*Science Report on the DOE funded research (*9/15/2011 to 9/14/2015*)*
(A no-cost extension was granted until Sep 2015)

PI: Alexander Marshak (NASA GSFC)

DE-SC0005457

Study of shortwave spectra in fully 3D environment: synergy between scanning radars and spectral radiation measurements

Some highlights and publication list

References to cited papers are given in []

Overview of 3D atmospheric radiative transfer in cloudy atmosphere for *Reports on Progress in Physics* [2]. We surveyed the 3D atmospheric radiative transfer literature over the past 50 years and identify three concurrent and intertwining themes: first, how to assess the damage (bias) caused by 3D effects in the operational 1D radiative transfer models? Second, how to mitigate this damage? Third, can we exploit 3D radiative transfer phenomena to invent new observation methods and technologies? Two equally important application areas for atmospheric radiative transfer in general, and 3D in particular, were identified: broadband radiative energy budget estimation and wavelength-specific optical remote sensing signal modeling. As illustrations, both satellite and ARM observations were highly used.

Spectrally invariant approximation within atmospheric radiative transfer [11]. Because leaves are much larger than wavelengths of solar radiation, the optical distance between leaves does not vary with wavelength. This suggests that wavelength dependence of solar radiation reflected from, or transmitted through, vegetation is governed by the leaf single-scattering albedo (SSA), the probability that a photon will scatter after interaction with a leaf. As a result, certain algebraic combinations of SSA and solar radiation do not vary with wavelength. In general, this wavelength-independence does not hold in the Earth's atmosphere, because the size of cloud droplets and aerosol particles is comparable with the wavelength of solar radiation. However, we were able to identify the atmospheric conditions under which the spectrally-invariant approximation can accurately describe radiative properties of *cloudy* atmospheres to better than 5%. Figure A1 illustrates an approximation of cloud absorption using the spectral invariant approach with just three wavelengths.

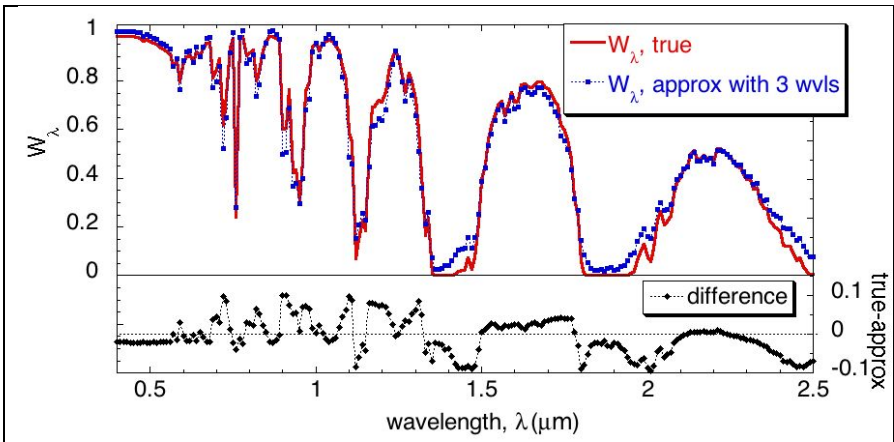

Fig. A1: Illustrates the reconstruction of the full spectrum W_λ=1-A_λ (where A_λ is spectral cloud absorption) using the spectral invariance approximation. The slope is obtained from only three wavelengths: 0.4, 1.6, and 2.1 μm. Retrieved values for all 211 wavelengths from 0.4 to 2.5 μm are shown.

Recently we have found a surprising spectral invariant relationship in ARM shortwave spectrometer observations **[7]**. The relationship suggests that the shortwave spectrum near cloud edges can be determined by a linear combination of zenith radiance spectra of the cloudy and clear regions with wavelength-independent coefficients. We confirmed these findings with intensive radiative transfer simulations using different aerosol and cloud properties and different underlying surface types. A clear physical understanding of the observed and simulated spectral invariant behavior of zenith radiance around cloud edges is still missing. The current study was the first step in this direction.

Spectrally independent properties of single-scattering albedo for water droplets and ice crystals [16]. We showed that for cloud particles at weakly absorbing wavelengths, the ratio of two single-scattering-albedo spectra, $\omega_{0\lambda}(r)$ and $\omega_{0\lambda}(r_0)$, is a linear function of $\omega_{0\lambda}(r)$ (Fig. A2). This relation does not vary with wavelength, only with particle radius. This found relationship allows one to predict any $\omega_{0\lambda}(r)$ from one known spectrum $\omega_{0\lambda}(r_0)$. We provided a simple physical explanation of the discovered relationship that helps us to better understand the physics of atmospheric radiative transfer in cloudy atmospheres and might substantially simplify remote sensing algorithms.

