Toward Cloud Tomography from Space Using MISR and MODIS: Locating the “Veiled Core” in Opaque Convective Clouds

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ABSTRACT: For passive satellite imagers, current retrievals of cloud optical thickness and effective particle size fail for convective clouds with 3D morphology. Indeed, being based on 1D radiative transfer (RT) theory, they work well only for horizontally homogeneous clouds. A promising approach for treating clouds as fully 3D objects is cloud tomography, which has been demonstrated for airborne observations. However, more efficient forward 3D RT solvers are required for cloud tomography from space. Here, we present a path forward by acknowledging that optically thick clouds have “veiled cores” (VCs). Sunlight scattered into and out of this deep region does not contribute significant information about the inner structure of the cloud to the spatially detailed imagery. We investigate the VC location for the MISR and MODIS imagers. While MISR provides multiangle imagery in the visible and near-infrared (IR), MODIS includes channels in the shortwave IR, albeit at a single view angle. This combination will enable future 3D retrievals to disentangle the cloud’s effective particle size and extinction fields. We find that, in practice, the VC is located at an optical distance of ~ 5 , starting from the cloud boundary along the line of sight. For MODIS’s absorbing wavelengths the VC covers a larger volume, starting at smaller optical distances. This concept will not only lead to a reduction in the number of unknowns for the tomographic reconstruction but also significantly increase the speed and efficiency of the 3D RT solver at the heart of the algorithm by applying, say, the photon diffusion approximation inside the VC.

KEYWORDS: Cloud retrieval; Radiative transfer; Remote sensing; Satellite observations; Sensitivity studies

1. Context, motivation, and outline

Convective clouds have an important impact on Earth’s weather and climate. By reflecting solar radiation and trapping thermal radiation, they play a key role in Earth’s radiation budget. In addition, deep convective clouds are one of the key drivers of the hydrological cycle by redistributing water throughout the depth of the troposphere (Jensen et al. 2016). Shallow convection, especially in trade wind cumuli, have been shown to be very sensitive to changes in their environmental conditions with a critical impact on future global warming (Bony et al. 2017). The IPCC AR5 (Boucher et al. 2013) reports that clouds and aerosols still contribute the largest uncertainty to estimates of Earth’s changing energy budget. Investigating and monitoring cloud properties is therefore of great importance in order to improve parameterizations of convection in numerical models, for operational weather forecasting as well as for the global climate. This, in turn, is an essential step toward a better understanding of convective

processes as well as aerosol–cloud interactions and their impact on climate.

Quantification and monitoring of cloud properties with global coverage is operationally performed by spaceborne passive and active remote sensing. While active remote sensing (e.g., millimeter-wave radar) provides information about vertical cloud structure, the advantage of passive remote sensing (e.g., multispectral imaging) is the significantly larger spatial coverage. Traditional passive retrieval methods for cloud optical properties such as cloud droplet effective radius and optical thickness often make use of a dual-wavelength approach using passive reflectance measurements in the visible and near-infrared (VNIR) and shortwave infrared (SWIR) as first developed by Nakajima and King (1990). While the absorbing wavelength in the SWIR provides sensitivity to particle size, the scattering-dominated VNIR spectral band is more sensitive to cloud optical thickness. Being based on one-dimensional (1D) radiative transfer (RT), this method applies reasonably well to extended stratiform cloud layers far away from cloud edges (e.g., Platnick et al. 2003; Zhang and Platnick 2011) but is not able to account for three-dimensional (3D) cloud morphologies driven by shallow or deep convection. This leaves a huge gap in the global observation of cloud optical properties (e.g., Cho et al. 2015). To close this gap, a retrieval method is needed that is tailored to the 3D morphology of convective clouds and applicable to satellite observations.

The 3D remote sensing of convective clouds using multiangle satellite imaging from Multiangle Imaging SpectroRadiometer (MISR) was pioneered by Seiz and Davies (2006) using

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sophisticated stereographic methods borrowed from photogrammetry. Only the outer shape of the cloud was targeted¹ and, in view of the labor involved, only one massive convective cloud was investigated, and only one 2D transect of the surface was retrieved. This procedure is entirely based on finding “features” that appear in two or more MISR images, which does not call for calibrated radiance fields. Given this best estimate of the outer cloud boundary in the (y, z) plane, Cornet and Davies (2008) assumed simple homogeneous or two-layered representations of the extinction coefficient and phase function inside the cloud, with uniformity in the x direction, and then performed Monte Carlo simulations to predict the calibrated MISR radiances. By trial and error, they found a reasonable match with the observed radiances, and thus determined the optical thickness of this vertically developed convective cloud. The same cloud as investigated in detail by Seiz, Cornet, and Davies was recently revisited by Lee et al. (2018) who used “space carving” to determine the outer bound of the 3D volume occupied by the cloud. This volume is defined on a 3D Cartesian grid based on MISR pixel footprints by intersecting back-projected cloud masks for all nine angles. Their outcome compared well with the feature-based surface reconstruction by Seiz and Davies along the specific transect they focused on.

