A practical way to detect and (partially) quantify the 3-D radiative (illuminating) effects in passive cloud property retrievals: theoretical basis and feasibility study

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ICWG-2 Workshop, Wisconsin, Madison

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Acknowledgement:

Daniel Miller, Frank Werner, Steven Platnick, Andrew Ackerman, Zhen Wang

Funding support from PACE Science Team (**PI S. Platnick**) and NASA NIP

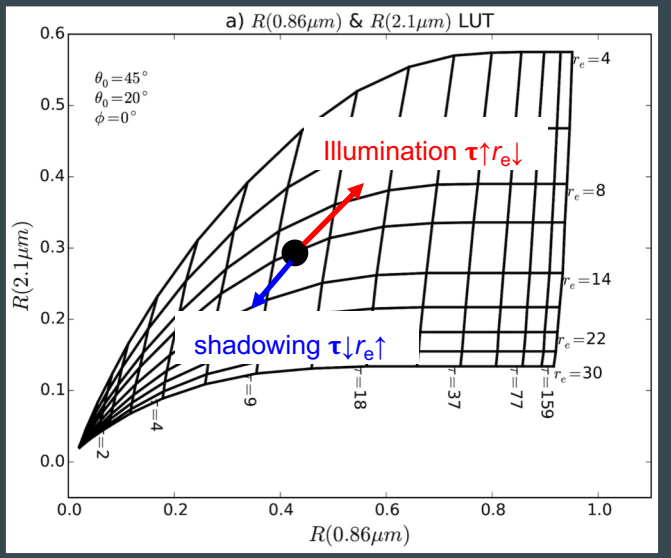
What are 3D effects?

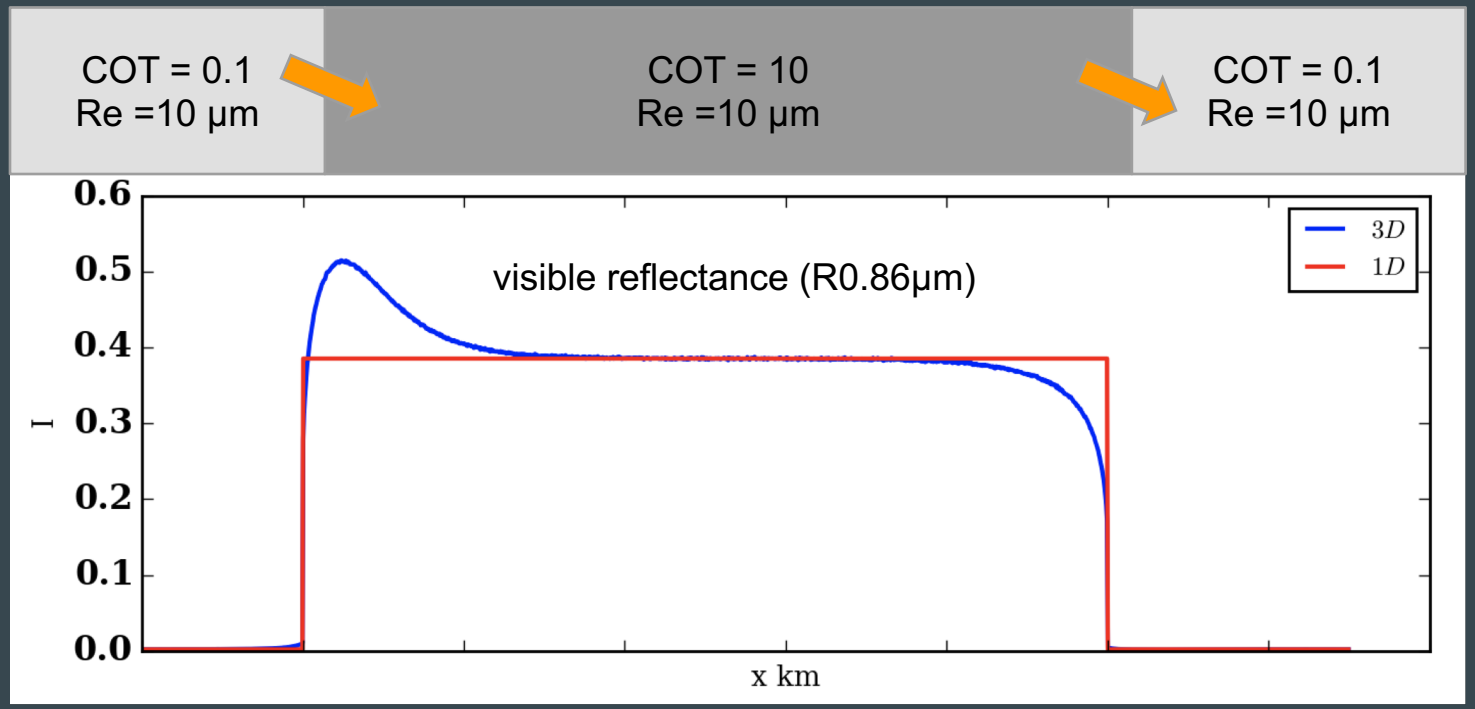
- Fundamental assumptions often made in passive cloud retrieval
  - Individual pixels are **independent** of one another (Independent pixel assumption)
  - Cloud field within each pixel is **homogenous** (homogeneous pixel assumption)

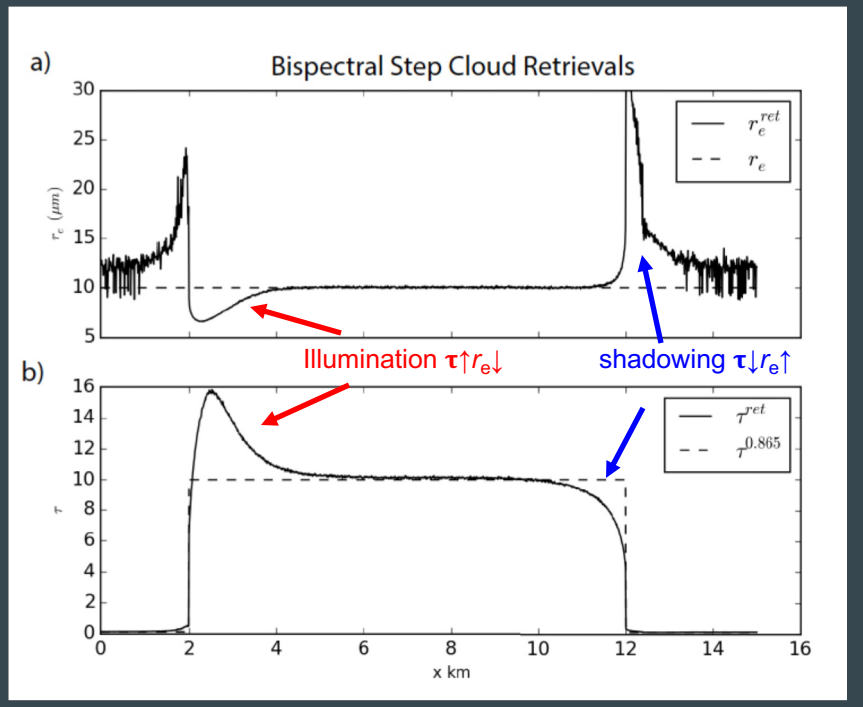
- Clouds in reality more or less deviate from these assumptions leading to 3D effects
  - Geometrical/optical illuminating and shadowing effects (Varnai and Marshak 2002, Marshak et al. 2006)
  - Photon side leaking effect (Barker 1996, Benner and Evans 2001)
  - Radiative smoothing and roughening (Marshak et al. 1995)
  - …

An example: Step Cloud

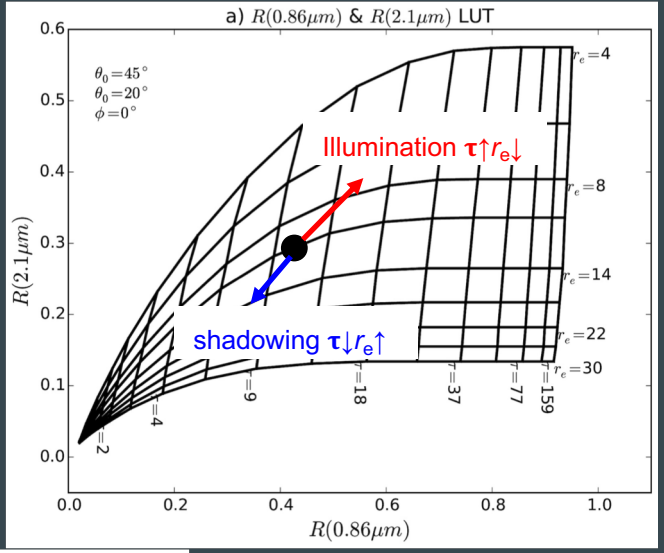
Deviation from Independent Pixel Assumption can lead to strong illumination and shadowing effects

