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CO retrievals based on MOPITT near-infrared observations

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Abstract. We report the first retrieval results of tropospheric carbon monoxide (CO) exclusively using near-infrared (NIR) radiances in the 2.3 μm CO overtone band observed by the Measurements of Pollution in the Troposphere (MOPITT) satellite instrument. For daytime overpasses over land, such observations complement MOPITT's thermal infrared (TIR) observations in the 4.7 μm CO fundamental band, especially for constraining the CO total column. Retrievals are performed in an optimal estimation framework in which effective radiance errors due to geophysical sources are estimated empirically. The new NIR-based retrievals are evaluated through comparisons with both the standard TIR-based MOPITT CO product and CO profile measurements.

1. Introduction

The Measurements of Pollution in the Troposphere (MOPITT) satellite instrument has been routinely monitoring tropospheric concentrations of carbon monoxide (CO) since March, 2000 [Deeter et al., 2003]. MOPITT is equipped with gas correlation radiometers incorporating both length modulation and pressure modulation cells operating in two distinct spectral bands: the near-infrared (NIR) CO overtone band near 2.3 μm and the thermal-infrared (TIR) fundamental band near 4.7 μm [Drummond, 1992]. Conceptually, the NIR observations sense the attenuation (by CO molecules) of solar radiation reflected from the earth's surface to the MOPITT instrument, whereas the TIR observations detect CO signatures in thermally-emitted radiation from the earth's surface and atmosphere. In principle, the NIR radiances provide information with respect to the CO total column with very weak sensitivity to the vertical distribution of CO whereas the TIR radiances are sensitive to differences in CO concentrations over broad layers in the troposphere. Over land, where the surface reflectance and hence NIR radiances are relatively high, the NIR radiances should provide more consistent sensitivity to CO in the lower troposphere than the TIR radiances, which are sensitive to lower-tropospheric CO only in favorable thermal constrast conditions [Deeter et al., 2007b]. Thus, the TIR and NIR radiances provide complementary information with respect to the CO vertical distribution [Turquety et al., 2008] and will ultimately be exploited in conjunction in a single retrieval product. As a prerequisite to exploiting the NIR radiances for this "merged" CO product, this paper mainly addresses the information content of purely NIR-based retrievals.

Operational MOPITT products have so far only exploited the TIR radiances. These radiances are useful both day and night over both land and ocean, and therefore yield a global view of tropospheric CO. Incorporation of the NIR radiances into the operational MOPITT retrieval products has been delayed by a variety of issues not affecting the TIR radiances. Some of these issues were described previously in an analysis of the MOPITT methane-channel radiances [Pfister et al., 2005]. Effects which can potentially degrade the quality of the MOPITT NIR radiances include (1) surface reflectivity spatial variability (on scales smaller than the instrument field of view), (2) low surface reflectivity over many land-surface types, resulting in low signal-to-noise ratio (SNR), (3) surface reflectivity spectral variability, (4) polarization induced by specular reflection over water (coupled with polarization-dependent losses in the instrument), (5) sunglint occuring over water at particular sun-surface-satellite geometries, resulting in saturation effects in the detectors and/or electronics, and (6) sensitivity to aerosols. Together, these instrumental and geophysical effects can make it difficult to estimate meaningful uncertainties for the calibrated NIR radiances. Such errors must be well characterized in order to properly balance the information from the NIR and TIR radiances in the operational MOPITT optimal estimation algorithm.

