Use of the ARM Measurements of Spectral Zenith Radiance for Better Understanding of 3D Cloud-Radiation Processes & Aerosol-Cloud Interaction

This is a collaborative project with the project DOE-FG02-ER64562. This report covers BU activities from February 2011 to June 2011 and BU "no-cost extension" activities from June 2011 to June 2012. This report summarizes results that complement a final technical report submitted by the PIs in 2011 that includes BU activities before June-2011.

MAIN RESULTS (REFERENCES TO CITED PAPERS ARE GIVEN IN []):

1. *Spectrally-invariant approximation within atmospheric radiative transfer* [1]. Certain algebraic combinations of single scattering albedo and solar radiation reflected from, or transmitted through, vegetation canopies do not vary with wavelength. These ''spectrally invariant relationships'' are the consequence of wavelength independence of the extinction coefficient and scattering phase function in vegetation. In general, this wavelength independence does not hold in the atmosphere, but in cloud-dominated atmospheres the total extinction and total scattering phase function vary only weakly with wavelength. We have identified the atmospheric conditions under which the spectrally invariant approximation can accurately describe the extinction and scattering properties of cloudy atmospheres. The validity of the assumptions and the accuracy of the approximation are tested with 1D radiative transfer calculations using publicly available radiative transfer models: Discrete Ordinate Radiative Transfer (DISORT) and Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART). It is shown for cloudy atmospheres with cloud optical depth above 3, and for spectral intervals that exclude strong water vapor absorption, that the spectrally invariant relationships found in vegetation canopy radiative transfer are valid to better than 5%. The physics behind this phenomenon, its mathematical basis, and possible applications to remote sensing and climate are discussed

2. *Spectral invariance of single scattering albedo for water droplets and ice crystals at weakly absorbing wavelengths* [2] The single scattering albedo $\omega_{0\lambda}$ in atmospheric radiative transfer is the ratio of the scattering coefficient to the extinction coefficient. For cloud water droplets both the scattering and absorption coefficients, thus the single scattering albedo, are functions of wavelength λ and droplet size r. We showed that for water droplets at weakly absorbing wavelengths, the ratio $\omega_{0\lambda}(r)/\omega_{0\lambda}(r_0)$ of two single scattering albedo spectra is a linear function of $\omega_{0\lambda}(r)$. The slope and intercept of the linear function are wavelength independent and sum to unity. This relationship allows for a representation of any single scattering albedo spectrum $\omega_{0\lambda}(r)$ via one known spectrum $\omega_{0\lambda}(r_0)$. We provide a simple physical explanation of the discovered relationship. Similar linear relationships were found for the single scattering albedo spectra of non-spherical ice crystals and green leaves from different species (e.g., hazelnut, aspen, jack pine, potato, etc).

3. *Seasonal changes in leaf area of Amazon forests from leaf flushing and abscission* [3]. The spectral invariant relationships found in atmospheric and vegetation radiative transfer were used to explain observed variation in near-infrared (NIR) reflectance of heterogeneous forested areas of Amazon. A large increase in NIR reflectance of Amazon forests during the light-rich dry

season and a corresponding decrease during the light-poor wet season has been observed in satellite measurements. This increase has been variously interpreted as seasonal change in leaf area resulting from net leaf flushing in the dry season or net leaf abscission in the wet season, enhanced photosynthetic activity during the dry season from flushing new leaves and as change in leaf scattering and absorption properties between younger and older leaves covered with epiphylls. Reconciling these divergent views using theory of spectral invariants and observations was the goal of this article. The observed changes in NIR reflectance of Amazon forests could be due to similar, but small, changes in NIR leaf albedo resulting from the exchange of older leaves for newer ones, but with the total leaf area unchanged. However, this argument ignores accumulating evidence from ground-based reports of higher leaf area in the dry season than the wet season, seasonal changes in litterfall and does not satisfactorily explain why NIR reflectance of these forests decreases in the wet season. More plausibly, the increase in NIR reflectance during the dry season and the decrease during the wet season would result from changes in both leaf area and leaf optical properties. Such change would be consistent with known phenological behavior of tropical forests, ground-based reports of seasonal changes in leaf area, litterfall, leaf optical properties and fluxes of evapotranspiration, and thus, would reconcile the various seemingly divergent views. The spectral invariant relationships were also used to assess impact of aerosol load on interpretation of satellite data.

4. Cloud droplet size and liquid water path retrievals from zenith radiance measurements [4]. The ground-based ARM and NASA AERONET routinely monitor clouds using zenith radiances at visible and near-infrared wavelengths. Using the transmittance calculated from such measurements, we have developed a new retrieval method for cloud effective droplet size and conducted extensive tests for non-precipitating liquid water clouds. The underlying principle is to combine a water-absorbing wavelength (i.e. 1640 nm) with a non-water-absorbing wavelength for acquiring information on cloud droplet size and optical depth. For simulated stratocumulus clouds with liquid water path less than 300 g m^{-2} and horizontal resolution of 201 m, the retrieval method underestimates the mean effective radius by 0.8 μm, with a root-mean-squared error of 1.7 μm and a relative deviation of 13%. For actual observations with a liquid water path less than 450 g m^{-2} at the ARM Oklahoma site during 2007–2008, our 1.5 min-averaged retrievals are generally larger by around 1 μm than those from combined ground-based cloud radar and microwave radiometer at a 5 min temporal resolution. We also compared our retrievals to those from combined shortwave flux and microwave observations for relatively homogeneous clouds, showing that the bias between these two retrieval sets is negligible, but the error of 2.6 μm and the relative deviation of 22% are larger than those found in our simulation case. Finally, the transmittance-based cloud effective droplet radii agree to better than 11% with satellite observations and have a negative bias of 1 μm. Overall, the retrieval method provides reasonable cloud effective radius estimates, which can enhance the cloud products of both ARM and AERONET.

REFERENCES

(Members of our team are in bold)

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