Reviewer #2 Comments

We thank the reviewer for the constructive comments.

This manuscript discusses the cause of the observed thermal infrared signal of a specific biomass burning episode in western US (the Dixie fires). Different causes are investigated using observations and radiative transfer modelling, and a conclusion is reached that the most important player is the surface cooling by the smoke plume. The data and analysis presented are mostly convincing, although not always straightforward to understand. I would appreciate seeing some additional physics in the discussion (examples given below in the specific comments), and I wonder why CrIS hyperspectral radiance data (in addition to its T and WV profiles, and skin T) is not examined together with the broad TIR channels of GOES and MODIS. That would show pretty nicely (at least it does in the IASI data I have looked at) how the TIR radiance is "flatly reduced" by about 25K for smoky observations, while the (low intensity) gas absorption lines are not toomuch affected. Such a flat reduction of atmospheric window TIR "baseline" BT directly points to a (skin) surface temperature reduction or a thin cloud (aerosols usually have specific signatures with slopes and/or different impacts on radiance at about 9 and 11µm - see for example Clarisse et al DOI 10.1364/AO.49.003713). The trick, I think, in this case, is to ensure that the observed lower BT is due to lower surface temperature and not to thin (water) clouds (ice clouds would have a typical TIR signature which is not observed). This is where combining the TIR with SWIR and visible observations comes in.

Comment: suggestion: mention the episode name in the paper title - it was important enough to even have a wikipedia page ;)

Response: Thank you for the suggestion. While we did consider including “Dixie Fire” in the paper title prior to submission, we chose to leave the title as “western US biomass burning aerosol plume” since we found that this behavior can be seen in many other cases of large wildfires from the western US.

Comment: lines 23-25: this sentence is rather unclear to me. I guess the authors means the very thick optical depth at visible wavelength? I am also very puzzled as to how a BT change in TIR could be mapped to a smoke signal, especially since the authors highlight that the smoke signal is due to surface cooling - I mean how would the difference be done between smoke and any other surface cooling reason, such as a cloud?

Response: Thank you for the question. That is correct: we mean the very thick visible optical depth. Traditional passive-based aerosol-retrieving algorithms struggle in very high-AOD situations (due to the misclassification of thick smoke plumes as clouds), but we hypothesize that if the strength of the surface cooling caused by the smoke-induced surface shadowing is a function of the visible optical depth of the smoke plume, it may be possible to retrieve AOD information from the surface cooling in those regions where the current algorithms struggle. Significant amounts of work would indeed be required to quantitatively make that connection and remove uncertainties (including screening out impacts from cloud and background meteorological changes), but the focus of this paper is to show that a significant TIR cooling signal from dense smoke plumes can be observed from multiple satellite platforms and the signal can be traced to surface cooling beneath the smoke.

Comment: lines 36-39: in addition to the scattering, the aerosol absorption plays a role in the TIR (usually a dominant role) and this can happen no matter the particle size - of course the particle number concentration needs to be higher for smaller particles to have an observable signal, and the particles need to be absorptive in the TIR

Response: Smoke aerosols are typically transparent at the IR spectrum from satellite observations, indicating the aerosol optical depth of smoke aerosols (including absorbing optical depth) is small at the TIR spectrum. Also, we would observe smoke TIR signals at night if aerosol absorption plays a significant role at the TIR spectrum. However, smoke aerosol signals are much less observable at night than during daylight hours. Thus, we expect the impact of smoke aerosol absorption at TIR spectrum to be marginal. Still, it is an interesting topic to explore and we leave this topic for a future study.

Comment: section 2: I suggest to re-define all acronyms within each sub-section here - but this is just a suggestion and may also be left to the editorial staff

Response: Thank you for the suggestion. We choose to leave this to the editorial staff to make the decision.

Comment: line 128: CONUS domain?

Response: Thank you for the note. We have added a definition for the CONUS acronym (contiguous United States).

Comment: line 133: 12Z and 03Z?

Response: Thank you for the comment. “12Z” and “03Z” refer to “12 Zulu” and “03 Zulu”, respectively, with “Zulu” being a common way to refer to UTC time. We replaced “Z” with “UTC” for clarity.

Comment: section 2.4 considering that the observations by CrIS are affected by the smoke, and that this is not accounted for in the CrIS retrieval algorithm (at least I would guess it is not), how confident may we be in the retrieved surface and atmospheric temperature and atmospheric humidity for the smoky observations?