NIR-based CO retrievals from space were first demonstrated using observations of the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) satellite instrument [Buchwitz et al., 2004]. SCIAMACHY CO retrievals are based on the same CO absorption band as the MOPITT NIR radiances. However, the SCIAMACHY and MOPITT instruments exploit fundamentally different design concepts yielding different observing characteristics (e.g., spatial resolution, SNR, etc.). One important difference between the two instruments relates to details of the timing of measurement acquisition. In a given SCIAMACHY observation, radiances for different spectral intervals within a band of interest are recorded simultaneously. Specifically, radiances for spectral intervals where CO absorption is significant are recorded simultaneously with radiances for the spectral "windows" between the lines. Analogous MOPITT radiances are derived from a set of raw instrument observations sampled at different stages of the modulation cycles of a set of length- and pressure-modulation cells. The combination of surface reflectance spatial variability and moving MOPITT field of view produces a unique source of error in MOPITT NIR radiances. Nevertheless, due to other instrumental effects, analyses of SCIAMACHY CO data indicate that the uncertainty in individual retrievals typically exceeds geophysical variability [de Laat et al., 2007]. Thus, in practice, SCIAMACHY results must be averaged (e.g., to produce gridded monthly-mean values) to significantly increase SNR.

This paper presents evidence of the value of the MOPITT NIR radiances for CO retrievals. In Section 2, principles underlying the MOPITT instrument and retrieval algorithm are briefly reviewed. An analysis of NIR radiance errors is presented in Section 3. Section 4 contrasts NIR-based and TIR-based MOPITT retrieval results in both (1) global monthly-mean comparisons and (2) comparisons of retrievals for two continental regions over three consecutive days of observations (with no averaging). NIR-based results are quantitatively compared with aircraft in-situ observations for three North American sites in Section 5. Finally, conclusions are presented in Section 6.

2. Retrieval Principles

2.1. Measurements

The MOPITT instrument includes four length-modulated radiometers (LMRs) (two of which are for retrieving methane, and are not discussed further) and two pressure-modulated radiometers (PMRs) [Drummond, 1992]. An instrument malfunction in May, 2001 resulted in the permanent loss of two LMRs (one CO LMR and one methane LMR) and one PMR. The remaining PMR modulates 4.7 μm band signals, while the remaining LMR modulates both 4.7 μm and 2.3 μm signals. The LMR modulates the signals by alternating a long (L) or short (S) gas path in the optical beam. Signals corresponding to the L and S states are recorded separately. Similarly, signals from the PMR are measured at several points during the pressure modulation cycle (but are characterized by "High" and "Low" states instead of the LMR's L and S states) and are recorded. These signals are then processed into uncalibrated instrument counts for the two opposite states of each of the three modulated data streams. In calibration, these counts are converted into the average radiance (A), corresponding to the mean of the L and S (or High and Low) signals and the difference radiance (D), corresponding to the simple difference of the L and S (or High and Low) signals [Deeter et al., 2002]. The MOPITT radiometers thus yield three pairs of A and D radiances from which to retrieve the CO profile. Channel 5 radiances (5A and 5D) are produced by the 4.7 μm LMR. Radiances 6A and 6D are produced by the 2.3 μm LMR, and are the primary focus of this paper. This channel was unaffected by the instrument malfunction in 2001. Radiances 7A and 7D are produced by the 4.7 μm PMR.

Because sequential LMR L and S measurements are not made simultaneously, but are 25 ms apart, the motion of the satellite produces a spatial offset of approximately 168 m on the ground. While this is less than 1% of the 22 km footprint, surface properties such as surface reflectance often vary on very fine spatial scales. Combining sequential L and S signals will in general combine data from slightly shifted fields of view, possibly characterized by different mean surface reflectances. To reduce this effect, the raw MOPITT data are processed using the “triplet method.” Within the radiance calibration algorithm, consecutive L(S) signals are averaged and compared to the intervening S(L) signal to provide a better approximation to the L(S) values at the time of the S(L) signal. If the surface reflectance varies linearly across the field of view, this method will provide an exact correction. In general this is not the case, but it is a significant improvement.

