JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D17, 4547, doi:10.1029/2003JD003385, 2003

Validation of surface retrieved cloud optical properties with in situ measurements at the Atmospheric Radiation Measurement Program (ARM) South Great Plains site

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Received 7 January 2003; revised 4 June 2003; accepted 17 June 2003; published 11 September 2003.

[1] Cloud optical properties inferred from a multifilter rotating shadowband radiometer have been validated against in situ measurements during the second ARM Enhanced Shortwave Experiment (ARESE II) field campaign at the ARM South Great Plains (SGP) site. On the basis of eight aircraft in situ vertical profiles (constructed from measurements), Forward Spectra Scattering Probe (FSSP), we find that our retrieved cloud effective radii for single-layer warm water clouds agree well with in situ measurements, within 5.5%. A sensitivity study also illustrates that (for this case) a 13% uncertainty in observed liquid water path (LWP, 20 g/m^2) results in 1.5% difference in retrieved cloud optical depth and 12.7% difference in inferred cloud effective radius, on average. The uncertainty of the LWP measured by the microwave radiometer (MWR) is the major contributor to the uncertainty of retrieved cloud effective radius. Further, we conclude that the uncertainty of our inferred cloud optical properties is better than 5% for warm water clouds based on a surface closure study, in which cloud optical properties inferred from narrowband irradiances are applied to a shortwave model and the modeled broadband fluxes are compared to a surface pyranometer. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing; *KEYWORDS:* cloud properties, validation

Citation: Min, Q.-L., M. Duan, and R. Marchand, Validation of surface retrieved cloud optical properties with in situ measurements at the Atmospheric Radiation Measurement Program (ARM) South Great Plains site, *J. Geophys. Res.*, *108*(D17), 4547, doi:10.1029/2003JD003385, 2003.

1. Introduction

[2] Clouds play key roles in the atmospheric energy balance and in the hydrological cycle. The transmission, reflection and absorption of radiation in a cloudy atmosphere are governed by the microphysical properties of the cloud medium, as well as cloud geometry and surface albedo. Knowledge of cloud properties and their spatial and temporal variation is crucial to studies of global climate change. Various efforts have been made to derive cloud optical properties from different radiation measurements of satellites [*Minnis et al.*, 1995; *King et al.*, 1997; *Minnis et al.*, 1998; *Masunaga et al.*, 2002, and reference therein]; meanwhile, several retrieval algorithms have been proposed to infer cloud optical depth and effective radius from surface-based systems: narrow band spectral measurements [*Min and Harrison*, 1996a], broadband measurements [*Leontieva and Stamnes*, 1996; *Dong et al.*, 1997], and normalized difference cloud indexes [*Marshak et al.*, 2000; *Barker and Marshak*, 2001]. A critical issue for all retrieval algorithms is validation against in situ measurements.

[3] Various comparisons and validations for the narrow band retrieval algorithm of *Min and Harrison* [1996a] have been done in the past. *Min and Harrison* [1996a] compared the surface inferred cloud optical depth from a multifilter rotating shadowband radiometer (MFRSR) with GOES results at the ARM South Great Plains (SGP) site, indicating substantial discrepancy between satellite and surface retrievals. *Min and Harrison* [1998] incorporated the relevant surface measurements and inferred cloud optical properties from the MFRSR into three atmospheric shortwave models at the ARM SGP site during ARM Enhanced Shortwave Experiment (ARESE), 1995. The model results under overcast conditions were consistent with pyranometer measurements (within uncertainty of broadband measurements of 5 W/m^2) at the surface, which demonstrates that the inferred cloud optical properties are reasonable. This retrieval algorithm has also been applied to MFRSR data at

0148-0227/03/2003JD003385$09.00

Barrow in the Arctic region during the Surface Heat Budget of the Arctic Ocean (SHEBA) campaign [*Barnard et al.*, 2001]. Recently, the second ARESE campaign at the ARM SGP flew a citation aircraft with various in situ measurements for cloud microphysical parameters and provided the opportunity to directly validate our retrieval algorithm. In this paper, we will validate the inferred cloud optical properties against the in situ observations, and discuss various issues of the retrieval.