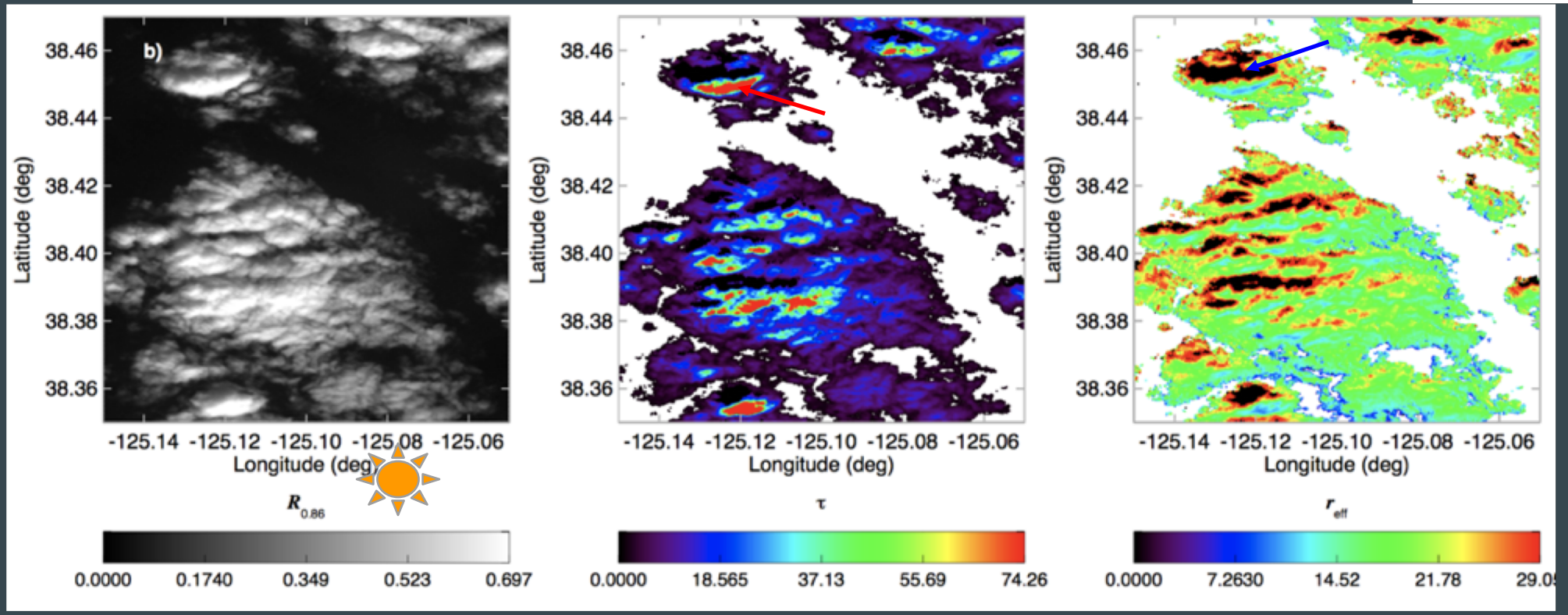






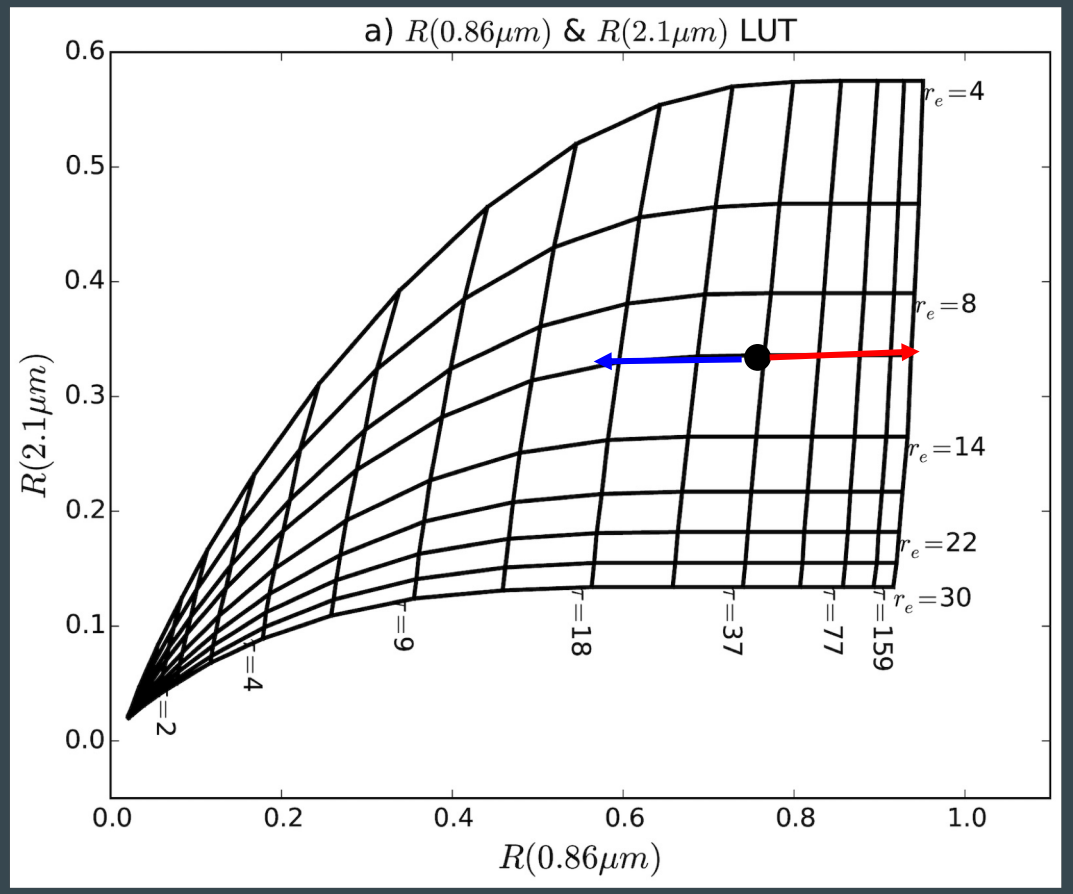
It is *not* just a cartoon!



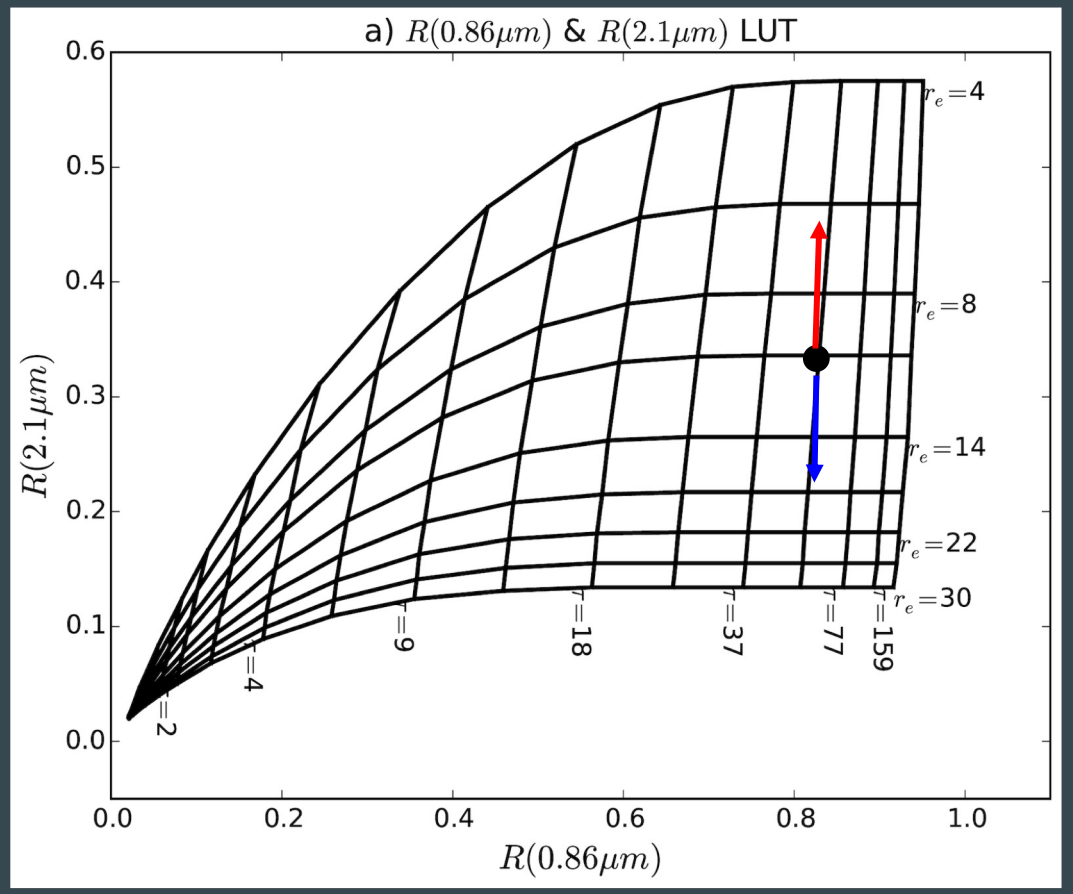


Real retrievals from ASTER (Werner et al. 2016)

Unfortunately, errors do not cancel out.



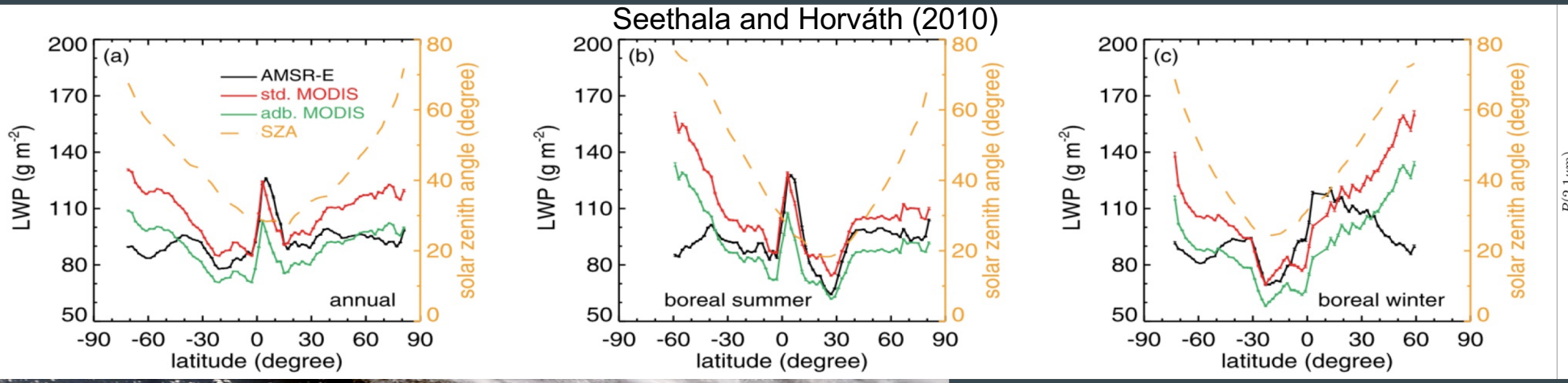
Illumination effect dominates COT bias (overestimation)

