On the angular effect of residual clouds and aerosols in clear-sky infrared window radiance observations: Sensitivity analyses

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[1] Accurate environmental satellite observations and calculations of top-of-atmosphere infrared (IR) spectral radiances are required for the accurate retrieval of environmental data records (EDRs), including atmospheric vertical temperature and moisture profiles. For this reason it is important that systematic differences between observations and calculations under well-characterized conditions be minimal, and because most sensors must scan the earth surface to facilitate global coverage, this should include unbiased agreement over the range of zenith angles encountered. This paper investigates the “clear-sky observations” commonly used in such analyses, which include “cloud-masked” data (as is typical from imagers), as well as “cloud-cleared radiances” (as is typical from hyper/ultraspectral sounders). Here we derive simple physical conceptual models to examine quantitatively the longwave IR brightness temperature sensitivity arising from the increasing probability of cloudy fields-of-view with zenith angle, or alternatively from increased slant-path through an aerosol layer. To model the angular effect of clouds, we apply previously derived probability of clear line-of-sight (PClos) models for single-layer broken opaque clouds. We then generalize this approach to account for the impact of high, semitransparent (non-opaque) cold clouds, by deriving analytical expressions for the mean slant-paths through each of the idealized shapes under consideration. Our sensitivity analyses suggest that contamination by residual clouds and/or aerosols within clear-sky observations can have a measurable concave-up impact (i.e., an increasing positive bias symmetric over the scanning range) on the angular agreement of hypothetical “observations” with “calculations.” The magnitudes are typically on the order of couple tenths of a Kelvin or more depending on the residual absolute cloud fraction and optical depth (i.e., the degree of cloud contamination), the residual aerosol optical depth (i.e., the degree of aerosol contamination), the temperature difference between the surface and the residual cloud/aerosol layers, and the shape and vertical aspect ratio of the clouds.


1. Introduction

[2] Accurate satellite observations and calculations of top-of-atmosphere infrared (IR) spectral radiances (hereafter “obs” and “calc,” respectively) are two necessary components required for the accurate retrieval of geophysical state parameters. Ideally, it is desired that systematic differences between obs and calc under well-characterized conditions be minimal, and because most environmental sensors must scan the earth surface to facilitate global coverage, this should include an unbiased agreement over the zenith angle scanning swath. A systematic angular dependence in calc minus obs (calc — obs) may lead to undesirable scan-dependent artifacts and/or errors in the calibration/validation (cal/val) of sensor data record (SDR) and environmental data record (EDR) products (also referred to as Level 1B radiances and Level 2 retrievals, respectively), as physical retrieval methodologies operate on the minimization of calc — obs (or equivalently, obs — calc). Generally speaking, SDR products include radiance observations that are flagged as “clear-sky.” EDRs derived from SDRs include atmospheric vertical temperature and moisture profiles (AVTP and AVMP, respectively) from hyper/ultraspectral sounding systems [e.g., Smith et al., 2009], as well as land and sea surface temperatures (SSTs). AVTP and AVMP products are Key Performance Parameters (KPPs) from the operational Joint Polar Satellite System (JPSS) Cross-track Infrared Microwave Sounding
Suite (CrMSS), and are also products routinely derived from the operational MetOp-A Infrared Atmospheric Sounding Interferometer (IASI) [for details on IASI, see Cayla [1993] and Hilton et al. [2012]) and Aqua Infrared Atmospheric Sounding Sounder (AIRS) [for details on AIRS, see Chahine et al. [2006]]. With the launch of the Suomi National Polar-orbiting Partnership (NPP) satellite in October 2011, cal/val of the CrMSS sounding system is now a priority for ensuring the KPP products comply with mission requirements and have met global performance specifications [Nalli et al., 2012].

For example, toward this objective for SST products, recent work on global-ocean comparisons of cloud-masked Advanced Very High Resolution Radiometer (AVHRR) IR window-channel obs against clear-sky calc (based upon MODTRAN using global SST and NCEP analyses fields, and assuming either blackbody or Fresnel specular surfaces) showed what may be referred to as a strong concave-up shape in the variation of calc – obs with zenith angle [cf. Dash and Ignatov, 2008, Figure 8]. (In this paper, we use the terms “concave-up” and “concave-down” to describe increasing positive or negative bias in calc – obs symmetric over the scanning swath, respectively.) If we only consider the surface emissivity and reflection, a concave-up surface-leaving radiance (SLR) calc – obs signal is theoretically expected from assuming a blackbody surface, but the opposite (concave-down) is expected from assuming a specular (Fresnel) surface. However, Dash and Ignatov [2008] showed only a reduced concave-up result in their specular case [cf. Dash and Ignatov, 2008, Figure 8]. Thus, clearly there must have been other factors aside from the surface model term at play in the analysis. Subsequent consistency checks with the Community Radiative Transfer Model (CRTM) had confirmed the expected concave-up shape for a black surface, whereas the CRTM surface emissivity resulted in nearly flat to slightly concave-down variation in the 3.7 μm band [cf. Liang et al., 2009, Figures 3a–3c]. Since these were published, over three years of nighttime data using the National Oceanic and Atmospheric Administration (NOAA) Monitoring of IR Clear-sky Radiances over Oceans for Sea Surface Temperature (MICROS) system [Liang and Ignatov, 2011] indicate that the calc – obs angular dependencies may be concave-up or concave-down, depending upon band and CRTM implementation, as well as the cloud-mask processing system used to identify clear-sky FOVs suitable for calc – obs comparisons (A. Ignatov and X.-M. Liang, personal communication, 2010).

These mixed results are indicative of the difficulties inherent in achieving agreement between calc and obs. This paper thus sets out to investigate this problem further. However, rather than attribute discrepancies in calc – obs to a forward model (calc) undergoing development, we proceed from a different premise concerning the last consideration mentioned in the above paragraph, namely, how might the clear-sky observations (obs) themselves contribute to calc – obs behavior? To answer this, we must first revisit what is meant by “clear-sky observations.” Generally speaking, when we refer to a set of IR observations as being “clear-sky,” what is really meant is that the data have been either “cloud-masked” (as is typical for imager systems such as AVHRR) or “cloud-cleared” (as is typical for sounding systems such as IASI or AIRS). In the former, the clear-sky observations are derived from a subsample of actual observations that have been “screened” for clouds using a cloud-mask algorithm. In the latter, “cloud-cleared radiances” (or “clear-column spectra”) are derived from extrapolation of multiple coincident measurements. It is important here to underscore that in both cases, an algorithm is employed to yield the desired “clear-sky” product.

