

FINAL REPORT

"Hyperspectral Estimation of Aerosol Parameters and Water-Leaving Radiance in Dusty Atmospheres Using Vertical Profiling Information"

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LONG-TERM GOALS

The scientific aims that motivate our work on this project were: (1) to understand quantitatively the multiple-scattering physics underlying spaceborne hyperspectral and lidar observations of atmospheric aerosols and surface reflectivity; (2) to develop rigorous, stable (i.e., genuinely useful) inverse methods to interpret such observations in terms of geophysical quantities, based on the mathematics of inverse radiative transfer; and (3) to apply such methods to gain otherwise unavailable insight into geophysical interactions of the ocean, the atmosphere, and land surfaces.

OBJECTIVES

The specific objectives of this project were: (1) to understand quantitatively how the accuracy of dust parameter and ocean color estimates from hyperspectral data depend on knowledge of vertical aerosol distributions and dust particle absorption; (2) to develop improved methods for estimating dust aerosol properties and water-leaving-radiance (WLR) from hyperspectral and limited vertical profile data, including data from the newest generations of NASA (SeaWiFS, MODIS, MISR, and spaceborne lidar) and DoD (COIS/NEMO) sensors; and (3) to demonstrate the initial use of such methods in investigation of dust outbreaks over littoral seas.

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APPROACH

We performed an initial analysis of the failures of current (SeaWiFS, MODIS, and MISR) algorithms for dust parameter and WLR estimation when the assumptions upon which those algorithms are founded do not hold. We employed a combination of analytical and numerical solutions of radiative transfer for multiple-scattering systems of several layers underlain by a reflecting ocean. Both our analytic and numerical models have the important property that we can easily 'turn off', and then restore, individual physical mechanisms to learn their precise importance. We approach inversion of the radiance data in light of our particular expertise and recent contributions in linear and nonlinear inverse scattering methods [Sylvester et al., 1996; Sylvester and Winebrenner, 1998]. We planned to use spaceborne lidar and AVHRR observations of a Saharan dust outbreak in a case study, and sought data for other such case studies in which our insights and methods could be tested.

WORK COMPLETED

We have adapted our radiative transfer codes (used previously in studies of cm-wavelength radiative transfer in snow) to address atmospheric optics, including modifications to phase functions and the inclusion of molecular (Rayleigh) scattering and absorption.

We have modeled and investigated idealized two-scattering-layer systems, varying vertical locations of a generic "red-dust" aerosol, examining radiances at wavelengths ranging from 400 to 1200 nm.

We have obtained and performed initial processing on AVHRR and Space Shuttle (LITE) lidar data [Winker et al., 1996] for a case study of a Saharan dust outbreak over the Atlantic in September 1994. Although AVHRR data acquisition lagged the lidar acquisition by approximately 8 hours (lidar data were acquired at night, AVHRR data the following morning), these data provide a realistic view of dust plume vertical structure together with red and near-IR radiance observations.

RESULTS

Because the radiative transfer equation in a plane-parallel atmosphere depends only on optical depth, radiances are constant throughout altitude intervals in which optical depth does not change. Thus parts of the atmospheric column in which the extinction coefficient (at a given wavelength) is negligible compared to its column average will have only a negligible effect on radiance (at that wavelength). At 700-1000 nm wavelength, the total optical depth due to Rayleigh scattering from air molecules is very small in comparison with typical aerosol optical depths. We therefore expect, and our simulations

confirm, that red and NIR radiances are virtually unaffected by atmospheric layers without aerosols. Estimation of dust and other aerosol parameters based solely on NIR radiances (e.g., as in the current SeaWIFS scheme) is therefore affected only by the altitude distribution of aerosol-laden layers themselves, and not by the thickness or distribution of any intervening clear air layers.

By contrast, the atmospheric optical depth due to Rayleigh scattering at short visible wavelengths is appreciable -- 0.1-0.2 -- and comparable to common aerosol optical depths. Thus we expect, and our simulations again confirm, that 443 nm-wavelength radiances resulting from dust high in the troposphere above clear air differ strongly from those resulting from dust at low altitude with clear air above. In the first case, the increased optical depth (and absorption) due to the dust partially masks the lower, Rayleigh-scattering layer and mutes its effect. In the second case, the Rayleigh-scattering layer only slightly masks the dusty layer and, in addition, produces (via scattering unattenuated by the dusty layer) a larger fraction the total upwelling radiance at the top of the atmosphere.

