

## Daily global maps of carbon monoxide from NASA's Atmospheric Infrared Sounder

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[1] We present the first observations of tropospheric carbon monoxide (CO) by the Atmospheric Infrared Sounder (AIRS) onboard NASA's Aqua satellite. AIRS daily coverage of ~70% of the planet represents a significant evolutionary advance in satellite trace gas remote sensing. Tropospheric CO abundances are retrieved from AIRS 4.55  $\mu\text{m}$  spectral region using the full AIRS retrieval algorithm run in a research mode. The presented AIRS daily global CO maps from 22–29 September 2002 show large-scale, long-range transport of CO from anthropogenic and natural sources, most notably from biomass burning. The sequence of daily maps reveal CO advection from Brazil to the South Atlantic in qualitative agreement with previous observations. Forward trajectory analysis confirms this scenario and indicates much longer range transport into the southern Indian Ocean. Preliminary comparisons to in situ aircraft profiles indicate AIRS CO retrievals are approaching the 15% accuracy target set by pre-launch simulations. **Citation:** McMillan, W. W., C. Barnet, L. Strow, M. T. Chahine, M. L. McCourt, J. X. Warner, P. C. Novelli, S. Korontzi, E. S. Maddy, and S. Datta (2005), Daily global maps of carbon monoxide from NASA's Atmospheric Infrared Sounder, *Geophys. Res. Lett.*, 32, L11801, doi:10.1029/2004GL021821.

### 1. Introduction

[2] Launched onboard NASA's Aqua satellite on 4 May 2002, the Atmospheric Infrared Sounder's (AIRS) cross-track scanning grating spectrometer covers the 3.7 to 16  $\mu\text{m}$  spectral range with 2378 channels and a 13.5 km nadir field-of-view (FOV) from its 705 km orbit [Aumann *et al.*, 2003]. Atmospheric retrievals are performed in conjunction with Aqua's Advanced Microwave Sounding Unit (AMSU) at the AMSU spatial resolution of 45 km at nadir, the retrieval field-of-regard (FOR), across the 1650 km cross-track scan (M. Chahine *et al.*, The Atmospheric Infrared Sounder

(AIRS): Providing new insights into weather and climate for the 21st century, submitted to *Bulletin of the American Meteorological Society*, 2004). In addition to temperature and water vapor, AIRS' channels include spectral features of the key carbon trace gases CO<sub>2</sub>, CH<sub>4</sub>, and CO [Haskins and Kaplan, 1992]. Current retrievals of CO are the most mature owing to its strong spectral signature and relative lack of interfering water vapor absorption.

[3] World-wide, approximately 50% of CO emissions derive from anthropogenic sources with the remainder coming from biomass burning and oxidation of naturally occurring volatile hydrocarbons [Logan *et al.*, 1981; Thompson *et al.*, 1994]. Thus, CO can be viewed as a proxy for monitoring the carbon cycle and global climate change [Sze, 1977]. In addition, CO's 1–3 month tropospheric lifetime makes it an excellent tracer for atmospheric motions and source variability [Badr and Probert, 1994]. Furthermore, as a major sink for hydroxyl (OH) and a precursor for tropospheric ozone and smog, global CO observations are crucial for modeling tropospheric chemistry and assessing atmospheric health [Crutzen *et al.*, 1979].

[4] The first global views of CO came from the 1981 flight of the Measurement of Atmospheric Pollution from Space (MAPS) instrument onboard the Space Shuttle [Reichle *et al.*, 1982] with subsequent MAPS flights in 1984 [Reichle *et al.*, 1990] and 1994 [Connors *et al.*, 1999]. However, MAPS small, nadir only FOV required a week or more to produce a spatially contiguous global map. Currently, the Measurement Of Pollution In The Troposphere (MOPITT) instrument on NASA's Terra satellite uses technology similar to MAPS to measure tropospheric CO [Deeter *et al.*, 2003]. Despite MOPITT's much greater spatial coverage per orbit than MAPS, daily phenomena are lost in the three to five days required to form a contiguous global map.

[5] With similar sensitivity to mid-tropospheric CO as MAPS and MOPITT, Figure 1, AIRS' unique daily global view provides nearly ten times as many retrievals per day as MOPITT and enables process studies of phenomena on daily timescales. For the first time, Figure 2 and the online auxiliary animations<sup>1</sup> present daily changes in the globe-encircling transport of biomass burning emissions heretofore seen only in computer models.

