Improvements in the ORAC system: Cloud-top correction for IR measurements

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Introduction

ORAC (Optimal Retrieval of Aerosol and Cloud) [Poulsen et al., 2012, Thomas et al., 2009] is a generalized optimal estimation system that retrieves cloud or aerosol parameters using visible and/or infrared measurements from satellite based multispectral observations which currently include AATSR, AVHRR, and MODIS. For cloud retrievals, measurements made in the infrared channels are most sensitive not to the cloud-top but to a vertical location within the cloud depending on channel wavelength and the temperature profile. If unaccounted for, this vertical sensitivity will lead to retrieved cloud-top locations that are lower than the actual cloud-top and/or biases in other retrieval parameters such as optical thickness and/or effective radius.

The forward model

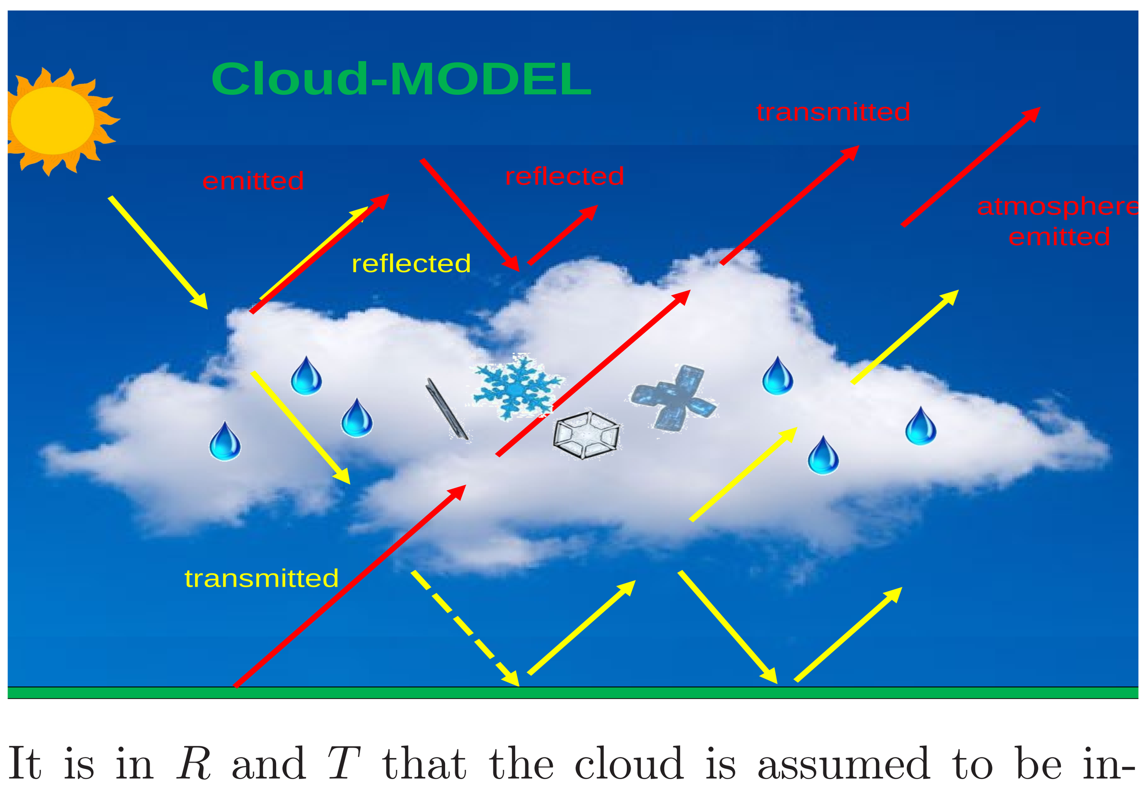
The forward model (FM) within ORAC must be fast to process imager pixels on large spacial and temporal scales. Therefore, it uses a simplified model in which the cloud is assumed to be infinitely thin in the vertical. For thermal infrared measurements the model (depicted by the red lines in the figure below) simulates upward radiance at TOA with