2.2. NIR-based Retrievals

The MOPITT CO retrieval algorithm incorporates a fast radiative transfer model [Edwards et al., 1999] and optimal estimation principles to iteratively solve for the CO profile which is statistically most consistent with both the observations (i.e., the satellite-measured radiances) and statistical “background” information, i.e., the a priori [Deeter et al., 2003]. A priori information is represented by both a mean state vector (the most probable state) and a covariance matrix which describes the expected variability around that state. The operational retrieval software was written to exploit all of the available radiances. However, any desired subset of the available radiances can be selected as the basis of the retrieval by amplifying the radiance uncertainties for the excluded radiances. The “Version 3” (or “V3”) operational MOPITT retrieval product for the period since August, 2001 is based on the 5A, 5D, and 7D TIR radiances [Deeter et al., 2004].

In Sections 4 and 5, we evaluate retrievals based solely on 6A and 6D, the two remaining NIR radiances. Unlike the way the TIR radiances are treated, the MOPITT retrieval algorithm exploits the ratio of corresponding D and A radiances for the NIR observations [Pan et al., 1998]. The underlying approximation is that both the D and A NIR radiances are directly proportional to surface reflectivity which cancels in the ratio R = D/A. This method eliminates the need for prior knowledge of surface reflectivity, which varies on both fine (sub-pixel) and coarse spatial scales.

However, for actual surface materials, reflectivity varies spectrally, although such spectral variability tends to be much smoother than for features associated with absorption in gases. Because D and A are spectrally integrated quantities characterized by very different instrument spectral response functions, they will strictly exhibit different sensitivities to the surface reflectance spectral variability. Fundamentally, A signals are weighted more heavily by the surface reflectivity in the part of the passband where the CO absorption lines are relatively sparse and weak, and D signals are weighted more heavily by the surface reflectivity where the lines are relatively abundant and strong. This degrading effect is small for MOPITT however because (1) the CO absorption lines are distributed uniformly and nearly symmetrically within the MOPITT optical filter passbands [Edwards et al., 1999] and (2) the filter passbands themselves are relatively narrow compared to the surface reflectance spectral features of common materials [Pfister et al., 2005]. Thus, the NIR CO D and A signals should both be fairly insensitive to the relatively weak spectral features of the surface reflectance, producing a high degree of cancellation in R. Such cancellation has been shown to be less effective for MOPITT's methane channels, both because of the distribution of the methane absorption lines and a much wider filter passband [Pfister et al., 2005].

3. Effective Radiance Errors

The magnitude of errors in the D/A ratio due to surface reflectance spatial and spectral variability probably varies significantly with local geophysical parameters (e.g., surface material and sub-pixel homogeneity). These errors are not easily analyzed from first principles. However, neglecting such errors in the retrieval algorithm entirely would lead to excessive retrieval error, with too much weight placed on the observed radiances. Therefore, some understanding of the magnitude of the effective radiance error, including both instrumental and geophysical effects, is necessary to properly exploit the MOPITT NIR radiances.

In the standard operational retrieval algorithm, the uncertainty in the R signal (i.e., D/A) is determined from uncertainties in the calibrated radiances by a standard propagation of errors analysis. Since standard radiance uncertainties are based only on onboard calibration results [Deeter et al., 2003], this analysis accounts only for instrumental errors. Assuming that errors in the 6A and 6D radiances are uncorrelated, the variance in the 6R signal is given by

$$\begin{aligned} \sigma_R^2 &= (\frac{\partial R}{\partial D})^2 \sigma_D^2 + (\frac{\partial R}{\partial A})^2 \sigma_A^2 \\ &= (\frac{1}{A})^2 \sigma_D^2 + (\frac{D}{A^2})^2 \sigma_A^2 \end{aligned} \tag{1}$$

where σ_D and σ_A are the uncertainties in the D and A radiances. However, since generally D $\ll$ A [Pan et al., 1995] and σ_D and σ_A differ by only a factor of two, Eq. 1 simplifies to

$$\sigma_R^2 \approx (\frac{\sigma_D}{A})^2 \tag{2}$$

Eq. 2 demonstrates that, in the context of the retrieval algorithm, the uncertainty in 6R (the basis of the retrieval) really just depends on the assumed uncertainty on 6D. Thus, increasing the 6D uncertainty value from its instrument-only value (by scaling, for example) is the simplest means for accounting for geophysical sources of error on 6R. The effective 6D radiance error, accounting for both instrumental and geophysical effects, can be estimated by comparing the expected instrument-only variability in the 6R signal (based on the 6D error produced by calibration, as predicted by Eq. 2) with the actual variability of 6R for observations within individual satellite overpasses. Such comparisons are presented below for three sites in North America used for retrieval validation.