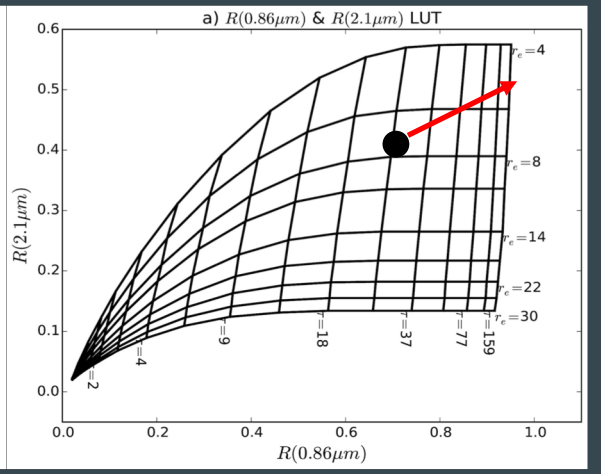


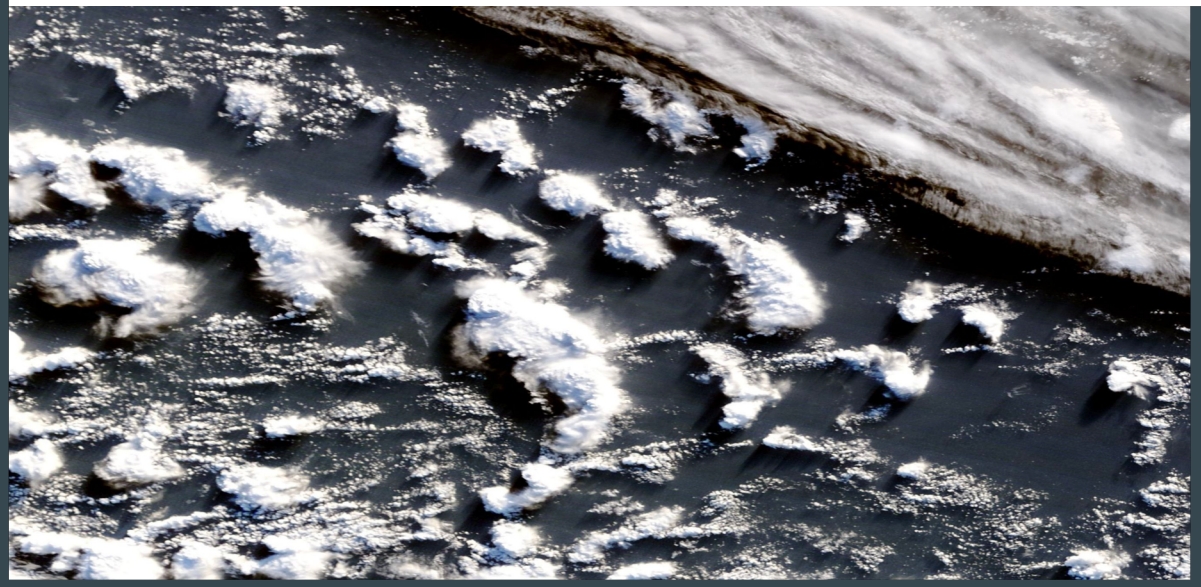
shadowing effect dominates CER bias (overestimation)

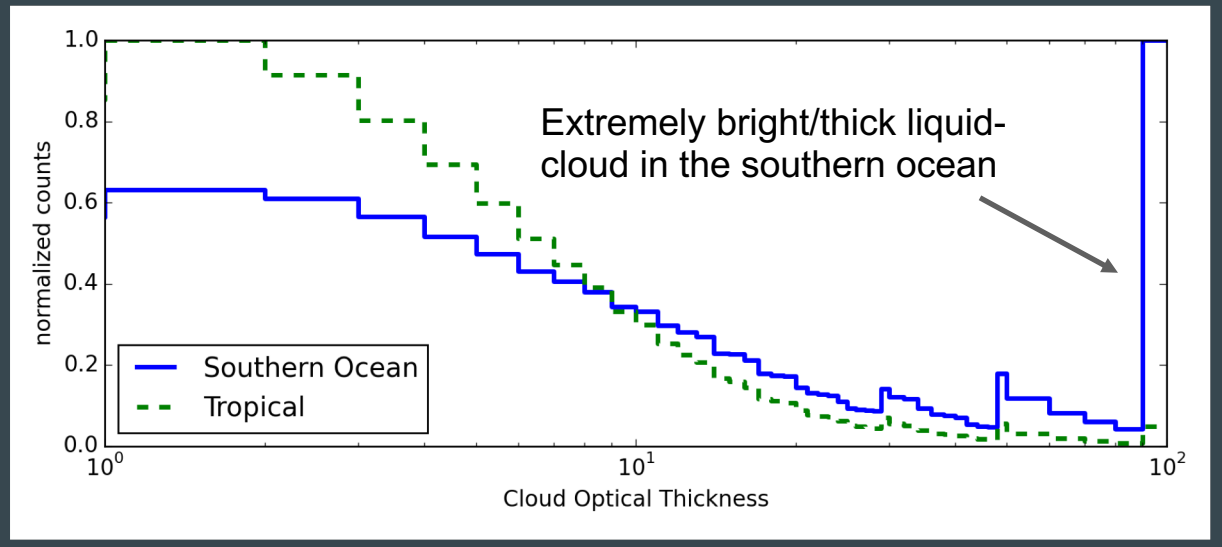
Why should we care?

Seethala and Horváth (2010)









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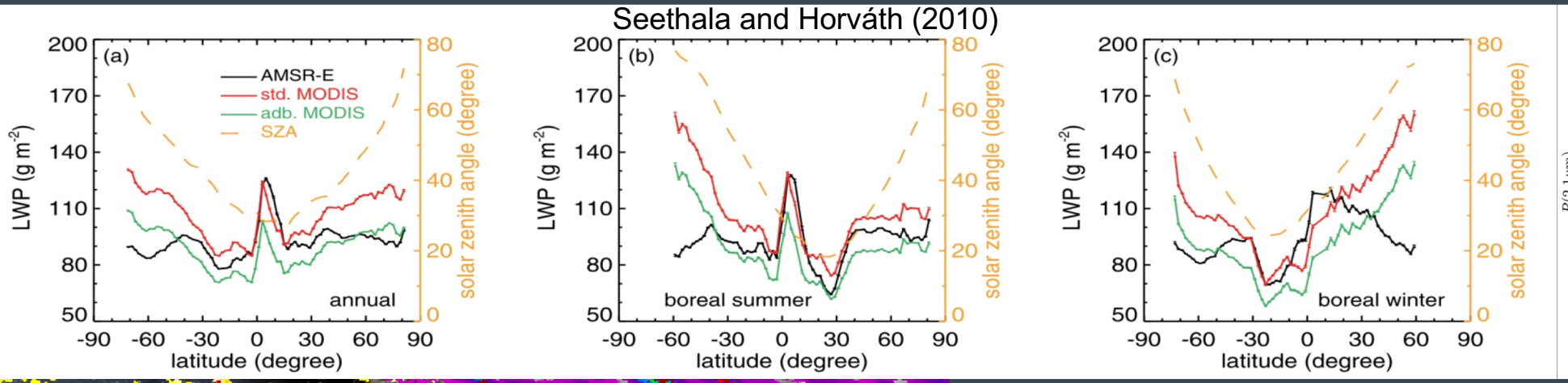
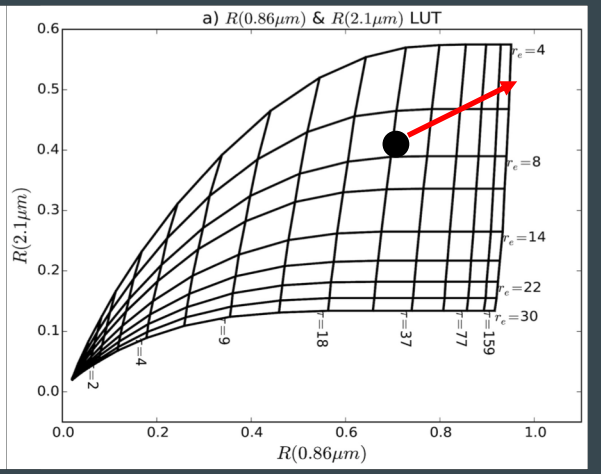
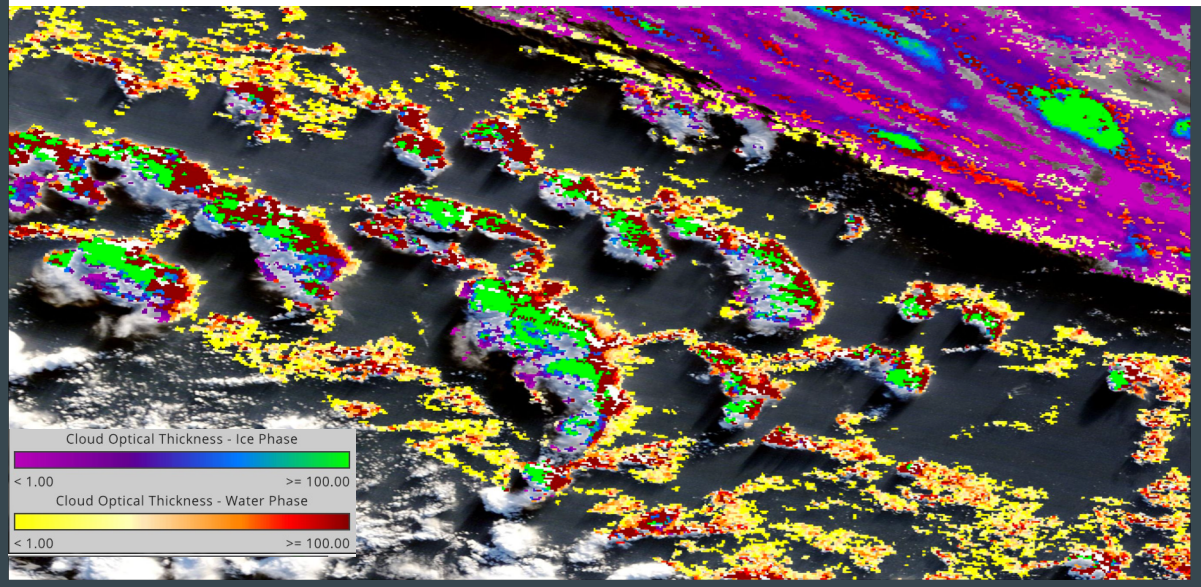
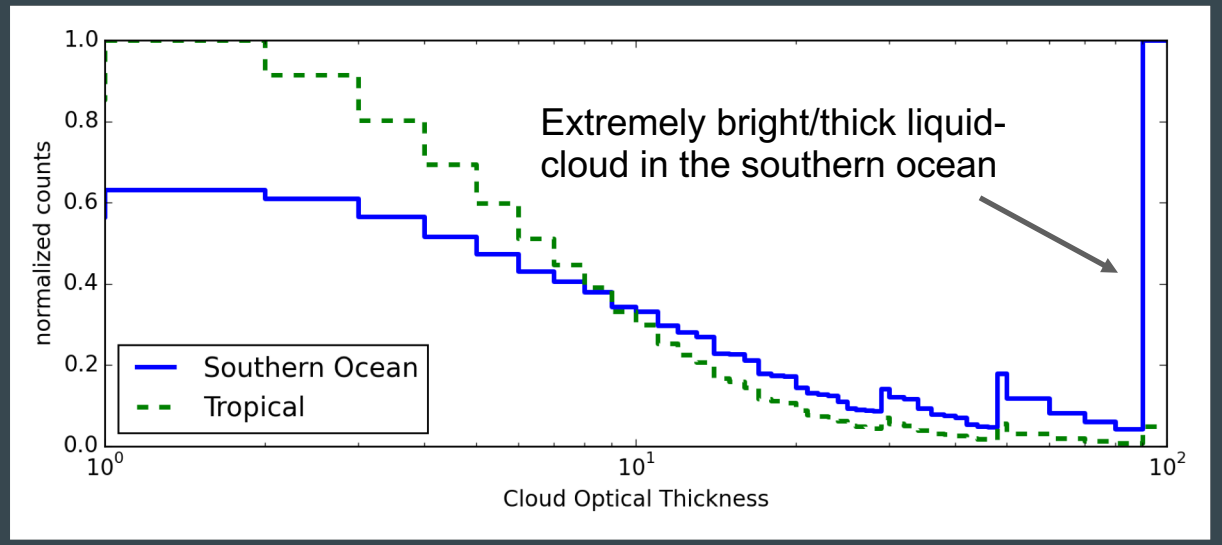