### 2. AIRS CO Retrieval

[6] To retrieve information from AIRS measured radiances, we numerically invert the radiative transfer equation [Susskind *et al.*, 2003] using a physical forward radiative

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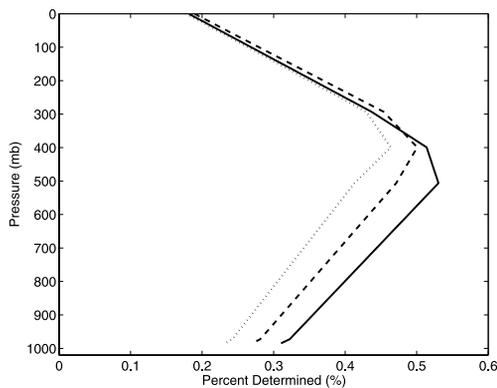
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**Figure 1.** AIRS CO percent determined functions for three retrievals on 22 September 2002 are shown: solid line for a fire/smoke plume FOR (62.3°W, 10.2°S), dashed line for a nearby smoke-free FOR (64.9°W, 10.9°S), and the dotted line for a clean Atlantic Ocean FOR (55.3°W, 20.6°N).

transfer model [Strow *et al.*, 2003]. Even with perfect molecular physics and measurements, these retrievals are limited by the vertical integrating effects of atmospheric radiative transfer. To constrain this ill-posed inversion, we include estimates of the precision and accuracy of our radiative transfer model and the errors and noise in the measurements and damp the least significant eigenfunctions of the singular value decomposition (SVD) as described below [Barnet *et al.*, 2003].

[7] AIRS CO retrievals utilize radiances in the 4.58–4.50  $\mu\text{m}$  (2183–2220  $\text{cm}^{-1}$ ) region of the 1-0 vibration-rotation CO fundamental. The overall AIRS CO retrieval technique follows that discussed by Susskind *et al.* [2003] for AIRS ozone retrievals. The current pre-launch CO retrieval divides the tropospheric CO profile into a series of four vertically overlapping trapezoidal functions empirically determined from pre-launch simulations. Using SVD, these four trapezoidal functions are redefined as a set of orthogonal eigenfunctions using the ongoing information content analysis to determine the best single function to represent the vertical information in the measured radiances. To constrain the solution, the least significant eigenfunctions are damped proportional to their eigenvalue. Based on the number of significant eigenvectors, AIRS CO retrievals possess 0.5 to 1.5 degrees of freedom in the vertical.

[8] Error covariances and the eigenfunctions are updated at each iteration of the retrieval with an ongoing information content analysis [Susskind *et al.*, 2003]. Because radiances in the CO spectral region are influenced by temperature, and to a lesser extent water vapor, the full AIRS retrieval algorithm utilizes a large number of channels throughout its operating range to first retrieve surface temperature, emissivity, tropospheric temperature and water vapor profiles before retrieving CO and other trace gases [Susskind *et al.*, 2003].

[9] Figure 1's three curves illustrate the variation in AIRS' CO verticality, the vertical distribution of sensitivity for three different cases. These functions are analogous to the averaging kernels used in an optimal estimation approach [e.g., Rodgers, 2000]. One minus this percent determined equals the amount of information from the first guess profile retained in the final retrieved solution. In terms of the AIRS retrieval approach, Figure 1 presents the

percent determined for each of the four overlapping trapezoidal functions used to perturb the CO profile. Each AIRS retrieval possesses a unique percent determined function as computed in the retrieval process. As Figure 1 shows, source regions with enhanced CO show more sensitivity in the lower troposphere. Previous retrievals of tropospheric CO from airborne spectra demonstrate this sensitivity to large CO abundances even in or near the boundary layer [McMillan *et al.*, 1996, 2003].

[10] Using cloud-clearing [Chahine, 1974], AIRS obtains high density global CO retrievals even in the presence of substantial cloudiness up to  $\sim 80\%$  cloudy [Susskind *et al.*, 2003]. For a typical day, approximately 45% of AIRS FORs produce high quality retrievals, those meeting all the current conservative convergence criteria in other steps of the retrieval including cloud-clearing. As presented in the global maps of Figure 2, binning these 144,000 daily retrievals onto a  $1^\circ$  latitude, longitude grid results in coverage of  $\sim 70\%$  of the planet from  $60^\circ\text{N}$  to  $60^\circ\text{S}$ . With cloud filtering rather than cloud-clearing, the yield would be closer to 2–5% spatial coverage.

