Radiative transfer: From plane parallel to 3D RT

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Most aerosol studies use 1D radiative transfer

Assume variations only in vertical direction: $\Delta \approx \frac{dy}{dz}$

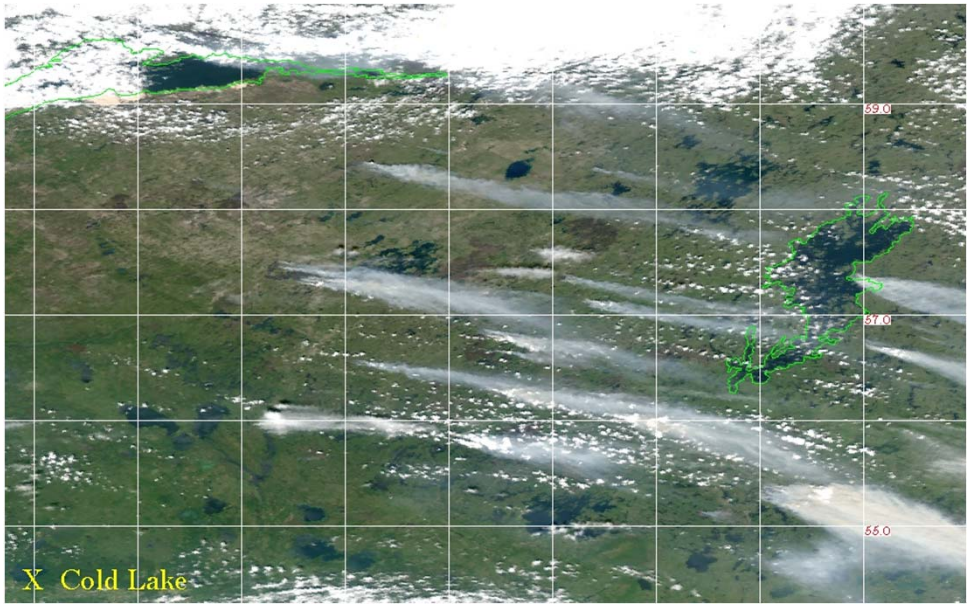
Arctic haze

Smog

Large 3D variations occur near strong point sources

$$\Delta \approx \frac{\partial y}{\partial x} + \frac{\partial y}{\partial y} + \frac{\partial y}{\partial z} \neq \frac{dy}{dz}$$

Farther from source, plumes become closer to 1D



MODIS Aqua, June 30, 2008

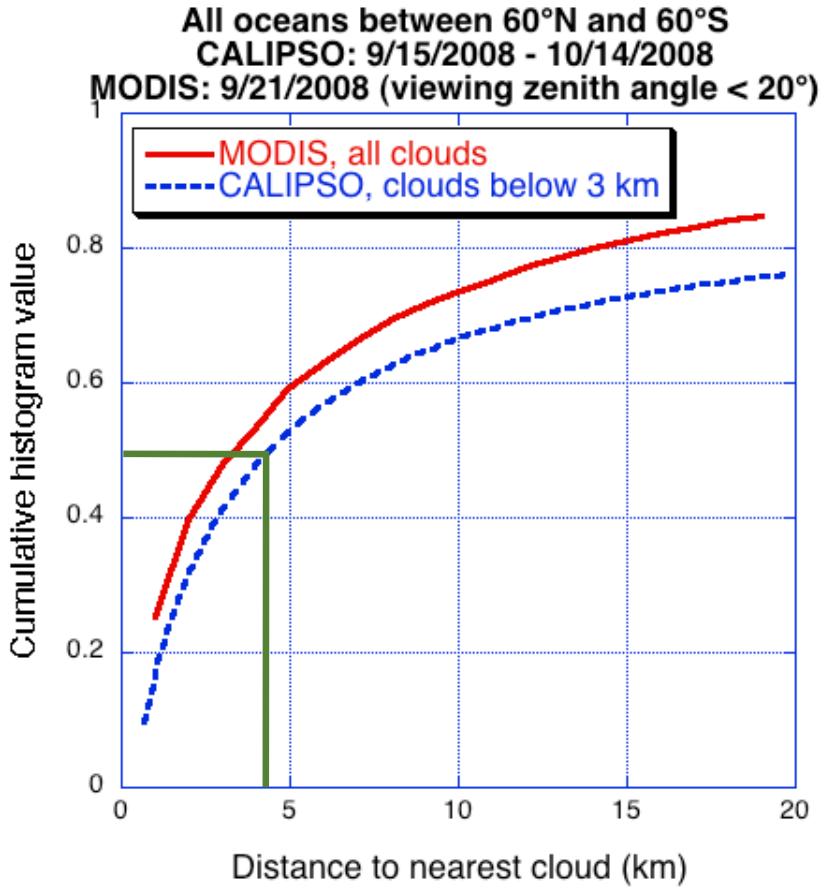
NASA P-3 camera, June 30, 2008

Variations are 3D around clouds

Saharan dust & clouds

Most clear areas are not too far from clouds

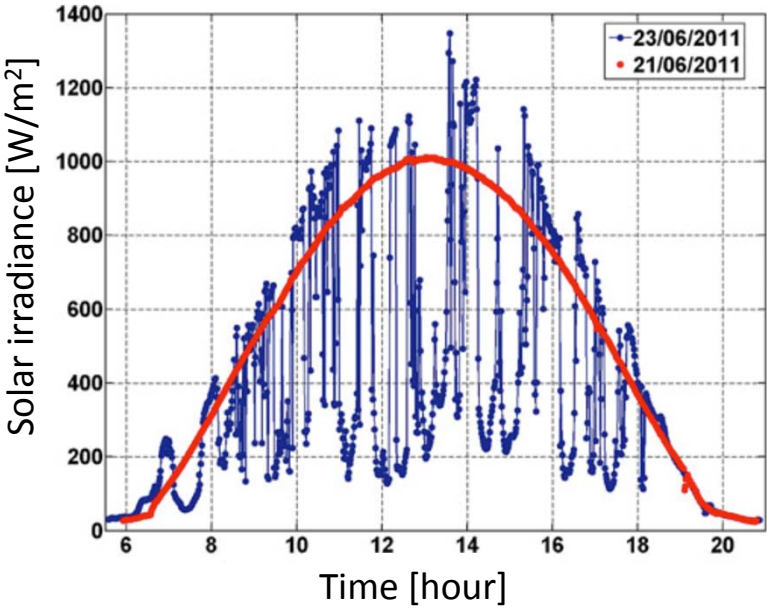
DSCOVR spacecraft, EPIC imager, July 16, 2015

