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Technical Note: Impact of nonlinearity on changing the a priori of trace gas profiles estimates from the Tropospheric Emission Spectrometer (TES)

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Abstract

Non-linear optimal estimates of atmospheric profiles from the Tropospheric Emission Spectrometer (TES) may contain a priori information that varies geographically, which is a confounding factor in the analysis and physical interpretation of an ensemble of profiles. A common strategy is to transform these profile estimates to a common prior using a linear operation thereby facilitating the interpretation of profile variability. However, this operation is dependent on the assumption of not worse than moderate non-linearity near the solution of the non-linear estimate. We examines the robustness of this assumption when exchanging the prior by comparing atmospheric retrievals from the Tropospheric Emission Spectrometer processed with a uniform prior with those processed with a variable prior and converted to a uniform prior following the non-linear retrieval. We find that linearly converting the prior following a non-linear retrieval is shown to have a minor effect on the results as compared to a non-linear retrieval using a uniform prior when compared to the expected total error, with less than 10% of the change in the prior ending up as unbiased fluctuations in the profile estimate results.

1 Introduction

Optimal estimation is a powerful technique for performing atmospheric retrievals because of its capability to characterize errors and sensitivity (Rodgers, 2000; Bowman et al., 2006). This characterization allows data to be assimilated into chemistry and transport models (Jones et al., 2003) compared to other datasets (Rodgers and Connor, 2003; Worden et al., 2007), and prior vectors to be changed (Rodgers and Connor, 2003). However, these approaches are based on the assumption that the retrieved atmospheric state is spectrally linear with respect to the "actual" atmospheric state, i.e. that a linear expansion of the forward model is accurate to significantly better than noise between the retrieved and true atmospheric states. We test the impact of this linearity assumption on post facto linear operations on TES retrievals such as "swapping" the a

priori profile.

Using the most accurate prior will lead to the most accurate results; however conversion to a uniform prior can be useful for scientific analysis, such as highlighting seasonal cycles, comparing observations from two different regions that may have different priors, or comparing results from different satellites. Recent papers which have used TES data linearly converted to a uniform prior include Zhang et al. (2006) which examined the global distribution of TES ozone and carbon monoxide correlations in the middle troposphere, Logan et al. (2007) which studied the effects of the 2006 El Nino on carbon monoxide, ozone, and water, and Luo et al. (2007) which compared TES and The Measurements of Pollution in the Troposphere (MOPITT) instrument (MOPITT) carbon monoxide results and explores the influence of the a priori. MOPITT processing currently uses a uniform prior to reduce artefacts arising from the prior and maximize the impact of the satellite data (Deeter et al., 2003).

The Tropospheric Emission Spectrometer (TES), on the Earth Observing System Aura (EOS-Aura) platform, obtains high spectral resolution nadir infrared emission measurements ($650\,cm^{-1}$–$2260\,cm^{-1}$, with spectral sampling distance of $0.06\,cm^{-1}$ for nadir viewing mode) with about 3500 observations every other day (Beer, 2006). The TES data provides profile retrievals for atmospheric temperature (Herman et al., 2007), water (Shephard et al., 2007), HDO (J. Worden et al., 2007), ozone (H. Worden et al., 2007; Nasser et al., 2007; Osterman et al., 2007; Richards et al., 2007), carbon monoxide (Rinsland, 2006; Luo et al., 2007a, b), and methane, as well as surface temperature, emissivity, and cloud information[1]. For details on the TES instrument, see Beer et al., 2006, and for information on the retrieval process see Bowman et al. (2006) and Kulawik et al. (2006a). TES products and documentation are publicly available from the Langley Atmospheric Science Data Center (ASDC), http://eosweb.larc.nasa.gov/PRODOCS/tes/table_tes.html.

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A retrieved profile can be expressed as a first order expansion in $(x - x_a)$ (Rodgers, 2000; Bowman et al., 2002):

$$\hat{x} = x_a + \mathbf{A}(x - x_a) + \varepsilon \tag{1}$$

where x_a, $\hat{x}$, and x are the prior, retrieved, and true profile state in log(volume mixing ratio (VMR)), A is the averaging kernel which describes the sensitivity of the retrieval to the true state, and ε represents the error resulting from spectral noise, spectroscopic errors, cross-state error, and inaccuracies of non-retrieved species, as discussed in Worden et al. (2004).

Adjustment to a new prior can be done using the following equation (Rodgers and Connor, 2003):

$$\hat{x} = \hat{x} + (\mathbf{A} - \mathbf{I})(x_a - x_a) \tag{2}$$

where x_a and x_a are the original and new priors, respectively, $\hat{x}$ is the original retrieved value, and $\hat{x}$ is the retrieved value with the new prior. Equation (2) shows that when averaging kernel matrix, $\mathbf{A}$, is unity then changes to the prior have no effect on the retrieved value. Conversely when the averaging kernel matrix is zero, Eq. (1) shows that the retrieved state is equal to the prior. The averaging kernel is almost always somewhere in between these two extremes for atmospheric retrievals.