Response: Thank you for the question. The reviewer's question is an important one which requires further study to support the answer provided here. The answer provided here is based on the data provided in this study and the published results of an independent study (Zhou et al., 2021). The conclusion from the independent study is based on airborne (NASA ER-2) hyperspectral radiance measurements, like those obtained with the satellite CrIS instrument, and co-located LIDAR data obtained during the FIREX-AQ field campaign conducted over the western US during August 2019.

A. Conclusions Based on the Dixie Fire Study:

The analysis of MODIS 2.1 reflectance and GOES-17 TIR (indicate significant thermal cooling below regions of relatively high NIR (2.25 micron) reflectance of the smoke plume. However, much of his TR cooling is believed to be due to the smoke induced reflectance shading of the atmosphere and surface beneath the plume. As shown in figure 1 below, the thermodynamic retrievals obtained from the CrIS radiance spectra (Smith et. al., 2012), provide consistent differences with the independent Rapid Refresh (RAP) 2-hour forecast atmospheric profiles, within (blue lines) and outside (orange and green lines) the smoke plume. These results indicate that the satellite retrievals (see figure 1 below) within the smoke plume are not being affected significantly by smoke particles. It is noteworthy that the retrieved cooling within the boundary layer near the surface, due to the plume sunlight reflection, is not captured by the RAP forecast, which apparently has not accounted for the Dixie Fire smoke plume in the model forecast.

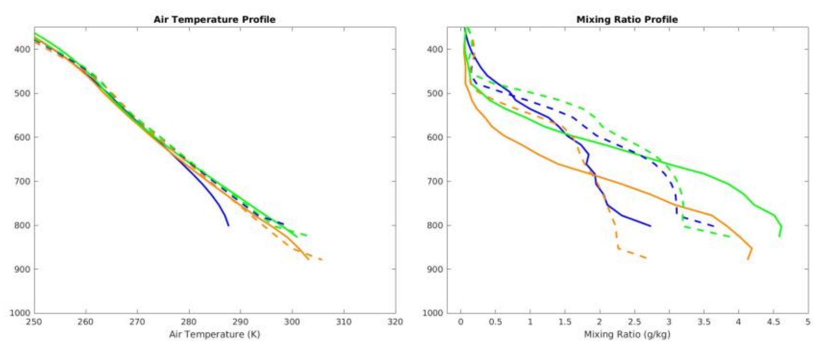

Figure 1. Retrieval Vs RAP 2-hr Forecast for the orange, blue, and green locations shown in Figure 3 of the manuscript. The retrieval values are denoted by the solid lines whereas the RAP forecast values are denoted by the dashed lines.

Also, the retrieved near-surface air temperature (295.4 K) and surface skin temperature (308.2K) shown in figure 2 below is consistent with the 2-m surface temperature of 23C (296.2 C) observed under the Dixie fire plume at station O05, as shown in figure 6 of the manuscript. Note that the surface skin temperature retrieved at this point is about 10 K warmer than the nearby-observed (O05) and retrieved near- surface air temperatures.

