Spectrally-invariant approximations within atmospheric radiative transfer

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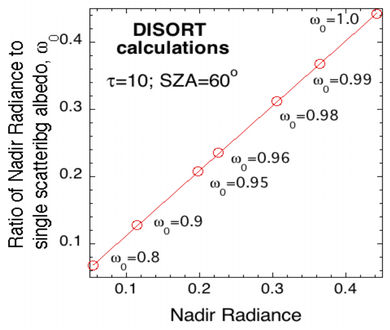
Certain algebraic combinations of single-scattering albedo and solar radiation reflected from, or transmitted through, clouds do not vary with wavelength



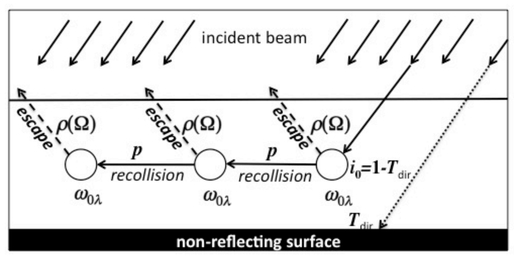
Linear relationship between radiance to single scattering albedo ratio, $I(\Omega)/\omega_{0\lambda}$, and radiance, $I(\Omega)$.

$$\frac{I_\lambda(\Omega)}{\omega_{0\lambda}} = pI_\lambda(\Omega) + R(\Omega) \qquad (*)$$

The slope p and the intercept $R(\Omega)$ are *spectrally invariant* recollision and escape probabilities, respectively.

Schematic of radiative transfer process

T_{dir} is the fraction of photons which reach the surface without interacting. A fraction, i_0=1-T_{dir}, interacts with a cloudy atmosphere. With probability $\omega_{0\lambda}$ these photons are scattered and then either interact again (with probability p) or escape the atmosphere in direction Ω (with probability $R(\Omega)$= $\rho(\Omega)i_0$).



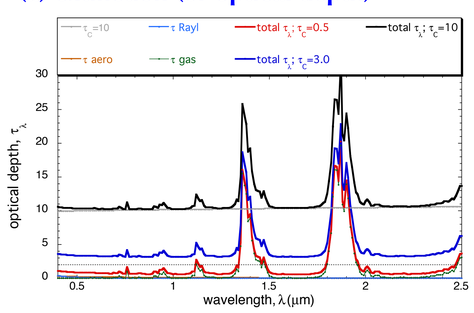
Under what conditions is Eq. (*) valid?

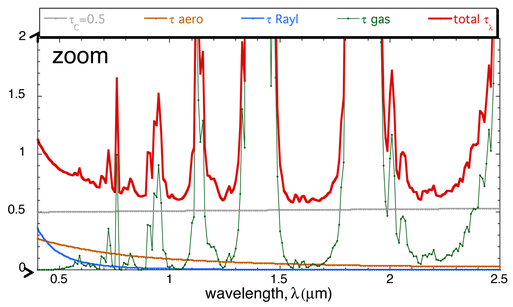
The extinction coefficient and the scattering phase function are wavelength independent!

Is it true in real cloudy atmospheres?

Cloudy atmospheres: spectral variability of the extinction and scattering

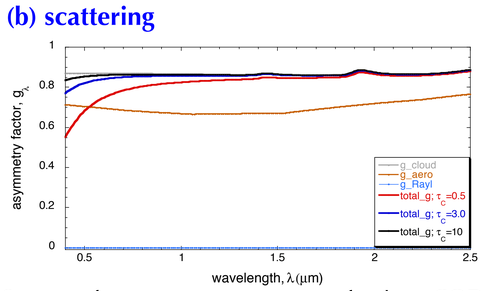
(a) extinction (or optical depth)



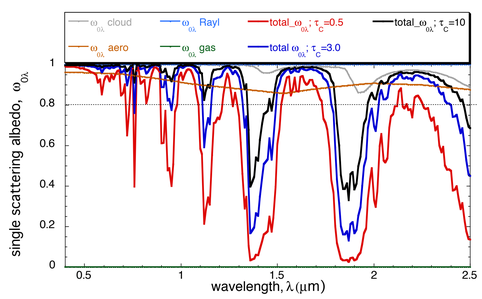


Spectra of *total* optical depth of a cloudy atmosphere and its constituents, air molecules, cloud droplets, aerosol particles and gases. AOD=0.2. *Left Panel*: Spectra for COD=0.5, 3 and 10. *Right Panel*: Zoom of spectra for COD=0.5.

(b) scattering



Spectra of asymmetry parameter g_λ for three COD: 0.5, 3 and 10. AOD=0.2.



Spectra of single scattering albedo $\omega_{0\lambda}$ for the same three cases as in left panel.

Conditions for spectral-invariance are NOT met!