Equation (1) assumes not worse than moderate non-linearity between the retrieved state and the true state while Eq. (2) assumes not worse than moderate non-linearity between the two retrieved states (Rodgers 2000). As a consequence, the averaging kernel derived from a non-linear optimal retrieval with a priori, x_a, should be sufficiently close to an averaging kernel derived from a non-linear optimal retrieval with a priori, x_a. This linearity assumption is tested with a day's worth of TES data. For non-linear optimal estimates, the initial guess used in the minimization does not affect the solution as long as that solution represents the global minimum. On the other hand, if a local minimum is reached, then neither Eq. (1) nor Eq. (2) may be valid and the estimated profile will depend on the choice of the initial guess. The dependency of the retrieval

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on the initial guess is tested as well by also comparing standard retrievals to those that are retrieved using a globally constant initial guess.

2   Method

One day's worth of data from the TES instrument, consisting of 1152 globally dis-
tributed profiles taken 20–21 September 2004, was processed in three different ways
with the dataset designation shown in parentheses:

1. standard processing with variable initial guess and prior (SS)

2. processing with variable initial guess and uniform prior (SU)

3. processing with uniform initial guess and variable prior (US)

4. standard processing converted linearly to a uniform prior using Eq. (2) (SSC)

The data was processed with prototype software which created products equivalent to
the publicly available v003 product, with tightened convergence criteria which will be in-
cluded in v004 processing. For dataset SS, the initial guess and the prior are the same
and vary by latitude and longitude as described below. For dataset SSC, the standard
processing (SS) result is converted to a global uniform prior using Eq. (2). Datasets
SSC and SU should be equivalent; assuming Eq. (2) is valid. Similarly, datasets SS
and US should be equivalent since, as seen in Eq. (1), the initial guess should not
impact the final answer. For the global uniform prior or initial guess, the global av-
erage was created by taking a linear average over all priors or initial guesses for the
run. The initial guess and prior for atmospheric temperature, surface temperature, and
water are taken from the Global Model Assimilation Office (GMAO) (Rienecker et al.,
2006). For ozone, carbon monoxide, and methane, the prior/initial guess are taken
from a climatological MOZART-3 run (Brasseur et al., 1998; Park et al., 2004) which
has averages binned by latitude and longitude bands (typically 10–30 degree latitude
bands and 60 degree longitude bands).

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To compare datasets quantitatively, histograms were made of the fractional differences defined as:

$$\text{fractional, difference} = \hat{x}_1 - \hat{x}_2 \tag{3}$$

Since $\hat{x}$ represents Log(VMR), a value of 0.10 for the fractional difference indicates a 10% difference.

We also plot differences between (SSC-SU) versus the amount of change in the prior, which shows whether there is a breakdown in the accuracy of the results if changes to the prior are too large, and shows whether changes in the prior introduce biases in the result. Linear regression is used to calculate the slope of differences between (SSC-SU) versus the change in the prior.

Finally, averaging kernels at the result state are compared between the SSC and SU datasets to see if the reported degrees of freedom are consistent when the prior is swapped. This gives an indication of the relative Jacobian strengths, and whether the error analysis is cross-applicable.

3 Results

A TES global survey (Run ID 2147) consisting of 1152 globally distributed targets from 20–21 September 2004 was run for three different configurations for the prior and initial guess, as described in the methods section. Following the non-linear retrievals, the standard retrieval dataset (SS) was converted to the fixed prior dataset (SSC) using Eq. (2).

Figures 1 and 2 show the initial and retrieved values at 681 hPa for ozone and carbon monoxide, respectively, for datasets SS, SU, and SSC. The TES target locations are shown with white +'s and interpolation is done between the TES targets. The TES standard prior for both figures (panel a) is taken from a climatological run of the MOZART-3 model binned by 60 degrees longitude, and 10 degrees latitude. For the ozone prior, shown in Fig. 1, panel a, enhancements are seen in the Northern latitudes (>60 N)

and an enhanced band from South America through southern Africa to Australia (the biomass burning region (discussed iiin Bowman et al., 2007)), and a minimum is seen north of Australia. The standard retrieval shown in Fig. 1b represents these same patterns with a marked enhancement in the biomass burning region. The constant prior cases (panels c and d) agree remarkably well with each other indicating that the linearly converting the prior is valid throughout most of the data. The features in panels c and d can be confidently attributed to the TES data without preconceptions introduced by the prior; however large differences between panels b and c or d indicate a dependence on the prior rather than the data. The absence or presence of particular points passing quality flags can cause minor changes in the three different results. Most of ozone enhancements between 60 S–60 N remain between the standard processing and the converted prior (Fig. 1b and c) indicating that TES retrievals are sensitive at this pressure level over those regions. Poleward of 60 N, enhancements seen in the prior and the standard retrieval are absent, indicating that TES retrievals are insensitive in those regions.

Figure 2 shows the same plots as in Fig. 1, for carbon monoxide. The carbon monoxide prior (Fig. 2a) indicates enhancement over South America and southern Africa (in the biomass burning region), north of 40 N, and over India and southeast Asia. The standard retrieval Fig. 2b displays marked enhancement over the prior in eastern South America and western sub-Sahara Africa, and in eastern Asia. The uniform prior results, panels c and d, show good agreement with each other. The East Asia enhancement is present but muted and the pattern and values in the biomass burning region are very similar between panels b, c, and d, however the CO enhancement poleward of 40 N is markedly reduced in c and d indicating that TES retrievals have less sensitivity in those regions.

