AIRS views of transport from 12-22 July 2004
Alaskan/Canadian fires: Correlation of AIRS CO and
MODIS AOD with forward trajectories and
comparison of AIRS CO retrievals with DC-8 in situ
measurements during INTEX-A/ICARTT

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Abstract.

We present observations of tropospheric carbon monoxide (CO) transport obtained by the Atmospheric InfraRed Sounder (AIRS) onboard NASA’s Aqua satellite during the Intercontinental chemical Transport EXperiment-North America (INTEX-A) and the International Consortium for Atmospheric Re-

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search on Transport and Transformation (ICARTT) field campaigns in the summer of 2004. In situ measurements from NASA’s DC-8 provide crucial assessment of AIRS mid-tropospheric CO retrievals (400-500 mb). Convolution of the in situ profiles with AIRS verticality functions demonstrate AIRS 400-500 mb CO retrievals are biased high by approximately 8% with a standard deviation slightly less than 5%. In some cases, AIRS CO retrievals are sensitive to CO in the lower- to mid-troposphere (500-700 mb). Focusing on one major transport episode, we investigate transport of CO from a large fire outbreak in the Alaskan/Canadian Yukon region on 11-14 July 2004 and follow it downwind to the southeastern United States and Europe until 22 July 2004. Correlations between AIRS CO and MODIS aerosol optical depths (AOD) indicate changes in the vertical distribution of CO as supported by in situ measurements, meteorological and forward trajectory analyses. Ground-based lidar observations show smoke plume altitudes from 3 to 11 km over Wisconsin and 1 to 4 km over Maryland in agreement with the forward trajectories. Comparison of AIRS CO maps and forward trajectories from the fire locations illustrate the great variations in fire emissions, especially emission height, that must be accounted for if any forecast model is to correctly predict the impact of fire emissions days to weeks downwind. Furthermore, the forward trajectory analysis reveals some of the fires must have injected emissions to at least 500 mb, and perhaps as high as 300 mb, in order for the smoke and CO to go where observed by AIRS.
1. Introduction

With a capacity for daily global observations of numerous atmospheric parameters, NASA’s Atmospheric InfraRed Sounder’s (AIRS) onboard the Aqua satellite provided a unique perspective for the Intercontinental chemical Transport EXperiment–North America (INTEX-A) [Singh et al., submitted 2006] and International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) [Fehsenfeld and et al., submitted 2006] field campaigns during July and August 2004. In particular, AIRS observations of tropospheric carbon monoxide (CO) during INTEX-A/ICARTT illuminate several North American industrial and biomass burning sources and subsequent transport paths [Thompson et al., 2006; Soja et al., 2006].

CO surface concentrations have long been known to exhibit influences from distant sources based on chemical lifetime estimates [Crutzen et al., 1979; Logan et al., 1981; Badr and Probert, 1994], in situ measurements and modeling [Harriss et al., 1992; Law and Pyle, 1993; Thompson et al., 1994; Chatfield et al., 1996; Hannan et al., 2003] and studies of surface concentrations [Parrish et al., 1993; Novelli et al., 1992]. Over the past decade, the impacts of such intercontinental, sometimes hemispheric, transport on distant locations have become clear [Chatfield et al., 1998; Parrish et al., 1998; Forster et al., 2001; Novelli et al., 2003; Duncan et al., 2003; Damoah et al., 2004; Colarco et al., 2004; Honrath et al., 2004].

Satellite observations starting with the Measurement of Atmospheric Pollution from Space (MAPS) instrument onboard the Space Shuttle in 1981 illustrated the global distribution of CO and large-scale biomass burning as a significant global source [Reichle et al.,
1982, 1990; Connors et al., 1989, 1999]. Since 2000, the wealth of CO retrievals from the Measurement Of Pollution In The Troposphere (MOPITT) instrument on NASA’s Terra satellite have shown transport on time-scales of several days [Deeter, 2003; Heald, 2003; Lamarque et al., 2003; Li et al., 2005; Liu et al., 2005], provided information on estimates of CO emissions from the 2004 Alaska/Canada fires [Pfister et al., 2005], and explored correlations between CO signatures and aerosols [Edwards et al., 2004; Bremer et al., 2004]. Retrievals of tropospheric CO from airborne remote sensors also have contributed to our appreciation of long range transport [McMillan et al., 1996, 2003; McCourt et al., 2004]. The latest instrument to measure tropospheric CO, the Tropospheric Emission Spectrometer (TES) was launched onboard the Aura spacecraft in 2004 and already has made contributions to improving our understanding of the CO budget [Jones et al., 2003].

Launched onboard NASA’s Aqua satellite on 4 May 2002, AIRS cross-track scanning grating spectrometer coupled with Aqua’s cross-track scanning Advanced Microwave Sounding Unit (AMSU) provide vertical profiles of the atmosphere with a nadir 45 km field-of-regard (FOR) across a 1650 km swath [Aumann et al., 2003; Chahine et al., 2004]. Although primarily designed as a prototype next generation temperature and water vapor sounder, AIRS broad spectral coverage (3.7 to 16 µm with 2378 channels) include spectral features of O3, CO2, CH4, and CO [Haskins and Kaplan, 1992]. With such a broad swath, AIRS infrared spectra and cloud-clearing [Susskind et al., 2003] enable day/night retrievals over nearly 70% of the planet every day, with substantial portions of the globe observed twice per day (ascending and descending orbits). Thus, AIRS readily observes global scale transport from large biomass burning sources [McMillan et al., 2005].
With biomass burning and oxidation of naturally occurring volatile hydrocarbons accounting for nearly 50% of CO emissions [Logan et al., 1981; Thompson et al., 1994], monitoring changes in these sources along with changes in anthropogenic sources and subsequent transport form key elements to assessing the impact on tropospheric chemistry and near surface air quality. CO’s relatively long lifetime, 1-3 months in the troposphere, make it an excellent tracer of transport and source variability [Badr and Probert, 1994]. Over the past several decades, studies have documented increases in tropospheric CO believed coupled to increasing anthropogenic emissions from 1970 to the late 1980’s [Khalil and Rasmussen, 1988; Yurganov et al., 1997]. Followed by a leveling off and decrease in tropospheric CO from 1990 to 2000 attributed to tighter controls on automobile emissions [Novelli et al., 1994; Khalil and Rasmussen, 1994; Bakwin et al., 1994; Parrish et al., 2002]. However, several recent studies have postulated possible large scale increases and variations in biomass burning sources in the boreal region due to climate change [Wotawa et al., 2001; Yurganov et al., 2004; Lapina et al., 2006; Kasischke and Turetsky, 2006].