$$L^{\uparrow} = fL^{\uparrow}_{\text{cld}} + (1-f)L^{\uparrow}_{\text{clr}},$$

where

$$L^{\uparrow}_{\text{cld}} = \left\{L^{\downarrow}_{\text{ac}}R + L^{\uparrow}_{\text{bc}}T + B\left[T(p_c)\right]\right\}e^{-(\tau_{\text{ac}})} + L^{\uparrow}_{\text{ac}},$$

and f is the cloud fraction, $L^{\uparrow}_{\text{cld}}$ and $L^{\uparrow}_{\text{clr}}$ are the upward radiances from cloudy (cld) and clear (clr) conditions, $L^{\uparrow}_{\text{ac}}$ is the upward radiance from above the cloud, $L^{\downarrow}_{\text{ac}}$ is the downward radiance from above the cloud, $L^{\uparrow}_{\text{bc}}$ is the upward radiance from below the cloud, τ_{ac} is the optical thickness above the cloud, B is the Planck function, $T(p_c)$ is the temperature at cloud-top pressure p_c, and R and T are the cloud hemispherical-directional reflectance and transmission factors for isotropic illuminations.



It is in R and T that the cloud is assumed to be infinitely thin. The result of this is that the model cannot account for cloud vertical structure, and therefore vertical sensitivity, allowing the retrieval to place the cloud-top in a radiatively consistent location.

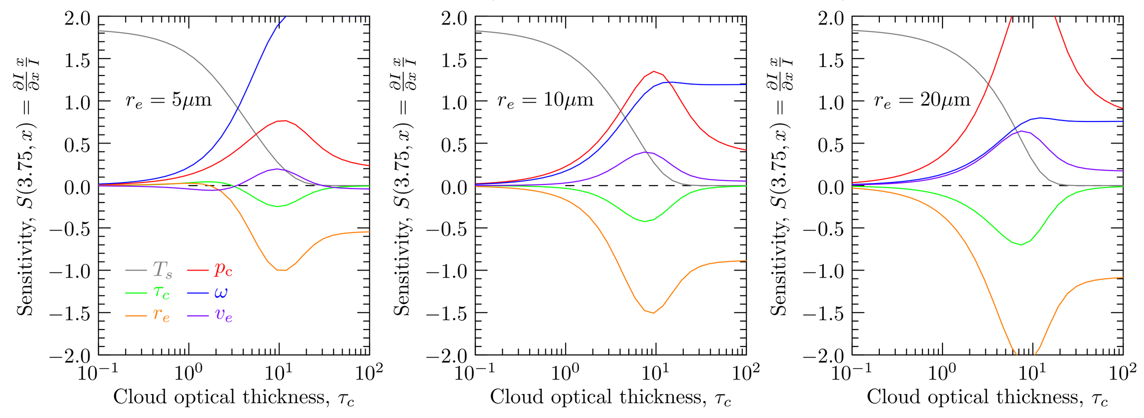
The reference forward model

The reference FM used for this study uses LMie [McGarragh, 2013a], a linearized Mie code for particle scattering, and XRTM [McGarragh, 2013b], a linearized plan-parallel multilayer radiative transfer solver with absorption, emission, multiple scattering and a general surface BRDF. Unlike the ORAC FM multiple scattering is allowed in each layer allowing for the sensitivity of measurements in the vertical to be resolved. Like the ORAC FM the reference model uses RTTOV for gas absorption and to account for the instrument spectral response function. For all theoretical simulations, unless otherwise stated, the cloud was discretized to 100 layers, the US standard atmosphere was used, the viewing direction $\theta = 0$, $p_c = 600$ hPa, $r_e = 10\mu m$, $v_e = 0.15$, and the surface albedo $A = 0$.