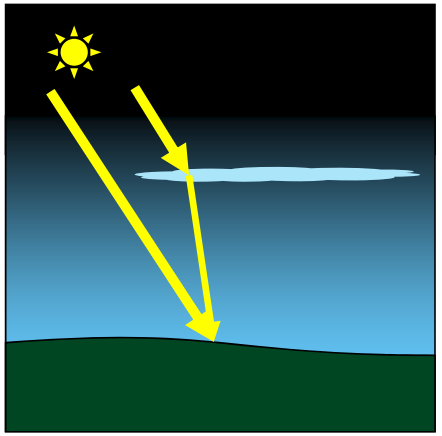


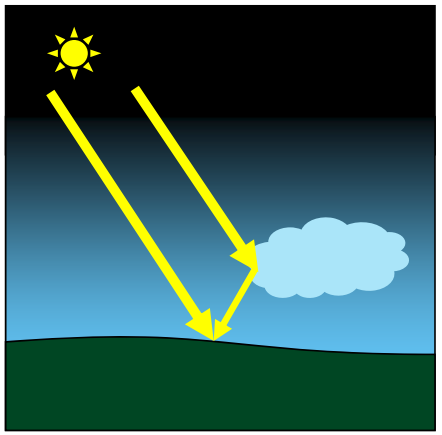
3D radiation near clouds is of interest to many

- Solar energy: peak periods (Yordanov et al., 2013)
- Health: UV enhanced for low CF (Nunez et al., 2016)
- Aerosols (energy budget, remote sensing)

Clear & partly cloudy day



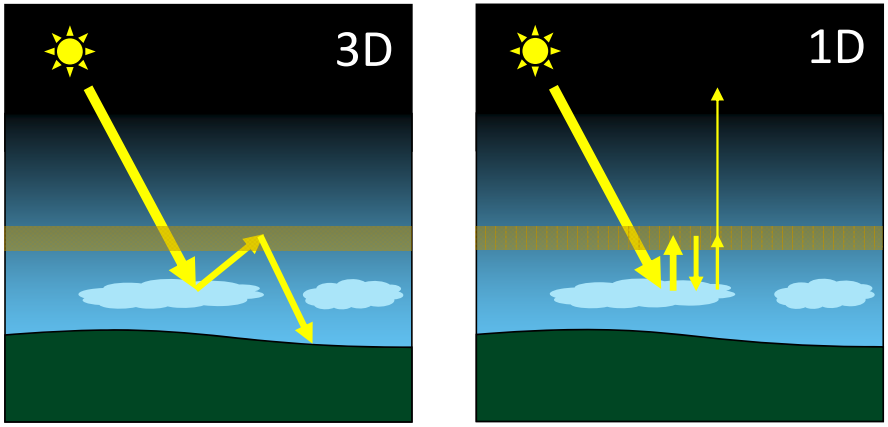




Absorbing aerosols above clouds: 3D effects enhance direct radiative effect (DRE) on TOA upward flux

0.49 µm, Sc field (most heterogeneous areas excluded), Solar zenith angle: 40°, [W/m²/µm]

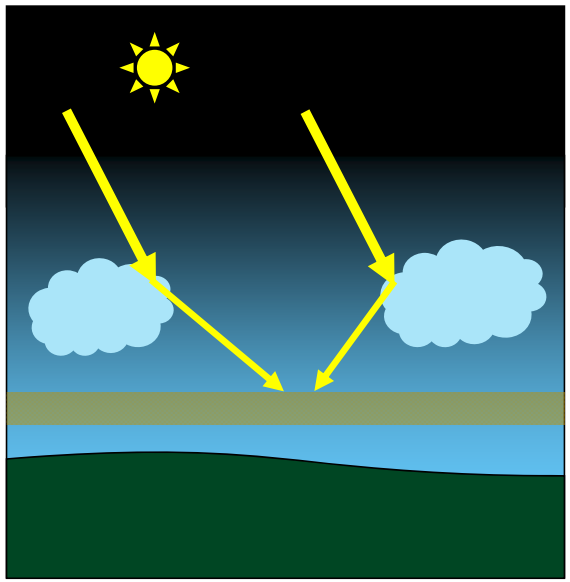
	3-D modeling	1-D modeling	$(F_{1\text{-D}}\text{-}F_{3\text{-D}})/F_{3\text{-D}}$ (%)
$F^{\uparrow}_{\text{cloud+aer}}$	569.01	564.48	−0.79
$F^{\uparrow}_{\text{cloud}}$	661.07	646.40	−2.22
$\text{DRE} = F^{\uparrow}_{\text{cloud}}\text{-}F^{\uparrow}_{\text{cloud+aer}}$	92.06	81.92	−11.01

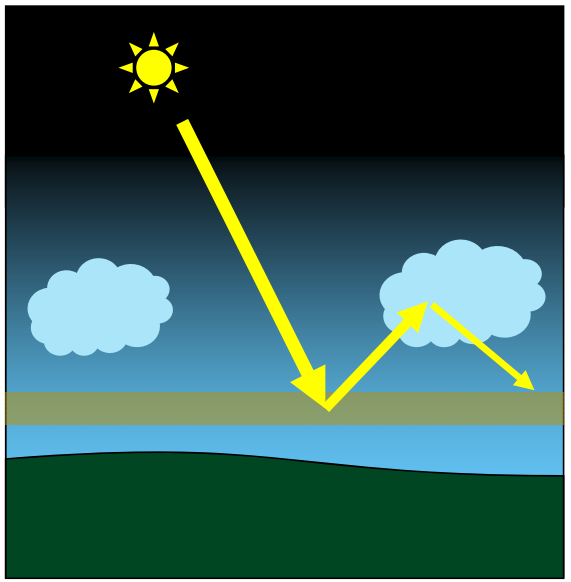


Peers et al. (ACP, 2015)

3D enhances aerosol absorption below clouds

3D increased aerosol absorption by less than 0.5 W/m^2 (for 1D abs. of 3-5 W/m^2)