Because of this, and because such algorithms are not intentionally designed to mask aerosols, the clear-sky observations will be subject to algorithmic errors beyond that of the sensor itself, something referred to as “contamination” by residual clouds and/or aerosols. We thus consider in this work the hypothetical potential angular effect of idealized residual clouds and aerosols upon clear-sky radiance samples. Approximations for quantitatively assessing the impacts on window channel radiances are derived for various scenarios, including single-layer broken opaque clouds (section 2), single-layer aerosols (section 3), single-layer aerosols overlying or underlying single-layer broken opaque clouds (section 4), empirical global-mean aerosols and residual clouds (section 5), and finally single-layer broken semitransparent (non-opaque) clouds (section 6). N. R. Nalli et al. (On the angular effect of residual clouds and aerosols in clear-sky infrared window radiance observations: 2. Experimental analyses, submitted to Journal of Geophysical Research, 2012, hereinafter referred to as part 2) then present results obtained using high spectral resolution IR data matched with correlative data from ocean-based validation field campaigns. We find that the likelihood of contamination by residual clouds and/or aerosols within hypothetical “clear-sky observations” can have a measurable concave-up impact on the angular agreement with “calculations.”

2. Modeled Impact of Single-Layer Broken Opaque Clouds

In a seminal paper, Kauth and Penquite [1967] analytically derived a general statistical model for predicting the probability of observing a clear line of sight through a cloudy atmosphere, assuming individual clouds modeled as opaque spheres, ellipsoids and semiellipsoids, and randomly distributed within a finite layer. Ellingson [1982] and Naber and Weinman [1984], based upon work by Avaste et al. [1974], independently devised models for calculating the impact of broken clouds upon hemispheric IR irradiance, assuming individual clouds modeled as Poisson distributed, right-cylinder isothermal blackbodies. Minnis [1989] derived similar expressions based upon the observed differences from nearly coincident observations taken at different zenith angles obtained from the East and West NOAA Geostationary Operational Environmental Satellites (GOES East and West, respectively).

Taylor and Ellingson [2008] recently compiled the earlier related works into a single paper providing a convenient reference for calculating probability of a clear line of sight (PCLoS) for various geometric cloud shapes, namely hemisphere, ellipsoid and semiellipsoid (circular base), isosceles trapezoid (square base) and right-cylinder. They then proceeded to find reasonable agreement of these PCLoS models against observations obtained from the tropical western Pacific (TWP) Atmospheric Radiation Measurement (ARM) sites. A brief review and expository of the PCLoS
model follows below; for complete details, the reader is referred to Taylor and Ellingson [2008] and references therein.

2.1. Application of Probability of Clear Line of Sight (PCLoS) Model

[8] The PCLoS model here assumes individual opaque clouds Poisson-distributed within a plane-parallel, horizontally unbounded layer. For any defined idealized cloud shape, the general expression for PCLoS is then given by [Kauth and Penquite, 1967; Ma, 2004; Taylor and Ellingson, 2008]

\[ P(\theta, \alpha, \ldots) = P(0)^f(\theta_0, \alpha_0, \ldots), \]

where \( P(0) \) is the vertical PCLoS, and \( f(\theta, \alpha, \ldots) \) is defined as the ratio of cloud fractional area projected onto \( \theta \) over that projected onto the horizontal plane \( (\theta = 0) \), called the “shape factor” by Taylor and Ellingson [2008]. The shape factor is generally a function of \( \theta \) and vertical aspect ratio, \( \alpha \), which is defined as the ratio of the cloud’s vertical to horizontal base dimensions, that is

\[ \alpha = \frac{\partial z}{\partial x}, \]

\( x \) being defined in the direction of the viewing azimuth; \( \alpha > 1 \) physically implies clouds taller than they are wide, and vice versa for \( \alpha < 1 \). Note also that

\[ P(0) = 1 - N, \]

where \( N \) is the absolute cloud fraction parameter commonly referred to in the meteorological literature. In this work, we assume \( N \) to be roughly representative of the nadir-viewing probability of a cloudy scene being mischaracterized as clear, which in practice is generally non-zero.

[9] Taylor and Ellingson [2008] found semiellipsoid (hemispherical) cloud shapes provided the best agreement with single-layer marine cumulus cloud observations. This is physically reasonable given that hemispheres best appear to resemble cumuliform clouds, possessing a rounded top and a flat bottom. Physical intuition also suggests that ellipsoids (spheroids) or isosceles trapezoids may best approximate high level clouds (viz., cirrus), and Taylor and Ellingson [2008] noted the latter has the capability to model anvil clouds. Trapezoids also include the special cases of rectangles and triangles. We thus consider these three basic cloud shapes (spheroids, hemispheres and isosceles trapezoids) in the present work, forgoing any further consideration of right cylinders. For spheroidal type clouds (i.e., semiellipsoidal and ellipsoidal clouds with equal horizontal semi-axes \( a = b \)), and major and minor axes, \( a \) and \( c \), aligned with the local horizontal and vertical axes, \( x \) and \( z \), respectively, \( f_\alpha \) is given by [Kauth and Penquite, 1967; Taylor and Ellingson, 2008]

\[ f_\alpha(\theta, \alpha) = \frac{1}{2} \left( 1 + \sqrt{1 + 4\alpha^2 \tan^2(\theta)} \right), \]

hemispherical clouds

\[ \sqrt{1 + \alpha^2 \tan^2(\theta)}, \]

spheroidal clouds.

For isosceles trapezoid cloud shapes (with square bases and edges aligned with \( x \) and \( z \)), an additional parameter is necessary, namely the inclination angle of the cloud sides [e.g., Ma, 2004], \( \zeta \), and the shape factor is derived as

\[ f_\zeta(\theta, \alpha, \zeta) = \begin{cases} 1, & |\theta| < \zeta \\ 1 + \alpha [\tan(\theta) - \tan(\zeta)], & |\theta| \geq \zeta \end{cases} \]

isosceles trapezoidal clouds

which for the special case of \( \zeta = 0 \) reduces to rectangles as given by

\[ f_\zeta(\theta, \alpha) = 1 + \alpha \tan(\theta), \]

rectangular clouds.

Equation (5) also reduces to isosceles triangles for the special case of the maximum possible inclination angle given by \( \max(\zeta) = \arctan\left(\frac{1}{\alpha}\right) \) [Ma, 2004].

