Thank you for your comments suggesting revisions to our manuscript. We made changes to the text as suggested by you.

The reviewers' suggestions are in italic.
All of the revisions, which were made by following the suggestions from reviewers, are in blue.

Reviewer #1's suggestions:

1. *One of the main conclusions given in the abstract and summary of the paper is the statement: "We find that the vertical resolution of the joint TES/OMI ozone profile estimate is sufficient for quantifying variations in near-surface ozone with a precision of 26% (15.6 ppb) and a bias of 9.6% (5.7 ppb)." I think this statement is not supported by the study. As I understood, the precision and bias given are taken from the results shown in Fig. 5 (although the numbers do not fully agree). In this analysis, the averaging kernels were applied as well as varying a priory profiles, so this uncertainty applies to the smoothed results. The real analysis of variations in "near surface" ozone (if 700 hPa is considered to be near surface) are shown in Fig. 8, and here much larger uncertainties are found. As an aside I note that TES retrievals alone perform better than the combined retrieval in Fig. 5 which illustrates that this is not the right metric to judge the quality of the retrieved surface ozone. I suggest to remove this sentence from the abstract and to replace it by a quantitative statement on the uncertainty based on the evaluation shown in Fig. 8.*

   Re: The following sentence replaced the quoted sentence in P27590 lines 17 to 20: "We also used a common a priori profile in the retrievals in order to evaluate the capability of different retrieval approaches on capturing near-surface ozone variability. We found that the vertical resolution of the joint TES/OMI ozone profile estimates show significant improvements on quantifying variations in near-surface ozone with RMS differences of 49.9% and correlation coefficient of $R = 0.58$ for the TES/OMI near-surface estimates as compared to 73.6% RMS difference and $R = 0.33$ for TES and 115.8% RMS difference and $R = 0.09$ for OMI. This comparison removes the impacts of the climatological a priori on the comparison and results in artificially large sonde/retrieval differences. The TES/OMI ozone profiles from the production code of joint retrievals will use climatological priors and therefore will have more realistic ozone estimates."

2. *I'm surprised by the lack of discussion of the problems that are relevant when using real data as opposed to synthetic spectra as was the case in previous studies. Some obvious examples would be*
   • Inconsistencies in the spectroscopic parameters
   • Differences in air volume probed
   • Differences in the cloud parameters retrieved
   • Differences in the additional parameters retrieved as compared to what is found in OMI / TES only retrievals – this could be indicative of calibration or

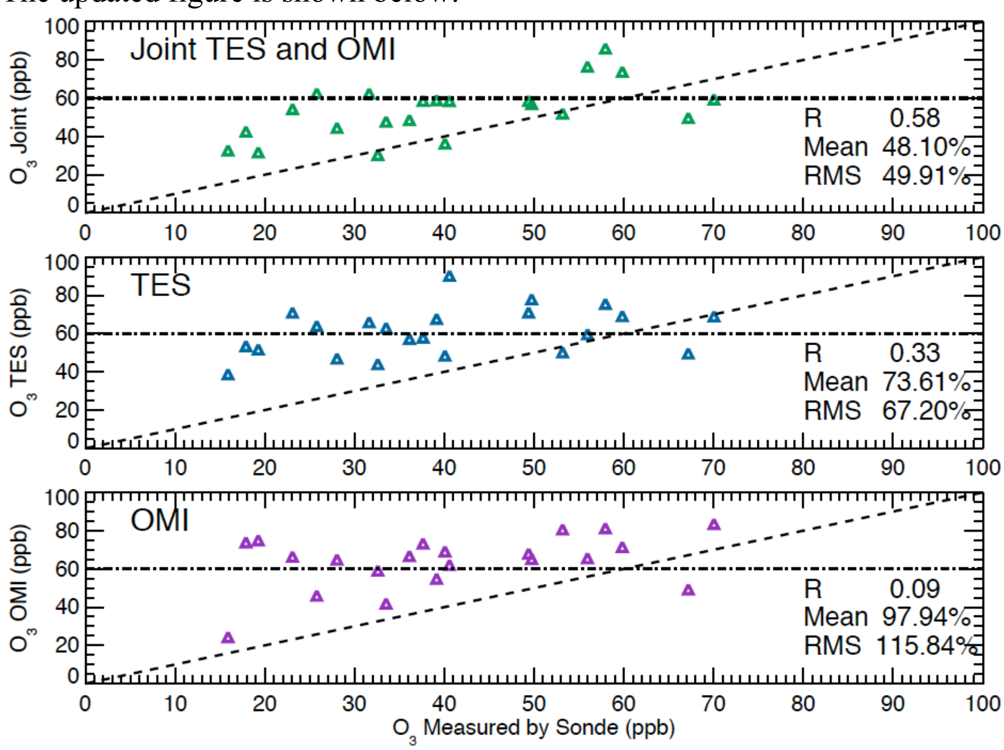
spectroscopic problems
I suggest to add some discussion on the effects of using real data as this is the strong point of this study.
Re: We added some discussions in section 4.3 to include the suggested topics.
The P27612 lines 3 to 13 were revised:
"Our joint retrieval algorithm utilizes spatiotemporally coincident measured spectral radiances to retrieve the vertical distribution of ozone concentration. The spectral radiances from 312 to 330 nm were coadded using measurements over two OMI UV-2 ground pixels prior to the spectral fitting yielding a group pixel size of 13 × 48 km^2 (along ground track × cross ground track of spacecraft) at Nadir. The co-addition approach, which has been used by Liu et al. (2010a) in OMI retrievals, helps in reducing forward model computation time compared to simultaneously fitting UV-2 spectra that represent these ground pixels. It also ensures both OMI UV1 and UV2 measurements probing common air volume, despite of introducing minor spectral wavelength registration artifacts. A TES measurement at Nadir yields a ground pixel size of 8.5 × 5.3 km^2 (along ground track × cross ground track of spacecraft). We expect that the differences on the size of ground pixels between TES and OMI measurements do not significantly affect the retrieved ozone VMR since the measurements of using TIR spectral region show most sensitivities over/above free troposphere where the spatial gradient of ozone concentration are weak."

