ESA Cloud_cci

Validation Report for MODIS multi-layer clouds

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Purpose

This document reports the evaluation results for the Climate Research Demonstrator Dataset for Validation Report for MODIS multi-layer clouds (CRDD-MLEV, D-1.11). This report (RMLEV) is deliverable for the final options milestone (CCN-1).

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1. Introduction

Most cloud climate records from passive remote sensing instruments currently assume a single later cloud model when performing retrievals e.g. CM-SAF (Karlsson et al., 2017), Patmos-X (Heidinger et al., 2014), MODIS C6 (Platnick et al., 2017), Cloud_cci v2.0 (Stengel et al., 2017). In reality much of the globe is covered by multiple layers of cloud and this assumption results in biases in retrieval cloud parameters, particularly when the upper layer is thin. In a recent paper by (Subrahmanyam et al. 2017), analysing Cloudsat-Calipso observation from 2010-2017, on average, it was observed, that over the globe, one-, two-, three-, four- and five-layer clouds occur 53, 20, 3.5, 0.4 and 0.04% of the time respectively. Figure 1-1 shows the fraction of multiple layers of cloud for the globe as measured by the active instruments CALIOP and Cloudsat. The tropical regions exhibit the highest fraction of multi-layer clouds although they are also common in the storm track regions. Figure 1-2 shows the vertical profile of multi-layer clouds which exhibit a distinct difference as a function of latitude. The upper and lower layer are higher in the tropics than at the poles. While the consistent application of a single layer cloud model to a long time series of satellite data will still enable trends to be identified. The individual retrievals, daily and monthly composites will be biased.

Retrieval techniques, relying on the different radiative features of each instrument channels, will show differing biases due to the single layer approximation. In the case of optically thick high-level clouds, these biases will be relatively minor, for example the cloud top height/pressure/temperature, and the effective radius, for which the retrieval has its peak sensitivity at approximately one optical depth into the cloud, will be close to the true values of the upper layer and the retrieved optical depth will be representative of the total cloud column. Multi-layer cloud retrieval biases will be at their strongest in the frequently encountered Heidinger et al. (2005) case of optically thin high level cirrus overlaying lower level cloud. For retrievals which rely on channels in the thermal infrared (especially window channels) for their sensitivity to cloud height, such as the long-term heritage channel ECV product to be produced in the baseline Cloud CCI project, the radiance observed will be a combination of emission from both upper and lower clouds. This results in a retrieved cloud top height/pressure/temperature which lies somewhere between the two clouds, an effective radiative height, and the retrieved effective radius is affected in a similar way, Poulsen et al. (2012). In the current single layer CC4CL retrieval when a multi-layer cloud is observed it is often not possible to accurately fit the observed spectral radiance of thin cirrus over low-level cloud with a single layer model, this results in an elevated retrieval cost function and large uncertainties in the state parameters.

In order to reduce these biases it is necessary to develop cloud models that can better model the vertical profile of a cloud. In this report we use a multi-layer retrieval model apply a multi-layer cloud model to MODIS data and evaluate the results.

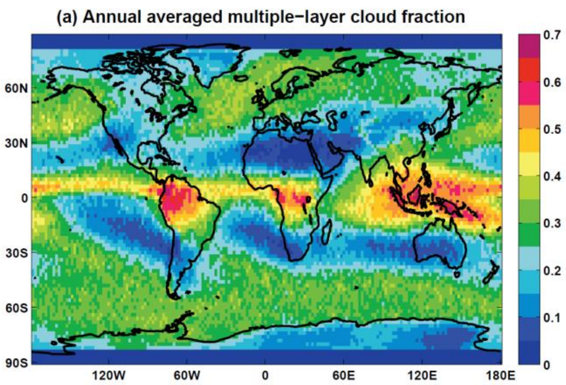

Figure 1-1 *Annual averaged Zonal variation of multiple layers cloud fraction as measured my Caliop/Cloudsat from J. Li et al. (2016).*

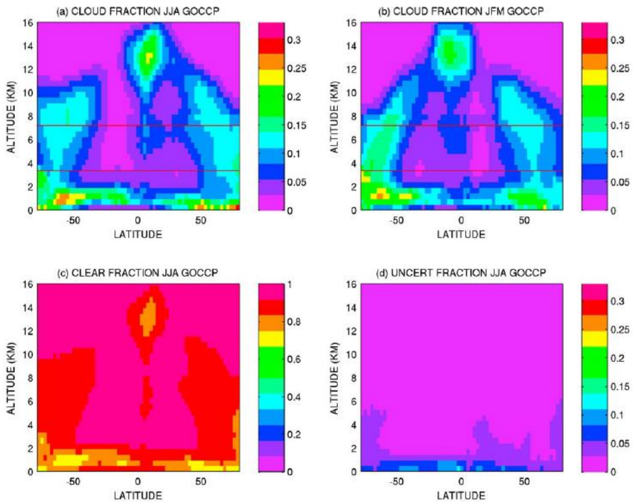

Figure 1-2 *Vertical distribution of cloud fraction from Calipso GCM cloud product (Chepher et al. 2010).*

2. The Multi-layer retrieval algorithm

This section summarises briefly the retrieval approach developed for the multi-layer retrieval when the report refers to multi-layer the reader should infer 2 layer cloud systems. For a full description the reader is directed to the ATBD (2016). It should be noted that this model will have minimal effect on the heritage channel retrieval as a 2 layer model requires more information than the 'heritage' channels (Sus et al., 2017; McGarragh et al., 2017) can provide. The model is applicable to instruments with any combinations of visible to infrared channels. It is currently applicable to both SEVIRI and MODIS instruments. The model has been developed by extending the existing CC4CL LUT approach to deal with two layers. This is accomplished without modification to the contents of the RT LUTs themselves, only making use of existing variables to simulate interactions between both layers. The visible 2 layer model is based the single layer model. This model is effectively nested within itself, so that one call to the model computes the effective (surface + lower cloud) BRDF parameters which are fed into a second call to represent the interaction with the upper cloud. The IR model explicitly models both layers in a separate, fast model. This retrieval approach maintains and expands on the key strengths of the single layer OE retrieval i.e.

- Spectral consistency of derived parameters, which is achieved by an optimal estimation (OE) approach based on fitting a physically consistent cloud model to satellite observations simultaneously from the visible to the mid-infrared.
- Uncertainty characterization, which is inferred from OE theory on a pixel level, is physically consistent (1) with the uncertainties of the input data (e.g. measurements, a-priori) and the uncertainties in forward model, and (2) among the retrieved variables. These pixel-level uncertainties are further propagated into the monthly products using a developed mathematical framework.

The MODIS instrument has additional channels compared to the ATSR and AVHRR instrument that provide increased sensitivity to the vertical profile of a cloud. The 13 and 14 um channels are particularly sensitive to thin cirrus while the 6 and 7 um channels are sensitive to the vertical profile. Simply including the additional channels into the single layer retrieval produces a notable improvement to the cloud top height as shown in Figure 2-1. The systematic bias is almost completely removed with the additional channels.

