UMBC

INTERACTIONS OF RADIATION WITH AEROSOLS AND CLOUDS IN A THREE-DIMENSIONAL ATMOSPHERE: IMPLICATIONS FOR AEROSOL AND CLOUD REMOTE SENSING

by Chamara Rajapakshe

Jun 25, 2020

Advisory Committee:

- Prof. Zhibo Zhang (Chair/Adviser)
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- Prof. Pengwang Zhai
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- Dr. Adriana Rocha Lima

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Overview

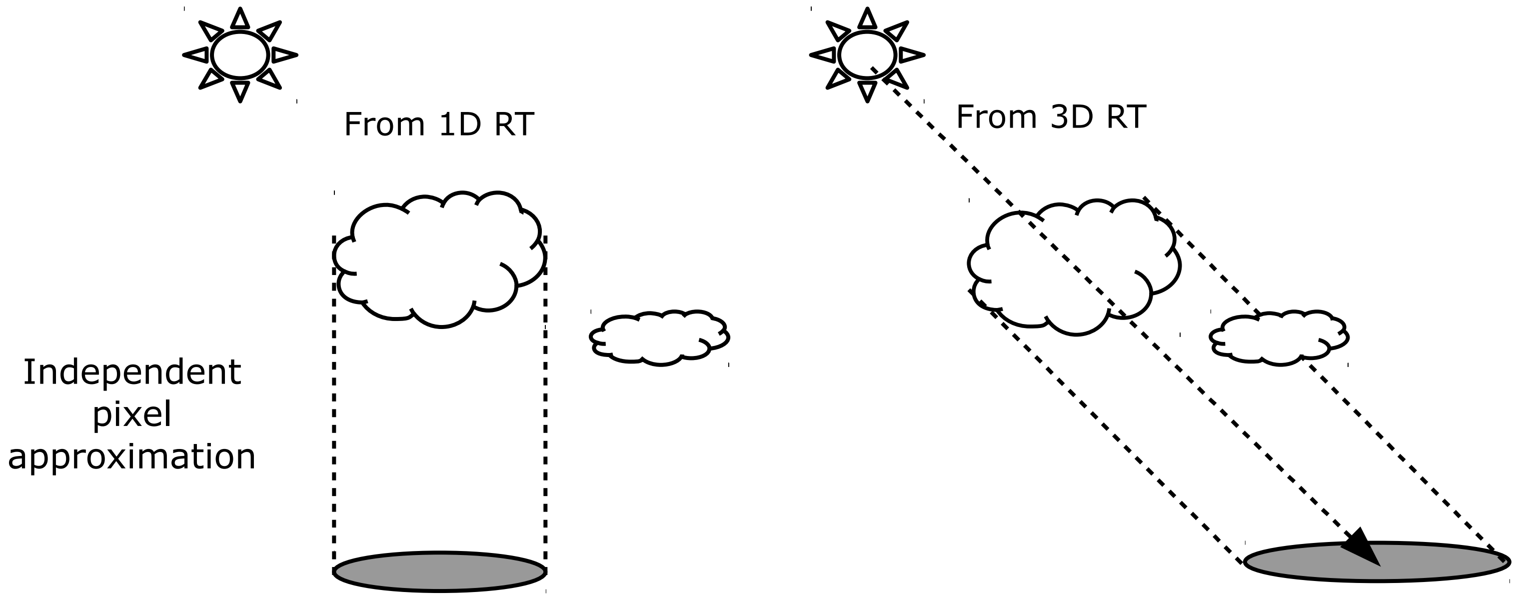
- Developed an advanced satellite retrieval simulator setup
- Introduced a new framework to understand the retrieval biases in the bi-spectral retrieval due to 3D radiative transfer effects
- Identified mechanisms that could induce biases in the polarimetric retrievals due to the 3D radiative transfer effects
- Introduced a new technique to detect and correct strong positive COT biases in the bi-spectral retrievals using polarimetric retrievals
- Found that the above-cloud aerosols in SE Atlantic region are closer to underlying clouds than previously expected

[1] **Rajapakshe, C.** and Zhang, Z. (2020). Using polarimetric observations to detect and quantify the three-dimensional radiative transfer effects in passive satellite cloud property retrievals: theoretical framework and feasibility study. *Journal of Quantitative Spectroscopy and Radiative Transfer*, page 106920.
[2] **Rajapakshe, C.**, Zhang, Z., Yorks, J. E., Yu, H., Tan, Q., Meyer, K., Platnick, S., and Winker, D. M. (2017). Seasonally Transported Aerosol Layers over Southeast Atlantic are Closer to Underlying Clouds than Previously Reported. *Geophysical Research Letters*, (410).
[3] Alexandrov, M. D., Miller, D. J., **Rajapakshe, C.**, Fridlind, A., van Diedenhoven, B., Cairns, B., Ackerman, A. S., and Zhang, Z. (2020). Vertical profiles of droplet size distributions derived from cloud-side observations by the research scanning polarimeter: Tests on simulated data. *Atmospheric Research*, 239.
[4] Lu, Z., Liu, X., Zhang, Z., Zhao, C., Meyer, K., **Rajapakshe, C.**, Wu, C., Yang, Z., and Penner, J. E. (2018). Biomass smoke from southern Africa can significantly enhance the brightness of stratocumulus over the southeastern Atlantic Ocean. *Proceedings of the National Academy of Sciences*, page 201713703.

Outline

- Above-cloud-aerosol in SE Atlantic [Rajapakshe et. al. (2017)]
- Introduction
  - What are 3D effects?
  - Background
  - Retrievals simulator setup
- 3D Effects in bi-spectral retrievals
- 3D Effects in polarimetric retrievals
- A new technique to detect and quantify large optical thickness biases in the bi-spectral retrievals due to the 3D effects [Rajapakshe & Zhang (2020)].

What are 3D radiative transfer effects?



- Most operational remote sensing algorithms → Based on 1D Radiative Transfer (RT) simulations instead of realistic 3D RT simulations.
  - Cloud field within each pixel is homogeneous (Homogeneous Pixel Approximation)
  - No net photon transport among pixels (Independent Pixel Approximation)
- When clouds deviate from these approximations, we can expect discrepancies in the retrievals.

Background

- Satellite retrievals - primary source of the global view of aerosol and cloud properties
- Helpful to evaluate global climate models
- To understand the role of aerosols and clouds in the climate system

Previous work

- Large-eddy simulations coupled with 1D radiative transfer

Current work

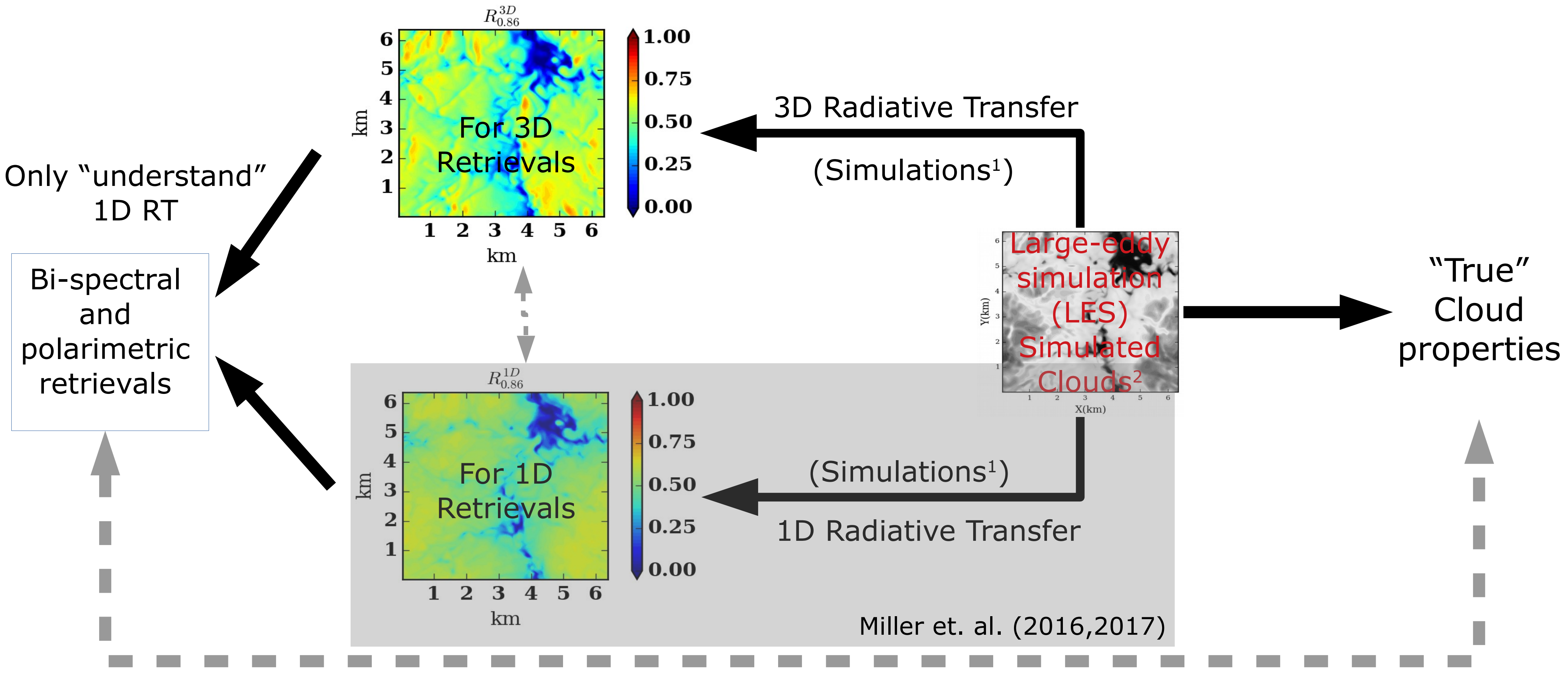
- Extended to perform 3D radiative transfer (both radiometric and polarimetric)

Future

- 1D Flux calculations

- For a given cloud field – biases in the radiance fields
- When the radiance biases are known – retrieval biases

Retrieval simulator

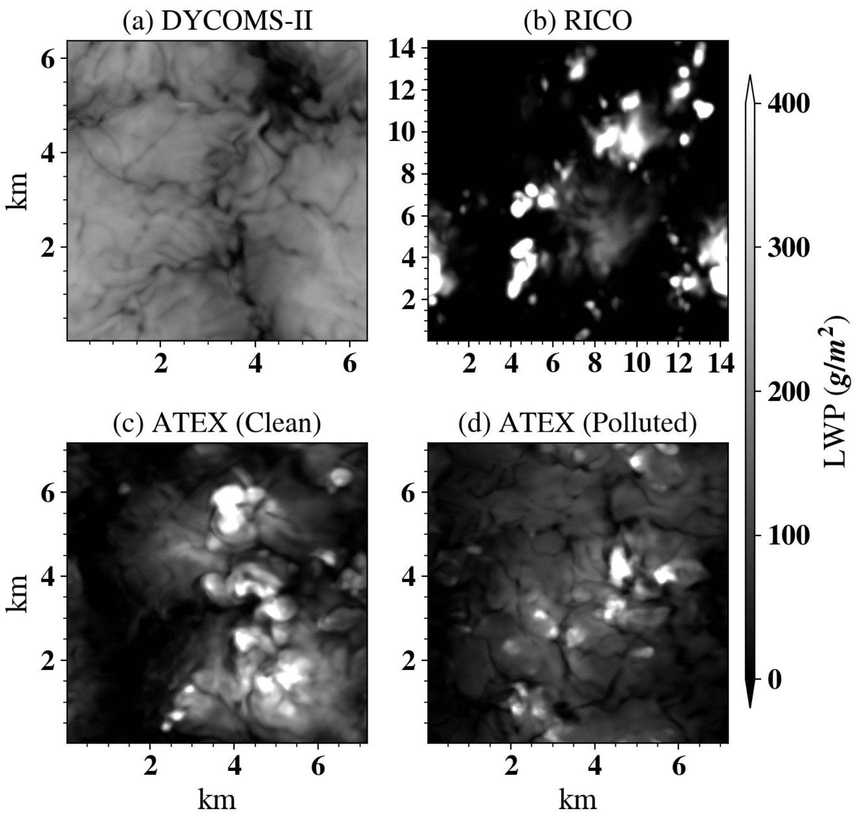


[1]MSCART - Wang et. al. (2017,2019); [2]DHARMA LES model - Ackerman et. al. (2004)

Retrieval simulator: LES clouds

- **DYCOMS-II**: Dynamics and Chemistry of Marine Stratocumulus[1]
  - Marine stratocumulus
- **RICO**: Rain in Cumulus over the Ocean[2]
  - Shallow maritime cumuli
- **ATEX**: Atlantic Trade wind Experiment[3]
  - With different aerosol loading
  - Scattered cumulus / Broken stratocumulus

Various types of cloud fields



[1]Stevens et. al. (2003), [2]Rauber et. al. (2007), [3]Stevens et. al. (2001)

Retrieval simulator: Vertically-weighted properties

Scale the multiple scattering *Solar and viewing zenith cosines*

Vertical-weighting function

$$w(\tau) = c\tau^b e^{-a\left[1/\mu_o + 1/\mu\right]\tau} \quad \text{and} \quad \int_0^\infty w(\tau)d\tau = 1$$

Weighted drop size distribution

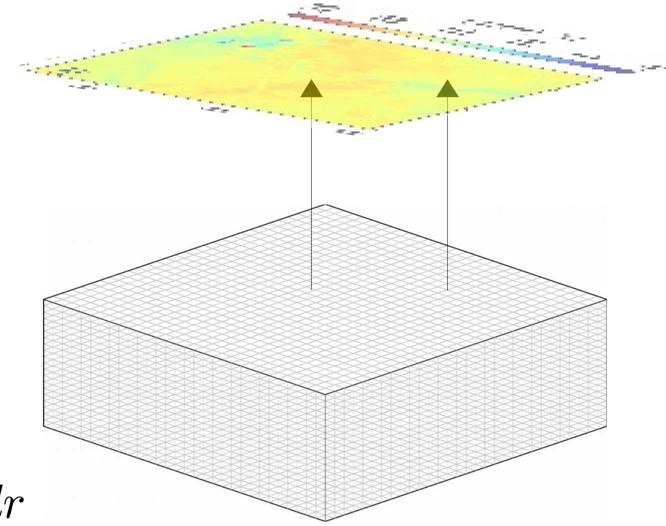
$$n_{vw}(r) = \int_0^\infty n(r,\tau)w(\tau)d\tau$$

Vertical-weighted cloud effective radius (r_e) and cloud effective variance (v_e)

$$r_e^{vw} = \frac{\int_0^\infty Q_s \pi r^3 n_{vw}(r)dr}{\int_0^\infty Q_s \pi r^2 n_{vw}(r)dr} \quad ; \quad v_e^{vw} = \frac{\int_0^\infty Q_s (r - r_e)^2 \pi r^2 n_{vw}(r)dr}{r_e^2 \int_0^\infty Q_s \pi r^2 n_{vw}(r)dr}$$

To define "ground truth"

$COT(\tau)$, $CER(r_e)$, $CEV(v_e)$

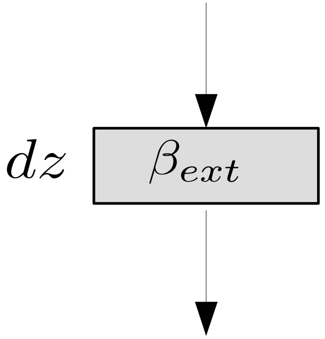


Platnick et. al. (2000), Alexandrov et. al. (2012), Zhang et. al. (2017), Miller et. al. (2017), Hansen and Travis (1974)

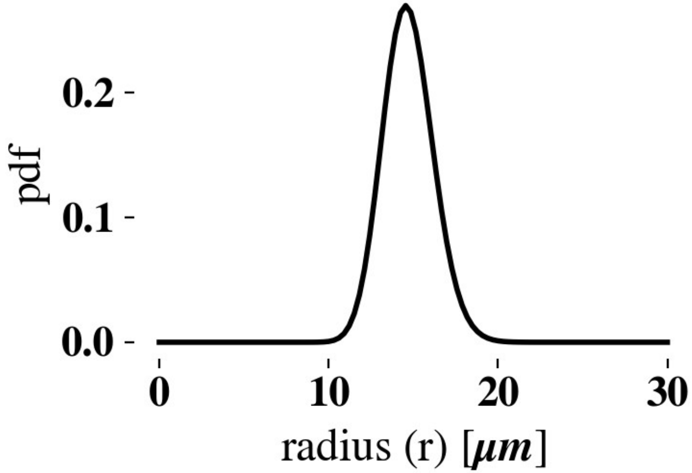
Cloud optical thickness and drop size distribution