The following discussions were added in P27612 line 14:
"This work focused on investigating the feasibility of multiple spectral observations of near surface ozone concentration, evaluating the performances using measured radiances from current satellite instruments and providing realistic advance studies for the future missions. Hence, the scenarios shown in this work are in the nearly clear sky conditions, in which the cloud fraction in each instrument's field of view is less than 10%. We retrieved cloud parameters for each instrument in order to account for the differences on the instrument's field of view. Since both a priori values and initial guess values were taken from TES standard products and OMI standard products, the jointly retrieved values are generally within 1% compared to the products from each instrument alone. When processing the entire TES and OMI measured radiances that were recorded from 2005 to 2008, we decided to filter out those scenes whose cloud fractions are greater than 30% using existing OMI released cloud products. We expect that the future satellite missions can achieve improvements on harmonizing the ground pixel sizes between TIR and UV bands, e.g., reducing the ground pixel sizes of UV bands improves the number of cloud free scenes since both OMI and GOME-2 provide larger ground pixels than TIR sounders onboard its common satellite platform."

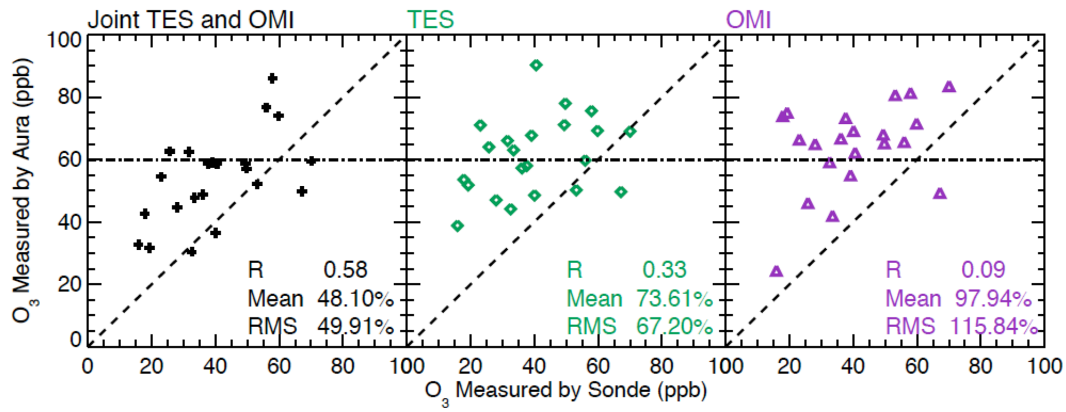
The estimated discrepancies of spectroscopic parameters between TIR and UV spectral regions used in this work are up to 3%, which is smaller than the estimated measurement uncertainties (Figure 5) and ozone natural variations near surface. To further improve the quality of ozone measurements using multiple spectral regions, next generation of ozone spectroscopic parameters should mitigate the existing discrepancies among different spectral regions (microwave, thermal infrared, visible and ultraviolet). Prior to the availability of the new ozone cross-sections that mitigate the existing discrepancy (3%) between UV and TIR spectroscopic parameters, we will implement an alternative correction to the forward model or retrieval, such as a retrieved or fixed line strength correction factor to address the discrepancy on the spectroscopic parameters.