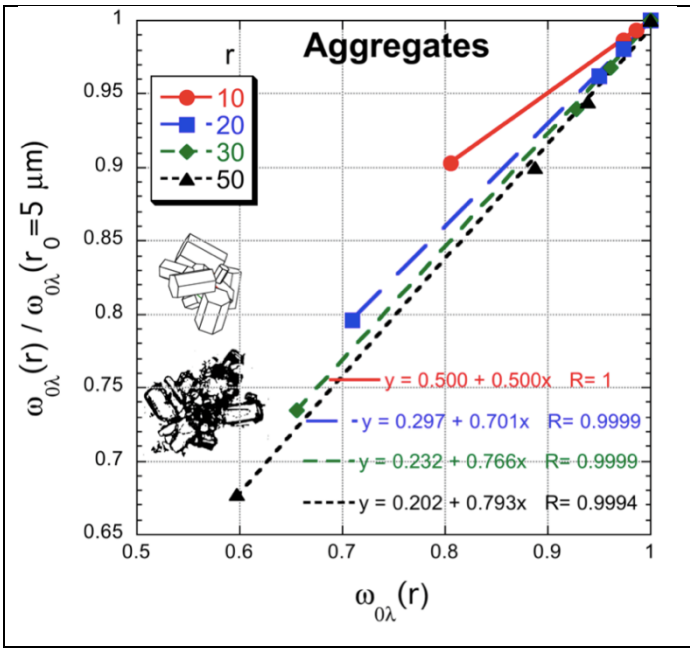

Fig. A2: The ratio of $\omega_{0\lambda}(r)/\omega_{0\lambda}(r_0)$ plotted against $\omega_{0\lambda}(r)$ for four wavelengths, λ=0.86, 1.65, 2.13 and 3.75 μm. An example for ice crystals is shown. Ice crystal effective radius r=10, 20, 30, and 50 μm; r_0=5 μm.

Dust shape matters for sedimentation [19, 26]. Dust aerosol has irregular shape making its optical properties different from spherical aerosols. We asked a question "Does the particle shape affect the dust property variation along the altitude and its evolution during transatlantic transport"? Because particles of more irregular shape experience more drag, they may during transport stay longer at higher altitudes compared to spherical-like particles, as shown in Fig. A3. We found the first observational evidence that the dust shape does play an important role in settling and consequently inducing shape-dependent stratification during transatlantic transport using CALIPSO data on vertical distribution of Saharan dust particulate depolarization. (Depolarization ratio is dominantly determined by particle irregularity, and its value for a spherical particle is close to zero.) Since the Amazon gets a lot of transatlantic dust, these results are very relevant to the ASR GoAmazon campaign.

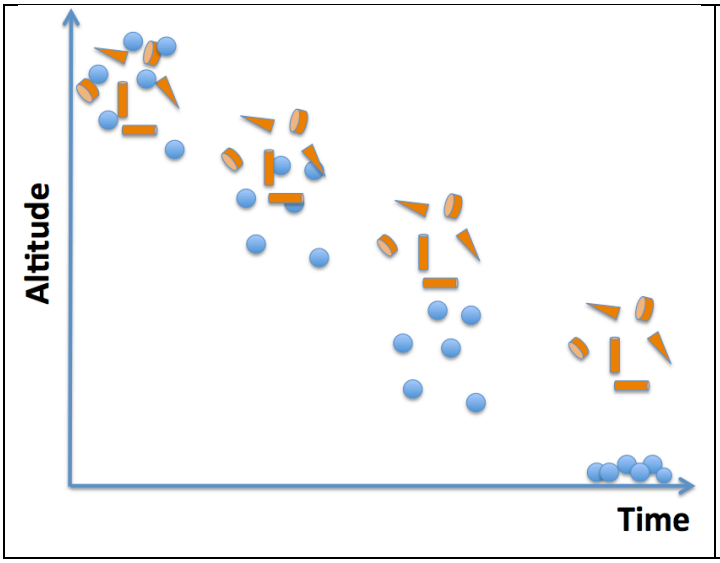

Fig. A3: Schematic illustration of shape-induced sedimentation. Spherical particles are blue while irregular shape (aspherical) particles are orange.