$CER(r_e)$ and $CEV(v_e)$

$COT(\tau)$



$$\tau = \int \beta_{ext} dz$$



$$n(r) = \frac{dN(r)}{dr} = N_0 r^{(1-3v_e)/v_e} e^{\frac{-r}{r_e v_e}}$$

Hansen and Travis (1974)

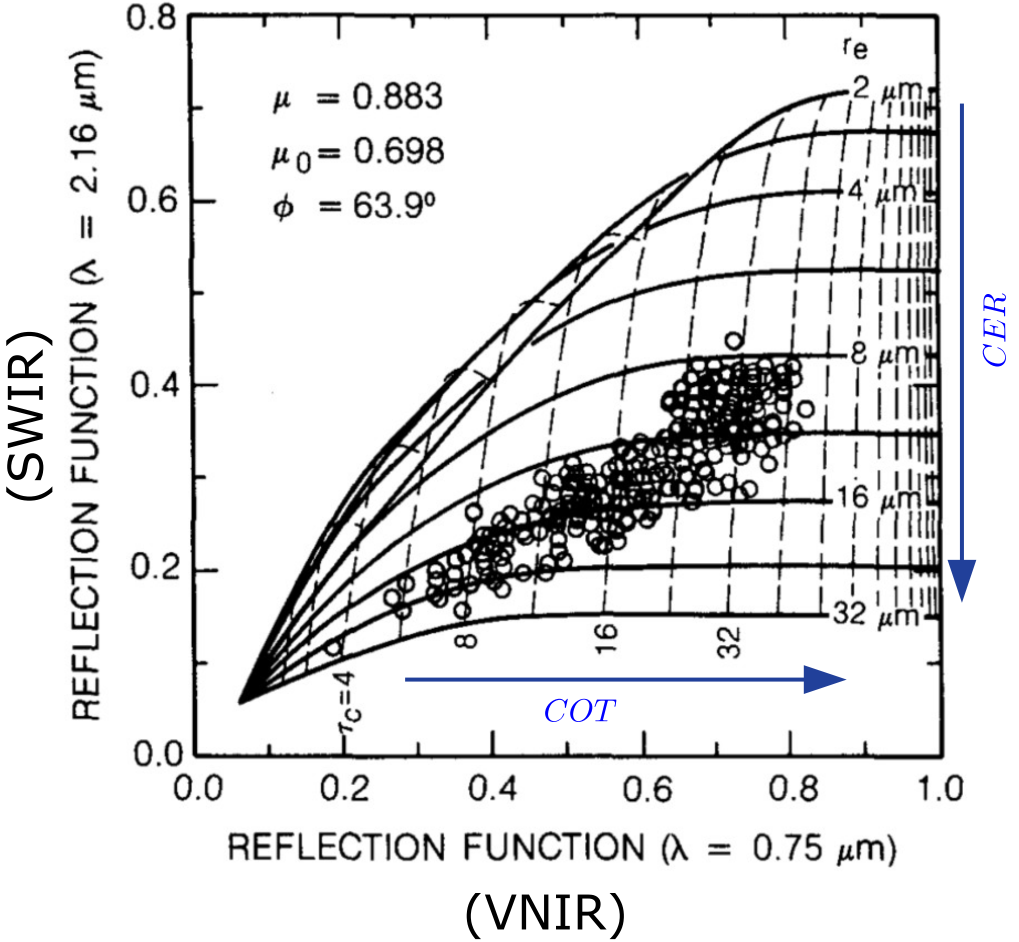
Bi-spectral retrievals (Nakajima-King)

- A pair of reflectances
  - VNIR (negligible water absorption)
  - SWIR (moderate water absorption)
- To retrieve,

$$COT(\tau)$$

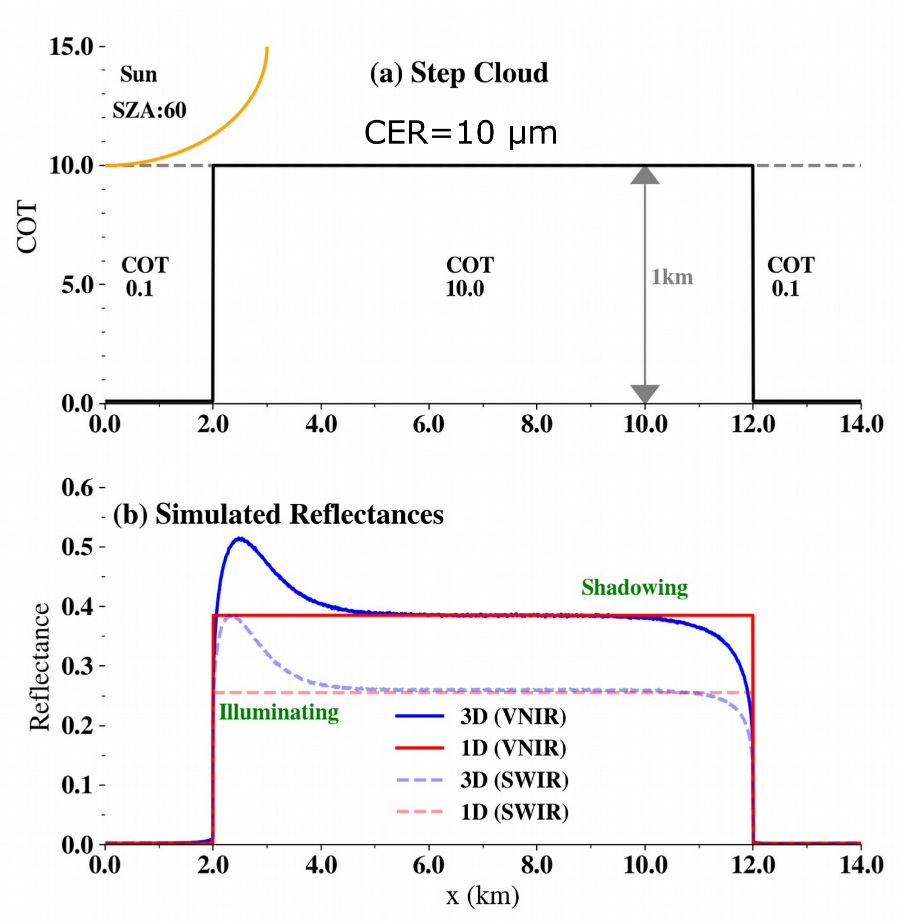
$$CER(r_e)$$

How the bi-spectral retrievals are influenced by the 3D RT effects?



Nakajima and King (1990)

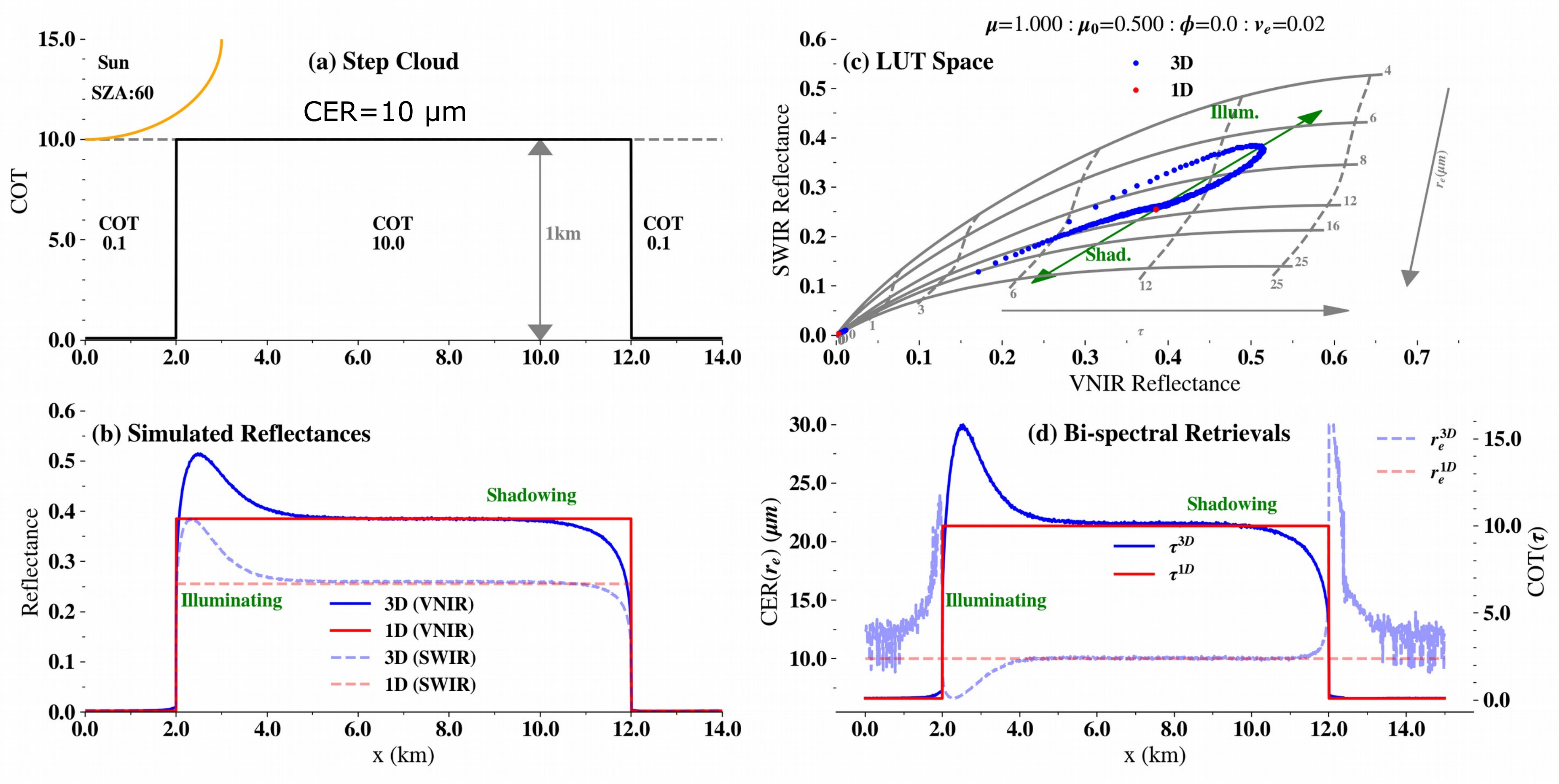
How do 3D RT effects influence to retrievals?



- Hypothetical 1D cloud
- Constant physical thickness with an optically thick region surrounded by optical thin edges
- VNIR (0.86 μm) and SWIR (2.13 μm) **3D and 1D radiative transfer** simulations from MSCART[2]

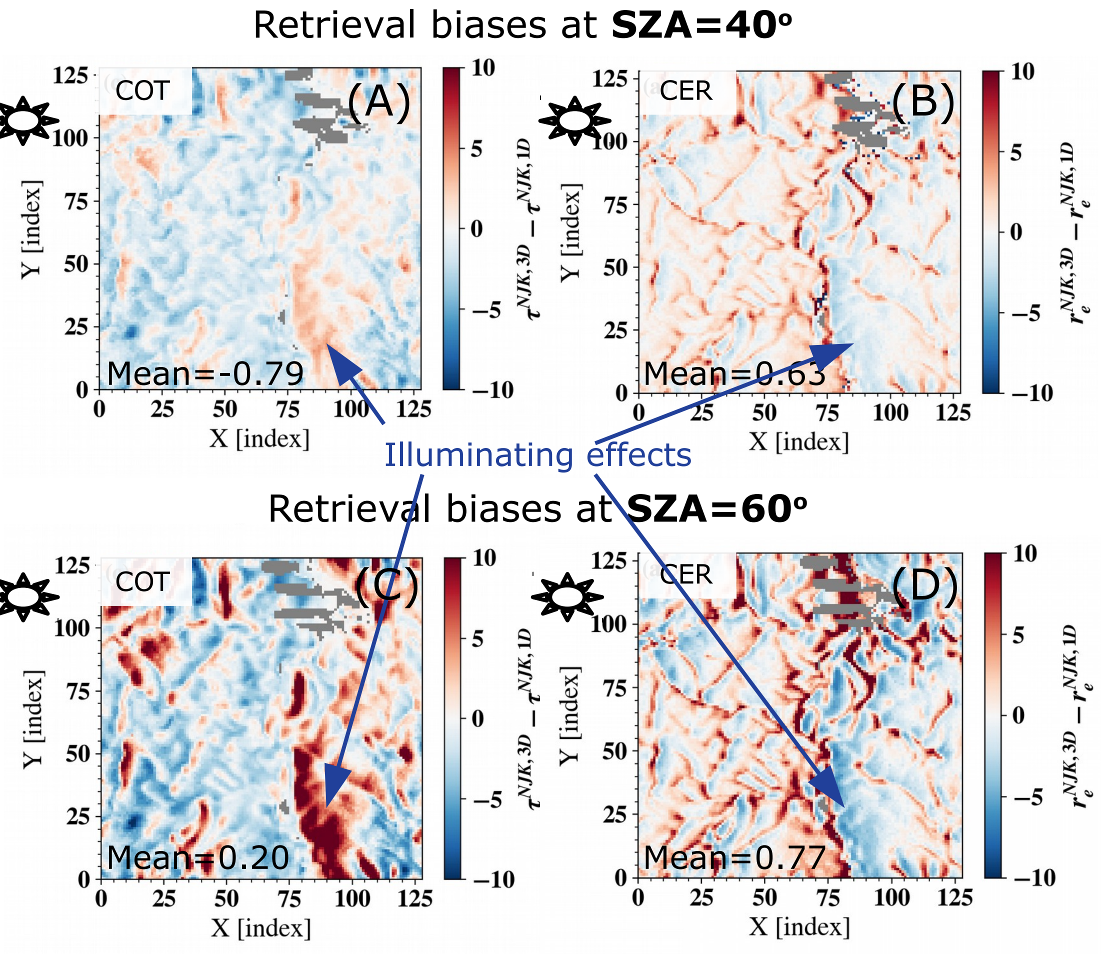
Rajapakshe and Zhang (2020), Wang et. al. (2017,2019)

How do 3D RT effects influence to retrievals?



Rajapakshe and Zhang (2020)

How do 3D RT effects influence to retrievals?



What is our current understanding?

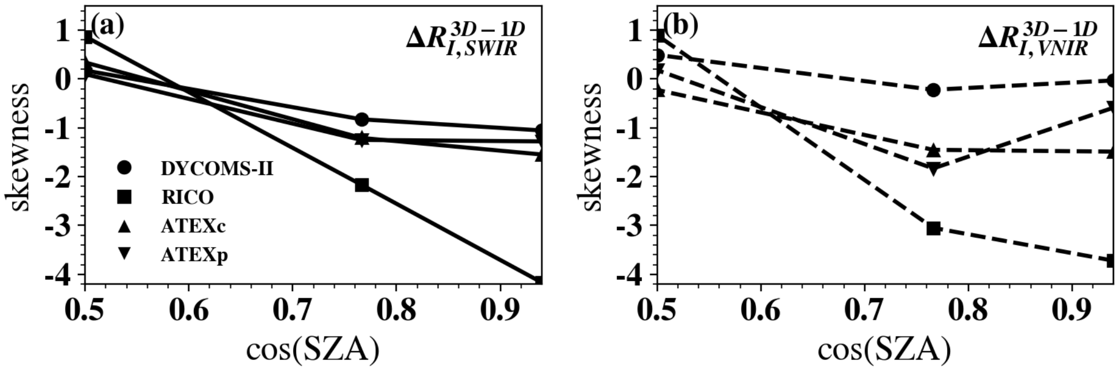
From previous studies[1],

- If the reflectance bias ($\Delta R_{I,\lambda}^{3D-1D}$) has a Gaussian distribution about zero,
- If CER and COT retrievals are independent,

$$\Delta\tau^{ill} > \Delta\tau^{shad.} \text{ and } \Delta r_e^{ill.} < \Delta r_e^{shad.}$$

[1]***Marshak et. al. (2006)***

PDF of radiance biases



From previous studies[1],

- If the reflectance bias ($\Delta R^{3D-1D}_{I,\lambda}$) has a Gaussian distribution about zero,
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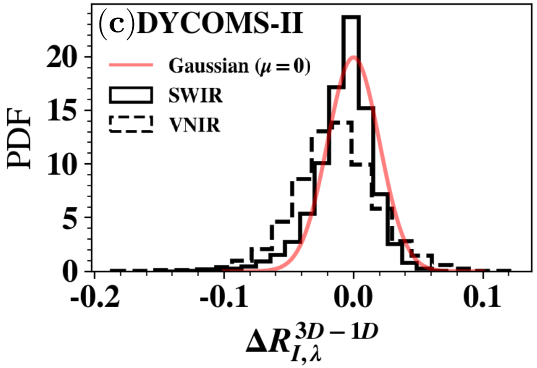
At **SZA=40°**



Skewness

$$\Delta R^{3D-1D}_{VNIR} = -0.21$$

$$\Delta R^{3D-1D}_{SWIR} = -0.82$$

- Homogeneous cloud fields tend to have closer shape to Gaussian (μ=0)
- For large SZAs – Closer to Gaussian (μ=0)
- As SZA decreases – More weight in the shadowing part (likely due to the photon leaking from the cloud-sides)

[1]*Marshak et. al. (2006)*

Are CER and COT retrievals independent?