2.2. Window Channel Radiance Sensitivity

[10] Figure 1 provides a 2-D schematic showing the application of the PCLoS model for modeling the angular effect of residual clouds (hemispherical shapes) on IR window channel observations. Naber and Weinman [1984] showed that a uniform broken cloud field (modeled as right cylinders or cuboidal arrays) should result in a decrease in observed brightness temperature with zenith angle. Assuming clouds to be isothermal blackbodies overlying a blackbody surface, the variation of average upwelling radiance in a “superwindow” (i.e., an idealized super-transparent micro-window whereby we consider gas attenuation to be negligible) for an ensemble of observations is then approximated simply as [e.g., Naber and Weinman, 1984]

\[ R_{\infty}(\theta, \alpha, T_c, T_e) \approx P(\theta, \alpha)B_e(T_e) + [1 - P(\theta, \alpha)]B_c(T_c), \]

(7)

where \( T_c \) is the cloud temperature. For this idealized case, given \( T_e \), the clear-sky “calculation,” which assumes \( P(\theta, \alpha) = 1 \), would simply be

\[ R_c(T_c) = B_c(T_c). \]

(8)

Taking the inverse Planck functions of radiative transfer equations (RTEs) (7) and (8), and differencing yields

\[ B^{-1}_e(R_e) - B^{-1}_c(R_c) = T_e - B^{-1}_e\left[ P(\theta, \alpha)B_e(T_e) \right] \\
+ [1 - P(\theta, \alpha)]B_c(T_c) \]

(9)

which can be used to calculate the change in brightness temperature resulting from cloud contamination, \( \delta T_{\infty} \). However, to convey the underlying physics, we choose instead to remain in radiance space, directly subtracting RTE (7) from (8)

\[ R_c(T_c) - R_{\infty}(\theta, \alpha, T_c, T_e) = [1 - P(\theta, \alpha)] \cdot [B_c(T_e) - B_c(T_c)]. \]

(10)

and then expressing the dual radiance terms on both sides as linear functions of temperature via first order Taylor series approximations

\[ B_c(T_1) \approx B_c(T_0) + (T_1 - T_0) \frac{\partial B}{\partial T} \bigg|_{T_c} \]

\[ B_c(T_2) \approx B_c(T_0) + (T_2 - T_0) \frac{\partial B}{\partial T} \bigg|_{T_c} \]

\[ \Rightarrow B_c(T_2) - B_c(T_1) \approx (T_2 - T_1) \frac{\partial B}{\partial T} \bigg|_{T_c}. \]

(11)
where $T_0$ is taken to be the mean of $T_1$ and $T_2$. Applying (11) to both sides of (10) results in a simple expression for the ensemble IR brightness temperature difference caused by broken clouds as a function of $q$

$$\delta T_{Bc} \approx \frac{1}{C_0} P(q, a) \left[ \frac{\partial R_n}{\partial T_{sc}} \right] \frac{T_{sc}}{C_2/C_3} \frac{\partial B_n}{\partial T_{sc}} \frac{T_{Bd}}{C_2/C_3}$$

where $dT_{Bc} = B_n / C_0 (R_n) / C_0 B_n / C_0 (R_{nc})$ represents the difference between a clear-sky “calculation,” $T_{Bc}^c$, and a cloud-contaminated “observation,” $T_{Bd}^c$, thus $\delta T_{Bc} = T_{Bc}^c - T_{Bd}^c$, and $\delta T_{sc} = T_s - T_c$ is the difference between the surface and cloud temperatures; the partial derivatives of the Planck function are analytically evaluated at $T_{sc} = T_s + T_c$ in the numerator and denominator, respectively. We have considered the potential errors resulting from using approximation (12) versus equation (9) and have determined that they are completely negligible in the longwave IR (LWIR) window ($<|\delta T|/C_1 < 1\%$), even for large $\delta T_{sc}$, with negligible angular dependence. However, unlike (9), approximation (12) provides a simple sensitivity model which shows direct dependence between the relevant variables, indicating that the angular brightness temperature change is directly proportional to $1/C_0 P(q, a)$ (the probability of a cloudy line of sight) and the surface-cloud temperature difference; the derivatives in the equation incidentally act as the operators locally mapping temperature changes to radiance changes. The approximation breaks down for large $\delta T_{sc}$ in the shortwave IR (SWIR) window (where the Planck radiance dependence on temperature is less linear), in which case strictly speaking equation (9) would have to be used.

The salient dependencies of LWIR $\delta T_{sc}$ indicated by equation (12) may be directly and quantitatively expressed graphically. Figure 2 shows contour plots of computed superwindow $\delta T_{Bc}$ (simulating “calc – obs”) as functions of $\theta$ and $\delta T_{sc}$ for cloud fractions, $N = 1 - P(0) = 0.01$ and 0.02, and aspect ratios $a = 0.25$, 0.5 and 1.0, assuming hemispheric (semiellipsoid) cloud shapes. In a nutshell, the model indicates that a measurable concave-up angular dependence in $\delta T_{Bc}$ is expected even for very small (residual)
$N$ as well as small $\delta T_{sc}$ typical of low-level marine boundary layer (MBL) clouds. The impact of the residual cloud amount $N$ (i.e., the degree of cloud contamination) acts as a near-linear multiplier, as is implied by equations (12) and (1) for small $\delta N$. The surface-cloud temperature difference $dT_{sc}$ acts in a similar manner. The effect is exasperated by larger aspect ratios (i.e., taller clouds), as would also be expected from the larger vertical surface areas.

These results are fundamentally unchanged for calculations in the SWIR, as can be seen in Figure 3, which shows the results for $2616 \text{ cm}^{-1}$ (i.e., the AIRS super-window) using equation (9). Comparison with Figure 2 reveals similar patterns and magnitudes, with the SWIR channel only exhibiting slightly less sensitivity. Furthermore, we compared these against SWIR calculations using the approximation (12) and found only a slight underestimation of the $\delta T_{Be}$ at the larger $\delta T_{sc}$ and $\theta$ (not shown here), thereby not altering the general conclusion. Thus, from here on in this paper calculations are performed for the LWIR window using sensitivity equations similar to (12) derived from the radiance linearization approximation (11) without loss of generality.

### 3. Modeled Impact of an Aerosol Layer

We may consider the angular variation of super-window radiance caused by a uniform, plane-parallel aerosol layer (e.g., Saharan dust) overlying a blackbody surface as

$$R_{sw}(\theta, \tau_{sw}, T_s, T_a) \approx B_v(T_s)T_{sw}(\theta, \tau_{sw}) + \int_{T_{sw}} B_v[T_a(z)]dT_{sw}[\theta, \tau_{sw}(z), z],$$  

where $T_a(z)$ is the aerosol layer temperature at level $z$, and $T_{sw}(\theta, \tau_{sw})$, the aerosol layer IR channel transmittance (assuming negligible scattering), is defined by

$$T_{sw}(\theta, \tau_{sw}(z_1, z_2)) = \exp[-\tau_{sw}(z_1, z_2)\sec(\theta)].$$
where $\tau_{z_1}(z_1, z_2)$ is the aerosol optical depth (AOD) in the IR channel $\nu$ from $z_1$ (bottom) to $z_2$ (top). Defining a mean aerosol layer radiance pertaining to an effective mean temperature $T_a$, that is

$$B_n(T_a) \equiv \frac{1}{\tau_{z_1}} \frac{d}{d\tau_{z_1}} B_n(T) d\tau_{z_1},$$

and applying to equation (13) yields

$$R_n(T_a) \approx B_{n}(T_a) T_s + \frac{1}{C_0} \exp \left( \frac{T_n}{C_1} \right).$$

which is similar in form to equation (7), but is more generally valid for each individual FOV as opposed to a large ensemble.