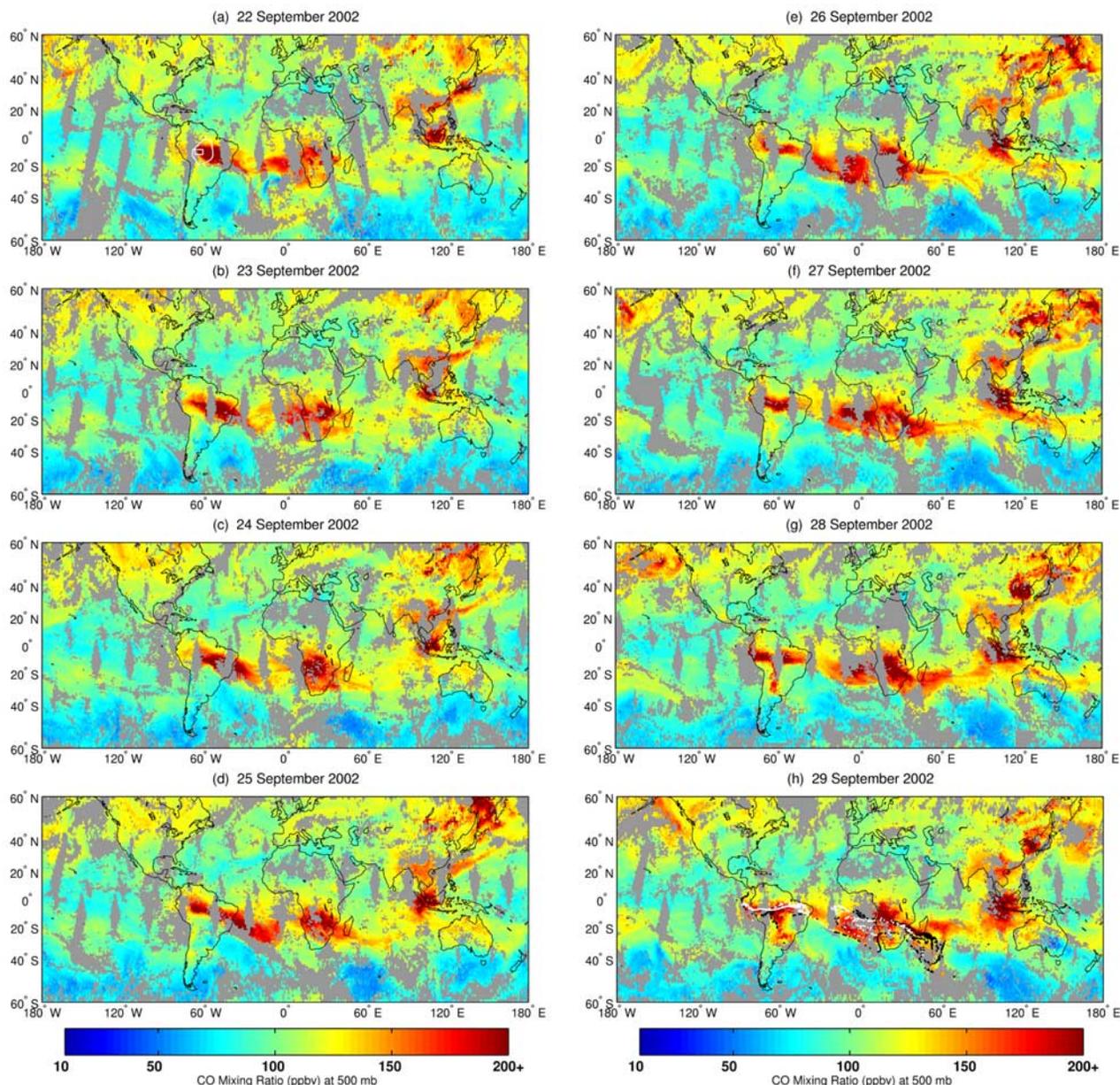
### 3. First in Situ Comparisons

[11] Optimization and validation of AIRS CO retrievals are in progress utilizing airborne in situ profiles from NOAA CMDL and other sources as ground truth. Comparisons with five CMDL profiles acquired during AIRS first month of operation (September 2002) indicate agreement to approximately 16% between 400 and 600 mb with AIRS systematically high. Three profiles over the continental United States show AIRS is 2% high with an RMS error of 4.5%; two profiles from the South Pacific Island of Rorotonga find AIRS 20–30% high. These large errors most likely result from the global use of the AFGL standard atmosphere CO profile [Anderson *et al.*, 1986] as the first guess. This profile is not typical of a clean southern hemisphere site far from CO sources. Thus, revising the first guess profile forms another component of the ongoing optimization. However, with Figure 1's demonstrated sensitivity in regions of enhanced CO, we believe the largest CO values retrieved in the Southern Hemisphere are as accurate as the Northern Hemispheric retrievals. Although these first comparisons between AIRS and in situ fall short of a statistically significant set, they illustrate the reasonableness of the presented retrieved CO values.