By considering,

$$\tau(R_{VNIR}, R_{SWIR})\ and\ r_e(R_{VNIR}, R_{SWIR})$$

We can expand both COT and CER into Taylor series[2], and write the 3D-1D bias as follows,

$$\begin{bmatrix}\Delta\tau \\ \Delta r_e\end{bmatrix} = \begin{bmatrix}\frac{\partial\tau}{\partial R_{VNIR}} & \frac{\partial\tau}{\partial R_{SWIR}} \\ \frac{\partial r_e}{\partial R_{VNIR}} & \frac{\partial r_e}{\partial R_{SWIR}}\end{bmatrix}\begin{bmatrix}\Delta R_{VNIR} \\ \Delta R_{SWIR}\end{bmatrix}$$

(Matrix of first derivatives)(Radiance biases)

Where,

$$\Delta\tau = \tau(R^{3D}_{VNIR}, R^{3D}_{SWIR}) - \tau(R^{1D}_{VNIR}, R^{1D}_{SWIR})$$

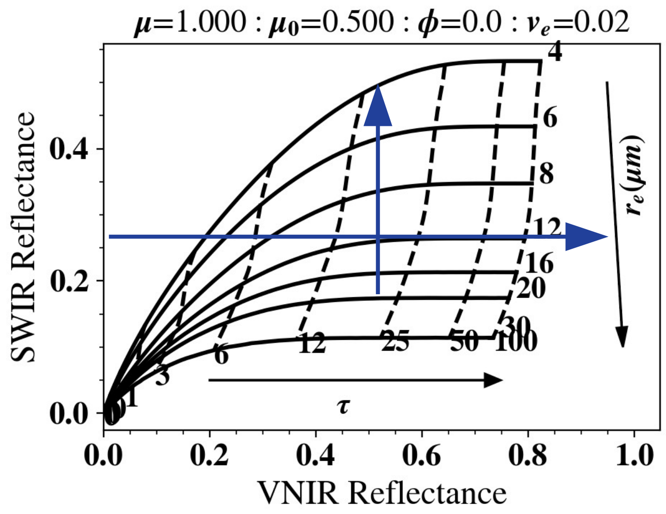
$$\Delta r_e = r_e(R^{3D}_{VNIR}, R^{3D}_{SWIR}) - r_e(R^{1D}_{VNIR}, R^{1D}_{SWIR})$$

From previous studies[1],

- If the reflectance bias ($\Delta R^{3D-1D}_{I,\lambda}$) has a Gaussian distribution about zero,
- If CER and COT retrievals are independent,

$$\Delta\tau^{ill} > \Delta\tau^{shad.} \text{ and } \Delta r_e^{ill.} < \Delta r_e^{shad.}$$

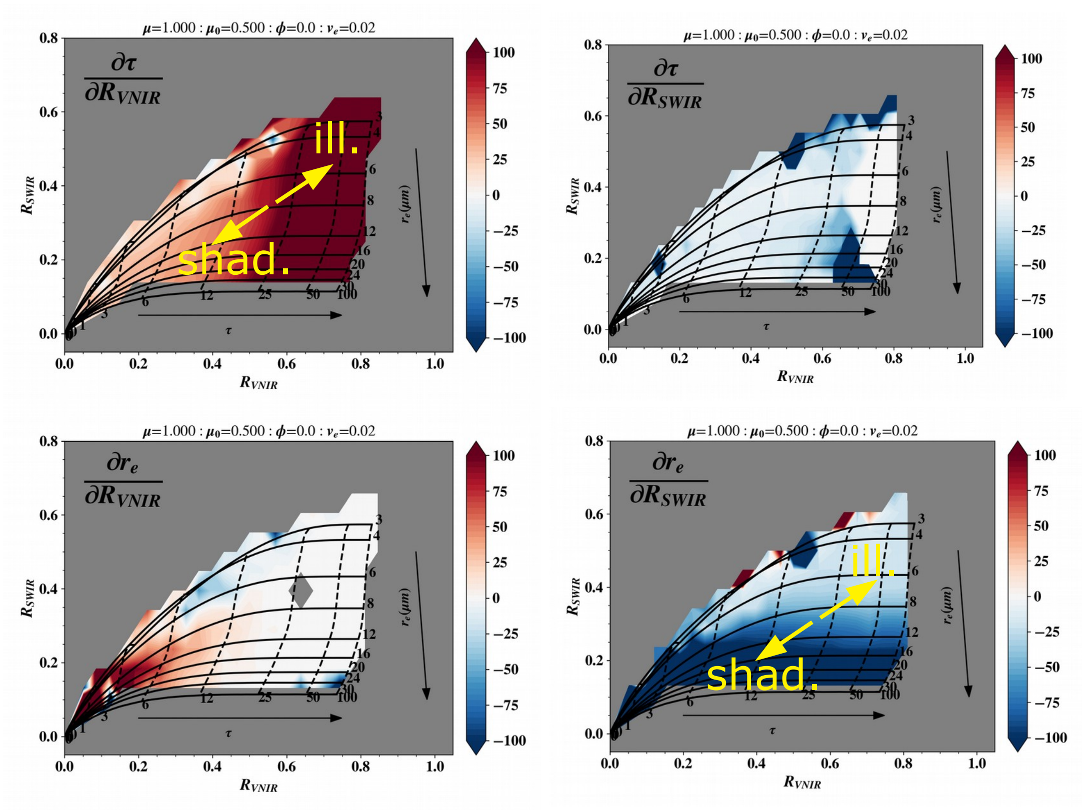
Bi-spectral LUT



[1]*Marshak et. al. (2006)*, [2]*Zhang et. al. (2016)*

Are CER and COT retrievals independent?

$$\begin{bmatrix} \Delta\tau \\ \Delta r_e \end{bmatrix} = \begin{bmatrix} \frac{\partial\tau}{\partial R_{VNIR}} & \frac{\partial\tau}{\partial R_{SWIR}} \\ \frac{\partial r_e}{\partial R_{VNIR}} & \frac{\partial r_e}{\partial R_{SWIR}} \end{bmatrix} \begin{bmatrix} \Delta R_{VNIR} \\ \Delta R_{SWIR} \end{bmatrix} \quad (2)$$



From previous studies[1],

- If the reflectance bias ($\Delta R_{I,\lambda}^{3D-1D}$) has a Gaussian distribution about zero,
- If CER and COT retrievals are independent,

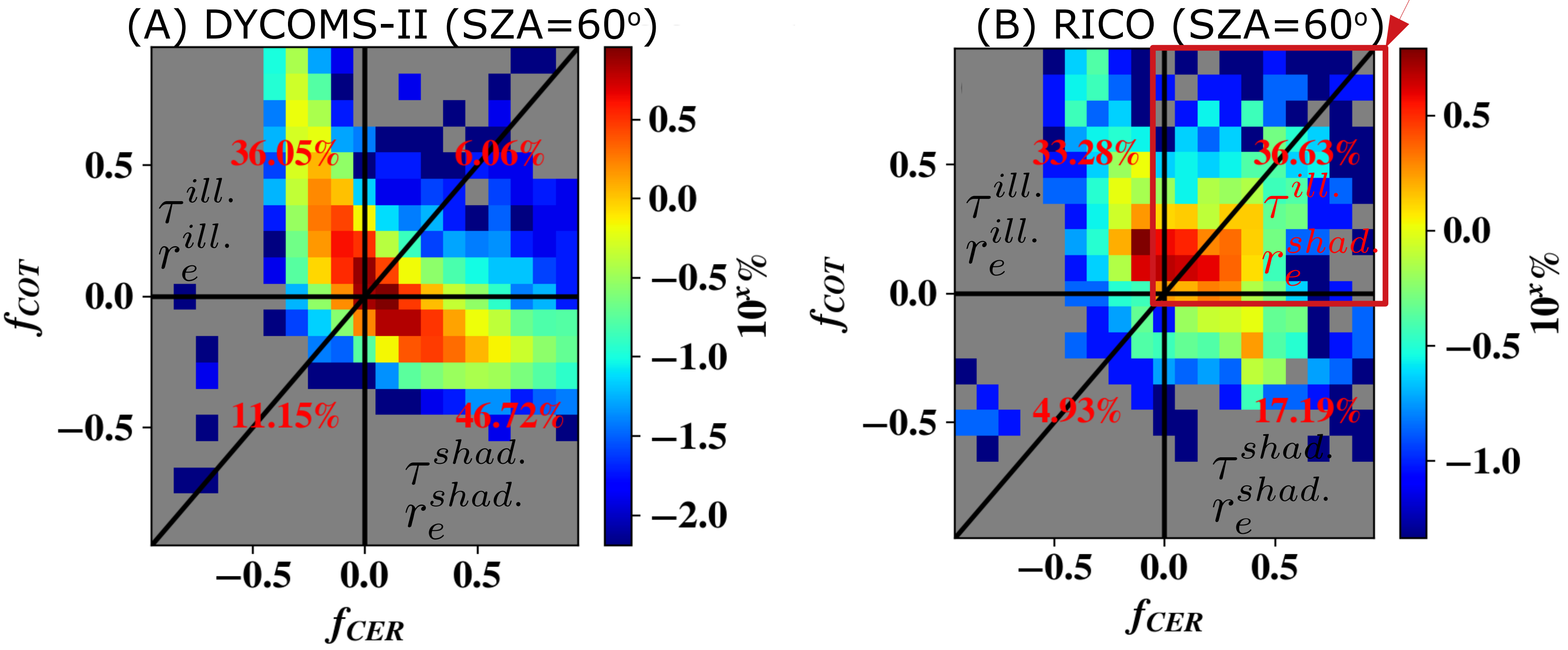
$$\Delta\tau^{ill} > \Delta\tau^{shad.} \text{ and } \Delta r_e^{ill.} < \Delta r_e^{shad.} \quad (1)$$

Equation (1) only true when the off-diagonal values of Equation (2) are negligible

3D effects impact factor

$$f_P = \frac{\Delta P^{3D-1D}}{P^{1D}} \qquad where \quad P = COT, CER, R_{VNIR}, \ldots$$

Can not understand based on previous studies



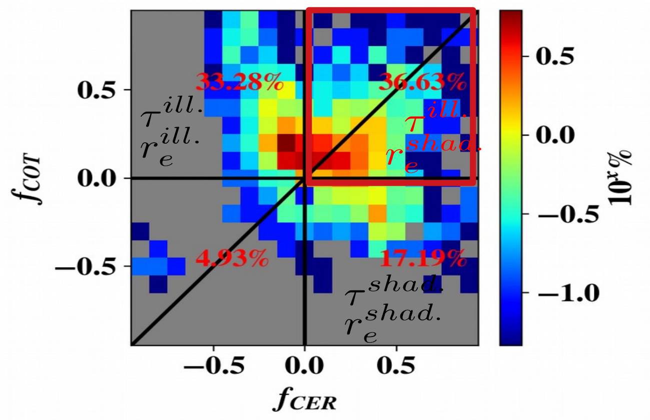
$$\Delta\tau^{ill} > \Delta\tau^{shad.} \text{ and } \Delta r_e^{ill.} < \Delta r_e^{shad.} \quad (1)$$

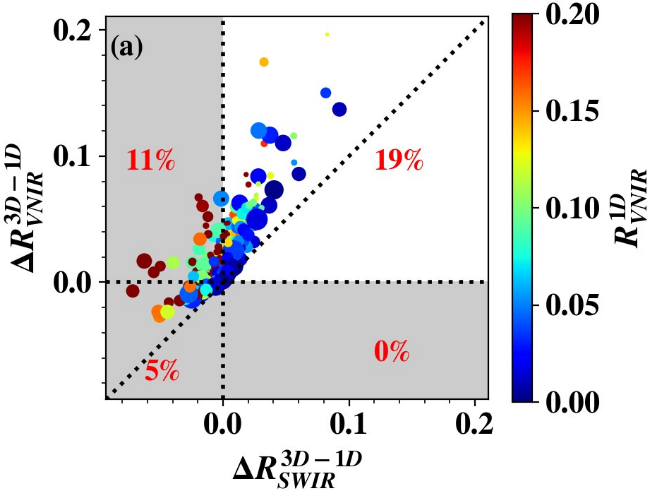
3D effects impact factor

$$\begin{bmatrix}\Delta\tau \\ \Delta r_e\end{bmatrix} = \begin{bmatrix}\frac{\partial\tau}{\partial R_{VNIR}} & \frac{\partial\tau}{\partial R_{SWIR}} \\ \frac{\partial r_e}{\partial R_{VNIR}} & \frac{\partial r_e}{\partial R_{SWIR}}\end{bmatrix} \begin{bmatrix}\Delta R_{VNIR} \\ \Delta R_{SWIR}\end{bmatrix} \quad (2)$$

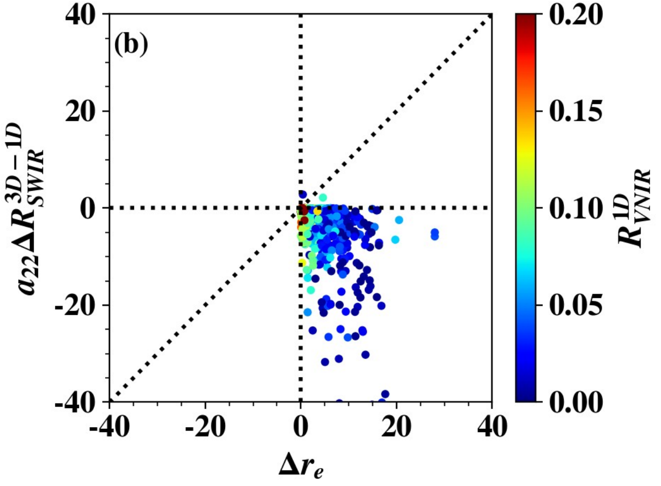
$$\Delta\tau^{ill} > \Delta\tau^{shad.} \text{ and } \Delta r_e^{ill.} < \Delta r_e^{shad.} \quad (1)$$

