Response to comment of Anonymous Referee #2 on “DARCLOS: a cloud shadow detection algorithm for TROPOMI” by Victor Trees et al.

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We thank the reviewer for his/her careful reading and for the comments and suggestions, which have improved the manuscript. Below, we give in *blue italic* the reviewer’s comment, in black our response, in *black italic* copied text from the manuscript and in *red italic* the changed or new text in the manuscript.

General Comments

The manuscript presents a scheme for the detection of cloud shadows in observations made by the spaceborne imaging spectrometer TROPOMI. The scheme is new in the sense that it is based on the measurements of a spectrometer (rather than on multi-spectral measurements from imagers). Undetected cloud shadows can cause significant biases in the TROPOMI L2 products. The flag produced by the scheme enables the analysis of such biases and the masking of affected observations and is therefore of interest to the remote sensing community. The description of the scheme is concise and clear up to a few items listed below. The testing and validation of the scheme with imager data is adequate to showcase the performance of the scheme and is well presented.

Specific Comments

1. *Novelty*

   It is reported that heritage cloud shadow detection algorithms often use a combination of geometric and spectral schemes. The new scheme described in the present manuscript follows this strategy and is not new in that sense. Please clarify, probably best in the introduction, in which sense(s) the new scheme is different from heritage schemes.

   DARCLOS exploits the spectral resolution of TROPOMI for computing the ACSF, as it uses the wavelength for shadow detection where the surface reflectance is strongest. For high spectrally varying reflectors, this means that DARCLOS can choose the wavelength in the spectrum (out of a large sets of wavelengths) where the most stable shadow detection is expected.

The spectral cloud shadow flag (SCSF) detects another type of shadow (see Sec. 5.2): the wavelength dependent shadow. The length of this shadow is not necessarily the same as the shadow observed by an imager. We found a wavelength dependence of shadow signature locations in the UV (see Fig. 12). We speculate that, because the gas scattering optical thickness decreases with λ^{-4}, at shorter wavelengths higher layers of the atmosphere are probed in which shadows may be geometrically shorter. With the SCSF, we obtain a shadow flag dedicated to specific UV wavelengths where air quality products are retrieved (e.g., 340 and 380 nm for the AAI, and 440 nm for NO_2). Such a cloud shadow detection at the precise wavelengths of the spectrometer's air quality products is unique for DARCLOS and cannot be done with data from an imager. We changed the following:

line 100: "*As TROPOMI is a spectrometer, DARCLOS exploits the spectral ranges of TROPOMI by searching in each pixel for the most optimal wavelength for shadow detection independent of surface classification. The spectral tests are only based on the darkness of shadows relative to the reference data. This means that no assumptions are made about the color of cloud shadows.*" –> "*The spectral tests are only based on the darkness of shadows relative to the reference data. This means that no assumptions are made about the color of cloud shadows. As TROPOMI is a spectrometer, DARCLOS exploits the spectra of TROPOMI by using the wavelength for shadow detection where the surface reflectance is strongest, independent of surface classification. We validate the PCSF and ACSF with true color images of Suomi NPP VIIRS which orbits in close constellation with TROPOMI. Because geometrical shadow extents may be wavelength dependent, DARCLOS also outputs a wavelength dependent cloud shadow flag for the wavelengths at which TROPOMI's air quality products are retrieved. Such a cloud shadow detection at the precise wavelengths of TROPOMI's air quality products is unique for DARCLOS and cannot be done with data from an imager.* "

We added the following paragraph to the conclusion:

"*At UV wavelengths, we have found cloud shadow signatures at different locations than determined with the ACSF, potentially indicating a wavelength dependence of cloud shadow extents. Because TROPOMI's air quality products are retrieved at specific wavelengths or wavelength ranges, DARCLOS also outputs the spectral cloud shadow flag (SCSF), which is a wavelength dependent alternative for the ACSF. Although the SCSF may not be retrieved at the wavelength where the most stable wavelength independent (visible) shadow detection is expected, it may be a better estimate of the cloud shadow locations at the specific UV wavelengths of interest. Such a cloud shadow detection at the precise wavelengths of TROPOMI's air quality products is unique for DARCLOS and cannot be done with data from an imager.*"

We adjusted the abstract as follows:

"*[...] DARCLOS raises potential cloud shadow flags (PCSFs), actual cloud shadow flags (ACSFs) and spectral cloud shadow flags (SCSFs). The PCSFs indicate the TROPOMI ground pixels that are potentially affected by cloud shadows based on a geometric consideration with safety margins. The ACSFs are a refinement of the PCSFs using spectral reflectance information of the PCSF pixels, and identify the TROPOMI ground pixels that are confidently affected by cloud shadows. Because we find indications of the wavelength dependence of cloud shadow extents in the UV, the SCSF is a wavelength dependent alternative for the ACSF at the wavelengths of TROPOMI's air quality retrievals. We* *validate the PCSF and ACSF with true color images made by the VIIRS instrument on board of Suomi NPP orbiting in close constellation with TROPOMI on board of Sentinel 5-P. We find that the cloud evolution during the overpass time difference of TROPOMI and VIIRS complicates this validation strategy, implicating that an alternative cloud shadow detection approach using colocated VIIRS data would be inaccurate.We conclude that the PCSF can be used to exclude cloud shadow contamination from TROPOMI data, while the ACSF and SCSF can be used to select pixels for the scientific analysis of cloud shadow effects.*"

To the summary diagram (Figure 1), we added "*Spectral cloud shadow flag (SCSF)*" to the last grey box.