Within each overpass of a particular site, variability statistics are calculated only for observations within a small radius (50 km) of the validation site. This limits the influences of atmospheric variability (e.g., variability of the CO and water vapor vertical profiles) and viewing geometry (i.e., satellite zenith angle) on the observed 6R values while providing a suitable number of independent observations for statistical analysis (usually at least ten). Thus, we assume that 6R variability over relatively small regions is typically dominated by (1) instrument noise and (2) spatial and spectral variability in the surface reflectance.

The observed variability for 6R is compared with corresponding instrument-only uncertainty values for overpasses of Carr, Colorado, Poker Flat, Alaska, and Harvard Forest, Massachusetts in Figure 1. Each plotted point compares the observed variability (i.e., the standard deviation of 6R for all observations within the 50 km radius) and mean instrument-only uncertainty value for a single MOPITT overpass of a particular validation site. Dotted lines indicate expected variability values according to a simple noise-scaling model to account for geophysical sources of radiance error. For example, the dotted line labeled "2x" indicates the expected 6R variability assuming that geophysical radiance errors effectively double the instrumental noise. Inspection of Figure 1 indicates that for the three North American MOPITT validation sites, the observed 6R variability is typically between two and 20 times the instrument-only noise value, with the largest variability (relative to the instrument-only values) observed for the Carr, Colorado overpasses. Although Figure 1 indicates that the optimal noise-scaling factor may vary geographically and temporally, we employ a noise-scaling factor of five as a "baseline" value for exploiting the NIR radiances. This choice is justified in Sections 4 and 5, where it is shown that NIR-based retrievals based on this noise-scaling factor largely agree with TIR-based retrieval results and are supported by in-situ validation results. The consequences of using both smaller and larger noise-scaling factors are reported in Section 5.

4. NIR and TIR Retrieval Comparisons

In this section, we demonstrate MOPITT NIR-based retrievals over land and compare them with TIR-based retrievals from simultaneous daytime observations. Problems inhibiting the use of NIR-based radiances over water include (1) generally weak surface reflectance resulting in small signal-to-noise ratios, (2) polarization effects and (3) sunglint. In any case, the potential benefits of the NIR radiances compared to pure TIR-based retrievals are greatest over land, where all major localized sources of CO emissions are located, and thus where improving the sensitivity to lower-tropospheric CO is especially important. Nighttime TIR-based retrievals are excluded from these comparisons because (1) they typically exhibit much weaker sensitivity to CO in the lower troposphere than daytime TIR-based retrievals and (2) they are not synchronized with the NIR observations.

The retrieval algorithm employed for this investigation assumes log-normal statistics for CO volume mixing ratio (VMR) variability [Deeter et al., 2007a]. Thus, the retrieved algorithm fundamentally yields a vertical profile of log(VMR) and exploits a log(VMR)-based a priori profile and covariance matrix. (Logarithms are calculated in base 10.) Otherwise, the retrieval algorithm is nearly identical to the V3 operational retrieval algorithm [Deeter et al., 2003]. Retrieved profiles are expressed as VMR values on a seven-level grid: surface, 850, 700, 500, 350, 250, and 150 hPa. The use of a single global a priori profile (invariant with respect to geographical location and season) ensures that differential features observed in the retrieval results are not associated with a priori information and therefore represent information actually contained in the satellite observations. The a priori covariance matrix used in the retrievals was calculated from a set of 525 in-situ vertical profiles.