3. *I do not fully understand Fig. 8. Why are the O3 mixing ratios from the ozone sondes different in the three panels? As no averaging kernel is applied, I would have expected that all points have the same O3 value from the ozone sondes. Please explain.*

Re: Those ozone sonde measurements were mapped into forward model pressure grids in the altitude range where the ozone sondes provided good-quality measurements. At the pressure levels where ozone sonde did not have good measurements, we filled the retrieved ozone volume mixing ratios from Aura measurements into the ozone sonde profiles. Since the retrieved ozone volume mixing ratios are different among TES+OMI, TES only and OMI only, the averaged ozone VMR slightly differ among three panels. In the revised manuscript, we corrected this impact based on your suggestion. For the updated comparisons as shown in the revised manuscript, the correction was made by filling the same ozone VMR values from TES+OMI retrieved ozone profiles.
The updated figure is shown below.



Then, we rearranged the orientation of the above figure, made the square plots and kept color scheme be consistent to other figures in the manuscript. The figure below is used as figure 8 in the updated manuscript.



4. *In Fig. 9, the caption claims "that joint TES and OMI observations have better capability of capturing the variations of ozone concentration than each instrument alone in the region from 700 to 200 hPa". Apart from the fact that in the figure, it says that O3 from 700 to 100 hPa is shown, I think that this plot illustrates that the TES only retrieval gives the best results for this altitude range, as is also evident from Figs. 5 and 6. This should be corrected in the caption and also in the text.*

   Re: The caption has been revised. "**Figure 9**. Correlations of Aura measured and ozonesonde measured ozone concentration (parts-per-billion) in the region from 700 hPa to 100 hPa: Joint OMI and TES (black plus); TES (green diamond); OMI (purple triangle). The discrepancy between joint observations and sonde measurements is larger (Mean: 1.24%; RMS: 0.75%) than that between TES only measurements and sonde measurements. Both Joint observations and TES only measurements show better agreement to sonde measurements than OMI only measurements. A common a priori ozone profile was used in the retrievals for all of the scenes. The averaging kernels of Aura measurements were not applied to the ozonesonde measurements."

5. *There is a change in colour scheme between Figs. 5-7 and Fig. 8. In addition, the caption in Fig. 7 refers to the wrong colours. Please homogenize and correct.*

   Re: The homogenizations on the color schemes were applied to Figures 5-9. The caption in Figure 7 was corrected to the right colors. "**Figure 7**. DOFS for the set of ozone measurements in Table 2: (Top panel) total DOFS; (Middle panel) DOFS for the region between the surface and 100 hPa; (Bottom panel) DOFS for the region between surface to 700 hPa; Joint OMI and TES (black plus); TES (green diamond); OMI (purple triangle)."

6. *In the caption of Fig. 6, reference is made to OMI data which is not shown.*

   Re: The OMI only retrievals used in this work were performed by this work. The agreement between our OMI retrievals and the results from Liu et al., 2010 were found within measurement certainties.

7. *Abstract: DOF defined twice*

   Re: the second time definition in P27590 line 12 was removed.

8. *p 27591, l16, check closing brace of Browell reference*

   Re: the closing brace of Browell reference was added.

9. *p 27592 / 27593, section on satellite instruments: difficult to read and not clear if really needed. Note that S5 is a polar orbit satellite.*

   Re: The international communities of atmospheric remote sensing (private communications) have showed great interests in the multiple spectral observations on atmospheric compositions from space. The section in p27592/27593 described the possible application of this work in the future satellite missions, e.g., the future GEO missions, whose advance studies are being performed by several international scientific communities. Thanks for mentioning the orbit of sentinels-S5. We included both sentinels-S5 and the Canadian PCW/PHEMOS-WCA mission since they provide the measurements over polar region where 'regular' geo stationary satellite cannot cover, e.g., the Canadian PCW/PHEMOS-WCA mission will have a special-type of polar orbit satellite since it will spend most of its measurement time over polar region acting as a semi-geostationary satellite over polar region. They will carry out measurements using multispectral regions and will provide most measurements over those regions where a geostationary satellite cannot cover. Hence, we prefer to keep this section together with S5 reference. And we also added the study made by Cuesta et al. 2013 in the introduction. Cuesta et al. in 2013 did a study on combining TIR and UV spectral region for improving the tropospheric ozone sounding (Cuesta et al. 2013). It closely related to our work, e.g., the similarity of observation systems (spectral regions and viewing geometry), retrieval algorithms, and retrieval quality.