Total optical depth and asymmetry parameter for wavelengths for which $\omega_{0\lambda} > 0.8$

Cloud optical depth, τ_C	Number of wavelengths from 0.4 to 2.5 μm (out of total 210)	Total optical depth, τ_λ	Standard deviation to mean ratio for τ_λ (%)	Total asymmetry parameter, g_λ	Standard deviation to mean ratio for g_λ (%)
0.5	97	0.72±0.12	17	0.79±0.07	9
0.5*	67*	0.65±0.05*	8*	0.83±0.02*	2*
3	154	3.34±0.16	5	0.85±0.02	2
5	166	5.44±0.24	4	0.86±0.01	1
10	179	10.66±0.44	4	0.86±0.01	1

* For wavelengths between 0.7 and 2.5 μm

However …

in cloud-dominated atmospheres the total *extinction* and total *scattering phase function* are only weakly sensitive to wavelength

Summary

For cloudy atmospheres with cloud optical depth above 3, and for spectral intervals that exclude strong water vapor absorption, the spectrally-invariant relationships are valid to better than 5%

Applications

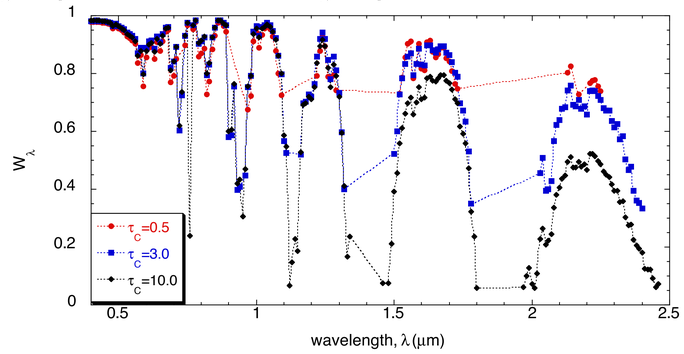
- Broadband calculations for climate models
- Physical interpretation of SWS measurements
- Testing the consistency of remote sensing retrievals
- Filling missing spectral data
- Testing 3D radiative transfer codes

SBDART simulations confirm spectral invariance in cloudy atmospheres

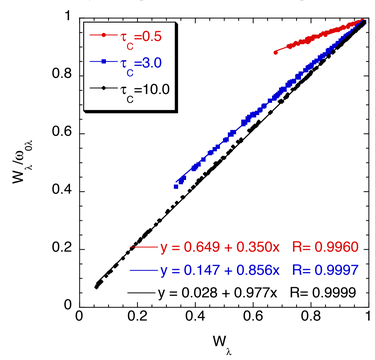
Spectral scattering properties of cloudy atmospheres are fully determined by spectrally *variable* single scattering albedo $\omega_{0\lambda}$ and spectrally *invariant* recollision probability p

$$W_\lambda = 1\text{-}A_\lambda = R_\lambda + T_\lambda$$

R_λ is spectral reflectance; T_λ is spectral diffuse transmittance; A_λ is spectral absorption



Spectra of total scattering W_λ for COD=0.5, 3 and 10 (r_{eff}=16 μm); AOD=0.2. Doglegs occur because only wavelengths for which $\omega_{0\lambda} > 0.8$ are plotted.

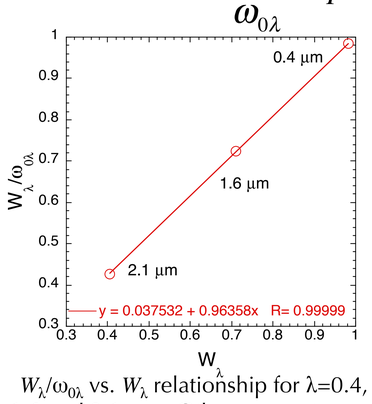


Ratio $W_\lambda/\omega_{0\lambda}$ vs. W_λ for the wavelengths from left panel.

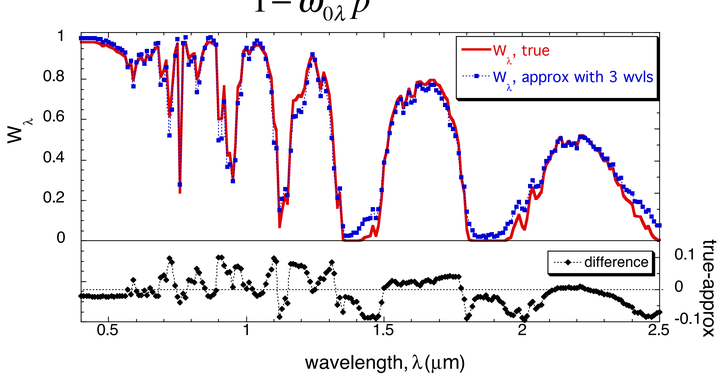
Example of applications: reconstruction of W_λ

Measurements at only three wavelengths accurately approximate scattering spectrum W_λ in cloud-dominated atmospheres

$$\frac{W_\lambda}{\omega_{0\lambda}} = pW_\lambda + R \quad \Leftrightarrow \quad W_\lambda = \frac{R\omega_{0\lambda}}{1-\omega_{0\lambda}p}; \quad R = 1-p$$



$W_\lambda/\omega_{0\lambda}$ vs. W_λ relationship for λ=0.4, 1.6 and 2.1 μm. Other parameters are COD=10, r_{eff}=16 μm, AOD=0.2.



Reconstruction of W_λ with slope and intercept obtained from left panel.