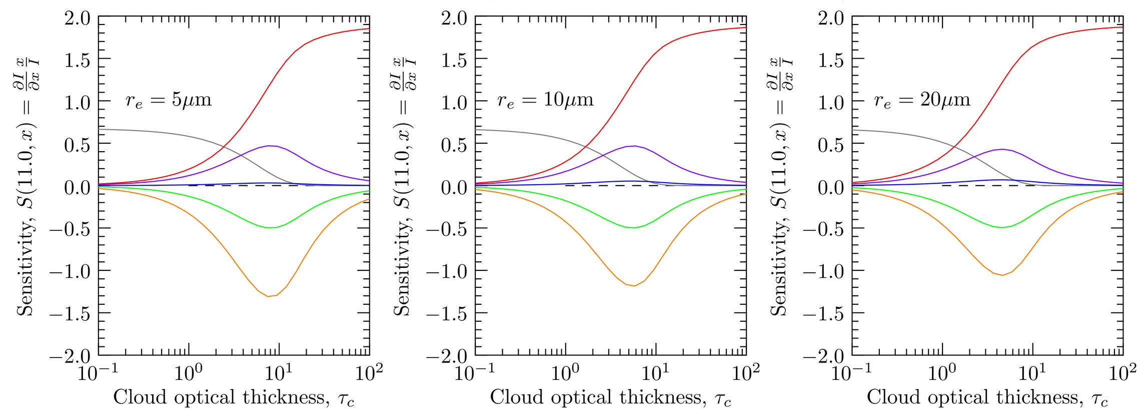
Cloud column sensitivities

Normalized measurement sensitivities to a cloud parameter x given by $S(\lambda, x) = \frac{\partial I_\lambda}{\partial x}\frac{x}{I_\lambda}$ as a function of cloud optical thicknesses τ_c are presented below for several parameters and for cloud optical thicknesses τ_c of 5, 10, and 20.

3.75 μm (MODIS band 20)



11.0 μm (MODIS band 31)

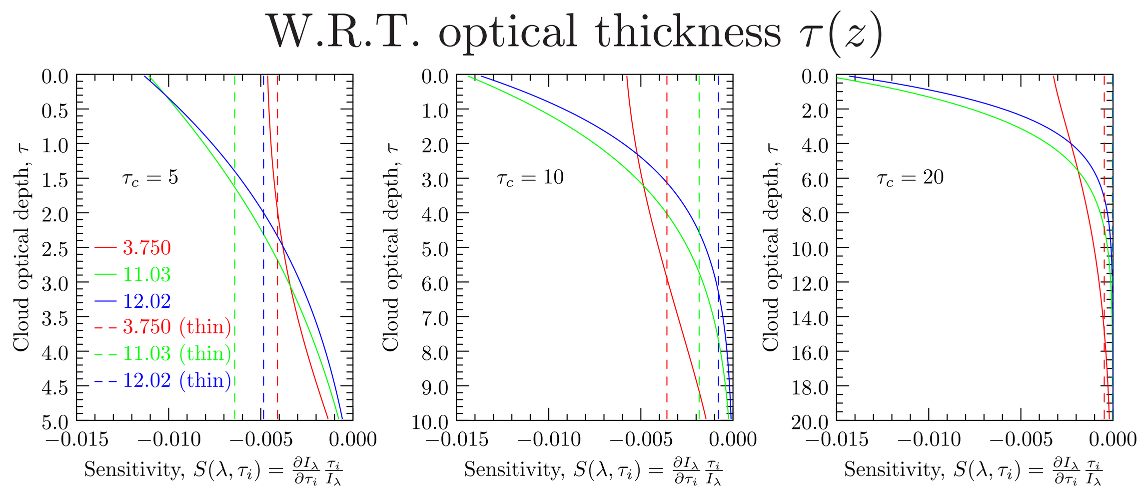


- As expected, $S(T_s)$ decrease with τ_c.
- $S(3.75, p_c)$ increases and peaks at $\tau_c \approx 10$ while $S(11.0, p_c)$ increases and levels off at larger values.