### 4. Daily Global CO Maps

[12] The eight maps in Figures 2a–2h and the online auxiliary animations present global views of AIRS CO retrievals at 500 mb from 22 through 29 September 2002 with evolution and propagation of many tropospheric CO features. 500 mb represents the average peak of AIRS CO verticality as illustrated in Figure 1. For brevity, discussion focuses mainly on the transport of CO from South American fires to the south Atlantic and over southern Africa to the southern Indian Ocean.

[13] Consistent with previous MOPITT studies [Edwards *et al.*, 2003], fire counts obtained from the Moderate resolution Imaging Spectroradiometer (MODIS) data (both Terra and Aqua) [Justice *et al.*, 2002] indicate numerous fires in the regions of enhanced CO over South America,



**Figure 2.** AIRS daily global 500 mb CO retrievals, binned on a  $1^\circ$  grid, from 22 to 29 September 2002. Grey indicates areas with no retrievals. In (a), 721 MODIS detected fires occurred within the large white irregular line; 382 within the small white box. In (h), the white dots mark the eight-day forward locations for parcels initialized at 500 mb over the 721 fire locations while the black dots denote parcels started at 700 mb.

Africa, and Borneo. In South America, the fire counts peaked on 21–22 September in Brazil, see Figure 2a. These three regions illustrate the widespread human application of fire for land-clearing during the Southern Hemispheric dry season, a regular annual occurrence in September and October [Andreae, 1991]. From Figures 2a–2h, and in the auxiliary animations, we follow the advection of the South American CO plume. Similar CO transport from Brazil to the south Atlantic was found during the TRACE-A and SAFARI 1992 field experiments [Thompson *et al.*, 1996]. Previously, only Africa has been cited as a source for enhanced CO over the Indian Ocean [Watson *et al.*, 1990].

[14] Figure 2h and the online auxiliary animations further illustrate this advection with the location of

parcels started at the fire locations in Figure 2a projected forward in time using NCEP reanalysis winds as inputs to the Goddard Trajectory Model [Schoeberl and Sparling, 1995]. Parcels released at 700 mb over the South American fires move to higher altitudes with rapid transport west and south past Africa (black dots in Figure 2h). However, parcels beginning at 500 mb over the South American fires mainly get caught in a South Atlantic recirculation with transport up to 300 mb, white dots in Figure 2h.

[15] Meanwhile in the Northern Hemisphere on 22 September 2002, elevated CO values appear over central and eastern Siberia, the northern Pacific Ocean, and along the coast of Southeast Asia. These three regions represent

biomass burning sources, long-range transport, and industrial/domestic fuel sources, respectively. Enhanced CO values in southern Siberia near Lake Baikal on 23 September, Figure 2b, correlate with MODIS fire counts and imagery of that region showing a large number of fires stretching into northern Mongolia near Hövsgöl Nuur. Subsequent maps (Figures 2c–2h) track this CO feature as it propagates to the east ending up off the west coast of northern North America. The dearth of MODIS fire counts over southeast Asia suggests the CO plume stretching from there to the east across the Pacific Ocean originates from industrial and domestic biofuel sources.

## 5. Conclusions

[16] Never before have such detailed views of a tropospheric trace gas (other than water) been available on a daily basis. Focusing on a major South American fire event, 22–29 September 2002, the AIRS maps show advection of a large CO plume with forward trajectories confirming long-range transport as far east as the southern Indian Ocean. Work remains to completely characterize AIRS CO retrievals through validation with in situ measurements and comparisons with chemical transport and trajectory models. Preliminary validation results find AIRS CO retrievals at 500 mb are accurate to at least 10% in the northern hemisphere and overall approach the 15% accuracy predicted in pre-launch simulations. Ongoing research focuses on optimizing and validating the AIRS CO retrieval algorithm to produce a standard product, and performing detailed global comparisons with MOPITT measurements. Over AIRS' projected seven-year lifetime, we expect the routine global CO maps will lead to a more complete understanding of the CO budget, and along with future AIRS CO<sub>2</sub> and CH<sub>4</sub> retrievals, will provide unique insights into the global carbon cycle and global climate change.

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