Figure 3 shows global maps of the VMR fractional difference (using Eq. 3) for O_3 and CO at 681 hPa for the SSC and SU datasets. The plots show that outliers occur predominately in the tropics, and to a lesser extent, Antarctica. The pattern may suggest two cloud layers, which occur frequently in the tropics (Zipser, 1969), could contribute

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to the retrieval variation since TES assumes one cloud layer (Kulawik et al., 2006b), however determining correlations between outliers and atmospheric conditions was not explored further in this paper.

3.1 Statistical analysis

To quantify differences, statistical analysis was done on the 681 targets which have good quality flags for all three runs (SS (and by extension SSC), SU, and US). The quality flags check for retrieval convergence using thresholds for the radiance residual and mean, maximum allowed changes in the retrieved surface temperature or emissivity, the amount of signal remaining in the residual; or other known issues (Osterman et al., 2007). The quality flags are set to screen out about 80% of the bad cases, but will also screen out perhaps 20% of good cases as well (Osterman et al., 2007).

A histogram of the fractional difference between the SSC and SU datasets shows the overall accuracy of changing the prior using Eq. (2) vs. using a uniform prior in the non-linear retrieval. From this histogram several relevant quantities can be calculated: (1) the fraction of the targets are within 5% of each other, (2) the fractional difference that encompasses 95% of the targets, and (3) the standard deviation of the fractional difference.

3.1.1 Results for ozone

In Fig. 4, a histogram of the VMR fractional difference, using Eq. (3), is shown comparing dataset SSC (the standard retrieval converted to a uniform prior using Eq. (2) to SU (the non-linear retrieval using a uniform prior) at 681, 178, 38 hPa, and over the entire profile. Figure 4 shows that for ozone, 70–80% of the SSC and SU results are within 5% difference. It is not surprising that histogram for the 177.8 hPa pressure level has the widest spread among the 3 pressure levels chosen because ozone at that pressure level has an order of magnitude variability due to the variations in the tropopause height; a globally constant value for ozone between 100–300 hPa is very challenging

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to the retrieval. Note that the errors introduced by changing the prior are small when compared to the TES reported total error (green dashed line in Fig. 4). In comparison, the VMR fractional difference of the prior had a 1-sigma value of 0.41, 1.08 (i.e. 108%), and 0.16 at 681, 178, and 38 hPa, respectively, indicating significantly more spread in the prior than in the resulting retrieval. The 1-sigma values for the results are shown in Table 1.

The histograms in Fig. 4 all show sharp peaks centered near zero but also show more outliers than would be expected from a Gaussian distribution. To determine if the outlying points are a result of a breakdown in the linear transform in Eq. (2) that occurs when the a priori change is too large, the difference (SSC-SU) is plotted versus the change in the prior, averaged over the profile, in Fig. 5. Figure 5 shows no obvious difference between small and large prior changes. In Fig. 5, panel a shows the rms of (SSC-SU), and panel b shows the mean difference, both averaged over the entire profile. For the rms difference, the slope tells whether, on average, larger differences in the prior lead to larger differences in the results. This slope was 0.10. For the mean difference, the slope indicates if the changes in the prior bias the results. The slope of this was found to be −0.02. Together these results mean that less than 10% of the prior's change will end up as unbiased fluctuations in the answer. The lack of bias show that the differences are not a function of the choice of the uniform prior.

To check the whether the outliers in Fig. 4 are a result of converging to a different local minimum, a run was done with a globally uniform initial guess (dataset US). The initial guess is the starting location for the retrieval, which iterates until convergence is reached. Since the initial guess is not included in the cost function, which determines the final solution, it should not affect the retrieval assuming the retrieval gets to the global minimum. However, an initial guess far from true can lead the retrieval to a non-global minimum, and systematic errors in the forward model or observed radiance can roughen the error landscape and introduce local minima. A more complete description of TES retrievals is discussed in Bowman et al. (2006). Theoretically, the initial guess does not influence the results (as seen also in Eq. (1) and dataset US should con-

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verge to the same answer as the standard retrieval (dataset SS). Differences in these datasets indicate convergence to different local minima, but we do not know whether either has reached a global minimum. The histograms from this run for ozone are shown in Fig. 6. In general, histograms of SS vs. US show a sharper peak and more
5 outliers than the histograms from Fig. 4. For O_3 at 681 hPa, for example, 17% of targets change greater than the TES reported error compared to 2% for results shown in Fig. 4.

Figure 7 has all "initial guess outliers" removed, and compares remaining targets for datasets SSC and SU. "Initial guess outliers" are set to be those where the average
10 rms difference over the profile between SS and US were more than 5%, and represent targets that show a tendency to converge to different minima. Results are shown in Fig. 7 for 681 hPa, and correlations shown for the profile standard deviation. In this case, there are significantly fewer outliers (compared to Figs. 4 and 5). The right plot in Fig. 7 shows that the spread in the prior is still about the same, but that the spread
15 in the result is markedly less. This means that the outliers in Figs. 4 and 5 likely result from retrievals converging to different local minima. Table 1 summarizes the results for Figs. 4, 5, and 7 for ozone.