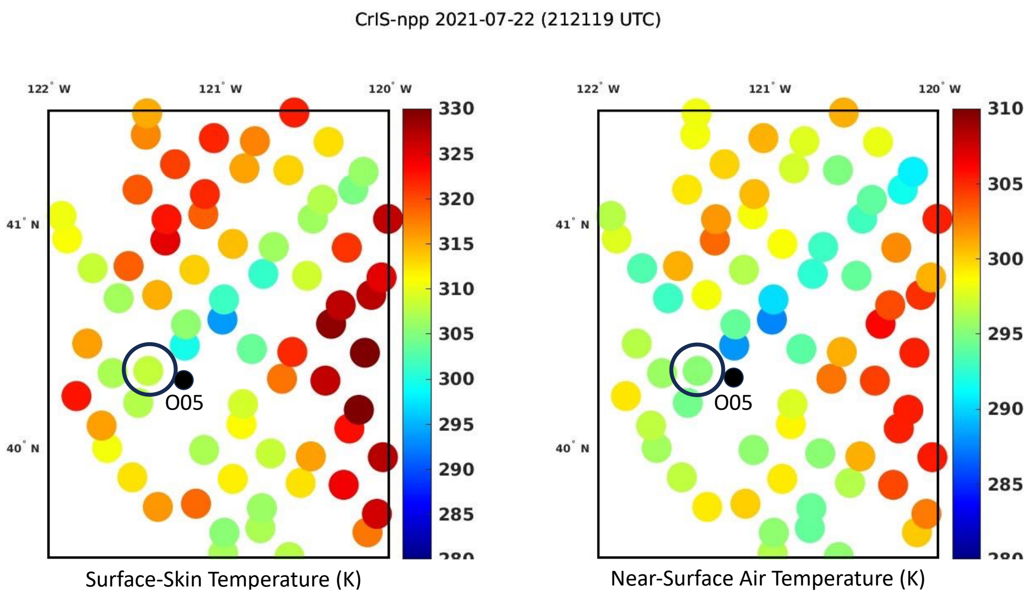

Figure 2. Surface-Skin and Near-surface Air Temperature retrieved from CrIS cloud-free radiance observations. The circled values are for the retrievals closest to the Roger's Field, Chester California, 2-m surface observation location. Note that the near-surface air temperature is the temperature profile retrieval value at the lowest profile level above the surface.

Considering that the retrieved profile discrepancies with RAP forecast profiles do not show any systematic dependence on the retrieval location relative to the smoke plume and that the retrieved near-surface air temperature under the smoke plume is in relatively good agreement with the observed 2-m surface air temperature, the retrieved surface-skin temperature being considerably warmer, it is concluded that the smoke particles have little radiance attenuation impact on the profile retrievals in this case.

B. Conclusions Based on FIREX-AQ Airborne Retrieval and LIDAR Fire Observations:

Results of an independent study (Zhou et al., 2021) utilizing airborne hyperspectral radiance measurements (NAST-I), which are like the radiance measurements with the satellite CrIS instrument, and co-located LIDAR (CPL) data, obtained during the August 2019 FIREX-AQ airborne campaign, support the conclusion stated above. In this reference paper, it is shown that the retrieval of the atmospheric humidity profile has little unexpected dependence on the density of smoke particles observed by the LIDAR and that the retrieved CO concentration profile coincides with the smoke plume particle density as expected (figure 8 of the reference). Most important, the retrieved CO retrieved values are in relatively good agreement with in-situ observations (figure 7 of the reference). Thus, this study supports the conclusion drawn in section A above, that hyperspectral infrared retrievals of humidity and trace gas profiles are not influenced significantly by smoke particle attenuation of the observed upwelling spectral radiance.

References:

Zhou DK, Larar AM, Liu X, Noe AM, Diskin GS, Soja AJ, Arnold GT, McGill MJ. Wildfire-Induced CO Plume Observations From NAST-I During the FIREX-AQ Field Campaign. IEEE J Sel Top Appl Earth Obs Remote Sens. 2021; 14:2901-2910. doi: 10.1109/jstars.2021.3059855.

Smith., W. L., E. Weisz, S. V. Kireev, D. K. Zhou, Z. Li, and E. E. Borbas (2012), Dual-Regression Retrieval Algorithm for Real-Time Processing of Satellite Ultraspectral Radiances, J. Appl. Meteor. Climat., 51, 1455-1476, doi:10.1175/JAMC-D-11-0173.1.

Comment: section 3.1: I would appreciate here some introduction about the expected effect of the studied phenomena (coarse / giant particles, pyrocumulus) on the radiance in the different channels used in this work; that would allow the reader to follow the developments and understand the conclusions more easily

Response: Thank you for the suggestion. We have added discussion to explain the expected impacts of the large particles on the observed radiances and reflectances.

Comment: figure 2: what are the Z after the hours? (as line 133)? Is this local time, or UTC, or other?

Response: Thank you for the question. As mentioned above, “Z” refers to “Zulu” time, which is a common way of referring to “UTC” time. Nevertheless, we have replaced the “Z” in the figure with “UTC” for clarity.

Comment: section 3.2: Again here I would appreciate an introduction about the signatures of gases in the TIR atmospheric window, especially the fact that they are rather small; maybe using cross-sections also. Within the GOES 10.35µm and MODIS 11µm channels, one would indeed find some weak WV absorption bands, some very weak CO2 absorption, relatively intense O3 absorption, possibly NH3 absorption if some is present but no N2O or CH4 absorption (no band in those channels). Because in that spectral range gas absorption is rather low, no increase within physical range of any of those gases would lead to 25K BT reduction at 11µm. This is also the conclusion that the authors reach after experimentally testing that hypothesis, and the proposed approach is also important and interesting but I think that the physical base should be discussed as a complement.