RICO

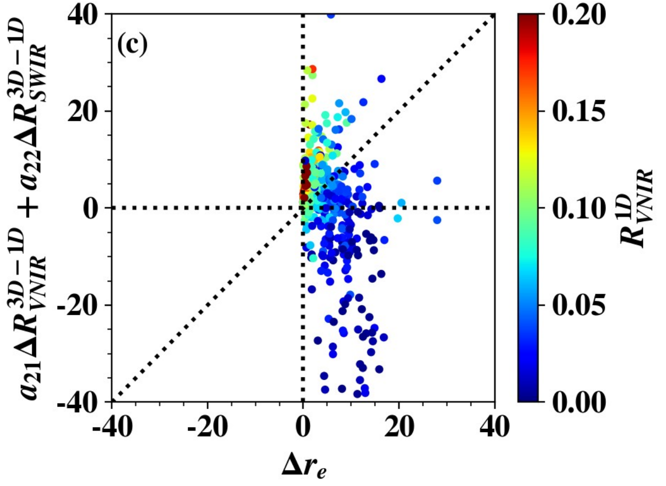




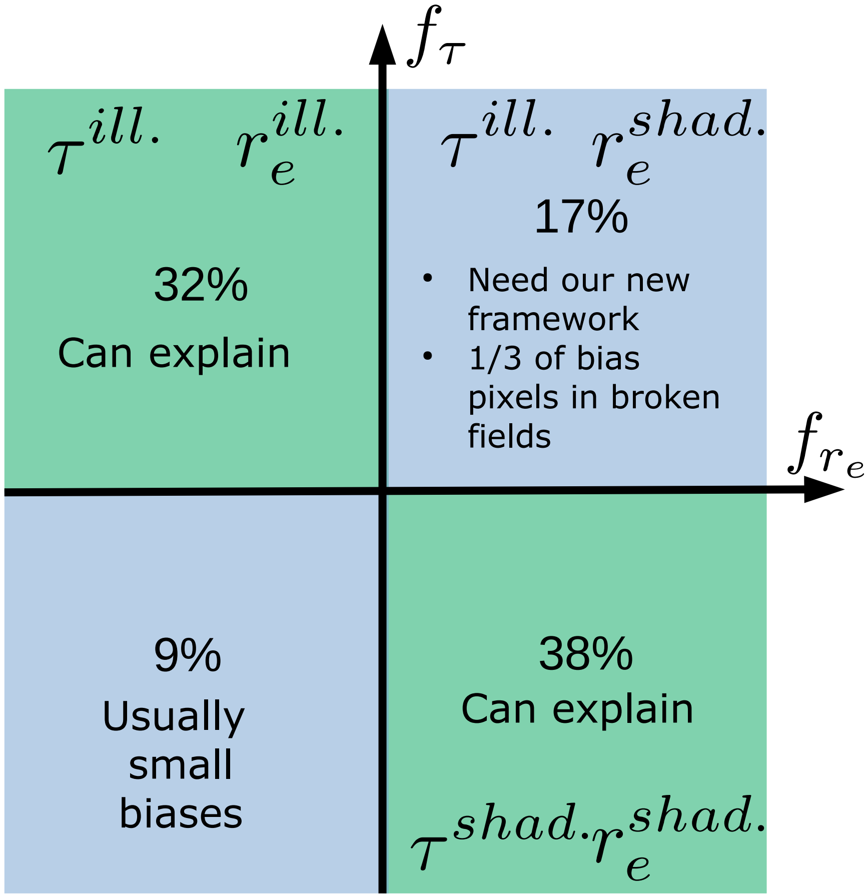
W/O off-diagonal term



With off-diagonal term



Bi-spectral retrievals - summary



- Previous studies assumed,
  I. $\Delta_{I,\lambda}^{3D-1D}$ as Gaussian about μ=0
  II. $\frac{\partial \tau}{\partial R_{SWIR}} and \frac{\partial r_e}{\partial R_{VNIR}}$ negligible

- Based on these assumptions, we can explain majority of biases in the homogeneous overcast cloud fields for large SZAs
- For small SZAs, Assumption (I) fails, since the reflectance bias-PDF tends to have more weight in the shadowing part
- For broken cloud fields, more than 1/3 of biased-pixels do not agree with Assumption (II)
- Our newly-introduced framework is required to explain these biases

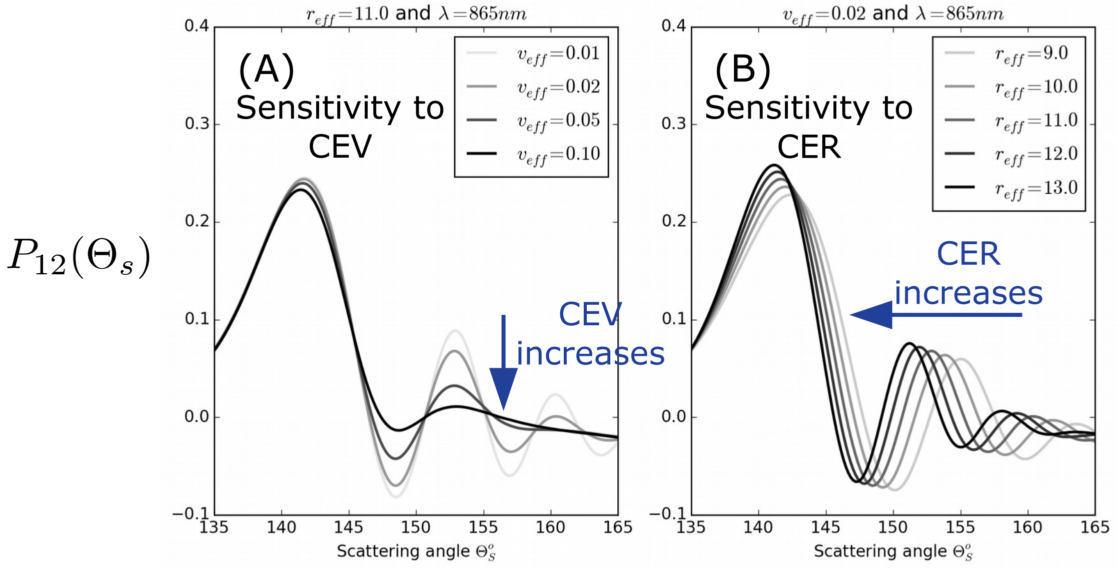
$$\begin{bmatrix} \Delta\tau \\ \Delta r_e \end{bmatrix} = \begin{bmatrix} \frac{\partial \tau}{\partial R_{VNIR}} & \frac{\partial \tau}{\partial R_{SWIR}} \\ \frac{\partial r_e}{\partial R_{VNIR}} & \frac{\partial r_e}{\partial R_{SWIR}} \end{bmatrix} \begin{bmatrix} \Delta R_{VNIR} \\ \Delta R_{SWIR} \end{bmatrix}$$

(Matrix of first derivatives)

Polarimetric retrievals[1]

Under the single scattering approx., polarized reflectance from liquid cloud droplets is related to polarized phase function P_{12} as follows,

$$R_p = \frac{\pi Q[\tau = 0, \mu, \phi]}{\mu_o F_o} = \frac{P_{12}[\Theta_s(\mu, \phi, \mu_o, \phi_o), CER, CEV]}{4(\mu + \mu_o)}$$

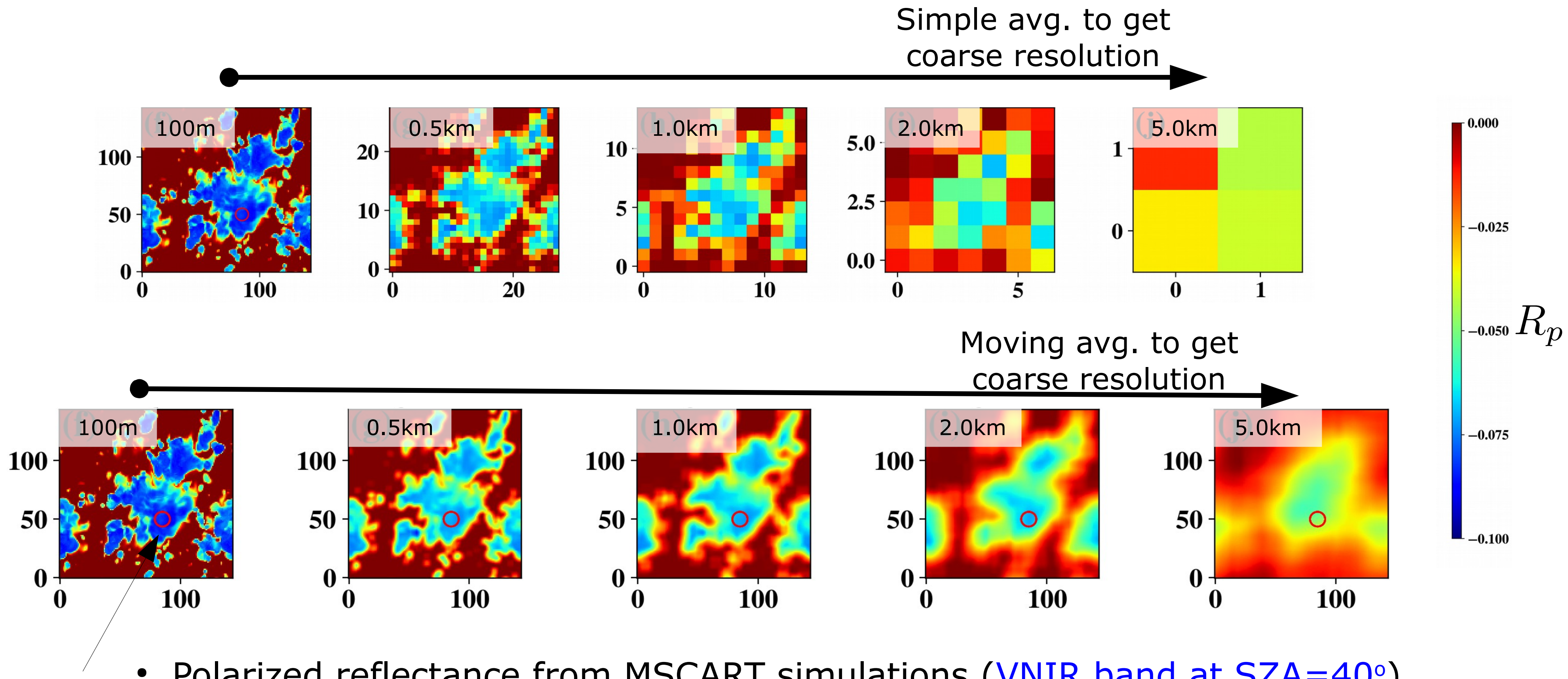


$$R_p^* = 4(\mu + \mu_o) R_p \Longrightarrow F(\lambda, \Theta_s) = aP[\Theta_s, \lambda, r_e, v_e] + b\Theta_s + c$$

POLDER[1], RSP[2,3], airHARP, HARP CubeSat[3,4]

[1]Breon et. al. (1998,2005), [2]Cairns et. al. (1999), Alexandrov et. al. (2016), [3]Martins et. al. (2018), [4]Mcbride et. al. (2019)

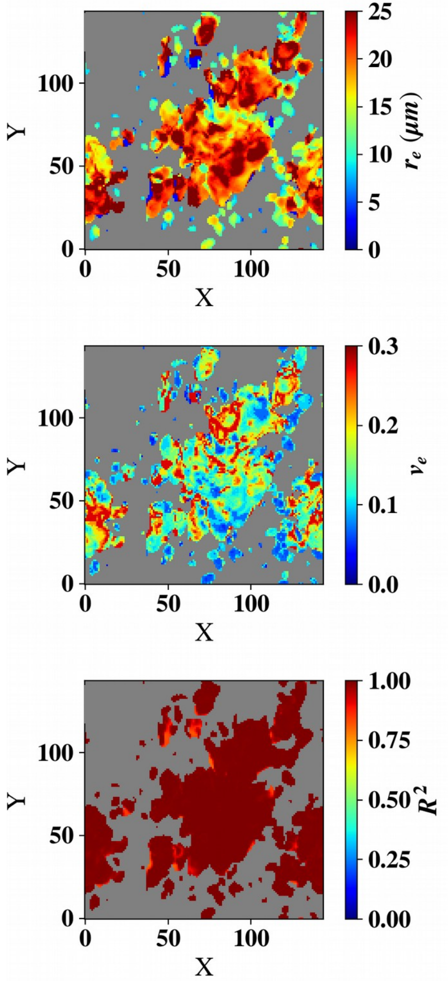
Polarized reflectance



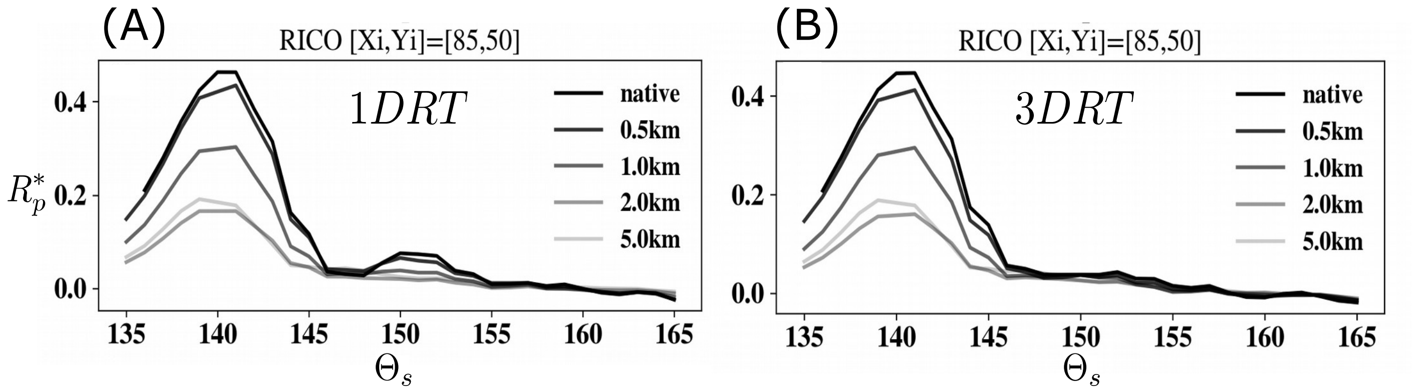
- Polarized reflectance from MSCART simulations (VNIR band at SZA=40°)
- RICO case – significant spatial variability – more “cloud edges”
- Simple-averaging/Moving-averaging
- Angular pattern of the Rp is used in the polarimetric retrievals

Polarimetric retreivals under 1D RT

Native resolution - SZA=40°



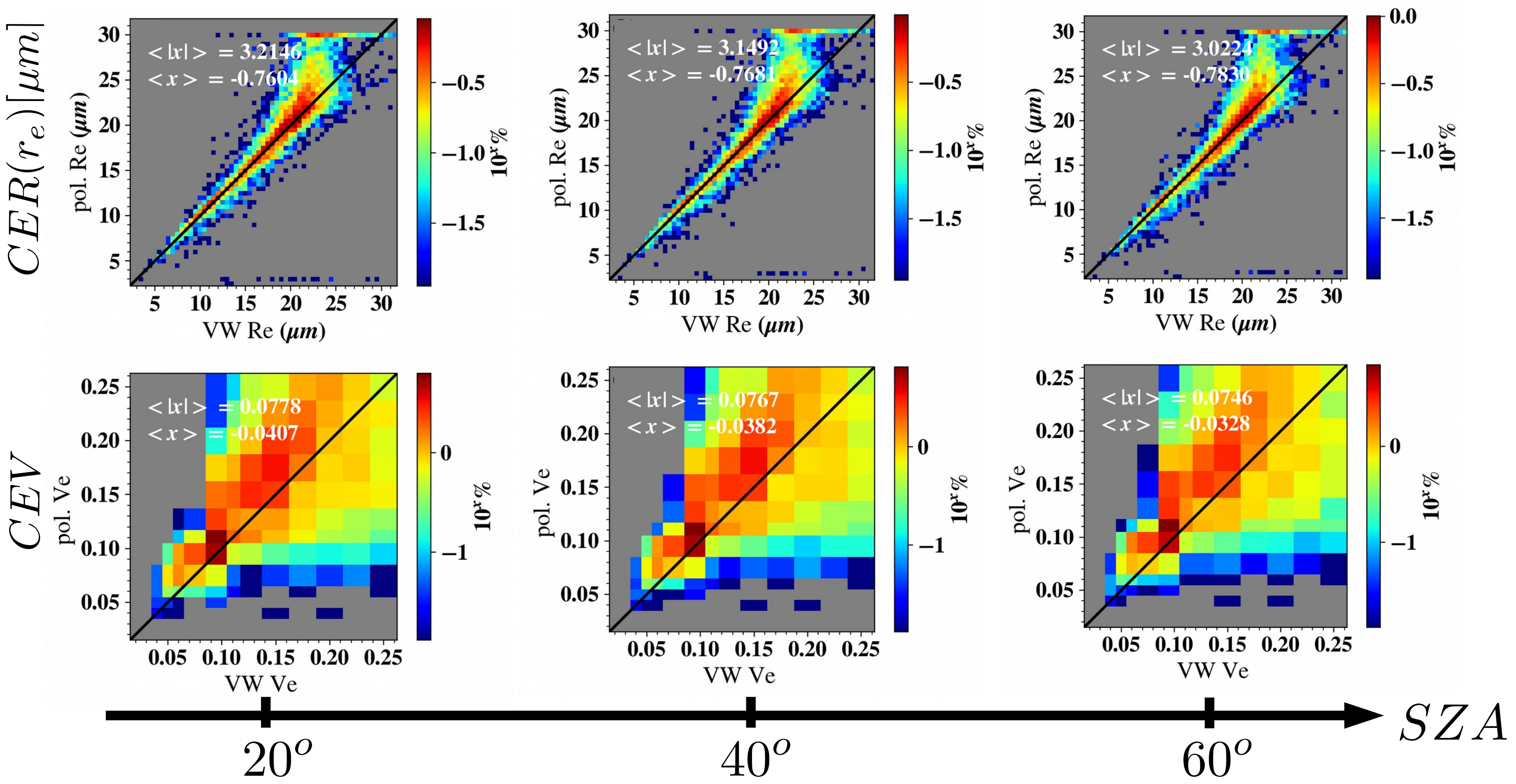
Angular pattern of the polarized reflectance at P