As discussed following Eq. (2), when a retrieval is not sensitive, it will converge to the prior and exchanging the prior will move the retrieval to the new prior, as seen for
20 retrievals poleward of 60 N in Fig. 1. The effects of changing the prior on the most sensitive points is of interest, so statistics were calculated for only those points with a corresponding averaging kernel diagonal value of 0.04 or greater. For 681 hPa, the number of samples dropped from 648 to 290; the bias increased from 0.01 to 0.02, the 1-sigma value increased from 2.0% to 2.7%, the 3-sigma value increased from 15% to
25 17%, and the fraction within 5% error dropped from 78% to 65%. For 177.8 hPa and 38.3 hPa, the changes are smaller, for example for 38.3 hPa the fraction within 5% error dropped from 78% to 72%. However the result that the error is unbiased and smaller than the reported total error still holds true for the most sensitive points.

3.1.2 Results for carbon monoxide

For TES retrievals, carbon monoxide is retrieved following the retrieval of temperature/water/ozone steps. Consequently, changes to the temperature, surface temperature, or cloud parameters resulting from the uniform ozone prior will propagate into differences in the carbon monoxide step. Swapping only the carbon monoxide, rather than all the species together, may improve on the results shown in this study. Figure 8 shows the histogram of the fractional VMR change for CO at 383 and 681 hPa (note Figs. 8 and 9 do not have initial guess outliers removed). Additionally results are shown for averages over the entire profile. Carbon monoxide shows fewer outliers beyond 10% than found with ozone. Results for CO are summarized in Table 2. In comparison, the VMR fractional difference of the prior had a 1-sigma value of 0.30 and 0.17 at 681 and 381 hPa, respectively, indicating significantly more spread in the prior change than in the resulting retrieval.

3.1.3 Results for methane

Methane is also retrieved following the temperature/water/ozone steps, and changes to the temperature, surface temperature, or cloud parameters resulting from the uniform ozone prior will propagate into differences in the methane step. The results seen in this study are likely to be worse than the results from swapping only the methane. Figure 9 shows results at 287 hPa and for the whole profile, and shows that changing to a uniform prior results in less than a 1% difference in methane for 95% of the cases. Results for methane are summarized in Table 3. In comparison, the VMR fractional difference of the prior had a 1-sigma value of 0.06 at 287 hPa indicating significantly more spread in the prior change than in the resulting retrieval.

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3.1.4 Error analysis differences when changing the prior

When one changes to a different prior following the nonlinear retrieval, the error analysis available is the one calculated at the original retrieval. This section determines whether this error analysis is accurate by looking the change in the averaging kernel between runs SS and SU. We compare the total degrees of freedom for signal, and at individual values in the averaging kernel diagonal, through comparisons of the mean values, and at the fractional difference (calculated for values greater than 0.001).

For ozone, the mean degrees of freedom for signal (DOF) is 3.80. The mean DOF changes 0.01 between the two runs. The rms difference of the DOF is 0.04, which is about 1%. The mean value of the averaging kernel diagonal between the surface and 10 hPa is 0.069. The mean difference between the two runs is 8×10^{-5}, and the rms fractional difference of the averaging kernel diagonals are 15%.

For retrievals in Log(VMR), sensitivity is positively correlated to the VMR (Deeter et al., 2007). We find that retrievals with a 10% increase in the retrieved ozone column density also have about a 0.15 increase in the degrees of freedom, a 4% increase. Since the uniform prior is set to the global mean, this does not cause a biased change between the two runs for this test.

For carbon monoxide, the mean DOF is 1.09, with a mean difference of 0.004 between the two runs. The rms difference is 0.02, or 2%. The mean value of the averaging kernel diagonal between the suface and 10 hPa is 0.039. The mean difference between the two runs is 0.0006, and the rms fractional difference of the averaging kernel diagonals are 22%.

For methane, the mean DOF is 1.27, with a mean difference of 8×10^{-6} between the two runs. The rms difference is 0.04, or 3%. The mean value of the averaging kernel diagonal between the suface and 10 hPa is 0.024. The mean difference between the two runs is 0.00003, and the rms fractional difference of the averaging kernel diagonals are 12%.

For all three species, the total DOF varies by less than 3% when the prior is changed,

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and the individual averaging kernel diagonal values vary by about 20%. This indicates that the error bars and sensitivities may have about a 20% unbiased change for any particular level when the prior is changed, however the total DOF remains fairly impervious to changes in the prior.

4 Conclusions

Linearly converting the prior following a non-linear retrieval is shown to have a minor effect on TES trace gas retrievals as compared to a non-linear retrieval using the desired prior, when compared to the reported total error. Histograms of differences between these two methods show a sharp peak centered near zero with some outliers, especially for ozone. Further analysis of the characteristics of the outliers, and comparisons to retrievals with a uniform initial guess indicates that the many of the outliers result from convergence to a local minimum rather than breakdown of the linear conversion in Eq. (2). For ozone, the 1-sigma difference is less than 4% for each of three pressure levels studied, and the mean change for all levels is 2.7%. For methane, the 1-sigma change is 0.3% at 287 hPa and 0.3% for the profile average, and for carbon monoxide the 1-sigma change is about 2%. The degrees of freedom comparison between shows a 1-sigma difference of less than 3% for all the species, and shows changes of the averaging kernel diagonal are on the order of 20% for individual levels.

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Table 1. Summary of the differences between the linear vs. non-linear application of a uniform prior for ozone.