4.1. Three-Day Composite Images

Composite images comparing NIR- and daytime TIR-based MOPITT CO total column retrievals for (1) Southeast Asia from March 2-4, 2006, and (2) South America from September 1-3, 2006 are presented in Figures 2 and 3, respectively. No retrieval averaging is applied. In both figures, large-scale features evident in the TIR-based retrievals are also obvious in the NIR-based retrievals. For example, sources associated with major East Asian population centers [Clerbaux et al., 2008] and biomass burning in both Southeast Asia and South America [Edwards et al., 2006] produce similar features in TIR- and NIR-based retrievals in Figures 2 and 3. Both figures also clearly exhibit corresponding minima over mountain ranges (the Himalayas in Figure 2 and the Andes in Figure 3), although this apparent correlation could just result from surface elevation variability (as explained in Section 5).

However, in both Figures 2 and 3, the NIR-based CO total column values appear to exhibit greater pixel-scale variability than the TIR-based retrievals. Further work is required to determine whether this variability simply reflects greater random error in the NIR-based retrievals or could actually represent fine-scale variability in the CO total column revealed by the greater sensitivity of the NIR radiances to CO in the lower troposphere. Most importantly, both figures demonstrate that MOPITT NIR-based retrievals produce geophysically reasonable CO distributions, even without retrieval averaging.

4.2. Global Monthly Mean Images

Global NIR- and TIR-based monthly-mean CO total column results are presented for March and September, 2006 in Figures 4 and 5, respectively. Total column results in both figures indicate similar patterns for the TIR and NIR results in major source regions, notably East Asia, Africa, and South America. The most obvious differences between the TIR and NIR results appear in March (Figure 4) over Northern and Central Europe, where TIR total column values are substantially higher than corresponding NIR values. It is currently unclear whether this feature suggests some sort of retrieval bias in one or both products or rather can be explained by the different total-column averaging kernels (i.e., different vertical sensitivities) for these two products. Future validation work will address the source of these differences.

4.3. Retrieved Profiles and Averaging Kernels

MOPITT TIR- and NIR-based retrievals are produced by the same optimal estimation-based algorithm but configured to use different subsets of the available measurements. Because the TIR and NIR radiances exhibit fundamentally different sensitivities to the CO vertical profile (as quantified by the weighting functions), retrieved profiles based on TIR and NIR radiances measure different geophysical quantities. Comparisons of both the retrieved profiles and associated averaging kernels may be interpreted in terms of features of the underlying weighting functions.

MOPITT NIR- and TIR-based retrieved vertical profiles and averaging kernels are compared for a small region in the upper Amazon Basin (bounded by 5S, 3S, 76W and 74W) observed in a MOPITT overpass on September 2, 2006 in Figure 6. Tropical rainforests are characterized by thermal contrast conditions which typically result in poor sensitivity to CO in the lower troposphere for MOPITT TIR-based retrievals [Deeter et al., 2007b] and thus might benefit from the better boundary-layer sensitivity of the NIR radiances. Such regions have also proven problematic for SCIAMACHY NIR-based retrievals, however, because they exhibit low NIR surface reflectance, leading to low SNR [de Laat et al., 2007].

Nevertheless, MOPITT NIR retrievals appear to be reasonable in the selected rainforest scene. Panels a and b present the individual profiles and mean grid-normalized averaging kernels for the TIR-based retrievals. The dashed blue line in panel a is the a priori profile, whereas the red dashed line and horizontal error bars indicate the mean retrieved profile and standard deviations at each level. Normalized averaging kernels for the surface, 700 hPa, 250 hPa, and total column are shown in panel b in purple, blue, red, and black, respectively. Panels c and d present the corresponding products for the NIR-based retrievals.