Levis et al. (2015) recently demonstrated full 3D tomographic cloud reconstruction using airborne multiangle images from JPL’s Airborne Multiangle SpectroPolarimetric Imager (AirMSPI; Diner et al. 2013). Specifically, the authors used reflectance measurements from AirMSPI’s red channel for nine different viewing angles and reconstructed the 3D cloud extinction field on a Cartesian grid. Levis et al. treat the reconstruction as a large inverse problem, using as the forward model their customized version of Evans’s (1998) popular open-source 3D RT solver, the Spherical Harmonics Discrete Ordinate Method (SHDOM). This first cloud tomography using multiangle VNIR² radiance fields was demonstrated on two synthetic clouds from a large-eddy simulation (LES) model (Matheou and Chung 2014) for rigorous retrieval error quantification. It was then applied to a real-world cloud observed with AirMSPI using eight views, saving the ninth view for a visual validation. In all cases, the cloud microphysics were prescribed and, for simplicity, held uniform across the cloud mass, leaving only the large 3D grid of extinction values to be determined.

Levis et al. (2017) built on their 2015 success by extending the retrieval to all AirMSPI channels, but *without* polarization. Interestingly, even without polarization or SWIR spectral channels, they gained enough sensitivity to reconstruct the cloud while treating the microphysical parameters (effective radius and variance) as unknown but constrained to vary only

along the vertical direction, which is as expected in nature at least in the bulk of the cloud. Moreover, the reconstruction of the 3D extinction grid becomes more accurate than with the prescribed microphysics.

To provide 3D cloud macro- and microphysical properties with global coverage, this computed tomography (CT) method has to be advanced so that it is applicable to satellite observations. To explore this approach, we use Terra’s MISR (Diner et al. 1998) for its multiangle viewing capability and Moderate Resolution Imaging Spectroradiometer (MODIS; King et al. 2003) for its multispectral coverage in the SWIR region. However, transition from the 10 m AirMSPI pixels to larger counterparts of 275 m in the case of MISR (250 and 500 m for MODIS) poses two significant problems: first, optically thick pixel-scale volumes will occur; second, unresolved subpixel spatial variability of cloud extinction and microphysics will be present. SHDOM, the RT model at the heart of the existing 3D reconstruction algorithm, is ill suited for very large and opaque clouds. Optically thick pixels will be subdivided by SHDOM’s adaptive grid refinement into very many optically thinner cells, causing it to rapidly swamp computer memory. To overcome these issues, a new approach must be developed to perform RT inside optically thick clouds more efficiently.

Sunlight scattered into and out of a cloud and detected by a passive imager carries information about the distribution of liquid water inside that cloud. This information is used by the 3D tomographic reconstruction algorithm to recover volumetric information about the cloud’s optical and microphysical properties. We hypothesize that this intricate spatial information originates primarily from the outer shell of the cloud, whereas the amount of information conveyed about the inner core of the cloud decreases significantly with depth due to multiple scattering.

To investigate this hypothesis, we define two concepts: Throughout the remainder of this study the general concept of the gradual loss of information toward the cloud core will be termed *core veiling*. Since core veiling increases as the photon mean-free pathlength decreases, we expect it to depend primarily on the optical depth and single-scattering albedo of the cloud as well as the viewing geometry determined by the solar and viewing zenith angles. This gradual core veiling will be investigated in the present study in a computational approach, whereas a more detailed explanation of the physics of core veiling will be given in a companion paper (Davis et al. 2020). Assuming a specific imager with its characteristic radiometric uncertainty, the contribution of information from increasing optical depths inside the cloud will eventually fall below the instrument’s noise level and thus become negligible.

Hence, the second concept is the *veiled core* (VC). It defines the region within which a given passive imager cannot resolve any details of the liquid water distribution even though the observed solar radiation may have entered, probed, and exited it. These details are thus “veiled” by multiple scattering throughout the cloud volume. The extent of the VC depends on the spatial and optical characteristics of the cloud as well as the radiometric noise limit of the given imager. This concept results in a binary partitioning of the cloud into a detectable shell and a veiled core, which will facilitate new,

¹ Photogrammetric determination of outer cloud shape is now performed routinely using three high-resolution stereocamera pairs at the ARM Southern Great Plains (SGP) site (Romps and Otkem 2018).

² Following the vision of Warner et al. (1986), cloud tomography has previously been achieved with scanning passive *microwave* radiometers at the ARM SGP site by Huang et al. (2008b,a).

TABLE 1. MISR camera labels and corresponding viewing zenith angles for nadir (n), aftward (a), and forward (f) view.

Df	Cf	Bf	Af	An	Aa	Ba	Ca	Da
+70.5°	+60.0°	+45.6°	+26.1°	0°	−26.1°	−45.6°	−60.0°	−70.5°

more efficient ways of solving the 3D RT inside potentially very large opaque clouds.

In the present study we investigate if a VC exists and where it is located inside optically thick clouds from a spaceborne perspective using synthetic MISR and MODIS observations. MISR provides the key multiangle information in the VNIR. SWIR observations are also required for the new approach of 3D cloud tomography from space to disentangle cloud optical thickness and droplet effective radius (Nakajima and King 1990), even if they are at a single view angle and at a degraded spatial resolution. This will be achieved by fusing data from MISR and MODIS.

The paper is organized as follows. In section 2 on methods, we describe the stochastic cloud model used to represent vertically developed convective clouds, with full details provided in the online supplement. We also describe the adopted numerical 3D RT modeling framework. We then set out to investigate the veiling of the cloud's core under a range of opacity and illumination conditions. In section 3, we describe our observational definition of the VC, and present our findings for the adopted class of cloud models taking MISR's VNIR perspective. At first, the sun is at zenith to facilitate the interpretation of the numerics, then oblique illumination is considered. In section 4, we switch from the MISR to MODIS perspective on the VC, with an emphasis on the impact of droplet absorption, hence sensitivity to particle size, in SWIR channels. We summarize and discuss our findings in section 5 and describe future VC-related research in support of CloudCT. In a companion paper (Davis et al. 2020), a digest of which is given in section 5, we relate our present findings to the physical fundamentals of RT in opaque spatially variable media.