2. Retrieval Algorithm and Measurements

2.1. Retrieval Algorithm

[4] We have developed a family of inversion methods to infer optical properties of warm clouds from surface measurements of spectral irradiance [*Min and Harrison*, 1996a]. Since details of this experimental algorithm are described by *Min and Harrison* [1996a], only a brief sketch of it is given below.

[5] To obtain cloud optical properties, we need the observed atmospheric transmittance (rather than absolute irradiance), and the surface albedo. The MFRSR allows us to obtain both accurately without depending on absolute calibration because it measures both total-horizontal irradiance and direct-normal irradiance using the same detector(s) by a blocking technique. Consequently Langley regression of the direct-normal irradiance taken on clear stable days can be used to extrapolate the instrument's response to the top of the atmosphere, and this calibration can then be applied to the total-horizontal irradiance. Transmittances can be calculated subsequently under cloudy conditions as the ratio of the uncalibrated output to the extrapolated top of the atmosphere value.

[6] We use climatological atmospheric gas profiles for Rayleigh scattering, and select the wavelength passband at 415 nm to avoid gaseous absorptions, in particular effects of Chappuis-band ozone absorption are eliminated. Several other factors favor the 415 nm passband compared to those in the 500 to 700 nm range: when snow is absent terrestrial albedos at 415 nm are relatively constant and significantly lower; single-scattering albedo, ω, and asymmetric factor, g, are less sensitive to effective radius, r_e. We parameterize the cloud droplet optics in terms of r_e, and total liquid water path (LWP), based on MIE theory [*Slingo*, 1989; *Hu and Stamnes*, 1993]. Retrievals of cloud optical depth at 415 nm are then done by a Nonlinear Least Squares Method (NLSM), implemented through the linearized iteration described by *Bevington* [1969], in conjunction with an adjoint formulation of radiative transfer to speed up the computation [*Min and Harrison*, 1996b]. There are two implementations: one where r_e is assumed to be 8 μm (a typical continental value), and the more complex case where r_e is simultaneously retrieved, with the total *LWP* obtained from a microwave radiometer retrieval. The advantage that this approach has over other retrieval algorithms based on broadband measurements or normalized difference cloud indexes from ground-based systems [*Leontieva and Stamnes*, 1996; *Dong et al.*, 1997; *Marshak et al.*, 2000], is that it minimizes uncertainties associated with absolute calibration of measurements, surface albedo variation across the shortwave, and the interference of various gaseous absorptions (particularly water vapor).

2.2. In Situ and Surface Measurements

[7] During ARESE II, the citation aircraft profiled stratus clouds on 3 and 21 March 2000, measuring cloud drops with a Forward Spectra Scattering Probe (FSSP), the key instrument, and five other instruments: A Cloud Particle Imager , 1D and 2D particle measurement systems imaging probes, a counter flow virtual impactor and a King liquid water probe. Correction algorithms of probe-dependent and distribution-dependent optical coincidence effects, Mie curve adjustment, and time response and laser beam inhomogeneity effects, have been applied to the raw FSSP data to yield final results with an accuracy of 15% in cloud drop radius and 34% in liquid water content (LWC) [*Baumgardner*, 1983; *Baumgardner and Spowart*, 1990]. The data collected from citation flights are, subsequently, divided into a set of ascents and descents to construct profiles of cloud effective radius and LWC. On the basis of cloud radar and GOES satellite data over the SGP site, there was a complex multilayered cloud system on 21 March 2000. Possible contamination of ice clouds in the multilayered system violates the assumption of surface retrieval. Furthermore, inadequate sampling by the citation aircraft over the full vertical extent of the clouds makes the intercomparison impossible on this date. Therefore we limit our validation to a period of single-layer warm water clouds on 3 March 2000. Since surface retrieved effective radius is the column-averaged radius over the observed cloud domain [*Min et al.*, 2001], we average the measured drop radius profile of the FSSP with two different schemes: one is given by simple average method as

$$\bar{R}_e = \sum r_i / \sum N_i,$$

where N is the total number of measurements. The other is given by drop size weighted average method as