1a – all good quality cases

Quantity	681 hPa	178 hPa	38 hPa	Average
1-sigma % difference	2.0%	3.8%	1.3%	2.7%
w/in 5% difference	78%	69%	78%	64%
95% w/in range	±0.15	±0.26	±0.12	±0.18
Slope (see Fig. 5)	−0.04	0.00	−0.07	−0.02*

1b – screened by convergence which is indicated by the initial guess results

Quantity	681 hPa	178 hPa	38 hPa	Average
1-sigma % difference	1.1%	1.6%	1.0%	0.7%
w/in 5% difference	95%	88%	94%	90%
95% w/in range	±0.06	±0.12	±0.05	±0.06
slope	0.01	0.01	−0.02	−0.01*

* The slope is calculated for the mean difference of the profiles. The other average quantities are calculated for the rms difference.

Table 2. Summary of the differences between the linear vs. non-linear application of a uniform prior for carbon monoxide.

Quantity	681 hPa	383 hPa	Average*
1-sigma	0.8%	2.0%	1.1%
w/in 5% difference	89%	87%	88%
95% w/in range	±0.09	±0.10	±0.22
Slope	0.02	0.07	0.02

* The slope is calculated for the mean difference of the profiles. The other average quantities are calculated for the rms difference.

Table 3. Table 3. Summary of the differences between the linear vs. non-linear application of a uniform prior for methane

Quantity	287 hPa	Average*
1-sigma	0.3%	0.3%
w/in 5% difference	100%	100%
95% w/in range	±0.01	±0.02
slope	−0.01	−0.01

* The slope is calculated for the mean difference of the profiles. The other average quantities are calculated for the rms difference.

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(a) Variable Initial Guess / prior   *(b) Standard processing (SS)*

(c) Converted to uniform prior (SSC)   *(d) Retrieved w/ uniform prior (SU)*

Ozone Volume Mixing Ratio (ppb)
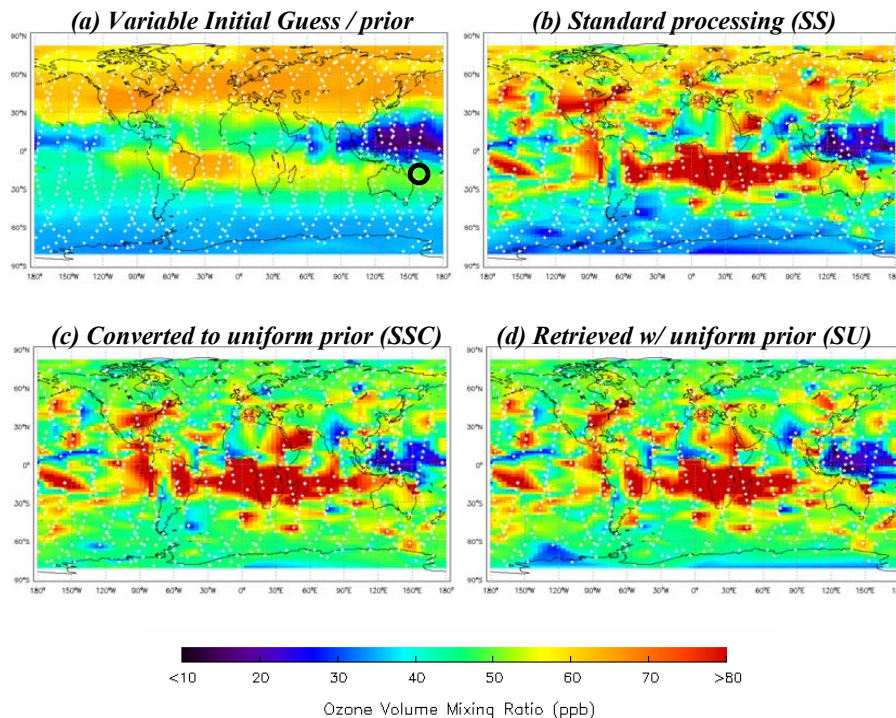
Fig. 1. TES retrieved ozone at 681 hPa. Panel **(a)** shows the standard globally variable TES a priori and initial states, with observation location shown with white +'s. Panel **(b)** shows the TES standard retrieval (SS). Panel **(c)** shows the TES standard retrieval converted to a uniform prior (SSC). Panel **(d)** shows TES retrieved with a uniform prior (SU). Panels (c) and (d) should agree in the linear regime. The circle in panel (a) shows the value of the uniform prior at this pressure which is 48 ppb. The color scale, which is the same for all plots, is shown below all 4 plots.

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(a) Variable Initial Guess / prior   *(b) Standard processing (SS)*