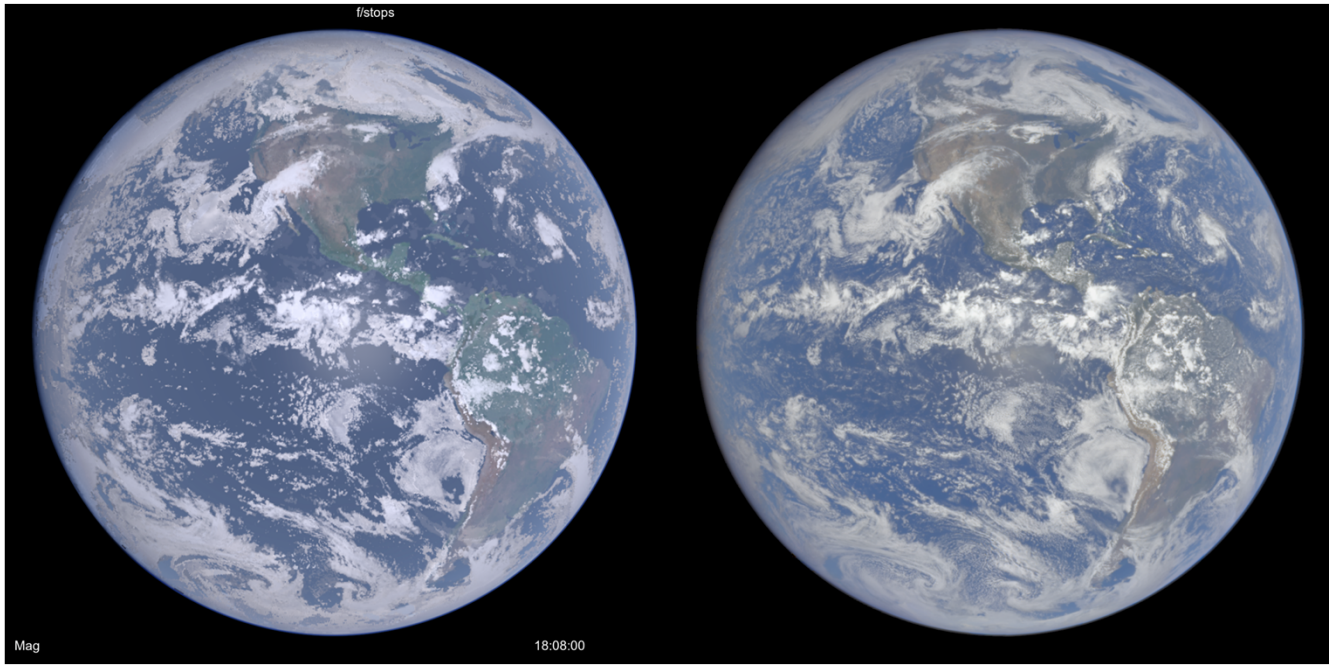


Fu et al. (JAS, 2000)

Impact of 3D effects on remote sensing can interest

Users of satellite-based aerosol observations in data assimilation or model testing

(Using satellite retrieval results or model-based satellite simulators)

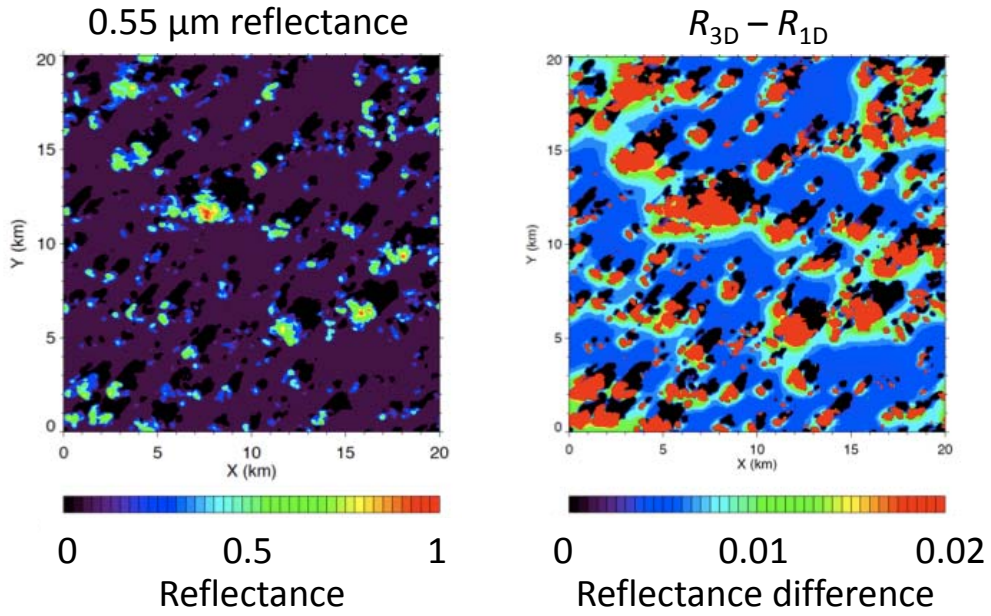


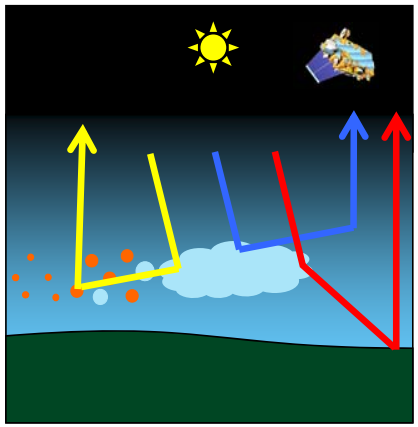
Simulation for G-LAPS analysis

DSCOVR EPIC image

Steven Albers

Simulations: 3D enhances radiances around clouds





In observations, other enhancements from:

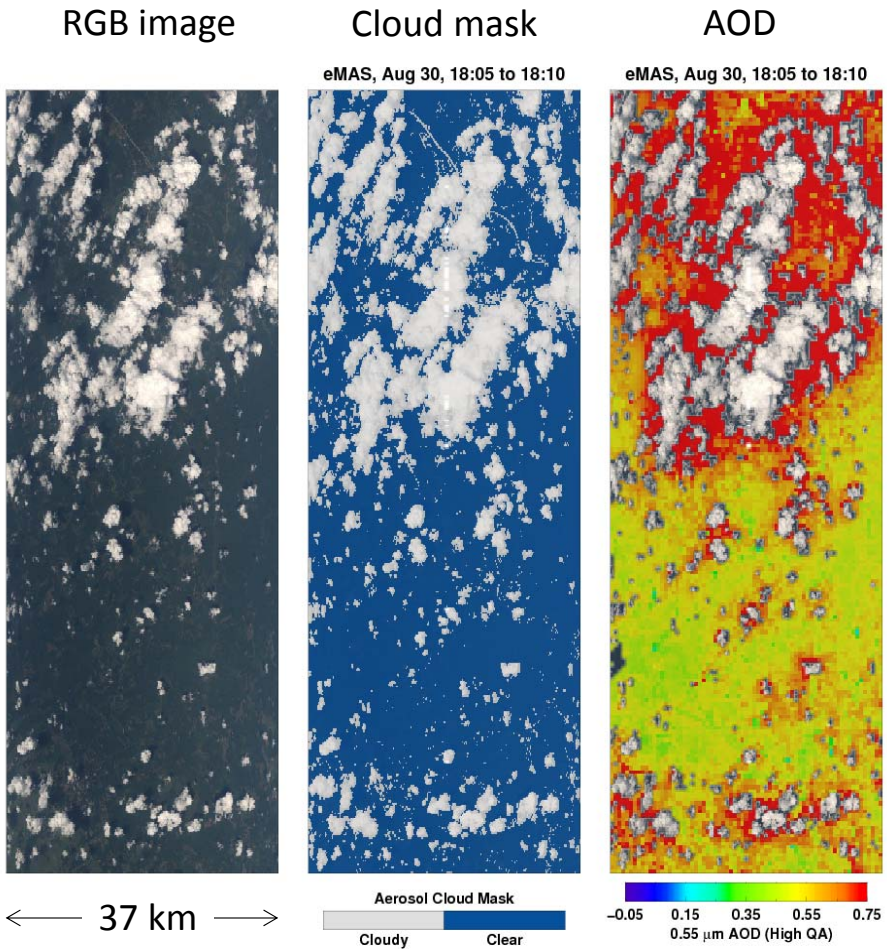
- Aerosol swelling
- Cloud contamination
- Cloud processing