Figure 2-1 also evaluates the associated retrieval uncertainty. The lower plots show the ration of CTH error to retrieval uncertainty where CTH error is defined as the difference between the Calipso CTH and the retrieved cloud top height. Ideally a Gaussian should fit to the distribution well and approx. 66% of measurements should lie within 2 sigma (indicated with '% good' in the plot). For the heritage channel retrieval this is not the case and the distribution exhibits a systematic bias due to underestimation of multi-layer and thin cloud. The multi-channel retrieval does not have this bias.

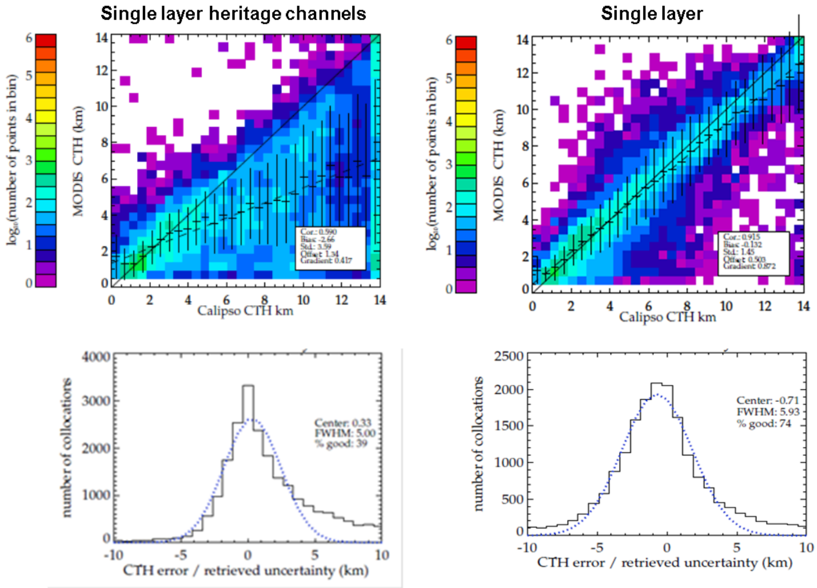

Figure 2-1 *Shows a comparison of the upper layer cloud top height with Calipso (top) and the corresponding uncertainty validation (bottom). The two retrievals shown are the single layer retrieval algorithm for the heritage CC4CL retrieval which uses only 5 channels (left), a multi-channel single layer retrieval from CC4CL (right).*

2.1 Multi-layer Cloud_cci cloud data set

The cloud properties derived on pixel level are shown in Table 2-1.

Table 2-1 *List of generated cloud properties. CMA/CFC and CPH are derived in a pre-processing step. In the next step, COT, CER and CTP are retrieved simultaneously by fitting a physically consistent cloud/atmosphere/surface model to the satellite observations using optimal estimation (OE). Moreover, LWP and IWP are obtained from COT and CER. In addition, spectral cloud albedo (CLA) for two visible channels is derived.*

Variable	Abbrev.	Definition
Cloud mask / Cloud fraction	CMA, CFC	A binary cloud mask per pixel (L2, L3U) and therefrom derived monthly total cloud fractional coverage (L3C, L3S) and separation into 3 vertical classes (high, mid-level and low clouds) following the ISCCP classification (Rossow and Schiffer, 1999).

Variable	Abbrev.	Definition
Cloud phase	CPH	The thermodynamic phase of the retrieved cloud (liquid, ice or multi-layer; in L2, L3U) and the therefrom derived monthly liquid cloud fraction (L3C, L3S).
Cloud optical thickness, upper layer	COT	The line integral of the extinction coefficient along the vertical in the upper cloud layer.
Cloud effective radius, upper layer	CER	The size distribution averaged area weighted radius of the cloud droplets and ice crystal particles in the upper layer.
Cloud top pressure/height/ temperature, upper layer	CTP/CTH/ CTT	The air pressure [hPa] / height [km] / temperature [K] at the top of the upper cloud layer.
Cloud ice water path, upper layer	LWP/IWP	The vertical integrated ice content of the upper layer; derived from CER and COT
Cloud optical thickness, lower layer	COT2	The line integral of the extinction along the vertical in the lower cloud layer.
Cloud effective radius,lower layer	CER2	The size distribution averaged area weighted radius of the cloud droplet particles in the lower layer.
Cloud top pressure/height/ temperature,lower layer	CTP2/CTH2/ CTT2	The air pressure [hPa] / height [km] / temperature [K] of the lower cloud layer.
Cloud liquid water path, lower layer	LWP2	The vertical integrated liquid content of the lower layer; derived from CER2 and COT2
Spectral cloud albedo, upper layer	CLA	The blacksky cloud albedo derived for channel 1 (0.67 µm) and 2 (0.87 µm)of the upper layer (experimental product)

2.2 Methodology

The multi-layer cloud retrieval was performed using MODIS AQUA data with the following settings and assumptions:

1. The retrieval used the following channel combination. 0.67, 0.87, 1.2, 2.13, 3.7, 6.7, 7.33, 11, 12, 13.3, 13.6, 13.9, 14.2 µm.
2. While the cloud retrieval algorithm is flexible such that different multi-layer scenarios are possible e.g. liquid water over liquid water or ice over ice, the retrieval validated here assumed ice cloud over liquid water cloud. This is a reasonable assumption for the majority of multi-layer cloud scenes.
3. An iteration check has been implemented that checks to see if the upper and lower layer clouds are too close or crossing. If they are, then it sets them a minimum distance away from each other centered on their current center. The minimum distance is currently 50hPa.

4. The sensitivity of the cloud retrieval: The cloud retrieval is only able to retrieve a second lower layer of cloud where the upper layer is sufficiently 'thin' typically less than 5 optical depths such that there is a signal (information) detectible from the lower layer of cloud.
5. Only 2 layers of cloud are modelled, where 3 (or more) layers are present and 2 upper layers are optically thin the retrieval will still be biased.
6. It is helpful to constrain the multi-layer retrieval where possible as deriving many new pieces of information is pushing at the limits of the number of degrees of freedom in the available channel set therefore:
   i. We assume in the case of multi-layer cloud retrievals that the retrieval is insensitive to the surface. Instead of a high a priori uncertainty on the surface temperature, as assumed for a single layer retrieval, the a priori uncertainty is set at ±1K.
   ii. The a priori lower cloud top height is set at 700 hPa with an uncertainty set to ±200hPa. This value was estimated by visual inspection of Cloudsat profiles and taking into consideration the monthly climatological profiles from the Calipso GCM product (Chepher et al., 2010).
   iii. The a priori lower cloud effective radius was set to 10µm ± 4µm.
   iv. For all other cloud variables the a priori/first guess value is unconstrained (i.e. the uncertainty is set to 10^8).

An example of the retrieval performance is shown in Figure 2-2. The top left plot shows the single layer retrieval. In the region of multiple layers of cloud, this cirrus over stratus, between -30 and -40 latitude the cloud top height is retrieved biased low. When the multi-layer retrieval is applied the upper layer cloud top height has a decreased bias and information on the second, lower layer of cloud is retrieved. The multi-layer retrieval cost is significantly less than the single layer retrieval cost indicating a 2 layer forward model is a better fit to the measurements.