   The following sentences were added in P27593 line 19:
   "In this paper, we explore the feasibility of estimating ozone using multiple spectral bands by using the measurements from the EOS-Aura mission. In addition to our work, Cuesta et al. (2013) developed a multiple spectral retrieval algorithm on tropospheric ozone soundings using IASI and GOME-2 simultaneously measured radiances from the MetOp satellite in the sun-synchronous orbit (local time of ascending node: 9:31 am). Both this work and Cuesta et al. (2013) used identical spectral regions of the υ_3 band in TIR and the Hartley and Huggins bands in the UV and showed similar vertical sensitivities and measurement uncertainties of ozone profile estimates."

   The following reference was added in P27616, line 23:

"Cuesta, J., Eremenko, M., Liu, X., Dufour, G., Cai, Z., Höpfner, M., von Clarmann, T., Sellitto, P., Forêt, G., Gaubert, B., Beekmann, M., Orphal, J., Chance, K., Spurr, R., and Flaud, J.-M.: Satellite observation of lowermost tropospheric ozone by multispectral synergism of IASI thermal infrared and GOME-2 ultraviolet measurements, Atmos. Chem. Phys. Discuss., 13, 2955-2995, 2013."

10. *p 27594, what is 1B2 and 2A1 for the TES bands?*
    Re: 1B2 refers to the spectral region of 950-1150 cm^{-1} (see p27594, Line 17)
    2A1 refers to the spectral region of 1100-1325 cm^{-1} (see p27594, Line 23)

11. *p 27595, l 6, remove "those"*
    Re: Removed. "The SO mode includes targeted measurements used for validation activities or to examine regional processes and emissions."

12. *p 27596, l 18: check grammar of sentence*
    Re: the sentence was changed to: "). A critical requirement for a forward model is that it be as accurate as possible and be capable of performing the calculations with acceptable computational cost (Clough et al., 2006)."

13. *p 27595, l 12: characterization => characteristics*
    Re: The suggested revision was found at P 27597, l 12: changed.
    "It also simulates the characteristics of the TES instrument. It provides simulated radiances and Jacobians of the spectral radiances with respect to specified parameters."

14. *p 27598, l 27, obtaining => obtained*
    Re: Changed.
    "We used the surface reflectance climatology constructed using 3 years of OMI measurements obtained between 2004 and 2007 (Kleipool et al., 2008)."

15. *sections 3.2 and 4.1 – reconsider how much is needed for the paper and what can be dealt with by a reference to Rogers or some previous work on TES retrievals*
    Re: We reduced the number of equations from 12 to 4 and deleted sentences in the following places:
    # Page 27601 lines 5 to 17
    # Page 27602 lines 6 to 14
    # Page 27604 lines 12 to 14
    # Page 27604 line 21 to Page 27605 line 4
    The text in Page 27601 line 5 to Page 27602 line 14 is replaced using following paragraphs:

    "The joint TES and OMI retrieval algorithm is based on the optimal estimation method (Bowman et al. 2002; Rodgers, 2000) that combines the a priori knowledge, which includes both a mean state and its covariance before the measurements are taken, and the information from combined TIR and UV measurements. The algorithm involves finding the best estimate state vector $\hat{\mathbf{z}}$ by minimizing the cost function shown in equation 1,

$$\chi^2 = \left\| \mathbf{L}_{\mathbf{obs}} - \mathbf{L}_{\mathbf{sim}}(\hat{\mathbf{z}}) \right\|^2_{\mathbf{S}_\varepsilon^{-1}} + \left\| \mathbf{z} - \mathbf{z}_{\mathbf{a}} \right\|^2_{\mathbf{S}_{\mathbf{a}}^{-1}}. \quad (1)$$

Equation 1 is a sum of quadratic functions representing the Euclidean distance, with the first term representing the difference between observed ($\mathbf{L}_{\mathbf{obs}}$) and simulated radiance spectra ($\mathbf{L}_{\mathbf{sim}}(\hat{\mathbf{z}})$) constrained by the measurement error covariance matrix ($\mathbf{S}_\varepsilon$), and the second term accounting for the difference between retrieved ($\hat{\mathbf{z}}$) and a priori ($\mathbf{z}_{\mathbf{a}}$) state vectors regulated by the a priori covariance matrix (S_{a}).