- Instrument blurring

Radiance enhancements → higher retrieved AOD values

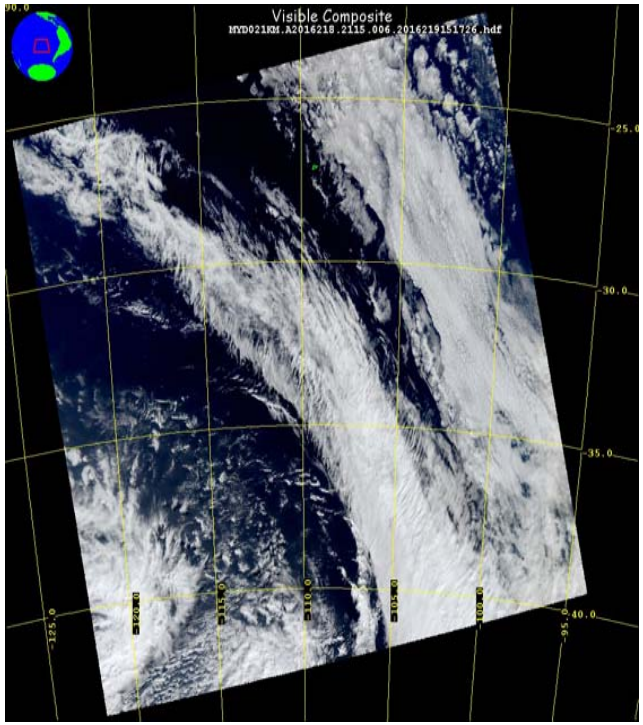
Airborne data shows near-cloud enhancements