2. Methods

To investigate the VC inside optically thick convective clouds from a satellite perspective, RT simulations are performed using synthetic clouds. In this study, we use the 3D Monte Carlo Code for the Physically Correct Tracing of Photons in Cloudy Atmospheres (MYSTIC) (Mayer 2009; Buras et al. 2011), which is part of libRadtran (Mayer and Kylling 2005; Emde et al. 2016).

Simulations are performed for MISR's red band at 670 nm for each of the nine viewing angles and a spatial resolution of 275 m. The nine MISR cameras are labeled An, Af/Aa, Bf/Ba, Cf/Ca, and Df/Da (Diner et al. 1998). The labels range from “A” for the central cameras to “D” for the most oblique cameras, with “n” representing nadir, and “a” representing aftward-viewing and “f” forward-viewing direction along track. The corresponding viewing zenith angles (VZAs) are listed in Table 1 where a positive (negative) VZA points the camera forward (aftward). MISR's observation geometry is displayed

in Fig. 1 for three of its nine cameras. MISR is passing over the cloud depicted in Fig. 1a from north to south (from right to left in the image) on its descending daytime orbit, as indicated by the arrow. First, the forward facing cameras (exemplified here by the Bf camera at 45.6° in pastel orange) observe the cloud, followed by the An (purple) and, finally, the aftward-facing cameras (exemplified here by Ba, orange).

RT simulations for MODIS are performed for the channels 1, 5, 6, and 7, assuming central wavelengths of 645, 1240, 1640, and 2130 nm (Barnes et al. 1998). The spatial resolution of MODIS's channels 5 to 7 is 500 m and for channel 1 is 250 m. For these simulations a single VZA of 9° is chosen as a typical value for a cloud at a random position within MISR's ~400 km cross-track swath width, which is near the middle of MODIS's 2330 km swath (King et al. 2003). MISR and MODIS are both aboard NASA's *Terra* spacecraft that was launched in December 1999 in a near-polar and sun-synchronous orbit at an altitude of 705 km and crosses the equator at 1030 LT on the descending node. Since local radiances are computed for different viewing zenith angles, all MYSTIC simulations are

FIG. 1. (a) MISR's observation geometry for an overpass over the Koch cloud. (b) Corresponding ground-registered red-channel (670 nm) radiances $I_{\text{cam}}(x)$ measured in $\text{mW m}^{-2} \text{nm}^{-1} \text{sr}^{-1}$ on the left-hand axis and in (nondimensional) bidirectional reflection function (BRF) $= \pi I_{\text{cam}}(x) / \mu_0 F_0$ units on the right-hand axis, with TOA irradiance $F_0 = 1529 \text{ mW m}^{-2} \text{nm}^{-1}$ and $\mu_0 = \cos(\text{SZA}) = 1$ in this case. Three of the nine cameras are displayed, An in purple and the Bf and Ba cameras at $\pm 45^\circ$ in (pastel) orange; see Fig. 2 for all nine views. The shaded areas in (a) symbolize the respective viewing angles with each bin corresponding to an along-track (push broom) pixel $[x, x + \Delta x]$ in (b) with a spatial resolution of $\Delta x = 275 \text{ m}$.

FIG. 2. (a) Extinction field of the reference Koch cloud with a central optical thickness of $\tau_{\text{central}} = 40$. (b) MISR radiances simulated with MYSTIC for the nine cameras Aa (Af) through Da (Df) and An registered to the ground. The sun is overhead (SZA = 0°) in these 3D RT simulations. The uncertainty of the results is represented by the width of the lines and amounts to less than 1% for a 2σ confidence interval. The symbols indicate the exact location of the sampled pixels along the x axis and are all larger than the 1% Monte Carlo error.

performed in “backward” mode for efficiency reasons, that is, photons start their journey at the observer and end their path at the source.

The sensitivity studies presented in the following use idealized two-dimensional (2D) convective clouds as shown in Figs. 1a and 2a. The synthetic clouds vary only in the x and z directions with internal turbulence simulated by a 2D high-resolution fractional Brownian motion (fBm) field (Mandelbrot 1977). Their outer shape is derived from a fractal Koch curve (von Koch 1904). Furthermore, we added a vertical gradient to the extinction field, since airborne in situ measurements have shown that cloud extinction increases with altitude inside the cloud (Pawlowska et al. 2000; Rosenfeld and Lensky 1998; Rosenfeld et al. 2006). See the supplemental material for more details on the generation of the synthetic clouds.

Compared to synthetic clouds from LESS, the Koch cloud represents a simplification for the subsequent sensitivity studies that still allows us to capture the most important properties that impact the core veiling. At the same time, the fBm model used for the Koch cloud’s internal turbulence allows for manipulation of the liquid water distribution while being able to control its statistical properties. Such controlled manipulation would be much more difficult and time consuming for LES clouds. This simplified setup therefore reduces computational costs and helps interpret the results; in particular, “images” in a 2D world can be displayed simply as monovariate functions of the x coordinate. Note that, although the cloud properties vary only in 2D, full 3D radiative transfer is employed to simulate the observed radiances.