Response: Thank you for the suggestion. We have added discussion to section 3.2 to describe the absorption lines of each of the gas constituents in the TIR spectrum.

Comment: lines 295-298: could you elaborate on what might be the reason for this difference? Would this be a sign that the CrIS "smoky" profiles are not "close to reality" because the smoke impacts the observation and this is not accounted for in the retrieval?

Response: Thank you for the question. There are many potential reasons for these differences, including uncertainties in the CrIS retrievals, but also from the simplistic nature of the SBDART simulations. In these simulations, we check only if the temperature and water vapor profiles in the smoke plume region are responsible for the observed TIR cooling signal, so we lack information about other gas species that could affect the water vapor channel signals. Additionally, we do not include any aerosol information in the SBDART simulations, which could also impact the comparison between the simulated and observed values. Thus, while there are several possible explanations for these differences, we cannot definitively state why the differences exist.

Comment: figure 4 (j): where is the orange line? I would guess exactly behind the green but I would mention it in the legend, or redo the plot with e.g. different line widths so that the line can be seen.

Response: Thank you for the note. We have widened the orange lines to make them more visible when they lie directly beneath the green lines.

Comment: section 3.3: again a bit of physical basis here would be useful, I think. The expected BT in channels around 11µm, in absence of clouds / aerosols (and at relatively low viewing angles), would be slightly lower than the surface skin temperature (unless looking above a surface with low emissivity, of course). This is indeed what the radiative transfer shows when using either the CrIS skin T from "clear" or "smoky" cases (but was this CrIS skin T "right" for the smoky pixel?). One question that remains non-addressed in this section would be if it is reasonable that the surface (skin T) would cool by 25K in a short time if under a thick smoke plume. I guess this could be done by looking at other days (without smoke) BT daily cycles and how much night BT differs from day BT under relatively similar circumstances (except the smoke), and how long the surface takes for cooling after sunset, for example.

Response: Thank you for the comment. We do not feel that comparing the diurnal temperature variation of the same area under a clear-sky case to the cooling in the smoky case would be valid, since on a clear-sky day the amount of incoming sunlight gradually decreases through sunset, but in this case there is a sudden “shutting off” of the incoming sunlight at the surface. In a way, this “control case” of clear-sky diurnal cooling speed can be seen from the blue dot in the figure, which is never under smoky or cloud conditions during the latter portions of the study day, so the timing of the gradual cooling can be seen there.

Comment: figure 5 (b): time is here given in local time while I think almost everywhere it was UTC time. This should be consistent and my preference would be to have both UTC and local time on each plot (local is interesting to know which part of the day we are looking at, while UTC time is interesting if the reader wants to compare with any other data)

Response: Thank you for the suggestion. We have added UTC time as a second x axis on the top of the time series.

Comment: lines 382-383: again some physical explanation here would be nice - indeed the atmospheric temperature has only a second order impact on the observed BT, being through the atmospheric gases thermal emissions, which depend on their temperature and cross-section - the latter being rather low in the used channels

Response: Thank you for the comment. We have added discussion accordingly.

Comment: line 410 and following: I am not so sure one can say that there is no noticeable cooling in the plume area - the plume is widespread and there's some widespread "reddish" area in VIIRS 10.76µm that seems to match the grey area in VIIRS DNB. However this "feeling" might come mostly from the fact that a completely different BT scale is used for that plot with respect to the 2 "day" plots. I would strongly suggest using the same scale, or at least the same range of temperatures for the color scale (currently 70K for daytime and 20K for nighttime)

Response: Thank you for the comment. We initially used the same BT scale across all VIIRS 10.76 um plots, but the contrast was far too low in the nighttime plot to definitively say if there is any nighttime TIR cooling in the plume region (see the original version of the figure below, which uses the same color bar across all three 10.76 um BT plots). Thus, we chose to use a smaller BT scale for the nighttime imagery to enhance the contrast and make it easier to determine if the smoky region in the nighttime plots are warmer or cooler than the surroundings. The enhanced contrast also allows one to clearly identify surface features in the nighttime TIR imagery from beneath the smoke plume. If the smoke particles themselves were causing any nighttime TIR cooling signal, we would expect any surface features to become obscured by a uniform region of decreased temperatures; thus, since clear surface features are visible in the nighttime imagery, the smoke particles themselves are not causing TIR cooling at night.

