Evaluation of GOES Biomass Burning Emissions using Modeled and Observed Carbon Monoxide (CO) during April – May 2007 Florida/Georgia Fires

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ABSTRACT

Biomass burning emissions from prescribed and natural fires impact local and regional air quality. Accounting for these emissions in an air quality prediction model using satellite detected fires and emissions is expected to improve the accuracy of model predictions. However, satellite-derived biomass burning emissions often have large uncertainties and are not validated because of lack of independent *in situ* measurements. Community Multiscale Air Quality Model (CMAQ) simulations and Atmospheric Infrared Sounder (AIRS) observations of CO are used in this study to evaluate Geostationary Operational Environmental Satellite (GOES) biomass burning emissions. CO emissions from forest fires in Florida and Georgia, derived from GOES observations, are used in the CMAQ model. For this study, CO is treated as a tracer in the model and its concentrations are compared to AIRS observed CO. Quantitative metrics such as root mean square difference, bias, and correlation coefficient are used to analyze the differences between AIRS and CMAQ CO to diagnose uncertainties in GOES emissions. Results from this analysis and relevant information on Florida/Georgia fires with respect to air quality impacts will be presented.

INTRODUCTION

Determining the accuracy of satellite-derived biomass burning emissions is challenging because of lack of truth data. This study attempts to indirectly evaluate the satellite-derived emissions by using them in a CMAQ model to simulate fire-induced air quality events of April and May 2007 in Florida and Georgia and comparing predicted CO concentrations to observed CO by AIRS instrument on Aqua satellite.

Air quality in the United States is continuing to improve due to Environmental Protection Agency (EPA) rules such as Clean Air Interstate Rule (CAIR) and regional haze rule to mitigate anthropogenic emissions of oxides of nitrogen (NOx) and Volatile Organic Compounds (VOCs)[1-2]. Despite the positive impact, large regions of the United States are often under exceptional events such as biomass burning (prescribed and natural) that lead to non-attainment of ozone and particulate matter standards[3]. Air quality forecasting is a critical component of EPA and National Oceanic and Atmospheric Administration (NOAA) efforts to warn public of unhealthy air quality due to anthropogenic sources as well as natural sources such as biomass burning[4]. Although NOAA's operational HYbrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) smoke forecasts include biomass burning emissions, the operational CMAQ model used to provide ozone forecast guidance currently does not include biomass burning sources[5-6]. Recent studies have shown that CMAQ ozone forecasts can be improved by including biomass burning emissions[7]. Recent studies have also shown that accuracy of CMAQ developmental particulate matter (PM2.5) forecasts is less than 20% for episodic events dominated by biomass burning emissions[8]. Accounting for biomass burning emissions is expected to improve the accuracy of model forecasts.

Near real time availability of biomass burning emissions to incorporate into CMAQ or other air quality models is not possible from ground observations and reports. Ground reporting of fires and estimated emissions is typically used for retrospective analysis. For operational forecasting, the immediate availability of data is critical. Remotely sensed fires from NOAA operational Geostationary Operational Environmental Satellite (GOES) are widely used for hazard monitoring[9]. NOAA expanded this capability by developing GOES biomass burning emissions product (GBBEP) that became operational in July 2008. Although the product has been evaluated for accuracy and tested for internal consistency before becoming operational, it has not been tested for applications in air quality models.

AIRS observations of CO are considered as truth and CMAQ model is evaluated by comparing simulated CO with and without fire emissions to measured CO. The bias between predicted and observed CO for simulations with and without fires will provide insight on the accuracy of emissions. Because CO is a long-lived species and changes in its concentrations are primarily guided by transport, observed and predicted CO are expected to be in agreement to within model and measurement uncertainties. Large disagreement between model and measured CO can be attributed to uncertainties in emissions estimates provided model transport is accurate.