Further note that time-dependent cloud turbulence as an additional source of randomness was not considered in this first VC study, that is, we assume simultaneous collection of the multiangle observations. In fact, it takes ~ 7 min for MISR to collect observations from all nine viewing angles, which is well within the range of relevant eddy turnover times. The impact of this additional source of randomness on the VC should therefore be addressed in future studies.

Figures 1a and 2a show the resulting cloud extinction field scaled to a central optical thickness of $\tau_{\text{central}} = 40$. This synthetic cloud is used as an input field for the RT solver MYSTIC. The 1025×1024 pixels are embedded in a ~ 53 km domain with a horizontal and vertical resolution of about 4.3 m,

resulting in a cloud width and physical thickness of about 4.4 km with a cloud-base height at 1 km, hence a cloud-top height of 5.4 km (cf. Fig. 1a). The domain size is chosen large enough to avoid artifacts caused by periodic boundary conditions, even for the most oblique MISR viewing angles ($\pm 70.5^\circ$ for Df/Da cameras). The MYSTIC simulations are performed for a sensor at the top of the atmosphere.

For simplicity, the surface albedo is set to zero (pure absorption) and the solar zenith angle (SZA) is set to 0° (overhead sun). For all simulations a constant effective droplet radius of $r_{\text{eff}} = 10 \mu\text{m}$ is chosen, with optical properties computed according to Mie theory (Wiscombe 1980). Aerosol as well as molecular scattering and absorption are neglected to focus on the cloud properties only. Finally, the RT simulations are calibrated with the solar spectrum by Thuillier et al. (2003).

The simulated radiances as observed at the nine MISR cameras are computed at the top of the MYSTIC grid (shown schematically by the field of views for three of the MISR cameras in Fig. 1) and subsequently projected to the ground in order to simulate correctly actual MISR observations (cf. Fig. 1b). The projection is computed by registering each camera pixel at the top of the atmosphere to a ground pixel along the camera’s viewing angle. The radiances of the high-resolution cloud field are then averaged over 64 pixels to obtain MISR’s resolution of 275 m. The results of three representative cameras (Bf, An, Ba) are displayed in Fig. 1b, and the observations for the full suite of MISR cameras are displayed in 2b. The numerical uncertainty was controlled and maintained at a level far below 3%, MISR’s absolute radiometric error at maximum signal (Diner et al. 1998).

For the following sensitivity studies, we assume that, for an average signal, differences in the simulated MISR radiances of $\lesssim 5\%$ are too close to the instrument’s noise, and thus considered negligible. In other words, we assume a sensitivity threshold for MISR of 5%. This corresponds to the root-mean-square (RMS) error of the difference between two independent MISR radiances at the 2σ level, assuming 3% radiometric error in each MISR radiance. To resolve these differences in the RT simulations, we determined that a numerical precision of $\leq 1\%$ is required. This is achieved by performing simulations with MYSTIC using 200 000 photons per cloudy pixel, or 12.8×10^6 photons per MISR pixel (64 aggregated cloud pixels).

We anticipate that spatial details in the cloud microphysics become increasingly veiled toward the core of the cloud due to additional multiple scattering. We further hypothesize that changes in the liquid water content (LWC) inside the VC lead to negligible differences in the observed MISR as well as MODIS radiances in the above sense of being $\leq 5\%$. Despite the expected gradual nature of the core veiling, it might be practical for some applications (e.g., developing a fast and efficient hybrid RT solver for large opaque clouds) to define the location of the VC with a distinct boundary between the outer shell and the core using this sensitivity threshold. To investigate the location of the VC inside these synthetic clouds, the LWC distribution in their inner core is manipulated and the observed radiances are compared to the reference cloud, as explained in the following.

Sensitivity studies are performed with a reference cloud field and three different scenarios of modifying the 2D LWC grid: in the first scenario, the LWC in an arbitrary region in the core of the reference Koch cloud is replaced by its mean value. In the other two scenarios, the liquid water distribution in the cloud's inner core is replaced by new realizations of the turbulence field. To investigate the effect of the manipulated core inside these synthetic clouds, the simulated radiances of the reference case are compared with the radiances of both cloud variations. The gradual veiling of the manipulated cloud region is then investigated by varying the location and extent of the manipulated core. While MISR's red band is controlled entirely by scattering, absorption plays an important role for the MODIS's SWIR channels, and its effect is investigated in section 4. First, we present sensitivity studies for locating the VC using MISR observations.

3. MISR's perspective on the VC

The optical thickness of the reference Koch cloud in Fig. 2a is scaled to $\tau_{\text{central}} = 40$ along the central vertical pixel column. Figure 2b shows the corresponding MISR radiances computed for the nine cameras described in Table 1. The simulated radiances are projected to the ground assuming a satellite overpass from north to south, as shown in Fig. 1. This projection is precisely how MISR's level 1 radiances and level 2 (e.g., stereo-matching) products are archived, which is to register the observations to the WGS84 ellipsoid (Diner et al. 1998). MISR radiances, as observed by the nadir pointing camera (An), are displayed at the center of the domain in purple. On the right-hand side of the An camera, the radiances observed by the aftward-pointing cameras are represented in blue (Aa), orange (Ba), green (Ca), and red (Da). On the left-hand side the results of the forward-pointing cameras are shown in pastel blue (Af), orange (Bf), green (Cf), and red (Df). The uncertainty of the MYSTIC simulations is represented here by the width of the lines, which amounts to less than 1% for a 2σ confidence interval. Assuming an overhead sun with $\text{SZA} = 0^\circ$ causes the detected radiances of the nadir An camera to be brightest. Since the geometry of the Koch cloud is symmetric around its vertical central axis, asymmetries in the radiances are due to large-scale turbulence in the extinction field. Darker shades correspond to larger extinction values, which in turn cause

larger reflected radiances. This asymmetry is clearly visible, for instance, for the An camera comparing the left versus right side of the cloud. How the spatial footprint of the cloud for the cameras characteristically increases for more oblique angles is also noticeable.