AIRS and its successors TES, IASI, CrIS, GIFTS, etc. are uniquely capable of helping assess the global impact of such changes in sources and downwind transport. Unfortunately, like its predecessors MAPS and MOPITT, the spectral resolution of AIRS yields a CO sensitivity that broadly peaks in the mid-troposphere (300 to 700 mb) with little information on the vertical distribution. Thus, while it is easy for AIRS to see CO, it is not always straight-forward to interpret AIRS CO retrievals. An observed increase in CO abundance by AIRS could mean more CO is present (stronger source) or that the CO has been lifted into the mid-troposphere where AIRS is more sensitive. Indeed, the latter is often the case as we document here. Most often, we see less CO enhancement near a
source than downwind where it has been lifted above the boundary layer. However, as described here, AIRS has some sensitivity to CO in the lower troposphere (700-500 mb) as demonstrated through comparisons to both in situ, and ancillary information that tells us where the biomass emissions (CO rich smoke) are located. A full validation of AIRS CO retrievals is beyond the scope of this paper and is not possible given the handful of CO validation profiles available from INTEX-A. However, the INTEX-A in situ profiles provide an excellent comparison set to assess the performance and accuracy of AIRS CO retrievals in the mid-troposphere.

2. AIRS CO Retrievals for INTEX-A/ICARTT

AIRS was designed as a prototype next generation atmospheric sounder for NASA and NOAA polar orbiting satellites [Chahine et al., 2004]. As such, AIRS’ performance was optimized to retrieve highly accurate temperature (1K RMS error in 1km tropospheric layers) and water vapor (15% RMS error in 2 km tropospheric layers) profiles [Chahine et al., 2004]. In practice, AIRS temperature and water vapor retrievals exceed the target accuracy for clear scenes [Tobin et al., 2006] and are only slightly worse for cloud-cleared scenes [Divakarla et al., 2006]. The full AIRS team retrieval algorithm is described in Susskind et al. [2003] including detailed discussion of AIRS cloud-clearing; and temperature, water vapor, and O₃ retrievals. Although, the AIRS Science Team always envisioned doing much more with the broad spectral coverage including retrievals of tropospheric trace gases O₃, CO₂, CH₄, and CO [Haskins and Kaplan, 1992], the present version of the CO retrieval algorithm is unchanged from pre-launch planning in 1997.

At UMBC, we run a research version of the AIRS team algorithm developed by co-authors at NOAA. For INTEX-A, the version we ran was intermediate between the
DAAC’s versions v4.0 and what will be v5.0. During INTEX-A, the NOAA co-authors provided access to AIRS L1b radiances in near-real-time (NRT), 3-24 hours after data acquisition. Each evening local time, after 0000 UT, we executed (often with human assistance) full retrievals on the L1b radiances for all AIRS granules (typically 60) within the INTEX-A/ICARTT study area (20N to 70N, 180W to 30E) from the preceding UT day. By the next morning local US east coast time (1400 UT) automated processing routines compiled the AIRS retrievals into web accessible daily AM and PM maps of AIRS retrieved CO at 500 mb, total column, and NetCDF data-files for distribution to the INTEX-A/ICARTT Science Teams. In collaboration with Brad Pierce (NASA LaRC), we also generated 48 hour forward trajectories from regions of enhanced 500 mb CO. These maps, data-files, and forward trajectories were then used to assist in INTEX-A/ICARTT flight-planning.

Since INTEX-A/ICARTT ended, we have reprocessed all the AIRS granules to fill in any gaps arising from missing data in the NRT processing scheme. All maps and data-files are available via our webpage (http://asl.umbc.edu/pub/mcmillan/www/index.html) for the full INTEX-A/ICARTT campaigns. A second reprocessing with the optimized AIRS CO algorithm in an AIRS v5.0 version will occur in the Fall of 2006. While CO is our standard product release for INTEX-A/ICARTT, by running the full AIRS retrieval algorithm, all AIRS products are available for all AIRS granules we process.

3. AIRS CO Retrieval Algorithm

As described by McMillan et al., [2005], tropospheric CO abundances are retrieved from AIRS measured radiances in the 4.58–4.50 μm (2183–2220 cm$^{-1}$) region of the 1–0 vibration-rotation CO fundamental through numerical inversion of the radiative transfer
equation employing Strow et al. [2003]'s fast forward radiative transfer model. We continue to utilize the pre-launch CO algorithm described in McMillan et al., [2005] where the tropospheric CO profile is broken down into a series of vertically overlapping trapezoidal functions empirically determined from pre-launch simulations. The overall methodology of the AIRS CO retrieval algorithm is analogous to the AIRS $O_3$ retrieval algorithm described in Susskind et al. [2003]. Unlike $O_3$ which performs a statistical regression to acquire a first guess profile, the CO algorithm begins with the AFGL standard atmosphere CO profile [Anderson et al., 1986] as a first guess.

Figure 1 presents the four AIRS pre-launch CO trapezoids which form the perturbation functions for the profile in the retrieval algorithm. In the middle of the atmosphere, they sum to one, at the top and bottom they sum to 0.5 to lessen impacts from portions of the atmosphere where AIRS has little CO signal. This set of trapezoids was developed based on a limited set of pre-launch retrieval simulations. These simulations showed the peak sensitivity of AIRS to tropospheric CO occurred between 300 and 500 mb, thus the thinnest functions were placed in these locations.

Unfortunately, as we have discovered in our AIRS CO validation research, the pre-launch functions of Figure 1 are insufficient to fully characterize AIRS CO retrievals and vertical sensitivity. However, the pre-launch algorithm is the tool we have at hand, so we will provide our best estimation of its accuracy. An optimized AIRS CO retrieval algorithm is in final testing and validation with a variant to be employed in v5.0 of the full AIRS retrieval algorithm expected to be running at the NASA Goddard DAAC in December 2006 producing CO as a new standard product.
With similar sensitivity to mid-tropospheric CO as MAPS and MOPITT, AIRS' unique daily global view provides nearly ten times as many retrievals per day as MOPITT and enables process studies of phenomena on 12-24 hour timescales [McMillan et al., 2005]. However, as previously mentioned, AIRS spectral resolution (nearly 2 cm$^{-1}$ in the CO region) does not provide much information on the vertical distribution of CO. AIRS vertical resolution is similar to MAPS, but somewhat lower than MOPITT or TES. AIRS CO retrievals possess 0.3–1.5 degrees of freedom (sum of the eigenvalues); no more than one eigenvector is ever completely undamped in the retrieval process and generally the largest eigenvector is only believed around 50% [McMillan et al., 2005]. Practically speaking, this means AIRS CO retrievals are sensitive to a weighted total column of tropospheric CO with some changes in shape of that weighting indicating changes in the vertical distribution of CO.