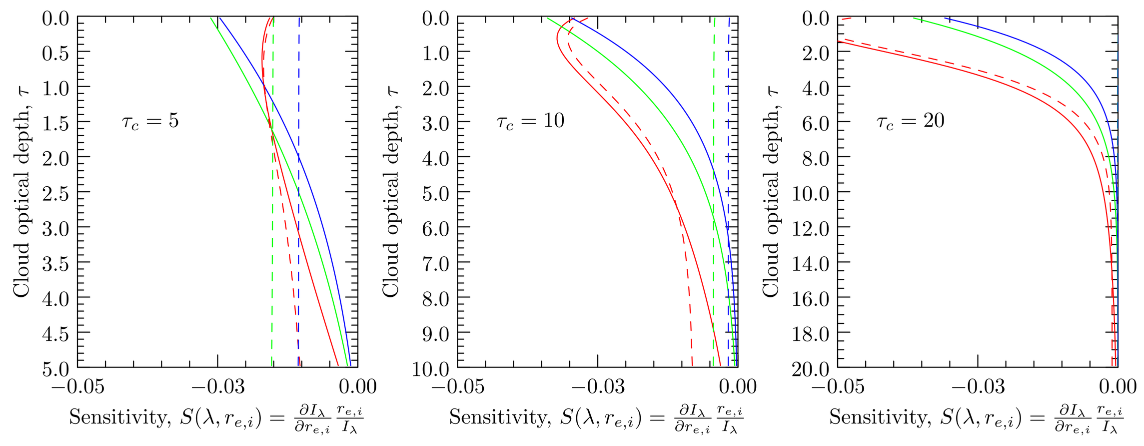
Cloud profile sensitivities

Normalized measurement sensitivities to a cloud parameter x in cloud layer i given by $S(\lambda, x_i) = \frac{\partial I_\lambda}{\partial x_i}\frac{x_i}{I_\lambda}$ are presented below for optical thickness τ_i, effective radius $r_{e,i}$, and effective variance $v_{e,i}$, and for τ_c equal to 5, 10, and 20. In addition, both the general case and the infinitely thin cloud layer case (thin) are shown.