[14] As above, a clear-sky superwindow “calculation” that assumes $T_{z_1}(\theta, \tau_{z_1}) = 1$, is again simply equation (8), and thus the LWIR $\delta T_{Ba}$ due to aerosol contamination would approximately be

$$\delta T_{Ba}(\nu, \theta, \tau_{z_1}, T_s, \bar{T}_a) \approx [1 - \exp(-\tau_{z_1} \sec \theta)] \frac{B_n}{C_0} \frac{d}{d\tau_{z_1}} B_n(T) d\tau_{z_1} \delta T_{sa}. \tag{16}$$

where $\delta T_{Ba}$ represents $B_{n}^{-1}(R_{n}) - B_{n}^{-1}(R_{so}) \equiv T_{Ba} - T_{Ba}^{ad}$, $\delta T_{sa} = T_s - T_a$ (the difference between the surface and aerosol layer temperatures), and $T_{sa}$ is the mean of $T_s$ and $T_a$.

[15] We again use contour plots to convey the implications of equation (16) for $\delta T_{Ba}$ in Figure 4, which, as above, shows computed superwindow $\delta T_{Ba}$ (simulating “calc – obs”) for AOD contamination with solar-spectrum magnitudes $\tau_a = \{0.05, 0.1, 0.15, 0.2, 0.3, 0.4\}$. Note that because AOD is commonly discussed in solar-spectrum magnitudes (due to the vast preponderance of measurements, both satellite and surface-based, in these wavelengths), we have chosen to present results in these terms. We approximate AOD at IR $\nu$ using $\tau_{z_1} = 0.25 \cdot \tau_{so}$, which Pierangelo et al. [2004] and DeSouza-Machado et al. [2010] both found as a good scaling for comparing dust AOD derived from AIRS against other A-Train visible-band sensors. Based upon the computed $\delta T_{Ba}$ in Figure 4, significant concave-up angular dependence in $\delta T_{Ba}$ is expected due to aerosol contamination (i.e., small $\tau_a$) as well as small $\delta T_{sa}$ typical of lower-tropospheric aeolian aerosol advection. Magnitudes of $\delta T_{Ba}$ for the smaller AOD values in the figure are similar to those $\delta T_{Ba}$ corresponding...
Figure 4. Modeled LWIR sensitivity $\delta T_B (\nu = 909 \, \text{cm}^{-1} ; \lambda = 11.0 \, \mu\text{m})$ due to dust aerosols as a function of surface-aerosol layer temperature difference, $\delta T_{sa}$, and zenith angle $\theta$ for a range of solar spectrum AOD values, $\tau_a = \{0.05, 0.10, 0.15, 0.20, 0.30, 0.40\}$, assuming $\tau_{sa} = \tau_a/4$ dust AOD scaling between IR and solar channels.
to small cloud-fractions in Figure 2. Because of the IR scaling factor, the IR $\delta T_{B_{IR}}$ depicted in the figure is relatively small (spanning only $\approx 0.09$), thereby leading to the near-linear sensitivity seen in the figure as implied by equation (16), similar to the residual cloud contamination discussed in Section 2.2.

4. Modeled Impact of an Aerosol Layer Over/Under Broken Opaque Clouds

[16] We may extend the above models to cases involving both clouds and aerosols. In the first case the aerosol layer is assumed to lie at or below the cloud top heights, that is, $z_a \leq z_c$, and similarly, in the second case the aerosol layer is assumed to lie at or above the cloud bases, $z_a \geq z_c$ (e.g., Saharan dust outflow over the Atlantic). Following the previous lines of reasoning in sections 2.2 and 3, the equations for the angular variation in radiance may be derived as

$$R_c(\theta, \alpha, \tau_{sa}, T_a, T_c, \Delta_T) \approx$$

$$\begin{cases}
P(\theta, \alpha) R_{c0}(\theta, \tau_{sa}, T_c, \Delta_T) + [1 - P(\theta, \alpha)] R_{c1}(\Delta_T), & z_a \leq z_c, \\
T_{sa}(\theta, \tau_{sa}) R_{c0}(\theta, \alpha, T_c, \Delta_T) + [1 - T_{sa}(\theta, \tau_{sa})] R_{c1}(\Delta_T), & z_a \geq z_c,
\end{cases}$$

(17)

where $R_{c0}(\theta, \tau_{sa}, T_a, T_c, \Delta_T)$ and $R_{c1}(\theta, \alpha, T_a, T_c, \Delta_T)$ are the radiances emerging from the aerosol or cloud layers (found in first terms on the right side), given by equations (15) or (7), respectively. Making these substitutions and subtracting from the clear-sky “calculation” (8) yields

$$\delta T_{B_{IR}}(\nu, \theta, \alpha, \tau_{sa}, T_a, T_c, \Delta_T) \approx$$

$$\left(\delta T_{sa}\left[\frac{\partial B_s}{\partial T}\right]_{T_a} - P(\theta, \alpha) \delta T_{sa}\left[\frac{\partial B_s}{\partial T}\right]_{T_a} \right) \left[\frac{\partial B_s}{\partial T}\right]_{T_0}^{-1}$$

$$- P(\theta, \alpha) T_{sa}(\theta, \tau_{sa}) \delta T_{sa}\left[\frac{\partial B_s}{\partial T}\right]_{T_a}^{-1}$$

(18)

and

$$\delta T_{B_{IR}}(\nu, \theta, \alpha, \tau_{sa}, T_a, T_c, \Delta_T) \approx$$

$$\left(\delta T_{sa}\left[\frac{\partial B_s}{\partial T}\right]_{T_a} + T_{sa}(\theta, \tau_{sa}) \delta T_{sa}\left[\frac{\partial B_s}{\partial T}\right]_{T_a} \right) \left[\frac{\partial B_s}{\partial T}\right]_{T_0}^{-1}$$

$$- P(\theta, \alpha) T_{sa}(\theta, \tau_{sa}) \delta T_{sa}\left[\frac{\partial B_s}{\partial T}\right]_{T_a}^{-1},$$

(19)

where $T_{sa}$, $\delta T_{sa}$ and $T_{sa}$ are as defined for equations (12) and (16), respectively, with $T_{sa}$ similarly defined as the mean of $T_a$ and $T_c$ and $\delta T_{sa} \equiv T_a - T_c$. For simplicity, it is useful to consider the special case of $T_a = T_c$, which, after substituting into either (18) or (19), then making the substitution for $T_{sa}$ given by (14), results in

$$\delta T_{B}(\nu, \theta, \alpha, \tau_{sa}, T_a, T_c, \Delta_T) \approx$$

$$[1 - P(\theta, \alpha) \exp(-\tau_{sa} \sec \theta)] \left[\frac{\partial B_s}{\partial T}\right]_{T_a} \delta T_{sa},$$

(20)

which is generally valid for an aerosol layer above or below the cloud layer.