4. AIRS CO Verticality

In more traditional numerical solutions to inverse problems, the vertical weighting of sensitivity is defined as the averaging kernel, $A$, [Rodgers, 2000; Rodgers and Connor, 2003]. In this formulation, $(1-A) =$ the amount of a priori remaining in the final retrieved solution. Although the AIRS team retrieval algorithm is not formulated as a maximum likelihood problem [Susskind et al., 2003], it does compute a quantity, $\Phi$, akin to an averaging kernel but in the reduced measurement space defined by the trapezoids. The 100 layer AIRS CO retrievals (column CO in each layer) are related to this reduced measurement space by a unitary transformation, Equation 32 of Susskind et al. [2003], and $\Phi$ as the damping factor in Equation 36.
\[ \Phi = \frac{\lambda}{\lambda + \Delta\lambda} \]  

(1)

\( \Phi \) then represents the amount of information in the radiances and \( (1 - \Phi) \) is the fraction of the first guess retained in the retrieval [Susskind et al., 2003]. \( \lambda \) are the eigenvalues of the eigenvectors from the unitary transformation damped by \( \Delta\lambda \). Thus, in the transformed trapezoid space, \( \Phi \) is the averaging kernel.

Transforming Equation 1 back into the reduced measurement space defined by the trapezoids we obtain the AIRS averaging kernel matrix

\[ A = U \cdot \frac{\lambda}{\lambda + \Delta\lambda} \cdot U^T \]  

(2)

where \( U \) are the eigenvectors from the unitary transformation [Susskind et al., 2003]. For the pre-launch algorithm, this is a \( 4 \times 4 \) matrix with each row corresponding to the averaging kernel for the respective trapezoid.

To assess the accuracy of AIRS retrieved mid-tropospheric CO mixing ratios, we utilize the AIRS verticality function, \( V \), [McMillan et al., 2005] to convolve in situ profiles to a representation of what AIRS would have seen. The sum of the rows of an averaging kernel matrix, \( A_s \), represents the fraction of information in the reduced measurement space determined directly from the radiances, and \( (I - A_s) \) represents the fraction of a priori information retained [Rodgers and Connor, 2003]. The coarse layering scheme of the reduced measurement space does not enable a good comparison with high resolution in situ data. Thus, we sum the rows of \( A \) from Equation 2 and expand from the 4 trapezoids to the 100 AIRS layers in the same manner as the AIRS retrieval algorithm expands...
the CO perturbations on the trapezoids back to 100 layer CO columns. This 100 layer function we call the \textit{verticality}, $V$, \hspace{1cm} (3)

\begin{equation}
V = I(1 \times 4) A(4 \times 4) Trap(4 \times 100)
\end{equation}

where $Trap$ are the 4, 100 layer trapezoids from Figure 1.

The verticality, $V$, defined in equation (3) up-samples the coarse layer averaging kernel sums, $A_s$, onto the 100 layer grid in the same way as the optimal functions are up-sampled (see Equation 32 in Susskind et al., [2003]). This process is similar to the column operator as described in Rodgers and Connor [2003], but is complicated by the details of the AIRS team retrieval algorithm.

Although the use of trapezoidal perturbation functions and corresponding interpolation rule (e.g. Equation 3) ensures a smooth retrieval product, the large extent of the bottom function does not enable one to adequately define where within that trapezoid an AIRS CO signature arises. For comparisons of AIRS CO products with in situ data (following section) we will focus on a region about 400-500mb where the uncertainty in the extent of the perturbation functions is mitigated by the use of thinner trapezoids.

5. INTEX-A AIRS CO Comparison

One of the goals of INTEX-A is to provide in situ measurements for validation of satellite remote sensing observations Singh \textit{et al.} [submitted 2006]. Of the 17 flights of the NASA DC-8 during INTEX-A, 9 included spiral profiles (ascent or descent) of the DC-8 that are usable for comparison to AIRS CO retrievals. These flights are summarized in Table 1 where the timing column refers to the proximity of the start of the spiral to AIRS...
overpass time. Other DC-8 flights either flew spirals for MOPITT validation, did not fly spiral profiles, flew spirals in areas where we have no AIRS retrievals, or flew spirals of insufficient altitude coverage for use here (must cover at least 250–900 mb).

Figures 2 (a) and (b) show the AIRS 500 mb CO retrievals for 1 and 20 July 2004 along with the DC-8 flight track (magenta) and the location of the spiral validation profiles. AIRS pixels are missing either in gaps between orbits or where retrievals were rejected due to clouds. The 1 July flight intercepted a plume of Asian pollution over the Pacific Ocean, while the 20 July flight crossed the large Alaskan/Canadian fires smoke plume over the southeastern United States on several occasions. Figures 3 (a) and (b) show the in situ CO measurements from the DACOM instrument [Suchse et al., 1987] along with AIRS CO retrievals, AIRS first guess profiles, and convolved DACOM profiles. First, we compare the DACOM profiles (red lines) to the AIRS retrievals (blue solid line = mean of AIRS retrievals within 100 km, blue dashed lines = ± 1 σ). The 1 July profile clearly indicates a CO rich plume above 500 mb with clean air below 600 mb. In contrast, the 20 July profile shows relatively clean air above 750 mb with polluted conditions in the boundary layer.

Directly comparing the in situ CO measurements to the AIRS CO retrievals in Figures 3 (a) and (b), one sees the in situ measurements cross the AIRS retrievals on 1 July between 400 and 500 mb, while on 20 July the AIRS retrievals are larger than the in situ measurements down to the boundary layer. As previously mentioned, AIRS CO sensitivity generally peaks between 400 and 500 mb. Comparing the mean in situ in this layer to the mean retrievals we see AIRS is larger in both cases, 3.8 ppbv (3%) on 1 July, and 24.4 ppbv (27%) on July 12. Similar results for all 9 of the INTEX-A comparisons appear
in column 5 of Table 1. Clearly, such a comparison does not put the retrievals in a very good light with a mean bias of 25% high.

Our next step in comparing in situ and retrieved CO involves convolving the in situ profile with the AIRS CO verticality function. Figures 4 (a) and (b) show the mean AIRS CO verticality functions for all CO retrievals within a 100 km radius of the center of the respective DC-8 spiral profile. These retrievals are marked in Figures 2 by the black circles. Though they have similar peak magnitudes, they have much different shapes. The 1 July verticality function peaks more sharply at 400 mb while 20 July peaks at 500 mb and is larger below 500 mb. In part, these subtle shape changes reflect the differences in the two in situ profiles.

Now, convolving the in situ mixing ratio profile with the verticality function yields the green lines in Figures 3. In both cases, this convolution brings the in situ measurements closer to the AIRS retrievals. It is noteworthy how the convolved profile of 1 July dramatically changes shape below 500 mb with a change in slope below 700 mb. This reflects the lack of information in these AIRS CO retrievals in this region of the atmosphere as the convolved in situ has taken on the general shape of the AIRS first guess profile. However, the fact that the 20 July convolved in situ does not similarly change shape below 700 mb could indicate those AIRS CO retrievals contain information in the lower troposphere, perhaps even down to the boundary layer. Here the extent of the bottom trapezoid limits AIRS ability to further specify the vertical sensitivity. Convolving the in situ with the verticality function reduces the mean 400 to 500 mb CO mixing ratio differences to 1.9 ppbv (1.5%) on 1 July and 7.7 ppbv (7.3%) on 20 July. Although AIRS is still high,
the bias is reduced to less than 10%. Results for all 9 INTEX-A comparisons appear in column 6 of Table 1.