Examination of the retrieved profiles in panels a and c shows that both NIR and TIR products indicate relatively high levels of CO (compared to the a priori) throughout the troposphere. Differences between NIR- and TIR-based retrieved profiles are most evident in the upper troposphere, where the NIR retrievals are closer to the a priori and exhibit less variability than the TIR retrievals. These features suggest a stronger weighting of the a priori in the upper troposphere for the NIR retrieved profiles than for the TIR retrievals.

The sensitivity of the CO retrieval product to the true CO vertical distribution is described quantitatively by the averaging kernel matrix [Pan et al., 1998; Deeter et al., 2003]. Averaging kernels presented in panels b and d in Figure 6 are normalized to account for the non-uniform spacing between levels in the MOPITT standard retrieval grid [Deeter et al., 2007b]. Differences in the TIR- and NIR-based averaging kernels in panels b and d are the result of fundamental differences in TIR and NIR weighting functions [Pan et al., 1995; Pan et al., 1998]. The TIR-based total column averaging kernel in panel b indicates that the retrieved total column is approximately three times as sensitive to CO in the middle troposphere (e.g., between 400 and 700 hPa) than to CO in the lower troposphere. This is the result of weak thermal contrast between the surface and lower troposphere [Deeter et al., 2007b]. In comparison, the NIR-based total column averaging kernel is more uniform because absorption of solar radiation by CO molecules in the troposphere exhibits a relatively weak dependence on altitude.

The clear similarity of the three pressure-level averaging kernels for the NIR product in panel d (apart from a scaling factor) indicates the lack of any vertical resolution in the NIR retrievals; this is because NIR retrievals are based on a single observation (the ratio R). In contrast, The 250 hPa level averaging kernel for the TIR product in panel b clearly peaks in the upper troposphere, whereas the corresponding 700 hPa and surface-level averaging kernels peak in the mid-troposphere. Comparison of the 250 hPa level averaging kernels in panels b and d shows that the TIR product is clearly more sensitive to CO in the upper troposphere than the NIR product; this may explain the weaker retrieval variability at 250 hPa for the NIR product and smaller departures from the a priori.

Because the TIR products are based on multiple thermal-channel radiances with weighting functions that peak at different altitudes (as described in Section 2), they allow some degree of vertical resolution. As quantified by "Degrees of Freedom for Signal" (or DFS), MOPITT TIR-based retrievals generally contain less than two independent pieces of information [Deeter et al., 2004; Deeter et al., 2007b]. For the TIR-based retrievals shown in Figure 6, the mean DFS value is 1.469; the corresponding mean DFS value for the NIR-based retrievals is 0.619.

5. In-situ Validation

Previous efforts to validate operational TIR-based MOPITT retrievals over land exploited in-situ vertical profiles sampled from aircraft over three North American sites: Carr, Colorado; Harvard Forest, Massachusetts; and Poker Flat, Alaska [Emmons et al., 2004]. An ongoing program to coordinate and process these measurements is managed by personnel within the Global Monitoring Division of NOAA's Earth System Research Laboratory (ESRL). Such in-situ observations are extremely valuable for validating satellite-based retrieval products quantitatively. We use the same observations here for validating the NIR-based retrievals.

As mentioned above, the retrieval algorithm employed for this work is configured to always use the same log(VMR) a priori profile; this helps to distinguish information contained in the satellite measurements from a priori information. However, when comparing validation results for several sites at different elevations, the a priori total column value varies from site to site; thus an apparent correlation between retrieved total column and in-situ total column values ("truth") could potentially just be an artifact of variations in surface elevation. Moreover, because MOPITT NIR-based retrievals are based on a single measured quantity (i.e., the D/A ratio), retrieved VMR values at any level and corresponding total column values are not independent, i.e. the retrieved profiles do not actually contain any useful information with respect to the profile shape. Thus, for NIR retrievals, VMR comparisons reveal the same information as total column comparisons but are immune to the effects of varying validation site elevation.