5. Empirical Impact of Aerosols and Residual Clouds

[18] In addition to the simple models discussed above, we may also turn to previous studies empirically examining the impact of aerosols on IR observations. Specifically, Nalli and Stowe [2002] and Nalli and Reynolds [2006] conducted extensive global ocean analyses examining the depression of AVHRR-derived multichannel SST (MCSSST) [e.g., Walton et al., 1998] against buoy meaured SST versus AVHRR 0.63 $\mu$m AOD. It was acknowledged in these papers that there would be an implicit correction for any residual clouds eluding the cloud mask and aliased as AOD. Because these are empirical studies, there are limits of strict applicability, but the results nevertheless are useful in providing an empirical quantitative sense of global mean $\delta T_{B_{IR}}(\theta, \tau_{a})$ resulting from aerosol contamination as follows.

[19] The cloud-masked aerosol correction (i.e., for anomalous levels elevated above background conditions, defined by $\tau_{a} \geq 0.15$) to a MCSSST algorithm trained using a sample with background aerosol and residual cloud conditions (i.e., $\tau_{a} < 0.15$) is given by a linear parametric equation of the form

$$\delta T_{B_{IR}}(\nu, \theta, \alpha, \tau_{sa}, T_a, T_c, \Delta_T) = 0.09,$$

and

$$\delta T_{B_{IR}}(\nu, \theta, \alpha, \tau_{sa}, T_a, T_c, \Delta_T) = 0.09,$$

where $\tau_{sa}$ is the aerosol layer in the aerosol-contaminated observation, $T_a = B^{-1}(R_{sa})$, where $R_{sa} = R_{sa}$ as defined by equation (13), and $\nu$ within the range of $\approx$800–1000 cm$^{-1}$. Thus, the empirical $\delta T_{B_{IR}}$ may be considered to approximate the model $\delta T_{B_{IR}}$ defined by equation (16) and we have

$$\delta T_{B_{IR}}(\theta, \tau_{a}) \approx b_1 \tau_{a} \sec \theta,$$

(21)

where the parameter $b_1$ was empirically determined to be $b_1 = 1.98$ by Nalli and Stowe [2002].

[20] Note that equation (21) has the advantage of having no explicit dependence on $\delta T_{sa}$ as in equation (16), but rather implicitly accounts for a global mean $\delta T_{sa}$ given it was derived from a global multiyear sample. However, we must
keep in mind that this approach is valid insofar as the MCSST used in the training of (21) accurately corrected for water vapor under all aerosol conditions. The premise of the MCSST algorithm is to correct a window channel measurement \( (11\text{ m m}) \) for water vapor given the known variation of continuum absorption in the 800–1000 cm\(^{-1}\) LWIR window. The greater the column H\(_2\)O, the more positive is the split-window difference \( (11–12\text{ m m}) \), which in turn provides the correction as desired. However, larger dust aerosol loading leads to a smaller split-window difference, thereby reducing the H\(_2\)O correction, and thus leading to an additional cold bias artifact not directly related to the aerosol attenuation in a given channel.

[21] Subtracting calculations derived from the hypothetical model equation (16) from those predicted by equation (21), assuming \( \tau_{\text{va}} = \tau_a/4 \) for dust aerosols in a nominal LWIR window channel \( \nu = 909.1\text{ cm}^{-1} (\lambda = 11.0\text{ \mu m}) \), provides a hypothetical estimate of the magnitude of errors to be expected from the use of (21) as given in Figure 6. Note the existence of a zero line, which remains approximately constant in the range of \( \delta_T \approx 8.2 \text{ to } 9.5 \text{ K} \), where the Nalli and Stowe [2002] aerosol correction is in exact agreement with the model prediction given by equation (16). Given that tropospheric aerosols typically reside just above or within the boundary layer, this value is physically reasonable, and corroborates that equation (21) implicitly corrects for a global-mean, ocean surface-aerosol temperature difference \( (8.2 \lesssim \delta_T \lesssim 9.5 \text{ K}) \). Note also that the value of \( \tau_a \) used acts primarily as a multiplier; thus, any minor deviations from our assumption of \( \tau_{\text{va}} = \tau_a/4 \) will not significantly alter the location of the zero line, nor substantially change the overall dependencies. We thus conclude that there is
reasonable agreement between the empirical and modeled aerosol effects.

6. Modeled Impact of a Layer of Broken Semitransparent Clouds

[22] In this section, we generalize the model for Poisson-distributed opaque clouds presented in Section 2 to clouds of a given arbitrary opacity and formulate the ensemble angular variation of superwindow radiance caused by a field of broken semitransparent clouds (assuming negligible IR scattering and that rays do not pass through more than one cloud), as is common with high level clouds composed of ice crystals (viz., cirrus):

\[
R_{\nu}(\theta, \alpha, \tau_{\nu}, T_{s}, \tilde{T}_{c}) = P(\theta, \alpha)B_{\nu}(T_{s}) + [1 - P(\theta, \alpha)]\cdot \{B_{\nu}(T_{s})T_{\nu}(\theta, \tau_{\nu}) + B_{\nu}(\tilde{T}_{c})[1 - T_{\nu}(\theta, \tau_{\nu})]\},
\]

where, similar to aerosols, \(\tilde{T}_{c}\) is the cloud mean temperature, and \(T_{\nu}(\theta, \tau_{\nu})\) is the mean cloud IR transmittance. Because cloud shapes have finite horizontal extents, the cloud mean slant-path optical thickness is a function of the cloud shape and aspect ratio, and thus cannot be determined simply by multiplying by the secant of \(\theta\), but instead is given more generally as

\[
T_{\nu}(\theta, \tau_{\nu_{1}}(z_{1}, z_{2})) = \exp[-\tau_{\nu}(z_{1}, z_{2})S_{\nu}(\theta, \alpha)],
\]

where \(\tau_{\nu}(z_{1}, z_{2})\) is the cloud mean IR optical depth from \(z_{1}\) to \(z_{2}\) (cloud bottom to top), and

\[
S_{\nu}(\theta, \alpha) = \frac{\bar{s}(\theta, \alpha)}{s(\theta, \alpha)}
\]

is the mean slant-path through the cloud shape, \(\bar{s}(\theta, \alpha)\), normalized by its value evaluated at \(\theta = 0\). We derive analytical
expressions of $\mathbf{S}$ for cloud shapes used in the PCLoS model below.