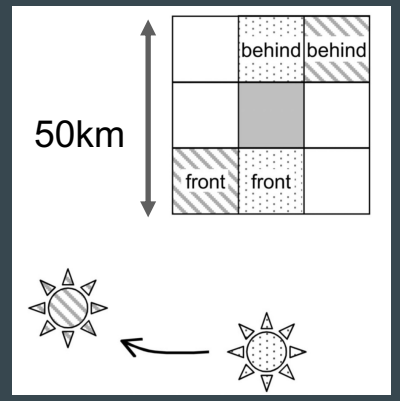


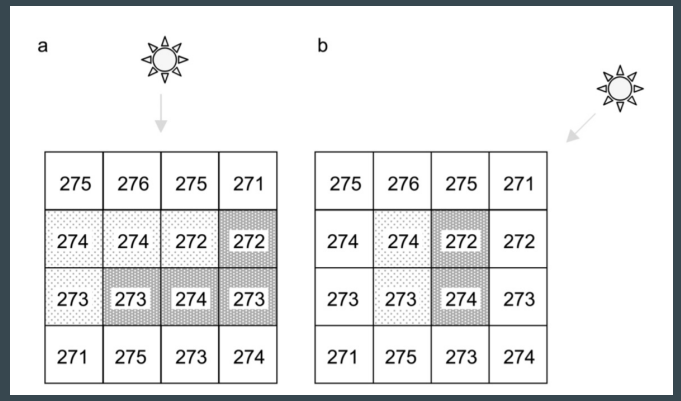


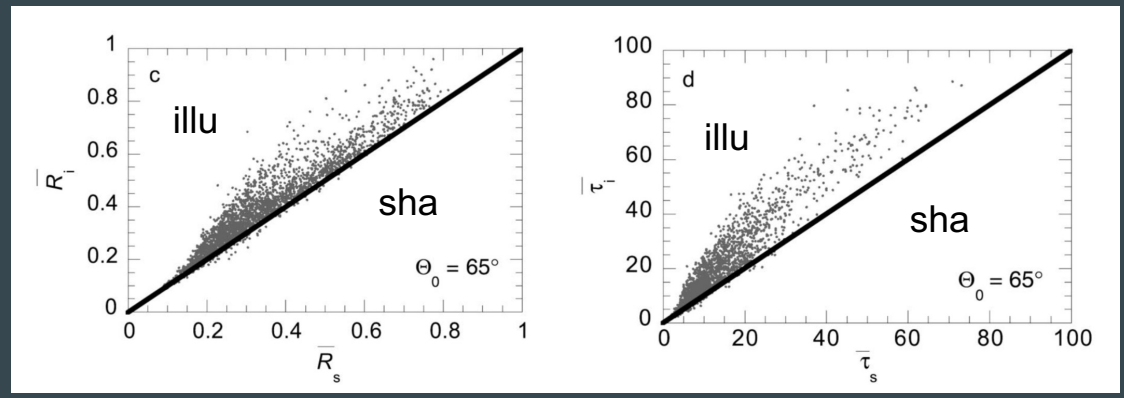


How can we detect and quantify 3D effect?

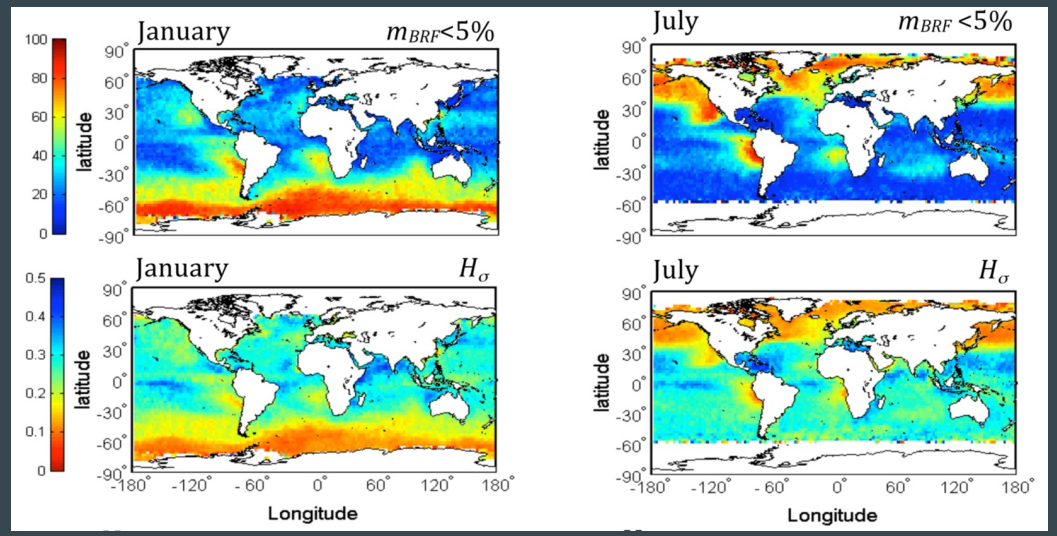
Varnai and Marshak 2002



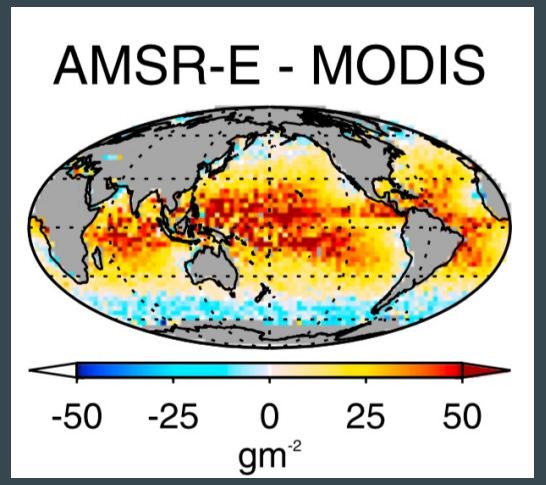


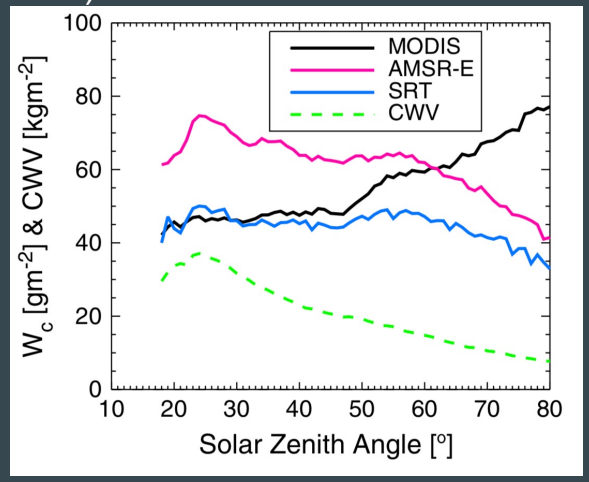


Di Girolarmo and Liang 2010)