a. Effect of a homogeneous core

Figure 3 shows the first scenario of manipulating the cloud core. Here, the internal core of the reference Koch cloud is replaced by its mean value. Size and shape of the core region is chosen arbitrarily but aiming at covering a significant portion of the cloud's volume. The resulting extinction field is displayed in Fig. 3a. Figure 3b compares the MISR radiances for the reference (I_{ref} , dashed line) and the manipulated cloud (I_{new} , solid line). The extinction difference (reference minus new) is depicted in Fig. 3c. Furthermore, the relative differences (in %) between the observed radiances of the reference cloud and its modified version $\Delta I/I$ are computed according to

$$\frac{\Delta I}{I} = \frac{I_{\text{new}} - I_{\text{ref}}}{I_{\text{ref}}} \times 100\% \quad (1)$$

and shown in Fig. 3d. The numerical uncertainty of the relative difference is represented by the shaded area around each line, corresponding to a 2σ confidence interval. The white area centered around the black dashed zero line, indicates a threshold of $\pm 5\%$. As previously explained, relative differences of simulated radiances within this threshold range are considered negligible in view of the instrument's radiometric noise.

In this sensitivity study, most camera pixels detect a significant difference between the manipulated and the reference cloud up to 26%. These relative differences are slightly larger for the forward-pointing cameras, which observe predominantly the optically thinner part of the cloud field. The optically thinner part of the cloud allows for larger photon mean-free pathlengths, hence larger penetration depths. This causes the modified inner region of the cloud to contribute more strongly to the observed radiances compared to the optically thicker cloud area, which is mainly visible for the forward facing cameras. The nadir together with the Aa and Af views exhibit the overall smallest relative differences with a magnitude up to about 6%. Most of the significant relative differences (i.e., $> 5\%$) have a positive sign, which implies that the radiances of the manipulated cloud field (I_{new}) are larger than the reference cloud.

Comparing Fig. 3d with the extinction difference in Fig. 3c explains these results: positive relative differences in the MISR radiances correspond to cloud pixels where the extinction was increased by replacing the LWC at the core of the cloud by its mean value. Increased values in the cloud extinction field are represented by reddish colors in Fig. 3c and are mainly detected by the forward facing cameras Bf, Cf, and Df. Two effects are responsible for the large differences in the observed radiances: first, replacing the turbulent medium by its mean value reduces the length of the effective photon mean-free path (Davis and Marshak 2004); second, by averaging over the inner core, the vertical gradient disappears in the manipulated cloud core. This results in an underestimation of the liquid

FIG. 3. (a) Extinction field of the reference cloud from Fig. 2 manipulated by replacing the extinction values of its inner core by their average of 8.34 km^{-1} , which results in $\tau_{\text{central}} \approx 38$. (b) MISR radiances registered to the ground for the nine cameras showing the results for the reference cloud (dashed) together with the results of the new cloud field (solid). (c) Absolute difference of the extinction field (km^{-1} , new extinction field minus reference). The gray curve indicates the outline of the cloud. (d) Relative differences (%) of the observed MISR radiances: new minus reference cloud relative to reference. The uncertainty of the relative difference is represented by the shaded area around each line, corresponding to a 2σ confidence interval. The white area around the black dashed zero line indicates the $\pm 5\%$ threshold. Within this range, differences in the observed radiances are considered below the instrument's noise level and thus negligible, but here most differences far exceed that threshold.

water content in the upper part of the core and an overestimation in the lower part. This underestimated (overestimation) of the LWC results in decreased (increased) observed radiances and thus negative (positive) relative differences in Fig. 3d. Since the lower part of the core is more “exposed” due to the lower LWC surrounding it, the positive relative differences are most pronounced. We therefore have to consider both the mean value and large-scale gradients when applying the concept of VCs to real-world clouds.

b. Effect of large-scale gradients, mean, variance, and spatial correlations

Figure 4 demonstrates similar experiments, this time the core region of the cloud is replaced by a new realization of the internal turbulence field, simulated with 2D fractional Brownian motion (fBm). The same parameters (incremental variance and Hurst index $H = 1/3$ and, hence, spectral slope $\beta = 2H + 1 = 5/3$) are used to model the new fBm. The adopted “diamond-square” algorithm (cf. supplement) is then used to ensure a seamless transition to the specified structure of the reference cloud outside the manipulated region. The vertical gradient for the ensemble-mean extinction remains the same. The new extinction field is therefore *visually* indiscernible from the reference field in Fig. 2a: only the random details in the core region have changed. This enforced continuity at the core's boundary belies the fact that the magnitude of the grid-scale differences at large distances from the unchanged boundary values are in fact comparable to those displayed in Fig. 3c where the core extinction is set everywhere to its mean. However, the new simulated MISR radiances (not shown) appear to be the same as in Fig. 2b. For this reason, cloud extinction and MISR radiances in Fig. 4 are only represented by

their differences with respect to the reference case. For Figs. 4a and 4b, the central core of the Koch cloud (cf. Fig. 3a) was manipulated by regenerating the fBm inside the core. For Figs. 4c and 4d, the liquid water distribution in a lower region of the cloud, which aligns with the cloud bottom at 1 km, was perturbed. The relative differences Δ/I of the simulated radiances are smaller than 5% for all MISR pixels. Thus, we can conclude that changing the internal turbulence field results in negligible differences as long as mean, variance, spatial correlations, and any cloud-scale trends are maintained.