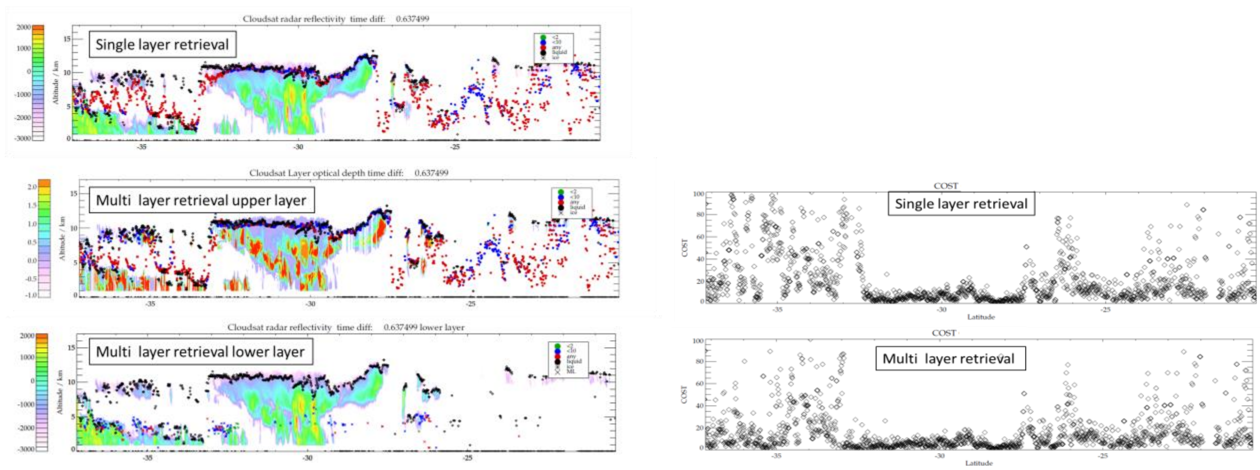

Figure 2-2 *Examples of Multi-layer Cloud_cci cloud products. Left: an example curtain plot showing the retrieval when a single layer model is assumed (top) and the retrieval of the cloud when 2 layers are assumed in the model (middle and bottom). Right: the impact on the costs for a single layer model (top) and a multi-layer model (bottom).*

3. Validation of Cloud_cci multi-layer products

An initial evaluation of CC4CL multi-layer Level-2 products has been carried out based on CALIPSO-CALIOP and Cloudsat data using data from the following, round robin days 2008/03/20, 2008/06/20, 2008/06/13, 2008/09/21 and 2008/12/20.

3.1 Validation strategy in this report

3.1.1 Evaluation measures

For cloud top height, we use the bias, i.e. mean difference between Cloud_cci and reference data as the metric for accuracy.

Bias (accuracy):	Mean error.
RMSE (precision):	Root mean squared error.

3.1.1 Reference datasets for CTH validation

CALIPSO-CALOP: The Caliop instrument is described in Appendix A-2 of the PVIR (2017). The Caliop data set used here is the 5km layer product version 2.02. Measurements from space-born active instruments (radar + lidar) provide probably the most accurate information we can get about cloud top height in the atmosphere. The product provides information for up to 10 layers of cloud. The instrument is much more sensitive to thin clouds than passive instruments hence the comparison is restricted to cloud with a retrieved optical thickness (from the MODIS CC4CL multi-channel multi-layer retrieval) greater than 0.3. Comparison of MODIS-CC4CL multi-layer retrievals are relatively straightforward and deliver confident results. Calipso retrievals of the lower layer are less straightforward as the Calipso is optimised to measure aerosol and ice cloud, measurements saturate at relatively low optical depths. Furthermore, the Calipso optical depths have high uncertainty (Calipso-QS). Hence Calipso may not always be sensitive to the lower layer of cloud. For this reason we also compare the layer heights with Cloudsat.

Cloudsat: The Cloud Profiling Radar (CPR) is a 94-GHz nadir-looking radar which measures the power backscattered by clouds as a function of distance from the radar. Cloudsat is less sensitive to thin ice cloud and more sensitive to the lower layers of liquid cloud. In that way the two instruments are complementary.

3.2 Validation Methodology

Cloud phase in CC4CL is determined by a modified application of the Pavolonis cloud typing algorithm (Pavolonis et al., 2005; Sus et al., 2017). The CC4CL version outputs 8 cloud types, switched to water, fog, water, super cooled, switched to ice, opaque ice, cirrus and overlap. The class switched to water contains clouds initially typed to be liquid which however were found to be too cold to hold liquid water (CTT<38°C). Analogously, clouds initially typed ice but found to be too warm (CTT>0°C) are contained as liquid clouds in the switched to liquid class.

A multi-layer retrieval was performed for pixels identified as ice. The retrieval was assigned as being multi-layer for this comparison if the retrieval cost for a multi-layer retrieval was less than the retrieval cost for a single layer retrieval.

The majority of multi-layer clouds identified were correctly classed as overlap by the Pavolonis cloud typing algorithm, however there was a significant number in the Pavolonis cirrus and opaque ice class.

From visual inspection it was clear that the 'overlap' class both under and over identified multi-layer cloud scenarios. Figure 3-2 shows an example of a retrieval that was identified as an overlap cloud type but is clearly a single layer. In this case (and others) the multi-layer cost was significantly greater than the single layer cost for the same retrieval. Approximately 20% of pixels were reassigned to be single layer using these criteria. That the overlap cloud type is often underestimated is not surprising as the typing algorithm is sensitive to the thickness of the upper layer and also the thickness of the lower layer of liquid cloud (Pavolonis et al., 2004). Two cloud layers may also have an insufficient vertical separation, making it difficult to distinguish the multi-layer cloud system from a single layer. Detection of thin clouds over polar ice surfaces is also difficult as the difference in thermal emission will be small. The algorithm will also be sensitive to the size of the particles in the cloud layers. These factors will also affect the multi-layer retrieval algorithm although to a different extent. The breakdown of clouds used in the following evaluation is shown in Table 3-1.

Table 3-1 *Number of retrievals included in this comparison and break down according to cloud type mask and multi-layer assignment*

Category	Number of pixels
Total number of days	5
Total number Cloudy Pixels	116048
Multi-layer-Cirrus type	993
Multi-layer-Ice type	I806
Multi-layer-overlap type	18815
Multi-layer pixels total	20614
Multi-layer cloud percentage	17.7%
Overlap which did not have lower cost	2393

The validation effort was based on CALIPSO-CALIOP and Cloudsat cloud observations which were simultaneously (i.e., within 3 minutes) observing the same spot on Earth as the MODIS on board the AQUA satellite.

CALIPSO-CALIOP was used to estimate the height of the upper layer of cloud. The lower layer height was evaluated using both CALIPSO-CALIOP and Cloudsat data. The lower layer of cloud was identified by looping over the profile of Calipso or Cloudsat and continuing until a minimum optical depth threshold was exceeded and at least 2 clear layers were identified between the upper and lower layer. This estimate is subject to additional uncertainty, compared with identifying the upper layer cloud top height. The complexity arises from uncertainty in the optical depth retrieval from the active sensors, the sensitivity (or not) of the lidar to lower layer cloud, the presence of more than 2 layers, many of them very thin, and the presence of spurious noise/clutter in the active instruments profile. Nevertheless, despite the uncertainty in the technique, we have been able to gain some insights.