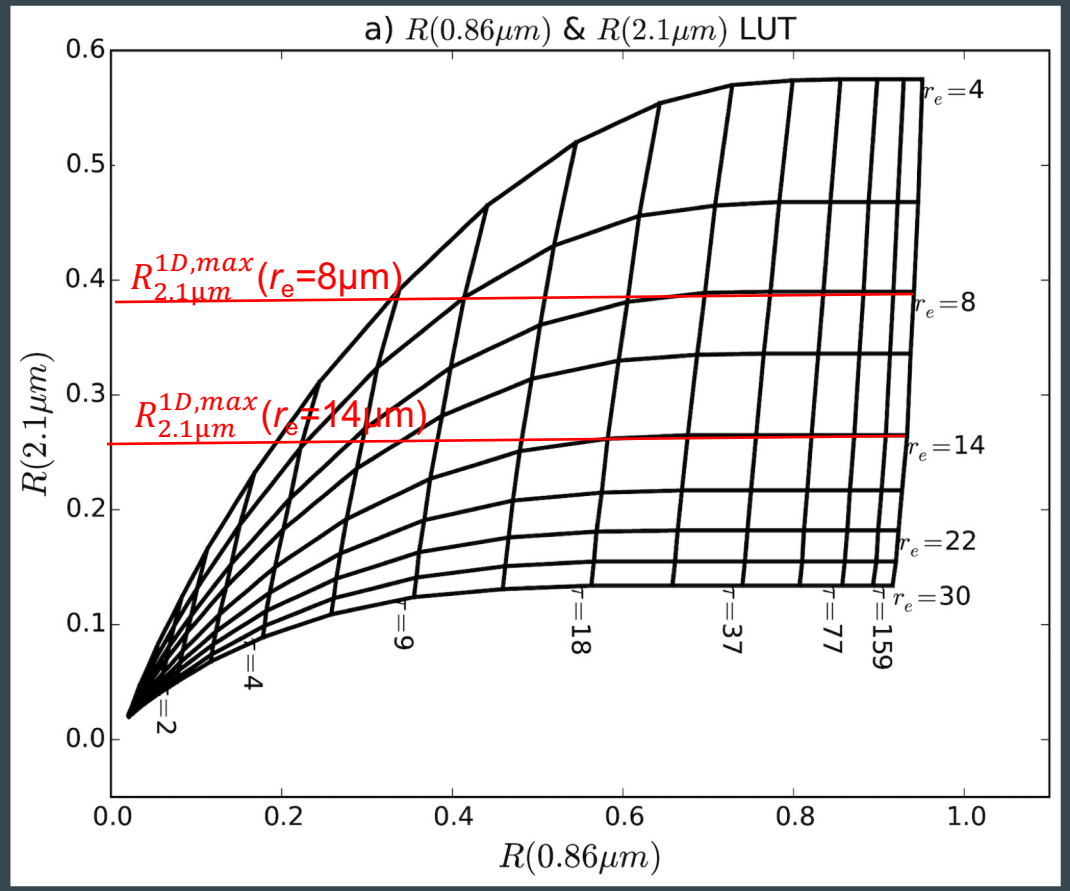


Lebsock et al. 2014)





Our method to detected pixels influenced by illuminating effect: detection of "maximum 1D SWIR reflectance $R_{SWIR}^{1D,max}$"



Given a r_e, the cloud reflectance in the SWIR band has an upper limit under the 1D radiative transfer, i.e. $R_{SWIR}^{1D,max}(r_e)$, as a result of cloud absorption.

If a cloud with known r_e appears brighter than $R_{SWIR}^{1D,max}(r_e)$, then it is probably caused by the illuminating effect.

In order to know $R_{SWIR}^{1D,max}(r_e)$, we need to know unbiased r_e (i.e., higher-than-expected brightness is due to 3D effect, not smaller r_e).

But how can we get unbiased r_e retrieval?
from collocated multi-angular polarimetric retrieval (Bréon and Goloub 2005**)!**

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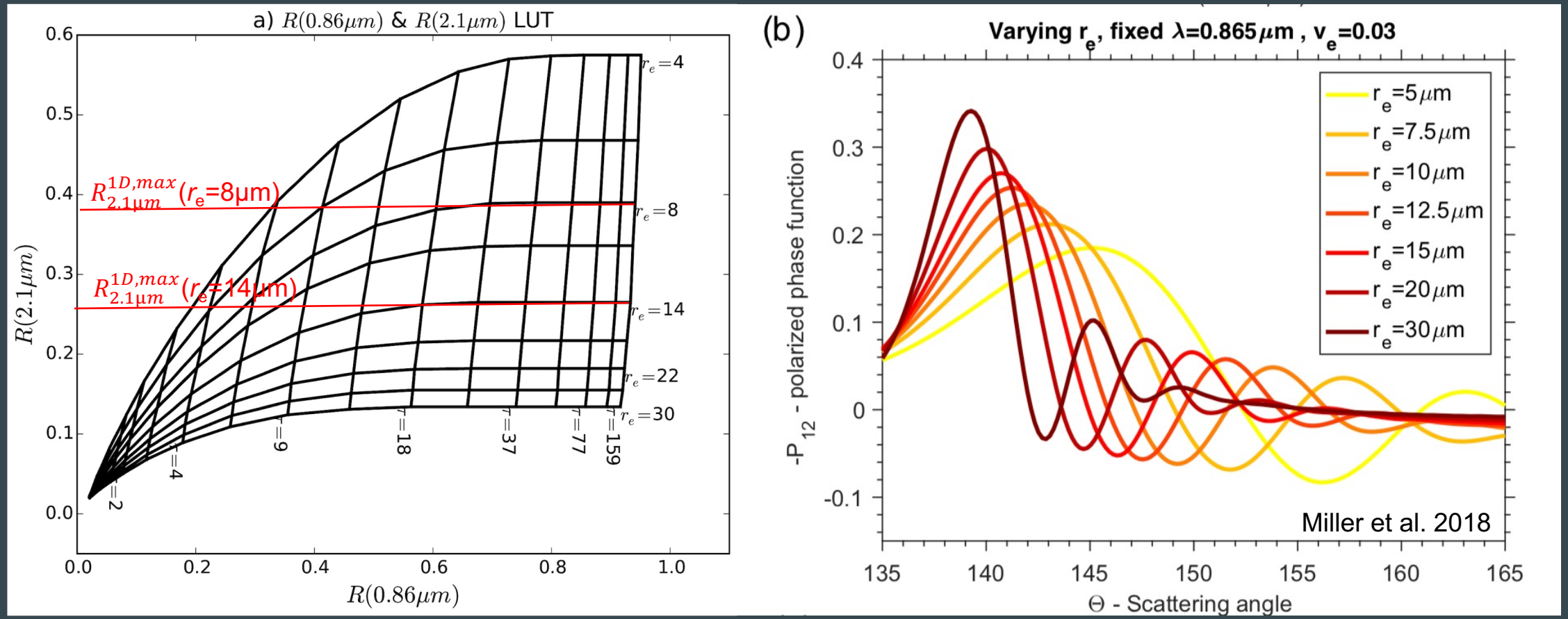
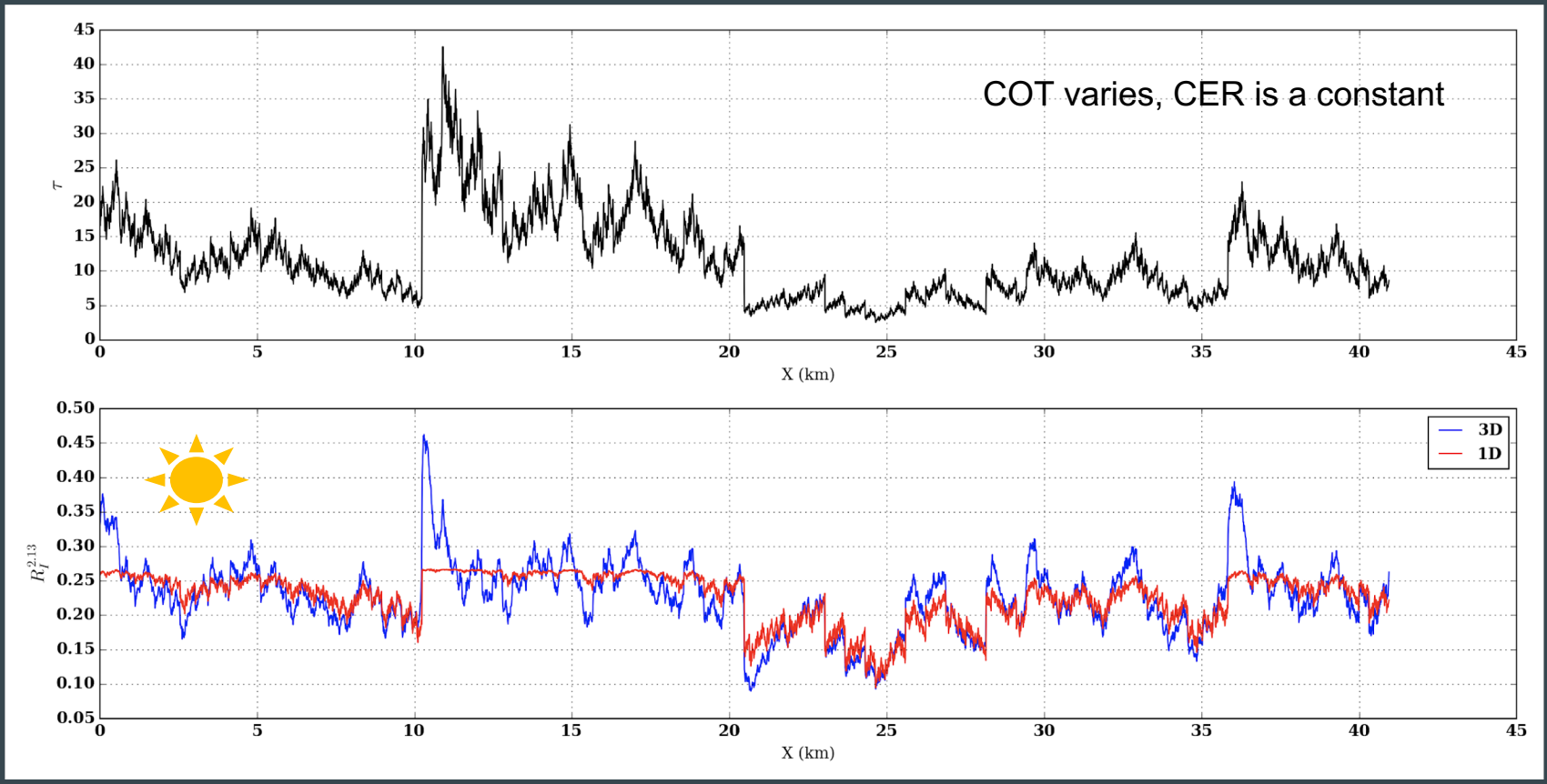
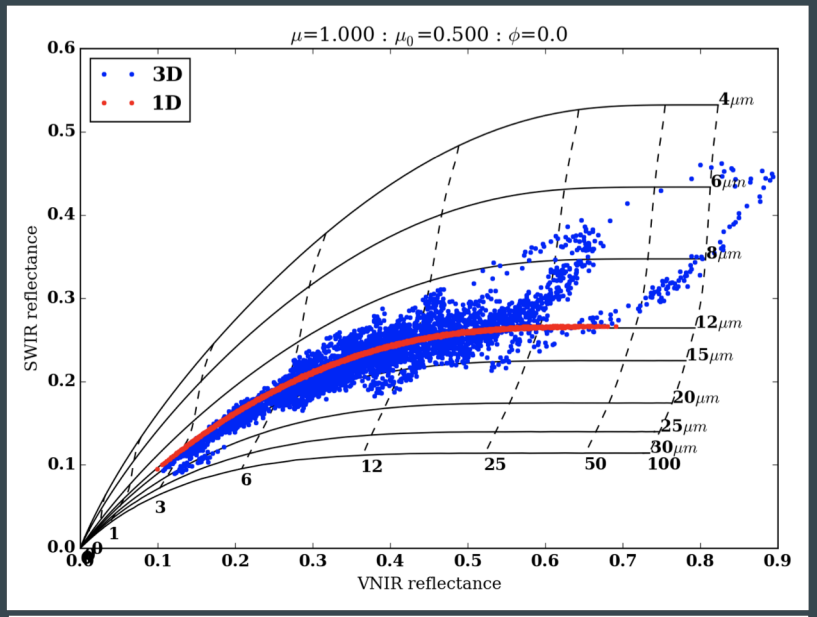
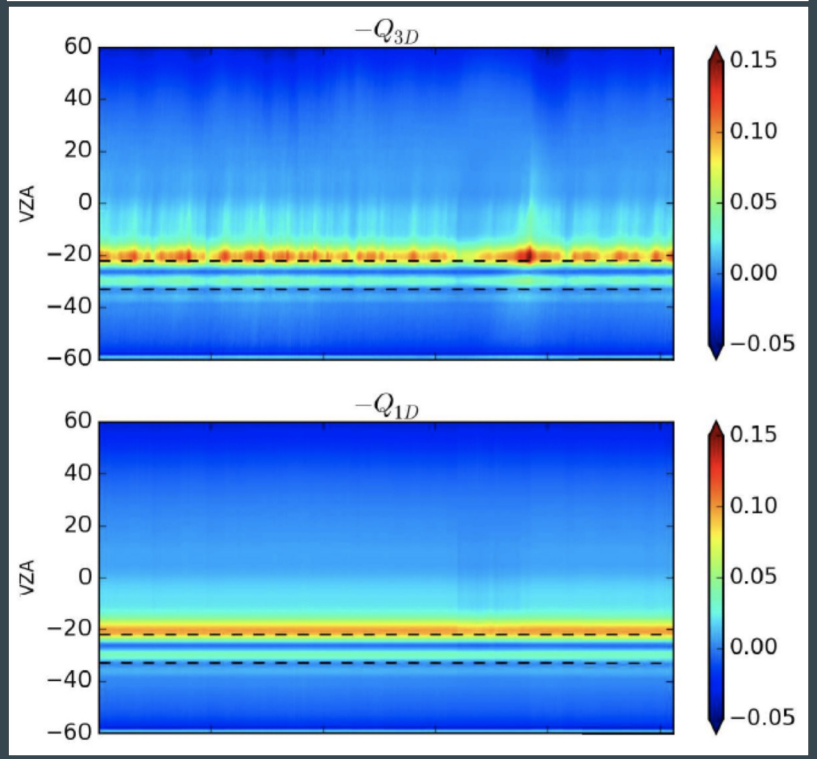


