomalies derived from MOPITT and AIRS data and compared to GFED2. Top panel, right-hand scale: Anomalies of global (70° S to 70° N) monthly mean CO burden observed by the two satellite sounders. Middle panel, left-hand scale: Anomalies of monthly mean CO global emissions calculated from burden anomalies assuming reaction with OH is the only sink for CO and [OH] according to Spivakovsky et al. (2000). Bottom panel, right-hand scale: Averaged MOPITT & AIRS emission anomalies minus fire CO emission anomalies from GFED2, representing all other changes except wild fires. Straight green lines correspond to ±STD.

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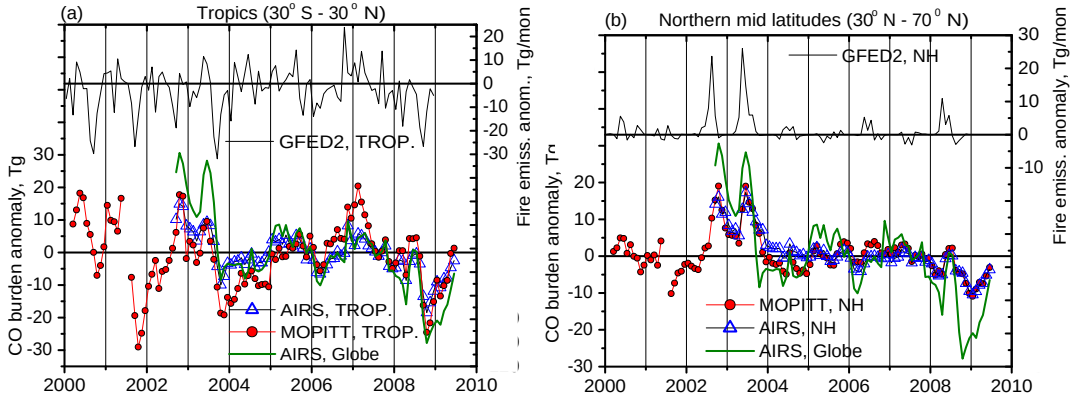


Fig. 9. CO burden regional anomalies compared with emission from biomass burning. **(a)** anomalies of CO emission from biomass burning according to GFED2. Bottom panel: anomalies of CO burden for the tropical belt measured by the two satellite sounders as corrected in Sect. 2. The anomalies of global burden are shown for comparison. **(b)**. The same as in (a), but for Northern mid latitudes.

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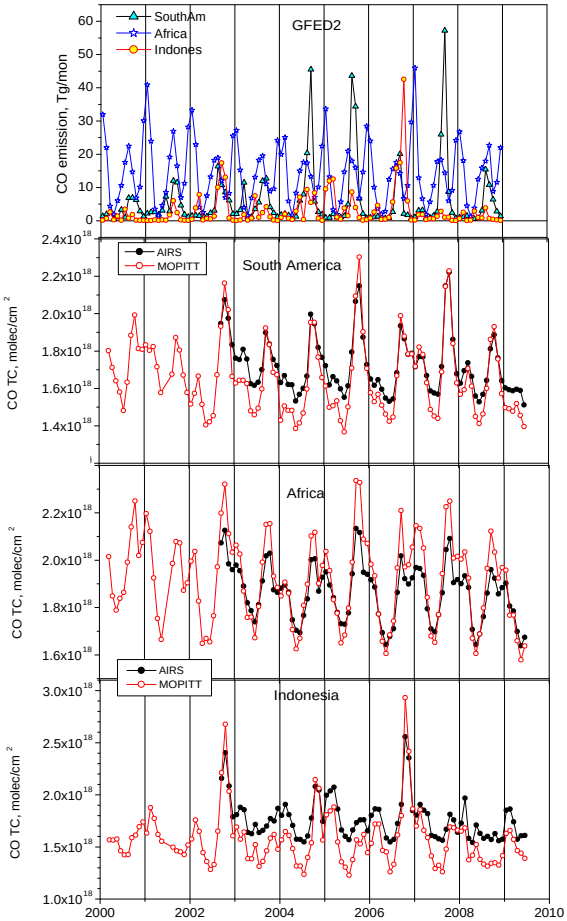


Fig. 10. Corrected monthly mean CO TC from the two satellite sounders averaged over three tropical regions subjected to biomass burning and in comparison with GFED2 emissions.

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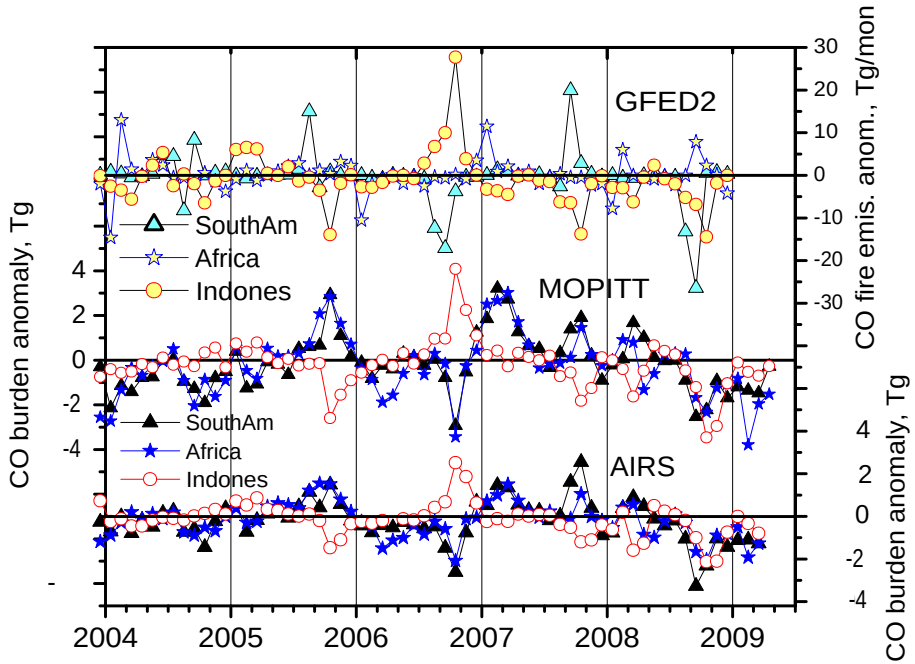


Fig. 11. Anomalies of CO fire emissions according to GFED2 and anomalies of CO burdens measured by MOPITT and AIRS for three regions since 2004.

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