MEASUREMENTS AND MODELING

GOES Biomass Burning Emissions Product

The GOES biomass burning emissions algorithm follows the conventional approach of using area burned (ha), fuel load (kgC/ha), emissions factors (g/kgC), and fraction of fuel consumed to compute emissions[10]. All inputs except emissions factors are obtained from satellites. GOES satellite provides fire hot spots and instantaneous fire size information from which burned area is derived[11]. Static fuel load, derived from MODerate Resolution Imaging Spectrometer (MODIS) land products, is used[12]. Emissions factors for trace gases (CO, NOx, TNMHC, SO2, etc.) and aerosols (PM2.5) are those from literature[13]. The fraction of fuel consumed depends on the moisture condition of the fuel and is derived using NOAA Advanced Very High Resolution Radiometer (AVHRR) vegetation index information[14]. The algorithm runs everyday on all observed fire hotspots over the CONtigious United States (CONUS) and computes emissions at 30-minute interval. The emissions data are averaged to hourly time scale and provided to users in ascii format via internet (http://satepsanone.nesdis.noaa.gov/pub/EPA/GBBEP). Internal consistency checks and comparison of 2002 PM2.5 emissions to EPA inventory show that the accuracy of GOES biomass burning emissions is between 20% and 50%[14].

CMAQ Simulations of Florida/Georgia Fires

The CMAQ model was developed by EPA and NOAA researchers for air quality assessment and other modeling applications[15]. It is a chemistry model that runs offline and is driven by MM5 wind fields. The model has 12 km X 12 km spatial resolution and 22 vertical layers up to 200 hPa. The boundary conditions for the model are static but they are less critical for this study because fire hotspots are within the modeling domain. Boundary conditions are very important when long-range transport influences regional and local air quality. The CMAQ model was run for a two-month time period (April 1 – May 30, 2007) during which fires continuously burned in Florida/Georgia border. These fires injected huge amounts of trace gases and aerosols into the atmosphere; for example, peak NOx emissions in May 2007 were four times greater than a 5-year monthly mean. Nearly 125,000 acres of land burned, which is mostly forested area. Compared to shrubs and grasslands, forest fires emit higher amounts of trace gases and aerosols due to high amount of fuel available[13]. Smoke aerosols from these fires spread across the southeast bringing several regions in the southeast into non-compliance for PM2.5 standard[16]. The CMAQ model was simulated with and without fire emissions in the model to study the impact of fires on air quality. The focus of this study is, however, to evaluate the CMAQ model predicted CO and use those results to determine the uncertainties in GOES emissions.

Atmospheric Infrared Sounder (AIRS) Carbon Monoxide (CO) Retrievals

The AIRS instrument flying on Aqua platform provides near real time CO retrievals twice daily at a nadir resolution of 45 km. Data used in this study were obtained from NASA DAAC (http://mirador.gsfc.nasa.gov/). AIRS is the first of a new generation of high spectral resolution infrared sounder with 2378 channels measuring outgoing radiance between 650 cm^{-1} and 2675 cm^{-1} [17]. CO is retrieved using radiances measured between 2183 and 2220 cm^{-1} (4.58 – 4.50 µm). The AIRS CO retrievals are more sensitive to mid-tropospheric CO changes than near surface; near-surface CO retrievals are therefore influenced by *a priori* (first guess). AIRS CO product files come with quality flags to indicate which profiles are heavily influenced by first guess. Only retrievals that have quality flag of 0, indicating that more than 50% of the information in the retrievals comes from measurements, are used in this analysis. Validation of CO retrievals compared to *in situ* aircraft profiles made during field campaigns indicate that mid-tropospheric CO retrievals have a mean bias of ~7%[18].

RESULTS AND DISCUSSION

Biomass burning typically peaks between June and August each year in the United States. Although wildfires occur occasionally, most burning in the southeast is agricultural land clearing and CO emissions from these fires average about 100 – 200 Mg (1Mg = 1000Kg). Continuous burning of fires in Florida and Georgia during April and May 2007 injected substantially higher amount of CO into the atmosphere early in the season compared to mean values observed in other years (Figure 1). Data shown in Figure 1 are emissions from multiple individual fires that were gridded into a $0.5^{o}X0.5^{o}$ grid box to compare 2007 emissions with climatological mean emissions between 2002 and 2006. High emissions in 2007 led to deteriorated air quality in the southeast and local agencies filed waivers with EPA under the exceptional events monitoring rule[16].