A test on fractal clouds

COT/CER retrieval using the bi-spectral method is clearly affected by 3D effects

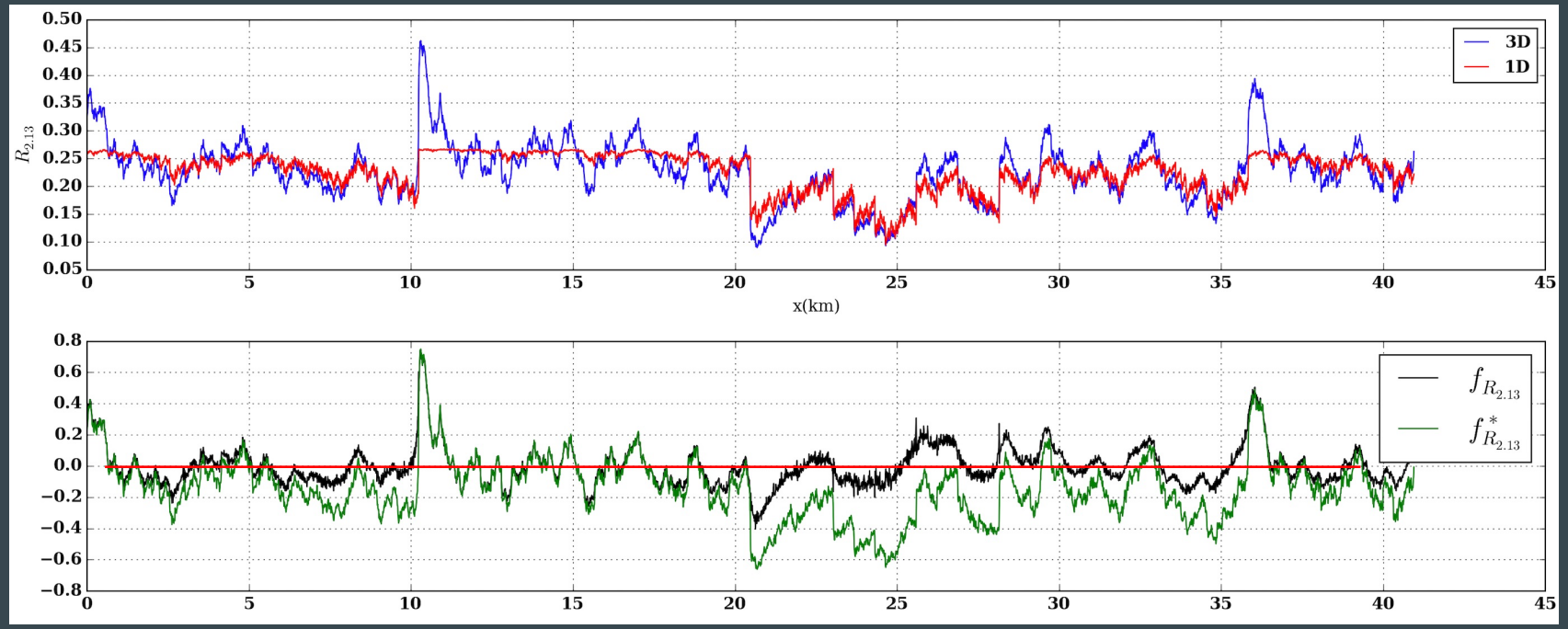






CER retrieval based on polarimetric method is **not** affected by COT inhomogeneity. Magnitude is influenced but the angular location of the prime and supernumerary cloud bows is not

Detection of illumination effect using M1R



Polarimetric CER retrieval

↓

Computation of $R^{1D,max}_{SWIR}(r_e)$

↓

Computation of $f^*_{R,SWIR}$

↓

$f^*_{R,SWIR} > 0$ Cloud brighter than the maximum 1D reflectance? Yes, Illumination effect