(c) Converted to uniform prior (SSC)   *(d) Retrieved w/ uniform prior (SU)*

CO Volume Mixing Ratio (ppb)
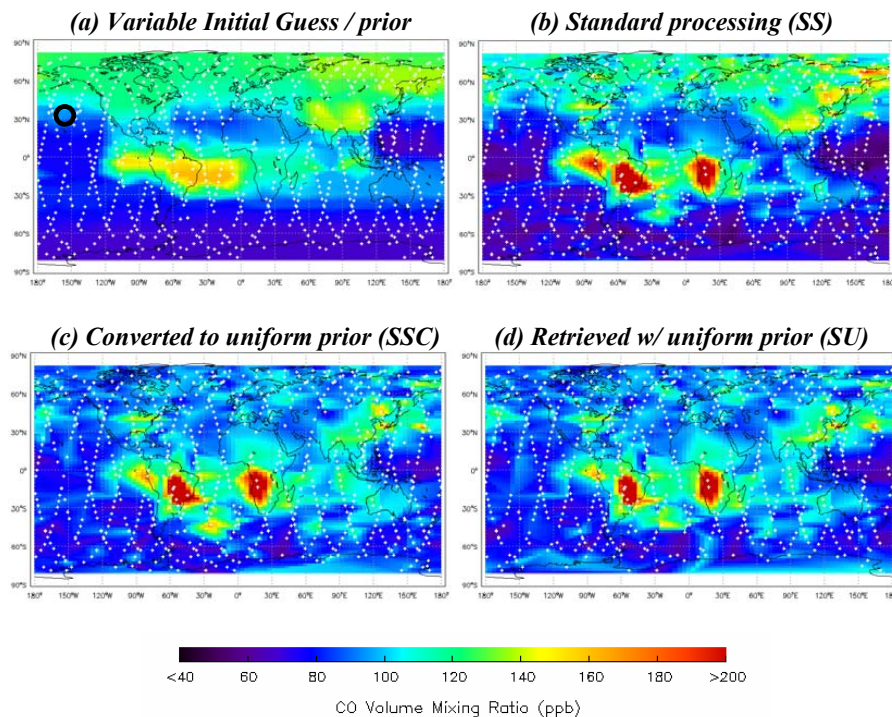
Fig. 2. TES retrieved carbon monoxide at 681 hPa. Panel **(a)** shows the variable TES a priori. Panel **(b)** shows the TES standard retrieval (SS). Panel **(c)** shows the TES standard retrieval converted to a uniform prior (SSC). Panel **(d)** shows TES retrieved with a uniform prior (SU). Panels (c) and (d) should agree in the linear regime. The circle in panel (a) shows the approximate value of the uniform prior at this pressure (97 ppb).
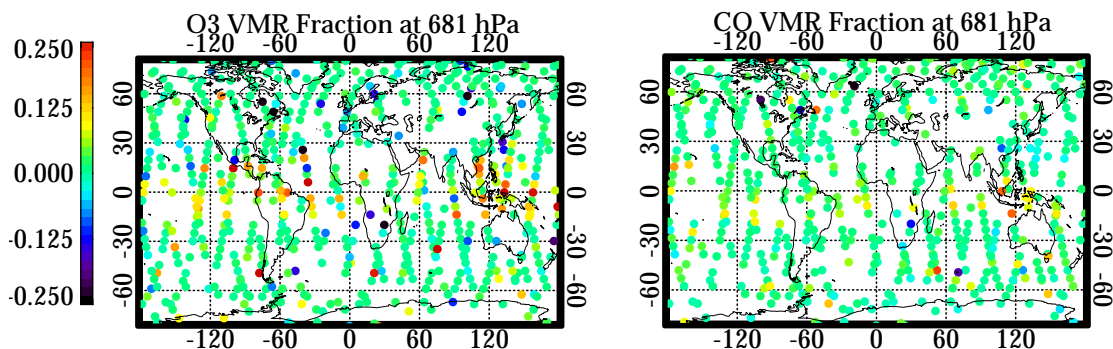
Fig. 3. VMR fraction difference for SSC-SU for O_3 (left) and CO (right) at 681 hPa. These plots show that the outliers occur predominately in the tropics.