Pioneering work on cloud property retrievals [3, 20] has attracted favorable notice well within and outside the ARM community. NASA AERONET has adopted our methods and operates sunphotometers in "cloud mode", promising the first worldwide observation of cloud optical depth from the ground (Fig. A4, left panel). In addition to cloud optical depth, we have developed a droplet size retrieval algorithm and tested it with LES-generated cloud fields (Fig. A4, right panel) as well as with the ARM Oklahoma site retrievals for a variety of situations.

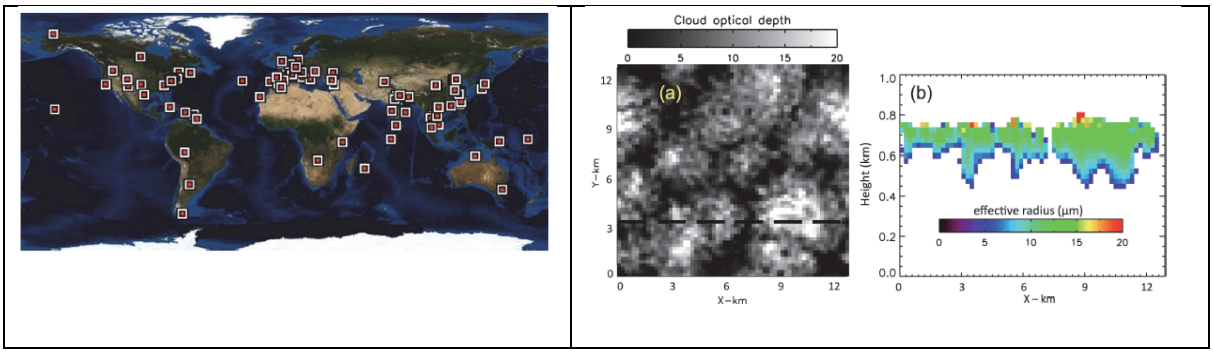

Fig. A4: (**left**) Potential cloud mode site locations in AERONET. (**right a and b**) LES-generated cloud optical depth field used to calculate zenith radiances that are then in turn used to test the retrieval method. Taking a transect along the thick black-dashed line gives the distribution of effective radii in the *x*- and vertical directions in (b).

During the past five years, our team has achieved many milestones proposed in the previous ARM-supported project, and has established a web of collaborations across the ASR Science Team. Since the dissolution of the old radiation Working Group (IRF WG) in 2009, we have worked to keep the radiation flame alive in ASR by joining in the activities of the new Cloud and Cloud-Aerosol-Precipitation Interaction Working Groups. We have brought ARM spectrometers to Goddard for calibration, and have engaged AERONET personnel to help in calibrating ARM Cimels working in cloud mode (which we invented). We have continued to interact with *Christine Chiu* on the shortwave spectrometer and cloud droplet size retrievals. During AM's Spring 2013 sabbatical we have engaged the University of Washington faculty, notably *Tom Ackerman*, *Qiang Fu*, and *Rob Wood*, in ASR and ARM radiation problems.

Publications (2010 – 2015)

(Members of our science team are in bold)

[1] Yang Y., A. **Marshak**, T. Varnai, W.J. **Wiscombe**, and P. Yang, 2010. Uncertainties in ice sheet altimetry from a space-borne 1064-nm single channel lidar due to undetected thin clouds. *IEEE Trans. Geos. Remote Sens.*, 48, 250-259.

[2] Davis A.B. and A. **Marshak**, 2010. Solar radiation transport in the cloudy atmosphere: A 3D perspective on observations and climate impacts. *Reports on Progress in Phys.*, 73, doi:10.1088/0034-4885/73/2/026801.

[3] Chiu, J.C., C.-H. Huang, A. **Marshak**, I. Slutsker, D.M. Giles, B.N. Holben, Y. **Knyazikhin**, and W.J. **Wiscombe**, 2010. Cloud optical depth retrievals from the Aerosol Robotic Network (AERONET) cloud mode observations. *J. Geophys. Res.*, 115, D14202, doi:10.1029/2009JD013121.

[4] Alexandrov, M.D., A. **Marshak**, and A.S. Ackerman, 2010. Cellular statistical models of broken cloud fields. Part I: Theory. *J. Atmos. Sci.*, 67, 2125-2151, doi:10.1175/2010JAS3364.1.

[5] Alexandrov, M.D., A.S. Ackerman and A. **Marshak**, 2010. Cellular statistical models of broken cloud fields. Part II: Comparison with dynamical model, statistics of diverse ensembles. *J. Atmos. Sci.*, 67, 2152-2170, doi:10.1175/2010JAS3365.1.

