General comment from the reviewer

“This paper addresses the long standing (and still of paramount importance) topic of convective cloud formation/development and the surrounding water vapour (WV) conditions that lead to it.

The problem of WV retrieval above clouds, although attempted in the literature (as mentioned by the authors), remains very appealing and very topical nowadays, because no systematic/operational retrieval exists at the moment in Meteorological agencies. The dedicated WV imager on the C3IL mission will cover this gap, allowing a 3-year long coverage.

The problem of WV retrieval above clouds is successfully addressed by proposing an optimal estimation approach, using SWIR imaging measurements in 3 relevant channels (covering the spectral range from ~1 to 1.3μm) in and off the water vapour absorption band and taking into account the relevant factors affecting (together with the water vapour profile) the observed radiances in these channels, i.e., the surface properties such as albedo and the cloud optical thickness (COT) and height).

The retrieval approach is motivated based on previous works conducted with POLDER and MERIS data and demonstrated using appropriate simulated data, and test retrieval using both idealized and realistic atmospheric profiles. The results are convincing (i.e., the proposed algorithm is clearly sensitive to the water vapour amount above clouds, and its quantification is reliable within well motivated uncertainty (i.e. impact of realistic cloud profiles, of high COT, of low WV content, etc.).

Although demonstrated on simulated data only, the method opens interesting perspectives for the 3-year limited C3IL mission, and maybe for possible longer future satellite missions equipped with the same channels as the C3IL/WV imager.

All this considered, I have no doubt in recommending the publication of this paper after minor revision. In the attached PDF, I added all my comments to the text. Most of them are typos corrections or request for clarifications (e.g., clarify in abstract/conclusion that the proposed algorithm is demonstrated only over ocean and excludes latitudes higher the ±60 deg). However, I also added suggestions and comments that in my opinion may further improve the quality of this work (e.g., future work using real profiles and 3D cloud reconstruction from EarthCARE). The authors shall go through them, providing feedback where required.”

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Dear Loredana Spezzi,

Thanks for your comments and the suggestions provided. In the revised manuscript, all the typos and suggested reformulations are accounted for. We have listed your comments that need an answer below (in red), explain, when necessary, how we have addressed each point in the revised manuscript, and provided new sentences (in green).

Comment on page 1 (old file):

"Please clearly state here that the retrieval proposed in this paper is demonstrated only over ocean and excludes latitudes higher the ± 60 deg."

New sentence (new file, page.1 lines.1-3):

"A retrieval algorithm of integrated water vapor content above cloud, using shortwave infrared observations, is developed and evaluated through idealized and realistic atmospheric profiles, with its application currently limited to oceanic regions and latitudes within ± 60 degrees."

Comment on page 2 (old file):

Do you mean "depending on the temperature"?

Yes, we'd like to say that at a given temperature, saturation is reached. We modify this sentence. New sentence (new file, page.2 lines.39-40):

"Indeed, at a given temperature, saturation is reached when the water vapor partial pressure equals the saturation vapor pressure."

Comment on page 4 (old file):

"Please specify that the C3IEL mission is still under development, launch is expected in 2027 and the duration is at least 3 years according to WMO OSCAR, see https://space.oscar.wmo.int/satellites/view/c3iel_b"

This is now clearly stated with an update of the expected launch date by adding this sentence (new file, page.4 lines.95-97):

"*The mission is under development and is scheduled to be launched at the end of 2028, with a minimum expected duration of two years that could be extended to three years.*"

Comment on page 5 (old file):

"Please clarify here in the caption or in the text why these tophat rectangular filters are shown and used for the sensitivity study. Are the filters SRFs not yet defined?"

Indeed, at the time of this study and still now, the SRFs are not yet defined. Consequently, the choice was made to use rectangular spectral response function. We add this information in the caption (new file, page.5 Figure 2. caption):

"Note that rectangular spectral response functions are used, as the actual SRF are not known."

Comment on page 7 (old file):

"This is just a suggestion for improvement. Instead of assuming a constant surface albedo over ocean, it could be easily calculated case by case (i.e. for the location and profiles shown in Figure 5) using the ECMWF wind speed and the Cox and Muck 1954 approach."