- Averaging broaden the DSD – large CEV
- Supernumerary bow vanishes in the 3D RT pattern
- Any changes in the angular pattern will be interpreted as a microphysical variation in the retrieval
- Before we move on to 3D radiative transfer, we investigated the **polarimetric retrieval biases under 1D radiative transfer,**
    - **As SZA varies**
    - **As horizontal resolution varies**

Polarimetric retreivals (1D RT): Varying SZA

RICO case



Polarimetric retreivals (1D RT): Varying SZA

Statistical quantities of the retrieval biases of $r_e^{pol.,1D} vs. r_e^{vw}$

case	SZA	μ	σ	μ^*	σ^*	rms	β_1	β_0	r value	$\beta_1^{std.}$
ATEXc	20	-0.27	1.02	0.53	0.91	1.05	0.93	1.07	0.83	0.01
ATEXc	40	-0.14	0.54	0.44	0.34	0.55	1.02	-0.57	0.96	0.00
ATEXc	60	-0.04	0.73	0.47	0.56	0.73	1.01	-0.19	0.95	0.00
ATEXp	20	-0.00	0.23	0.18	0.14	0.23	1.05	-0.41	0.95	0.00
ATEXp	40	0.00	0.25	0.19	0.16	0.25	1.05	-0.38	0.94	0.00
ATEXp	60	0.00	0.26	0.20	0.17	0.26	1.04	-0.29	0.95	0.00
DYCOMS2	20	-0.24	0.22	0.28	0.15	0.32	1.02	-0.60	0.97	0.00
DYCOMS2	40	-0.22	0.23	0.28	0.16	0.32	1.03	-0.68	0.97	0.00
DYCOMS2	60	-0.19	0.26	0.27	0.17	0.32	1.04	-0.80	0.97	0.00
RICO	20	0.59	1.53	1.10	1.22	1.64	1.25	-4.50	0.92	0.01
RICO	40	0.50	1.43	1.02	1.13	1.52	1.21	-3.56	0.93	0.01
RICO	60	-0.08	4.42	1.34	4.22	4.42	0.49	9.94	0.70	0.01

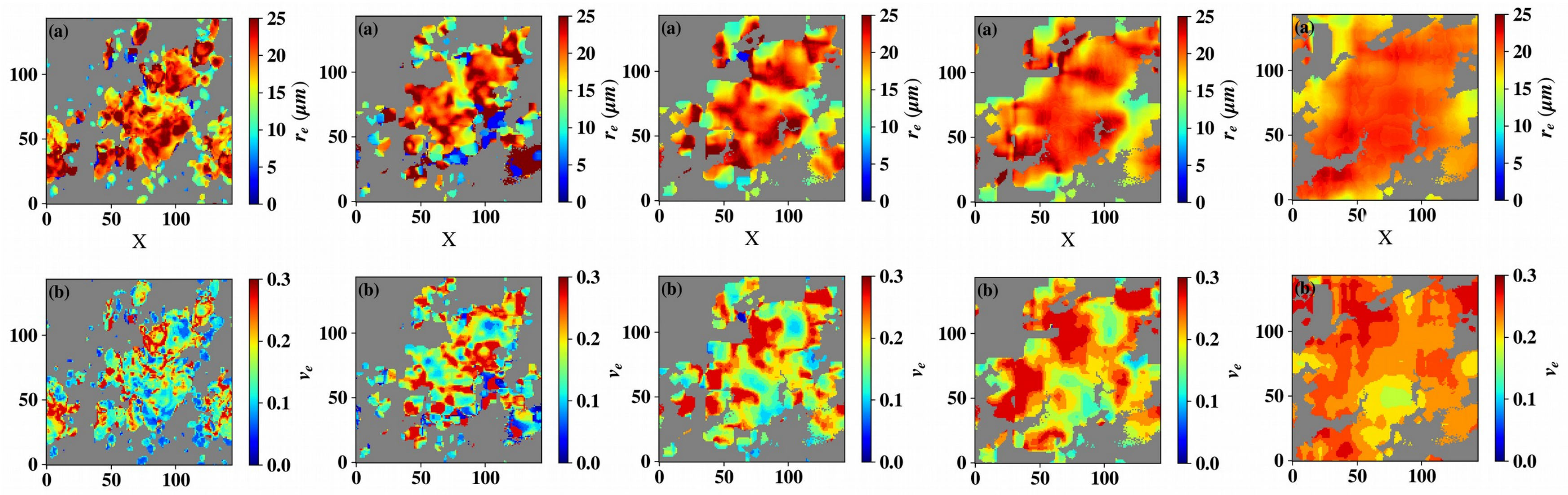
- After applying a cloud mask (CEV-fil) to ignore CEV>0.2 pixels
- Pixels with COT<0.1
- In the native-resolution
- Biases are very small, no significant variability due to the SZA variation.
- R-values of the correlations ~1 in most of the cases

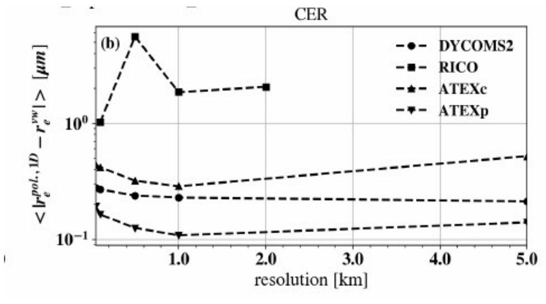
Under 1D RT,

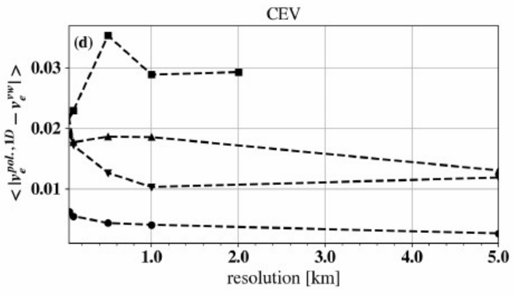
- Small biases
- No significant changes as SZA varies

Polarimetric retreivals (1D RT): Varying resolu.

Footprint size increases





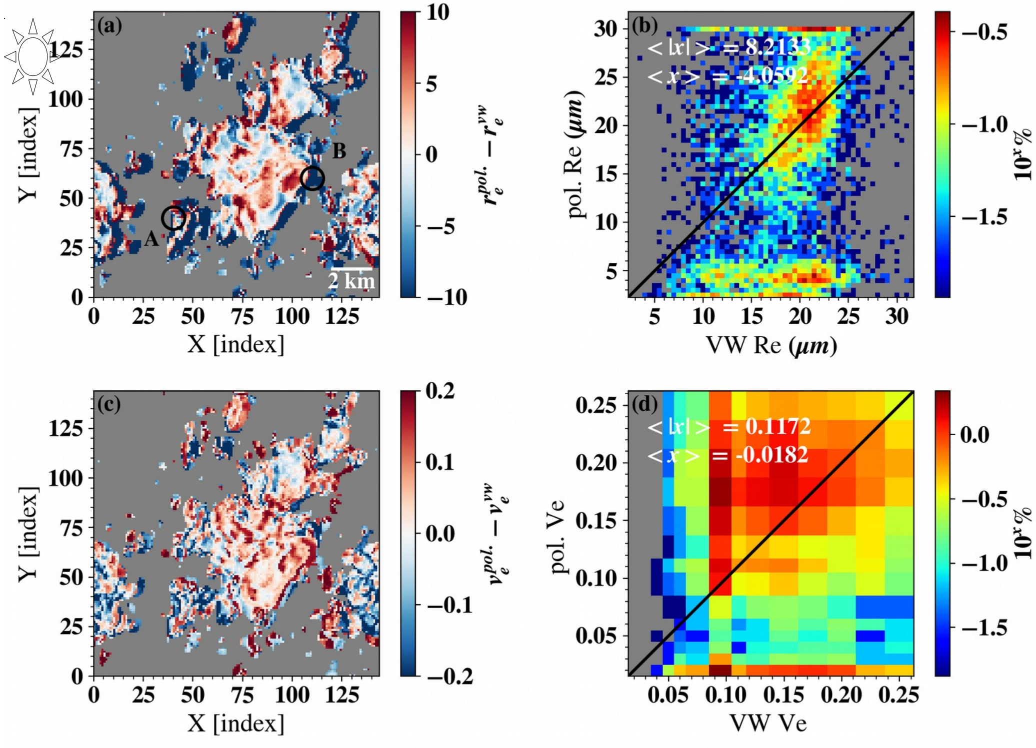


Under 1D RT,

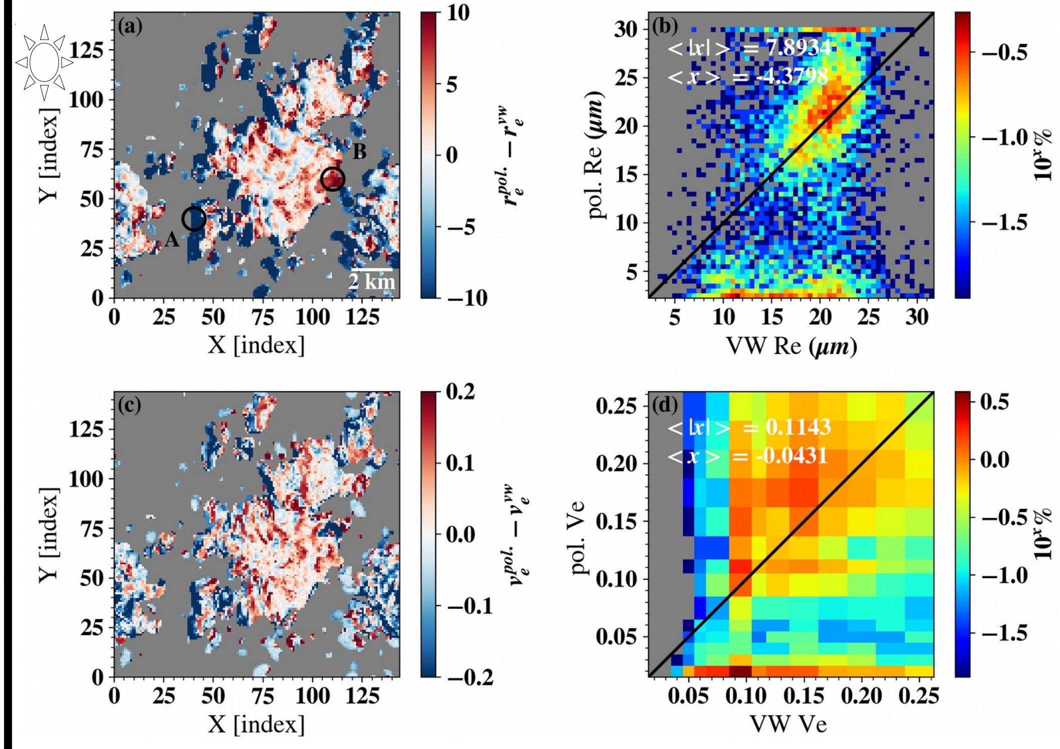
- Small biases
- No significant changes as SZA varies
- Gradually decreases as footprint size increases

3D RT effects in the polarimetric retrievals

SZA=60

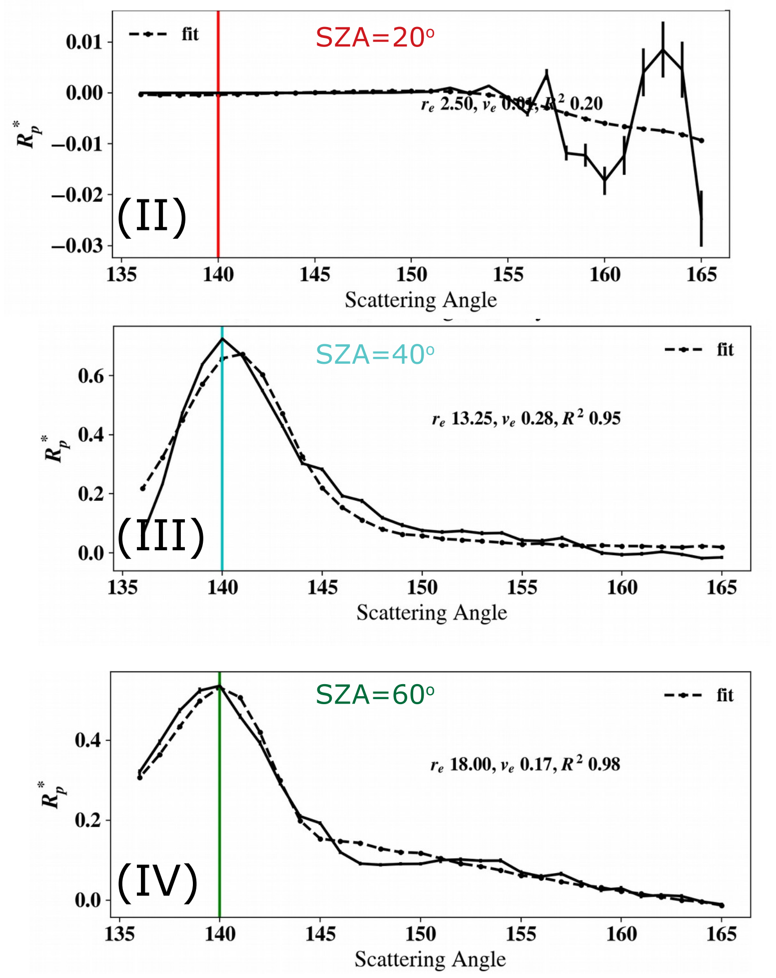


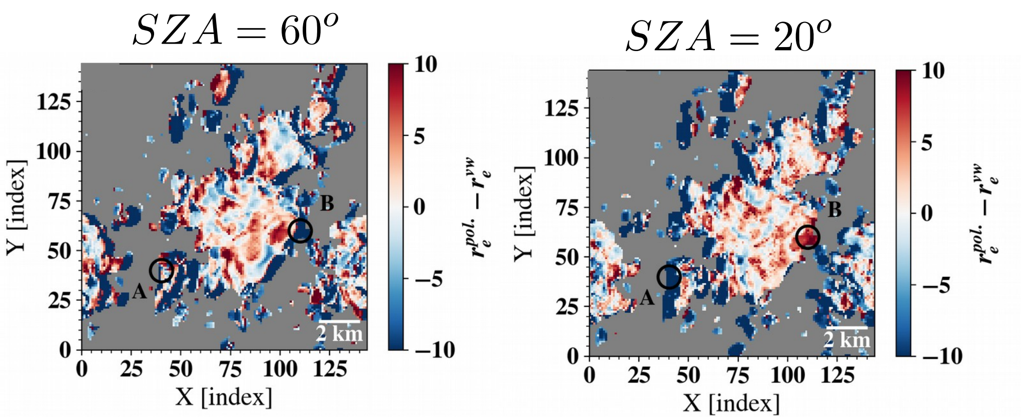
SZA=20



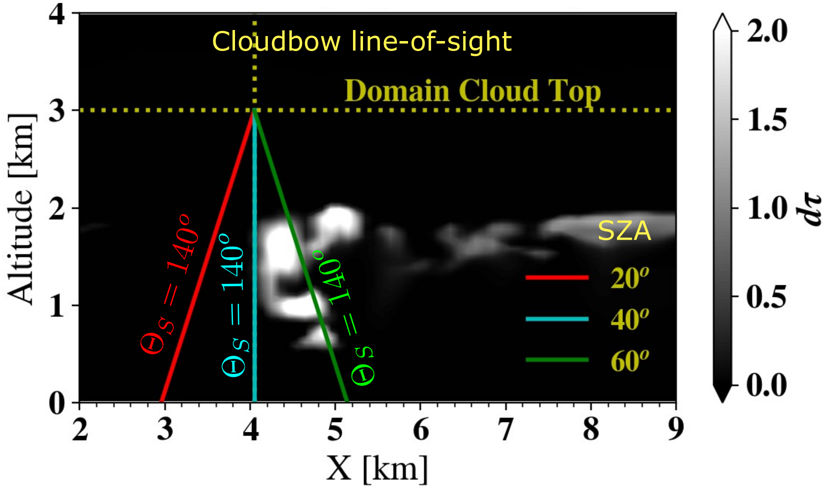
Cloud-edge parallax effect

Point 'A'