[6] Lyapustin, A., C.K. Gatebe, R. Kahn, R. Brandt, J. Redemann, P. Russell, M.D. King, C.A. Petrsen, S. Gerland, R. Poudyal, A. **Marshak**, Y. Wang, C. Schaaf, and D. Hall, and A. Kokhanovsky, 2010. Analysis of snow BRF from ARCTAS spring-2008 campaign. *Atmos. Chem. Phys.*, 10, 4359-4375.

[7] Chiu, J.C., A. **Marshak**, Y. **Knyazikhin**, and W.J. **Wiscombe**, 2010. Spectral invariant behavior of zenith radiance around cloud edges simulated by radiative transfer. *Atmos. Chem. Phys.*, 10, 11295-11303, doi:10.5194/acp-10-11295-2010.

[8] Yang Y., A. **Marshak**, S. Palm, T. Varnai, and W.J. Wiscombe, 2011. Cloud impact on surface altimetry from a spaceborne 532 nm micro-pulse photon counting lidar: system modeling for cloudy and clear atmospheres. *IEEE Trans. Geos. Remote Sens.*, 49, 4910-4919, doi: 10.1109/TGRS.2011.2153860.

[9] Varnai, T. and A. **Marshak**, 2011. Global CALIPSO observations of aerosol changes near clouds. *Geosci. Remote Sens. Lett.*, 8, 19-23.

[10] Palm, S.P., Y. Yang, J. Spinhirne, and A. **Marshak**, 2011: Satellite remote sensing of blowing snow properties over Antarctica, *J. Geophys. Res.*, 116, D16123, doi:10.1029/2011JD015828.

[11] Marshak, A., Y. **Knyazikhin**, J.C. **Chiu**, and W.J. **Wiscombe**, 2011. Spectrally-invariant approximation within atmospheric radiative transfer. *J. Atmos. Sci.*, 68, 12, 3094-3111.

[12] Martins J. V., A. **Marshak**, L. Remer, D. Rosenfeld, Y. J. Kaufman, R. Fernandez-Borda, I. Koren, V. Zubko, and P. Artaxo, 2011. Remote sensing the vertical profile of cloud droplet effective radius, thermodynamic phase, and temperature. *Atmos. Chem. Phys.,* 11, 9485–9501, 2011, doi:10.5194/acp-11-9485-2011.

[13] **Knyazikhin**, Y., M.A. Schull, L. Xu, R.B. Myneni, and A. Samanta, 2011: Canopy spectral invariants. Part 1: A new concept in remote sensing of vegetation. *J. Quant. Spectr. Radiat. Transfer*, 112, 727-735.

[14] Varnai, T. and A. **Marshak**, 2012. Analysis of co-located MODIS and CALIPSO observations near clouds. *Atmos. Measur. Tech.*, 5, 389-396.

[15] Korkin S.V., A.I. Lyapustin, and A. **Marshak**, 2012. On the accuracy of double scattering approximation for atmospheric polarization computations, *J. Quant. Spectrosc. Radiat. Transfer*, 113, 172-181.

[16] Marshak, A., Y. **Knyazikhin**, J.C **Chiu**, and W.J. **Wiscombe**, 2012. On spectral invariance of single scattering albedo for water droplets and ice crystals at weakly absorbing wavelengths. *J. Quant. Spectrosc. Radiat. Transfer*, 113, 715-720.

[17] Vogelmann, A.M., G.M. McFarquhar, J.A. Ogren, D.D. Turner, J.M. Comstock, G. Feingold, C.N. Long, H. Jonsson, A. Bucholtz, D.R. Collins, G.S. Diskin, H. Gerber, P.R. Lawson, R. Woods, E. Andrews, H.-J. Yang, C. J. **Chiu**, D. Hartsock, J.M. Hubbe, C. Lo, A. **Marshak**, J. Monroe, S.A. McFarlane, B. Schmid, J.M. Tomlinson, and T. Toto, 2012. RACORO extended-term, aircraft observations of boundary-layer clouds, *Bulletin Amer. Meteor. Soc. (BAMS)*, 93, 861-878.

[18] **Yang** W., A. **Marshak**, Varnai, T., and Z. Liu, 2012. Effect of CALIPSO cloud aerosol discrimination (CAD) confidence levels on the observation of aerosol properties near cloud. *Atmosph. Res.*, 16, 134-141.

[19] Yang W., A. **Marshak**, T. Varnai, O.V. Kalashnikova and A.B. Kostinski, 2012. CALIPSO observations of transatlantic dust properties: vertical stratification and effect of clouds, *Atmos. Chem. Phys.*, 12, 11339-11354, doi:10.5194/acp-12-11339-2012.