Thank you for your good suggestion. We've added a paragraph in the conclusion and perspective section regarding the account for more realistic surface albedo in the next version of the algorithm. New paragraph (new file, page.21 lines.423-426):

"*This first version of the algorithm is currently over ocean with a constant surface albedo. In future versions, more realistic surfaces could be implemented using wind speed and the Cox and Munk (1954a, b) model above ocean, and surface albedo above continents coming from ancillary data such as ECMWF-IFS data for wind speed and MODIS or Sentinel-2 products for surface albedo values.*"

Comment on page 8 (old file):

"I could not find in the text the assumed the first guess values for COT and IWV_ac. Can you please specify them? Are they the same in all test retrievals?"

You are right, we missed to indicate these values here. We've added this sentence (new file, page.8 lines.188-190):

"*For the COT, the first guess value is 10 and for the IWV_AC, the first guess value is calculated by integrating the SAS (Sub-Arctic Summer) water vapor profile from the cloud top altitude up to 20 km.*"

Comment on page 9 (old file):

"Are the radiance measurements expected from the C2IL/WV image precise enough to appreciate this small differences? In the state vector "x" you have both COT and IWV_AC, and you are assuming an uncertainty of 5% in the measurement vector Y (see Sect. 3.1). Is this enough to allow the retrieval to distinguish among the COT in curves? Please clarify both points in the text."

The C3IEL WV imagers should provide radiance data with an accuracy better than 5% (random error at 1 sigma). This is why we consider an uncertainty of 5% in the measurement vector Y. Figure 3 are sensitivity curves and corresponds to simulations without accounting for the measurement error. So, you are right, it is not obvious that the random error on the measurement, linked to instrument precision, allows to distinguish among the COT in curves. To consider the limited accuracy of the measurements, we realized the retrieval described in section 5, and which consider the measurement noise (through 5% uncertainty on measurement vector). Results regarding the ability to measure COT despite the noise measurement are given in lines 238 to 241 (new file, page.10) and show that 5% accuracy is enough. We made the following changes in the text (new file, page.6 lines.141-143):

"Measurement vector data are associated with an uncertainty of 5%. This value corresponds to the requirement on the accuracy of the radiance measured by the instrument (random error at 1 sigma), corresponding to random noise."

We also rephrased and completed this sentence (new file, page.10 lines.217-221):

"*The differences between the curves indicate a sensitivity of the two absorbing spectral bands to the 1D equivalent COT. This value is obtained using the information contained in the non-absorbing band centered at 1.04 µm. The*

hypothesis of a 1D homogeneous cloud assumption with a uniform extinction vertical profile is used and leads to errors in the IWC_AC retrieval as it will be discussed in section 5.2.4."

We also completed the analysis of the results, section 5.1, by adding the following paragraph (new file, pages.10-11 Lines.241-246):

"When COT is correctly retrieved, the in-cloud extinction profiles are identical in the simulated observations and in the model used for the retrieval. The differences in IWV_AC are thus explained mainly by the differences of in-cloud water vapor profiles. For optically thick clouds COT is systematically underestimated leading to an underestimation of the in-cloud extinction coefficient. Although radiation penetrates less in optically thick clouds, the underestimation of the COT leads to more radiation interaction with in-cloud water vapor at the top of the cloud in the retrieval algorithm than in reality."

Comment on page 10 (old file):

"Moreover, please note that your nonabsorbing channel centered at 1.04 µm is not one the standard ones used to retrieve the COT (normally 0.6 or 0.8 microns are used), so you may consider adding a figure showing the relationship between the 1.04 µm non-absorbing channel and COT."

Our first idea was to not put this plot in the paper as it is similar to the well-known one with visible channels. However, following your suggestion, we add it as a third subplot in Figure 3, modify the title of section 4, adjust the introductory paragraph of this section, and add a sentence to comment on the new subplot.

