Mitigation of OCO-2 CO_2 Biases in the Vicinity of Cloud

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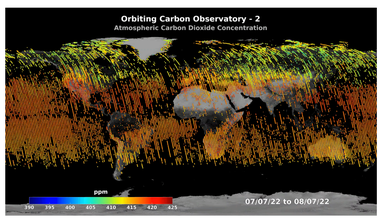
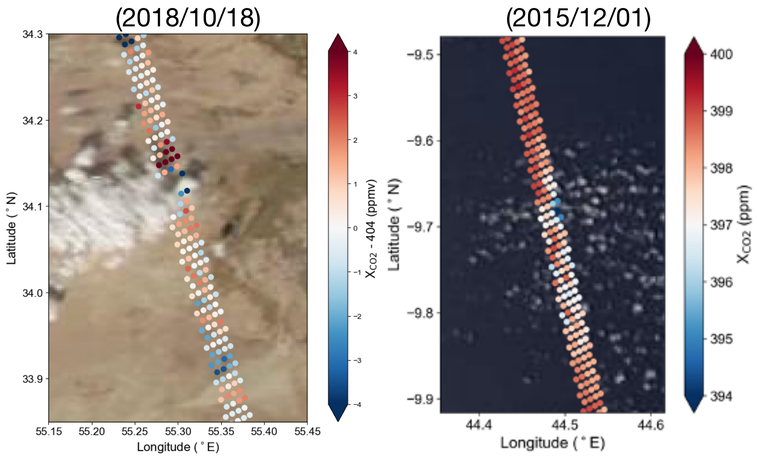
Abstract The NASA Orbiting Carbon Observatory (OCO-2/3) satellites provide precise measurements of the column-averaged CO_2 dry air mixing ratio (X_{CO2}). However, adjacent clouds can induce biases in X_{CO2} retrievals (Massie et al., 2023). These biases result from neglecting the scattering caused by the nearby cloud in the retrieval algorithm, a phenomenon termed the three-dimensional (3D) effect. Schmidt et al. (2016) initially proposed a linear approximation to model the 3D cloud effect, significantly reducing the computational load for simulating the spectra for OCO-2/3 spectrometers. Following this, we have developed a parameterization method for the coefficients in this linear approximation based on the effective cloud distance and proposed a targeted mitigation approach for land-nadir measurements of OCO-2. This study introduces a novel mitigation strategy for OCO-2's land-nadir measurements that applies spectral adjustment to counteract the 3D cloud spectroscopic effect. Our approach effectively reduces the X_{CO2} retrieval errors near clouds over land, marking a significant improvement in the accuracy of CO_2 monitoring for climate research and emission tracking. This preliminary investigation enhances our ability to precisely measure atmospheric CO_2 levels, contributing to our understanding of climate change.

Motivation

Positive or negative X_{CO2} anomalies near clouds have been observed over land and ocean.

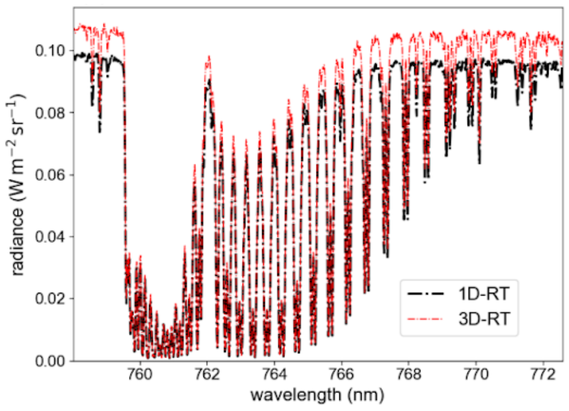




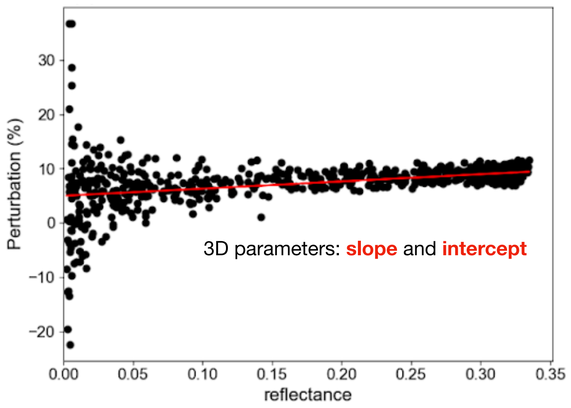
Spectrum with and without 3D cloud effect

OCO-2 observes O_2-A, weak and strong CO_2 bands to derive X_{CO2}. Simulations present a linear relationship between the perturbation (radiance different with and without cloud scattering effect) and the reflectance.