[20] Chiu, J.C., A. **Marshak,** C.H. Huang, T. Varnai, R. Hogan, D.M. Giles, B.N. Holben, E. O'Connor, Y. **Knyazikhin**, and W.J. **Wiscombe**, 2012. Cloud droplet size retrievals from zenith radiance measurements: examples from the Atmospheric Radiation Measurement Program and the Aerosol Robotic Network. *Atmos. Chem. Phys.*, 12, 10313-10329, doi:10.5194/acp-12-10313-2012.

[21] **Knyazikhin**, Y., M.A. Schull, Y. Yang, P. Stenberg, M. Mõttus, M. Rautiainen, A. **Marshak**, P.L. Carmona, R.Kaufmann, P. Lewis, V. Vanderbilt, A.B. Davis, F. Baret, S. Jacquemoud, A. Lyapustin, and R.B. Myneni, 2012. Hyperspectral remote sensing of foliar nitrogen content. *Proc. Nat. Acad. Sci.*, 10.1073/pnas.1210196109 PNAS Dec 4, 2012 201210196.

[22] Yang Y., A. **Marshak**, S. Palm, Z. Wang, C. Schaaf, 2013. Assessment of using apparent surface reflectance for cloud screening in support of the ICESat-2 mission. *IEEE Trans. Geos. Remote Sens.*, 51(2), 1037-1045, 10.1109/TGRS.2012.2204066.

[23] Yang Y., A. **Marshak**, J. Mao, A. Lyapustin, and J. Herman, 2013. A method of retrieving cloud top height and cloud geometrical thickness with oxygen A and B bands for the Deep Space Climate Observatory (DSCOVR)

mission: radiative transfer simulations. *J. Quant. Spectrosc. Radiat. Transfer*, 122, 141-149.

[24] Varnai, T., A. **Marshak** and W. **Yang**, 2013. Multi-satellite aerosol observations in the vicinity of clouds. *Atmos. Chem. Phys.*, 13, 3899–3908, doi:10.5194/acp-13-3899-2013.

[25] Wen, G., A. **Marshak**, R. Levy, L. Remer, N. Loeb, T. Varnai, and R.F. Cahalan, 2013. Implementation of the correction algorithm of the MODIS aerosol retrievals near clouds. *J. Geophys. Res.* 118, doi:10.1002/jgrd.50617.

[**26**] **Yang** W., A. **Marshak**, A.B. Kostinski, and T. Varnai, 2013. Shape-induced gravitational sorting of Saharan dust during transatlantic voyage: evidence from CALIOP lidar depolarization measurements, *Geoph. Res. Lett.*, 40, doi:10.1002/grl.50603.

[27] Varnai, T., and A. **Marshak**, 2014. Near-cloud aerosol properties from the 1-km resolution MODIS ocean product. *J. Geopys. Res.*, 119, doi:10.1002/2013JD020633.

[28] Yang Y., S.P. Palm, A. **Marshak**, D.L. Wu, H. Yu, and Q. Fu, 2014. First satellite-detected perturbations of outgoing longwave radiation associated with blowing snow events over Antarctica, *Geoph. Res. Lett.*, 41, 730–735, doi:10.1002/2013GL058932.

[29] **Marshak**, A., K.F. Evans, T. Varnai, and G. Wen, 2014. Extending 3D near-cloud corrections from shorter to longer wavelengths. *J. Quant. Spectrosc. Radiat. Transfer*, 147, 79-85, doi:10.1016/j.jqsrt.2014.05.022.

[30] **Yang**, W, A. **Marshak**, T. Varnai and R. Wood, 2014. CALIPSO observations of near-cloud aerosol properties as a function of cloud fraction. *Geoph. Res. Lett.*, doi: 10.1002/2014GL061896.

[31] Knobelspiesse, K., B. van Diedenhoven, A. **Marshak**, S. Dunagan, B. Holben, H. K. Baltink, and I. Slutsker, 2015. Cloud thermodynamic phase detection with polarimetrically sensitive sky radiometers. *Atmos. Meas. Tech.*, 8, 1537–1554, doi:10.5194/amt-8-1537-2015.

[32] Varnai, T., and A. **Marshak**, 2015. Effect of cloud fraction on near-cloud aerosol behavior in the MODIS atmospheric correction ocean color product. *Remote Sens.*, 7, 5283-5299; doi:10.3390/rs70505283.

[33] Alexandrov, M.D., I.V. Geogdzhaev, K. Tsigardidis, A. **Marshak**, R. Levy and B. Cairns, 2015. New statistical model for variability of aerosol optical thickness: Theory and application to MODIS data. *J. Atmos. Sci.*, doi:10.1175/JAS-D-15-0130.1.