$$f_{R\,2.13} = \frac{R^{3D}_{2.13\mu m}}{R^{1D}_{2.13\mu m}} - 1$$

unknown

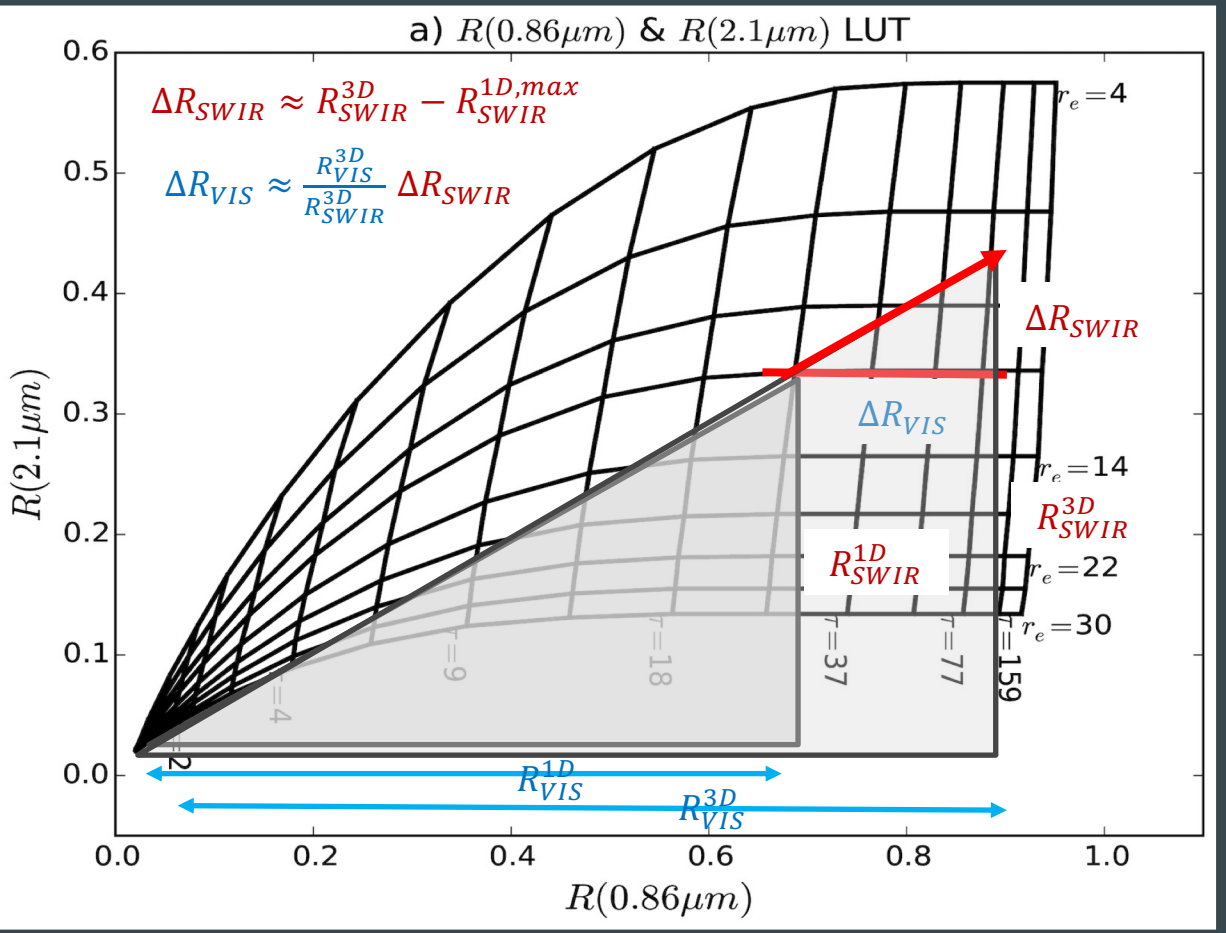
$$f^*_{R\,2.13} = \frac{R^{3D}_{2.13\mu m}}{R^{1D,max}_{2.13\mu m}} - 1$$

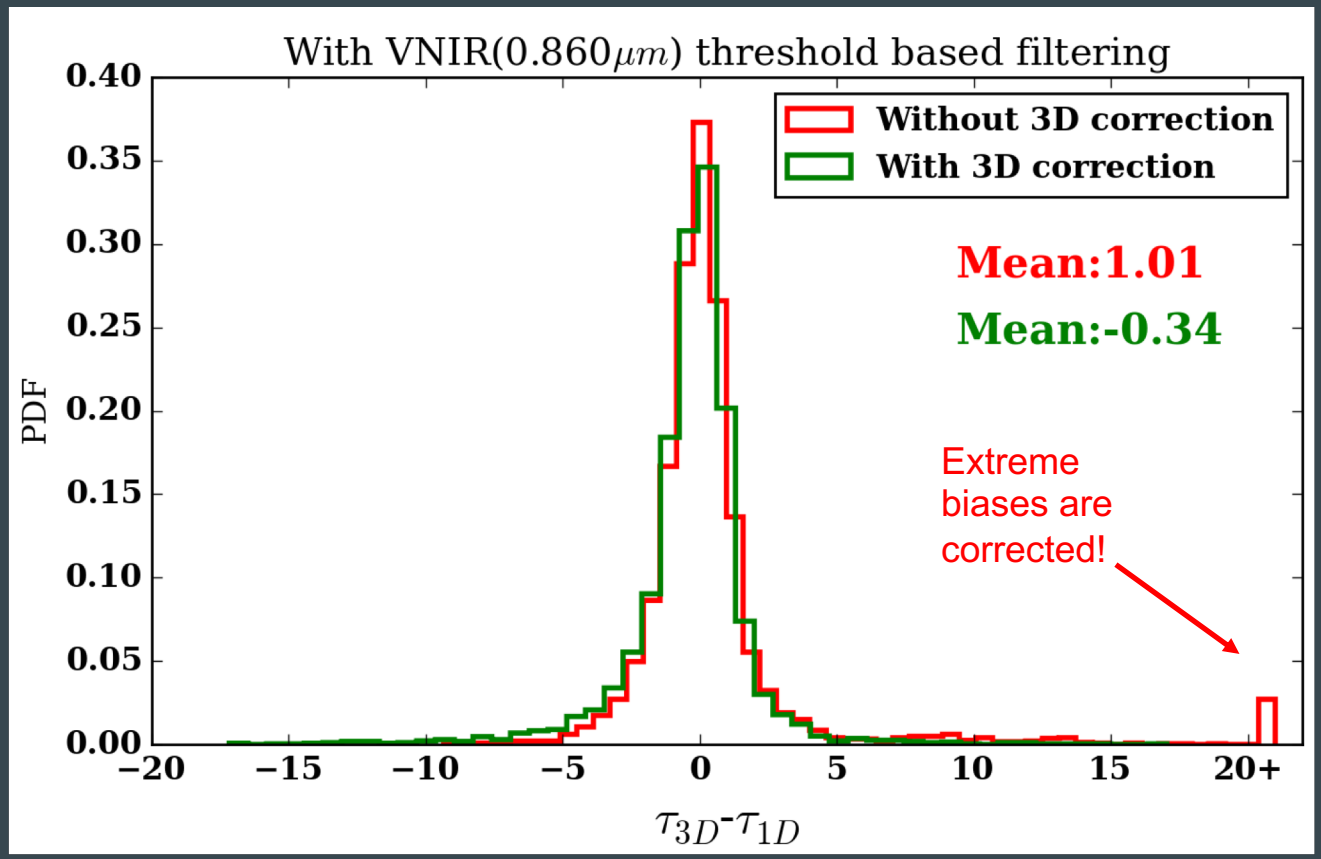
can be derived from polarimetric CER

Correct the illuminating effect a much harder job

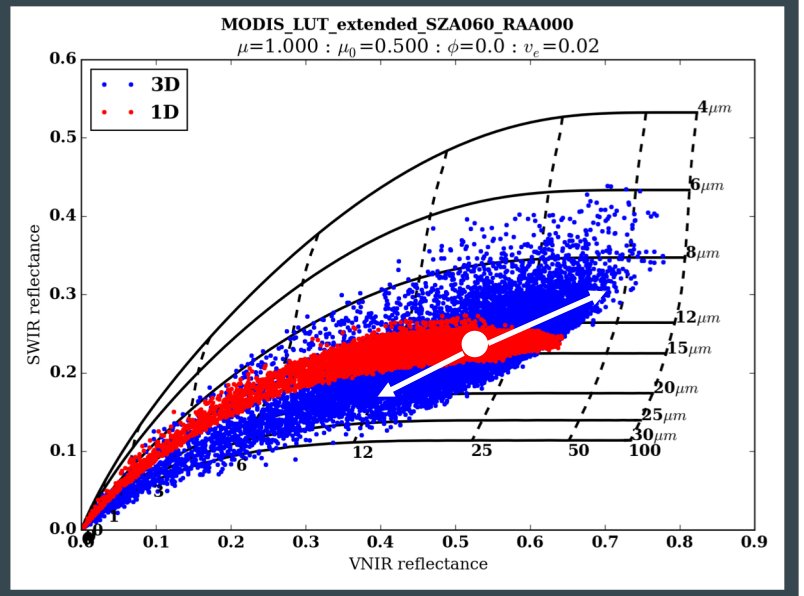
Assumption: 3D effect does not change $R_{SWIR}/\ R_{VIS}$

$$\frac{R^{3D}_{SWIR}}{R^{3D}_{VIS}} \approx \frac{R^{1D}_{SWIR}}{R^{1D}_{VIS}} \approx \frac{R^{1D,max}_{SWIR}}{R^{1D}_{VIS}}$$