### 6.1. Derivation of Slant-Paths Through Finite Shapes

[23] To arrive at expressions for the mean slant-path $\bar{s}$ through finite idealized shapes, it is convenient to choose a coordinate system $(x', y', z')$ rotated by $\theta$ around the orthogonal horizontal axis $y'$, thus aligning the line of sight with the $z'$ axis. The mean path through the shape (in our case, an idealized cloud) can then be calculated via the mean value theorem in the rotated coordinate system as

$$
\bar{s}(\theta) = \frac{\int_{y_1}^{y_2} \int_{x_1(\theta)}^{x_2(\theta)} [s'(x', y') - s(x', y')]dx'dy}{\int_{y_1}^{y_2} \int_{x_1(\theta)}^{x_2(\theta)} dx'dy},
$$

(25)

where $x'_1(\theta)$ and $x'_2(\theta)$ are the limits of the shape along the axis $x'$ rotated by $\theta$ from $x$, and $s'(x', y')$ and $s(x', y')$ are the analytical expressions describing the shape above and below the $x'$-$y'$ plane, respectively. In the cases of the idealized shapes discussed in this paper, we can then make use of the fact that the numerator in equation (25) is simply the volume of the shape, and that the volume is invariant for any rotation of the cartesian space. This allows simplification of equation (25) as

$$
\bar{s}(\theta) = \frac{V_s}{x_2'(\theta) - x_1'(\theta)|y_2 - y_1|} = \frac{V_s}{\delta x'(\theta)|y_2 - y_1|},
$$

(26)

where $V_s$ is the volume of the shape, and $\delta x'(\theta) \equiv x'_2(\theta) - x'_1(\theta)$ and $\delta y = y_2 - y_1$. Furthermore, the PCLoS model assumes $\delta y = \delta x = \delta x'(0)$, which allows further simplification of (26) as

$$
\bar{s}(\theta) = \frac{V_s}{\delta x'(\theta)}.
$$

(27)

Equation (27) implies that the slant-path for any idealized shape with known volume $V_s$ can be determined given horizontal dimensions that include expressions describing the variation of the integration limits with $\theta$ along the line-of-sight $x'$-axis. However, the dependence on volume in equations (26) or (27) disappears altogether after substituting into equation (24) for normalized slant-path, leaving simply

$$
\mathbf{S}(\theta, \alpha) = \frac{\delta x'(0)}{\delta x'(\theta)} = \frac{\delta z}{\alpha \delta x'(\theta)}.
$$

(28)

[24] As argued at the end of section 2.1, we propose that high level clouds be modeled assuming either trapezoidal, spheroidal or hemispheroidal shapes. We begin by deriving the expressions for isosceles trapezoids (including rectangles and triangles), which is the simplest case.

#### 6.1.1. Trapezoidal, Rectangular and Triangular

[25] Figure 7 provides a diagram of the geometry, which shows that $\delta x'(\theta)$ for a trapezoid can be calculated as

$$
\delta x'(\theta) = \begin{cases} 
\cos(\theta)\delta x, & |\theta| < \zeta \\
\cos(\theta - \zeta)\delta z, & |\theta| \geq \zeta 
\end{cases}
$$

(29)

where $\delta x$ is the larger of either the base or top, and $\theta_d$ is the angle of the diagonal given by

$$
\theta_d = \arctan\left(\frac{\alpha}{1 - \alpha \tan(\zeta)}\right). 
$$

(30)

Recognizing that $\delta x'(0) = \delta x$, the expression for normalized slant-path can thus be derived from equation (28) as

$$
\mathbf{S}(\theta, \alpha) = \begin{cases} 
\sec(\theta), & |\theta| < \zeta \\
\frac{1}{\alpha \sin(\theta_d)\sec(\theta - \theta_d)}, & |\theta| \geq \zeta
\end{cases},
$$

(31)

slant-path, trapezoid.

Note that equations (29)–(31) are also valid for rectangles or triangles, where $\zeta = 0$ or $\zeta = \arctan(\frac{1}{\tan(\zeta)})$, respectively, these being special cases of trapezoids.

#### 6.1.2. Ellipsoidal (Spheroidal)

[26] For ellipsoidal and semielipsoidal (viz., spheroidal and hemispheroidal) shapes, the problem of finding the integration limits is a bit more involved. We consider the case of a spheroid first. Figure 8 provides a diagram showing the geometry for an ellipsoid within the rotated coordinate system $(x', y', z')$ described above. Specifically shown is the $y = 0$ cross-section, which forms an ellipse in the $x-z$ plane. It can be seen that the $x'$ integration limits $x'_1$ and $x'_2$ can be obtained from the inflection points of this ellipse, which we proceed to derive as follows. Using the coordinate transformations $x = x'\cos(\theta) - z'\sin(\theta)$ and $z = x'\sin(\theta) + z'\cos(\theta)$, the equation for an ellipse in the rotated coordinate system is given by

$$
\left[\frac{x'\cos(\theta) - z'\sin(\theta)}{a}\right]^2 + \left[\frac{x'\sin(\theta) + z'\cos(\theta)}{c}\right]^2 = 1. 
$$

(32)

Equation (32) can be solved for $z' \equiv s$ by first rewriting in the monic quadratic form

$$
z'^2 + \frac{B}{C} z' + \frac{A}{C} z' + F = 0, 
$$

(33)

where

$$
A = \frac{\cos^2(\theta)}{a^2} + \frac{\sin^2(\theta)}{c^2},
$$

$$
B = 2\cos(\theta)\sin(\theta)\left(\frac{1}{a^2} - \frac{1}{c^2}\right),
$$

$$
C = \frac{\sin^2(\theta)}{a^2} + \frac{\cos^2(\theta)}{c^2},
$$

$$
F = -1.
$$

Then grouping the terms in (33) as

$$
\frac{B}{C} z' + \left(\frac{A}{C} + F\right) = 0, 
$$

(34)

one can then solve for $z'$ using the quadratic formula. Subsequent simplification of the solution results in

$$
z'(\theta) = \frac{x'(a^2 - c^2)\sin(2\theta) \pm 2ac\sqrt{(a^2 - c^2)\cos^2(\theta) + c^2 - x'^2}}{2[(a^2 - c^2)\cos^2(\theta) + c^2]} = s(\theta).
$$

(35)
and taking the second derivative yields

\[ \frac{\partial^2 x'}{\partial x^2} = \pm \frac{ac}{[(a^2 - c^2)\cos^2(\theta) + c^2 - x'^2]^{3/2}}. \tag{36} \]

Further inspection of Figure 8 reveals that the inflection points occur where the first derivative \( \partial x'/\partial x \rightarrow \infty \); this implies that we may expect that \( \partial^2 x'/\partial x^2 \rightarrow \infty \) at the inflection points as well. This is certainly true for the cases of the ellipse in canonical position (\( \theta = 0^\circ \)) or for a rotation of 90\(^\circ\), where we know that the inflection points are simply \( \pm a \) or \( \pm c \), respectively — in both cases the denominator goes to zero in equation (36). Therefore we seek a solution to

\[ \frac{1}{\partial^2 x'/\partial x^2} = 0, \tag{37} \]

which upon substitution of (36) yields the critical points

\[ x_1'(\theta) = \pm \sqrt{(a^2 - c^2)\cos^2(\theta) + c^2}. \tag{38} \]
To establish that \( x' \) are indeed inflection points, we tested for a change in concavity by evaluating \( \frac{\partial^2 z'}{\partial x'^2} \) at \( x'_c \). The diagram shows the ellipse cross-section at the \( x-z \) plane, with the observer line-of-sight directed along the \( z' \) axis, and is drawn with the vertical semiminor axis \( c = a/2 \) (\( \alpha = 0.5 \)). The \( x' \)-limits for integration, \( x'_1 \) and \( x'_2 \), are derived from the inflection points of the ellipse, \( p_1 \) and \( p_2 \).