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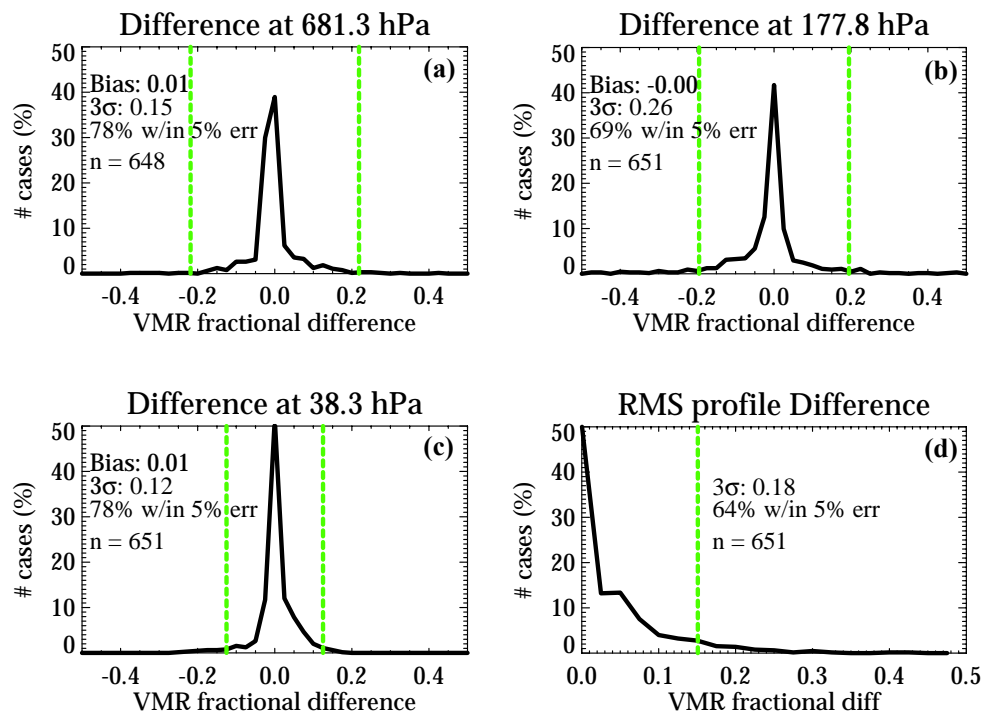
Fig. 4. Statistical comparison between non-linear retrievals using a uniform prior (SU) vs. conversion to a uniform prior using Eq. (2) (SSC). The black line shows the histogram of the Fractional difference of (SSC-SU) for 3 different pressure levels. The green dashed line is the mean TES reported total error. The lower right plot is the standard deviation of the VMR fractional difference averaged over the entire profile.
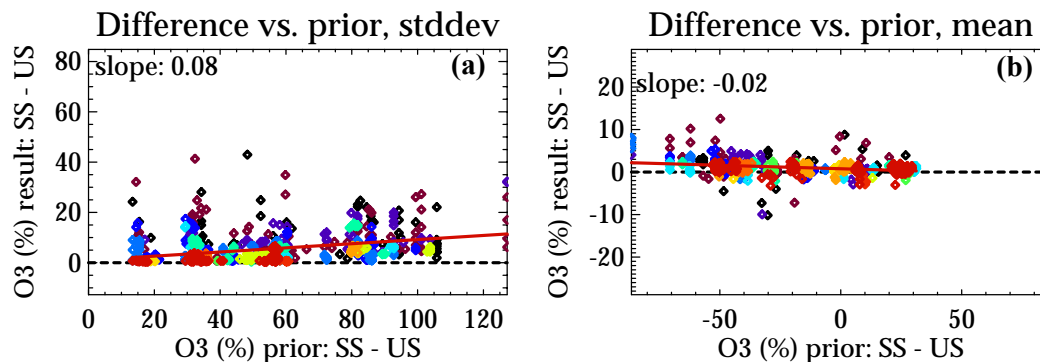
Fig. 5. Change in (SSC-SU) as a function of the change in the prior. The colors represent density of points using the same color progression as used in Figs. 1 and 2, where red indicates the highest density of points. The calculated slope is shown as a red line. These results indicate that less than 10% of the prior's change will end up as unbiased fluctuations in the answer.