3.3 Summary of findings for Multi-layer Cloud retrieval

A summary of the comparison of upper and lower layer cloud top height with Calipso and Cloudsat is shown in **Table 2-1** the key findings are outlined below.

1. The single layer retrieval, using the same channels as the multi-layer retrieval, performs well, the retrieval shows considerable improvement compared with MODIS C6 retrieval which shows a bias where the algorithm switches between the IR window channel CTH retrieval and the CO2 slicing retrieval. The CC4CL retrieval, which uses all channels simultaneously, makes this transition smoothly see Figure 3-1.
2. Approximately 17% of cloudy pixels were identified as likely being a multi-layer retrieval according to cloud type and cost criteria (see Table 3-1 for a breakdown). This is much less than the 53% estimated by active instruments, however the algorithm is insensitive to multi-layer clouds which have optically thick upper layers of cloud. Some multi-layer cases will be missed because the upper layer was very thick. Some will be missed because they were misidentified by the cloud mask as liquid rather than ice and some will have been missed because for other reasons such as they were a greater than 2 layered cloud system the retrieval cost was still higher for the 2 layer than the single layer retrieval.
3. The Pavolonis cloud flag under detects multi-layer cloud and occasionally is false positive. Many of these false positives can be effectively removed by requiring the multi-layer retrieval cost to be less than the single layer retrieval cost, see Figure 3-2. The Pavolonis flag has limited sensitivity to multi-layer clouds when the upper layer is thick.
4. Approximately 10% additional pixels are identified as multi-layer scenes by reassigning the cloud top to multi-layer when the multi-layer cost is less than the single layer. These clouds were identified as cirrus of opaque ice by the cloud typing.
5. Cost alone is not sufficient to identify multi-layer cloud scenes. There may be other reasons that the cost is high such as 3D edges effects, bright surfaces, poor cloud masking or additional layers of cloud. Although in the case of 3 layer clouds, the 2 layer retrieval is likely to be a better fit then the single layer model.
6. Clouds with a liquid or super cooled cloud type were not considered candidates for multi-layer cloud however it is likely some are. This will be investigated in the future.
7. The upper layer cloud top height is retrieved with high accuracy compared with Calipso for both the single layer and multi-layer retrievals see Figure 3-3. The upper later CTH retrieval is slightly more accurate for ice clouds and clouds over sea (not shown).
8. The multi-layer retrieval reduces the upper layer CTH bias by approximately 100 m. The improvement is largest for high clouds i.e. clouds top height greater than 10 km, the bias is reduced by approx. 150 m. For cloud top heights less than 5 km the results are slightly degraded see Figure 3-4.
9. Figure 3-5 shows the comparison of the lower cloud top height as a function of upper layer optical depth. The information on the lower layer decreases as the upper layer becomes thicker. As the retrieved optical depth of the upper layer approaches approximately 5, the lower layer CTH reverts to the a priori value. The results are summarized in Table 3-2.
10. Figure 3-6 shows histograms comparing MODIS-CC4CL cloud top height with Cloudsat with multi-layer retrieval of upper (black/green) and lower layers (blue/red) and for a single layer only retrieval (yellow). On the upper left is a comparison with Cloudsat data for the polar region (latitude > abs(60^o)), upper right mid latitudes (abs(30^o) <latitude <abs(60^o)) and on the bottom a comparison for the tropics (-30^o <latitude < 30^o). In the polar region it is clear that an a priori estimate of 700 hPa and an uncertainty of ± 200 hPa was a good assumption. As the

retrieval moves towards the tropics this constraint looks less appropriate (although as mentioned in the next point the upper layer cloud is also thinner towards the poles). The tropics in particular show a much broader distribution of lower layer cloud top height. Future global retrieval schemes could implement a more dynamic a priori and uncertainty. The cloud type information could also be used to refine the apriori.

11. Figure 3-7 compares the multi-layer effective radius and optical depth (blue-upper, black-lower) with the equivalent single layer (yellow) retrieval. The comparison is separated into polar, mid latitude and tropics. In general the total optical depth for the multi-layer retrieval is similar to the single layer retrieval. The upper layer optical depth is retrieved as significantly thinner for the polar clouds than the tropical clouds. Hence the sensitivity and ability to retrieve information on the lower layer will be greater.
12. In Figure 3-7 the effective radius retrieved for the multi-layer and single layer forward models are as would be expected quite different. The single layer effective radius shows a clear peak at approx. 8 µm and also a peak <3 µm. The multi-layer retrieval shows 2 distinct peaks, a peak centered around 10 µm (which was the a priori) and another broad peak centered around 30 µm. The peak in the single layer retrieval < 3 µm is evidence of the single layer model having difficulty retrieving an effective radius for multi-layer cloud cases. The upper layer peak is more distinct for the tropical clouds. The secondary lower layer peak at low values reduces when a stricter cost threshold is applied suggesting less confidence in these retrievals.
13. In Figure 3-8 the LWP and IWP is estimated for the different regions. In this case there are no distinct differences between regions however the results show that the total Cloud Water Path (CWP) for the multi-layer scenario is significantly higher than the single layer retrieval.

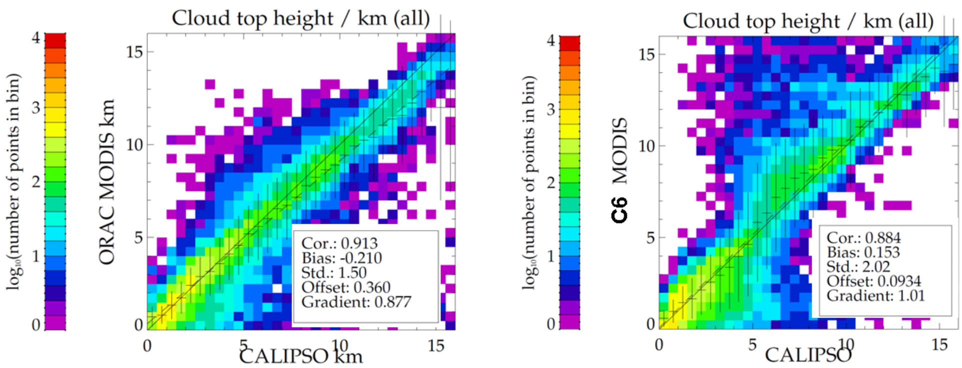

Figure 3-1 *Comparison of CC4CL single layer retrieval and Calipso (left) with MODIS collection 6 single layer retrieval and Calipso (right).*