**Figure 8.** Same as Figure 7 except showing geometry for an spheroidal cloud (i.e., an ellipsoid with equal horizontal semi-axes, \( a = b \)). The diagram shows the ellipse cross-section at the \( x-z \) plane, with the observer line-of-sight directed along the \( z' \) axis, and is drawn with the vertical semiminor axis \( c = a/2 \) (\( \alpha = 0.5 \)). The \( x' \)-limits for integration, \( x'_1 \) and \( x'_2 \), are derived from the inflection points of the ellipse, \( p_1 \) and \( p_2 \).

For the case of a semiellipsoid (hemispheroid), the situation is similar to that of the ellipsoid (spheroid), except that the \( x' \)-limit at the observer side is no longer at the inflection point, but rather at \( x'_1 = a \cos(\theta) \), as seen in Figure 9. Thus, given equation (38), \( \delta x'(\theta) \) becomes

\[
\frac{\delta x'(\theta)}{x'} = a \cos(\theta) + \sqrt{(a^2 - c^2) \cos^2(\theta) + c^2},
\]

yielding the hemispheroid mean slant-path from (27) as

\[
\bar{s} = \frac{\pi a c}{3 \sqrt{(a^2 - c^2) \cos^2(\theta) + c^2 + a^2 \cos(\theta)}},
\]

and the normalized slant-path in terms of \( \alpha \) as

\[
\bar{s}(\theta, \alpha) = \frac{2}{\cos(\theta) + \sqrt{(1 - 4\alpha^2) \cos^2(\theta) + 4\alpha^2}}; \quad \text{slant-path, hemispheroid.}
\]

### 6.1.4. Discussion

The expressions for normalized mean slant-paths, \( \bar{s} \), as given by equations (31), (41), and (44), are plotted in Figure 10 for shapes with aspect ratios of 0.5. The left plot shows the results on cartesian axes, whereas the right plot shows the same results on polar axes. Slant paths are seen to increase from unity at \( \theta = 0^\circ \) to twice that at \( \theta = 90^\circ \), as expected. The rectangular shape actually experiences a reduction in mean slant path from \( 0^\circ \) to \( 53.1^\circ \), rising a minimum at the diagonal angle, which from equation (30) is \( \theta_y = 26.6^\circ \). This behavior stems from the large reduction in path lengths at the corners. The trapezoid and semiellipsoid (hemispheroid) shapes exhibit similar behavior for this particular trapezoid inclination angle, \( \zeta = 0.75 \times \max(\zeta) = 33.75^\circ \), but this similarity is lost as \( \zeta \) is modified from this value, as seen
Figure 9. Same as Figure 8 except showing geometry for deriving mean slant-path through a hemi-spheroidal cloud (i.e., a semiellipsoid with equal horizontal semi-axes, $a = b$). The diagram shows the semiellipse cross-section at the x-z plane, with the observer line-of-sight directed along the $z'$ axis, and it is drawn with the vertical semiminor axis $c = a/2$ ($\alpha = 0.25$). The $x'_2$ integration limit is derived from the ellipse inflection point $p_2$ as in the spheroid case, but the $x'_1$ limit is derived from the edge of the semimajor axis at $p_1$.

Figure 10. Angular variation of mean normalized slant-path, $\mathcal{S}(\theta, \alpha, \zeta)$, through the idealized cloud shapes considered in this paper: Trapezoids (including rectangles and triangles as special cases), ellipsoids (spheroids) and semiellipsoids (hemispheroids), assuming aspect ratios of 0.5. For the trapezoid, we assumed a nominal value of $\zeta = 33.75^\circ$ by multiplying $\max(\zeta)$ by a factor of 0.75 [e.g., Ma, 2004].
in the results for the rectangle ($\zeta = 0^\circ$) and triangle ($\zeta = 45^\circ$) cases. This is interesting given the potential similarity of the two shapes (both with a flat end and tapered end) and the fact that Ma [2004] found the factor $0.74$ brings the two into closest agreement in terms of the PCLoS. In the polar plot it is interesting to see how the angular variations of $S_q(\theta)$ take on coherent characteristics related to the corresponding shapes.

6.2. Window Channel Radiance Sensitivity

Given expressions for the angular variation of transmittance through finite shapes, equation (23), along with (31), (41), or (44), we return to equation (22). Introducing the cloud effective emissivity, $\varepsilon_{eq}(\theta, \tau_{sc})$, defined from conservation of energy as [e.g., Platt and Stephens, 1980; Ackerman et al., 1990]

$$\varepsilon_{eq}(\theta, \tau_{sc}) = 1 - T_{sc}(\theta, \tau_{sc}),$$

(22) is then be expressed as

$$R_{we}(\theta, \alpha, \tau_{sc}, T_s, \tilde{T}_c) \approx P(\theta, \alpha)B_c(T_s) + [1 - P(\theta, \alpha)]C_{22}T_{sc} \partial B_n/\partial T_c,$$

which may be rewritten in a form analogous to (7), possessing individual surface and cloud emission terms

$$R_{we}(\theta, \alpha, \tau_{sc}, T_s, \tilde{T}_c) \approx [1 - \varepsilon_{eq}(\theta, \tau_{sc})]B_c(T_s) + \varepsilon_{eq}(\theta, \tau_{sc})B_c(\tilde{T}_c),$$

(46)

Subtracting (47) from the clear-sky “calculation” (8), rearranging and canceling terms, then yields a general LWIR cloud sensitivity equation

$$\delta T_{sc}(\nu, \theta, \alpha, \tau_{sc}, T_s, \tilde{T}_c) \approx \varepsilon_{eq}(\theta, \tau_{sc})[1 - P(\theta, \alpha)]C_{22}T_{sc} \delta T_{we},$$

(48)