NASA ER-2 eMAS
Centreville, Alabama, August 30, 2013

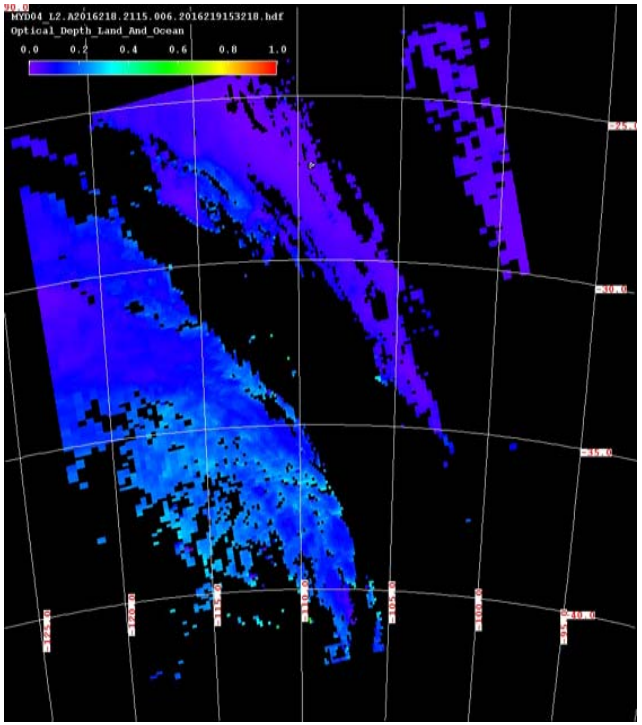


Satellite images also show near-cloud enhancement

MODIS image

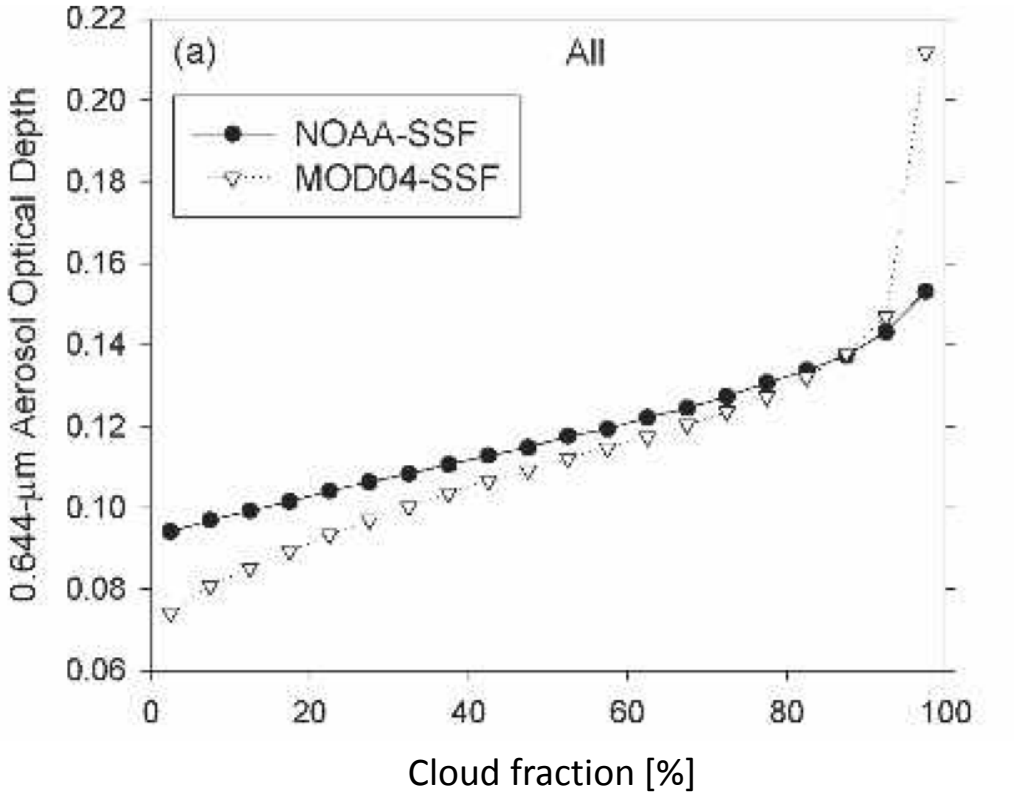


AOD

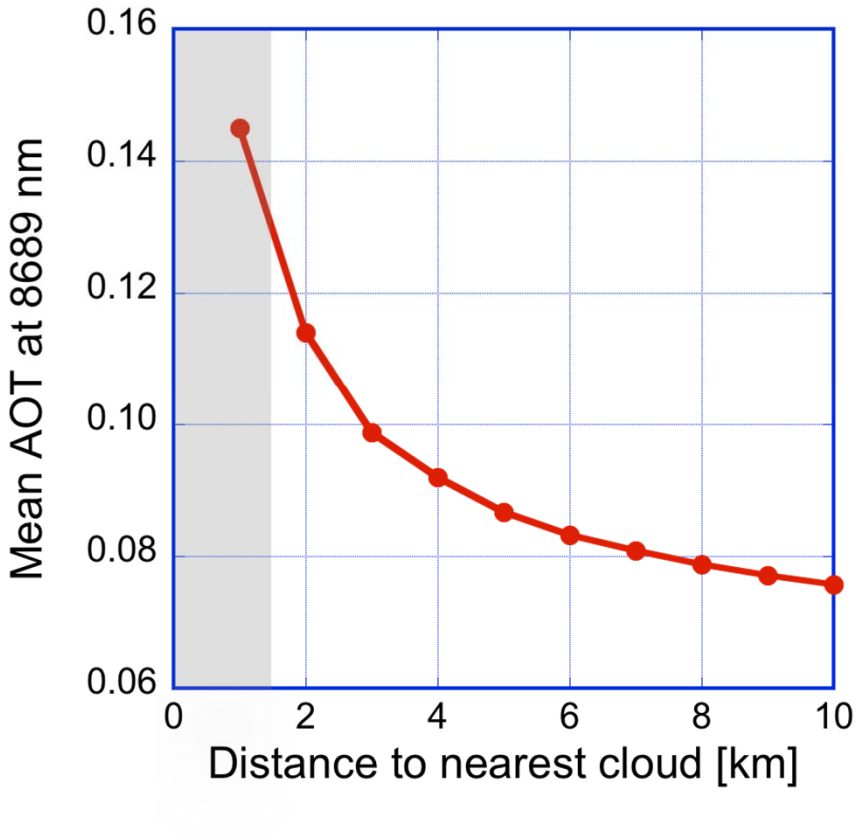


Aqua MODIS, August 5, 2016

Near-cloud enhancements are statistically large



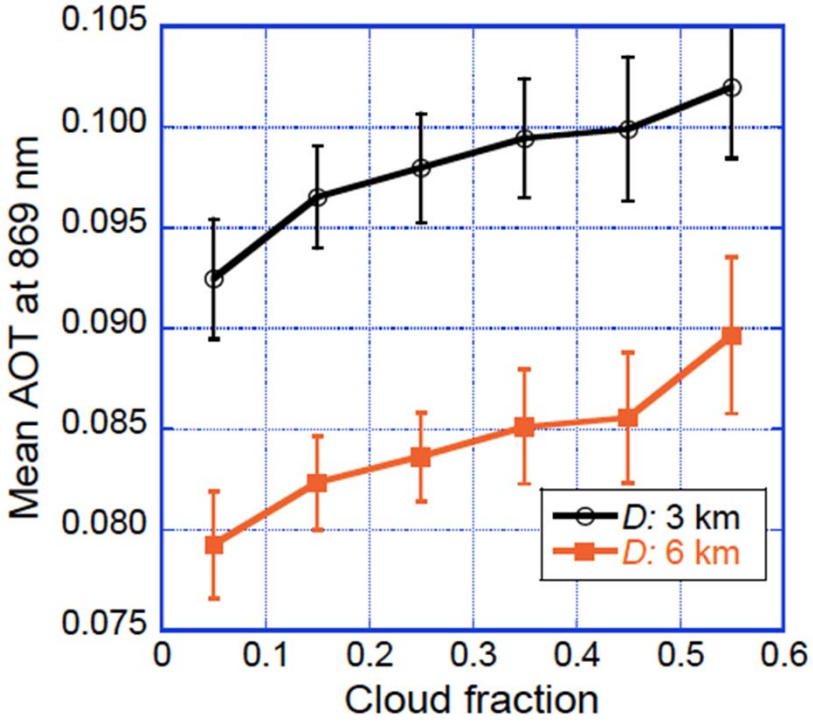
Loeb and Manalo-Smith (J. Clim., 2005)



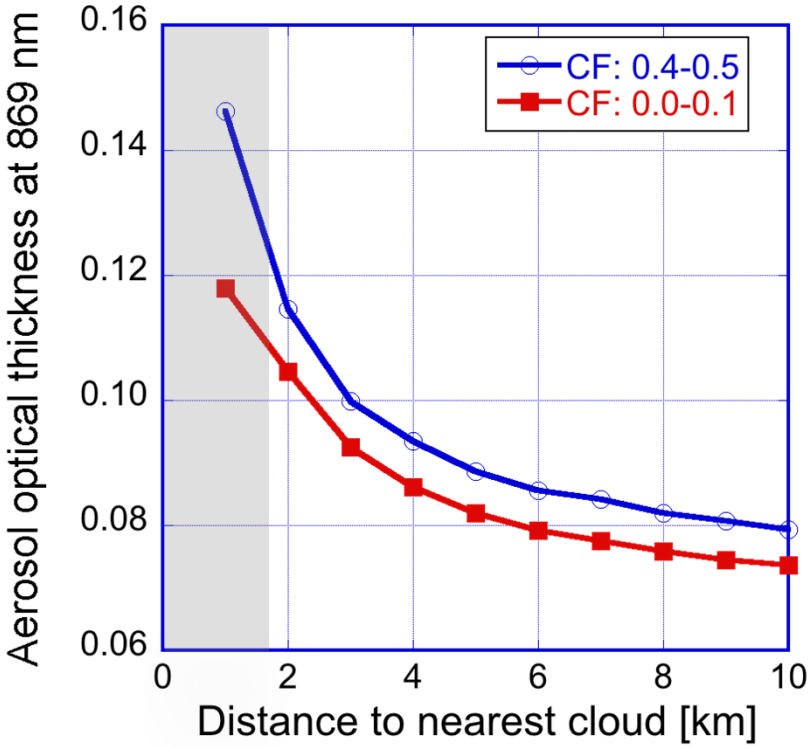
Based on Várnai and Marshak (Rem. Sens. 2015)

CF & distance to cloud impact AOD separately

Constant distance to cloud (*D*)



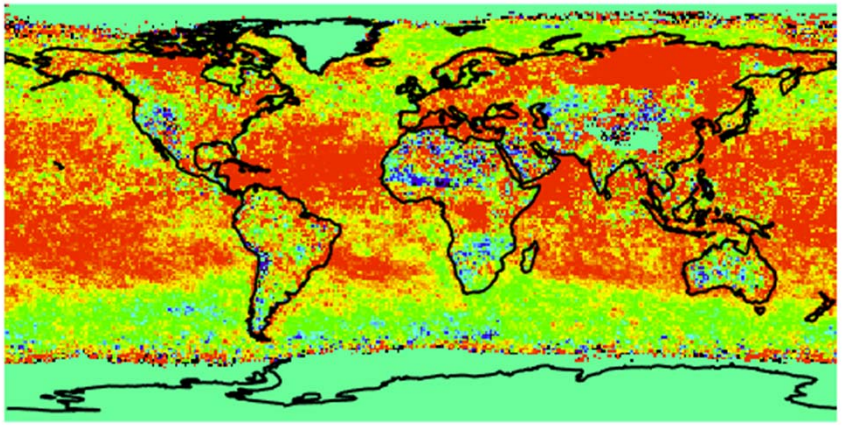
Constant cloud fraction (CF)



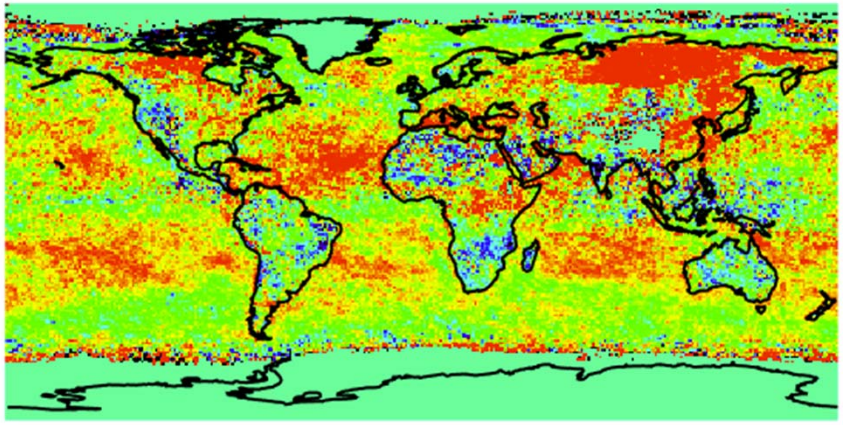
Várnai and Marshak (Rem. Sens., 2015)