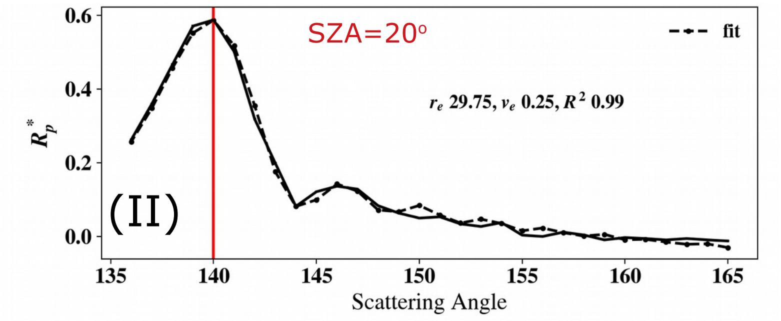


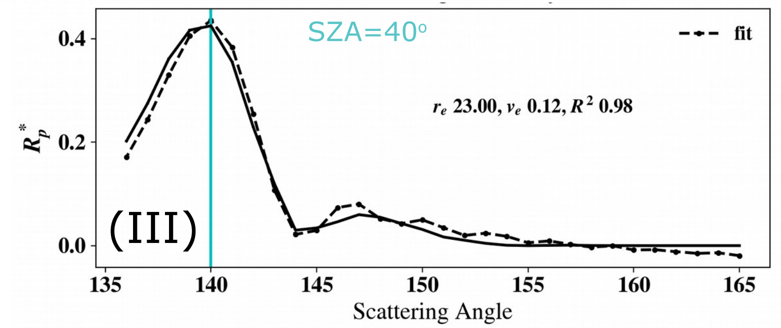
(I) Point 'A'

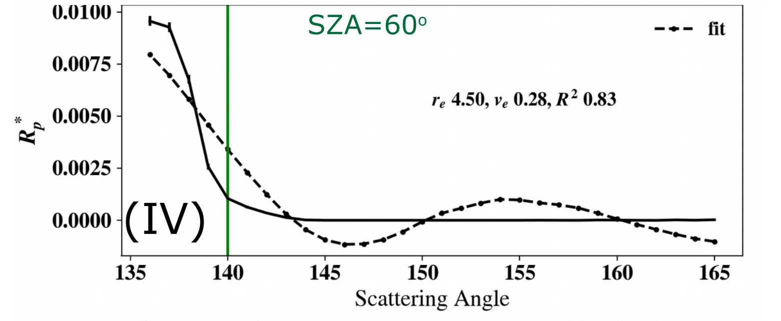


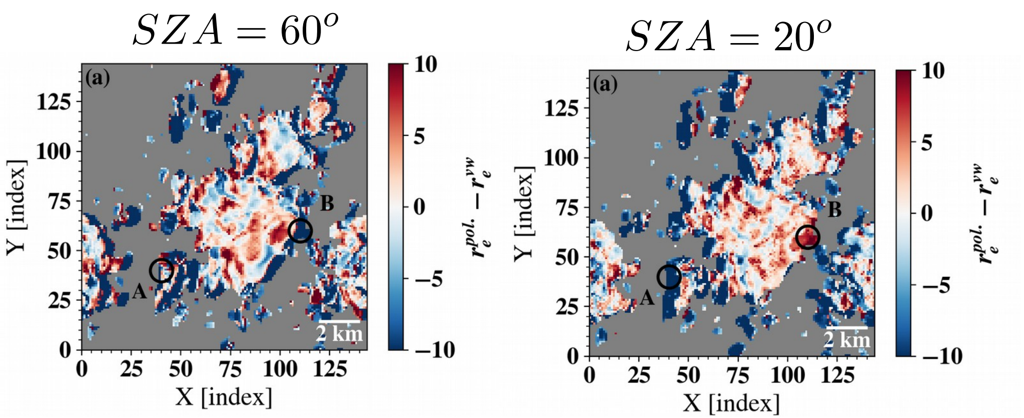
Cloud-edge parallax effect

Point ‘B’

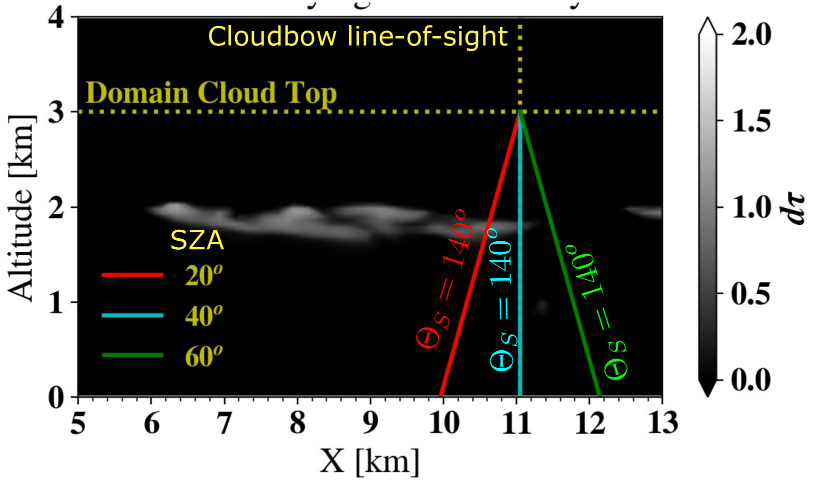






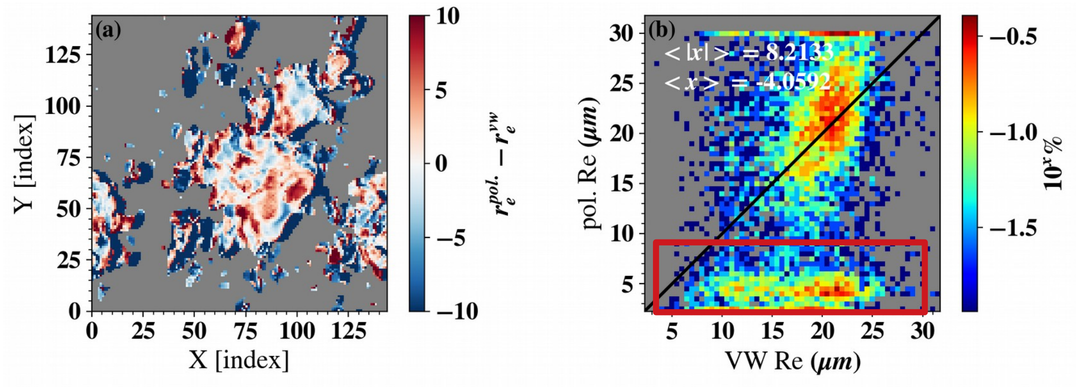


(I) Point ‘B’



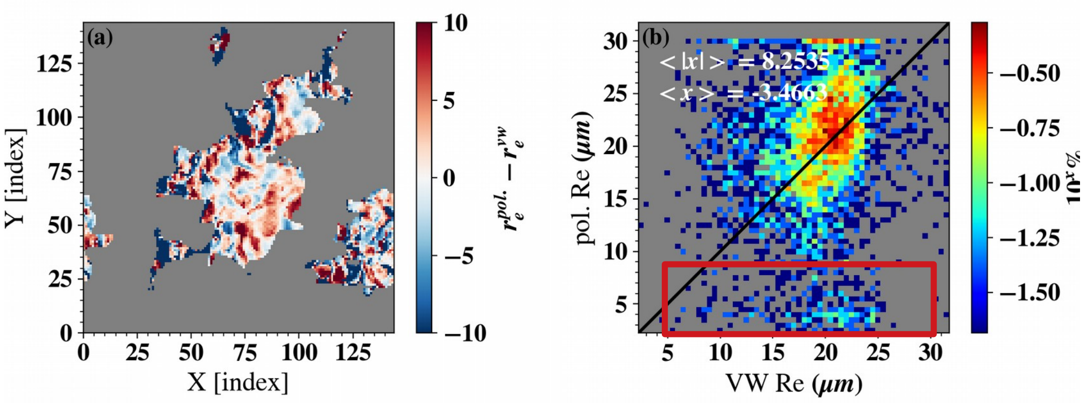
Multi-angular cloud mask

With COT>0.1 mask

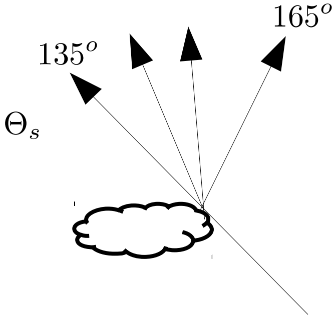


with multi-angular mask

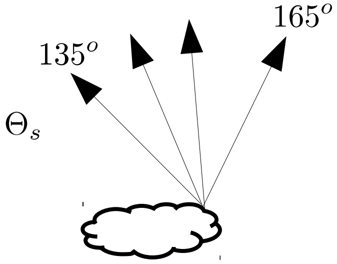
135^o

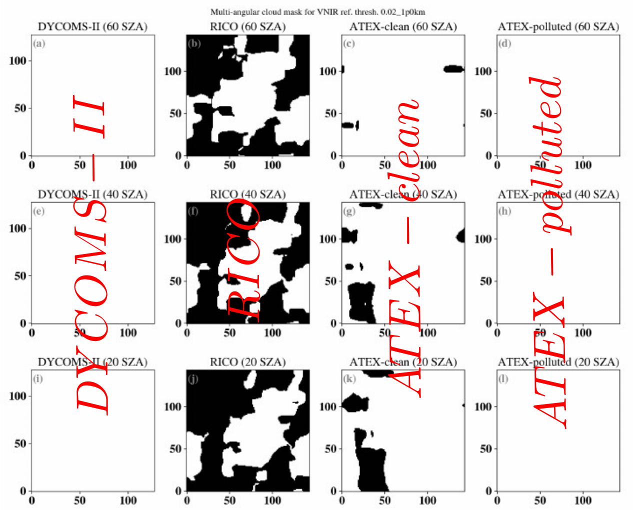


Not a cloudy pixel



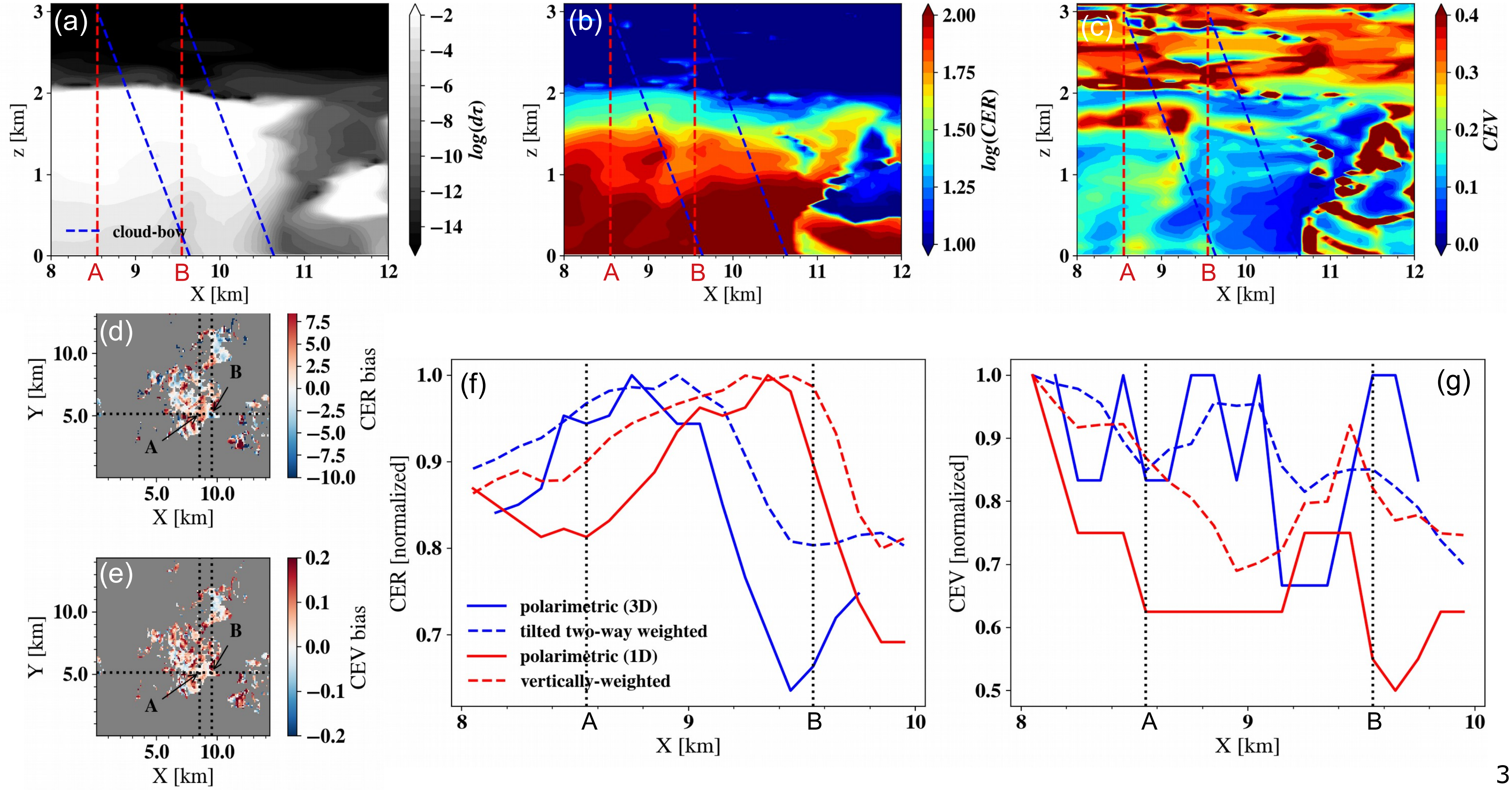
Cloudy pixel





In-cloud parallax effect

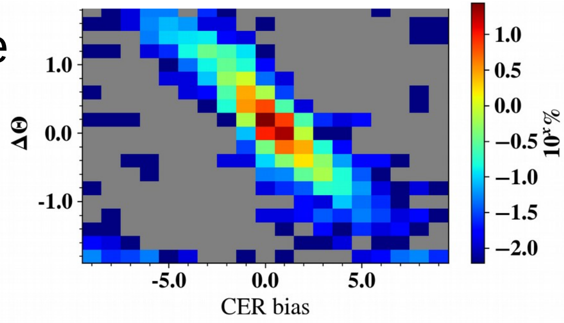
SZA=60°



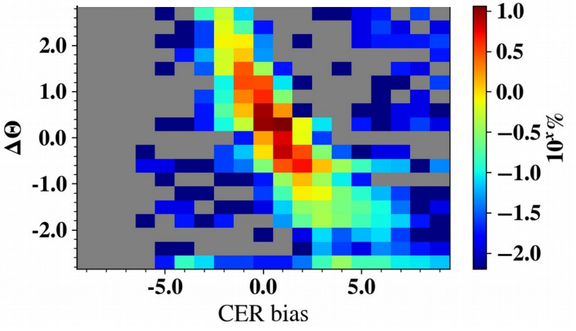
Angular shift of the cloud-bow

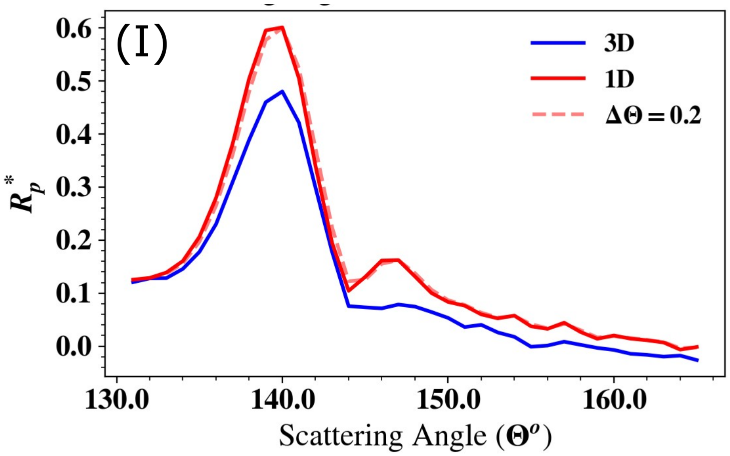
- The main source of biases (cloud-edge and in-cloud) are from the parallax effects
- Whether the biases are correlated with the angular shift?