The location and size of the manipulated core in the previous experiments was decided by no other considerations than maximizing its size (half of the cloud size) and assuming a simple geometric shape at the same time (as required by the specific fBm generation technique we adopted in the supplement). To provide a universal method of determining the size and location of the VC in arbitrary 3D clouds, a general criterion is required, independent of the cloud's geometric shape. Since the veiling of the cloud core is caused by multiple scattering, we choose the optical distance along the line of sight of each MISR camera, as shown in Fig. 5a for the Af camera. MYSTIC's grid sweep function is used to calculate the optical distance for each MISR camera. This is achieved in practice by switching off scattering and tracking the photon's location in the (x, z) plane. To obtain the optical path, the optical thickness at each photon step is integrated along the camera's line of sight.

For a specific passive imager, the VC (i.e., a binary separation between the cloud shell and core) can be defined by assuming a certain sensitivity threshold of the instrument. The location of the VC can be determined by applying a mask to the optical distance by assuming a certain threshold τ_{thres} . The exact value of the threshold depends on the application and the

FIG. 4. (a),(c) Absolute difference of extinction fields (km^{-1} , new minus reference), as in Fig. 3c but for a cloud field generated by replacing the internal extinction core by a new realization of the turbulence field constrained to have the same values all along its boundary. The gray curves indicate the outline of the Koch cloud. (b),(d) Relative difference (%) of the observed MISR radiances, as in Eq. (1) and Fig. 3d.

assumed sensitivity threshold of the instrument. The criterion for the mask is that the optical distance is larger than the threshold for a certain pixel for all nine cameras simultaneously. As an example of special interest further on, the outcome for threshold optical depth of $\tau_{\text{thres}} = 5$ is displayed in Fig. 5b. Due to the turbulence-induced asymmetry of the cloud extinction field, the forward-pointing cameras “see” deeper into the cloud, and thus the VC is shifted slightly to the left. Figure 5c overlays the region where the turbulence field was modified in the previous section (cf. Fig. 4a). We can now determine the optical depth from the cloud’s outer fractal boundary at which the inner extinction was manipulated for each MISR camera and pixel.

We expect that the relative differences in the observed MISR radiances between manipulated and reference cloud decrease as the optical distance between cloud surface and manipulated core increases. In other words, the deeper inside the cloud the manipulation occurs, the more it is veiled by additional multiple scattering. Figure 6 shows the relative differences of the simulated MISR radiances as a function of

increasing optical distance between the cloud surface and the manipulated core. In Fig. 6a the relative differences of all nine cameras and all MISR pixels are combined from both simulations shown in Figs. 4b and 4d and for different total cloud optical thicknesses ($\tau_{\text{central}} = 10, 20, 40$) assuming a constant effective radius of $10 \mu\text{m}$. This representation yields a simple relationship between the relative difference of the MISR radiances and the optical distance defining the VC. A threshold for the boundary of the VC can be directly inferred in terms of the optical distance from the cloud surface, given a certain sensitivity threshold of the instrument.

For MISR, we assumed a sensitivity threshold of about $\pm 5\%$, which is indicated by the white area in Fig. 6. For a VC at optical distance 5 (dashed vertical line), all measured relative differences from the three previous experiments shown in Figs. 4b and 4d are below 5%. This implies that for a sensor-driven uncertainty threshold of 5%, the VC starts at optical distance of ~ 5 inside the cloud. Another implication is that, for that particular sensitivity threshold of 5%, only clouds with total optical thickness in excess of 5 exhibit a VC at all.

FIG. 5. (a) Optical distance along the line of sight of each cell at the top of the turbulence grid for the Af camera at VZA = -26.1° when $\tau_{\text{central}} = 40$. (b) Optical distances for all nine MISR cameras for a threshold $\tau_{\text{thres}} = 5$. The criterion for the masked area is that all pixels of the nine cameras have optical distances in excess of τ_{thres} . (c) The VC region of the cloud where the turbulence field was modified in Fig. 4a is also displayed.

FIG. 6. Relative absolute difference of MISR radiances (%) between the manipulated and reference cloud (from Figs. 4b and 4d) as a function of the optical distance from the cloud boundary. The results comprise (a) all nine MISR angles and different total cloud optical thicknesses $\tau_{\text{central}} = 10$ (dark blue), 20 (light blue), and 40 (orange) and (b) varying effective radii between 5 and 15 μm in addition. The vertical dashed black line indicates an optical distance of 5 for the VC, which corresponds to a relative difference of less than $\pm 5\%$, indicated by the white area.