We added to the introduction of the Method section:

line 114: "*The spectral cloud shadow flag (SCSF) is a wavelength dependent alternative for the ACSF and will be explained in Sect. 5.*"

2. *Strategy*

While it is stated that the scheme is the first one that works on spectrometer measurements (rather than on multi-spectral measurements from imagers), it does not exploit the high spectral resolution capability of the spectrometer. For TROPOMI observations, co-located VIIRS imager data are available with observation time differences of a few minutes. Therefore is seems valid to consider an alternative approach applying a performant cloud shadow detection algorithm to VIIRS data. Please discuss the benefits (eg availability of additional TIR information, better spatial resolution, wrt TROPOMI) and drawbacks (eg changes in clouds within the observation time difference (now discussed in the context of validation), dependence on another sensor and processing chain) of this alternative approach.

DARCLOS does exploit the spectral resolution capability of TROPOMI for computing the ACSF and SCSF, as explained in the answer to previous comment. The spatial size of cloud shadows in TROPOMI data is 1 or several TROPOMI pixels. In the Validation Section, it was explained that clouds can change shape, appear, disappear and can shift at least 1 TROPOMI pixel during the VIIRS-TROPOMI measurement time difference interval for high clouds (and cloud shadows are particularly detectable from space when clouds are high). That is, the possible spatial error due to the cloud evolution is of the same order of magnitude as the spatial accuracy needed for shadow detection. Therefore, we find it fundamentally not accurate to use VIIRS measurements for shadow detection in TROPOMI data. This point was raised in the footnote on page 19.

We added to the abstract:

"*We find that the cloud evolution during the overpass time difference between TROPOMI and VIIRS complicates this validation strategy, implicating that an alternative cloud shadow detection approach using co-located VIIRS observations could be problematic.*"

3. *Performance*

The performance is reported in terms of omission and commission errors and a derived score without reference to the performance of other cloud shadow flags. Please discuss the performance also in the context of the comparable products, as far as such performance data is available.

We added the following paragraph to the Validation section:

In order to put the validation results in perspective, we note that the state-of-the art imager cloud and cloud shadow detection code Fmask version 4.0 (Qiu et al., 2019) reports shadow detection commission errors of 0.49 for Landsat 4-7 and 0.38 for Landsat 8, and omission errors of 0.27 for Landsat 4-7 and 0.31 for Landsat 8. Using multi-temporal reference images of specific regions, Candra et al. (2019) achieved omission and commission errors ranging from 0.001 to 0.084 and 0 to 0.058, respectively, depending on the region. The PCSF omission errors and ACSF commission errors in Table 1 are lower than those of Fmask 4.0, and are of the same order of magnitude as those achieved by Candra et al. (2019). Of course, because of the much higher spatial resolution of Landsat than that of TROPOMI, the error values for Landsat actually refer to a much larger number of pixels.

Technical corrections

The processing flow chart (Figure 1) is inaccurate. Please distinguish data and processing steps clearly; Identify input data and output data, per processing step; Identify which parameters is passed on from one processing step to the next; distinguish climatological input from dynamic input from TROPOMI observations.

Figure 1 is supposed to give a summary of the input and output data of DARCLOS. For readers that do not go through the technical details of the paper, Figure 1 is still readable as is. We incorrectly named Figure 1 'flow diagram'. A more suitable name would be 'summary of inputs and outputs'. We changed the following:

caption of Figure 1: "*Flowchart of the algorithm.*" –> "*Summary of the inputs and outputs of DARCLOS.*"

line 109: "*The flowchart in Fig. 1 summarizes the algorithm setup and serves as a road map for this section.*" –> "*Figure 1 summarizes the inputs and outputs of DARCLOS.*"

In the introduction (Section 2.2, line 194) it is stated that the actual cloud shadow flag (ACSF) is raised "based on the darkness of the shadowed pixels with respect to non-shadowed pixels", which suggests that multiple pixels in a field of regard are evaluated, for each pixel. In contrast, according to Section 2.2.3, the ACSF is raised based on radiometric criteria for each pixel independently. Please clarify and align.

We thank the reviewer for pointing out this confusing formulation. The ACSF is indeed raised based on radiometric thresholds. We found it most clear for the reader to shorten this paragraph, since this level of detail is not necessary in this introductory part of the Section:

line 192: "*Then, we compare this corrected reflectance to the expected surface reflectance from climatological observations by TROPOMI, revealing the actual shadowed pixels. The ACSF determination is based on the darkness of the shadowed pixels with respect to non-shadowed pixels, which is most apparent at the wavelength where the surface reflectance is strongest.*" –> "*Then,* *we compare the corrected reflectance to the expected surface reflectance from climatological observations by TROPOMI, revealing the actual shadowed pixels. This comparison is done at the wavelength where the surface reflectance is strongest.*"

References

Candra, D. S., Phinn, S., and Scarth, P.: Automated Cloud and Cloud-Shadow Masking for Landsat 8 Using Multitemporal Images in a Variety of Environments, Remote Sensing, 11, 2060, https://doi.org/10.3390/rs11172060, 2019.

Qiu, S., Zhu, Z., and He, B.: Fmask 4.0: Improved cloud and cloud shadow detection in Landsats 4-8 and Sentinel-2 imagery, Remote Sensing of Environment, 231, 111 205, https://doi.org/10.1016/j.rse.2019.05.024, 2019.