Admittedly, the INTEX-A matchups form a limited set of validation cases and do not cover a wide range of conditions. However, these excellent first comparison results point to the reliability of AIRS CO retrievals if care is taken to interpret them as demonstrated by the following analysis. A more detailed and comprehensive validation effort is underway as part of optimization and improvement of the AIRS CO retrieval algorithm for v5.0 of the AIRS team algorithm. The improved AIRS CO retrieval algorithm also will yield far superior information content along with a more straight-forward product.

6. AIRS CO during INTEX-A/ICARTT

Figure 5 22 panels show AIRS CO retrievals at 500 mb (near the peak of AIRS tropospheric sensitivity) over the INTEX-A/ICARTT study area every 12 hours (ascending and descending orbits) from 12-22 July 2004. Similar pairs of daily maps were created in NRT mode for support of INTEX-A/ICARTT flight planning. Note the large increase in CO over the Alaska/Canadian Yukon region commencing on 12 July with subsequent movement to the southeast. On 16 July, the plume appears to split: a portion moves south into the United States reaching as far as the Gulf of Mexico by 19 July; while the main portion moves rapidly to the east and becomes caught in a cyclonic system just west of England by 20 July. This sequence of maps demonstrates AIRS capability to track CO changes in some areas of the planet on timescales as short as 12 hours. A more detailed discussion of these maps along with comparisons to aerosol optical depths derived from MODIS, ground-based lidar observations, and forward trajectories follows in subsequent sections.
Other than the obvious pattern changes in CO due to the motion of the smoke plume, one also sees differences in AIRS retrieved CO abundances in nighttime (AM) vs. daytime (PM). Most of this is difference results from changes in the spectral signature of CO due to changes in the surface temperature, not due to real changes in CO abundance. In addition, more retrievals are rejected over land in the daytime, particularly in more arid regions, resulting from issues involving lower surface emissivities in these areas and perhaps diurnal changes in cloud cover.

Overall, the 2004 Alaskan fire season was the worst on record with more than $2.7 \times 10^6$ ha burned, nearly 10 times the average [Damoah et al., 2005, 2006; Fuelberg et al., submitted 2006; Kasischke and Turetsky, 2006]. Fuelberg et al. 2006 describe the meteorological conditions that led to the perfect conditions for the fires to occur as well as the conditions for the ensuing transport of the smoke downwind.

A large fire outbreak occurred in the Alaskan and Canadian Yukon region on 11-14 July 2004 [Hoff et al., 2005]. Satellite detected fire counts in the region depicted in Figure 6 increased from a few hundred on 10 July to nearly 6000 on 12 and 13 July, see Figure 7. Hot-spot locations were obtained from the NOAA Satellite Service Division archive as a composite of all satellite fire detections (www.ssd.noaa.gov). Figure 8 co-locates the fire locations on these days with individual AIRS CO 500 mb retrievals from afternoon (PM) orbits. While the exact satellite derived hot-spots do vary in location from day to day, the obvious pattern of these large-scale fires is similar for each day. While some AIRS CO retrievals are enhanced in the direct vicinity of the fires, generally the largest CO amounts are seen to the east, downwind of the fires.
Many more fires over much larger areas of Alaska and Canada burned during different portions of INTEX-A/ICARTT. Here we focus on one large episode that produced a several day pulse of CO. As discussed with regard to forward trajectory computations, the AIRS CO data show evidence of heterogeneity in CO emission from these fires in terms of both CO amount and injection altitude. In reality, the AIRS CO maps presented here show evidence for many different sources.

7. AIRS CO vs. MODIS

With the Alaskan/Canadian fires as the obvious source of a tremendous amount of the CO seen by AIRS from 12-22 July 2004, comparison of AIRS CO retrievals to a measure of total smoke optical depth is a logical place to begin to look for changes in CO vertical distribution. Retrievals of aerosol optical depth (AOD) from observations by the MODIS onboard Aqua, are largely insensitive to the altitude distribution of the aerosols, i.e. it is a true total column measurement [Chu et al., 2003]. However, as CO moves up in the troposphere into AIRS region of peak sensitivity, 400-600 mb, the abundance of CO will appear to increase. We assume here that the CO produced by the fires will stay in the same air mass as the smoke absent some aerosol scavenging. Most of the downwind AOD is not due to flyash which is expected to fallout near the fires. Thus, changes in the correlation between AIRS CO and MODIS AOD will reflect changes in the vertical distribution of CO.

Figure 9’s 11 panels show AIRS afternoon CO maps side-by-side with MODIS AOD maps from 12–22 July 2004. Since MODIS AOD retrievals rely on visible channels, only daytime maps are available for comparison [Kaufman et al., 1997; Chu et al., 2003; Remer
Correlations between the two sets of maps are obvious by the similarities in the day-to-day pattern changes.

However, a more detailed comparison shows there are distinct changes in the correlations as the CO rich smoke moved southeast. The colored box regions that shift from day-to-day through Figure 9’s maps indicate different regions where we have examined AIRS CO vs. MODIS AOD as illustrated in the scatter plots of Figure 10 (a)–(d) for 15–18 July, respectively. The different boxed regions of the maps correspond to the different colored symbols in the scatter plots. Prior to 15 July, the correlation between AIRS CO and MODIS AOD over the fire region and following the advancing plume (Plume 1) are similar. However, starting on 16 July as the CO/smoke plume appears to split in two, the correlation between AIRS CO and MODIS AOD for the two plumes appears to diverge with Plume 2 (the Atlantic plume) following a much steeper distribution.

Figure 11 presents the best fit lines, computed via the MATLAB robustfit linear regression \[DuMouchel and O'Brien, 1989\], to the different regional correlations to better illustrate the differences in slope. Notice that Plume 1 (the southeast US plume) and the fire region have very similar slopes. This appears to be the case for Plume 1 and the fire region throughout this period. Figure 12 (a) and (b) present the best robustfit lines to the Plume 1 and 2 AIRS CO vs. MODIS AOD for each day from 13–22 July. Note the, dramatic difference in the correlation for Plume 2 on 17–19 July. For the other days, the slope of the Plume 2 correlation is nearly identical to Plume 1.

According to our hypothesis, an increase in the slope of AIRS CO vs. MODIS AOD would occur if the CO and smoke was uplifted. Thus, from this analysis we surmise Plume 2 was uplifted with respect to Plume 1 beginning on 17 July. After 19 July, Plume 2 must
have experienced a broadening in its vertical distribution to return to similar slopes vs. Plume 1. Underlying this argument we have assumed that either all of the downwind CO and AOD come from the Alaskan/Canadian fires or any sources along the plumes’ travel produce CO and smoke in similar amounts. To test that relatively simple explanation, we turn to additional sources of information to determine changes in the vertical motion and distribution of the CO rich smoke plume. As we discuss below, the true changes in their distribution are far more complex.