New section 4 title (new file, page.8 line.199):

"*Sensitivity of the three spectral bands to COT and IWV_AC"*

Adjustment of the introductory paragraph (new file, page.8 lines.200-201):

"*In this section, we examine how the radiances simulated in the non-absorbing band (1.04 µm) and in the water vapor spectral bands (1.13 and 1.37 µm) vary with COT (figure 3a) and IWV_AC (figures 3b and 3c)."*

New Figure 3 caption (new file, page.9 Figure 3. caption):

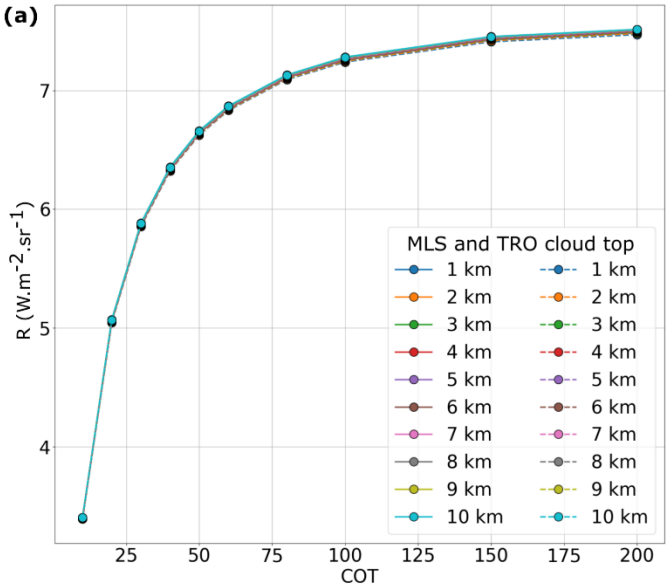
"*Simulated radiances of the C3IEL 1.04 µm band as a function of the COT (a), of the 1.13 µm band (b) and 1.37 µm band (c) as a function of IW VAC for two atmospheric*

profiles from the AFGL database (Mid-Latitude Summer and Tropical profiles), for several cloud top heights (Zt = 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 km), and various COT ranging from 10 to 200."

Added sentence (new file, pages.8-9 lines.206-209):

"*Figure 3a shows the relationship between the radiance of the non-absorbing band according to the COT for two atmospheric profiles under the 1D cloud homogeneous assumption. The relation is monotonically increasing and non-depending on the water vapor absorption as excepted from the transmission curve shown in Figure 1. This band is thus necessary and useful to obtain information on the COT.*"

Subplot added to Figure 3 (new file, page. 9 new subplot a):



"I would say that the 3 channels method is better behaved, because the error increases almost monotonically with the WV. When using the 2 channels approach, the error behavior is ok until 5 kg/m2 but the flattens between 5-10 kg/m2 and above."

New sentence (new file, page.11 lines.250-253):

"*While both the 2-channel and 3-channel retrieval approaches show an increase in absolute error (IWV_AC retrieved minus IWV_AC target) with increasing water vapor content and decreasing COT, the 3-channel method exhibits a more consistent, nearly monotonic error growth with water vapor. In contrast, the 2-channel method*

performs reasonably well up to 5 kg.m−2, but the error tends to flatten between 5–10 kg.m−2 and beyond.”

Comment on page 11 (old file):

“It is clear to me why you concentrate over ocean given the complex behavior of the albedo over land and especially high contribution over snow/ice covered surfaces (which indeed you encounter especially at high latitudes). However, C3IL is on a polar orbit, so it observed high latitudes and polar areas. Thus, I think you should give in the text these explanations/motivations that lead you to exclude land and high latitudes.”

Indeed, for simplicity, this first version of the algorithm was only developed for cloudy scenes over ocean but extension to scene over land is planned for the future. Concerning the observation at high latitudes, no sequence of acquisitions will be programmed first because the stereo-restitution algorithm for the CLOUD imager is excepted not to work well with low solar incidence and, also because convective clouds in development stage, not numerous at high latitude, are the main targets of the C^{3}IEL mission. We have rephrased the first sentence of section 5.2.1 (new file, page.13 lines.292-296):

“We restrict our analysis to profiles with clouds over the ocean to minimize surface effects (e.g., land, ice, snow), since the developed algorithm does not currently account for the underlying surface. Profiles at latitudes higher than 60° N/S are also excluded, since the C^{3}IEL mission will not observe at these latitudes because the stereo-restitution algorithm for the CLOUD imager (e.g., Dandini et al., 2022) is expected not to work well with low solar incidence, and also because convective clouds in development stage, not numerous at high latitude, are the main targets of the C3IEL mission.”