Figure 11. Modeled LWIR sensitivity $\delta T_{we}$ ($\nu = 909.1 \text{ cm}^{-1}$; $\lambda = 11.0 \text{ \mu m}$) due to non-opaque (semi-transparent) trapezoidal clouds as a function of cloud mean optical depth, $\tau_{sc}$, and zenith angle $\theta$, with residual cloud fraction $N = 0.01$ for aspect ratios (top) $\alpha = 0.25$ and (bottom) $\alpha = 0.5$ and surface-cloud layer temperature differences (left) $\delta T_{sc} = 40 \text{ K}$, (middle) $\delta T_{sc} = 60 \text{ K}$, and (right) $\delta T_{sc} = 80 \text{ K}$. The equivalent values of cloud nadir-view effective emissivity, $\varepsilon_{eq}(\theta = 0, \tau_{sc})$, are given on the right y-axes for reference. As in Figure 10, nominal values of $\zeta$ are arrived at via $0.75 \times \max(\zeta)$ [e.g., Ma, 2004].
Figure 12. Same as Figure 11 except due to ellipsoidal (spheroidal) clouds.
which reduces to the special case of opaque clouds, equation (12), for $t_{nc} \to \infty$, $\varepsilon_{nc}(\theta, t_{nc}) = 1$. Note that the term $\varepsilon_{nc}(\theta)[1 - P(\theta, \alpha)]$ represents the “effective cloud fraction,” a cloud parameter retrieved by IR sounders (viz., CrIMSS, IASI and AIRS) as will be discussed in part 2. Equation (48) implies that $\delta T_{Bc}$ results from this parameter, which is a multiplicative combination of two effects, namely non-unity PCLoS, $P(\theta, \alpha) < 1$, along with non-zero effective emissivity, $\varepsilon_{nc}(\theta, t_{nc}) > 0$. Because increasing $\theta$ brings about a decrease in $P(\theta, \alpha)$ and a simultaneous increase in $\varepsilon_{nc}(\theta, t_{nc})$ (for clouds with $\alpha < 1$), both effects act in the same direction with increasing angle. Increasing $\alpha$ serves to increase the angular impact of $P$, while simultaneously reducing the impact of $\varepsilon_{nc}$.

[30] Figures 11–13 show contour plots of computed LWIR superwindow $\delta T_{Bc}$ for high clouds modeled as semi-transparent (non-opaque) trapezoids, spheroids and hemispheroids, respectively, with residual absolute cloud fraction ($N = 0.01$) at mid-to-high altitude temperatures (e.g., characteristic of cirrus). The $\gamma$-axes span the range $\tau_{vc}$ considered to be “transmissive” or non-opaque, namely $\tau_{vc} < 3.0$ [e.g., Wylie et al., 2005], and this is verified by the nadir-view cloud effective emissivities ($\varepsilon_{nc}$) shown on the right axes calculated from equations (45) and (23). As in results above, there is a comparable, measurable impact of residual clouds on the angular variation of radiance, even for optically “thin” clouds (i.e., $\tau_{vc} < 0.7$) [e.g., Wylie et al., 2005] with small $\alpha$. Comparisons between the top and bottom plots of each figure show the impact of vertical extent (manifested by $\alpha$), which has little impact on optically thin clouds, but larger impact on the optically “thick” clouds ($0.7 < \tau_{vc} < 3.0$) [e.g., Wylie et al., 2005] as is expected from equation (48), as the effect of reduced PCLoS becomes maximized with opaque, high emissivity clouds. The spheroidal cloud shapes, on the other hand, yield somewhat reduced magnitudes at larger $\tau_{vc}$ and $t_{nc}$ (or $\varepsilon_{nc}$) (i.e., the upper right domains in the plots). This stems primarily from the effect of reduced PCLoS, given that this domain (high $\tau_{vc}$ and $t_{nc}$) constitutes opaque clouds, as indicated by the reduced dependence on $\tau_{vc}$ (i.e., isolines running more parallel to $\gamma$). Physically, this is a consequence of the rounded bottoms of the spheroids, which intercept less obliquely oriented rays.

7. Summary and Conclusion

[31] Because IR-based physical retrieval algorithms for EDR products (e.g., AVTP, AVMP, skin SST, etc.) operate
on the premise of minimizing clear-sky obs — calc, where obs and calc are clear-sky observations and forward model calculations, respectively, it is important that differences between obs and calc be minimal under well-characterized conditions. In this vein, comparative analyses of calc and obs are often employed to improve the forward model physics, or otherwise “tune” the model for use with a particular sensor. In performing global analyses of this sort, however, there is an implicit assumption of accurate “clear-sky observations.” In this work, we revisited this assumption with consideration given to the fact that global clear-sky observations themselves are usually obtained from either cloud-masking (in the case of imagers) or cloud-clearing (in the case of sounders), and therefore in actuality constitute “products.” Furthermore, cloud-masking and cloud-clearing algorithms are not generally designed to mask or correct for aerosols. Because of this, clear-sky observations will be subject to algorithmic errors beyond that of the sensor itself; this effect being referred to as residual cloud and/or aerosol contamination. Generally speaking, residual clouds and aerosols remaining in clear-sky window radiances will lead to an obs that is cold-biased [e.g., Benner and Curry, 1998; Nalli and Stowe, 2002; Sokolik, 2002; Maddy et al., 2011]. This work has explored this issue with attention given to the potential for angular dependence resulting from residual cloud and/or aerosol contamination. In this paper, we presented idealized models that assume that residual cloud contamination may result in a signal similar to observations obtained from a uniform cloud field with a very small cloud fraction, where the probability of clear lines of sight (PCLoS) fundamentally diminishes with zeroing observing angle. To model quantitatively the sensitivity of residual clouds on “superwindow” radiances, we uniquely applied PCLoS models previously developed [for applications different from ours] for single-layer broken opaque clouds (viz., Kauth and Penguine [1967] and Taylor and Ellingson [2008]). Simple equations were derived for computing the impact of opaque broken clouds on superwindow brightness temperatures, with similar equations derived for the impact of contamination by an aerosol layer, first in isolation, then over or underlying a cloud layer. The aerosol modeling results were then found to be reasonably consistent with previous global empirical parametric analyses using satellite imager data [e.g., Nalli and Stowe, 2002; Nalli and Reynolds, 2006]. We then generalized the expression for opaque clouds to include semitransparent (non-opaque) clouds (viz., high-level cold clouds composed of ice-crystals). The latter effort required deriving analytical expressions for calculating the mean slant-paths through finite idealized shapes. [33] Overall this work suggests that the possibility of contamination by residual clouds and/or aerosols within clear-sky observations can have a measurable concave-up impact on the angular agreement with clear-sky calculations that do not, by definition, take into account these missing transmittance terms (i.e., residual clouds and/or aerosols). Our hypothetical “superwindow” sensitivity models predict increasing cold bias in contaminated “observations” with zenith angle on the order of tenths of Kelvin, the actual magnitudes depending variously on the residual N and τrus (i.e., the degree of cloud contamination), the residual AOD (i.e., the degree of aerosol contamination), the 8T between the surface and the residual cloud/aerosol layers, and the cloud shape and vertical aspect ratio. The angular dependence physically stems from the increased probability of clouds at these angles, as well as increased optical path in cases of non-opaque clouds with α < 1. The same goes for aerosol contamination due to increased optical path through the aerosol layer with angle. In the case of semitransparent clouds, the two effects tend to compensate each other: Larger (smaller) aspect ratios imply taller (shorter) clouds, which tend to enhance (reduce) the fundamental decrease in PCLoS (increase in cloudiness) with angle, but also reduce (enhance) the increase of slant-path (which can even be reversed in the cases of α > 1, assuming rays do not traverse more than one cloud). While the assumed cloud shapes have an impact the results, these do not change the main thesis in any way. In all cases, the magnitudes are directly sensitive to the temperature difference between the cloud/aerosol layer and the surface. We test these hypothetical sensitivity results with experimental data in part 2.

References


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