8. AIRS CO vs. Lidars

During the INTEX-A/ICARTT field deployment, we came to rely on data from several ground-based lidar instruments to provide more precise information on the vertical distribution of smoke from the Alaskan/Canadian fires. As fortune had it, as Plume 1 moved southward from Canada into the United States, the east edge of it passed directly over the continuously operating High Spectral Resolution Lidar (HSRL) at the University of Wisconsin in Madison, Wisconsin [Eloranta, 2005], see Figure 13. As Plume 1 moved east and subsequent smoke plumes moved toward the southeast out of Canada, they passed over the Elastic Lidar Facility (ELF) at the University of Maryland Baltimore County near Baltimore, Maryland [Engel-Cox et al., 2006].

Figure 14 presents vertical cross-sections of HSRL data from 18–19 July in both backscatter cross-section and and linear depolarization. The depolarization is particularly useful for distinguishing between: anthropogenic aerosols, low depolarization shown in the blue colors in the lower panel of Figure 14; larger smoke aerosols, moderate depolarization as indicted by the green-orange colors; and ice particles (cirrus) with a high
degree of depolarization represented by the red colors. Examination of Figure 14 indicates several different smoke plumes crossed the site at different altitudes on 18–19 July.

The first smoke plume appears between 3 and 4 km early 18 July and appears to mix into the top of the boundary layer beginning at 0800 UT. From 0300-1300 UT several thinner smoke plumes are evident in 0.5 to 2 km thick layers from near 5 km to above 11 km. The thickest smoke plume appears over Madison starting near 1700 UT on 18 July and continues through 1200 UT on 19 July, again with apparent mixing into the top of the boundary layer. Note the general descent of this thicker plume with time along with the decreasing height of the mixed layer and cirrus clouds. This decrease in height occurred as this air slid down the west side of the persistent trough dug in across the eastern United States [Fuelberg et al., submitted 2006].

Thus, as Plume 1 moved southward into the central and eventually the southeastern United States, it started as several distinct smoke plumes at a range of altitudes on 18 July, and ended up with a vertically thicker plume mainly in the lower-mid troposphere (2-6 km) with descent as it moved south. Already, we see the previous section greatly oversimplified the situation by assuming Plume 1 is a single coherent structure. The lidar reveals it as extremely temporally and spatially inhomogeneous with vastly different vertical extents. In retrospect, this is not a surprise, as the 11-14 July fire episode involved several large fire complexes with minute-to-minute changes in fuel consumption, fanning winds, rise heights, etc. all giving rise to many separate smoke plumes that may or may not mix with each other depending on transport details. The forward trajectories discussed in the next section further reveal this complex transport event.
Further evidence for the heterogeneity of this smoke event comes from the Polar ELF lidar near Baltimore, Maryland [Engel-Cox et al., 2006]. Figure 15 shows aerosol backscatter from 1150-2021 UT on 20 July 2004. Two distinct smoke plumes are evident in the image, the first from 1200-1400 UT between 1 and 2 km; and the second appearing near 1600 UT above 4 km. The lower plume mixed into the boundary layer as it grew in the afternoon.

With both the HSRL and ELF lidars indicating mixing of the smoke into the boundary layer, we can see that this large fire episode in Alaska and Canada had direct impacts on surface air quality in distant locations. In fact, the worst air quality in the Mid-Atlantic and Northeastern United States during the summer of 2004 occurred from 21-23 July with PM2.5 peaking in Baltimore near 60 µg/m³ [Hoff et al., 2005]. Downwind mixing into the boundary layer of biomass burning emissions previously has been documented [Forster et al., 2001; Honrath et al., 2004], and it is documented in this case on 18-19 July 2004 over southern Texas [Morris et al., 2006] through the use of AIRS CO retrievals, TOMS aerosol indices and back trajectory analyses to understand ozonesonde and aircraft in situ $O_3$ profiles over Houston, Texas.

9. AIRS CO vs Trajectories

To model the transport of CO emitted from the Alaskan/Canadian forest fires, we have employed forward trajectory analyses. Initializing air parcels at 4 different altitudes over the locations of satellite detected hot-spots, we then follow their 3-dimensional motion downwind and compare to the CO distributions retrieved from AIRS. All forward trajectories were computed with the Goddard Kinematic Trajectory Model [Schoeberl and Sparling, 1995] using NCEP reanalysis winds [Kalnay et al., 1996]. A more detailed anal-
ysis including photochemical and thermodynamic influences on the CO rich smoke plume along with mixing into the boundary layer remains the focus of ongoing research.

With reanalysis winds limited to 0000 and 1200 UT each day, we ran seven sets of forward trajectories starting every 12 hours from 1200 UT on 11 July to 1200 UT on 14 July 2004 originating from the respective day’s satellite detected hot-spots. Due to the large number of hot-spots in this area each day, see Figure 7 and Table 2, trajectories only were launched from every third spot to reduce the computational load. The number of trajectories run for each day are given in Table 2. Given the number of hot-spots associated with each fire complex, this reduced number of trajectories suffices to characterize the downwind flow.

Because we do not know the injection height for emissions from each hot-spot, in our forward trajectory simulations we initialized parcels at four altitudes above the surface, 850, 700, 500, and 300 mb. By tracking the motions of each group of parcels and comparing to the AIRS CO maps, we gain insight as to the contribution to the downwind fire plume from each emission height above each fire complex.

From the AIRS and MODIS maps, along with the ground-based lidar cross-sections, we already have made the case for the complexity of this transport episode. The results of our trajectory simulations only add fuel to this point; this forest fire episode, though only 4 days long, was far from a single impulse release of CO into the troposphere. We will start the trajectory discussion with an overview for the flow from July 12-22, then follow that with subsections detailing specific aspects of the transport.
9.1. Trajectory Overview

Fuelberg et al. [submitted 2006] provides an excellent discussion of the meteorological context for the Alaskan/Canadian fires and subsequent transport into the INTEX-A/ICARTT study area. Several aspects of the meteorology are evident in the set of Figures 16 to 27 showing forward trajectories launched at 1200 UT on 12 July 2004 (listed as 12.5 July) and shown at subsequent daily intervals 13.5 July, 14.5 July,...,22.5 July. Below 500 mb, we see initial flow to the east and south with increased stretching of the flow at higher altitude. At 300 mb we see the parcels initially are trapped in an Alaskan high pressure with a complete revolution over Alaska occurring in less than three days before they depart to the southeast. However, at 500 mb we see an interesting stretching of the flow during the first five days (12.5–17.5 July) with the eastern most portion rapidly moving off toward Greenland, the central portion descending in altitude as it moves toward the midwestern United States, and the western portion ascending as it, too, is caught in the Alaskan high before looping around over southwestern Hudson’s Bay by 17.5 July.