The GOES derived emissions were combined with anthropogenic emissions in the CMAQ model to simulate their impact on regional air quality in the southeast. Comparing model simulated CO with observed AIRS CO will provide insight into the accuracy of model predictions and emissions estimates. This study focuses on assessing the accuracy of emissions estimates and the investigation of impact of emissions on regional air quality is beyond the scope of this paper.

Figure 2 shows CMAQ CO predictions on May 12, 2007 at 19 UTC for base case simulation with only anthropogenic (local) sources, for fire case simulation where biomass burning emissions were included in the model, and AIRS observed CO concentrations. These are total column CO values in units of number density ($molecules/cm^2$). AIRS CO map has spatial gaps because either the retrievals are not available at every location due to cloud cover or quality of the retrievals is not high. AIRS measurements have a varying degree of sensitivity to changes in CO at different altitudes and this sensitivity can vary from scan to scan (*i.e.*, location to location). AIRS measurements are in general more sensitive to CO changes in mid-troposphere and where there is no sensitivity, the algorithm relaxes to *a priori* (first guess). The algorithm provides a quality flag indicating whether AIRS CO retrieval at a particular scan depended on *a priori* information or not. A quality flag of zero is set if dependence on *a priori* is less than 50%. AIRS CO data shown in Figure 2 have this quality flag and therefore have gaps but these are high quality data.

CO values in the CMAQ simulation with fire emissions compared to base simulation without fires show a distinct plume originating in FL/GA border and spreading wide into the Gulf. AIRS CO map shows similarly elevated CO values in that region but a continuous plume cannot be seen due to gaps in the data. Higher values of CO in AIRS map, however, are also seen over the Atlantic. CMAQ CO plume does not reach that far indicating that plume injection height in the CMAQ model needs further investigation. Additionally, incorrect winds (horizontal and vertical) can place the plume in wrong location as well. In general, for the two-month simulation time period, elevated CO concentrations in CMAQ that originated near the fire source and got transported regionally are consistent with AIRS observations in May but not in April.

Figure 3 shows time series of CO concentrations for the two-month time period. The rapid rise in AIRS CO in early April with a peak in April 7^{th} is missing in CMAQ for both base case simulation and simulation with fire emissions. Further analysis is needed to diagnose this discrepancy. CMAQ base case simulation (blue line in figure 3) shows no day to day variability for the two month time period. These emissions in the base case simulation have anthropogenic source and are based on EPA national emissions inventory. CMAQ simulation with fire emissions shows variability in CO consistent with AIRS due to fire emissions although the values are biased low. Near the source region (where most of the fires occurred) bias between AIRS CO and CMAQ base case CO is 1.07 ± 0.34 molecules/cm^2 and bias between AIRS CO and CMAQ fire emissions CO is 0.97 ± 0.36 molecules/cm^2.

Figure 4 expands the analysis to include all grid cells in the CMAQ domain that were influenced by fire emissions. This scatterplot shows correlation between AIRS and CMAQ total column CO for all the CMAQ grids where fire emissions had an influence and AIRS retrievals are available. Essentially, only CO data from grid cells that showed a non-zero difference in CO between base case simulation and simulation with fire emissions are used in comparison with AIRS CO. For the two month simulation time period, the base case CMAQ simulation shows no correlation ($r = 0.03$) with AIRS observations. There is a substantial variability in AIRS observed CO ($2X10^{18}$ – $6X10^{18}$ molecules/cm^2) whereas CMAQ values only range between $1X10^{18}$ – $2X10^{18}$ molecules/cm^2 with one value at higher concentration. The correlation coefficient increases to 0.17 when biomass burning emissions are included in the CMAQ simulation. Similar comparisons between CMAQ and AIRS CO at individual layers show that correlation is similar, especially in the mid-troposphere where AIRS retrieval sensitivity is highest. Results shown in figures 3 and 4 indicate that despite the inclusion of fire emissions in the CMAQ model, improvements in predicted CO are marginal indicating that GOES CO emissions product is underestimating the emissions.