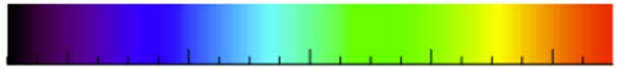
CF-AOD correlation is positive throughout the globe

MODIS



MERRA-2

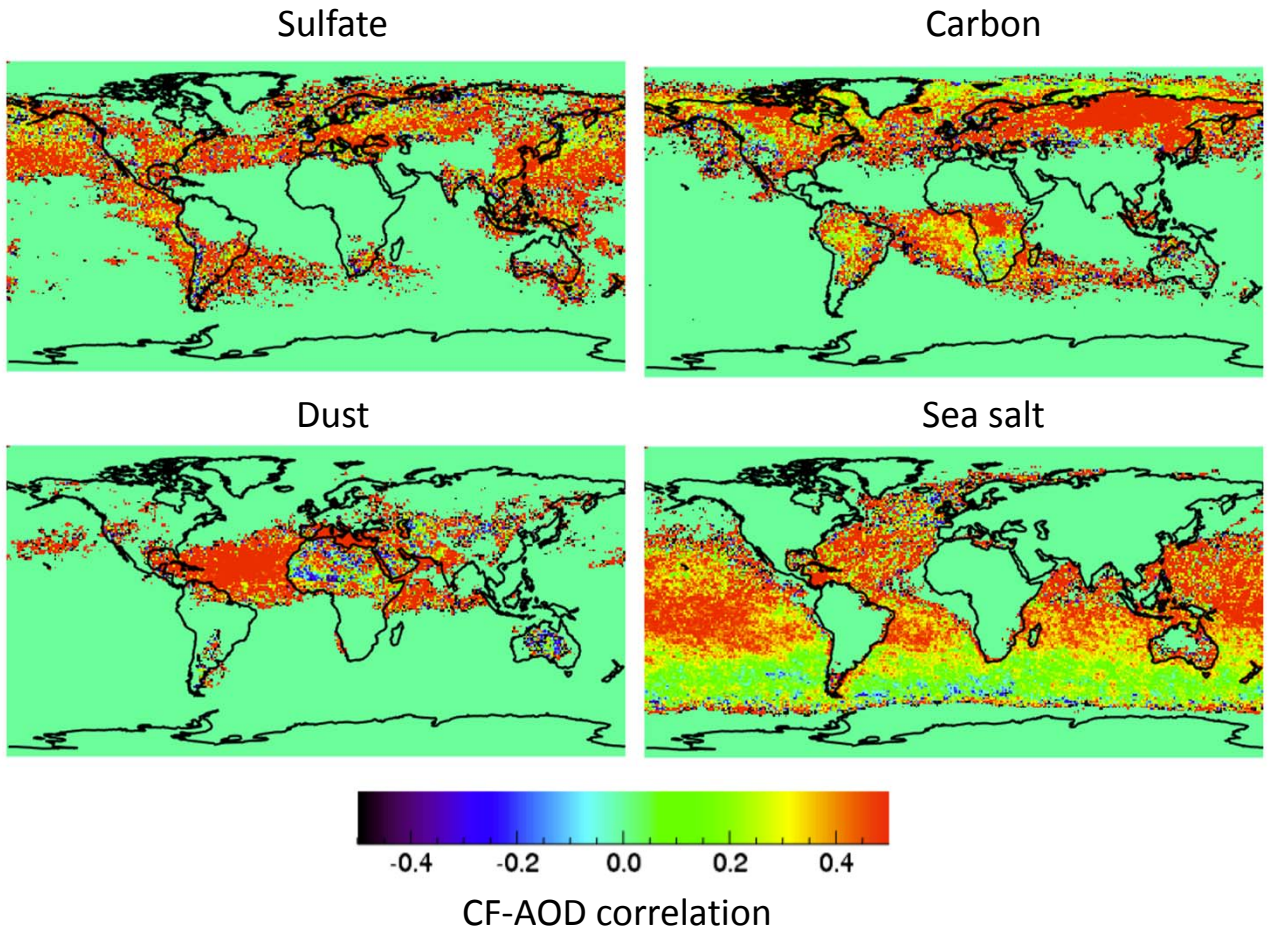




June-July-August, 2012-2014

Similar behavior for other models (e.g.,Quaas et al., ACP, 2010)

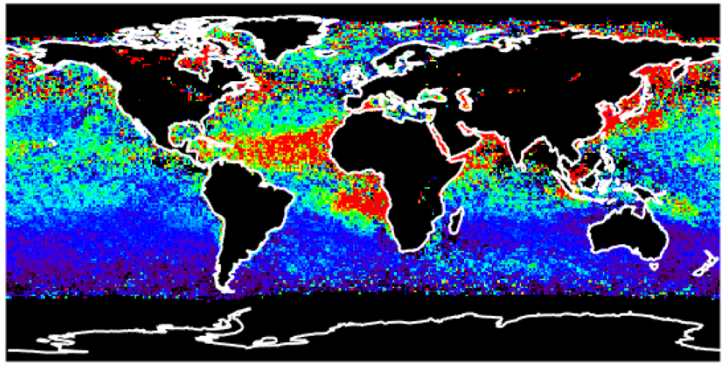
MODIS CF & AOD well-correlated for all MERRA-2 aerosol types