Between 17.5 and 19.5 July, rapid transport to the Atlantic Ocean over New Foundland is seen for parcels initialized at all altitudes. Meanwhile, the flow into the southeastern United States appears to stagnate. Recall from our discussion of AIRS CO and MODIS AOD, we termed the flow into the United States: Plume 1, and the flow toward the Atlantic Ocean: Plume 2. From 20.5–22.5 July, the trajectories continue to show stagnation of Plume 1 over the southeastern United States as the parcels slowly drift east. However, the eastward transport of Plume 2 toward Europe continues with some parcels wrapping around a low pressure system off the west coast of England while another branch moves over eastern Greenland.
9.2. 16-17 July Plume Divergence

The sequence of trajectory maps from 16.5–19.5 July indicate that what appears from the AIRS CO maps to be plume divergence is less the splitting of one plume into two, but more like the diverging and intertwining of several different plumes. In particular, we see that the parcels moving into the United States generally descend (16.5–18.5 July), but a significant number of parcels remain at 500 and 300 mb. However, the parcels moving rapidly to the Atlantic ocean show uplift with no parcels below 600 mb over the Atlantic by 19.5 July.

This altitude separation confirms the differences in motion we proposed for Plumes 1 and 2 based on the computed changes in slope for AIRS CO vs. MODIS AOD. Plume 1 intruded into the United States at a range of altitudes from 800 to 300 mb. Plume 2 moved rapidly to the North Atlantic entirely above 600 mb. Recall the extent of the geographic regions used to compute the AIRS CO vs. MODIS AOD correlations. The large area selected for Plume 1 easily contains several if not all of the filaments represented by the trajectories. Interestingly, it appears the portion of the 500 mb parcels moving most toward the Atlantic are the ones that were briefly trapped in the Alaskan high.

9.3. Plume 1

What we have termed Plume 1 moving into the southeastern United States, the trajectories reveal to be a succession of plumes at different altitudes. The sequence of maps from 16.5–19.5 July indicate at least two filaments each of 300, 500, and 700 mb parcels dropping into the United States at a range of altitudes. While there is descent from the earliest of these filaments down to below 800 mb, there is also evidence for filaments at both 500 and 300 mb over the southeastern United States on 20.5 July. These trajectory
results are consistent with both sets of ground-based lidar cross-sections showing numerous smoke plumes at a range of altitudes. Recall the Wisconsin lidar data also indicated descent of the smoke plume over Madison from 18-19 July.

Now we begin to consider the additional complexity of trajectories launched on multiple days. We do this because we know this fire episode alone covered four days, 11-14 July. Rather than show the full trajectory sequences for each of our other 6 trajectory simulations, we will focus on the maps for 21.0 July with trajectories started at 11.5, 12.5, 13.5, and 14.5 July shown in Figures 28 to 31, respectively.

From these 4 figures we clearly see that significant transport to the southeastern United States only occurs for parcels initialized over the Alaskan/Canadian hot-spots after 1200 UT on 11 July and before 1200 UT on 14 July. Focusing only on the differences over the southeastern United States, Plume 1, we see many more 500 mb 13 July parcels appear to make it to the southeastern United States in a much denser cluster than do 12 July parcels. However, the more eastward filament of 12 July 500 mb parcels appears to be at somewhat higher altitudes. The 700 mb trajectories for Plume 1 look very similar between 12 and 13 July launches. The only apparent difference for 300 mb parcels is those from 13 July over the east coast of the United States appear to be a bit to the southwest of those from 12 July.

Figure 32 illustrates the overall complexity of the trajectories from our simulations with all parcels launched from each day/time (11.5 to 14.5 July) shown at their location on 21.0 July. Clearly, only parcels in our simulations originating at 700 and 500 mb over the Alaskan and Canadian hot-spots contributed to CO over the southeastern United States. Moreover, only 500 mb parcels made it as far south as the Gulf of Mexico. Interestingly,
parcels from all seven launch times make it to both the Gulf of Mexico and the coasts of Europe. However, there are distinct filaments of parcels in both regions with origins from different launch times.

Thus, to accurately model the particular filaments that contributed to each observed plume, one requires information on the emission height(s) for each hot-spot. Unfortunately, for the highly desired forecasting model to predict air quality impacts from such distant sources, such trial and error computations are not possible. However, in such a retrospective analysis as this, such a process is possible in some cases.

Specifically, for this case we examine whether parcels from particular fire complexes contributed to enhanced CO concentrations in certain geographic regions. Our trajectories reveal mainly the most northeastern Alaskan and northern Canadian fires contribute to 500 mb parcels that reach the United States Gulf Coast, with different locations dominating for different trajectory start times as summarized in Table 3. A larger number of fires dominate the contribution to 500 mb parcels that reach the southeastern United States, but still limited in geographic extent to those northward of 66 N and eastward of 148 W. For 500 mb parcels starting on 11.5 or 14.0 July, the only ones that reach the Gulf Coast originate from the Canadian fire near 67 N, 138 W. Therefore, we conclude that at least the fire complexes in these areas reached emission altitudes of at least 500 mb and perhaps to 300 mb or above. This conclusion is consistent with modeling of in situ measurements from the NOAA P-3 during ICARTT which require high altitude injection forest fire emissions [de Gouw et al., 2006] as well as satellite indications of smoke aerosols in the lower stratosphere from one of the Yukon fires in late June 2004 [Damoah et al., 2006].
9.4. Plume 2

Turning our attention back to the plume divergence on 16 July, we follow the development of Plume 2 as it races across the North Atlantic towards Europe. As previously mentioned, the trajectory maps Figures 16 to 27 illustrate the parcels starting at all altitudes experienced uplift along one or more portions of their travel towards the Atlantic coast of Canada. By the time these parcels reached and passed New Foundland on 18.5-19.5 July, none were below 600 mb. However, by 20.5 July, many show signs of descent as they near the coast of Europe, particularly those parcels that move south caught up in an upper level high. The parcels curving to the north over the United Kingdom appear to be caught up in a strengthening low pressure system.

Looking back at our hypothesis for the changes in AIRS CO vs. MODIS AOD correlations, we see the reduction in slope after 20 July, Figure 12, is consistent with the vertical distribution of CO once again covering altitudes from near the surface to 300 mb. The only portions of any trajectories within our boxed regions from Figure 9 that occurred only in the mid-upper troposphere were those from 17–19 July in Plume 2. Thus, the trajectory simulations support our hypothesis and indicate that in some instances AIRS CO retrievals are sensitive to CO in the lower- to mid-troposphere (800-500 mb).