(II) DYCOMS-II (SZA=60°)



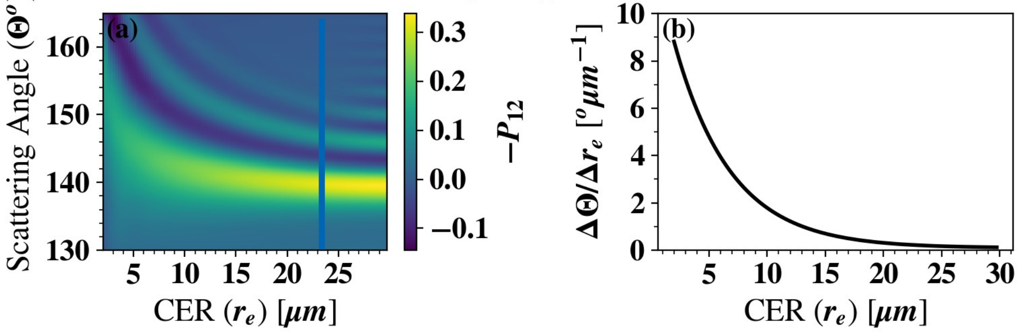
(III) ATEX-clean (SZA=60°)



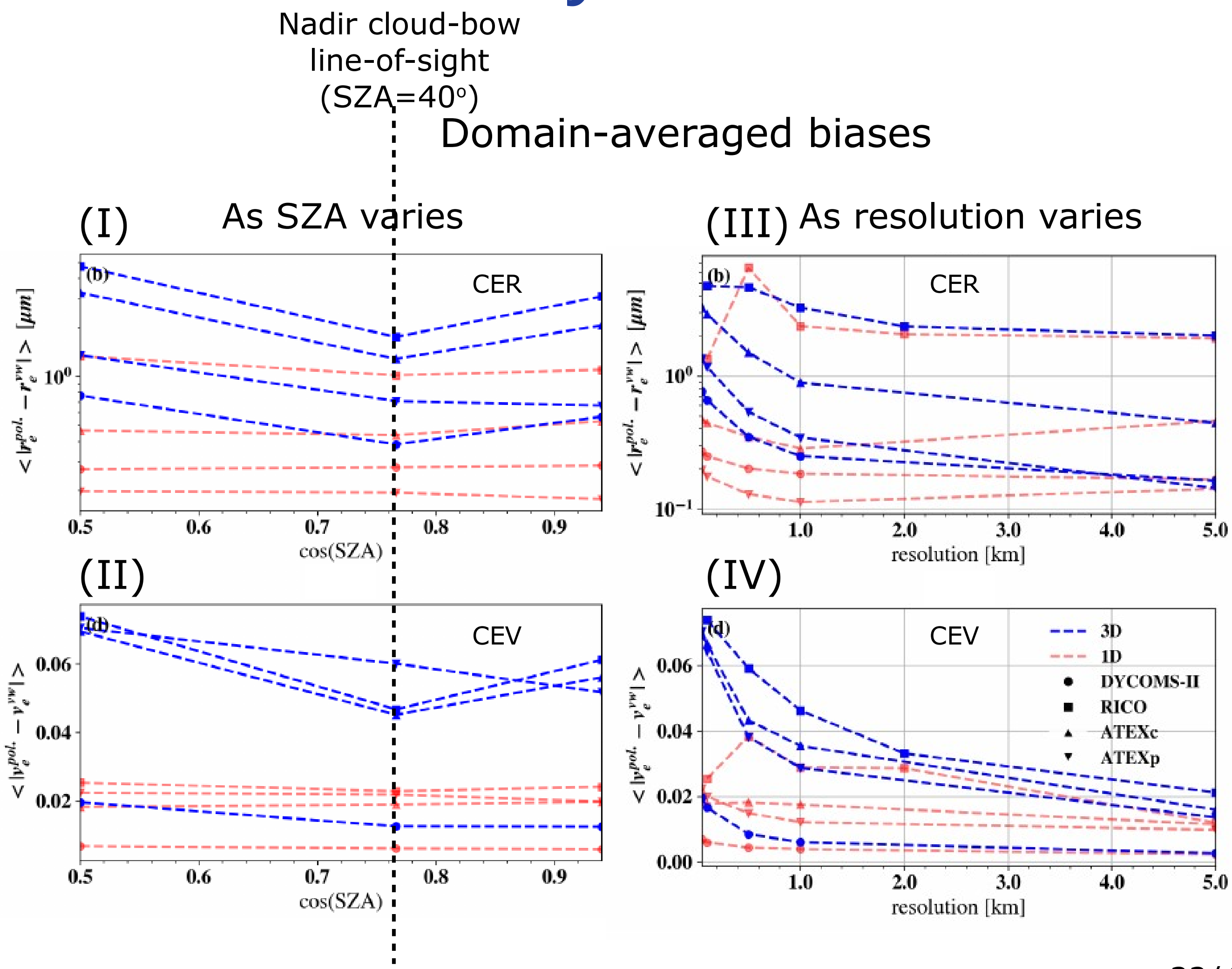


(IV)

P12 cloud bow angular pattern illustration



Polarimetric retrievals - summary



- Identified new mechanism that cause potential biases in the polarimetric retrievals due to the 3D radiative transfer effects,
  - Cloud-edge parallax effect
  - In-cloud parallax effect
- Biases increases as resolution becomes finer

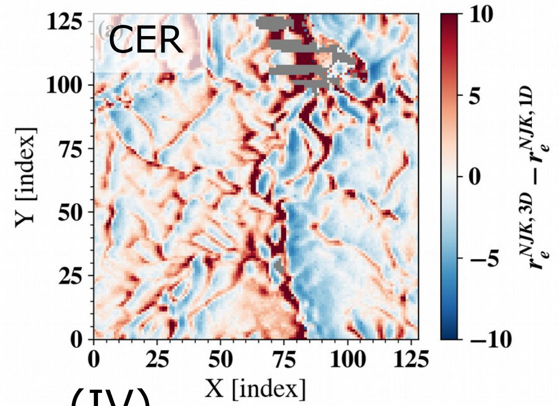
Can we correct these biases?

SZA=60°

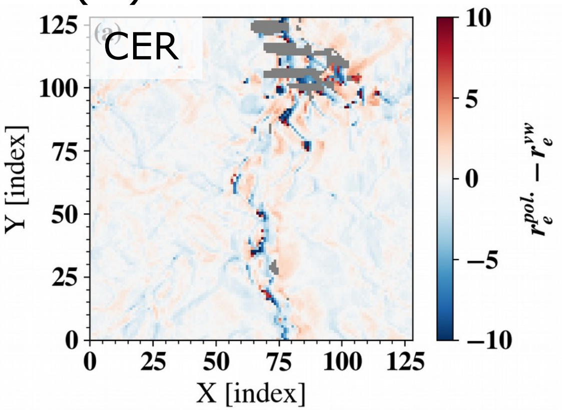
Bi-spectral retrievals

Polarimetric retrievals

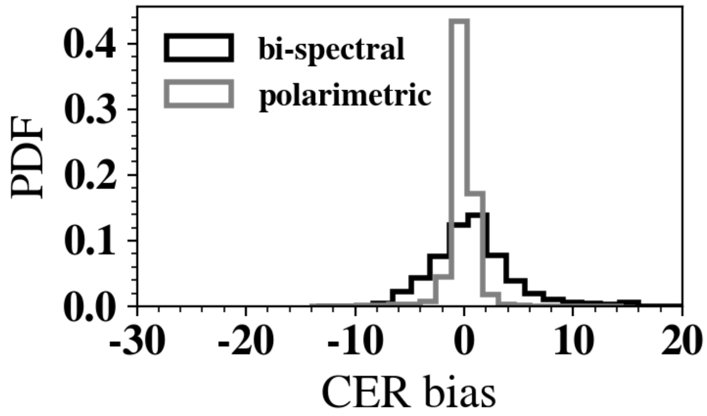
(I)



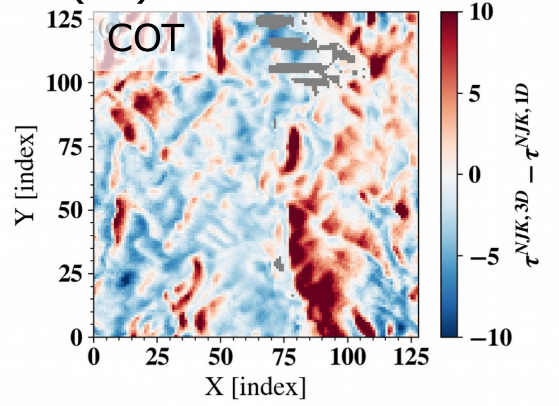
(II)



(III)



(IV)

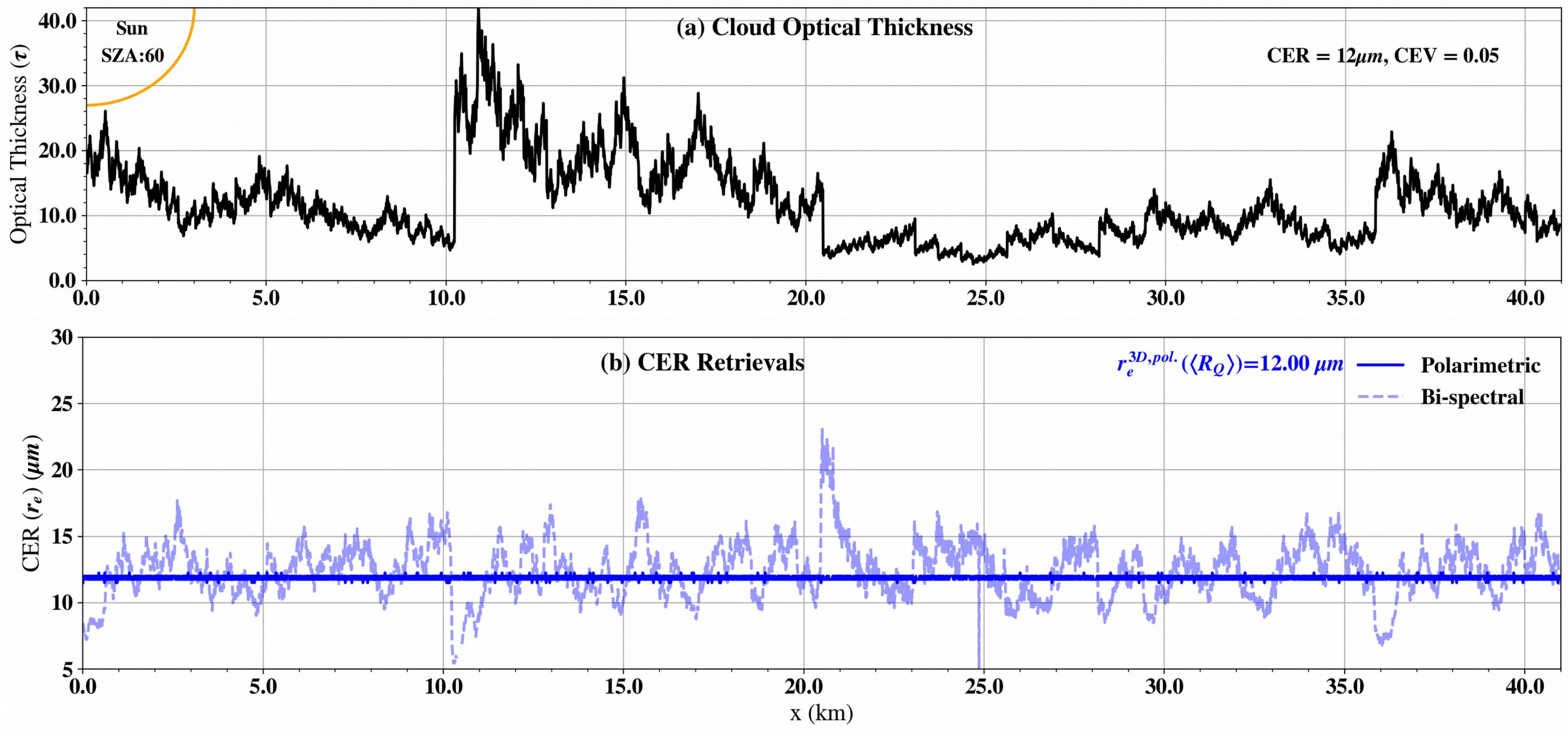


- Some attempts have been made to correct the biases in bi-spectral retrievals[1]
- We introduced a new technique[2] to **detect and correct strong COT biases in the bi-spectral retrievals** due to the 3D effects using polarimetric retrievals

[1]Varnai and Marshak (2002), [2]Rajapakshe and Zhang (2020)

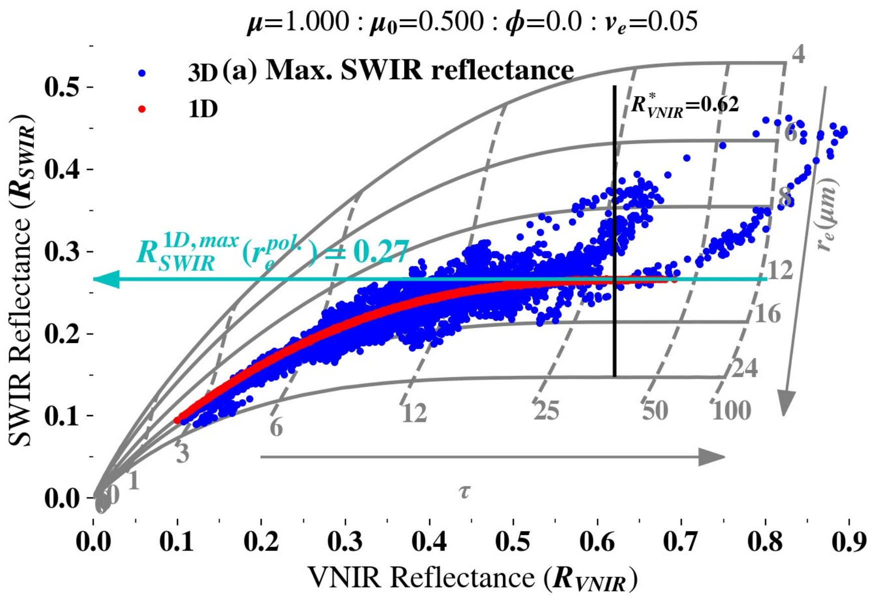
Using polarimetric retrievals to correct NJK ret.