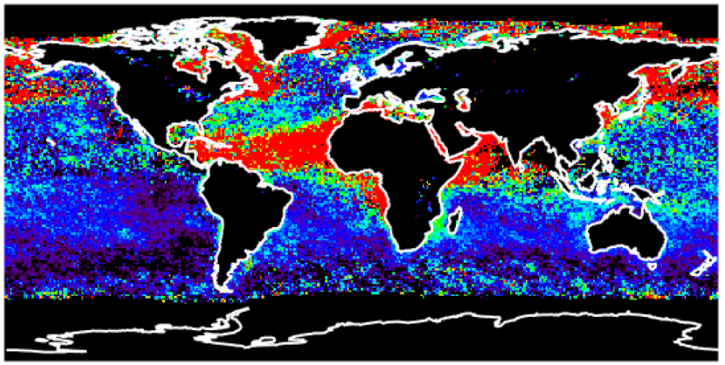
MODIS Aqua, JJA 2012-2014

AOD often increases with CF more for small mode

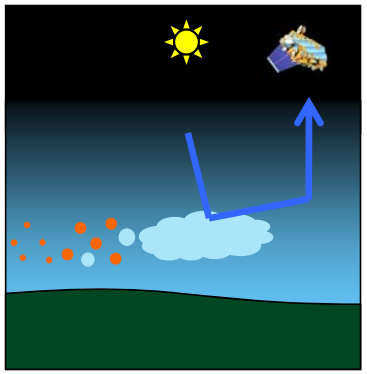
Small mode

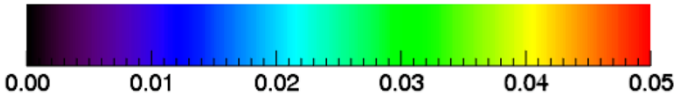


Coarse mode



3D “bluing” effect



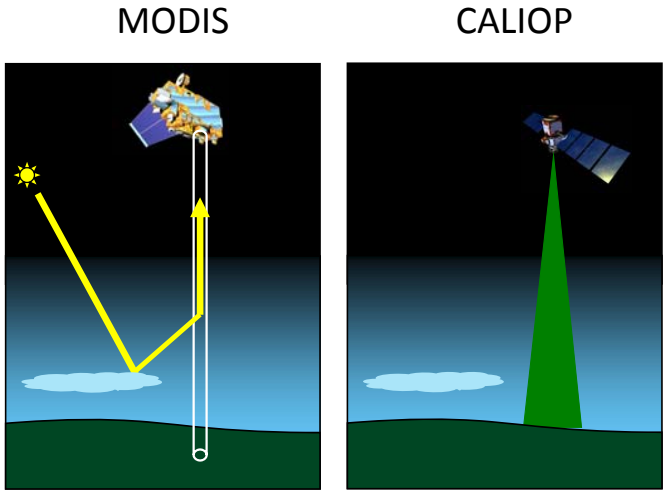


AOD(high CF) – AOD(low CF)

- 3D effect: bluing
- small mode is more hygroscopic
- coarse mode aerosol is at altitudes with dry air
- cloud processing creates small aerosols

MODIS Aqua, JJA 2012-2014

3D causes significant part of near-cloud enhancements

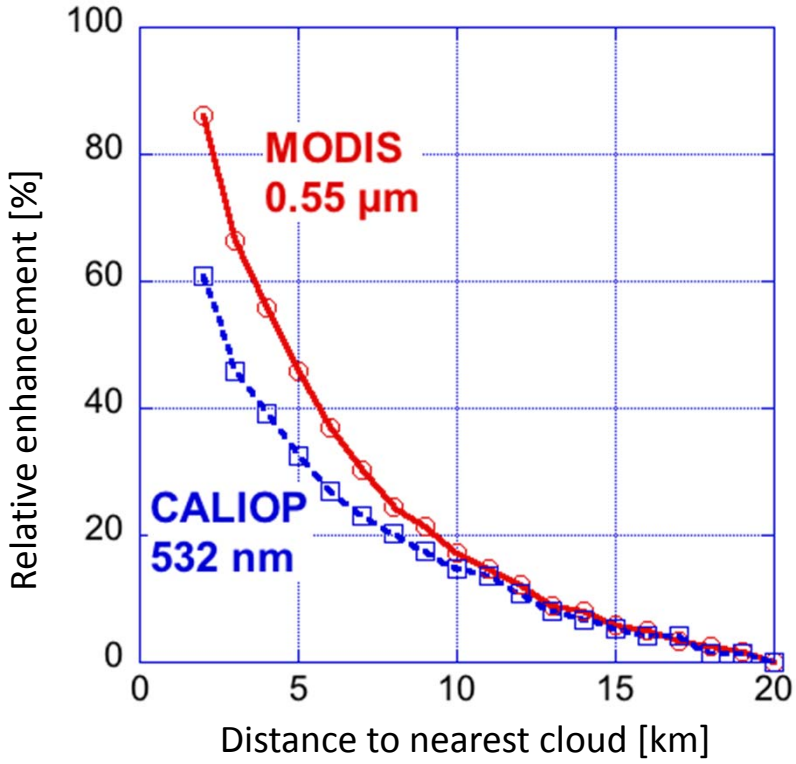


CALIOP can observe enhancements from:

- Aerosol swelling
- Cloud contamination
- Cloud processing

It is not affected by:

- 3D enhancement
- Instrument blurring



Global oceans, 60°N – 60°S (Várnai et al., ACP, 2013)

Impact of 3D effect varies with retrieval algorithm

3D effects vary with
- Wavelength (deep blue vs. dark target)
- Polarization (POLDER vs. MODIS)
- View directions (MISR vs. MODIS)

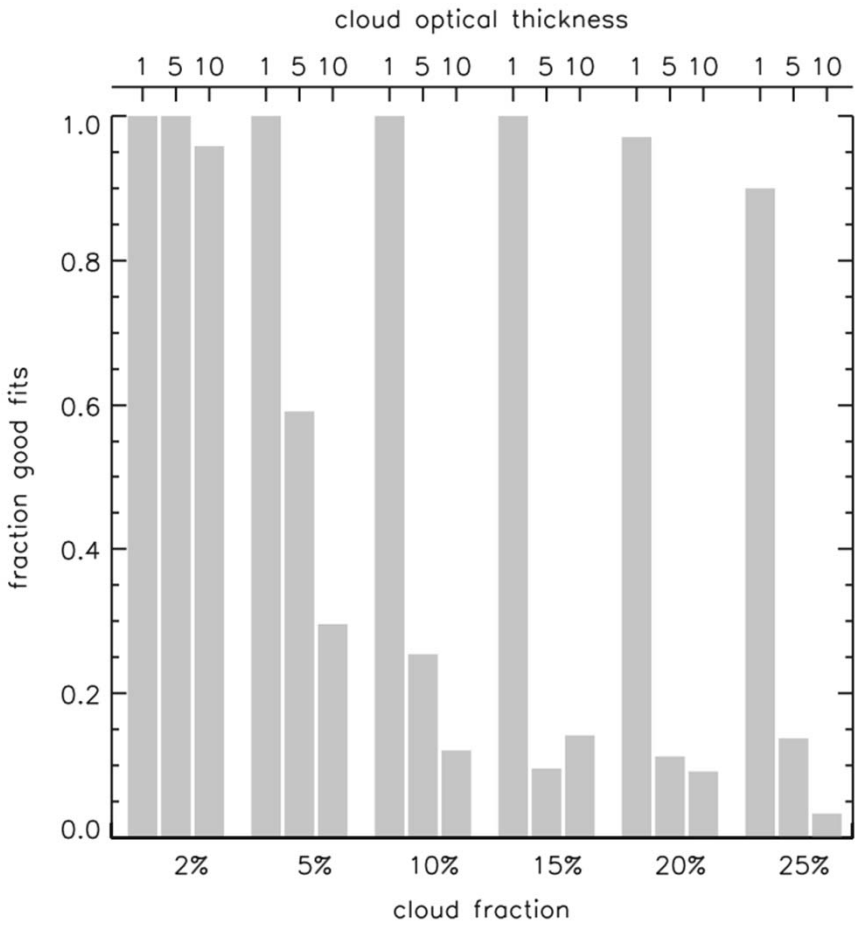
POLDER: 3D effects do not cause problems if