For larger effective radii, clouds with a fixed LWC have a smaller cloud optical thickness [cf. supplement, Eq. (1)]. Also, following Mie theory (Mie 1908), the forward-scattering peak of the phase function narrows slightly. For a fixed optical thickness, this causes the light to penetrate slightly deeper, resulting in the VC moving deeper inside the cloud. This is demonstrated in Fig. 6b. The sensitivity of the relative differences in MISR radiances to changes in the effective droplet radius between 5 and 15 μm is displayed here for a fixed total optical thickness. In this case, the boundary of the threshold optical distance τ_{thres} that defined the VC increases from 4.5 to 4.8 for $r_{\text{eff}} = 5$ and 15 μm , respectively. This implies that the location of the VC in terms of optical distance from the outer cloud boundary is only weakly sensitive to changes in the effective droplet radius as well as to the total cloud optical thickness. The only limitation is that the total cloud optical thickness must exceed $\tau \gtrsim \tau_{\text{thres}}$ ($\tau \gtrsim 5$ in our case) for a VC to exist.

c. Effect of the solar zenith angle

Figure 7 shows synthetic MISR observations from all nine cameras for the same Koch cloud as used in Fig. 2, but

assuming an oblique sun at $\text{SZA} = 60^\circ$ with the off-nadir viewing directions in the principal plane. Compared with MYSTIC simulation outcomes for overhead sun ($\text{SZA} = 0^\circ$), these MISR radiances here are clearly more asymmetric. The sun is illuminating the cloud from the left, whereas its right side is in the shade. This effect is visible in the observed MISR radiances, which are now larger for the aft-facing cameras (Aa to Da) and decreased for the forward facing cameras (Af to Df) that are facing the self-shaded side of the cloud.

Figure 8 shows the same sensitivity study as in Fig. 4, but for $\text{SZA} = 60^\circ$. In comparison with the results for overhead sun, the relative difference in the observed MISR radiances is more asymmetric as well. The oblique sun is now illuminating the left side of the cloud, which becomes optically thinner toward its base. This counteracts the veiling of the manipulated cloud core. Especially the forward facing cameras, which are pointing at the more tenuous side of the cloud, detect larger relative differences. For this oblique illumination, light thus travels a shorter optical distance through the cloud side, so there is less multiple scattering to veil the manipulated core. Most of the

FIG. 7. (a) Extinction field of reference Koch cloud for $\tau_{\text{central}} = 40$. (b) MISR radiances for its nine cameras as in Fig. 2b, but for $\text{SZA} = 60^\circ$. The viewing angles of MISR's cameras are in the principal plane with the sun in the south, illuminating the left side of the cloud.

FIG. 8. (a),(c) Relative difference (new minus reference) of the extinction field, as in the same panels for Fig. 4. (b),(d) Relative differences of observed MISR radiances as in the same panels for Fig. 4, but for SZA = 60°.

$\Delta I/I$ values are still within the 5%, which we can still consider as the sensitivity threshold of MISR's sensors.

4. MODIS's perspective on the VC

The RT simulations in the previous section were performed for MISR's red band at 670 nm. Light interaction with water droplets at this wavelength is dominated by scattering while absorption is negligible. Figure 9 shows the relative differences of the radiances simulated with MYSTIC using the same clouds as in Fig. 4 but for MODIS. This instrument is a single downward-looking “whisk broom” imager, but it provides additional information about cloud microphysics from its SWIR channels. Here, we assume a mean VZA = 9°, averaged over the ~400 km MISR swath near the center of MODIS's 2330 km counterpart. For MODIS's SWIR channels, absorption by water droplets becomes increasingly more important. This is exploited by the operational Nakajima–King retrieval (Nakajima and King 1990) to gain information about the effective droplet radius along with cloud optical thickness.

To investigate the effect of additional absorption on the VC of convective clouds, RT simulations were performed for MODIS channels 1, 5, 6, and 7, assuming central wavelengths of 645, 1240, 1640, and 2130 nm, and indicated in Figs. 9b and 9d in blue, green, orange, and red, respectively. In a post-processing step, the MYSTIC-computed radiances at the spatial resolution of about 4.3 m (turbulence grid scale) were averaged and interpolated to 250 m for channel 1 and 500 m for channels 5, 6, and 7.

The relative differences of the radiances $\Delta I/I$ are well below 5% for all MODIS pixels. The blue curve representing channel 1 at 645 nm in Fig. 9 is very similar to what MISR's An camera would observe in the nadir at 670 nm (cf. purple lines in Fig. 4). At those two wavelengths, scattering dominates and absorption is negligible. For increasing wavelengths from channel 1 to 7 the relative differences in the observed radiances decrease, as expected, due to increasing absorption by the cloud droplets. Observing the cloud scene at an absorbing wavelength leads to shorter photon mean-free paths inside the cloud that, in turn,

cause the VC to extend toward a smaller optical distance. For a tomographic cloud reconstruction using fused MISR and MODIS observations, this implies that estimating the location of the VC using all nine MISR viewing angles in the visible is safe to assume for MODIS as well. In other words, what is veiled for MISR will be equally veiled for MODIS's red channel 1, and even more veiled in the SWIR channels 5, 6, and 7.

5. Summary, discussion, and outlook

In this study, we investigated the “veiled core” (VC) inside optically thick convective clouds, as observed with MISR and MODIS on *Terra*. We addressed two questions: first, is there a VC in opaque convective clouds, and second, where is it? To address these questions, we simulated multiangle observations of MISR using simplified 2D cloud models with a finely resolved Koch fractal outer shape and internal turbulence-like variability from the ~4 km cloud size down to ~4 m scales, consistent with in situ observations (Davis et al. 1999). The results presented in this study indicate that a VC exists inside opaque clouds and that the “veiling” of spatial details of the liquid water distribution increases exponentially toward the core of the cloud due to increased multiple scattering.