Simulated 1D and 3D O_2-A spectra



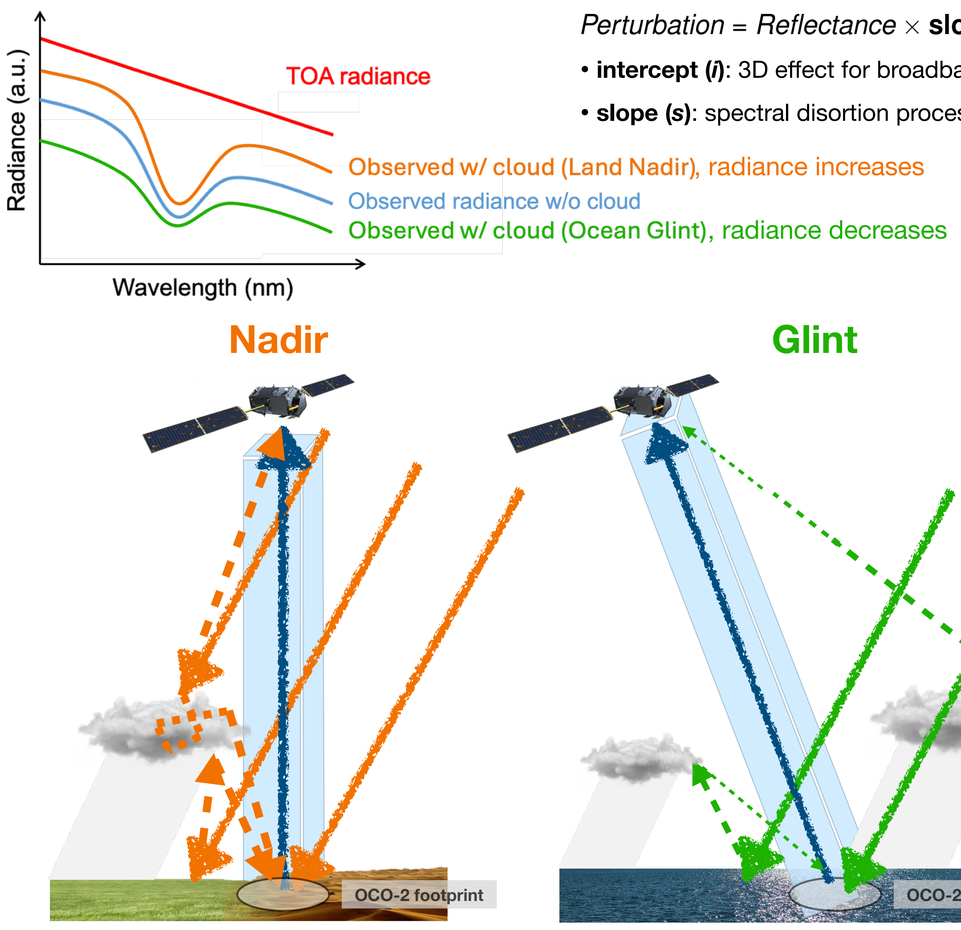
Perturbation versus **reflectance**



$$Perturbation = \frac{Radiance_{3D} - Radiance_{1D}}{Radiance_{1D}} \times 100\%$$

High absorbance ⟷ Low absorbance

Mechanism of 3D cloud effect in spectroscopy



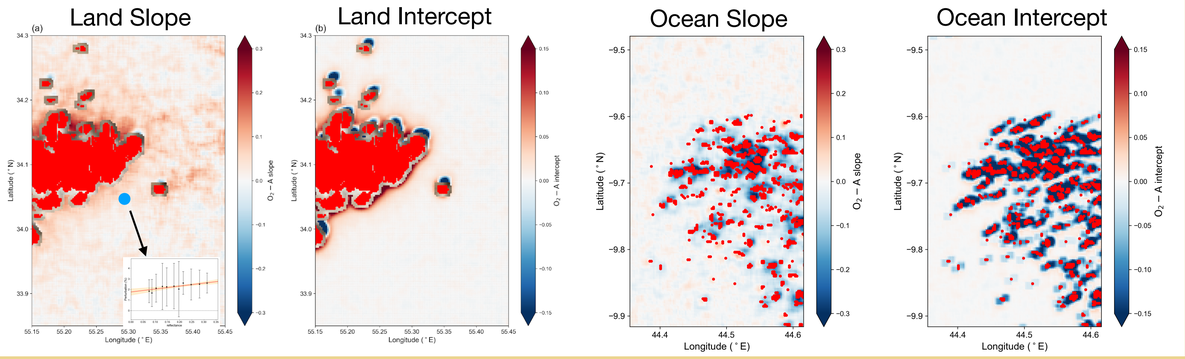
Perturbation = *Reflectance* × **slope** + **intercept**