The biomass burning emissions in the model were injected into the CMAQ model's lowest layer. Unless there are aircraft measurements during the biomass burning events or satellite-based LIDAR measurements, it is difficult to know the altitude of the plumes. Extensive analysis of MISR satellite data showed that most plumes stay in the boundary layer, while at times plumes can reach free troposphere and get transported long distance[19]. Figure 5 (left panel) shows vertical profile of CO in CMAQ compared to AIRS near the source region for May 12, 2007. The CMAQ CO profile for base case simulation shows 100 ppb near the surface and with decreasing amounts with increasing height. This is in contrast to AIRS observed CO profile, which shows a peak in CO concentration near 700 mb. AIRS CO profile is higher than base case CMAQ CO profile at all altitudes. CMAQ simulation with fire emissions show enhanced CO near the surface which is 50% higher than base case CO simulation. Because AIRS CO retrievals have more sensitivity to CO changes in mid-troposphere than near surface CO changes, for meaningful comparisons with CMAQ CO profiles, one has to adjust the CMAQ profiles with AIRS CO averaging kernels. Averaging kernels shown in the right panel of Figure 5 are sensitivity curves. For example, if there is a known CO change near 500 mb, the measurements will capture 35% of that change at that altitude. Similarly, a known change of CO at 250 mb is captured in the measurements at 10%. Algorithm places 15% of that change at 500 mb. Because of this varying sensitivities for varying CO at different altitudes, CMAQ profile is adjusted (retrieved) prior to comparing with AIRS CO using equation 1:

$$X_{cmaqretrieved} = A.X_{cmaq} + (I\text{-}A)X_{apriori} \qquad (1)$$

In equation 1, $X_{cmaqretrieved}$ is the retrieved profile, A is the averaging kernel, X_{cmaq} is CMAQ profile, I is the identity matrix, and $X_{apriori}$ is AIRS a priori CO profile. The red curve shown in Figure 5 is retrieved CMAQ profile. This profile shows CO values are still lower than AIRS observed profiles at all altitudes. For example, retrieved CMAQ CO for fire emissions simulation is 33% lower near the surface and 45% lower than AIRS near 700 mb where AIRS CO peaks. These results are consistent with analysis of total column CO shown in scatterplots. CMAQ simulations where CO is introduced at different altitudes in the model may help resolved some of the discrepancies because wind speeds are different at different altitudes and CO transport may be more spatially aligned with observed transport.

CONCLUSIONS

This study investigated the use of satellite-derived biomass burning emissions for April and May 2007 in a CMAQ model. CMAQ model runs with and without emissions were compared to AIRS observed CO. CMAQ model simulations with fire emissions captured the CO plumes from fires spatially and temporally. Elevated CO near and downwind of fires in the CMAQ model showed a qualitative agreement with AIRS CO. Quantitative analysis, however, revealed that CMAQ CO concentrations are under-predicted compared to AIRS CO implying that GOES CO emissions are biased low. Further analysis is needed to diagnose and fully understand the differences between AIRS and CMAQ CO due to other errors such as transport errors.