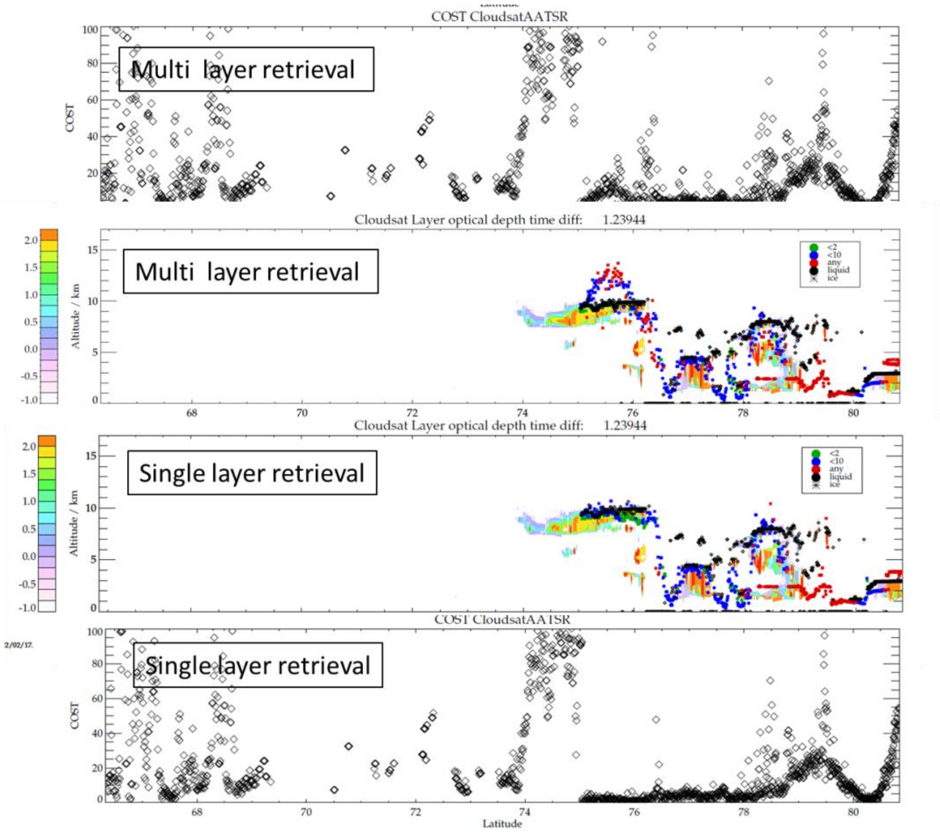

Figure 3-2 *Example of a multi-layer retrieval where the Pavolonis cloud typing misidentified a single layer cloud as a multi-layer cloud. Between 75 and 76 degrees the cloud was incorrectly identified as a multi-layer cloud by the Pavolonis cloud mask. This was correctly reassigned to a single layer by comparing the cost of the single layer and multi-layer retrievals. The black circles indicate cloud height as measured by Cloudsat. The coloured circles indicate the retrieved cloud height with the green dots having a cost < 2 the blue < 10 and the red >10.*

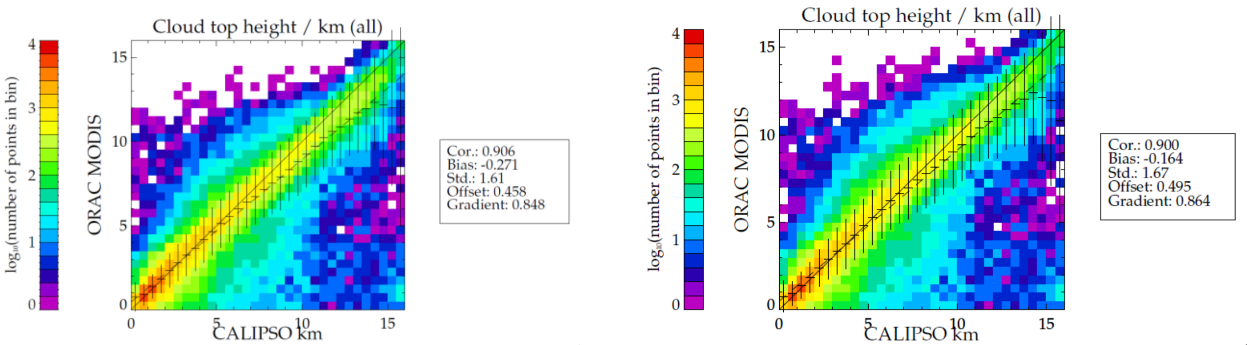

Figure 3-3 *Scatter density plots comparing cloud top height for the single layer retrieval (left) and the multi-layer retrieval (right). Calipso is used to validate the upper layer cloud top height. This is the comparison for all pixels both single layer and multi-layer for the round robin dates analysed.*

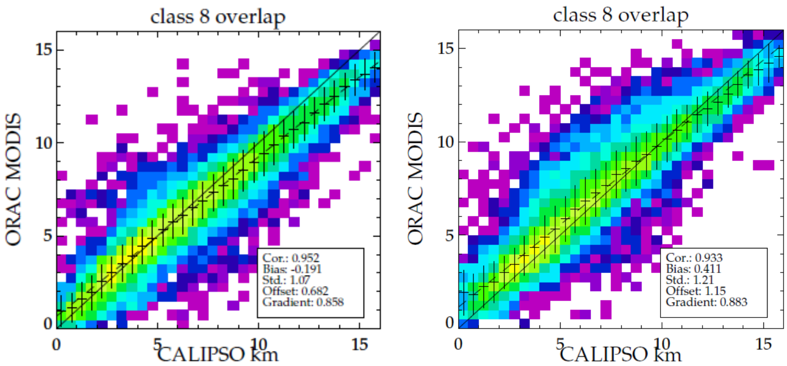

Figure 3-4 *Scatter density plots comparing cloud top height for the single layer retrieval (left) and the multi-layer retrieval for retrievals identified as overlap by Pavolonis cloud type mask (right). The multi-layer retrieval improves the comparison for high clouds but degrades it for low clouds.*