- **intercept (*i*)**: 3D effect for broadband wavelength
- **slope (*s*)**: spectral disortion process of 3D effect

- **Spectral distortion**: absorbance difference of each wavelength leads to inconsistent radiance change and the tilting of the linear relationship between perturbation and reflectance.
- **Nadir**: brightening effect governs the positive 3D cloud bias
- **Glint**: shadowing effect from thin clouds dominates the negative 3D cloud bias

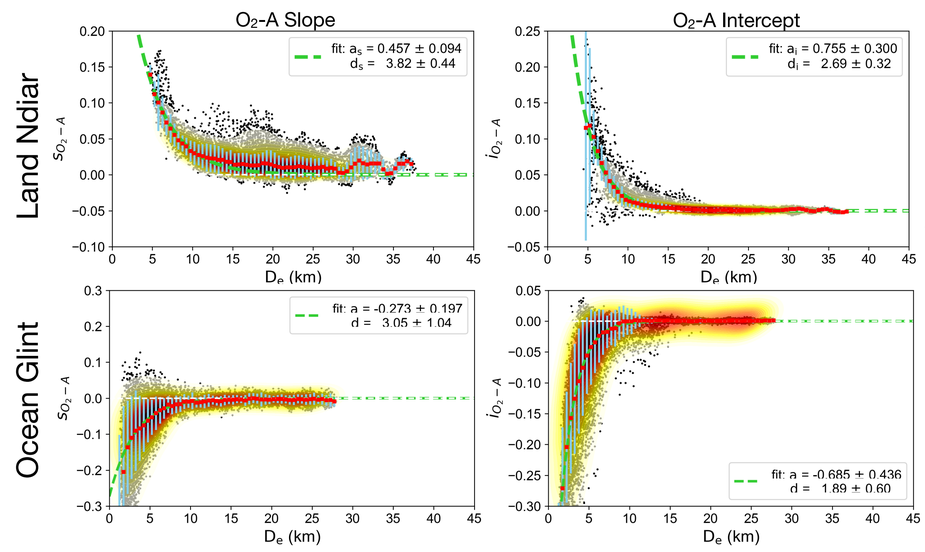
Simulation and 3D effect parameters derivation

By simulating the radiance of only a few wavelengths of across the entire spectrum, we can derive 3D effect parameters using linear regression.



3D effect parameterization to bypass 3D-RT simulation

Slopes and intercepts are well-correlated with effective cloud distance, so we parameterized them with an exponential decay equation to reduce calculation demand.



$$D_e = \frac{\sum_{i \in \{surrounding\ clouds\}} w_i D_i}{\sum_{i \in \{surrounding\ clouds\}} w_i}$$

$$s = a_s \times \exp(-\frac{D_e}{d_s})$$

$$i = a_i \times \exp(-\frac{D_e}{d_i})$$

Please see Poster "*Reducing OCO-2 regional biases through novel 3D cloud, albedo, and meteorology estimation*" by Susan Kulawik for related research.

Cloud-induced bias mitigation

With derived slopes and intercepts from effective cloud distance, 3D cloud retrieval bias can be mitigated via spectra adjustment.

L1B Radiance → $I_\lambda^{IPA\,(adjusted)}(x,y) = \frac{I_\lambda^{IPA\,(obs)}(x,y)}{(\frac{i_{xy} + s_{xy} \times R_\lambda^{obs}}{100\%} + 1)}$ → Adjusted Radiance → Retrieval → Mitigated X_{CO2}

Footprint locations → imagery → effective cloud distances → bypass → ***s*** & ***i***

- slope (s) and intercept (i) are scene dependent
- Nadir and glint modes affect the bypass method

Conclusions

- The 3D cloud effect is present in spectroscopy, exerting opposite influences on OCO retrievals over land and ocean.
- This 3D effect can be modeled using a linear equation with two parameters: slope and intercept.
- The slopes and intercepts can be parameterized based on the effective cloud distance.
- The retrieval bias can be partially mitigated through radiance adjustment

References

- Chen et al., Mitigation of Satellite OCO-2 CO2 Biases in the Vicinity of Clouds with 3D Calculations using the Education and Research 3D Radiative Transfer Toolbox (EaR^{3}T), in preparation.
- Massie et al., Insights into 3D cloud radiative transfer effects for the Orbiting Carbon Observatory, Atmos. Meas. Tech., 16, 2145–2166, 2023.
- Schmidt et al., Uncovering the Mechanism Behind Trace Gas Spectroscopy Biases in the Vicinity of Clouds With the OCO-2 Three-Dimensional Radiative Transfer Radiance Simulator, in preparation.