These results explain physically the sensitivity of WLR estimation at 443 nm wavelength to absorbing-aerosol vertical structure found by Gordon [1997], and show that in the simple layer structure he considered that the sensitivity is due entirely to sensitivity of 443 nm, rather than NIR, radiances to vertical structure. We can now clarify the roles and relative importance of the various mechanisms Gordon cites as potentially important. In particular, vertical structure can be significant, even when multiple scattering is not, in any case where the various layers have comparable optical depths. Varying assumptions about the dust size distribution are more important for their effect on dust albedo than for their effect on the dust scattering phase function -- changes in the latter change the quantitative details of the simulation results, but do not alter the overall picture. Finally, while absorptive aerosols produce a more noticeable effect for smaller optical depths (because by turning light into heat they reduce energy available for scattering elsewhere), vertical structure effects also arise for sufficient optical depths of non-absorbing aerosols.

We note that Fukushima and Toratoni (1997) have correctly argued that the color of desert dust, which is typically redder than that of other aerosols, independently confounds current atmospheric correction schemes. Effects of vertical structure, however, appear to be at least as important as dust color in correcting radiances to estimate ocean color.

IMPACT/APPLICATIONS

The vertical distribution of dust aerosols is consequential not only for the estimation of oceanic optical properties from space, but also for the prediction of naval infrared sensor performance [Westphal and Lui, 1996] and for the improvement of numerical weather prediction by inclusion of tropospheric heating profiles due to dust [Alpert et al., 1998;

Tegen et al., 1996]. Insight from this project on how hyperspectral and sparse profile data may be combined to map parameters of vertical dust distributions will thus be directly relevant to all three of these applications.

TRANSITIONS

This project did not lead to immediate transitions to other programs.

PUBLICATIONS FROM ONR-SPONSORED WORK - FY 98/FY 99

98-P Sylvester, J., and D.P. Winebrenner, "Linear and nonlinear inverse scattering", *SIAM Journal of Applied Mathematics* 59(2), pp. 669-699, 1998.

98-P Golden, K.M., M. Cheney, K.-H. Ding, A.K. Fung, T.C. Grenfell, D. Isaacson, J.A. Kong, S.V. Nghiem, J. Sylvester, and D.P. Winebrenner, "Forward electromagnetic models for sea ice", *IEEE Transactions on Geoscience and Remote Sensing* 36(5), pp. 1655-1674, 1998.

98-P Golden, K.M., D. Borup, M. Cheney, E. Cherkaeva, M.S. Dawson, K.-H. Ding, A.K. Fung, D. Isaacson, S.A. Johnson, A.K. Jordan, J.A. Kong, R. Kwok, S.V. Nghiem, R.G. Onstott, J. Sylvester, D.P. Winebrenner, and I.H. Zabel, "Inverse electromagnetic models for sea ice", *IEEE Transactions on Geoscience and Remote Sensing* 36(5), pp. 1675-1704, 1998.

98-P Kwok, R., S.V. Nghiem, S. Martin, D.P. Winebrenner, A.J. Gow, D.K. Perovich, C.T. Swift, D.G. Barber, K.M. Golden, and E.J. Knapp, "Laboratory measurements of sea ice: connections to microwave remote sensing", *IEEE Transactions on Geoscience and Remote Sensing* 36(5), pp. 1716-1730, 1998. pp. 1655-1674, 1998.

98-P Barabanenkov Yu.N., M. Yu. Barabanenkov, and D.P. Winebrenner, "Effect of pulse entrapping on diffuse reflection from a resonant random medium: exact solution to the scalar albedo problem", *Waves in Random Media* 8, pp. 451-463, 1998.

99-IC Sylvester, J., and D.P. Winebrenner, "Linear and non-linear inverse scattering, or layer-stripping via the Hilbert transform", presented at the International Congress on Industrial and Applied Mathematics, Edinburgh, Scotland, UK, 5-9 July 1999.

99-C Winebrenner, D.P., and J. Sylvester, "On the invertibility of near-infrared hyperspectral ground reflectance observations for lower-tropospheric water vapor profiles", presented at the 1999 Fall Meeting of the American Geophysical Union, San Francisco, CA, 13-17 December 1999.

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- Tegen, I., A.A. Lacis, and I. Fung, "The Influence on Climate Forcing of Mineral Aerosols from Disturbed Soils", *Nature* 380, pp. 419-422, 1996.
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- Winker, D.M., R.H. Couch, and M.P. McCormick, "An Overview of LITE: NASA's Lidar In-Space Technology Experiment", *Proceedings of the IEEE* 84(2), pp. 164-180, 1996.

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