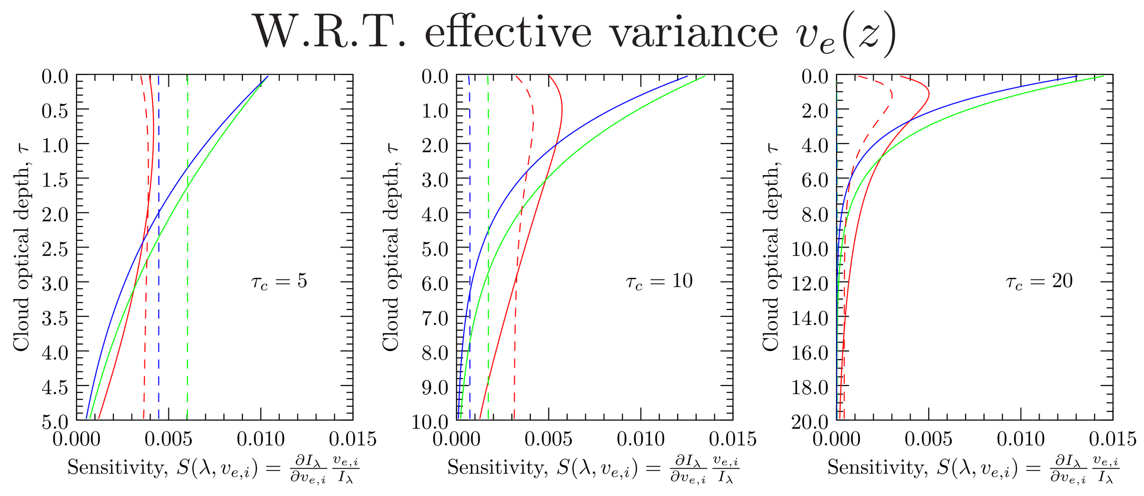
W.R.T. optical thickness $\tau(z)$



W.R.T. effective radius $r_e(z)$



W.R.T. effective variance $v_e(z)$

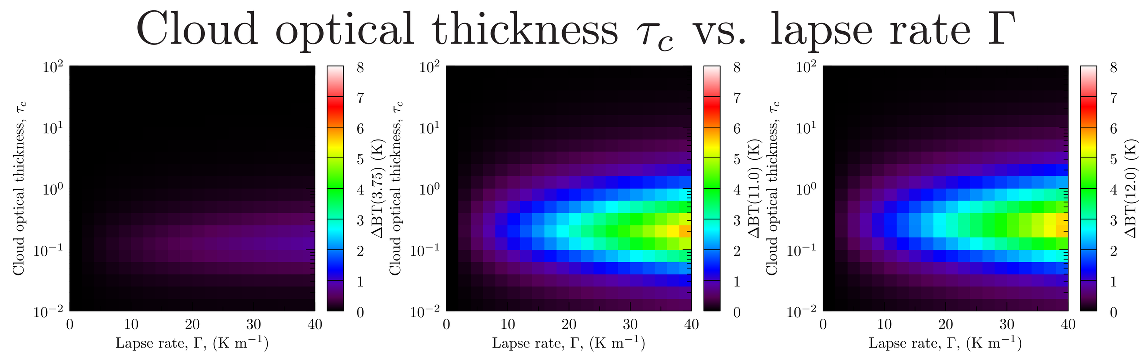


- $S(\lambda, x_i)$ increases/decreases with τ_c for the upper/lower layers.
- $S(3.75, x_i)$ is smaller than $S_i(11.0, x_i)$ and $S_i(12.0, x_i)$ for upper layers and larger for lower layers.
- The infinitely thin cases have an almost constant sensitivity with cloud layer.

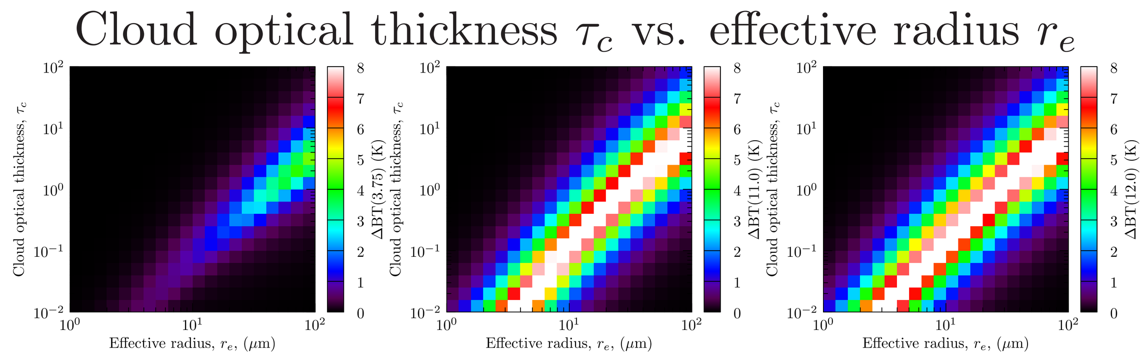
Correction implementation

To correct the ORAC FM we have implemented a simple lookup table approach from which a radiance offset is obtained. The LUT is represented as $\Delta L_\lambda = f(\tau_c, \lambda, \Gamma, r_e, v_e)$, where Γ is the atmospheric lapse rate. Below are density plots showing ΔL_λ for Γ, r_e, v_e as a function of τ_c.

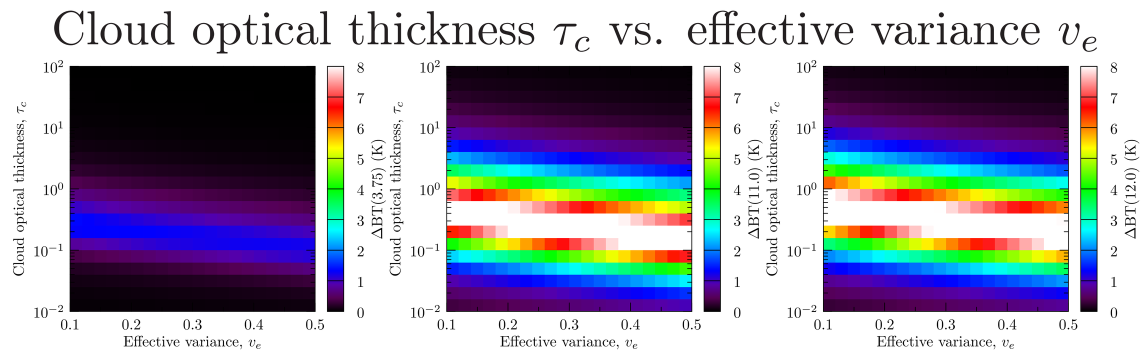
Cloud optical thickness τ_c vs. lapse rate Γ