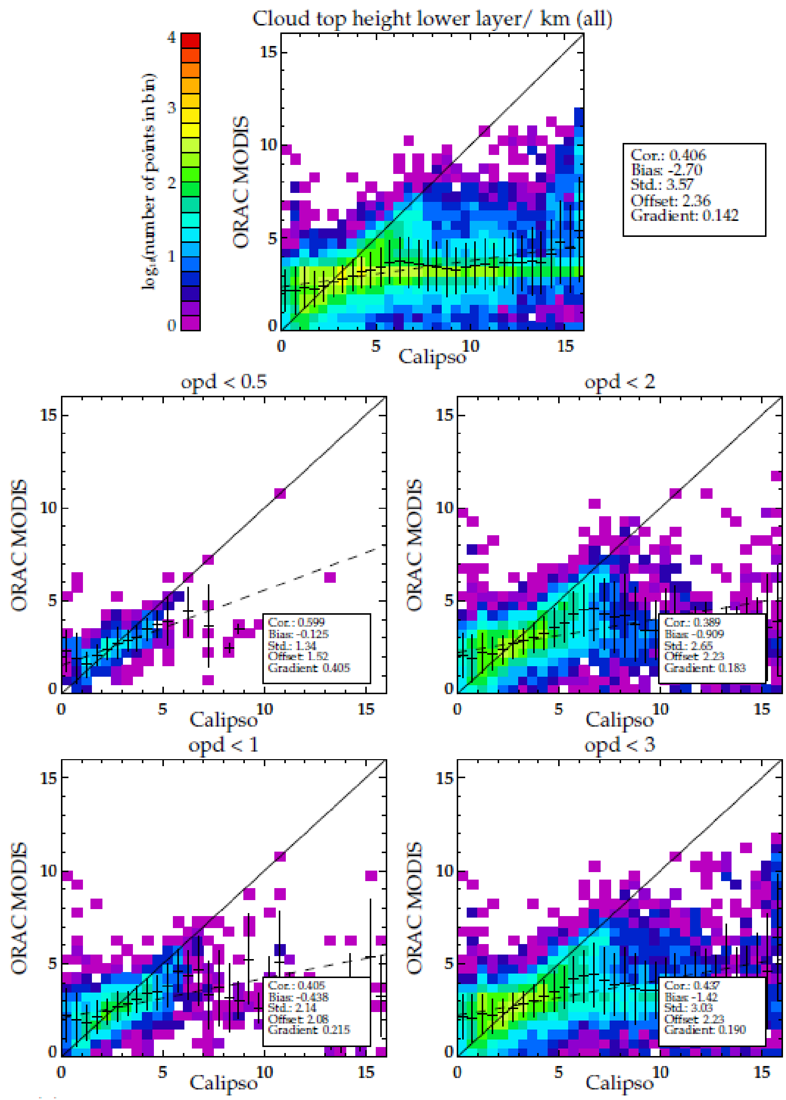

Figure 3-5 Scatter density *plots showing the comparison of MODIS-CC4CL multi-layer retrieval lower cloud top height with Calipso lower layer cloud top height as a function of MODIS-CC4CL upper later cloud optical depth. Note that as the upper layer cloud increases in optical thickness the bias also increases.*

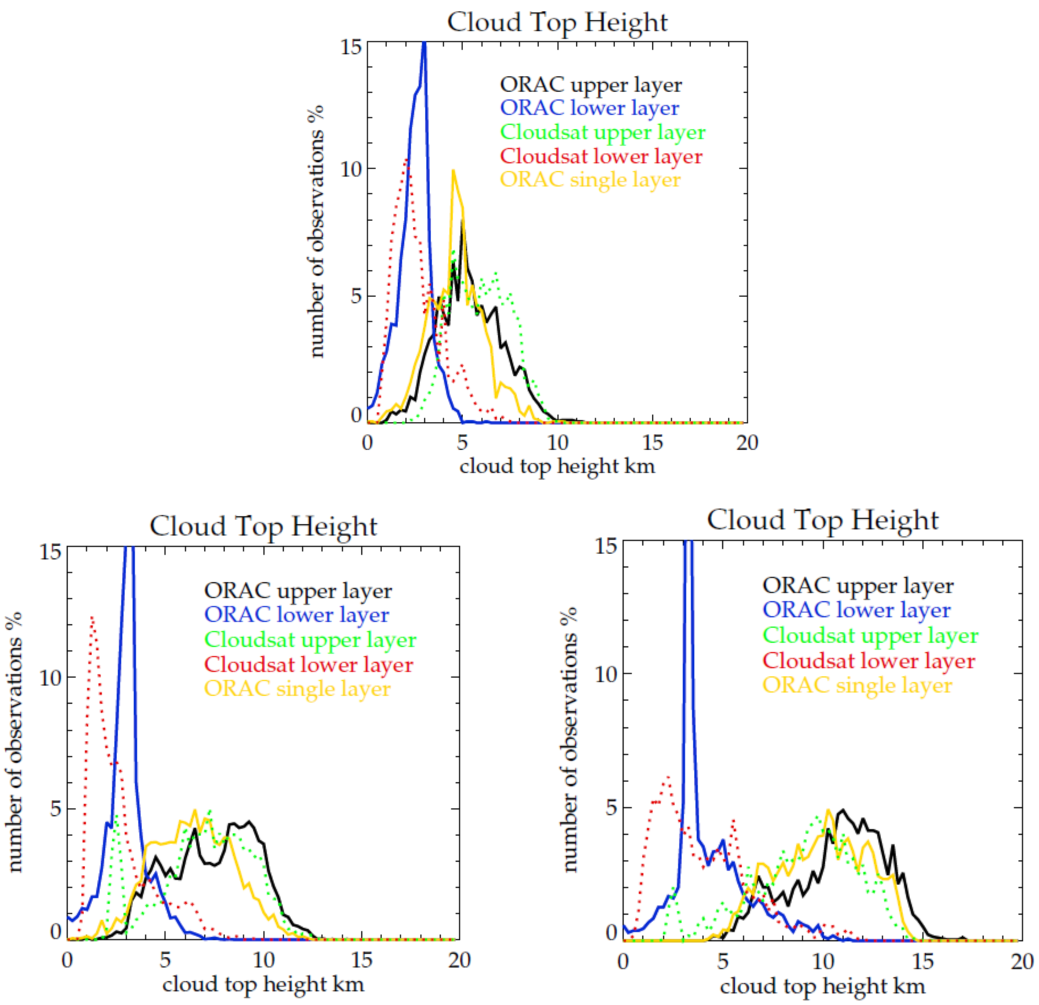

Figure 3-6 *Histograms comparing MODIS-CC4CL cloud top height for a multi-layer retrieval of the upper (black/green) and lower (blue/red) layers and for a single layer only retrieval (yellow). At the top is a comparison with Cloudsat data for the polar region, lower left for the mid latitudes and on the lower right for the tropics.*