Despite the gradual nature of the core veiling, we anticipate in a tomography of large opaque clouds the need for transitioning between bona fide 3D RT in the outer shell and an approximate but far more expedient 3D radiation transport model in the VC such as photon diffusion. This motivates the definition of the VC with a well-defined VC–outer-shell interface somewhere in the cloud. Such a hybrid 3D RT model would be both accurate enough for predicting the multiangle images to within a fraction of the sensor uncertainty, and computationally efficient enough to drive the 3D tomographic reconstruction algorithm. The adopted binary definition of the VC lays the foundation for such hybrid 3D RT modeling where different equations are solved inside and outside of the VC, and fluxes are properly matched at the interface.

The results of this study indicate that, assuming a sensitivity threshold of 5% for MISR, a de facto boundary of the VC can

FIG. 9. (a),(c) Absolute difference of the extinction field (km^{-1} , new vs reference) as in Fig. 4, assuming $\tau_{\text{central}} = 40$. (b),(d) Relative differences (%) of observed MODIS radiances for wavelength channels 1, 5, 6, and 7 (assuming central wavelengths of 645, 1240, 1640, and 2130 nm) associated, respectively, with the extinction field modifications in (a) and (c). For MODIS's (whisk broom) camera, a mean VZA of 9° was assumed, averaged over the whole MISR swath inside of MODIS's much larger one. Furthermore, the MYSTIC results were averaged and interpolated to a spatial resolution of 250 m for channel 1 and 500 m for the remaining channels.

be drawn at an optical distance of ~ 5 inside the cloud along all directions of observation. Changes in the liquid water distribution inside this core result in less than 5% variability of the multiangle radiances observed by MISR, as long as mean, variance, correlations, and cloud-scale gradients of the liquid water field are preserved. For MISR and MODIS, with an estimated measurement uncertainty of about 3%, a variability of 5% or less can still be considered within the noise and is thus negligible in the sense that it should not be viewed as signal in cloud tomography.

In the present study, a *computational* approach is used to investigate the core veiling and to define and locate the VC. In a complementary companion paper to this one, Davis et al. (2020) explain in considerable detail the *physics* of core veiling. In particular, the VC is revisited in the framework of continuous loss of spatial detail by blurring, as in the perennial problem of visibility through a scattering medium. The authors thus introduce the notions of contrast ratio and point-spread function. In essence, the VC comes out as a smooth background over which the multiscale image of the cloud's rich texture is formed. Várnai and Marshak (2003) also used the basic physics of 3D RT to explain how gradients form in radiance fields both inside and escaping clouds. Radiometrically speaking, the role of the VC is to maintain the cloud-scale gradient between the illuminated and shadowed sides of the 3D cloud. It therefore controls the bulk of the solar radiant energy fluxes through the cloud, which underscores its importance for the 3D cloud tomography from a climate perspective. We anticipate that physical insights from the companion paper will accelerate the development of 3D cloud tomography from satellites. Beyond MISR+MODIS/Terra, a beneficiary will be the CloudCT mission (Schilling et al. 2019) that will fly 10 CubeSats in a formation optimized for tomographic reconstruction of vertically developed convective clouds.

In general, making use of this VC opens up new ways to increase the efficiency in the rendering synthetic observations

of optically thick cloud volumes using RT models. Specifically, for application to the 3D cloud tomography inversion problem, where the forward solver has to be called at each iteration, a fast and efficient RT solver is crucial to speed up the reconstruction algorithm. The RT solver can be optimized to treat the outer shell of the cloud (where details matter) with higher accuracy and fidelity than the VC, where the details of the liquid water distribution are negligible within the instrument's measurement uncertainty. Applying photon diffusion approximation inside the VC would be a promising way to significantly increase the speed and efficiency for RT simulations of optically thick clouds. Replacing the detailed RT solver by a fast and efficient way to stream radiation through the VC, a significant amount of computational time and computer memory resources can be saved. Since the size of the VC increases with a larger cloud volume and higher optical thickness, the increase in computational effort will be balanced.

Moreover, treating the VC as a connected object, mainly determined by its bulk optical properties significantly reduces the number of unknowns in the inverse problem. Instead of solving the minimization for each pixel separately, only the bulk statistical properties of the core volume need to be estimated. The statistical properties comprise mean, variance, and correlation of the extinction volume, which can be parameterized for the RT solver.

Apart from 3D cloud tomography, other applications that involve RT modeling of optically thick cloud volumes can benefit from acknowledging the existence of a VC. For example, the efficiency of RT modeling for the analysis of ground-based cloud images (e.g., at DOE/ARM sites) as demonstrated by Romps and Öktem (2018) could be increased by making use of the VC. Another application is the estimate of surface radiation budget at satellite pixel scales, for example, for near-real-time support of solar energy harvesting. Here, fast RT modeling of cloudy scenes is needed for characterizing broken cloud structure, which can help to mitigate the current

fluctuations they induce to the electrical grid (Mejia et al. 2018). Moreover, satellite remote sensing of aerosols in the vicinity of clouds can benefit from this approach. In these regions, we need to characterize the optical properties of aerosol and cloud particles most accurately to unravel indirect aerosol effects. At the same time, 1D RT-based aerosol retrievals fail here due to 3D cloud radiative effects (Várnai et al. 2017).

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