$$\bar{R}_e = \frac{\int dz \int r^3 n(r) dr}{\int dz \int r^2 n(r) dr}.$$

The MFRSR has been continuously operated at the ARM SGP site for years. Over 60 Langley events have been obtained each year. The solar constants at the passband obtained from Langley regressions are interpolated and extrapolated to any particular day by using a temporal and spectral analysis procedure [*Forgan*, 1988]. The accuracy of solar constant at a nongaseous absorption passband, based on the Langley regression calibration, is within 1% [*Michalsky et al.*, 2001]. Therefore we expect the transmittance under cloudy conditions is better than 1%. Cloud liquid water path (LWP) and water vapor path are retrieved from microwave brightness temperature measured by a dual channel microwave radiometer at the ARM SGP site. The standard retrieval algorithm is based on a statistical approach [*Liljegren*, 1994]. The LWP retrieval has been improved in this analysis by taking into account the atmospheric profile of temperature, pressure and relative humidity as measured by a nearby in time radiosonde. This approach has been referred to in the literature as a "physical-iterative" approach [e.g., *Han and Westwater*, 1995; *Liljegren et al.*, 2001]. The overall retrieval accuracy

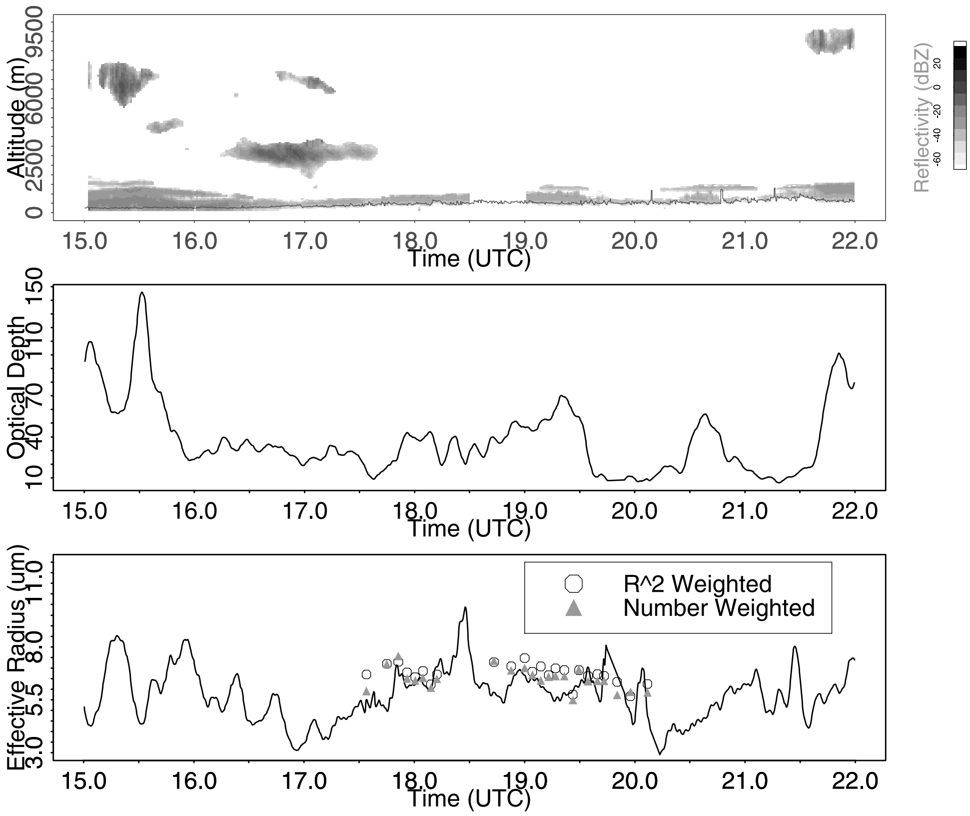

Figure 1. (top) Millimeter-wave cloud radar reflectivity, (middle) cloud optical depth inferred from surface, and (bottom) effective radius retrieved from surface and in situ measurements on 3 March 2000 at the ARM SGP site.

is influenced by the accuracy of the instrument measurements and the quality of the atmospheric profiles of temperature, pressure and the assumed temperature of liquid and water vapor, as one would expect. But also critical is the uncertainty in the absorption coefficients used in the microwave radiative transfer model, which can introduce a bias in the retrieval. On the basis of an analysis of clear-sky data (that is looking a periods where no clouds are present but nonetheless retrieving a liquid water path), we find that the accuracy of the microwave radiometer liquid water path from the physical-iterative approach is no worse than 30 g/m2 and typically better than 20 g/m2 (as long as the radiometer is dry).