Moreover, we added this information to the conclusion section as mentioned above (new file, page.21 lines.423-426). Then, we added complementary information in section 2 (new file, page.4 lines.99-100):

“*Indeed, the satellites will rotate to track the same scene for 200 seconds and capture a sequence of 11 acquisitions of two simultaneous observations.”*

And (new file, page.4 lines.102-106):

"The viewing angles for each satellite will be approximately ±50°, -42°, -32°, -20°, and -7° on each side of the observed scene. Additionally, the first satellite will include a -55° angle, while the second satellite will include a +55° angle. Between each sequence of acquisitions, the satellites will have to return to their initial attitude, which implies a limited number of 4 sequences per orbit. The latitudes of these observation sequences will be chosen according to climatology of convective clouds."

Comment on page 12 (old file):

"What do you mean by "initially"? Did you then try with more mid-high profiles? I would say it is better to try again with realist profiles rather than artificially modified."

The ECMWF-IFS database doesn't have many profiles with cloud top at intermediate levels. For test purposes, we add artificially to the database these intermediate clouds by decreasing the cloud top value of high cloud by 4km. We agree with your comment on the use of more realistic profiles, which will be the subject of future developments and improvements as stated in the conclusion (new file, page.21 lines.429-431):

"Once the definition of the vertical profile in the algorithm has been improved, one way to test it with realistic convective cloud profiles could be to use LES simulations or the EarthCARE reconstruction (Barker et al., 2011)"

Comment on page 17 (old file):

"Same as in the abstract, please remind here to the reader that the algorithm is proven over ocean only and high latitudes are excluded."

We added the following sentence in the conclusion section (new file, page.20 lines.396-398):

"*tested above ocean surfaces to minimize the effect of the surface, and it excluded high latitudes, above 60° N/S as the C^{3}IEL instruments will not acquire measurements at these latitudes.*"

Comment on page 18 (old file):

I think it is worth to mention that the proposed algorithm can be possibly proven using realistic profiles from EarthCARE. Of course this would required extra simulation of C3IL/WV imaging measurements matching the date/time of EarthCARE observations. EarthCARE offers also a 3D cloud-reconstruction product that should be available by end 2025

(https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/qj.824).

Thank you for your comment, indeed EarthCARE is a very good candidate to evaluate the algorithm and the upcoming improvements. We added this sentence in the perspective section (new file, page.21 lines.429-431):

"*Once the definition of the vertical profile in the algorithm has been improved, one way to test it with realistic profiles of convective cloud can be to use LES simulations or the EarthCARE reconstruction (Barker et al. 2011).*

"Will the cloud height vary so much in 20 sec? Maybe in certain condition of high wind speed and vorticity, but not in all conditions."

C3IEL is dedicated to convective clouds during their development stage (before the anvil formation) with one of the main objectives being to retrieve the cloud vertical development we expect (and hope) that the cloud top altitude will vary sufficiently between two acquisitions. LES simulations used to develop the CLOUD algorithm (Dandini et al. 2022) show cloud top altitude increase of 3-5 m/s which leads to 60-100 meters in 20s and 600 to 1000 meters in 200s. We have reformulated it in the perspective section and added the reference below (new file, page.22 lines.439-441):

"However, using acquisitions spaced 20s apart requires the development of a more complex algorithm, as the retrieved cloud top height is expected to vary sufficiently between two successive acquisitions (e.g., Dandini et al., 2022)."

New references (new file, page 24):

Barker HW, Jerg MP, Wehr T, Kato S, Donovan DP, Hogan RJ. 2011. A 3D cloud-construction algorithm for the EarthCARE satellite mission. Q. J. R. Meteorol. Soc. 137: 1042–1058. DOI:10.1002/qj.824

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Dandini, P., Cornet, C., Binet, R., Fenouil, L., Holodovsky, V., Y. Schechner, Y., Ricard, D., and Rosenfeld, D.: 3D cloud envelope and cloud development velocity from simulated CLOUD (C3IEL) stereo images, Atmos. Meas. Tech., 15, 6221–6242, https://doi.org/10.5194/amt-15-6221-2022, 2022.