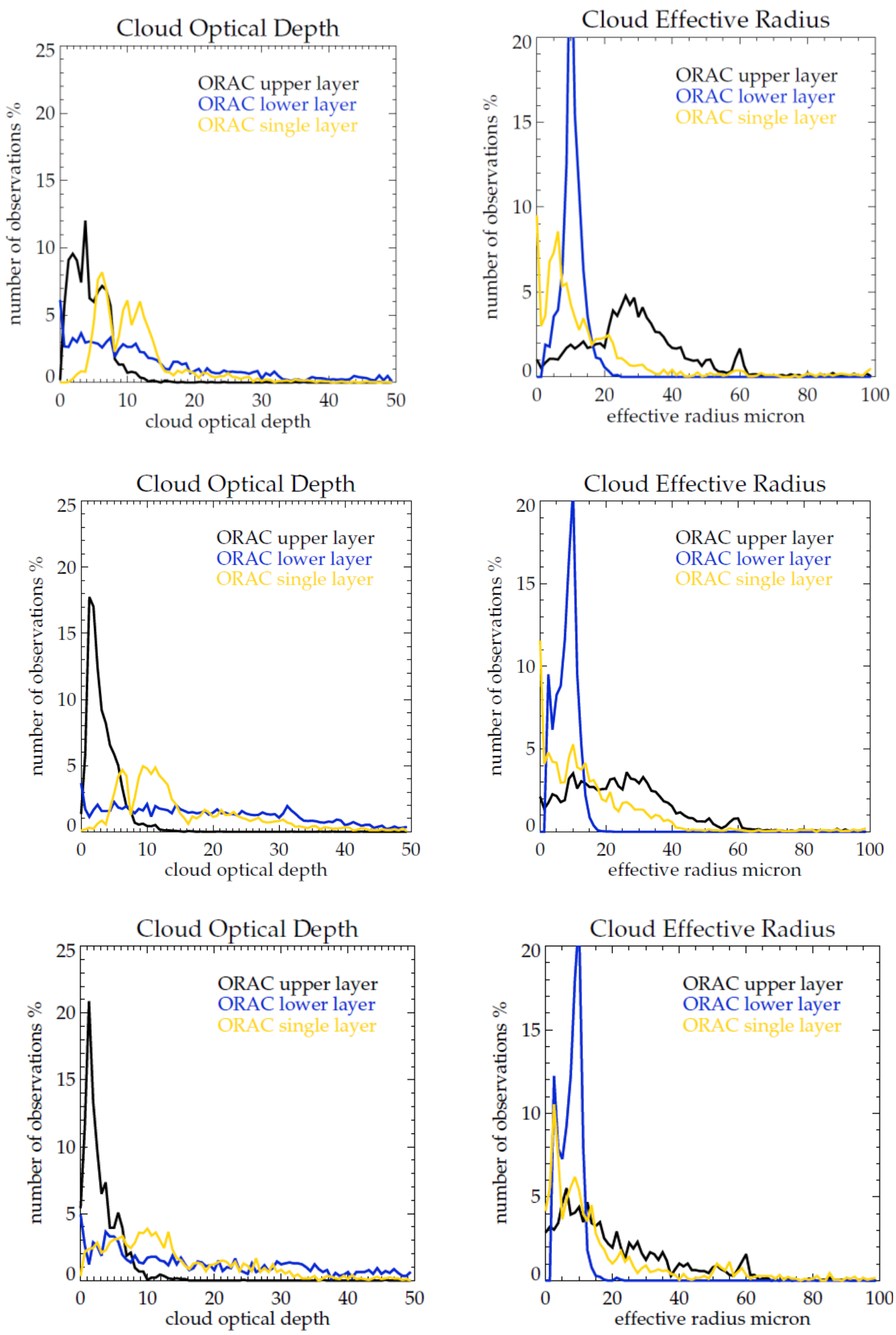

Figure 3-7 *Histograms comparing multi-layer (blue/black) and single layer (yellow) retrieved cloud optical depth (left) and effective radius (right) for the tropics (top), mid latitude (middle) and the polar region (bottom).*

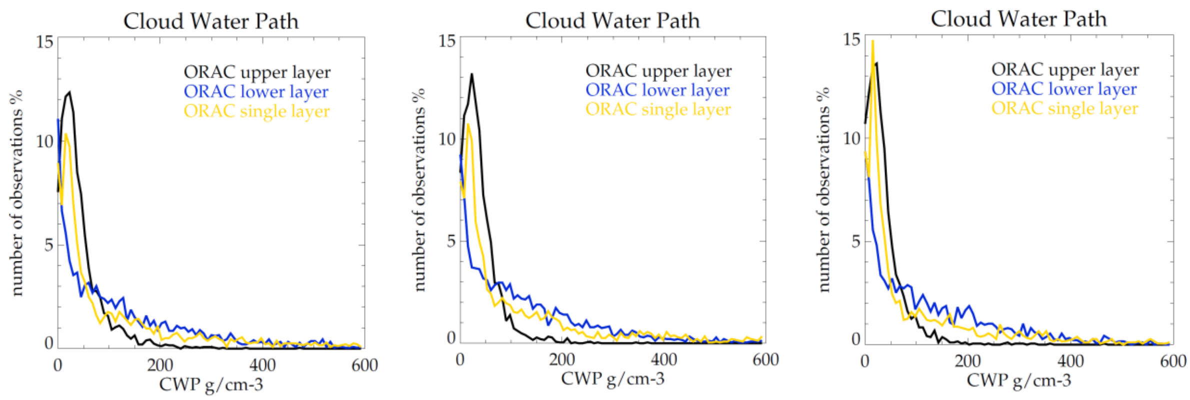

Figure 3-8 *Histograms comparing multi-layer (blue LWP/black IWP) and single layer (yellow -IWP (total for the pixel)) retrieved cloud water path for the tropics (left), mid latitude (middle) and the polar region (right).*

Table 3-2 *Summary of CC4CL (MODIS) validation results for single and multi-layer cloud retrievals validated vs CALIOP and Cloudsat (for the lower layer).*

Cloud category	CC4CL (MODIS) Bias km (SD km) Single layer Upper cloud Calipso	CC4CL (MODIS) Bias km (SD km) Multi-layer Upper cloud Calipso	CC4CL (MODIS) Bias km (SD km) Corrected Single layer Upper cloud Calipso	CC4CL (MODIS) Bias km (SD km) Corrected Multi layer Upper cloud Calipso	CC4CL (MODIS) Bias km (SD km) Multi-layer Lower cloud Calipso	CC4CL (MODIS) Bias km (SD km) Multi layer Lower cloud Cloudsat
All clouds	-0.271(1.61)	-0.164(1.67) all -0.511(1.89)Land/ice -0.615(2.07)Land/liquid -0.252(1.64)Sea/ice -0.179(1.58)Sea/liquid	0.0271 (1.72)	0.164 (1.81)	-0.125(1.34)<0.5 -0.438(2.14)<1 -0.909(2.65)<2 -1.42(3.03)<3 -2.09(3.39)<5 -2.7(3.57) all	-0.889(1.67)<0.5 -1.37(2.47)<1 -1.5(2.75)<2 -1.66(2.88)<3 -1.83(3.00)<5 -2.08(3.01)all
Lower level <5 km	-0.0227	-0.0500				
Medium-level >5 km and <10 km	-0.104	0.0852				
High-level >10 km	-0.615	-0.458				

4. Summary

We have successfully demonstrated a multi-layer (2 layer) cloud retrieval which has improved the retrieval of upper layer clouds and extracted useful information on the lower layer. Where the upper layer is thin (i.e < 5 optical depths) then accurate information on the lower layer can be retrieved. As the optical depth of the upper layer increases the ability to identify multi-layer cloud and retrieve it accurately diminishes. Calipso and Cloudsat retrievals were used to validate the CC4CL MODIS retrieval of cloud top height. Calipso provides the best reference source for the upper layer while Cloudsat was more appropriate for the lower layer. The retrieval could be further optimised by improving the cloud typing, a machine learning or neural network approach as already employed for the cloud mask and phase could be applied. The a priori information and uncertainty could be applied more dynamically globally according to the location of the cloud to improve the retrieval of the lower layer cloud properties.

Evaluation of the changes to optical depth and effective radius when a retrieval is performed using a multi-layer forward model and the subsequently derived liquid and ice water path show that current cloud climatology's generated form passive vis/IR instruments will be significantly biased if a single phase (ice or water) is assumed for the entire vertical profile. Liquid water path will be significantly underestimated in regions with multi-layer cloud and globally. The difference in IWP is mixed as the change in IWP is more sensitive the vertical profile of optical depth and effective radius.

The retrieval technique, could with minor modification, be applied with success to geostationary instruments such as SEVIRI, GOES and Himawari. For geostationary instruments an additional possibility is to constrain the lower layer of the cloud system using temporal information on previous cloud coverage.

For Sentinel-3 the ability to retrieve with accuracy multi-layer cloud will depend on the combination of instruments and channels used. The 1.3um channel on SLSTR is sensitive to high thin clouds however its implementation is currently untested. If the retrieval includes collocated OLCI data this instrument has channels such as O2A band which have good sensitivity to the vertical structure and hence the additional layers of the cloud.