Cloud optical thickness τ_c vs. effective radius r_e



Cloud optical thickness τ_c vs. effective variance v_e

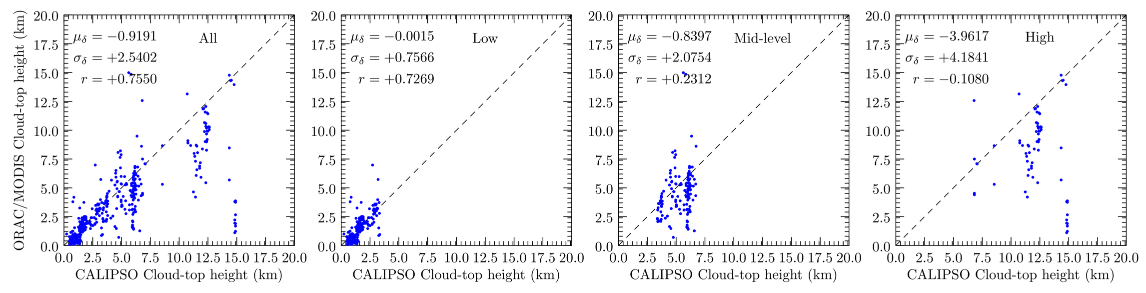


- As expected, differences increase steadily with Γ and increase, peak, then decrease with r_e due to a larger temperature gradient.
- Differences increase, peak, then decrease with τ_c due to competing influence between signal and penetration depth.
- Differences with r_e are strongly correlated with τ_c due to a larger penetration depth with larger particles.

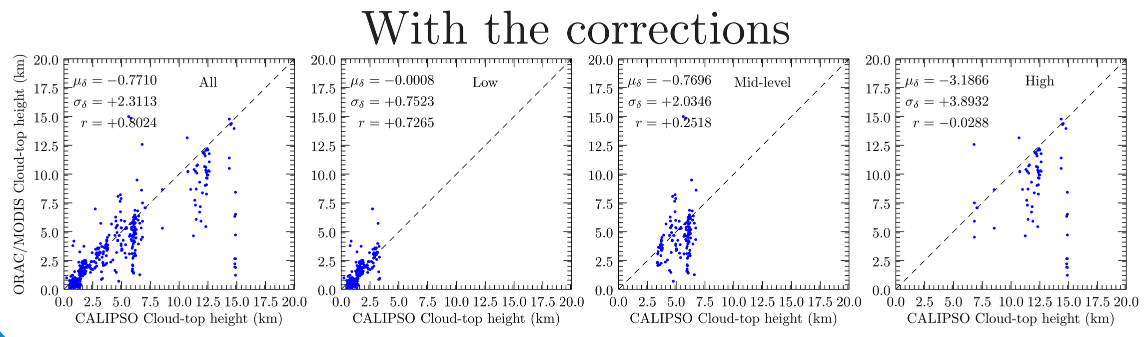
Evaluation

As a simple validation for our approach we apply the ORAC retrieval to a single MODIS granule with and without the correction and validate the retrieved cloud-top heights (CTH) with collocated CALIPSO "layer top altitude" retrievals. Below are scatter plots of CALIPSO CTH v.s. ORAC CTH for all clouds, low clouds, mid-level clouds, and high clouds. Included are the mean deviation μ_δ, standard deviation of the deviations σ_δ, and correlation coefficient r.

W/o the corrections



With the corrections



Conclusions

Our correction method provides a small improvement in CTH retrievals for high and mid-level clouds. This improvement is relatively small compared to other know problems in CTH retrievals for high thin clouds. If these other problems are alleviated our method will increase in importance.

References

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