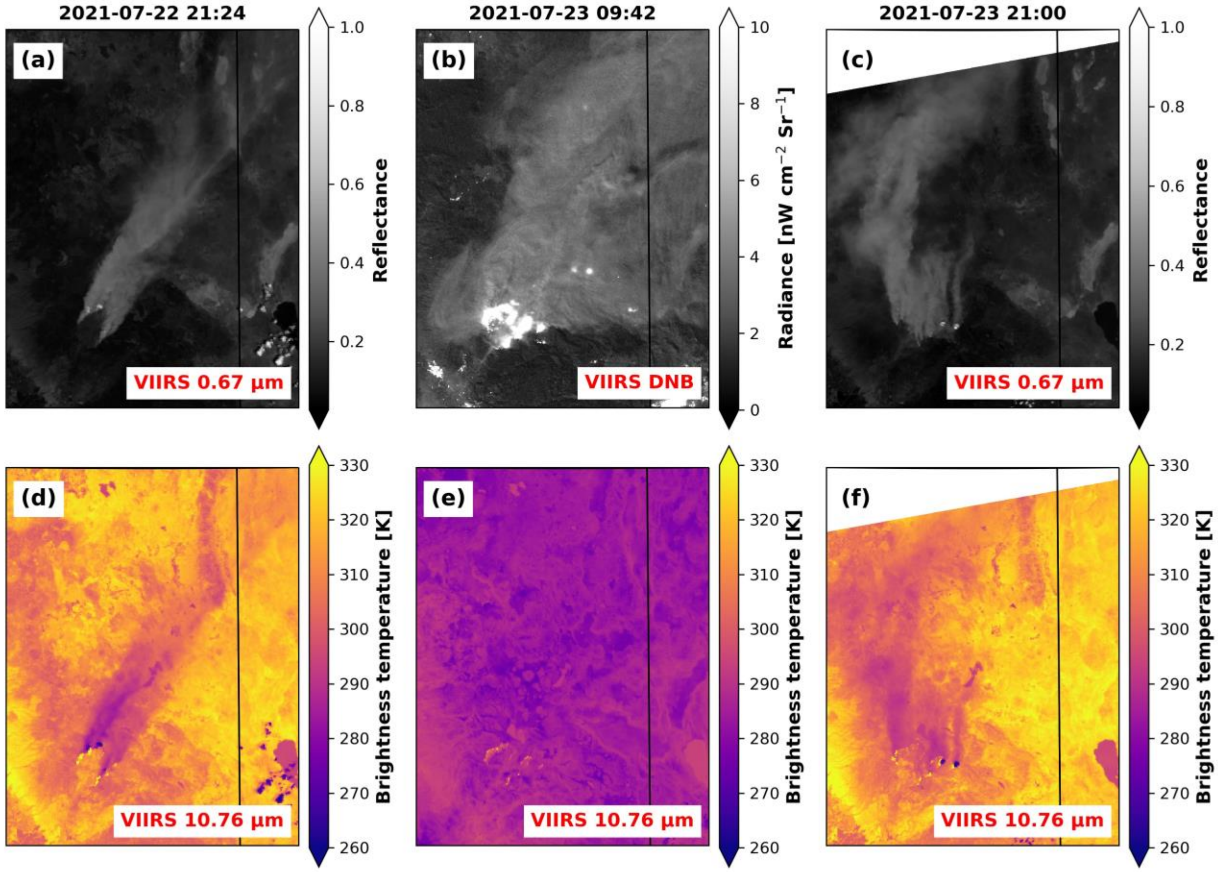

Figure 3. Suomi-NPP VIIRS visible (0.67 µm) reflectance from the 22 July 2021 21:24 UTC granule. (b) VIIRS day/night band (0.5 – 0.9 µm) radiance from the 23 July 2021 09:42 UTC granule. (c) VIIRS visible (0.67 µm) reflectance from the 23 July 2021 21:00 UTC granule. (d) VIIRS thermal infrared (10.76 µm) radiance from the 22 July 2021 21:24 UTC granule. (e) VIIRS thermal infrared (10.76 µm) radiance from the 23 July 2021 09:42 UTC granule. (f) VIIRS thermal infrared (10.76 µm) radiance from the 23 July 2021 21:00 UTC granule. This figure is the same as Figure 6 in the paper, but with the same colorbar range used for all three VIIRS thermal IR plots.