CF < 5% or $\tau_{cloud} < 5$

For CF = 25% and $\tau_{cloud} = 10$:

ΔAOD = 0.12 (≈25%), ΔSSA = 0.09

Stap et al. (JQSRT, 2016):

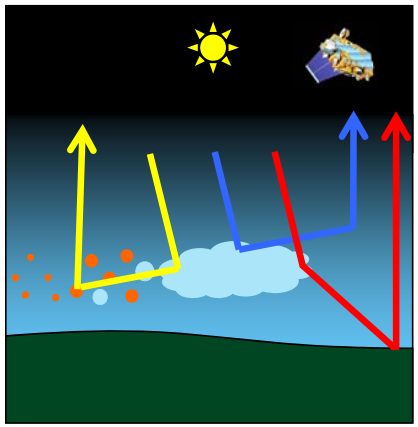


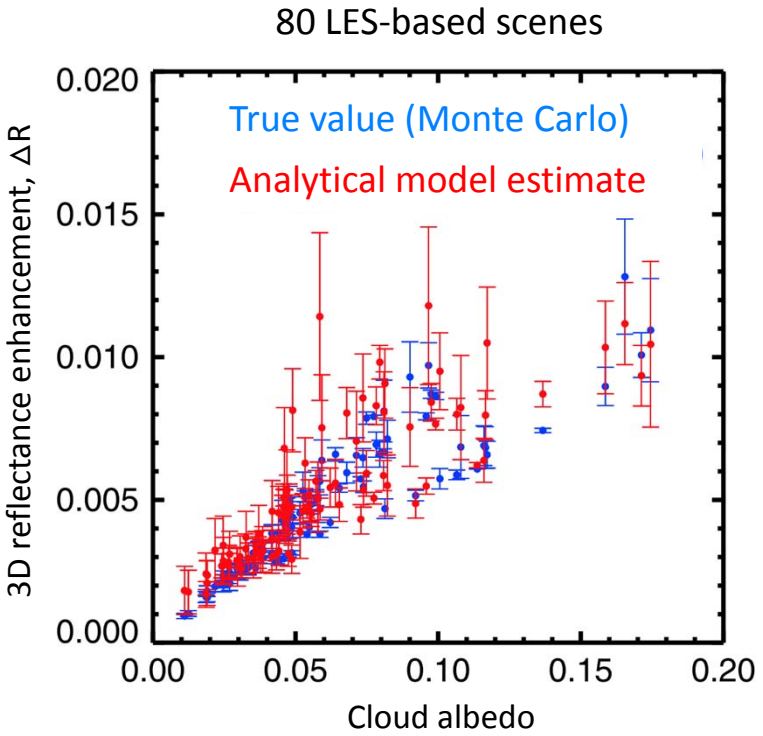
Analytical model is tested for removing 3D enhancements

$R_{1D} = R_{MODIS} - \Delta R$

ΔR is function of:

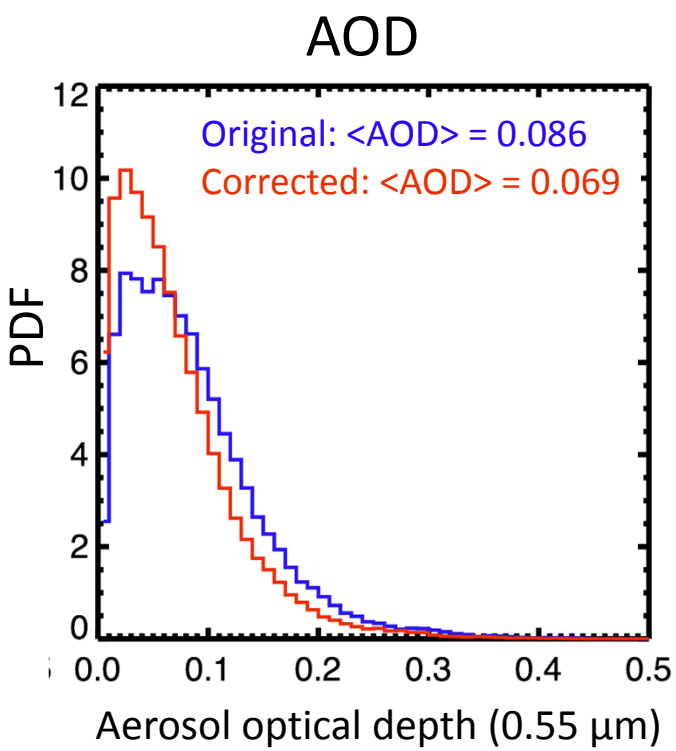
- sun-view geometry
- mean cloud altitude and albedo
- surface albedo
- aerosol parameters

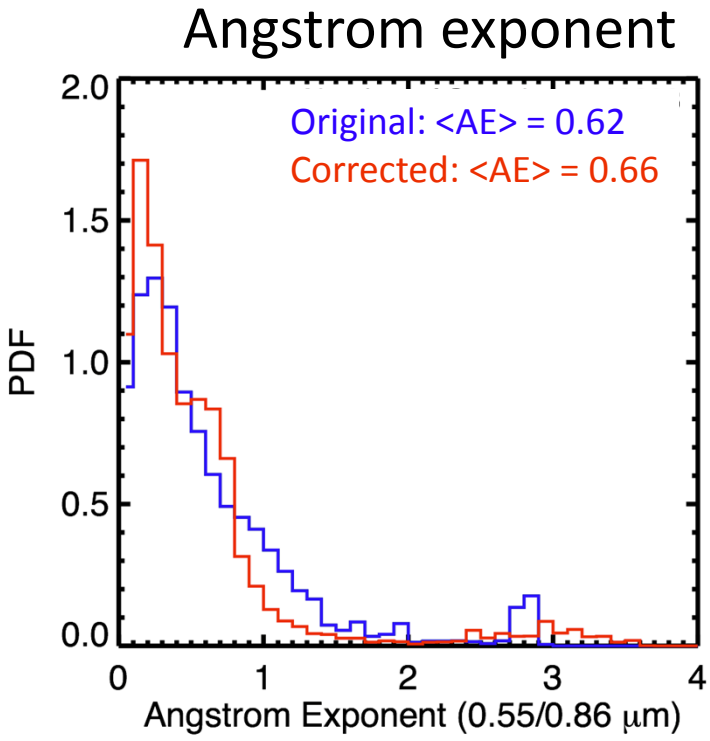




Wen et al. (JGR, 2016)

3D correction reduces retrieved AOD-s and can change Angstrom exponents either way





31 MODIS granules off the West coast of North & South America, August 1-8, 2013

Summary

- Simulations: 3D effects increase both the radiative effect of absorbing aerosols above Sc clouds and the absorption by below-cloud aerosols.
- MODIS & MERRA-2: Cloud fraction and AOD are positively correlated through most the globe and for all aerosol types. Correlation is often stronger for MODIS & fine mode.
- Simulations, MODIS + CALIOP: 3D radiative effects have a significant impact on satellite radiances near clouds, where a large portion of clear-sky columns occur.
- An analytical model is being developed to help dark target aerosol retrievals by estimating 3D reflectance enhancements.