5. Annex A - Additional examples of multi-layer retrievals

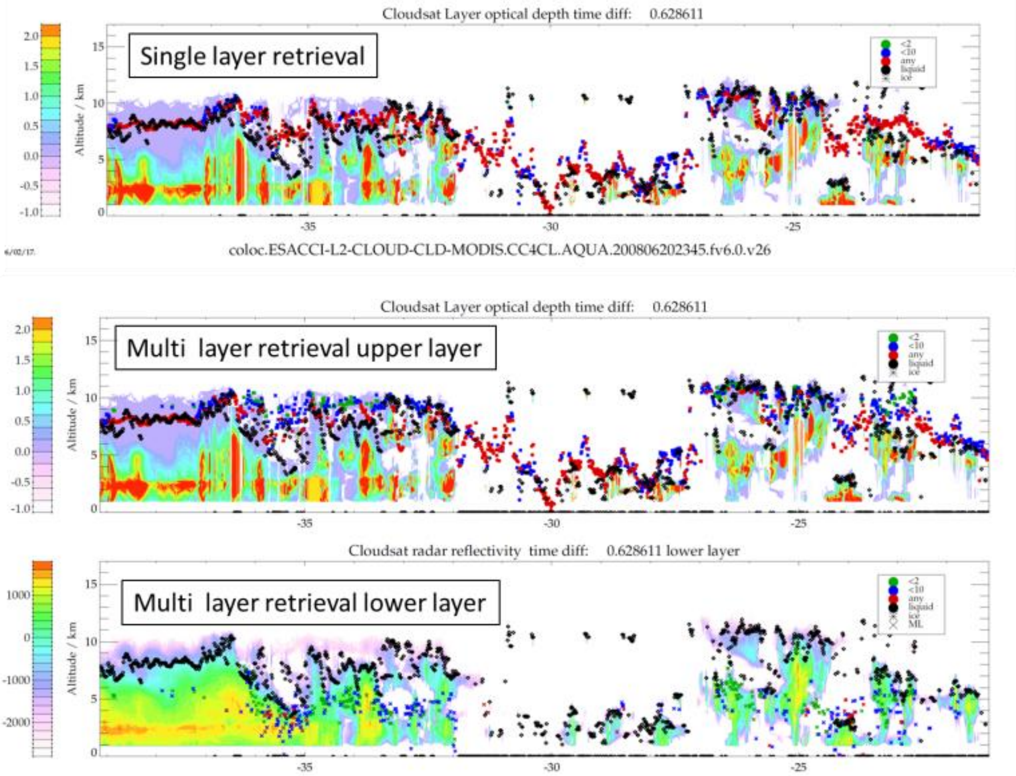

Figure A-1 *Example multi-layer retrieval from 06/20/2008 compared with single layer retrieval and collocated with coincident Cloudsat data.*

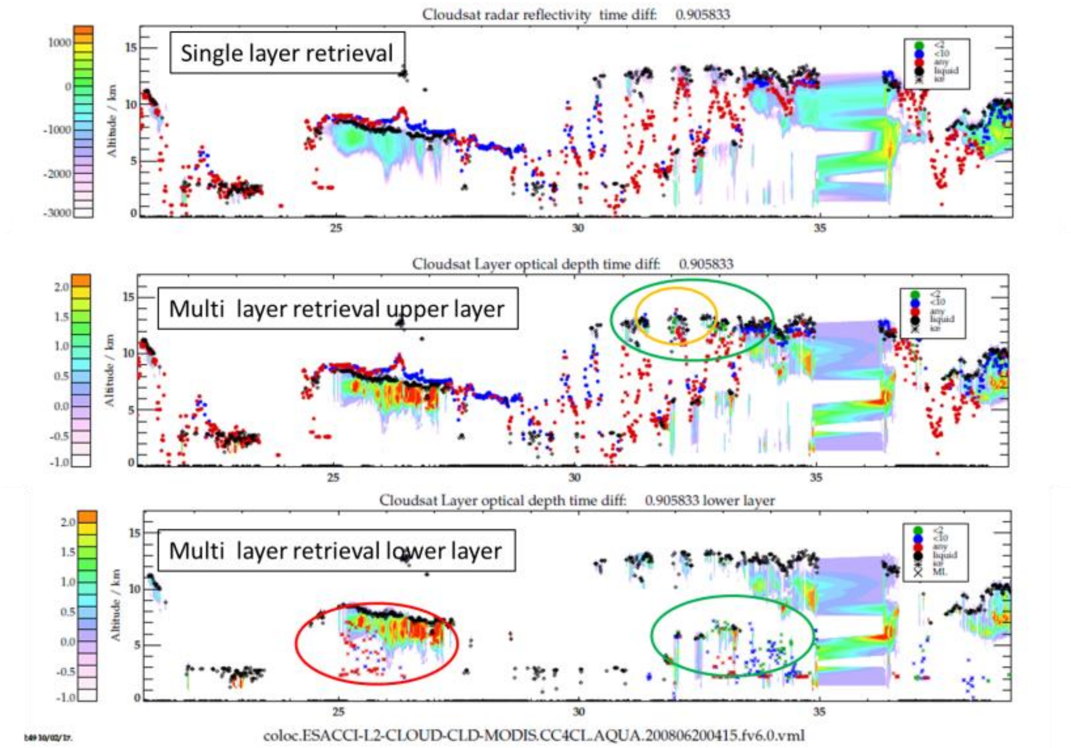

Figure A-2 *Example multi-layer and single layer retrieval from 06/08/2008 collocated with Cloudsat data.*

6. Glossary

Acronym	Explanation
AATSR	Advanced Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BRDF	Bi-directional Reflectance Distribution Function
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CC4CL	Community optimal estimation Cloud retrieval For CLimate
CER	Cloud Effective Radius
CFC	Cloud Fraction
CloudSat	Cloud Satellite
CM	Cloud Mask
COD	Cloud Optical Depth
COT	Cloud Optical Thickness
CPH	Cloud Phase
CPR	Cloud Profiling Radar
CPS	Cloud Particle Size
CTH	Cloud Top Height
CTP	Cloud Top Pressure
CWP	Cloud Water Path
ECVs	Essential Climate Variables
ENVISAT	Environmental Satellite
EUMETSAT	European Organisation for the Exploration of Meteorological Satellites
IR	Infrared
IWP	Ice Water Path
L3C	Level 3 Collated, i.e. monthly averages
L3S	Level 3 Super-collated, i.e. monthly averages of a sensor family (e.g. AVHRR) or of all

Acronym	Explanation
	sensors available (e.g. MODIS + AVHRR + AATSR)
L3U	Level 3 Uncollated, i.e. daily near-nadir samples or referred to as level 2b
LWP	Liquid Water Path
LWRTM	Longwave Radiative Transfer Model
LUT	Look-Up Table
MetOp	Meteorological Operational Satellite
MODIS	Moderate Resolution Imaging Spectroradiometer
ORAC	Oxford RAL retrieval of Aerosol and Cloud
OE	Optimal Estimation
PATMOS-x	AVHRR Pathfinder Atmospheres-Extended
RT	Radiative transfer.
TOA	Top of atmosphere
TOC	Top of cloud

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