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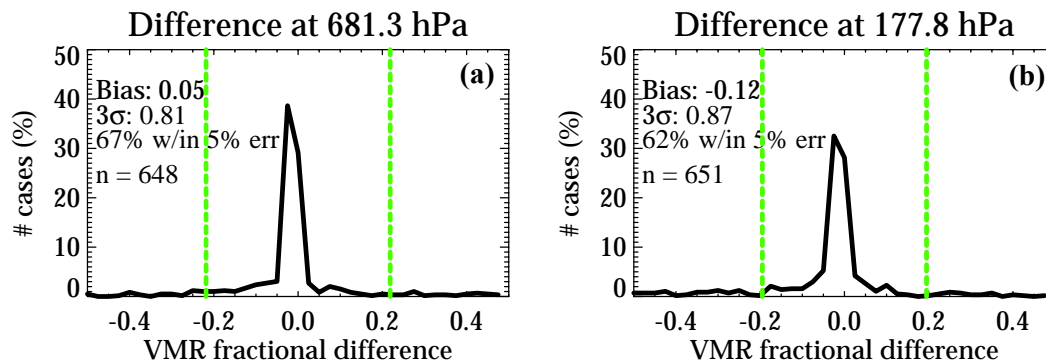
Fig. 6. Statistical comparison between non-linear retrievals using a globally constant initial guess vs. variable initial gues. The black line shows the histogram of the VMR fractional difference for SS-US for 2 different pressure levels (681 and 178 hPa).
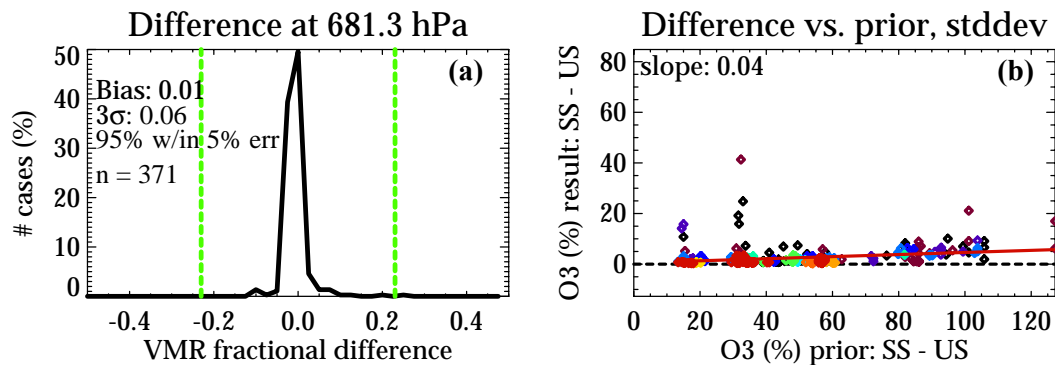
Fig. 7. The effects of removing outliers on the prior comparison. Cases which are outliers from swapping the initial guess are removed from the prior comparison. The remaining cases show better characteristics compared to Figs. 4 and 5.
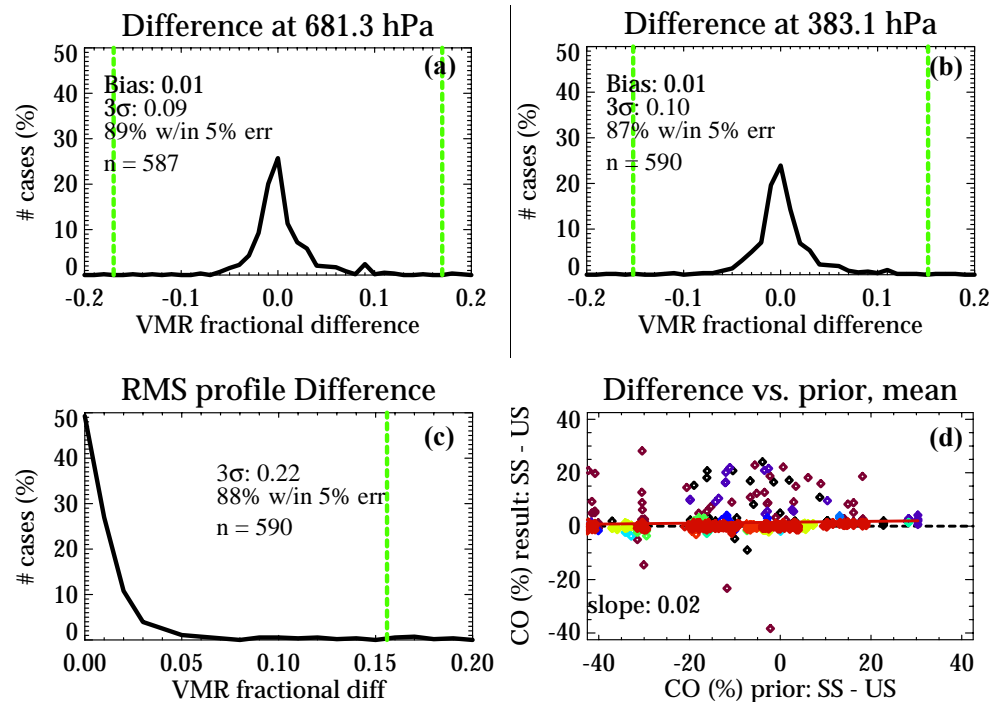
Fig. 8. Statistical comparison for carbon monoxide between non-linear retrievals using a uniform prior vs. conversion to a uniform prior using Eq. (2). The black line shows the histogram of the VMR fractional difference of SSC and SU using Eq. (3) for 2 different pressure levels for carbon monoxide. The lower right panel shows the mean change in the result vs. the mean change in the prior.
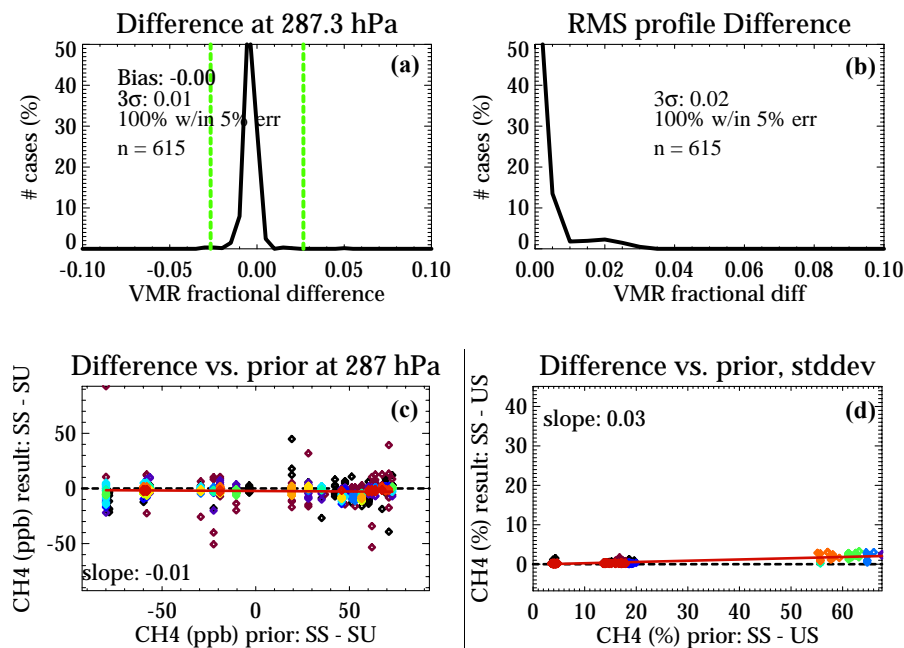
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Fig. 9. Statistical comparison for methane between non-linear retrievals using a uniform prior vs. conversion to a uniform prior using Eq. (2). The black line shows the histogram of the Fractional difference using Eq. (3) of SSC-SU for 287 hPa. The red line shows the histogram of the differences in the priors, which show significantly more spread. The upper right panel shows the histogram of the average error for all pressures. The lower right panel shows the difference in the retrieval result vs. the difference in the prior for 287 hPa, and the lower right is the same for the mean difference over the whole profile.

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