Table 3 lists the sources for the a priori vector and covariance matrix for those parameters that were being retrieved. The constraint matrix ($\mathbf{S}_{\mathbf{a}}^{-1}$) in equation 1 is to regularize the ill-posed problem to obtain a stable solution that is an approximation to the exact solution. The standard constraints for atmospheric retrievals include climatology and Tikhonov constraints. The TES ozone retrievals use an altitude-dependent Tikhonov constraint matrix based on minimizing the expected error over an ensemble of retrievals (Steck 2002; Kulawik et al. 2006c). The altitude-dependent Tikhonov constraint, which is different from the classic Tikhonov constraints, is composed of combinations of the zeroth-, first-, and second-order Tikhonov constraints with altitude–dependent weights. (Kulawik et al., 2006c). This procedure was adopted because the TES retrieval algorithm development team empirically found that low-thermal contrast conditions could result in many ozone retrievals showing unphysical results, or retrievals with significantly large errors, near the surface. ”

The text in Page 27604 line 6 to Page 27602 line 14 is replaced using following paragraphs:

“If the retrieval has converged and it can be shown that small changes in atmospheric state result in small and linear changes in the modeled radiances, then the estimated state vector $\hat{\mathbf{z}}$ can be written as the linear expression (Rodgers 2000):

$$\hat{\mathbf{z}} = \mathbf{z}_{\mathbf{a}} + \mathbf{A}_{\mathbf{zz}}\left[\mathbf{z}_{\mathbf{true}} - \mathbf{z}_{\mathbf{a}}\right] + \mathbf{G}\varepsilon + \delta_{\mathbf{cs}}, \quad (2)$$

where $\mathbf{z}_{\mathbf{a}}$ is the a priori constraint vector, $\mathbf{A}_{\mathbf{zz}}$ is the averaging kernel matrix whose rows represent the sensitivity of the retrieval to the true state, $\mathbf{z}_{\mathbf{true}}$ is the true state vector, ε is the spectral noise, and $\mathbf{G}$ is the gain matrix. The “cross-state” error, δ_{cs}, (Worden et al., 2007a) is incurred from retrieving multiple parameters (e.g., water vapor, surface temperature, cloud extinction and top pressure in TIR, cloud fraction in UV, surface albedo, and wavelength shifting parameters). The trace of the averaging kernel matrix gives the number of independent pieces of information in the vertical profile, or, the Degrees of Freedom for Signal (DOFS) (Rodgers, 2000). A larger DOFS value indicates a better sensitivity.

Figure 1 shows sample averaging kernel matrices for TES, OMI and joint TES and OMI observations over Naha, Okinawa, Japan on August 1st, 2007. These three measurements show different sensitivities to tropospheric ozone. TES can better resolve the lower/upper troposphere than OMI. Figure 1 shows the improvement in vertical resolution of tropospheric ozone by combining TES and OMI measurements. There is a clear enhancement of DOFS in the troposphere (TES only: 1.84; OMI only: 1.16; Joint TES and OMI: 2.21). The combined TES and OMI measurement also shows an increased sensitivity to the layer surface-700 hPa. In addition to the spring/summer season when the thermal contrast is usually high, these improvements have been also observed during the fall/winter season (Figure 2).

To validate the estimated ozone profiles, collocated ozonesonde measurements were compared to the estimated ozone profiles from TES only, OMI only, and joint TES and OMI measurements. The differences between the satellite retrievals and ozonesonde measurements smoothed by instrument averaging kernels can be written as (Worden et al., 2007a):

$$\Delta_{\mathbf{satellite-sonde}} = \hat{\mathbf{z}} - \hat{\mathbf{z}}_{\mathbf{sonde}} = \mathbf{A}_{\mathbf{zz}}\left[\mathbf{z} - \mathbf{z}_{\mathbf{sonde}}\right] + \mathbf{G}\varepsilon + \delta_{cs}, \qquad (3)$$