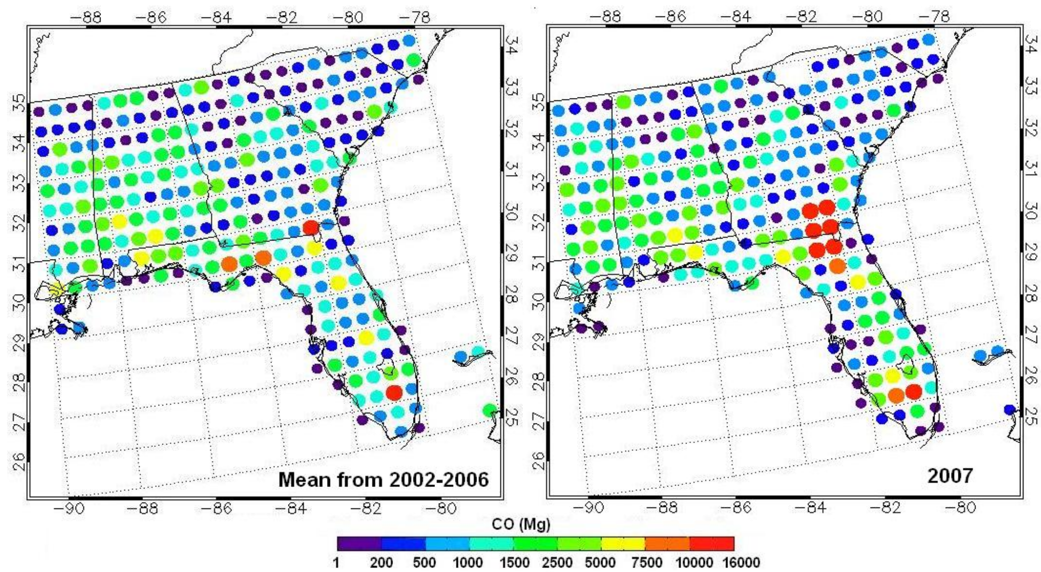

Figure 1: Gridded CO emissions data on a 0.5° X 0.5° spatial resolution in the southeast. Individual pixel emissions were obtained for GOES observed fire detections and then averaged to 0.5° grids. Left panel shows climatological mean for 2002-2006 and right panel shows mean values for 2007. Note that emissions are substantially higher in 2007 due to continuous fires compared to 2002-2006 climatology.

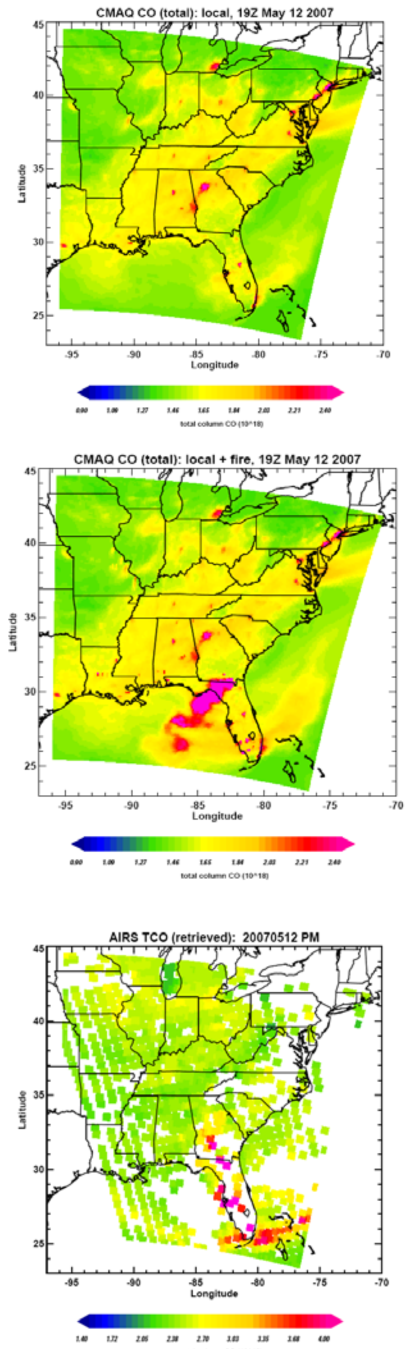

Figure 2: Simulated CO (base case CMAQ in top panel, fire emissions CMAQ in middle panel) compared to AIRS observed CO (bottom panel) for May 12, 2007. Note that color bar is different for CMAQ and AIRS.