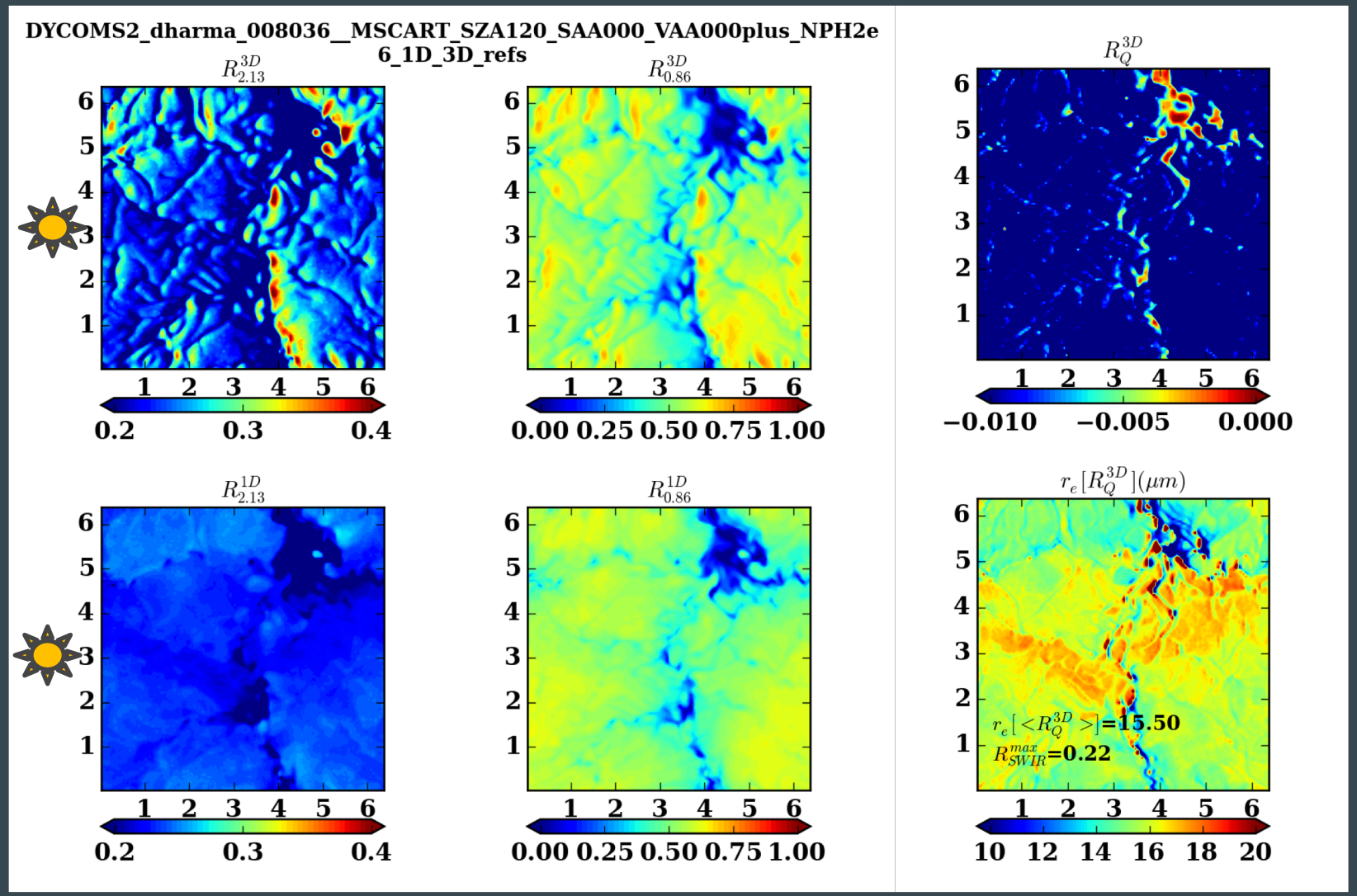


Test on LES cloud field (on-going)

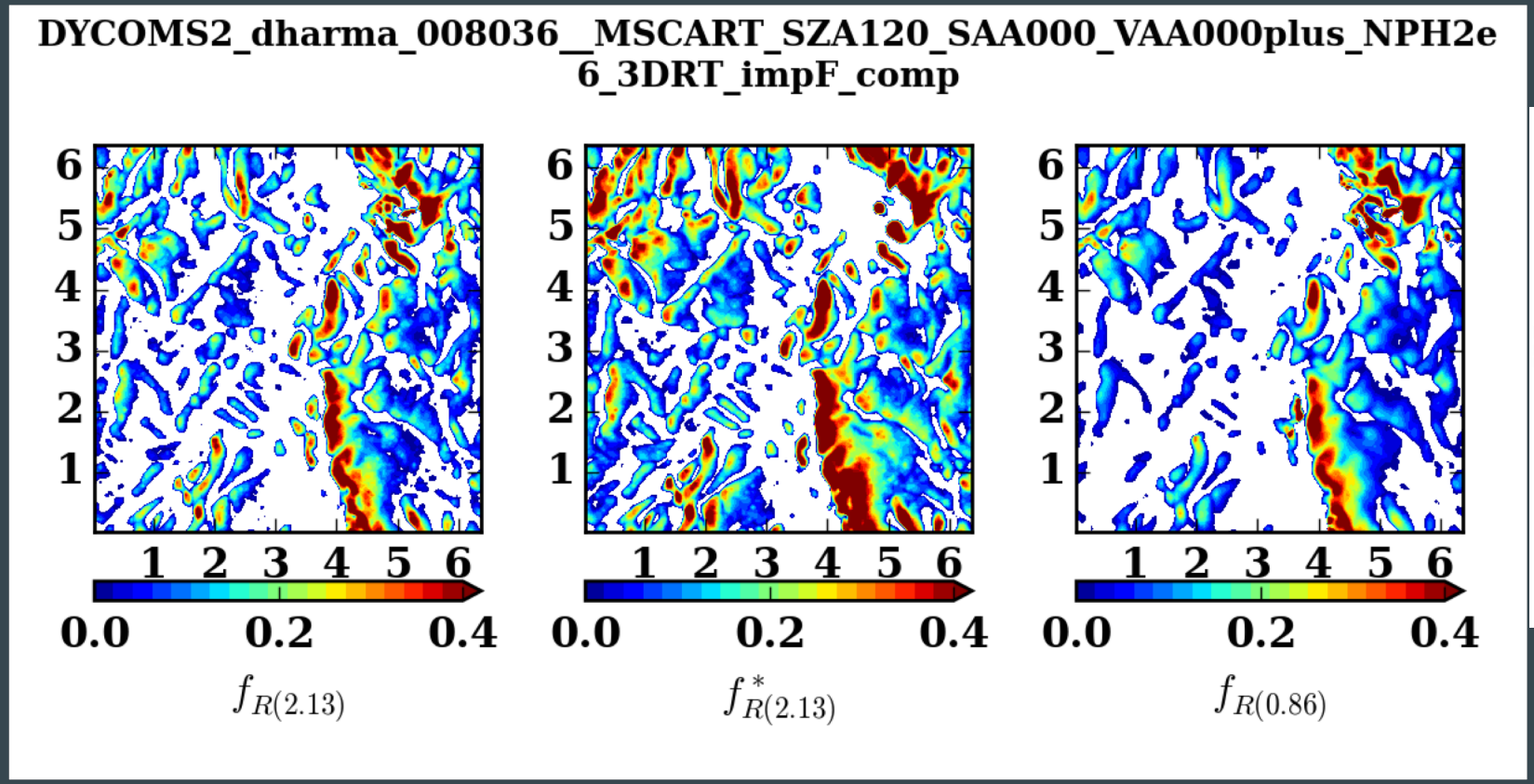


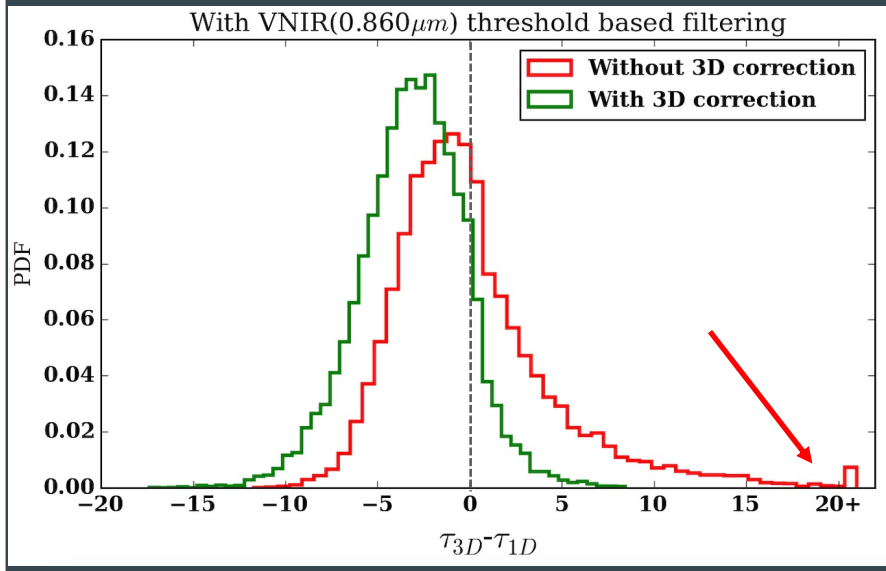
Case set up:

- DYCOMS-II RF 02 case
- DHARAMA LES model (Ackerman) et al. 2004
- Solar zenith 60° azimuth 0 (from left to right)
- Radiative Transfer Model: 3D polarimetric (MSCART Wang et al. 2018)



Detection and correction:





"True" illumination effect in SWIR band

Detected illumination effect using M1R method

"True" illumination effect in VIS band

Extreme COT bias resulted from the illumination effects are corrected.

Problem: positive biases are corrected. Now the statistics are dominated by negative bias (shadowing effect)

Summary and outlook

- *3D radiative effects can cause significant error in radiometric-based passive cloud property (i.e., COT & CER) retrievals*
  - There are increasing evidences showing that 3D radiative effect might have caused significant overestimation of cloud LWP over high latitude under low sun condition.
- *A novel method ("maximum 1D reflectance" detection) using the combination of polarimetric and radiometric observations has been developed to detect and correct 3D effects*
  - Currently, our method is able to detect those pixels that are strongly affected by the illuminating effects.
  - Correction of COT retrieval seems possible based on some assumptions.
- *Future research is needed to:*
  - Better understand the impacts of 3D effects on polarimetric-based CER retrieval
  - Explore pathways to detect and correct "shadowed" pixels.
  - Study the sensitivity to spatial resolution of instruments.
  - Test on real observations and validate/evaluate the results?

Thanks and Questions?
You suggestions/comments are most welcome!

Instrument requirements

- *Requirements on polarimeter*
  - Tempo-spatially collocated with radiometric measurements
  - High-angular resolution that is able to resolve cloud bows at the spatial resolution not larger than ~10 km (CER can be assumed as constant within pixel)
  - Angular-sampling covers the supernumerary and primary cloud bow
- *Requirements on radiometer*
  - Tempo-spatially collocated with polarimetric measurements
  - High-spatial resolution that is able to resolve the 3D effect due to IPA violation
  - Need both VNIR (0.6 µm or 0.8 µm) and SWIR (1.6 µm, 2.1/2.25 µm) bands
- *Possibilities in the near future?*
  - Airborne: RSP-eMAS, airHARP-eMAS
  - Space-borne: OCI-polarimetric on PACE mission, 3MI?