where $\mathbf{A}_{\mathbf{zz}}$ represents the averaging kernels of TES, OMI, or combined TES and OMI measurements. $\mathbf{z}$, $\mathbf{G}$, ε, and δ_{cs} are the state vector, gain matrix, the noise of measured radiances, and cross state error respectively. Equation 3 shows that the difference is not biased by the a priori constraint vector, $\mathbf{z}_{\mathbf{a}}$, and can be used to identify other biases in ozone profiles estimated using satellite measurements (equation 4). The expected error for the differences between the satellite retrievals and ozonesonde measurements smoothed by instrument averaging kernels is:

$$E\left[\left(\hat{\mathbf{z}} - \hat{\mathbf{z}}_{\mathbf{sonde}}\right)\left(\hat{\mathbf{z}} - \hat{\mathbf{z}}_{\mathbf{sonde}}\right)^{\mathbf{T}}\right] = \underbrace{\mathbf{A}_{\mathbf{zz}}\mathbf{S}_{\mathbf{sonde}}\mathbf{A}_{\mathbf{zz}}^{\mathbf{T}}}_{\substack{\text{ozonesonde}\\\text{measurement}\\\text{Error}}} + \underbrace{\mathbf{G}\mathbf{S}_{\varepsilon}\mathbf{G}^{\mathbf{T}}}_{\substack{\text{satellite}\\\text{instrument}\\\text{measurement}\\\text{error}}} + \underbrace{\mathbf{A}_{\mathbf{cs}}\mathbf{S}_{\mathbf{cs}}\mathbf{A}_{\mathbf{cs}}^{\mathbf{T}}}_{\substack{\text{cross}\\\text{state}\\\text{error}}}, \qquad (4)$$

where $\mathbf{A}_{\mathbf{cs}}$ is the submatrix of the averaging kernel for the full state vector of all jointly retrieved parameters that relates the sensitivity of $\mathbf{z}$ (the vector of cross-state parameters) to $\mathbf{z}_{\mathbf{cs}}$ (corresponding cross-state a priori constraint vector) (Worden et al., 2007a), $\mathbf{S}_{\mathbf{sonde}}$ is the sonde error covariance, $\mathbf{S}_{\varepsilon}$ is the spectral radiance measurement error covariance and $\mathbf{S}_{\mathbf{cs}}$ is the block diagonal matrix presented in equation 5. $\mathbf{S}_{\mathbf{cs}}$ contains the a priori covariance for the other jointly retrieved parameters including water vapor, surface temperature, surface emissivity, cloud parameters in infrared (extinction and cloud top pressure), surface albedo in UV, wavelength shifting in UV, cloud parameter in UV (cloud fraction) parameters.

$$\mathbf{S_{cs}} = \begin{pmatrix} \mathbf{S_{H_2O}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{S_{surf\_TATM}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{S_{surf\_emis}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{S_{cloud\_IR}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{S_{surf\_alb\_UV}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{S_{ring\_UV}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{S_{wls\_UV}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{S_{cloud\_UV}} \end{pmatrix}. \quad (5)$$

16. *p 27605, l 7: troposphere => tropospheric*
Re: Changed.
"These three measurements show different sensitivities to tropospheric ozone."

17. *p 27607, l 3: For the unmeasured => The unmeasured*
Re: Changed.
"The unmeasured part of the stratosphere is approximated by appending the ozone a priori VMR."

18. *p 27609, l 13: the bias increases but the precision decreases: : :*
Re: Changed.
"For example, Figure 6 shows that the bias increases but the precision in the lower troposphere decreases from 9% ± 23.7% to 16.56% ± 39.7%."

19. *p 27610, l 3: does => do*
Re: Changed.
"In the troposphere, the peak altitudes of TES averaging kernels slightly vary with pressure level while OMI averaging kernels almost do not change."

20. *p 27610, l 16: that => those*
Re: Changed.
"TES shows better sensitivity in the troposphere than OMI since the DOFS of TES measurements are larger than those of OMI (Figure 7 middle panel) in the troposphere, whereas in the stratosphere the OMI observations show better sensitivity than TES as indicated from the differences in DOFS between top and middle panels in Figure 7."

21. *p 27610, l 24. Check grammar of sentence*
Re: Removed the 'throughout'. Page 27610 line 24: "To further investigate the improvements on the tropospheric ozone sounding due to using both TIR and UV bands, we ran retrievals using a common a priori ozone profile for all of the

scenes in Table 2 and compared the estimated ozone concentration to the ozonesonde measurements."

22. *Why are the tables repeated in the supplement?*
    Re: Removed the extra tables.

In addition, we made numerous corrections on typo and grammar in the manuscript, which are also highlighted in blue.