Comment: lines 434-436: is this also true at night?

Response: Thank you for the suggestion. We do not expect this relationship to hold at night, as Figure 6e shows that there is no distinguishable longwave cooling signal within the plume region compared to the nearby clear regions, and we anticipate that CERES LWF measurements will exhibit similar behavior to the TIR brightness temperatures (for example, see the similarities between the MODIS TIR brightness temperatures shown in Fig. 1f and the Aqua CERES LWF measurements shown in Fig. 1h). Nevertheless, we analyzed nighttime NOAA-20 CERES fluxes over the same region for the satellite's nighttime overpass on 2021-07-23 and found no distinguishable warming/cooling pattern in the plume region relative to the surrounding regions, which verifies that the longwave behavior exhibited during the daytime comparison does not hold at night.

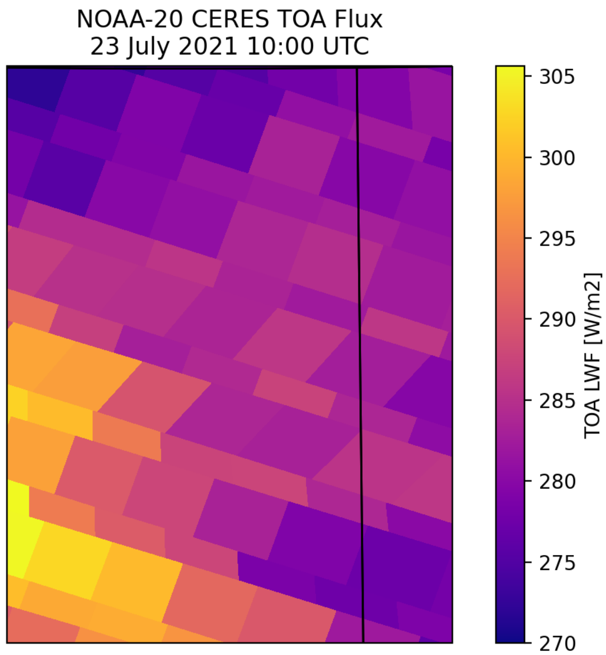

Figure 4. NOAA-20 CERES TOA LWF observations around the Dixie Fire at night, during the hour of 10:00 UTC 23 July 2021.

Comment: lines 439-441: those numbers are rather different from the numbers given lines 430-436: +80 -50 W/m2 do not compensate, while -2 and +1.9 W/m2K almost exactly compensate. Am I missing something? Or is this within error margin?

Response: Thank you for the question. The first numbers represent the general difference between the SWF/LWF values in the clear region versus the smoky region, while the second numbers represent the slope of the change in forcing with respect to brightness temperature (the slopes of the trend lines fitted in Figure 7). You are correct that the two slopes do indeed compensate, causing the slope of the trend line fitted to the summed SWF/LWF values in Figure 7c to be near zero, but the general total flux values in the smoky region are overall slightly larger than the total flux values in the clear region.

Comment: Figure 7a (and c to a smaller extent): I find it rather hard to really see the linear relationship in these clouds of points. In Figure B it is much more clear. Are you sure that a linear relationship is expected between the SW flux and the TOA LW 11µm BT?

Response: Thank you for the question. While there certainly are outliers in the clouds of points, partially due to limitations in the algorithm used to select the smoky MODIS pixels, we find that the linear relationship works well enough to reflect the behavior of the SWF within the smoky and clear regions, which can be seen in Figure 1. The biggest takeaway from the figure is that there is no real relationship between MODIS TIR brightness temperature and CERES total flux in the smoke plume region, while there are at least weak relationships between MODIS TIR brightness temperature and CERES SWF and LWF.

Comment: lines 455-457: this sentence is a bit too straightforward and maybe misleading. The characteristics of the plume can not be retrieved based on the TIR channels, at least this is not what the manuscript is about. Maybe the authors could say that plumes could be identified from the observed BT changes in the TIR, after additional work allows discriminating the reason for those BT changes (clouds, Ts changes, smoke).

Response: Thank you for the suggestion. We have modified the sentence to indicate that a possible avenue of future research is to expand this analysis to possible AOD retrieval, after much additional work is done to clean the signal.