Examination of Figures 28 to Figures 31 shows striking similarities for some trajectories launched on different days, and yet dramatic differences among others regarding where the parcels end up on 21 July. For example, comparing those parcels started on 12.5 July to those started on 13.5 July, very few 850 mb parcels from 13.5 July reach the Atlantic, but many starting from 12.5 July do. The spatial patterns of the 12.5 and 13.5 July 700 mb parcels are nearly identical, but the vertical distributions differ. At 500 mb, many more
13.5 July parcels appear to make it to the southeastern United States in a much denser cluster while there is more uplift and faster eastward transport to the Atlantic than 500 mb parcels from 12.5 July. At 300 mb, the 13.5 July parcels over the United States appear to be a bit more to the southwest but there is far greater and more distant transport to the Atlantic. The 12.5 July 300 mb parcels appear much more tightly confined over the Atlantic.

Integrating these more complex views of the downwind transport into Figure 32, we see that like Plume 1, the detail structure of Plume 2 is much more complex than the initial impression from the 22 AIRS CO maps of Figure 5. Looking closer at the maps, and even more so looking at the ungridded data, one can see some finer structure. However, AIRS’ 45 km sub-satellite spot size is not sufficient to reveal the real detailed structure of the CO rich smoke plumes.

9.5. Other Features

One feature of the CO transport from the Alaskan/Canadian fires we have not discussed is the apparent southward motion of some CO over the Gulf of Alaska, see Figure 5. Southward motion is evident on 12 and 13 July and then becomes lost in CO that appears on the western edge of these maps. By 16 July, we see a developing upper level low pressure system in the Gulf of Alaska evident by the deepening blue hole of low CO. On subsequent day, enhanced CO appears to wrap around this cyclone eventually crossing the United States west coast on 20 July. The sequence of trajectories started on 12.5 July, Figures 16 to 27, do not show this feature, but trajectories started on 11.5 July do as illustrated by the 300 mb parcels in Figure 32 across the western United States and off the coast of California.
The 22 AIRS CO maps, Figure 5, show several CO features appearing at the west edge of the map domain. Some of this CO could come from the Alaskan/Canadian fires with motion to the northwest, over Siberia and then south and east across the Pacific. Additional sources further to the west also are possible including Asia, Indonesia, India, etc. We have performed retrievals of AIRS data for the full globe for the INTEX-A/ICARTT period and are studying this data to place the observations discussed in this paper into a global context.

Finally, anthropogenic emissions and transport from North America, the primary focus of INTEX-A/ICARTT, during this period are overwhelmed by the obvious large smoke plumes. However, careful examination of the AIRS CO maps for 12 and 14 July in Figure 5 reveals enhanced CO along and off the United States east coast possibly due to export of anthropogenic pollution from North America. Several similar features appear in AIRS CO maps from the full INTEX-A/ICARTT period but have yet to be further investigated.

10. Conclusion

We have demonstrated (1) the capability of AIRS to track long-range transport of biomass burning emissions through analysis of AIRS tropospheric CO retrievals and (2) the accuracy of AIRS mid-tropospheric (500 mb) CO retrievals. Comparison to INTEX-A in situ profiles from the DACOM instrument onboard the NASA DC-8 establish the accuracy of AIRS mid-tropospheric CO retrievals: AIRS 400-500 mb CO is biased 7.7% high with a standard deviation of 4.7%. This is facilitated via convolution of the in situ with the AIRS verticality function defined as the 100 AIRS layer representation of the sum of the rows of the AIRS averaging kernel. In one case presented here, it appears AIRS CO retrievals exhibit sensitivity to CO in the lower to mid-troposphere (500-700 mb).
Investigating a major transport episode of emissions from forest fires burning in Alaska and Canada 11-14 July 2004, we show changes in the correlation between AIRS mid-tropospheric CO (500 mb) and MODIS AOD are indicative of changes in the vertical distribution of CO. Forward trajectory analysis of transport from this fire episode support the proposed changes in plume height inferred from the AIRS CO vs. MODIS AOD correlations. Detailed examination of the AIRS CO maps and forward trajectories disclose great variations in fire emissions are required from 11-14 July in order match trajectories to where AIRS CO moved downwind. Injection height of the forest fire emissions appears as a critical variable in this comparison. In order for any forecast model to accurately predict the influence of forest fire emission products on locations and times many days downwind, they must place the emissions at the correct altitude(s). Furthermore, our trajectory analysis demonstrates some of these fires must have injected emissions at least to 500 mb and perhaps up to 300 mb to explain some of the features evident in the maps of AIRS 500 mb CO.

Acknowledgments.

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Figure 1. Trapezoidal perturbation functions used in the AIRS pre-launch CO retrieval algorithm. These functions overlap to minimize discontinuities in the retrieved profiles.
**Table 1.** INTEX-A DC-8 Profile Matchups to AIRS and comparisons of in situ and Proxy convolved in situ mixing ratios to AIRS CO retrievals. Percent errors were computed for mean mixing ratios between 400 and 500 mb with DACOM taken as truth.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Timing</th>
<th>AIRS Overpass</th>
<th>DACOM</th>
<th>Convolved DACOM</th>
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<tbody>
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<td>1 July</td>
<td>Pacific</td>
<td>coincident</td>
<td>21.81</td>
<td>-3.0</td>
<td>-1.5</td>
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<tr>
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<td>Illinois</td>
<td>1 hour</td>
<td>18.63</td>
<td>-21</td>
<td>-12</td>
</tr>
<tr>
<td>10 July</td>
<td>South Carolina</td>
<td>coincident</td>
<td>18.39</td>
<td>-53</td>
<td>-10</td>
</tr>
<tr>
<td>12 July</td>
<td>Oklahoma</td>
<td>coincident</td>
<td>19.83</td>
<td>-23</td>
<td>-2.1</td>
</tr>
<tr>
<td>15 July</td>
<td>Wisconsin</td>
<td>1 hour</td>
<td>18.75</td>
<td>-23</td>
<td>-8.5</td>
</tr>
<tr>
<td>18 July</td>
<td>Atlantic</td>
<td>0.5 hours</td>
<td>15.98</td>
<td>-10</td>
<td>-4.4</td>
</tr>
<tr>
<td>20 July</td>
<td>Illinois</td>
<td>coincident</td>
<td>19.03</td>
<td>-28</td>
<td>-7.3</td>
</tr>
<tr>
<td>22 July</td>
<td>Gulf of Maine</td>
<td>1 hour</td>
<td>17.19</td>
<td>-19</td>
<td>-7.3</td>
</tr>
<tr>
<td>11 August</td>
<td>Kentucky</td>
<td>0.1 hours</td>
<td>18.40</td>
<td>-50</td>
<td>-16</td>
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<table>
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<tr>
<th></th>
<th>mean</th>
<th>-25</th>
<th>-7.7</th>
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<tbody>
<tr>
<td>σ</td>
<td>17</td>
<td>4.7</td>
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</tr>
</tbody>
</table>
Figure 2. The individual AIRS FOR CO retrievals at 500 mb are plotted along with the flight-track of the NASA DC-8 (magenta). The AIRS retrievals within 100 km of the DC-8 spiral profile are indicated by the black circles.
Figure 3. The in situ CO profiles from the DC-8 DACOM appear in red along with the closest AIRS CO retrievals (mean in blue and standard deviation in dashed blue), the AIRS first guess CO profile (black) and the in situ convolved with the verticality functions of Figure 4 (green). Differences in terms of ppbv are listed on the figures.