1D fractal cloud



Rajapakshe and Zhang (2020)

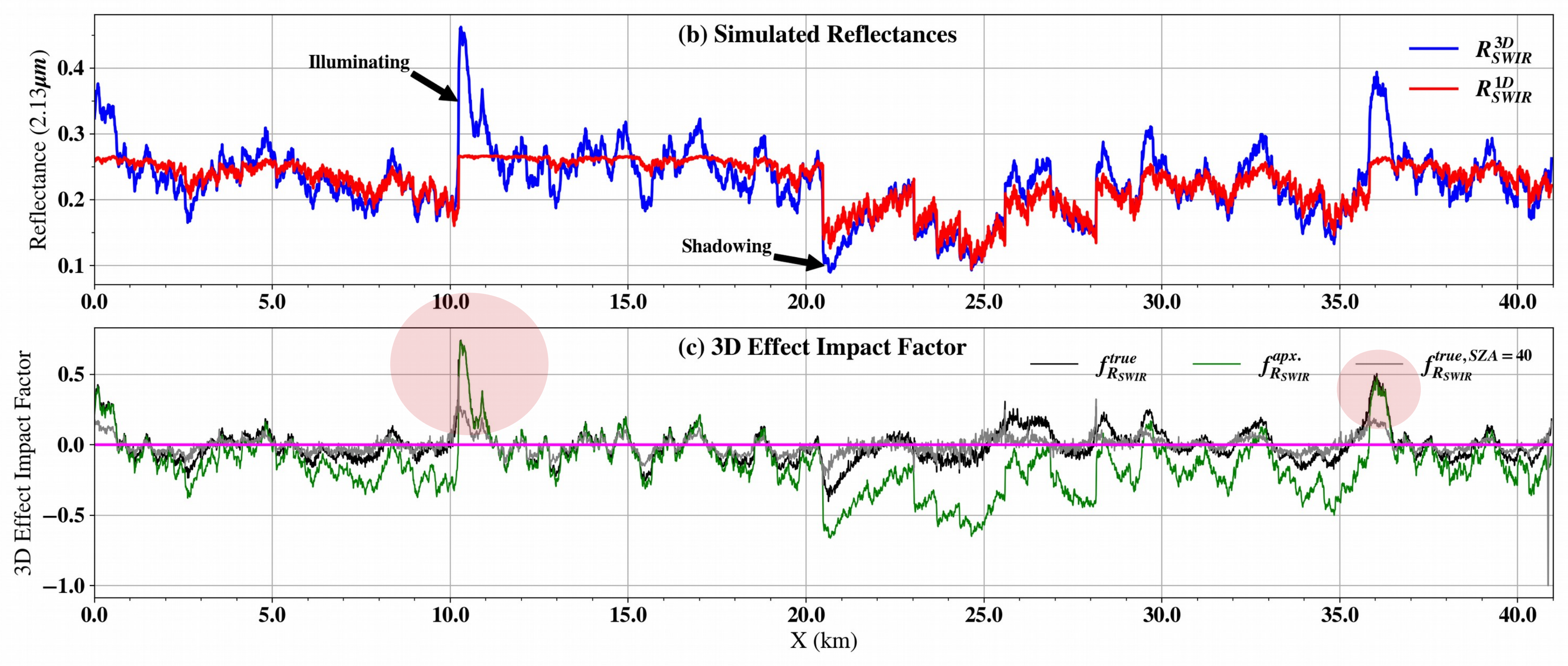
Maximum 1D reflectance method



- As VNIR reflectance increases, the SWIR reflectance reaches to an asymptotic maximum
- This asymptotic SWIR-maximum can be used as a proxy to 1D refelctance of the SWIR-saturated observations

Rajapakshe and Zhang (2020)

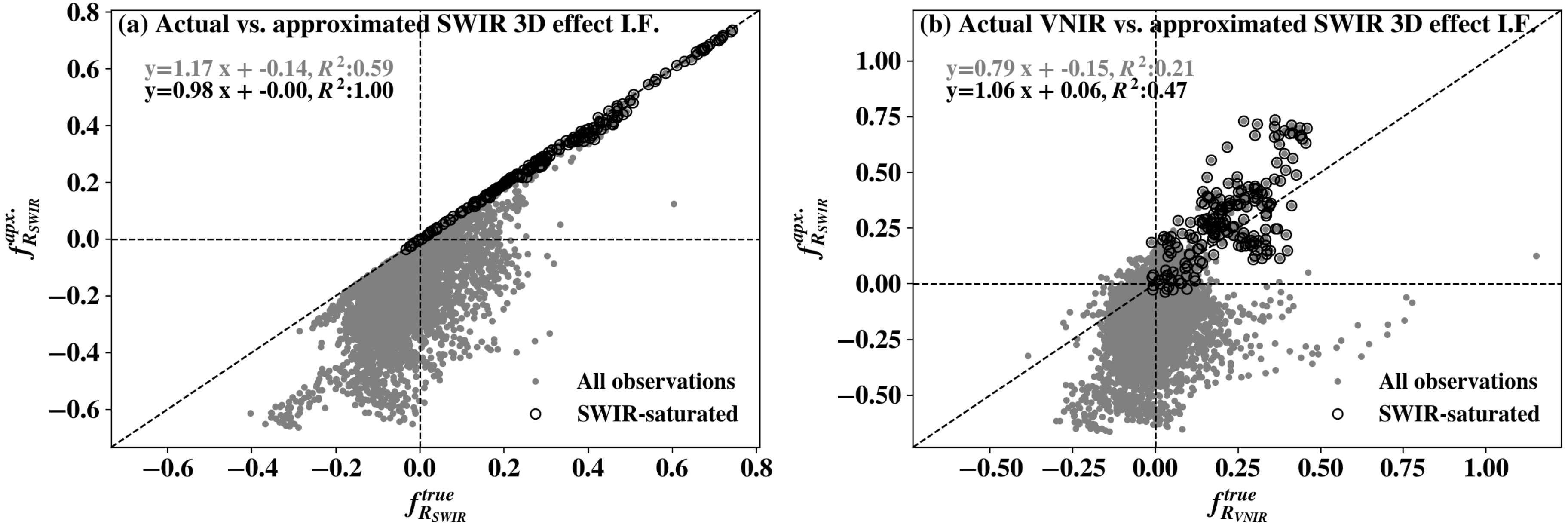
True and approx. 3D effect impact factors



Strong illuminating effects can be identified accurately!

Rajapakshe and Zhang (2020)

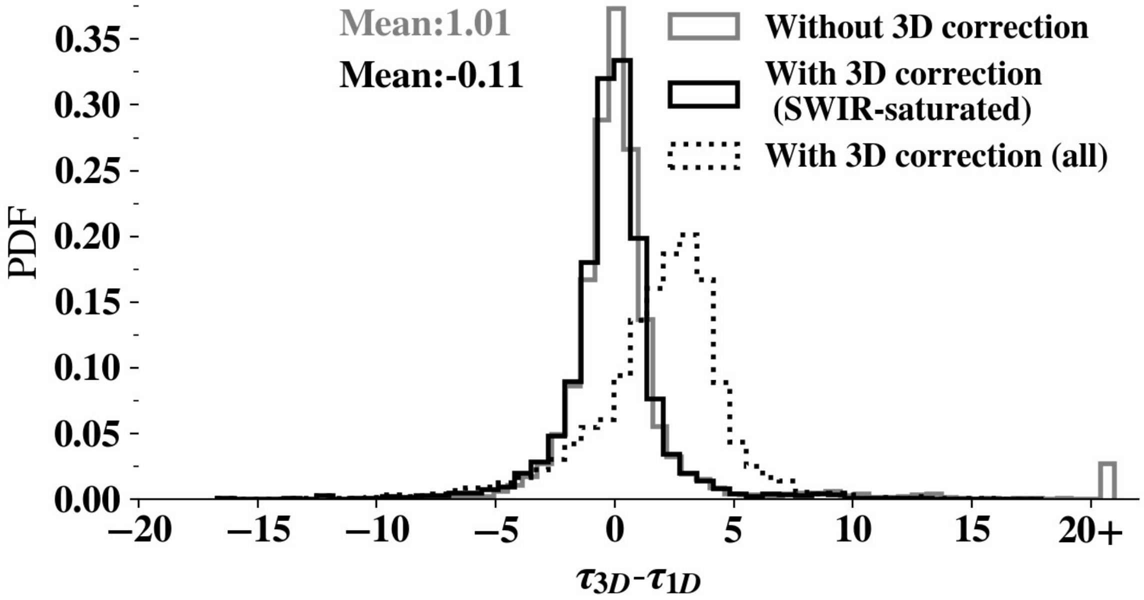
True and approx. 3D effect impact factors



Strong 1-to-1 correlation exists for SWIR-saturated observations in the SWIR band

Rajapakshe and Zhang (2020)

Using polarimetric retrievals to correct NJK ret.



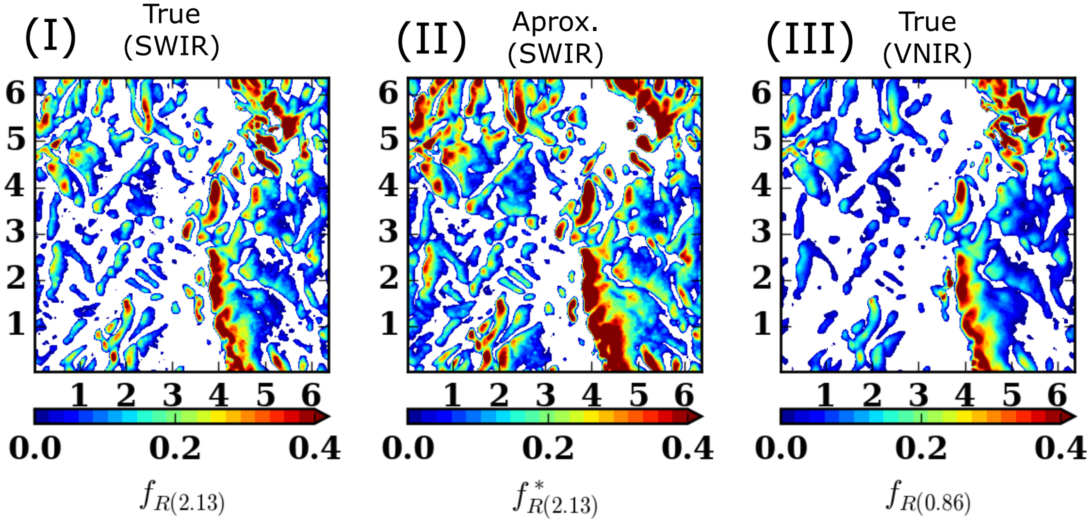
- The impacts of the 3D effects are assumed to be equal in both SWIR and VNIR bands
- Extreme positive optical thickness biases are corrected
- Remaining shadowing effects dominate

Rajapakshe and Zhang (2020)

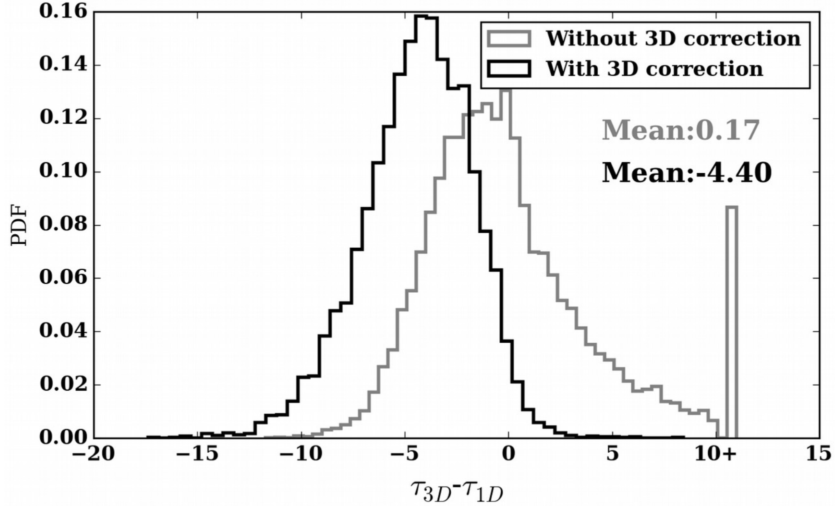
DYCOMS-II

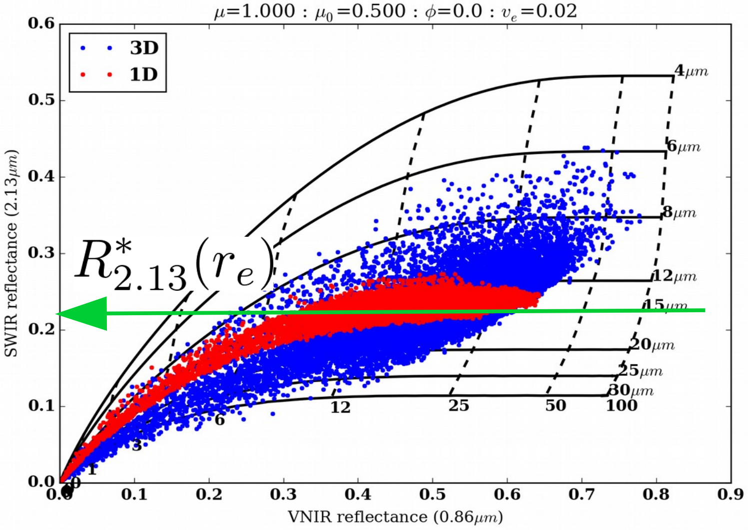
- The impacts of the 3D effects assumed to be equal for both VNIR (0.86 μm) and SWIR (2.13 μm) bands.
- Extreme positive optical thickness biases are corrected.
- Remaining shadowing effects dominate.

3D effect Impact Factor for illuminated pixels



(IV) Optical thickness bias after VNIR filtering





Summary and publications

- Developed an advanced satellite retrieval simulator setup
- Introduced a new framework to understand the retrieval biases in the bi-spectral retrieval due to 3D radiative transfer effects
- Identified mechanism that could induce biases in the polarimetric retrievals due to the 3D radiative transfer effects
- Introduced a new technique to detect and correct strong positive COT biases in the bi-spectral retrievals using polarimetric retrievals
- Found that the above-cloud aerosols in SE Atlantic region are closer to underlying clouds than previously expected

[1] **Rajapakshe, C.** and Zhang, Z. (2020). Using polarimetric observations to detect and quantify the three-dimensional radiative transfer effects in passive satellite cloud property retrievals: theoretical framework and feasibility study. *Journal of Quantitative Spectroscopy and Radiative Transfer*, page 106920.
[2] **Rajapakshe, C.**, Zhang, Z., Yorks, J. E., Yu, H., Tan, Q., Meyer, K., Platnick, S., and Winker, D. M. (2017). Seasonally Transported Aerosol Layers over Southeast Atlantic are Closer to Underlying Clouds than Previously Reported. *Geophysical Research Letters*, (410).
[3] Alexandrov, M. D., Miller, D. J., **Rajapakshe, C.**, Fridlind, A., van Diedenhoven, B., Cairns, B., Ackerman, A. S., and Zhang, Z. (2020). Vertical profiles of droplet size distributions derived from cloud-side observations by the research scanning polarimeter: Tests on simulated data. *Atmospheric Research*, 239.
[4] Lu, Z., Liu, X., Zhang, Z., Zhao, C., Meyer, K., **Rajapakshe, C.**, Wu, C., Yang, Z., and Penner, J. E. (2018). Biomass smoke from southern Africa can significantly enhance the brightness of stratocumulus over the southeastern Atlantic Ocean. *Proceedings of the National Academy of Sciences*, page 201713703.

Selected references

[1] Ackerman, Andrew S., Michael P. Kirkpatrick, David E. Stevens, and Owen B. Toon. 2004. "The Impact of Humidity above Stratiform Clouds on Indirect Aerosol Climate Forcing." Nature 432 (7020): 1014–17.
[2] Bréon, François Marie, and M Doutriaux-boucher. 2005. "A Comparison of Cloud Droplet Radii Measured From Space" 43 (8): 1796–1805.
[3] Bréon, François Marie, and Philippe Goloub. 1998. "Cloud Droplet Effective Radius from Spaceborne Polarization Measurements" 25 (11): 1879–82.
[4] Marshak, Alexander, Steven Platnick, Tamas Varnai, Guoyong Wen, and Robert F. Cahalan. 2006. "Impact of Three-Dimensional Radiative Effects on Satellite Retrievals of Cloud Droplet Sizes." Journal of Geophysical Research Atmospheres 111 (9): 1–12.
[5] Miller, Daniel J., Zhibo Zhang, Steven Platnick, Andrew S. Ackerman, Frank Werner, Celine Cornet, and Kirk Knobelspiesse. 2017. "Comparisons of Bispectral and Polarimetric Cloud Microphysical Retrievals Using LES-Satellite Retrieval Simulator." Atmospheric Measurement Techniques, no. September.
[6] Nakajima, Teruyuki, Michael D. King, Teruyuki Nakajima, and Michael D. King. 1990. "Determination of the Optical Thickness and Effective Particle Radius of Clouds from Reflected Solar Radiation Measurements. Part I: Theory." Journal of the Atmospheric Sciences.
[7] Platnick, S. 2000. "Vertical Photon Transport in Cloud Remote Sensing Problems." Journal of Geophysical Research Atmospheres 105 (D18): 22919–35.
[8] Várnai, Tamás, and Alexander Marshak. 2002. "Observations of Three-Dimensional Radiative Effects That Influence MODIS Cloud Optical Thickness Retrievals." Journal of the Atmospheric Sciences 59 (9): 1607–18.
[9] Wang, Zhen, Shengcheng Cui, Jun Yang, Haiyang Gao, Chao Liu, and Zhibo Zhang. 2017. "A Novel Hybrid Scattering Order-Dependent Variance Reduction Method for Monte Carlo Simulations of Radiative Transfer in Cloudy Atmosphere." Journal of Quantitative Spectroscopy and Radiative Transfer 189: 283–302.
[10] Zhang, Zhibo, Frank Werner, H.M. Cho, G. Wind, Steven E Platnick, Andrew S. Ackerman, L. Di Girolamo, A. Marshak, and Kerry Meyer. 2016. "A Framework Based on 2-D Taylor Expansion for Quantifying the Impacts of Subpixel Reflectance Variance and Covariance on Cloud Optical Thickness and Effective Radius Retrievals Based on the Bispectral Method." Journal of Geophysical Research Atmospheres 121 (12): 7007–25.

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- Fellow grad students
- UMBC HPCF
- My family

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