NIR-based retrievals of CO VMR at 700 mb over Carr, Harvard Forest, and Poker Flat are compared with corresponding in-situ values in Figure 7. VMR values are plotted on logarithmic axes since retrieval errors are expected to follow a log-normal distribution with respect to VMR. Each plotted point corresponds to a single MOPITT observation; no averaging was applied. Retrievals were processed with a noise-scaling factor of 5.0 applied to the 6D instrumental radiance error as described in Section 3. Results are presented for all MOPITT overpasses of these three sites coincident with aircraft in-situ profiles acquired between September, 2001 and November, 2006. In-situ VMR values presented as the abscissa value in Figure 7 are extracted from the "ideal" retrieved log(VMR) profile $\hat{x}$ calculated according to the equation

$$\hat{x} = x_a + A(x_{true} - x_a) \tag{3}$$

where x_{true} is the in-situ log(VMR) profile, x_a is the a priori log(VMR) profile, and A is the MOPITT averaging kernel matrix [Emmons et al., 2004]. Within each overpass, all MOPITT retrievals within 100 km of the location of the in-situ profile are extracted for analysis.

Overall, validation results presented in Figure 7 and summarized in Table 1 indicate that MOPITT NIR-based retrievals at all three validation sites exhibit reasonable error characteristics. The data density contours (shown in black) clearly demonstrate a correlation between the retrievals and in-situ measurements and the lack of any significant retrieval bias. For the entire dataset plotted, base-ten log(VMR) bias and rms errors are 0.020 and 0.107, respectively, corresponding to fractional bias and rms errors of about 5% and 28%. The linear correlation coefficient of the entire dataset is 0.51. The dotted line in Figure 7 is a least-squares fit to all of the data, and closely follows the ideal response indicated by the dashed line.

As a measure of retrieval information content, histograms of Degrees of Freedom for Signal (DFS) for retrievals shown in Figure 7 are presented in Figure 8, panel a. The mean DFS value for all retrievals is 0.80. DFS values for Poker Flat and Harvard Forest tend to fall between 0.6 and 1.0 whereas DFS values for Carr tend to be closer to 1.0 (the theoretical maximum for NIR-based retrievals). Histograms of the corresponding 6A calibrated radiances are shown in Figure 8, panel b. Comparison of panels a and b indicates that larger DFS values for Carr are likely the result of generally larger 6A radiance values, which yield larger signal-to-noise ratios. Thus, the information content of NIR-based retrievals probably depends on both surface albedo, which exhibits significant geographical variability [Pfister et al., 2005] and solar zenith angle, which varies predictably with latitude and season.

Results presented in Figures 7 and 8, based on a noise-scaling factor of 5.0, were also compared to retrievals performed using noise-scaling factors of 1.0 and 10.0. Setting the noise-scaling factor to 1.0 (i.e., neglecting geophysical radiance errors) results in fractional bias and rms errors of about 3% and 29%, respectively, a linear correlation coefficient of 0.47 and a mean DFS value of 0.98. Conversely, increasing the noise-scaling factor to 10.0 results in fractional bias and rms errors of about 4% and 19%, respectively, a linear correlation coefficient of 0.62, and a mean DFS value of 0.57. As expected, increasing the noise-scaling factor leads to stronger weighting by the a priori and significantly decreases information content (as indicated by DFS). Although based on observations over just three validation sites in North America, these results suggest empirical noise-scaling factors between one and five yield reasonable results. Larger values yield smaller rms errors at the expense of decreased DFS.

6. Conclusions

For applications such as air quality monitoring, satellite-based methods capable of distinguishing CO in the atmospheric boundary layer from CO in the free troposphere would be extremely valuable. Although methods based solely on TIR radiances are sensitive to CO in the lower troposphere in some situations over land, such methods are not generally capable of sensing boundary-layer CO specifically (i.e., without significant sensitivity to CO in the free troposphere). In contrast, NIR-based methods are generally more sensitive to the boundary-layer than TIR-based methods, but offer no ability to resolve the CO vertical profile. Thus, the original concept behind the design of the MOPITT instrument was to fully exploit the complementary nature of TIR and NIR radiances to maximize vertical resolution, especially in the lower troposphere. Fully exploiting all of MOPITT's TIR and NIR radiances in a single retrieval product remains the ultimate objective for the MOPITT retrieval algorithm developers.