Figure 4. Mean CO verticality functions for the closest AIRS retrievals to the location of the DC-8 spirals on 1 July (a), and 20 July (b).
Figure 5. AIRS 500 mb CO retrievals, binned on a 1° grid, from 12 to 22 July 2004 over the INTEX-A/ICARTT study area. Grey indicates areas with no retrievals either due to gaps between orbits or rejected AIRS retrievals due to clouds or problems with bright surfaces. Each maps represents either local nighttime (AM) or daytime (PM) orbits for the respective UT day.
Figure 6. Locations of all satellite detected hot-pots in Alaska and the Canadian Yukon from 11–14 July 2004.
Figure 7. July 2004 timeseries of the number of satellite detected hot-spots in Alaska and the Canadian Yukon. The peak at the start of the month is the end of a large series of fire outbreaks that occurred in the region throughout June 2004.
Figure 8. AIRS 500 mb CO individual retrievals appear as the filled colored circles with the corresponding color scale below. Locations of each day’s satellite detected hot-spots are plotted as solid white dots. Notice the clumping of the hot-spots into the different fire complexes. Some CO enhancement is seen over or very near some fires on some days, but generally the CO enhancement is seen to the east of the fires until 14 July when much of Alaska is covered in high CO.
Figure 9. MODIS AOD retrievals binned on the same 1° grid as used in Figure 5 appear on in the left panels for 12-22 July 2004. Corresponding AIRS 500 mb CO retrievals for PM orbits appear in the right-hand panels (same as Figure 5). Colored outline boxes follow features identified in the text used for computing AIRS CO vs. MODIS AOD correlations.
Figure 10. Scatter plots of the correlation of AIRS 500 mb CO to MODIS AOD from 15–18 July indicate a change in the slope of the correlation for the 1° bins associated with Plume 2 (black box in Figure 9. Colors of the symbols correspond to the colored boxes outlined in Figure 9 with the exception of the blue symbols which go with the white boxes in Figure 9.
Figure 11. The scatter plot is identical to that of panel (d) in Figure 10 but now robust fit lines have been computed for the three geographic regions as noted.
Figure 12. The left panel presents the robust fit lines for the AIRS CO vs. MODIS AOD for the geographic region following Plume 1 (green box in Figure 9) as it moved from 13–22 July. The right panel presents similar fits for the geographic region following Plume 2 (black box in Figure 9) from 16–22 July.
Figure 13. False color image from AIRS visible channels (RGB 321) over the central United States on 18 July 2004. The smoke plume from the Alaskan/Canadian fires appears as a brownish haze stretching from Lake Superior south to Louisiana. Clouds appear white, water blue, and land in shades of red and green. Note the extensive smoke plume coverage over Wisconsin. See Gautier et al. [2003] for details of the visible portion of AIRS.
Figure 14. Timeseries of Lidar backscatter cross-section and linear depolarization from the HSRL instrument in Madison, Wisconsin, from 18–19 July 2004. See text for detailed description.
Figure 15. Timeseries of Lidar backscatter cross-section from the ELF instrument in at UMBC near Baltimore, Maryland on 20 July 2004. See text for description.
**Table 2.** Number of hot-spots and trajectories run for each day.

<table>
<thead>
<tr>
<th>Date</th>
<th>hot-spot count</th>
<th>trajectory count</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 July</td>
<td>3178</td>
<td>1059</td>
</tr>
<tr>
<td>12 July</td>
<td>5977</td>
<td>1992</td>
</tr>
<tr>
<td>13 July</td>
<td>6008</td>
<td>2002</td>
</tr>
<tr>
<td>14 July</td>
<td>2840</td>
<td>946</td>
</tr>
</tbody>
</table>
Figure 16. Trajectories initialized at 1200 UT on 12 July over that days’ satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 17. Trajectories initialized at 1200 UT on 12 July over that days’ satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 18. Trajectories initialized at 1200 UT on 12 July over that days’ satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 19. Trajectories initialized at 1200 UT on 12 July over that days' satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 20. Trajectories initialized at 1200 UT on 12 July over that days’ satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 21. Trajectories initialized at 1200 UT on 12 July over that days’ satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 22. Trajectories initialized at 1200 UT on 12 July over that days’ satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 23. Trajectories initialized at 1200 UT on 12 July over that days' satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 24. Trajectories initialized at 1200 UT on 12 July over that days’ satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 25. Trajectories initialized at 1200 UT on 12 July over that days' satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 26. Trajectories initialized at 1200 UT on 12 July over that days’ satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 27. Trajectories initialized at 1200 UT on 12 July over that days’ satellite detected starting at 4 altitudes and followed downwind for 11 days.
Figure 28. Location of parcels at 0000 UT on 21 July for trajectories initialized at 1200 UT on 11 July over that days’ satellite detected starting at 4 altitudes.
Figure 29. Location of parcels at 0000 UT on 21 July for trajectories initialized at 1200 UT on 11 July over that days’ satellite detected starting at 4 altitudes.
Figure 30. Location of parcels at 0000 UT on 21 July for trajectories initialized at 1200 UT on 11 July over that days’ satellite detected starting at 4 altitudes.
Figure 31. Location of parcels at 0000 UT on 21 July for trajectories initialized at 1200 UT on 11 July over that days’ satellite detected starting at 4 altitudes.
Figure 32. Location of parcels at 0000 UT on 21 July for all trajectories initialized every 12 hours starting 1200 UT on 11 July to 1200 UT 14 July over the respective days’ satellite.
Table 3. Locations of fires that contribute to enhanced CO over the southeastern United States and along the Gulf of Mexico.

<table>
<thead>
<tr>
<th>Trajectory Start Date/time</th>
<th>Pressure start (mb)</th>
<th>Starting Location</th>
<th>Ending Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 July 1200 UT</td>
<td>300</td>
<td>146 W, 66.4 N</td>
<td>U.S. west coast</td>
</tr>
<tr>
<td>11 July 1200 UT</td>
<td>300</td>
<td>145.5 W, 65.8 N</td>
<td>U.S. west coast</td>
</tr>
<tr>
<td>11 July 1200 UT</td>
<td>300</td>
<td>137.75 W, 67.2 N</td>
<td>U.S. Gulf coast</td>
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<tr>
<td>12 July 0000 UT</td>
<td>700</td>
<td>145.8 W, 67.25 N</td>
<td>central U.S.</td>
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<td>U.S. Gulf coast</td>
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<td>and 150–145 W</td>
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<td>southeast U.S.</td>
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<tr>
<td>14 July 00– UT</td>
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<td>138.2 W, 67 N</td>
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