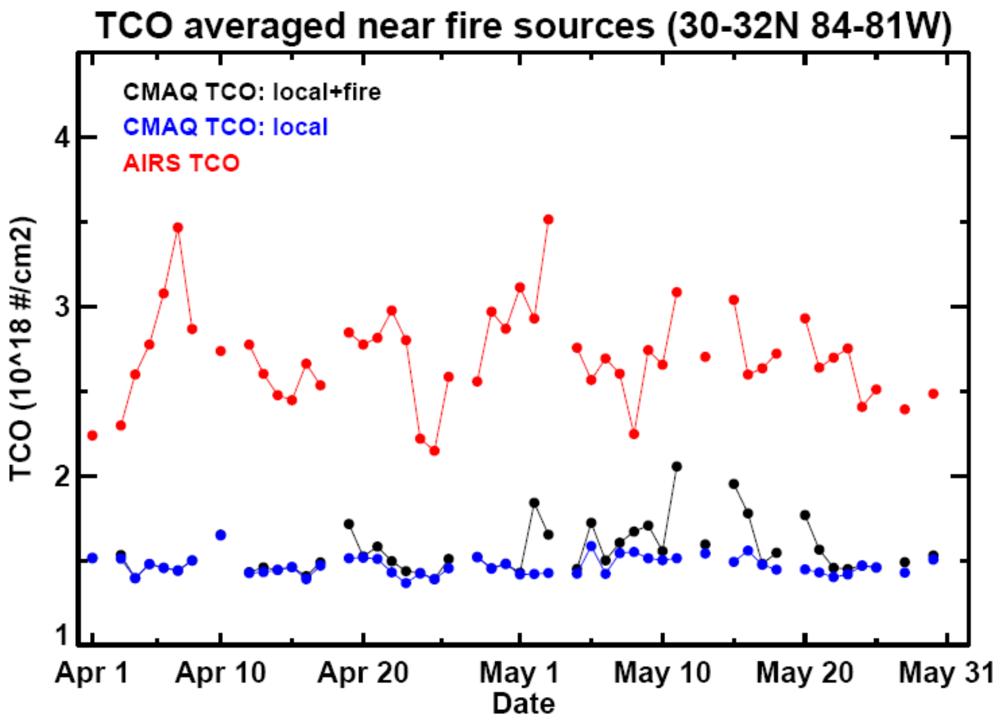

Figure 3: Time series of total column CO for April and May 2007 near Florida/Georgia border where fires were observed. Base case CMAQ CO (blue) shows no day to day variability and is about 1.5 X 10^{18} molecules/cm^2. CMAQ simulations with fire emissions (black) shows enhanced CO compared to base case simulation but still substantially lower than AIRS observed CO (red).