3. Results

[8] Before discussing validation of our surface retrieval against each ascent or descent profile, we first exhibit cloud geometry and layer information observed from the millimeter-wave cloud radar and micropulse lidar using the algorithm of *Clothiaux et al.* [2000]. Both of these instruments are located within about 100 m of the radiation instruments at the ARM SGP site. On 3 March 2000, there were multiple cloud decks in the morning between 1530 and 1740 UTC with a multiple tiered lower-level cloud deck in the afternoon between 1900 and 2000 UTC and after 2030 UTC, shown in the top panel of Figure 1. The bottom two panels of Figure 1 show the cloud optical depth and effective radius derived from the combination of the MFRSR and MWR datasets. The cloud optical properties are processed in 5-minutes time intervals to monitor cloud variations on a cloud lifetime scale. For this case cloud optical depth varied from 7.2 to 139.6, while cloud drop effective radius varied from 3.2 μm to 9.4 μm. Small effective radii at 1530 and 1650 UTC may result from having thick ice clouds over lower-level water clouds because the ice water path, while having an impact on the total horizontal transmittance measurements by the MFRSR, is not part of the cloud liquid water path retrieved by the microwave radiometer.

[9] In the bottom panel of Figure 1 we plot the averaged cloud drop radii based on all ascent and descent profiles from in situ FSSP measurements. As mentioned previously, both size weighted radius (open circus) and simple number averaged radius (solid triangle) are compared with surface retrievals. The size-weighted radius is systematically larger than the simple averaged radius. For the period between 1730 and 1815 under single-layer cloud conditions the temporal variation of surface retrieval is consistent with the in situ measurement, and the mean surface retrieved effective radius of 6.14 μm agrees with the FSSP observations of 6.79 and 6.59 μm for size-weighted and simple averaged radii, respectively. The differences between surface retrievals and in situ measurements over eight profiles are 0.65 and 0.45 μm for size-weighted and number averaged, respectively.

[10] The domain of the radiation field or the field of view of an upward looking MFRSR under lower level cloud

Table 1. Mean Effective Radius and Cloud Optical Depth Over Six Ascent and Descent Profiles Between 1750 and 1815 UTC Under Single-Cloud Conditions

	FSSP (Size Weighted)	FSSP (Simple Averaged)	LWP 147.9 g/m^2	LWP (+) 167.9 g/m^2	LWP (−) 127.9 g/m^2
Effective radius, μm	6.74 ± 0.35	6.60 ± 0.51	6.43 ± 0.45	7.24 ± 0.66	5.60 ± 0.24
Optical depth			36.7	37.2	36.2

condition is about a couple of kilometers [*Min et al.*, 2001]. Therefore it is no surprise that the largest difference occurred before 1745 UTC, when the edge of the upper layer cloud was still within the field of view of the MFRSR. If we exclude two points, the differences between surface retrievals and in situ measurements over six profiles are 0.31 and 0.17 μm for size-weighted and number averaged, respectively, as listed in Table 1. In Table 1 we also include retrieved cloud optical depths and effective radii based on the upper and low limits of the LWP from the MWR, which are estimated from potential errors in the brightness temperature measurement and potential errors in the forward microwave transfer modeling. It shows that an uncertainty of about 20 g/m^2 in the LWP will results in an uncertainty of about 0.82 μm or 12.7% in retrieved effective radius, but only 0.55 or 1.5% in inferred cloud optical depth. While we believe the MWR data on this day to be excellent, pessimistically the error in the LWP could be somewhat larger than 20 g/m^2. Nonetheless, the uncertainty in the retrieval is not significantly larger than that of in situ FSSP measurements. For the period between 1840 and 2010 UTC, the citation aircraft was not flying near the center facility of the SGP site where surface radiation instruments were located. Therefore we provide no comparisons between surface retrievals and in situ measurements during this time interval.