The incorporation of MOPITT's NIR radiances into operational products demands a thorough characterization of radiance errors. NIR radiances are affected by a variety of geophysical effects such as spatial and spectral variability in the surface reflectance. These effects lead to radiance errors which likely vary with surface type. For the NIR-based retrievals reported in this work, we account for non-instrumental errors in the NIR radiances by amplifying the radiance errors produced by calibration. Resulting retrievals appear reasonable in comparison with standard TIR-based MOPITT retrievals in both global monthly means and regional swath-level (non-averaged) data. Moreover, NIR-based results at three MOPITT validation sites in North America have been validated using in-situ data acquired from numerous aircraft flights. These results clearly demonstrate the capacity of the MOPITT NIR radiances for providing independent information with respect to the CO total column. Future development work will evaluate NIR radiance errors over a wider range of surface types than were considered here and compare alternative strategies for estimating meaningful uncertainties for the NIR ratio signal. Finally, merged retrievals based on both MOPITT TIR and NIR radiances will be demonstrated.

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Table 1. Validation statistics (mean DFS, fractional bias, fractional rms error, and linear correlation coefficient) corresponding to three choices of noise-scaling factor in MOPITT NIR-based retrievals. See Section 5.

Noise-Scaling Factor	⟨DFS⟩	Bias (%)	RMS Error (%)	r
1.0	0.98	3	29	0.47
5.0	0.80	5	28	0.51
10.0	0.57	4	19	0.62

Figure 1. Comparison of instrument-only uncertainty and observed variability for 6R signal for MOPITT overpasses of three validation sites in North America, including Carr, Colorado ("CAR"), Harvard Forest Massachusetts ("HFM"), and Poker Flat, Alaska ("PFA"). Dotted lines indicate expected variability values based on simple noise-scaling model to account for geophysical sources of radiance error.

Figure 2. Comparison of MOPITT TIR- and NIR-based CO total column retrievals for Southeast Asia for March 2-4, 2006. See Section 4.1.

Figure 3. Comparison of MOPITT TIR- and NIR-based CO total column retrievals for the Amazon Basin in South America for September 1-3, 2006. See Section 4.1.

Figure 4. Global comparison of monthly-mean MOPITT TIR- and NIR-based CO total column retrievals for March, 2006. See Section 4.2.

Figure 5. Global comparison of monthly-mean MOPITT TIR- and NIR-based CO total column retrievals for September, 2006. See Section 4.2.

Figure 6. Comparison of TIR- (panels a, b) and NIR-based (panels c, d) profiles (a, c) and mean averaging kernels (b, d) for September 2, 2006 for region in upper Amazon Basin (bounded by 5S, 3S, 76W and 74W). A priori profile is shown in panels a and c as blue dashed line. Mean retrieved profile is shown as red dashed line, along with error bars indicating the standard deviation at each level. Panels b and d present grid-normalized averaging kernels for retrieved VMR at surface (purple), 700 hPa (blue), and 250 hPa (red), and retrieved total column (black).

Figure 7. Scatterplot comparison of VMR values at 700 hPa retrieved using MOPITT NIR radiances and corresponding in-situ values (calculated using MOPITT averaging kernels) based on observations at Carr, Harvard Forest, and Poker Flat. VMR values are plotted on logarithmic axes since retrieval errors should ideally follow a log-normal distribution. Data density contours are shown in black. Dotted line indicates least-squares fit to all plotted data.

Figure 8. Histograms of DFS (panel a) and 6A radiance (panel b) corresponding to validation results presented in Figure 7. Both DFS values and radiances tend to be largest at Carr and smallest at Poker Flat.