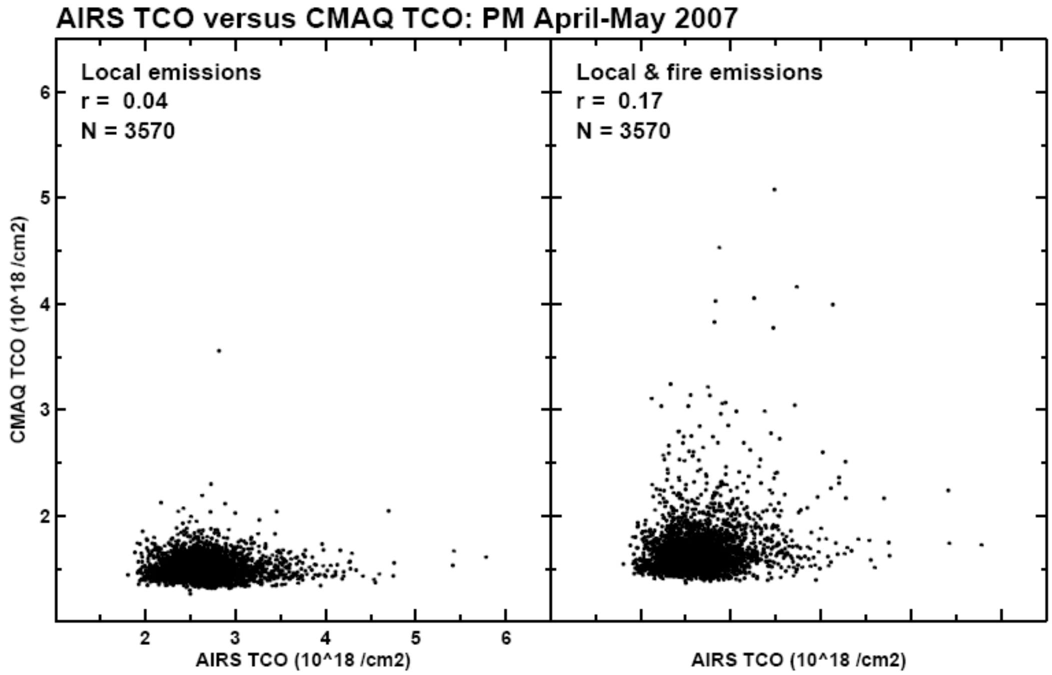

Figure 4: Correlation between CMAQ total column CO and AIRS observed CO. Left panel is for CMAQ base case simulation and right panel is for CMAQ with fire emissions. Correlation improved for fire case simulation but overall CMAQ CO is biased low compared to AIRS observed CO.

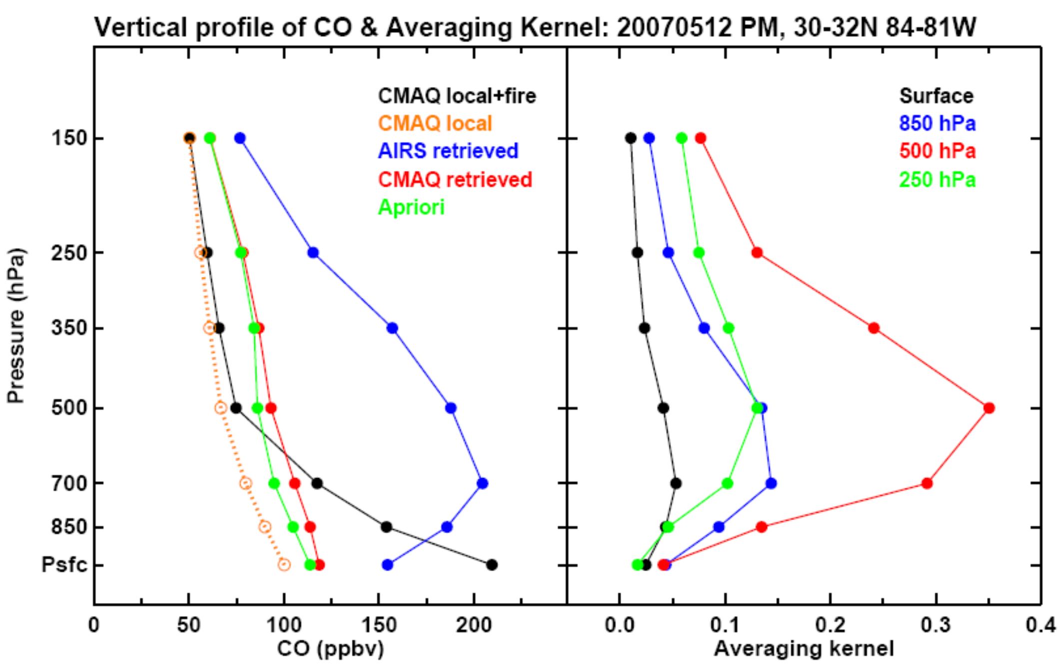

Figure 5: Vertical profiles of CO from CMAQ simulations and AIRS observations (left panel) and AIRS averaging kernels in the right panel.

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