[11] Figure 2 shows an ascent profile of radius and LWC from the FSSP as the citation aircraft was flown over the central facility at 1801 UTC on 3 March 2000. For this particular case, our inferred value from combined MFRSR and MWR measurements is 6.2 μm, and the size-weighted (green dot with deviation bar) and number averaged (red dot with deviation bar) radii are 6.6 and 6.4 μm, respectively. It illustrates an excellent agreement between our retrieval and in situ measurement.

[12] To further validate our inferred cloud optical properties and to study the role of clouds in the radiation balance, we used retrieved cloud optical properties from our surface retrieval as inputs to an atmospheric shortwave model [*Fu and Liou*, 1993], and compared the results to surface pyranometric observations (BSRN). The atmospheric profiles of temperature and pressure were measured by the Balloon-Borne Sounding System (BBSS) every 3 hours. The water vapor profile was taken from the BBSS data, and scaled and interpolated with time based on total column water vapor measured by the MWR. We adopted climatologic profiles for ozone and other gases. Since our retrieval assumes one layer warm water cloud, in the simulation, we used cloud base heights measured by the lidar, and cloud top heights were estimated based on cloud radar for the lower layer clouds. Possible aerosol effects under the cloud conditions are expected to be small compared with cloud effects for those thick cloud optical depth cases. We use the closest clear-sky aerosol optical depth obtained from the MFRSR measurements as the aerosol optical depth under the cloud. The surface albedo plays an important role in predicting the shortwave. Surface albedos for wavelengths less than 1000 nm were obtained from the measurements of the MFRSR for downward irradiances as well as the tower measurements of the multiple filter radiometers (MFR) for upward irradiances at corresponding wavelengths at 10 and 25 m heights (over pasture and wheat) [*Michalsky et al.*, 2003]. From the SIROS, the downward looking broadband pyranometer measurements at the tower provide the total shortwave surface albedo.

[13] Figure 3 shows the measured and calculated surface shortwave on 3 March 2000. The modeled shortwave reaching the surface agrees with the observation. As shown in the bottom panel, the differences illustrate a closure of the observed vs. modeled surface fluxes to within 10 W/m^2, except for a short period when direct solar beam can be observed through a hole of thin cloud as a consequence of inhomogeneous 3-D cloud effects. Part of the difference over all may be due to our inability to partition cloud optical properties for multiple layer clouds, contamination of ice clouds, the uncertainty of water vapor profiles with respect to cloud geometry, and uncertainty of cloud optical parameterization used in the model. Nevertheless, it demonstrates

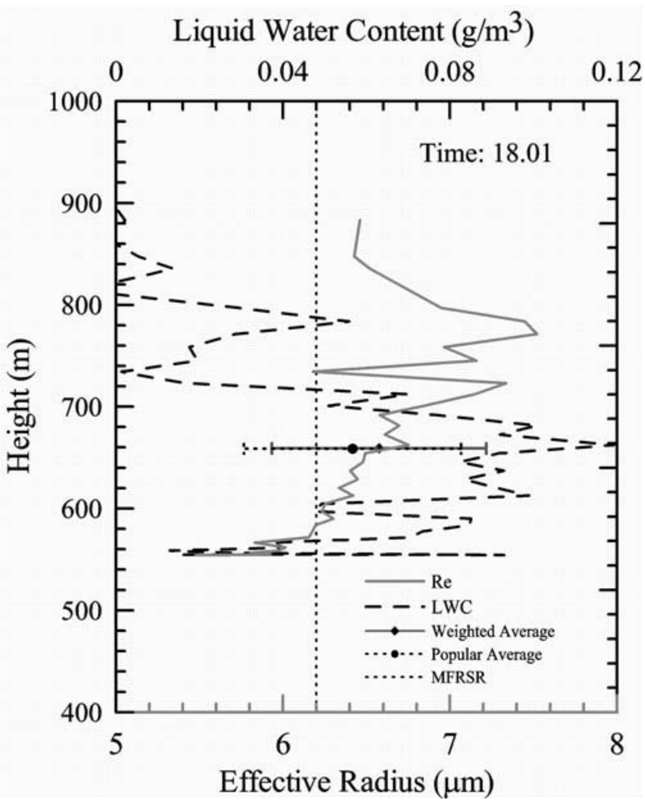

Figure 2. An ascent profile of effective radius and LWC from the FSSP in situ measurements and our surface retrieved effective radius.

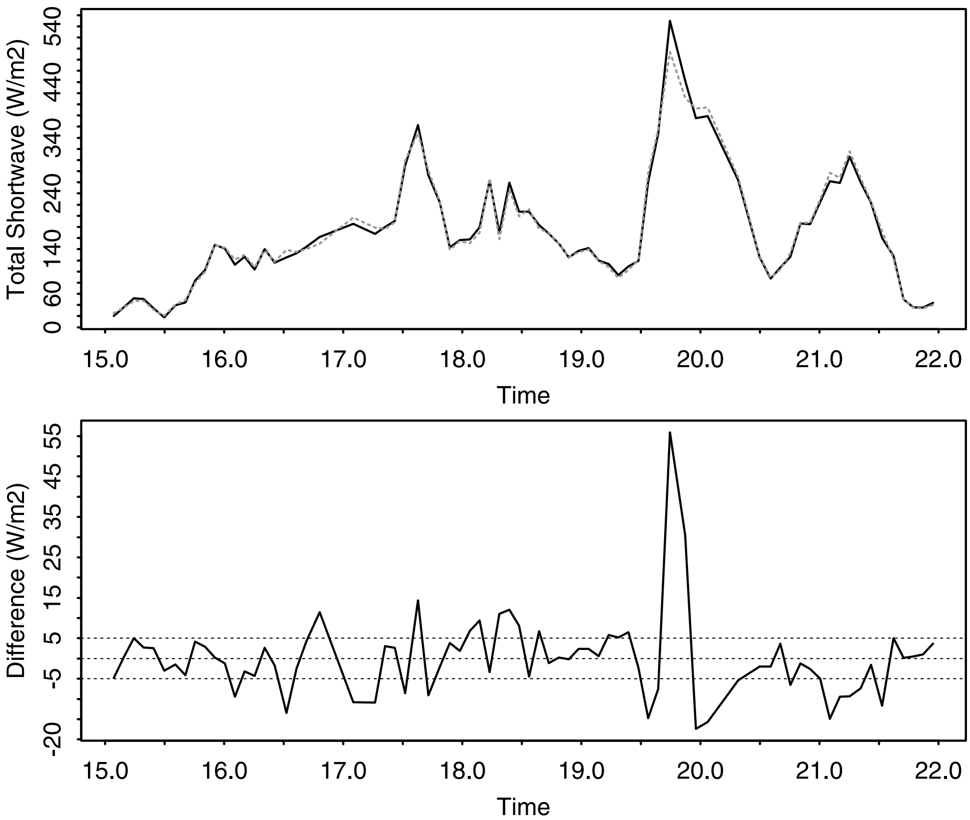

Figure 3. Measured and modeled total shortwave and its difference on 3 March 2000 at the ARM SGP site.

that the cloud optical properties derived from the MFRSR measurement at 415 nm must be accurate to better than 5%.

4. Discussion and Conclusion

[14] Validating the retrieval algorithm and understanding the uncertainty of the products are issues critical to the success of the technique. We took advantage of ARESE II field campaign for validating of surface inferred cloud optical properties. On the basis of six effective radius profiles measured by the in situ FSSP probe, our retrieved cloud effective radii agree well with in situ measurements, within 5.5%. As pointed out by *Min and Harrison* [1996a], the transmittance observed by a radiometer is more sensitive to the cloud optical depth than the cloud effective radius. For this case, a 13% uncertainty in observed LWP (20 g/m^2) results in 1.5% difference in retrieved cloud optical depth, and 12.7% difference in referred cloud effective radius, on average. The uncertainty of the LWP measured by the MWR is the major contributor to the uncertainty of retrieved cloud effective radius. Further, we conclude that the uncertainty of our inferred cloud optical properties is better than 5% for warm water clouds based on a surface closure study, in which cloud optical properties inferred from narrowband irradiances are applied to a shortwave model and the modeled broadband fluxes are compared to a surface pyranometer.

[15] **Acknowledgments.** This research was supported by the Office of Science (BER), U.S. Department of Energy, grants DE-FG02-03ER63531. Data were obtained from the Atmospheric Radiation Measurement (ARM) Program sponsored by the U.S. Department of Energy, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division.

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